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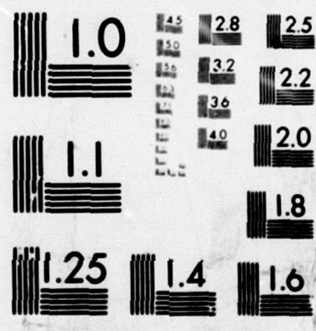

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Final Technical Report
September 1979

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INVESTIGATION OF IN SITU COMPOSITES FOR ELECTROMAGNETIC DEVICE APPLICATIONS; WITH EMPHASIS ON DEVELOPMENT OF MICROWAVE TUBE CATHODES AND HIGH RESOLUTION DISPLAYS

Georgia Institute of Technology

John W. Goodrum, et al

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in-situ composite	field emission cathodes
eutectic composites	solar cell
directionally solidified eutectics	photovoltaic cell
displays	strain gauge
cold cathodes	eutectics (cont'd on reverse)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report documents the results of a study to evaluate the potential of eutectic composite materials for use in electronic, optical and other devices. The composite materials may be a combination of metal-metal, metal-semiconductor, semiconductor-semiconductor, semiconductor-insulator, or insulator-insulator classes of materials.

Device concepts, based on eutectic composites, were given preliminary → next page (Cont'd)

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19. Key Words (continued)

electron beam
microwave tube
photodiodes
thin-film luminescent display
infrared detector
magnetic sensor
electro-optic devices

20. Abstract (continued)

technical and economic evaluation; brief descriptions of promising devices are listed. Eutectic-based cold cathode and display devices were evaluated by experiments to determine the performance of a prototype cathode device and to determine the design requirements for fabrication of a diode-type display.

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EVALUATION

This effort has identified and described half a dozen distinct electromagnetic device categories utilizing in situ formed composites. They cover a wide range of Air Force functional applications requiring advanced device and materials capabilities. Some may warrant designation as future-technology or application far in advance of expressed or perceived need; i.e., "look forward twenty years."

Time, manpower and jurisdictional or mission limits have permitted experimental investigation only in the areas of:

(1) Field-effect emitters (cold cathodes).

(2) Miniaturized, high resolution displays.

This work fits into the RADC Technology Plan under TPO 5 - C^3 System Availability; Thrust - Advanced C^3 Electronic Materials and Devices.

The intended application of aligned needle-array composite field-effect emitters is to supersede thermionic cathodes in microwave tubes in order to gain the obvious advantages of instant-on operation, long lifetime, ruggedness and reliability; with concomitant cost-to-lifetime benefit.

The intended application of the composite-based display is as a helmet-mounted, head-up display having high resolution and rapid refresh capability.

JOSEPH J. HUTTA
Contract Monitor

I. Introduction: Background on In-Situ Composites

In recent years it has been demonstrated that one can prepare a wide range of eutectic materials whose microstructure consists of geometrically aligned phases. For example, the synthesis of parallel one-micron semiconductor rods (Si) in an aluminum matrix has been demonstrated (Filonenko, '72). Researchers have prepared eutectics which contain combinations of many types of materials ranging from metal-insulator to semiconductor-semiconductor to insulator-semiconductor, etc. Many combinations of optical, I.R., superconducting, and magnetic characteristics have been experimentally prepared.

The work in this report is the result of a broad-scope effort in the field of in-situ grown composite materials. The intent of this project was to identify highly promising device concepts in the early phase of the program, and to conduct experiments to prove out technical feasibility in later stages of the program.

Among the most promising new eutectic applications pursued during this program is the field emitter array for microwave cathodes. Continual use of microwave tubes will be essential for a number of years to come, since neither existing nor projected solid state devices can fill Air Force needs for both power and high frequency. Composite cold cathodes, or thermal-field cathodes, have inherent potential for high power and particularly high power and high frequency microwave cathodes. Currently, additional programs are being initiated by both the Air Force and Navy to continue development of high performance cathodes based on field emission in composite materials (see later sections).

These new materials hold great promise for application in a wide range of current and future electro-magnetic devices. Directional solidification permits one to "fabricate" composites containing geometrical arrangements of micron-sized structures made up of two or more materials. One may also select, from a wide range of components, materials to combine into a eutectic structure which has optimal properties for a given device. In addition, dramatic increases in specific bulk properties, such as magnetic anisotropy, may be obtained by proper selection of eutectic components. In the latter case, a synergistic effect has been observed: the magnitude of a composite property may be greater than that property exhibited by the pure component materials. It is conceivable that by proper combining of materials, relatively weak optical, magnetic, etc., effects may be amplified in a eutectic composite to usable magnitudes and thereby make possible new electro-optic devices.

In very broad terms, composites offer the device fabricator a means of "designing around" the fundamental limitations most single-phase materials present to the developer of electro-magnetic devices. A great many radiation detectors, semiconductor diodes, etc., require combinations of properties that are not found in single-phase materials, e.g., a solar cell requires the photoelectric response of a semiconductor and the low resistance of an electrical conductor. Working devices, with less than theoretical efficiencies are usually based on compromise designs which work around the basic limitations of single-phase materials.

I.A. Objectives of the Program

This program was conducted in order to identify possible electronic, electromagnetic, or electro-optic device applications of controlled-microstructure eutectics ("in-situ grown composites"). This was accomplished by means of a coordinated interdisciplinary study, involving staff members active in the areas of electronic devices and materials science. The study was directed under the constraint that the ultimate goals of this program would be totally new devices or device components or significant improvements in the efficiency or function of state-of-the-art devices.

Concurrently with device identification efforts, eutectics likely to be useful as device materials were screened from among various literature sources. Phase equilibria, solidification kinetics, and other pertinent data were reviewed, and extrapolated when deemed useful and rational, in order to postulate the existence of new eutectic materials with device potential.

Specific objectives of this program included: (1) the analysis of a comprehensive literature base, (2) identification and analysis of new device concepts, and (3) limited experimental activity to further evaluate interesting device concepts. In the initial phase, the program was operated in an iterative fashion, in order to survey many classes of eutectic materials and many classes of devices. Starting with either a known device concept or new concepts generated by the project staff, the objective was to discover, by comparing various combinations of properties, how one could go from the initial point (A) to point (B) at which a eutectic-based device and corresponding eutectics could be described. An alternative approach would have been to select specific in-situ composites, determine or estimate their properties, and match that combination of geometrical, electrical, etc., characteristics with the requirement of various devices. This latter approach to the study was rejected at the outset as too narrow since this entire study may well have been limited to evaluation of two or three composite materials.

I.B. Research Plan

The study plan was designed so that the research effort was based on a systematic procedure that leads to the desired objectives. The plan consisted of a sequence of tasks leading from a thorough review of background information to the evaluation of new device applications of controlled-microstructure eutectics.

This study was conducted in an on-going iterative sequence, based upon Tasks I through III described below. The procedure was continued for the duration of the contract period. Thus, as information was added to the data base, it was reviewed by the interdisciplinary technical staff for (1) potential device applications and (2) basic materials information relating to the formation or characteristics of in-situ grown composites. Frequent staff meetings were held in order to facilitate the exchange of ideas and to speed the evaluation of concepts identified during the course of this study.

Task 1. Establish a literature base.

The purpose of this task was to collect and compile available technical information relevant to device applications of controlled-microstructure eutectics.

The data collected included all pertinent information related to the development of devices from eutectic-type composite materials. Also, information relating to the practical and theoretical range of composite material characteristics and factors which control the development of eutectic microstructures was included in the literature base.

The output of Task I served as input for Task II.

Task 2. Preliminary search for new devices/applications and useful eutectic systems.

The task included choosing broad bases for selecting eutectic materials for device categories. Using these materials criteria, the data were scanned to identify eutectics or specific micro-structures which have the general characteristics required for device application(s). Subsequent scans were made specifically to identify data which had relevance to a specific device or class of devices (e.g., I.R. detectors).

This task included consideration of technically innovative device applications of composites, such as:

(a) compact, high resolution displays

(b) more sensitive I.R detectors

(c) electronic components based on low voltage cold cathode elements.

Output of this task served as input for task III, the preliminary technical evaluation of device candidates and eutectic systems.

Task 3. Preliminary technical and economic analysis.

The purpose of this task was to review the technical and economic feasibility of the device candidates and eutectic systems identified in Task II and to identify the pacing technology required to improve the attractiveness of some of the devices.

This task utilized data collected in Task I on the current and projected feasibility of specific composite material applications. Candidate composite materials for devices had to meet the general criteria of (1) promise of significant improvement in state-of-the-art in communications, energy conversion and other applications, (2) technical feasibility, and (3) economic viability (economically competitive).

Task 4. Experimental studies.

The purpose of this task was to evaluate key elements of conceptual device designs and also to conduct limited prototype development experiments.

The most promising device concepts identified in terms of technical/economic feasibility and in terms of projected Air Force needs, were further evaluated. This task was confined to limited (1) prototype studies of a field emission cathode and (2) experimental evaluation of display concepts.

Task 5. Reporting results of study.

The purpose of this task was to assure that project results were effectively disseminated to the Air Force and interested D.O.D. agencies.

This task involved preparation of materials for several conference presentations as well as the compilation of interim reports and a final report. Report material approved by the Solid State Sciences Laboratory, Hanscom AFB, was published in the proceedings of the Materials Research Society.

This task included the collection and compilation of the results of Tasks I through IV and the preparation of additional material, as required by the results of Task IV, for the final report.

The main body of the report includes the methodology, procedure, data, findings, rationale and recommendations. The primary emphasis of the main body of the report is on the experimental phases of the program effort. This includes descriptions of preliminary material characterization, prototype device fabrication, and the results of device characterization analyses. The main body of the report will also include a series of concise summaries of study findings on specific new device applications.

I.C. Project Organization and Management

The study was conducted as a cooperative interdisciplinary effort between staff members of the Georgia Institute of Technology. The study was coordinated by Dr. John W. Goodrum, who served as principal investigator and had overall supervisory and administrative responsibility for the program. The study team to support Dr. Goodrum included personnel with backgrounds in solid state physics, ceramics, electrical engineering, metallurgy, and other areas.

II. Cold Cathode Devices Based on Field Emission from Composite Materials

II.A. Introduction

The current and projected needs for improved cathodes for microwave tubes and other applications has led to a renewed interest in field emission, and also thermal field emission. Much of the renewed interest is due to the development of eutectic composite materials containing arrays of aligned needle-like structures which are efficient electron emitters. These materials are still in the process of development; however, extensive testing of diode structures has been conducted by several groups including Chapman et al. at Georgia Tech.

An additional application involves exploitation of the small beam size and high intensity of a field emission electron beam. There is a projected need for small (0.5μ), intense (10^5 A/cm^2) beams for electron lithography in the fabrication of high speed (VHSI) and large scale (VLSI) integrated circuits. Currently, circuit dimensions on the order of 5 microns are attained, but it would be desirable to obtain 0.5 micron dimensions. Considine et al.[1] have shown that lanthanum hexaboride and other field emission materials are capable of at least (10^7) A/cm^2 in a beam focused to 0.5 micron dia. spot.

For many years the idea of employing field emitters as cathodes for microwave tubes has been an attractive one. The obvious advantages of eliminating the heater, instant warmup, emission densities in excess of those achievable from thermionic cathodes, long life, and high reliability have appealed to both tube and systems designers. Unfortunately, progress in developing field emitters has been disappointing. Erratic and unpredictable performance has, until recently, relegated the field emitter to the role of a laboratory curiosity, as opposed to a useful tool for the microwave tube designer.

Recently, efforts have been initiated at the Naval Research Laboratory, Air Force Avionics Lab, and several academic laboratories to further pursue the development of field emission microwave cathodes. It is felt that the above projects, making use of the results of this and other studies, will lead to development of a reliable high performance cold cathode for tubes.

If one considers the current status of solid state microwave devices, and also the expected progress in solid state development, the continued future need for cathodes for high power, high frequency mw tubes is apparent. Note in Table I that power output at higher frequencies is a fraction of a watt. The field emission cathode, with its unique potential for simplicity, instant switch-on, and high beam intensity, appears to be an exciting area for developmental cathode studies. The continuing improvement in composite emitters, including the low voltage configurations, is a key element in the viability of field emission as a basis for improved cathodes.

II.B. Background

In recent years the Schools of Ceramic and Electrical Engineering at Georgia Tech have been studying the use of melt-grown oxide-metal composites for high field-effect electron emitters. This work has progressed to the extent that emitting arrays consisting of W fibers aligned in a UO_2 matrix, possessing the geometry shown in Figure 1, have produced emission current densities of up to 1 A/cm^2 for several hundred hours. Thus these emitters have current densities and operating lifetimes that are attractive for a variety of electronic and related applications.

At the time this study was conducted the W-UO_2 represented the best available eutectic for testing purposes (see Figure 1). In theory, there are many potential in-situ composites which could provide the array of emitting pins needed for a cold-cathode. The needle phase might be a refractory boride (i.e., Lanthanum hexaboride [7]), carbide or nitride compound, as well as refractory elements such as tungsten or molydenum. In particular, if the needle component has a low work function potential, then an applied field may be able to more efficiently extract an electron beam at lower voltages. It is

TABLE I. IMPATT DIODE LABORATORY RESULTS *
April, 1978

Freq. (GHz)	Power Output(W)	Eff. (%)	Mode of Operation PW	Mode of Operation DC	Material	Structure	Comments
4.8	29.5	29.5	CW		GaAs	SDR	
6.8	15.3	23.4	1 μsec	20%	GaAs	SDR	
8.6	30	23	1 μsec	10%	GaAs	DDR	
8.7	22.5	20.5	CW		GaAs	SDR	series/parallel chips (6)
9.0	23	20.8	1 μsec	25%	GaAs	DDR	
9.4	9.7	26.5	CW		GaAs	DDR	
11.5	60.4	24.9	1 μsec	20%	GaAs	SDR	series chips (4)
13	20.5	21	1 μsec	10%	GaAs	DDR	
12.0	28.0	16	1 μsec	20%	GaAs	DDR	series chips (2)
14	3.5	16.8	CW		GaAs	DDR	
15.4	15	18	1 μsec	10%	GaAs	DDR	
35	17.4	5	1 μsec	10%	Si	DDF	epi-grown
40	1.7	12	CW		Si	DDF	epi-grown
40	11.5	5.8	100 nsec	10%	Si	DDF	epi-grown
60	0.8	6	CW		Si	DDF	epi-grown
94	0.5	5	CW		Si	DDF	epi-grown
94	9.2	6	100 nsec	0.5%	Si	DDF	epi-grown
130	0.8	4.6	50 nsec	0.1%	Si	DDF	ion-implanted
140	0.1	3	CW		Si	DDF	ion-implanted
170	0.03	1	CW		Si	DDF	ion-implanted
213	0.5	2.6	50 nsec	0.5%	Si	DDF	ion-implanted
225	0.01	1	CW		Si	DDF	ion-implanted

* Data Obtained from AFAL

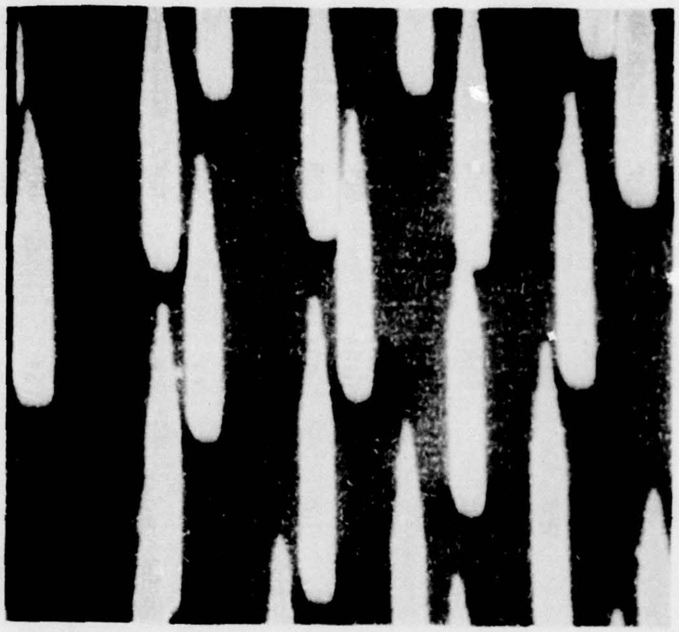


Figure 1. Scanning Electron Micrograph of UO_2-W Composite Containing Approximately 1.5 w/o W Displaying Widely Spaced Fibers.

hoped that future efforts will be directed toward development of such new in-situ composites. An example of the known eutectics of the metal/metal oxide type is given in Table II.

Recently, Dr. Jules Levine of RCA experimented with different cathode-anode geometries using the Georgia Tech UO_2-W field emitter, and has achieved much higher current densities. The highest currents achieved were on the order of 1000 A/cm^2. He also ran one life test to 1200 hours with a sample operating at 1000 A/cm^2. The life test was accidentally terminated at that point. Best results at RCA were achieved with a macroscopically pointed field emitter, operating in a tapered cylindrical anode.

The UO_2-W composite is produced by a modified floating zone process to form single crystals. The net result is 10 million uniformly spaced continuous 0.3 micron diameter tungsten fibers per square centimeter imbedded in a UO_2 matrix. Reproducible samples 2 cm long × 2.5 cm diameter are produced. Etching removes the UO_2 more rapidly than the tungsten, so the tungsten fibers extend above the UO_2 after etching, and the fibers are also sharp (<0.1 micron spherical radius).

II.B.1. Advantages and Geometry of Low Voltage Field Emitters

A technique has been developed to fabricate a low voltage field emitter (LVFE) based on UO_2-W composites. The geometry of the cathode consists of an array of free standing tungsten fibers with each fiber centered in individual conical holes in a thin film insulator layer and a metal extractor layer. Fabrication of the structure was made possible by the discovery that when immobile materials are vapor deposited by line of site deposition parallel to the axes of exposed fibers, the film on the fiber tip grows laterally as the thickness increases producing a deposit shaped like an ice cream cone. The lateral growth of the cone provides a mask to shadow the area surrounding the fibers which resulted in free standing fibers centered in cones in the deposited film

TABLE II. KNOWN METAL/INSULATOR EUTECTICS**

Well-Defined Eutectics

Oxide Phase	Metal Phase	Ref.***
$(Al,Cr)_2O_3$	Cr	3
$(Al,Cr)_2O_3$	Mo	1
$(Al,Cr)_2O_3$	W	1
CeO_2	Mo	*,2
CeO_2	W	*,2
Cr_2O_3	Cr	4
Cr_2O_3	Mo	5
Cr_2O_3	Nb	9
Cr_2O_3	Re	5
Cr_2O_3	Ta	9
Cr_2O_3	V	9
Cr_2O_3	W	5
$Er_2O_3(CeO_2)$	Mo	2
$Gd_2O_3(CeO_2)$	Mo	5
$Gd_2O_3(CeO_2)$	W	5
GeO_2	Ge	4
$HfO_2(CeO_2)$	W	6
$HfO_2(Y_2O_3)$	W	6
$Ho_2O_3(CeO_2)$	Mo	2
$La_2O_3(CeO_2)$	Mo	2
$La_2O_3(CeO_2)$	W	2
MgO	W	5
$Nd_2O_3(CeO_2)$	Mo	2
$Nd_2O_3(CeO_2)$	W	2
Sm_2O_3	W	*
$Sm_2O_3(CeO_2)$	W	*
UO_2	Nb	7
UO_2	Ta	7
UO_2	W	8
Y_2O_3	Ta	*
$Y_2O_3(CeO_2)$	Mo	*,2
$Y_2O_3(CeO_2)$	W	2
ZrO_2	Ta	9

Ill-Defined Doubtful Eutectics

Oxide Phase	Metal Phase	Ref.***
$CeO_2(ZrO_2)$	W	*
La_2O_3	Mo	2
La_2O_3	W	2
Nd_2O_3	Mo	2
Nd_2O_3	W	2
TiO_2	Cr	9
TiO_2	Mo	*
TiO_2	Nb	9
TiO_2	Ta	9
UO_2	Mo	7
$Y_2O_3(CeO_2)$	Ta	*
Y_2O_2	Mo	*
ZrO_2	W	*

* This study.

** Adapted from reference 76 B J
Briggs, J., and P.E. Hart, "Refractory Oxide-Metal Eutectics," Journal of the American Ceramic Society-Discussions and Notes, Vol. 59, No. 11-12, p. 530, 1976.

*** References listed at end of Section II.

on the substrate. (See Figures 2 and 3.)

The technique provides for independent variation of the dimensions of each feature of the structure. Cathode array density variations are provided by UO_2-W unidirectionally solidified eutectic composites which are available in fiber packing densities of 1 to $50 \times 10^6/cm^2$. Variation of W cathode (fiber) height and shape is accomplished by time variation of chemical etches to provide cylindrical tipped or conical tipped fibers of desired height. In addition, the shape of the fiber tip may be varied from a right circular cylinder, to a hemisphere, to a pointed tip in that order by argon milling for increasing periods of time.

The thickness of the insulator and extractor layer may be varied to any desired thickness to match the length of the W fiber cathode. Thus the tip of the fiber can be placed above, at the level of, or below the metal extractor grid. The diameter of the holes in the extractor grid is dependent on the insulator layer thickness for a single deposition but by removal of cathode cones and multiple insulator deposition, the extractor grid hole diameter can be varied independently of the insulator layer thickness. As a result, any desired dimensions of the emitter structure can be produced by this technique.

Low voltage emission testing has demonstrated that 60-80 volts will initiate field emission and at 180 volts macroscopic current densities of 14.0 A/cm^2 has been obtained under pulsed conditions.

Cathodes of this type offer several advantages compared to the exposed parallel fiber arrays tested in this work. First, the grid structure of the LVFE provides an identical field for each fiber and thereby provides uniform emission across the array. This eliminates edge effects and should allow much higher current densities than even that already demonstrated. Secondly, the low operating voltages should reduce pin failure and increase lifetime. At the low voltages, ionization is decreased significantly and any ions that are

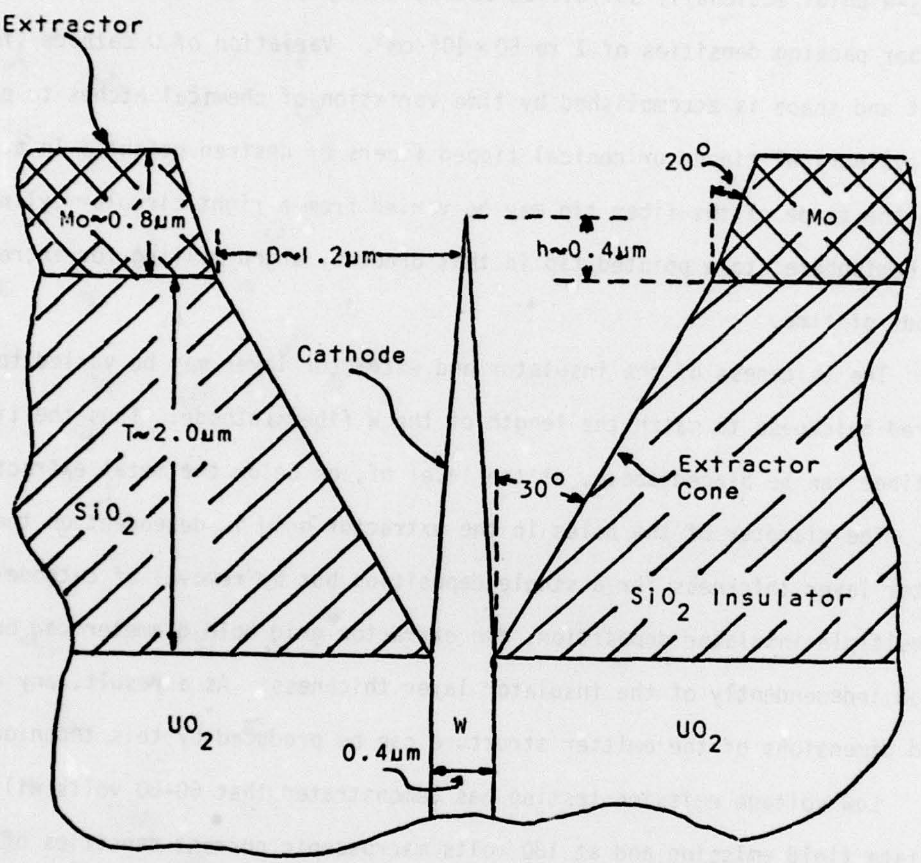


Figure 2. Schematic Diagram of a Single LVFE Showing Typical Dimensions.

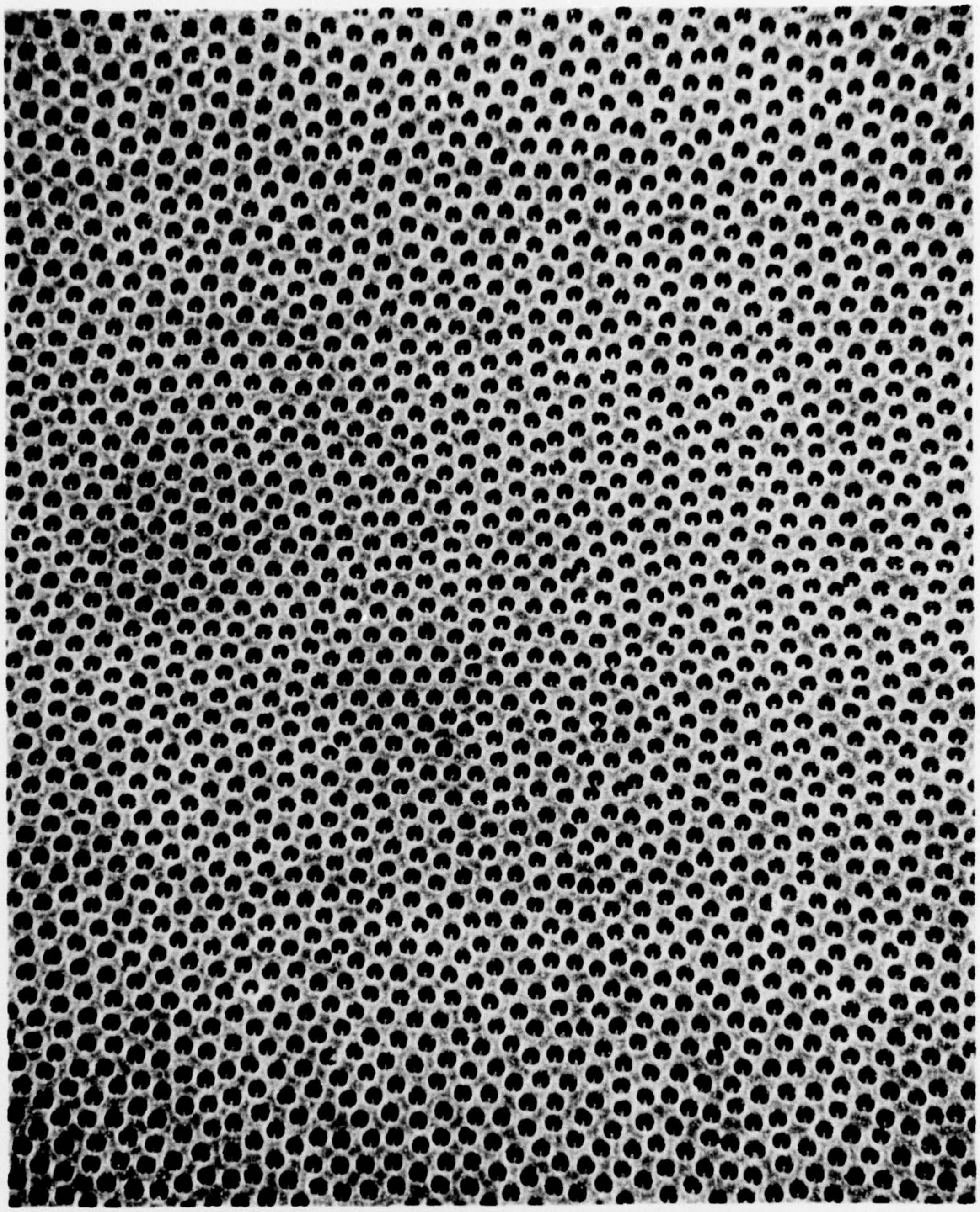


Figure 3. Scanning Electron Micrograph of a UO_2-W Low Voltage Field Emitter Array, 1.3 KX, 30° Tilt.

created have low energy due to the low voltage. Thus, erosion caused by ion bombardment is minimized. In addition, the LVFE has all the advantages of the conventional field emitter, i.e., instant on, high brightness, cold operation, etc.

II.C. Development of Cold Cathode Devices for Microwave and Other Applications

Based on the study objective to evaluate eutectic materials and based on the need for improved cathodes for Air Force microwave tubes, a project to examine a eutectic material as tube cathode element was conducted. The objective was to demonstrate technical feasibility by operation of a prototype device generally compatible with the requirements of a microwave tube. This prototype development work was regarded as a step toward the ultimate goal of producing an electron source suitable for one or more microwave tubes.

II.C.1. Conceptual and Engineering Designs

The development of conceptual and engineering designs involved (1) addressing several general problems associated with field emission devices, and (2) integrating the known properties of composite emitters into realistic prototype designs.

A primary problem addressed in the design concepts was obtaining large, stable currents. Existing thermonic cathodes provide electron beams of 50 mA or more in operational microwave tubes. Total currents of this magnitude have been difficult to extract from field emission devices. Single pins, for example, normally are capable of no more than 100-200 μA currents. Composite emitters with arrays of pins have produced total currents of a few milliamps.

A further and critical design concept area lay in the identification of microwave beam geometrics which are compatible with the electrode configuration required for field emitters. Also included in this area are the needs to reconcile the conditions of field, etc. for field emission with the dimensions and electric and magnetic fields often present in a microwave tube. One problem area is beam transmission through an anode aperture. It is assumed that the electron beam must be transmitted from the cathode device into other tube elements for modulation, etc. For example, in a klystron or O-type TWT, it is necessary to have a dense, usually cylindrical (solid or hollow), constant velocity electron beam, interact with cavities or a slow wave circuit. This is usually accomplished by having an aperture in the anode. The aperture may be lightly gridded if power density is sufficiently low. If a field emitter were used in a conventional gun design, the edge effect problem would have to be overcome so that the cathode-anode spacing could be large compared to the aperture size. Otherwise, the aperture would reduce the electric field at the cathode and limit emission. An anode grid would severely limit beam power density. Alternately, a control grid could be employed to provide the high cathode field. If a conventional control grid which intercepts electrons on a strictly geometrical basis were used, electron beam power would be severely limited. On the other hand, a shadow grid would circumvent this problem, but an innovative design would be required to overcome the reduction of field at the cathode surface caused by the grid holes. The low voltage field emitter being investigated by Dr. J.K. Cochran at Georgia Tech would be a solution to this problem.

Another general problem area is consideration of space charge effects on a field emission device. All conventional electron guns are space charge limited. Therefore, the electric field at the cathode surface is zero. Clearly, a field emitter could not be operated space charge limited because with zero field at the cathode surface, there could be no emission. There will be sufficient space charge to cause a significant field reduction, however, and design procedures must take space charge into account. The procedure for doing this is straightforward, but needs to be carried out.

It has been demonstrated by Chapman, Feeney, and their students that the exposed-pin composite will emit reliably at current densities in the neighborhood of 1 A/cm^2. This work was done primarily with planar geometry, and no effort was made to get electrons past the anode.[2,3] Levine, at RCA, achieved much higher current densities from a stylus-shaped cathode, and also succeeded in getting a fair percentage of the current through an anode aperture.[4] Efforts to increase the cathode area to increase total current were generally unsuccessful because the enhanced field at the edge of the cathode caused only the edge pins to emit. This problem had pushed most of the work in the exposed-pin emitter area toward geometries like the RCA stylus, resulting in much higher current densities, but less total current. Both Chapman and Levine had operated high voltage devices for long periods of time at high current densities and total currents of a few mA. These studies left many unanswered questions as to the suitability of the composite field emitter as a cathode element in vacuum tubes. We therefore decided that a series of engineering feasibility experiments seemed the most promising approach to further evaluate the potential use of this material.

Alternatively, we could have opted for more basic studies of the field emission process. Surface films, number and distribution of emitting pins in an array, local electric field effects, and other properties were of scientific interest and might have assisted in engineering development of these cathodes. However, such an approach would have taken much time and effort. It was therefore decided that the objectives of the composite study would best be served by development and testing of a prototype cathode. Problem areas identified in this way can be solved by appropriate basic studies.

In the early stages of field emission electron gun development, it was expected that noise (i.e., current instabilities) would be present to some extent. Therefore, in the formulation of cathode designs, various noise-tolerant applications were reviewed. It should be noted that control of noise, which is currently less than 1%, is considered a realistic goal at this time through electronic means or by further refinement of techniques for preparing emission surfaces.

Assuming a modest noise level of $\sim$ 1%, there would be several tube types in which the cold cathode could be successfully operated. Magnetron and "ECM" tubes should operate at high efficiency with the field emitter cathode. That is, magnetrons employed in radar transmitters and traveling wave "ECM" tubes (used in barrage noise systems) should not be affected by low level noise in eutectic field emission cathodes.

It appears feasible also to "design around" low level noise in the case of klystrons used as microwave oscillators. This would be done by using a "balanced mixer" circuit which tends to cancel out noise effects in a klystron oscillator. Also, for example, if the noise of the composite cathode is primarily A.M. in character, such current variations would not affect the circuit performance of a klystron tube used in an F.M. type system (e.g., pulsed doppler system).

Several linear beam cathode designs were considered. These included (1) the solid beam magnetron injection gun, (2) the annular hollow beam and (3) the annular solid beam.

The success of the RCA experiments with the UO_2-W field emitter suggested a geometry similar to the pointed emitter in a tunnel which they employed. The magnetron injection gun investigated extensively in the early 1960's by Kino, and others[5,6] has a similar geometry. Figure 4 shows such a magnetron injection gun. Electrons initially travel almost radially toward the anode. As they gain velocity, the magnetic field forces them into helical trajectories and they proceed through the anode aperture. Since the magnetic field is very strong, electrons never reach the anode. Because of the close cathode-anode spacing,

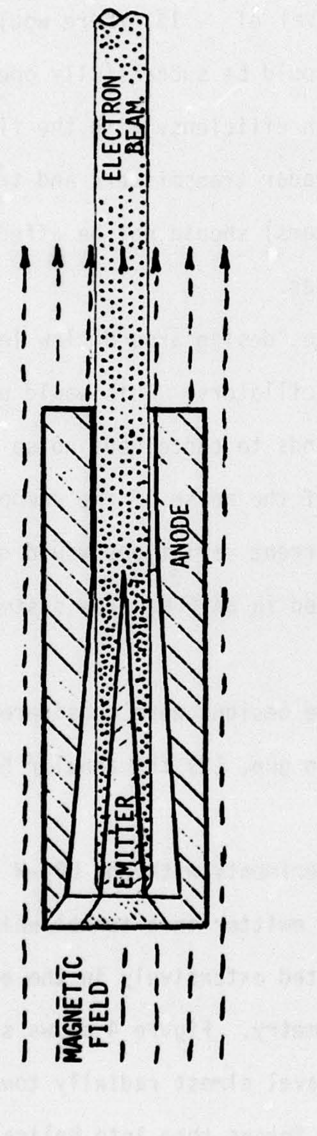


Figure 4. Solid Beam Magnetron Injection Gun

high electric field at the cathode surface is maintained.

A considerable part of the magnetron injection gun study would have been in the area of fabricating the cone-shaped composite. It appeared unlikely that methods could be devised to achieve the ideal condition of perpendicularity between tungsten fibers and cone surface. However, it was felt that sufficient field enhancement could be realized with tips parallel to the cone axis. Optimum tip sharpness and spacing for this geometry were other areas requiring investigation. The use of control grids with this concept were also considered.

A supplementary study could have investigated shadow grid techniques to see if a shadow grid design could be devised which would still provide high electric field at the emitter surface.

Annular Hollow Beam Cathode Concept. Analysis of a literature base relating to cold cathode devices, and consultation with personnel experienced in field emission research led to the development of an annular, hollow beam cathode design concept. Since edge effects produce higher electric fields near the edge of a field emitter, it was tempting to treat this as an advantage rather than a problem and design the electron gun to produce a hollow electron beam. Such a design would have a number of applications since many microwave tubes utilize hollow beams, particularly low frequency (below 2-3 GH_z) TWT amplifiers and most backward wave oscillators. More recently, hollow beams have been employed in millimeter wave gyrotrons.

Figure 5 shows schematically the hollow cathode design. This design was based on general microwave tube concepts combined with known properties of eutectic emission surfaces.

A solid beam cold cathode concept was considered. Edge effects become the dominant emission mode with large arrays of field emitters. That is, if a planar array of emitters has a planar mode of comparable dimensions, essentially all the electrons are emitted at the edges of the array. This is presumably due

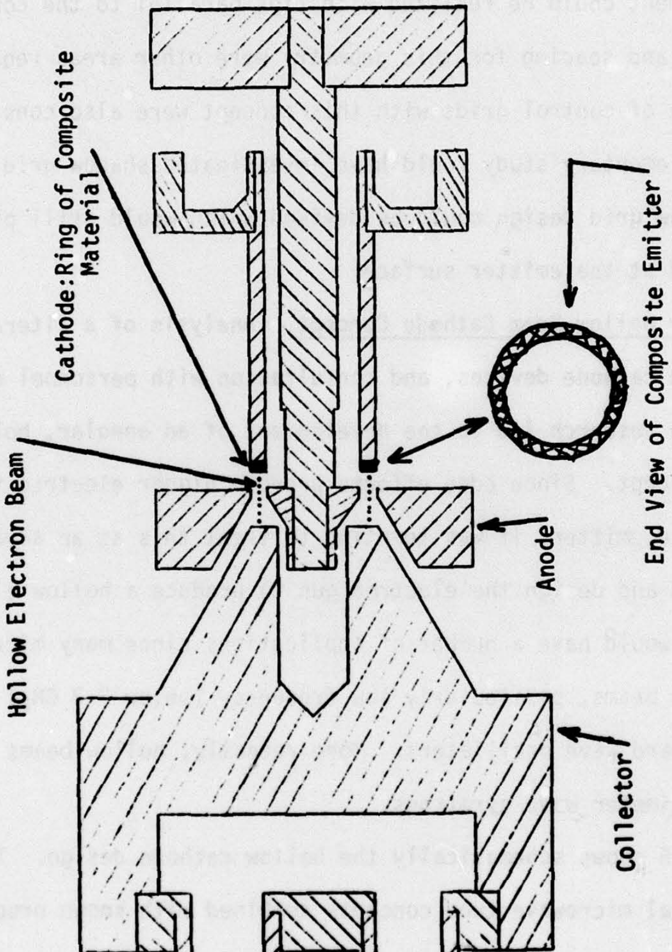


Figure 5. Schematic of Initial Hollow Cathode Test Apparatus.

to the enhanced field effects at the edges; the equipotential electro magnetic lines are closer to the edges. In general, one approach to obtaining uniform solid emission over the entire array of emitters would be to place secondary fields so that these would modify the anode potential lines. Instead of a "distorted" field at the array edges, a uniform field would be applied across the entire array of emitters. If serious engineering problems were not encountered, these secondary fields should lead to a uniform solid beam. This concept would require (1) computer simulation to identify the necessary geometry of the secondary fields and (2) design of structures to generate such fields.

II.C.2. Preliminary Experiments Study: Annular Hollow Beam

After consideration of the three concepts—magnetron injection gun, annular hollow beam, and annular solid beam—it was decided to conduct some preliminary experiments to assess the technical feasibility of the annular hollow beam. This decision was based primarily on the projected experimental difficulty in developing a working prototype cathode based on each of the concepts. Also considered was the fact that "edge effects", upon which the hollow beam concept was based, were a demonstrated experimental fact, whereas the magnetron gun concept and the field deflection concept (solid beam) lacked experimental results to support them.

Much of the initial engineering design for the hollow beam cathode was based on the experimental studies of Chapman, Feeny, et al.,[2] Levine,[4] and others who conducted diode-type emission studies with eutectic composite materials. The studies by Chapman and Levine had established that the $W\text{-}UO_2$ composite developed at Georgia Institute of Technology was capable of long emission life at high current densities; however, this work was conducted with diode tubes which were designed for total currents of a few milliamps. Much greater total current—at least 50 to 100 milliamps—are desired for microwave tubes. Therefore, these early experiments were undertaken to (1) establish the technical feasibility of operating a field emission cathode whose electron beam geometry is suitable for a microwave tube, and (2) identify variables which will increase emission current to minimal levels for operation of a microwave tube.

The $W\text{-}UO_2$ eutectic material was selected for experimental studies after review of available alternate in-situ composite materials. Of the known systems (see Figure list) the $W\text{-}UO_2$ material contains the most refractory metal emission surfaces (W pins), and this material has been produced with large surface areas unable for emission experiments. Further, in experiments conducted by Chapman et al,[2] the above material showed greater promise as a field emitter than other composites tested (see Table II). Other potential eutectics were not yet characterized as to field emission properties.

Fabrication of the emitter (cathode element) required the development of several techniques. It was necessary to form an electrically conductive bond between the composite element and the metal cathode support. Various grinding steps were required to form the desired composite geometry. The $W\text{-}UO_2$ eutectic behaves mechanically much like a brittle ceramic, so that grinding could not unduly shock the material. Moreover, tolerances on the order of ±1 mil (see Figures 6 and 7) were needed, which further increased the difficulties of emitter fabrication. Many processing techniques were surveyed so that the experience gained in this effort would permit the staff to prepare much superior cathode elements for use in subsequent studies of this composite material.

Results of Preliminary Study

Cathode elements were fabricated and tested in a vacuum system. The results are primarily qualitative, but some useful quantitative data was collected. The results include emission current measurements, visual behavior, and current/voltage relationships.

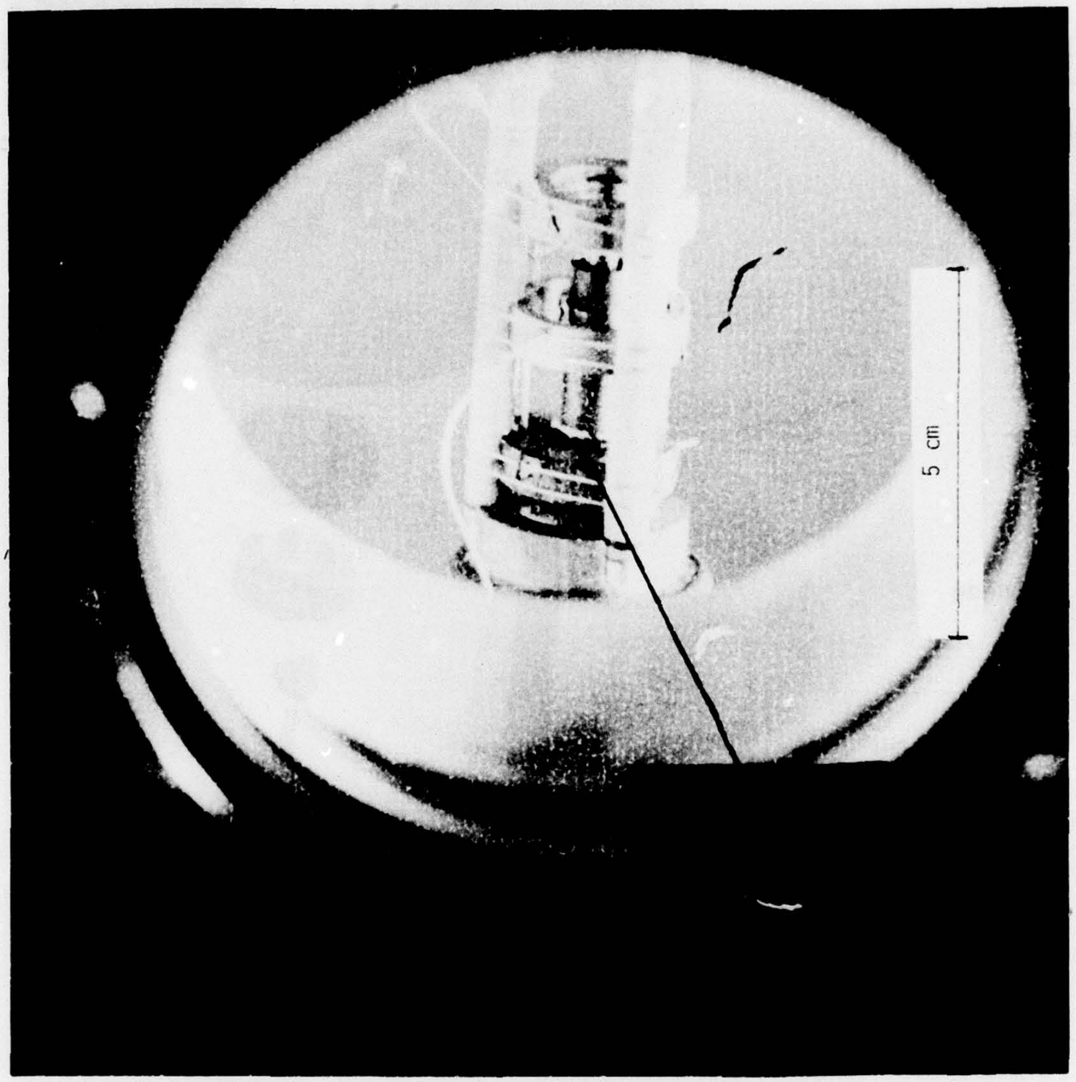


Figure 6. View of Operating Cathode and Electrode Glow (inset)

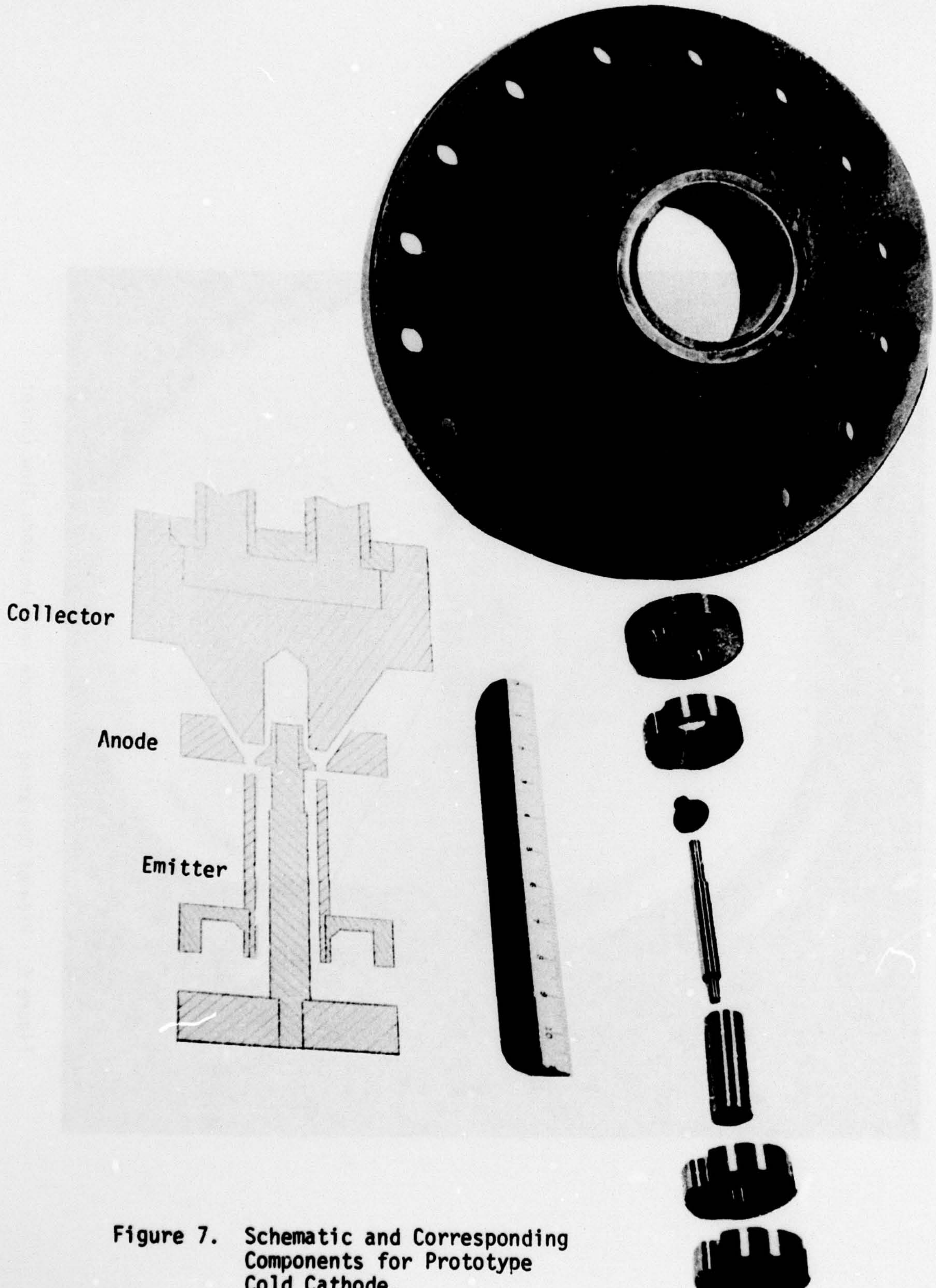


Figure 7. Schematic and Corresponding Components for Prototype Cold Cathode.

This initial experimental study was concerned with first, demonstrating that the hollow cathode geometry would be compatible with the conditions needed for field emission, and secondly to demonstrate that an electron beam of significant magnitude could be generated.

It was of great interest to observe empirically whether field emission would tend to be concentrated at a few narrow gaps, rather than emitting uniformly over the cathode surface. The experiments to date have produced what visually appears to be a remarkably uniform emission pattern over the surface intended for emission, i.e., over most of the "end view" surface shown in Figure 5 (also see Figure 6). The project staff was pleased to see such behavior in view of the rather large fabrication tolerances which were unavoidable on the first cathode elements.

Since the $W\text{-}UO_2$ composite must be "aged" before maximum field emission is obtained, a series of current vs. voltage relationships could be measured during the aging process. The exponential form of the current/voltage curves provided further evidence that the cathode was operating in a field emission mode.

After completion of the aging sequence, currents of five milliamps were recorded. Total current levels were stable over periods of several hours; meter readings of emission current were essentially constant. Thus, the preliminary emitter tests showed that gross instability or noise effects were not present. In future tests, it would be of great interest to analyse the current stability in some depth to determine frequency and amplitude variations.

These preliminary experiments indicated that future work should continue to be directed toward the development of a high current, reliable cold cathode with minimal beam noise. This should involve design refinement based on equipotential lines of electric field models. Thereafter, precision machining techniques should be developed as necessary to fabricate concentric cathode assemblies to small tolerances.

In the preliminary experimental study, engineering design tests were conducted on the hollow beam concept. Composite elements were machined, and a series of tests were conducted in vacuum chamber. These showed first order current-voltage dependences for the hollow beam geometry. Various extractor electrode spacings were tried and corresponding tendencies to arcing were noted. This body of information and experience formed the foundation for the following prototype program.

II.C.3. Prototype Cathode Study

On the basis of the very promising results from the preliminary experiments, a project to fabricate and test a prototype cold cathode was initiated. The hollow beam concept was retained and both the engineering design and fabrication techniques were extensively modified in view of the previous study results.

As an alternative approach to the exposed-pin configuration, work at Georgia Tech and elsewhere on low-voltage emitters holds great promise for a material which would serve as both a cathode and a non-intercepting control grid. However, at the time this work was initiated, the low voltage device was not yet ready for testing in a prototype cathode. A description of this emitter design was given earlier in this section.

As in the preliminary study, this work was initiated to determine if the exposed-pin material holds promise for applications as linear beam cathodes. It was deemed necessary to demonstrate not only that it would produce high current density, but also that it would deliver high total current—on the order of tens to hundreds of milliamperes. The goals for this project included demonstration of a uniform, high density beam with total current adequate for use in a microwave tube. Also the effect of electrical circuits for control and protective purposes was to be examined. As far as practical, magnetically-compatible materials were to be used in device fabrication.

The first version of the thin annular ring emitter was designed to operate at a cathode-anode voltage less than 1 KV. The cathode surface was inserted into the anode .0015" and the radial clearance was .003" for both inner and outer anodes. The geometry is shown in Figure 8. This design incorporated the observation of previous Georgia Tech experimenters that close spacing of the electrodes generally leads to longer lifetimes. The lower operating voltages are believed to reduce damage from arcing and ion bombardment. Tests showed that larger tolerances permitted higher performance. Protective electronic circuitry also contributed to higher device performance.

Prototype Cathode Design and Fabrication

Figure 8 shows schematically the conceptual design for the hollow cathode. It can be seen that the anode is made in inner and outer sections. The anode is spaced a few mils from the emitter, while the water-cooled collector is perhaps 3/8 inch from the anode. The device is shown in Figure 9. High density alumina was used for electrical stand-offs; other components were fabricated from austenitic stainless. The spacing of emitter/anode/collector was readily adjustable. Various tools were made to assist in assembly of the prototype to tolerances on the order of one mil. The tools also served a protective function; the emitter and anode mounting structures were exactly aligned with these tools before the composite was installed. This procedure reduced the chances of touching or otherwise contacting the emission-ready composite, since the 1 micron diameter pins were very susceptible to mechanical damage.

Composite Element

Rings of W-UO_2 composite were cut from wafers of as-grown material. After cleaning and bonding this ring to a stainless pedestal, the emission surface was lathe ground to the desired geometry: a beveled ring approximately

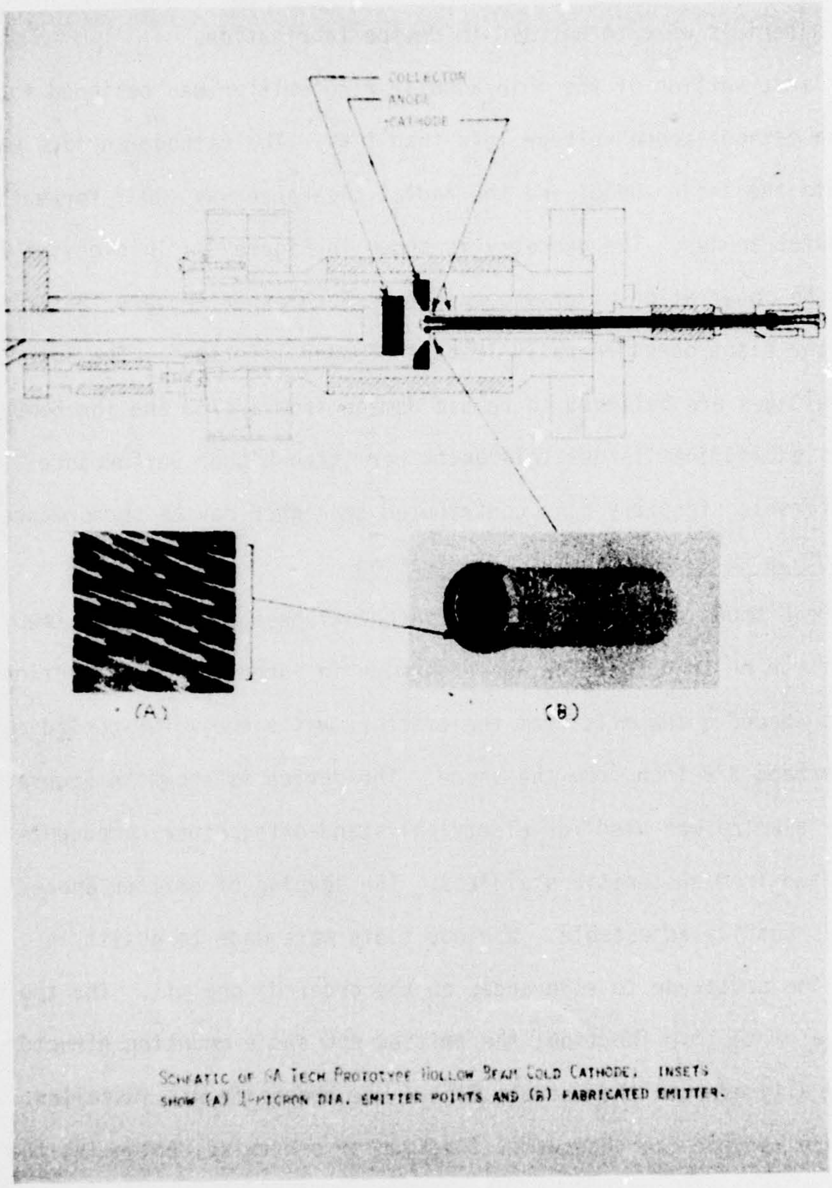


Figure 8. Schematic of Prototype Cathode

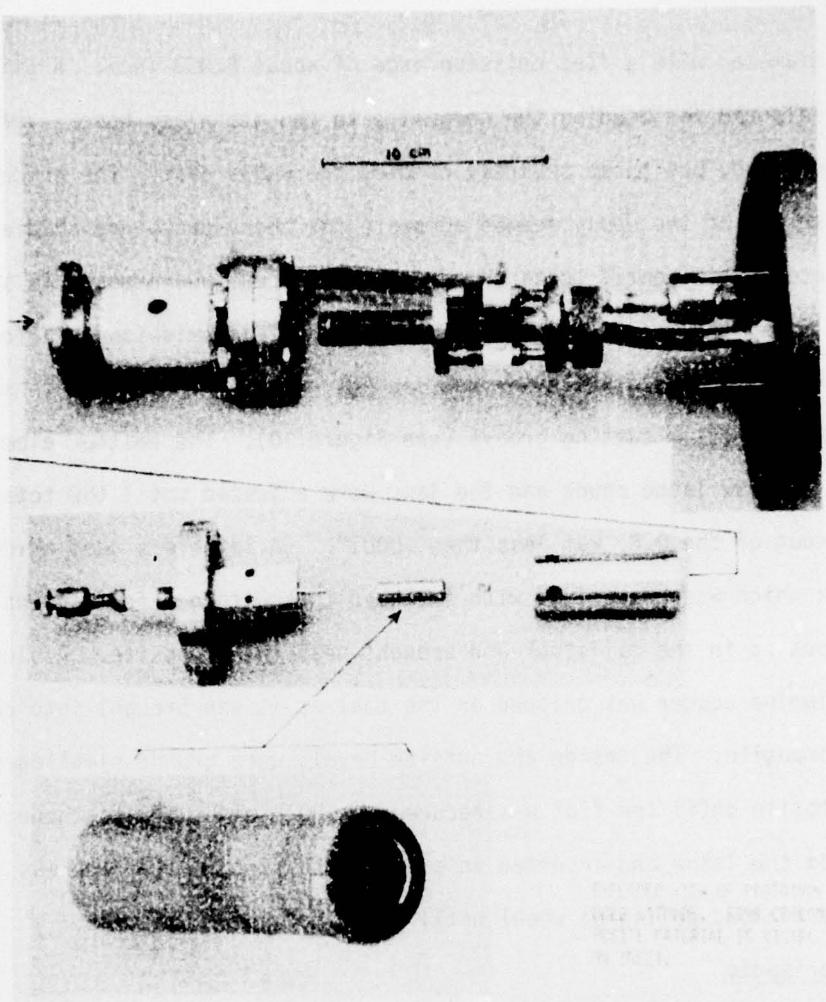


Figure 9. Prototype Cathode

0.25 inch diameter with a flat emission edge of about 0.003 inch. A silver epoxy was selected for bonding the composite to the stainless base. Various brazes were tried, but these severely cracked the $W\text{-}UO_2$ disc. The conductivity and strength of the epoxy seemed adequate for these prototype studies. However, later experimental tests showed that in vacuum and exposed to several kilovolts, this material is severely degraded and field emission is affected.

The best technique which was devised for grinding the composite utilized a tool with a circular cutting groove (see Figure 10). The emitter element was mounted in a 4-jaw lathe chuck and the jaws were adjusted until the total indicated runout of the O.D. was less than .0001". (A lathe was used which had a tailstock which was concentric with the headstock within a few microns.) The tool was mounted in the tailstock and brought near the composite. A slurry of 600 grit alumina powder was dripped on the tool as it was brought into contact with the composite. The inside and outside bevels were ground simultaneously on the composite until the flat was reduced to .001" wide. The cathode was removed from the lathe and inserted in a polishing block. The face was then ground on a diamond polishing wheel until the flat was 0.003" wide.

Experiments

As discussed earlier, the emitter/anode spacing was initially made as small as practicable in order to reduce operating voltage and increase lifetime. In tests, the device current was slowly increased with a large resistance in the circuit to suppress sudden current changes. This "aging" procedure for new emitters was based upon the successful practice of Chapman, et al. at Georgia Tech (see Figure 11). The first tests with with a .001" gap resulted in rather small currents and very frequent shorts between emitter/anode.

At currents on the order of 0.4 mA, a blue glow became visible over the emitter surface, and occasional white or reddish sparks were seen. This first series of experiments yielded maximum currents (CW) on the order of 0.5 mA at

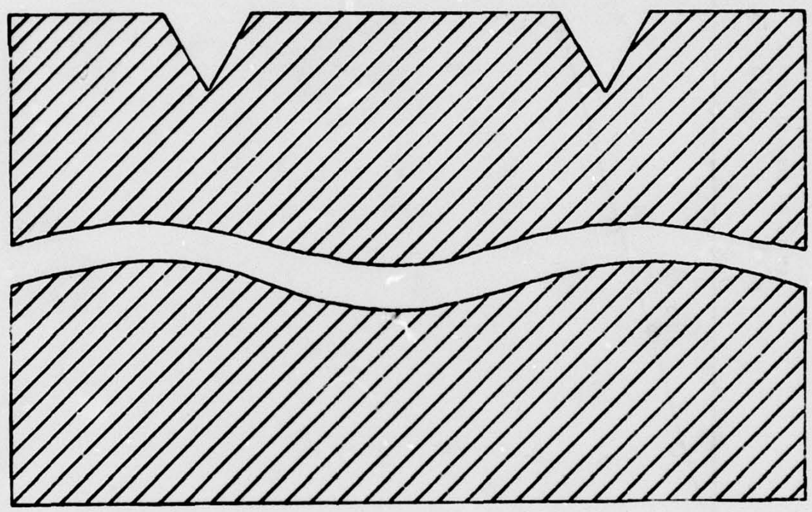


Figure 10. Cross Section of Grinding Tool

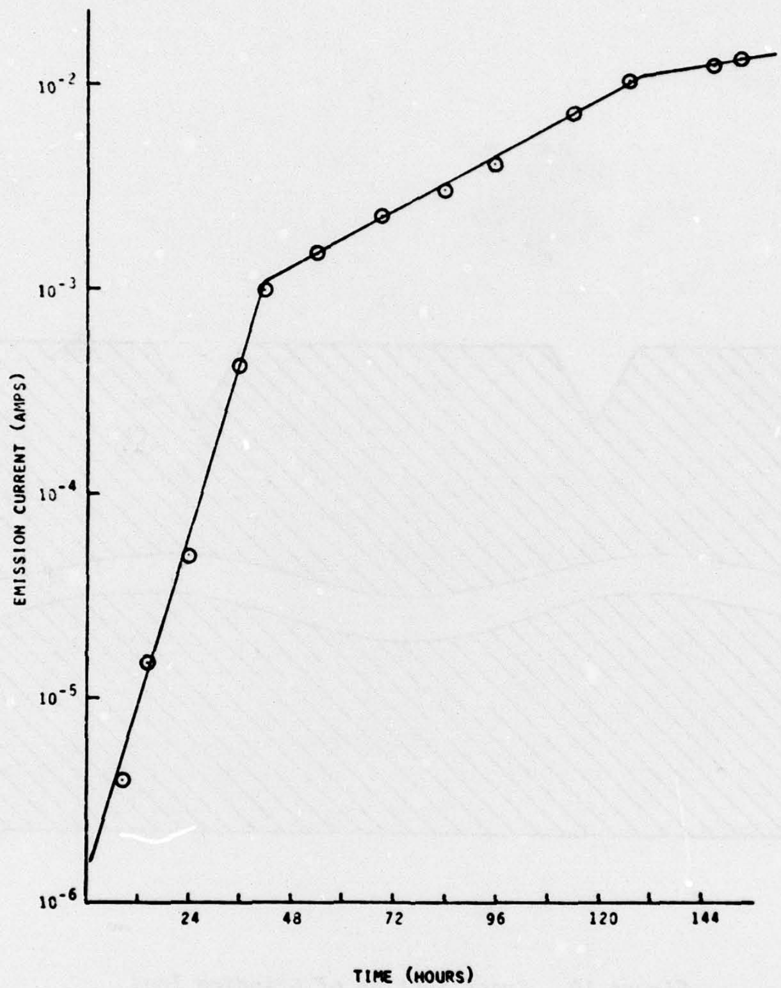


Figure 11. Typical Conditioning Curve for W-UO_2 Field Emitter

700 V (see Table III). However, the current-limiting factor was the onset of the presence of shorts and arcs; subsequent disassembly showed damage to the tungsten pins (see Figure 12), damaged areas of exposed silver epoxy, and some damage to anode surfaces.

It was concluded after several experiments that the problem of assembly tolerances, which was known to be serious, was too severe to continue with this geometry for several reasons, including eutectic quality (small cracks) and difficulty in grinding composites and aligning components to less than 1 mil tolerances. It should be borne in mind that with these spacings, tolerances of the order of ±.0002" were required for concentricity and parallelism. This, coupled with our inability to touch the emitter surface, caused major difficulties.

In any event, the problems encountered with the close tolerances required for the closely-spaced emitter led us to redesign the test vehicle to provide approximately .010 inch radial spacing. Larger tolerances provided better alignment precision. If one assumes that an error of ±1 mil is unavoidable under the existing working conditions, then larger tolerances lead to smaller fractional variations in field strength over the emission surface. This greater uniformity implies more uniform electron emission over the array.

Considerably more success was encountered with the more widely spaced device. Some of the success was doubtless due to material with fewer cracks, improved grinding techniques, and improved assembly techniques.

With the radial tolerance of 10 mils, currents of 5 mA were obtained. Electrical noise was reduced and shorts were much less frequent. However, the maximum current continued to be limited by arcing. At this point a current-limiting power supply was installed, and stability of operation was greatly improved. Total currents of 15 mA were now measured.

The fraction of emitted current which reached the collector, rather than

TABLE III. PERFORMANCE OF DEVICE MODIFICATIONS

Exp.	I_{max}	Density* (mA/cm^2)	% Trans.** (max)	Composite-Anode Gap	Exp. Duration
11	0.4 mA	14.	0.	0.001"	120 hours
21	5. mA	173	45.	0.010"	240 hours
32	15. mA	520	30.	0.010"	96 hours

* Emission averaged over composite surface.
** (I collector)/(I cathode).

Figure 12. Pins Damaged by Arcing

the anode, was determined by comparing total emitter current to anode current. This "% beam transmission" factor represents the usable beam in a vacuum tube application. In early experiments, the transmitted beam was negligible. However, with the 10 mil tolerances, transmission approached 50%. The beam which goes through the anode appears to be sensitive to anode alignment as well as to anode/collector bias voltage. Experiments where emitter and anode elements were less concentric or parallel had visibly less uniform emission and corresponding beam transmission was negligible. Anode/collector bias voltage tended to saturate at about 500 V. For example, at emitter/anode potential of 3000 V, transmission increased from 0 to 45 percent as bias voltage was increased from 0 to 500 V.

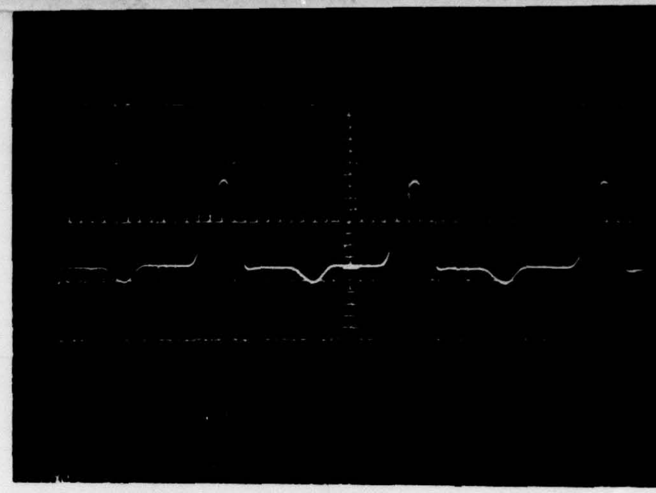
In Table III, the general characteristics of the devices tested (CW) are given. Early versions were affected by poor fabrication methods and unrealistically small tolerances.

In addition to the CS(DC) tests, a series of experiments were conducted with A.C. power supply (60 Hz). Currents of approximately 5 mA at 1500 VAC with very little reversal current were observed (see Figure 13). There was an unexplained relationship between the small reversal currents and arcs in the device. The reverse current would slowly increase until one or more arcs appeared, after which the current would fall to a very small value. Notice also in Figure 13 the expected exponential curve shape from a sine-wave input.

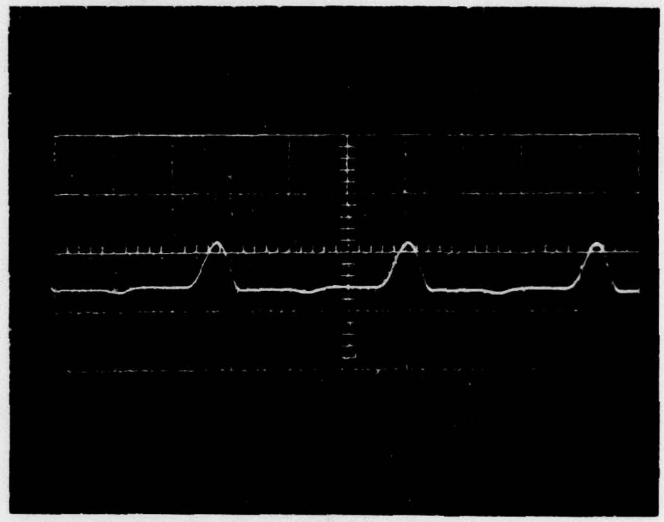
In order to distinguish field-emission behavior from leakage or arcing within the apparatus, current-voltage data were frequently plotted to show the linear Fowler-Nordheim relationship. Linear relationships were normally observed as current varied over three orders of magnitude. (See Figure 14.)

Based on observations during this study, it is suggested that fast-response constant-current power supplies may both reduce the damage of spurious arcs and contribute to noise reduction in practical field-emission cathodes. In

Amount of anode current
obtained before arcing.



Anode current obtained
immediately after arcing.



Anode current obtained
after a series of
arcing.

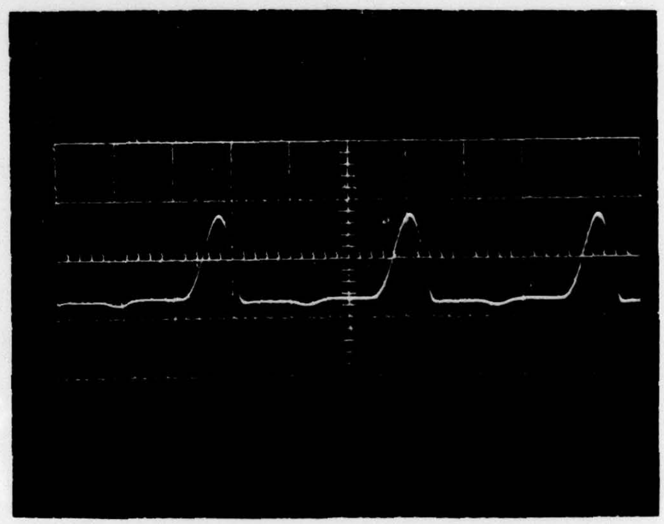


Figure 13. Operation with 60 HzAc

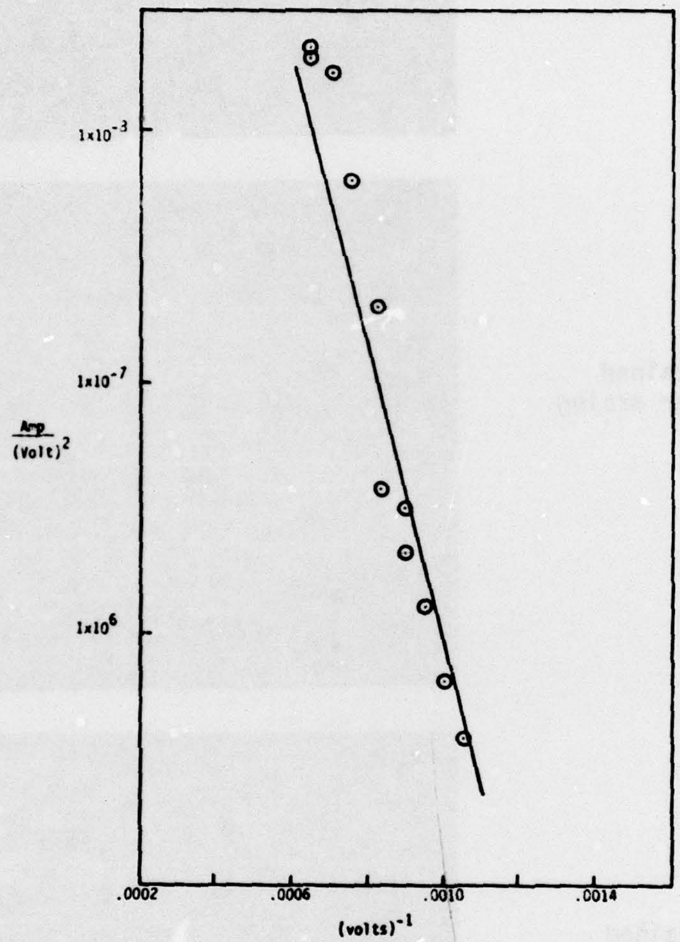


Figure 14. Fowler-Nordheim Plot Showing Linear Behavior Characteristic of Field Emission

arrays of thousands of pins, some will tend to conduct more than others and local overheating may lead quickly to an arc, then pin destruction. However, a constant current power supply reduced pin destruction at sites from fifty or more pins to one or two pins. The "noise" due to small arcs was proportionately reduced by use of the circuit.

The decomposition of silver epoxy bonding agent complicated efforts to identify variables which control the current, stability, and lifetime of the W-UO_2 emitter. In vacuum and in high electric fields, the epoxy seems to decompose and is transported from cathode to anode. In the future it seems advisable to avoid use of this type bonding agent. Preliminary tests indicate that T-C (thermal compression) bonding would be effective for bonding. A gold bonding film, for example, showed good bonding when tested to fracture. Bonding between composite and stainless steel occurred at 10,000 psi and 300°C.

Suggestions for Future Work

This prototype study has shown that much additional work is needed in the areas of improved composites, understanding of emission from large arrays, and development of device fabrication technology. For example, there is a need for larger, better quality eutectic specimens. Also, a search should be made for new eutectic composites with lower work functions, low vapor pressures, and resistance to ion bombardment damage. As pointed out earlier in this section, there are many potential in-situ composites which could provide the array of emitting pins needed for a cold cathode. The needle phase might be a refractory boride (Lanthanum hexaboride, for example), carbide or nitride compound, as well as refractory elements such as tungsten or molydenum. In particular, if the needle component has a low work function potential, then an applied field may be able to more efficiently extract an electron beam at lower voltages. It is hoped that future efforts will be directed toward development of such new in-situ composites. Surface studies of arrays could answer such questions as these: Are the pins which are emitting oxide-coated? Could the emission be enhanced by removing the oxide, or would this have adverse effects on stability? What is happening during the long, slow "activation" process? Also, future studies should consider new design concepts such as grid type anodes and solid beams using electromagnetic fields to control emission uniformity.

II.D. Summary

This study has shown that a hollow type field emission cathode design can be operated CW for periods of days.

Currents on the order of 15 mA and current densities (approx. 500 mA/ cm^2) comparable to operational microwave cathodes have been demonstrated.

The device was operated with low frequency (60 Hz) at 5 mA currents.

Uniform average emission over the relatively large array of pins (ca. 0.03 cm^2) was observed; emission uniformity also was implied by the distribution of rounded pin tips after experiments.

Use of constant-current power supply markedly reduced the amplitude of current transient and associated damage to composite emitters.

The performance obtained in this work suggests that, with additional development, the composite-based field emitter could form the basis for a high performance cathode or high intensity "cold" electron beam.

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III. New or Improved Devices Utilizing In-Situ Grown Composites

In this section we present a series of articles, each dealing with a single device concept. The intent of the articles is to describe in a very concise format the potential unique or superior characteristics, as well as limitations, of each concept.

The search activity for new devices was mainly conducted during the first phase of this project. After the first phase, in which a number of concepts were evaluated, the search consisted of a supplementary effort based on a continuing review of new literature and based on observations during experimental activity.

The descriptions emphasize the potential of the devices for meeting the needs of the Air Force and for advancing the state of the art in electro-optics devices. The present quality of available eutectic composite materials has not been regarded as inherently limiting the potential of a given device concept. This position was taken in light of the fact that relatively little effort has been expended on perfecting the growth processes for "device quality" eutectic composites. To date, many known composites have been "evaluated" only as part of a broad survey of many compositions, with no effort given to finding optimal conditions for aligned eutectic growth.

Also included in each article are (1) the current status of the eutectic-based device, (2) theory basic to the function of the device (and general material properties required), and (3) suggested specific materials for use in prototype devices. References by article are listed at the end of Section III.

The need for new or pacing technology has been pointed out in some cases. It was thought useful to indicate areas where technical breakthroughs would permit the fabrication of specific eutectic composite devices. For example, a composite with graphite fibers in an insulating matrix could make a significant reduction in the electronic complexity of a proposed plasma display device.

III.A. Photovoltaic Devices: Detectors and Specialized Solar Cells

Several device concepts have been formulated and reviewed. These include I.R. filters, detectors, and novel solar cells for Air Force applications. The unique geometry of eutectic composite materials provides a basis for projected improvements in sensitivity, radiation resistance, reduced internal resistance and greater conversion efficiency.

The photovoltaic response of a material may form the basis for either an IR/visible radiation detector or a solar cell for power generation. A conceptual device would be developed for one of the above uses by choice of suitable component materials. An I.R. detector, for example, might require a semiconductor component which strongly absorbs 10.6μ radiation.

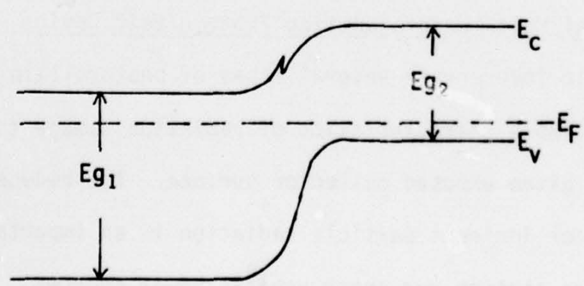
Solar cells of the silicon p-n junction type received much attention in the space program while other materials and types are now being investigated. The power requirements for military, weather, communications and navigation satellites can be met with solar cell arrays. The efficiency, temperature behavior, radiation tolerance and reliability are some of the critical factors that are considered for space applications. Additional factors, such as cost and availability of materials, are critical for terrestrial applications.

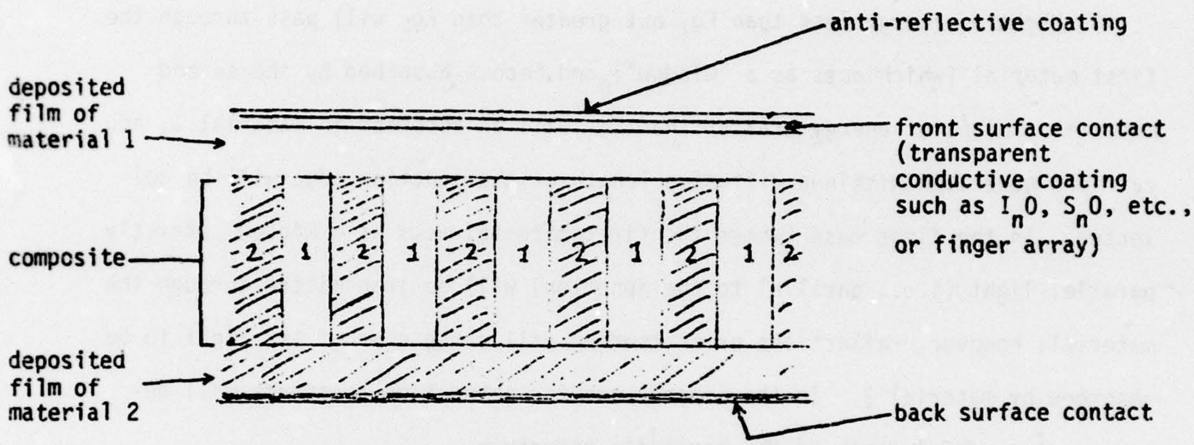
In this section, examples are given of different photovoltaic concepts based upon idealized composite geometries. These are a vertical multi-heterojunction solar cell/detector, a vertical multi-Schottky barrier device, and a multiple Schottky barrier polycrystalline semiconductor film solar cell.

III.A.1. Vertical Multi-Heterojunction Photovoltaic Device

This concept would incorporate several types of photovoltaic devices in order to attain the desirable characteristics of radiation damage tolerance and high power output for a given exposed collector surface. The reduced performance of a solar cell under incident particle radiation is an important consideration for satellite space station and space vehicle power sources. When radiative particles enter the solar cell, they cause a considerable amount of lattice damage (vacancies and interstitials, vacancy-impurity complexes, defect clusters, etc.). The defects produced usually act as recombination centers which lower the lifetime and diffusion lengths of minority carriers in the cells.

Shay, Wagner, Bachmann and Buehler[1] have recently reported on high efficiency (12.5 - 14%) heterojunction solar cells prepared by the epitaxial growth of an n-type CdS layer on a p-type single-crystal substrate of InP. The advantages of this device result from the material properties of the two semiconductors. The CdS has a large band gap (2.42 eV) and, therefore, most of the solar radiation impinging on the cell is transmitted through the CdS layer. InP has a direct band gap (1.34 eV) close to the optimum for solar power conversion and the absorption length is short. The requirements for minority-carrier diffusion lengths are not critical. Thus reduction of lifetime and diffusion length by exposure to particle radiation is not so degrading for these cells as it would be for p-n junction solar cells where it is necessary for minority carriers generated by light to diffuse to the junction. Vertical multi-heterojunctions of these materials in parallel, possibly made from a eutectic composite, would have the further advantages of increased junction area and the trapped-radiation geometry of the narrow CdS "window" as well as the tolerance to particle radiation. The energy band diagram of a typical heterojunction between two single crystal materials is shown below:





Characteristics;

(1) Inherent tolerance to effects of damaging radiation due to geometry of device design

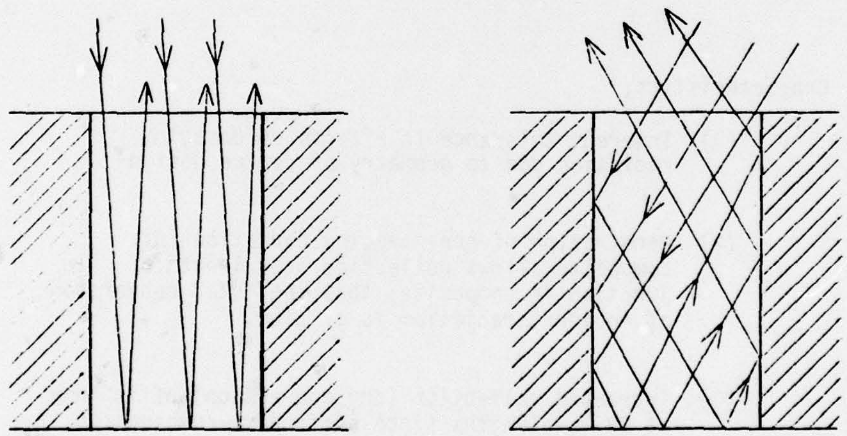
(2) Penetration of non-damaging radiation into composite allows collection over length of junction in composite; thus the total conversion of incident radiation is greater.

(3) Increased collection (and conversion) efficiency at UV wavelengths since surface re-combination is reduced.

Figure 1. Schematic of Vertical Multi-Heterojunction Solar Cell

The proposed concept for a vertical multi-heterojunction device is shown in Figure 1. A lamellar eutectic composite made of two semiconductor materials is required for the device. Also, semiconductor materials must have markedly different optical/IR absorption properties.

Light of energy less than Eg_1 but greater than Eg_2 will pass through the first material (which acts as a "window") and become absorbed by the second material. Light of energy greater than Eg_1 will be absorbed in material 1, and carriers generated within a diffusion length of the junction edge will be collected. In the first case (where the first material acts as a window) strictly parallel light (i.e., parallel to the junction) will be transmitted through the material; however, reflections or scattering will cause some of the light to be absorbed by material 2. In the second case the absorption constants will determine the useful depth of the composite structure.



Nearly parallel radiation with material 1 as window.

Non-parallel radiation with material 1 as window.

Figure 2. Radiation within Composite Material

The advantage that the heterojunction can have over most normal p-n junctions (planar-type) is in the short wavelength response; if Eg_1 is large, high energy photons will be absorbed inside the depletion region of material 2 where the carrier collection should be very efficient. A composite structure as envisioned should also have enhanced collection efficiency for uv radiation.

The following list of semiconductor pairs have either lattice match, electron affinity, or expected high efficiency when used in a vertical multi-heterojunction solar cell:

* GaP-Si, N/P
  GaP-InP, N/P
  GaP-GaAs, N/P
  GaAs-InP, N/P
* GaP-Si, P/N
  GaP-InP, P/N
  GaP-GaAs, P/N
  GaAs-InP, P/N
* ZnSe-GaAs, N/P
* $Ga_{1-x}Al_xAs$-GaAs
* ZnS-Si
  PbTe-Ge, P/N

* Most promising heterojunction pairs from the lattice match, electron affinity, and expected efficiency points of view.

III.A.2. Vertical Multi-Schottky Barrier Photovoltaic Device

The desired composite consists of metal platelets or rods in a semiconductor matrix. Light incident on the front surface of the cell is transmitted through the antireflection coating and transparent thin film conductor into the semiconductor. Electron-hole pairs are created in a depth determined by the absorption coefficient. Minority carriers then diffuse to the potential barrier at the metal-semiconductor junction where they are collected and give rise to a photocurrent. The vertical arrangement has an advantage over a conventional planar junction cell in terms of collection efficiency when longer wavelength photons are created deep in the material. (See Figure 3.) In this cell, as in the vertical multi-pn junction cell, the minority carriers need only to diffuse to the nearby junction rather than to the distant planar junction of a conventional cell. The materials requirements would involve the barrier heights between different metal-semiconductor pairs. Sze[2] lists measured barrier heights for a large number of materials combinations. The indirect band gap semiconductors are more likely to have a large absorption depth than are the direct band gap materials.

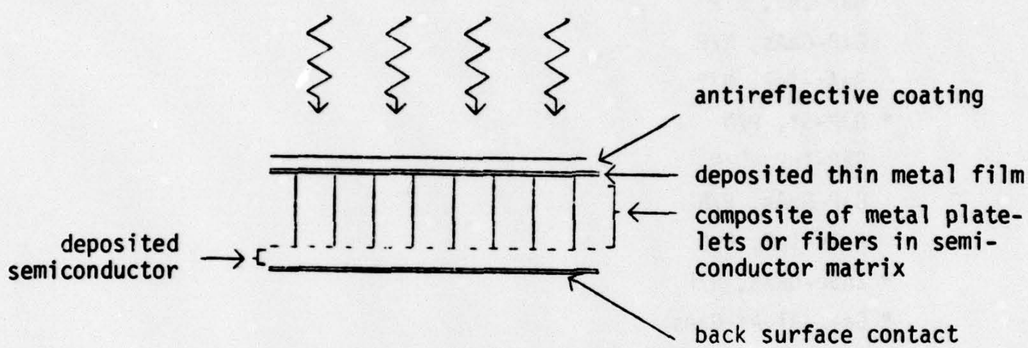
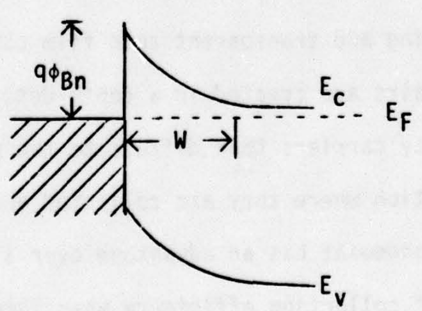


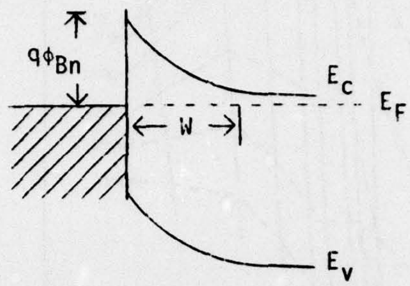
Figure 3. Schematic of the Vertical Multi-Schottky Barrier Solar Cell

The vertical multi-Schottky barrier solar cell is based upon the following physical phenomena and effects:



$$q\phi_{Bn} = q(\phi_m - \chi)$$

The limited value of the barrier height (neglecting Schottky lowering) is simply the difference between the metal work function and the electron affinity of the semiconductor in the absence of surface states.



In the presence of a sufficient number of surface states, the barrier height is determined by semiconductor surface properties and is independent of the metal work function. The absorption coefficient determines the penetration of the radiation.

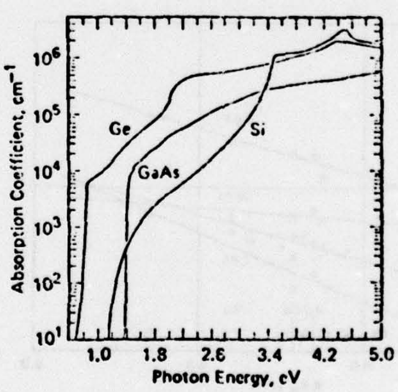


Figure 4. Intrinsic Coefficients of Si, Ge, and GaAs (from Hovel, 3)

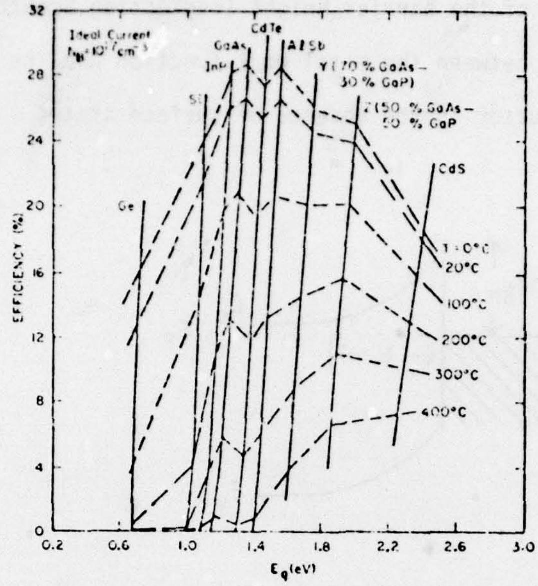


Figure 5. Conversion Efficiency as a Function of Energy Gap for Ideal Current-Voltage Characteristics (from Sze,4)

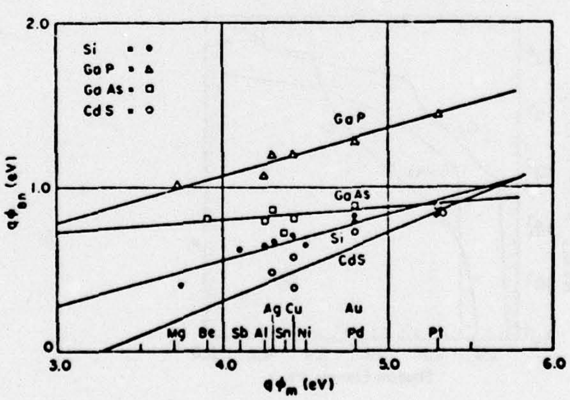


Figure 6. Experimental Barrier Heights for Metal-Semiconductor Systems (from Sze, 5)

III.A.3. Multiple Schottky (or Metal Oxide)—Polycrystalline Semiconductor Film Concept

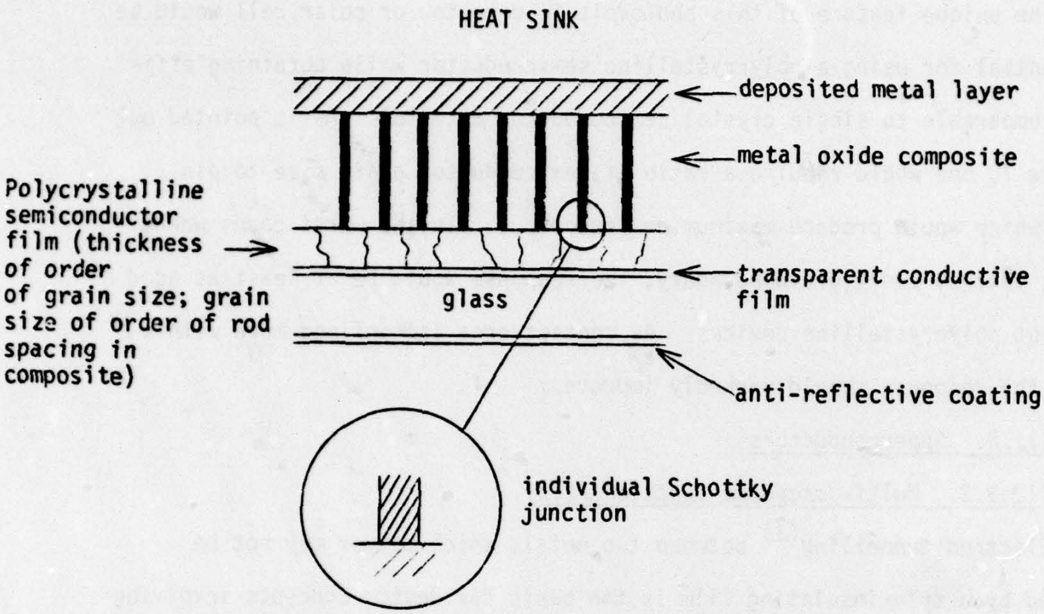
The unique feature of this photovoltaic detector or solar cell would be the potential for using a polycrystalline semiconductor while obtaining efficiency comparable to single crystal semiconductor material. As is pointed out on Figure 7, one would require a ratio of semiconductor grain size to pin spacing which would produce maximum device output. In the worst cases where contacts touched every grain boundary, the response would be at least as good as current polycrystalline devices. As contact area is confined more within grains, the response should markedly improve.

III.B. Superconductors

III.B.1. Multi-Josephson Junction Array

Electron tunnelling[1] between two metals which may or may not be separated by a thin insulating film is the basis for device concepts involving arrays of point contacts. The metals may be normal metals (N-N), a normal metal and a superconductor (N-S), or both may be superconductors (S-S). Josephson tunnelling, predicted by Josephson in 1962[2] is the tunnelling of electron pairs (Cooper pairs[3]) between two metals that are superconducting. At finite voltages there is a regular DC current but also an AC supercurrent; this condition is described as due to the transfer of electron pairs across the barrier with photon emission. At zero voltages a DC supercurrent exists up to a maximum value; this condition occurs when there is electron pair transfer without photon emission.

Following Josephson's predictions and their immediate confirmation by Anderson and Rowell[4] in a series of carefully designed experiments, a number of experimental[5-12] and theoretical[13-23] studies were then published. Some of the devices subsequently developed using the Josephson effects are voltmeters,[24,25] magnetometers,[26-29] memory elements[30] and infrared



<u>Characteristics</u>

a. Design reduces recombination at grain boundaries

b. Semiconductor film may be deposited on composite substrate

c. Device can be used with concentrators, such as Winston design

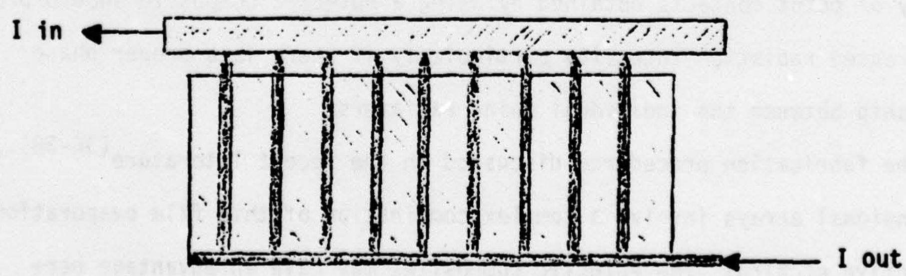
Figure 7. Multiple Schottky (or Metal-Oxide) – Polycrystalline Semiconductor Film Photovoltaic Device

detectors.[31] Extending these concepts to arrays fabricated from eutectic composites one would conclude that similar devices with high lateral spatial resolution may have interesting applications.

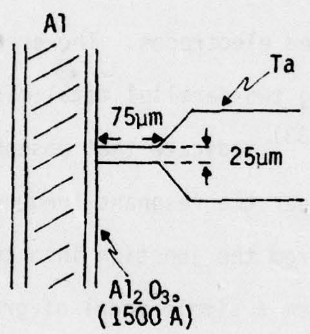
III.B.2. Far-Infrared Radiation Source

Clark[32] reported on experiments which suggest that large numbers of point contact junctions can be coupled together to form a coherent source of far infrared radiation. Close-packed planar arrays of superconducting balls (1mm dia., Sn) were combined such that point contact between the balls provided the tunnel junctions. Electrical contacts were made to the ends of the arrays (1×1 cm^2) by means of silver-plated electrodes. The array was then placed centrally in a "cavity" comprising two parallel metal mirrors. Analog computer studies by Werthamer and Shapiro[33] indicate that Josephson junction-cavity systems oscillate predominantly near the resonant frequency of the cavity whenever significant power is drawn from the junction into the cavity.

The array of sphere may form a simple model of granular superconductors, that is, thin films in which it is assumed that there are Josephson junctions between the individual grains. To use the eutectic composite material it would be necessary to consider an array consisting of a large number of point contacts in parallel.



Leopold, Gregory and Bostock,[34] in 1969, predicted the occurrence of stimulated radiative emission at the energy-gap frequency in properly formed normal-superconductor contacts. Gregory, Leopold and Repici[35] reported on observations that are consistent with that theory. The basic experiment involved passing an alternating current through Ta-Al point contacts and phase-sensitive detection of the radiation which traveled through free space from the point contact to a bolometer a few centimeters away. The stimulated radiative emission at point contacts is analogous to the emission from a semiconductor injection laser. The sample geometry is as shown below.



It should be possible to use superconducting materials with larger critical temperatures, and therefore larger energy gaps, to obtain intense, tunable, narrow band radiation at submillimeter and far infrared wavelengths. The array of point contacts obtained by using a eutectic composite should provide increased radiation intensity particularly if there is a proper phase relationship between the individual point radiators.

The fabrication procedures discussed in the recent literature[36-38] for two-dimensional arrays involve a complex combination of thin film evaporation and selective etching. The eutectic composites may have an advantage here since they would only require etching of the matrix to expose multiple rods which then could contact a uniform sheet of metal.

Materials requirements for superconductor-superconductor junctions would probably be a composite comprising superconducting rods in an oxide matrix. For example, rods of niobium in some oxide matrix would make contact with another superconductor in the form of a uniform sheet, in the following combinations:

Nb - Nb

Nb - NbOx - Nb

Nb - NbOx - Pb

Nb - NbOx - Sn

A rather large listing of other materials combinations is included in Solymar.[39]

A number of reviews related to the Josephson effect are also listed in Solymar[40] including popular reviews and reviews on point-contact junction devices, on magnetrometers, on infrared detectors and on devices in general.

III.C. Thermal Fatigue Monitor

The environments seen by military equipment are strongly determined by tactical situations. Tactical missile systems are constructed and then expected to remain dormant for many years unless an emergency or testing requirement leads to their firing. This dormant period could be as high as fifteen years, depending upon further technical developments. The electronic guidance system must remain reliable regardless of the imposed environments.

Because of the rapid developments in electronic technology, there does not exist a meaningful backlog of failure rate data on systems currently being deployed which would permit long-term life predictions of electronic systems which are dormant most of their lives. It is therefore important that characteristics of the materials used to construct these devices be well understood so that estimates can be made of how specific environmental conditions will affect the potential dormant failure processes devices. Two most important environmental conditions identified for military systems are temperature cycling and moisture. Temperature cycling leads to mechanical fatigue damage in microcircuit materials just as it does for structural materials. Moisture is particularly critical in that its presence can cause either a direct chemical attack or electrochemical corrosion within the very thin device members. The synergistic effect of temperature cycling and moisture leads to device degradation at rates much greater than either environment alone. It is therefore important that the cumulative damage introduced by each of these environments be somehow monitored for future prediction of service failures in electronic systems. Direct temperature measurements over the lives of large number of individual systems would be entirely outside the area of practicality. However, the thermal fatigue monitor described herein could well provide the needed thermal cycling damage parameter.

Temperature cycling of military equipment may introduce mechanical degradation processes in electronic systems as well as structural materials. Temperature changes and moisture are two of the major factors determining the life of many items of military equipment. The life cost of complex systems which may even be electrically dormant is closely related to these factors. Tactical systems are exposed to a wide range of environments due either to operational or storage conditions. For example, measured temperatures above 160°F have been recorded within the guidance module of missiles exposed to solar radiation in the American desert. Diurnal temperature cycling over a long time period may result in mechanical fatigue at critical points due to differences in thermal expansion coefficients of component materials. For example, wire bond failure has been shown to be an important wear-out reliability factor in microcircuits after several thousand temperature cycles. Larger electronic assemblies which include solder joints are still more susceptible to mechanical damage from temperature cycling. Structural materials are also known to have problems. Composites planned for certain high performance aircraft are suspected to deteriorate under the combined environment of atmospheric moisture and temperature cycling. An effective monitor of the thermal cycling history should therefore be of great value to accessing service or storage damage to components in military systems.

The amount of materials research and development effort devoted to fatigue gauges is actually very small in relation to the potential usefulness. Only a few metal systems and configurations have been examined. The current thin wire and film gauges have both structural and sensitivity limitations.

The previous efforts to develop useful fatigue monitors have involved only a few candidate materials. Current devices are limited by low sensitivity, low fatigue strength of the device material itself and too much dependence on environmental factors such as temperature. Directionally solidified composite materials offer potential advantages in meeting each of these problems.

The concept of a thermal cycling monitor has been formulated which takes advantage of the special characteristics of directionally solidified composite materials. As currently conceived (see Figure 8), the monitor could serve equally well to record either thermal or mechanical fatigue. Mechanical cycling may cause fatigue damage to the conducting rods which alters the net electrical resistance of the thin section. Mechanical fatigue damage processes are known to include such mechanisms as rod fracture, matrix delamination at the rods and slip processes leading to rod surface damage (see Figure 9). The thermal cycling monitor may either involve a composite material where the two phases have widely different thermal expansion coefficients or else it may be mechanically stressed by a second material to which it is bonded having a large thermal expansion coefficient. Such devices might be passive in that they would not be continuously connected to monitoring equipment but rather checked on a periodic basis to plot the accumulation of fatigue damage.

It has been established that potentially useful materials for such a monitor do exist. For example, the aligned eutectic $CrSi_2$-Si consists of $CrSi_2$ high conductivity rods in a much lower conductivity silicon matrix. This

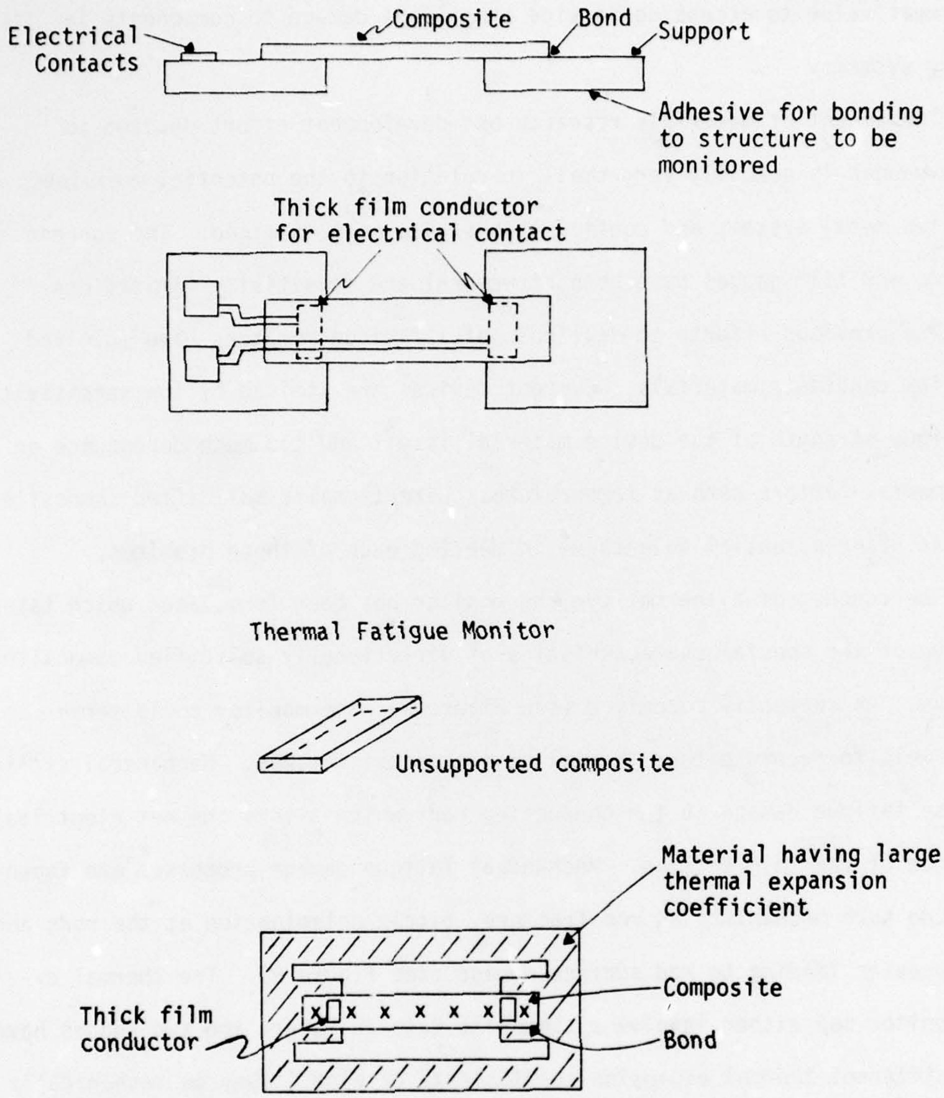


Figure 8. Fatigue Monitor

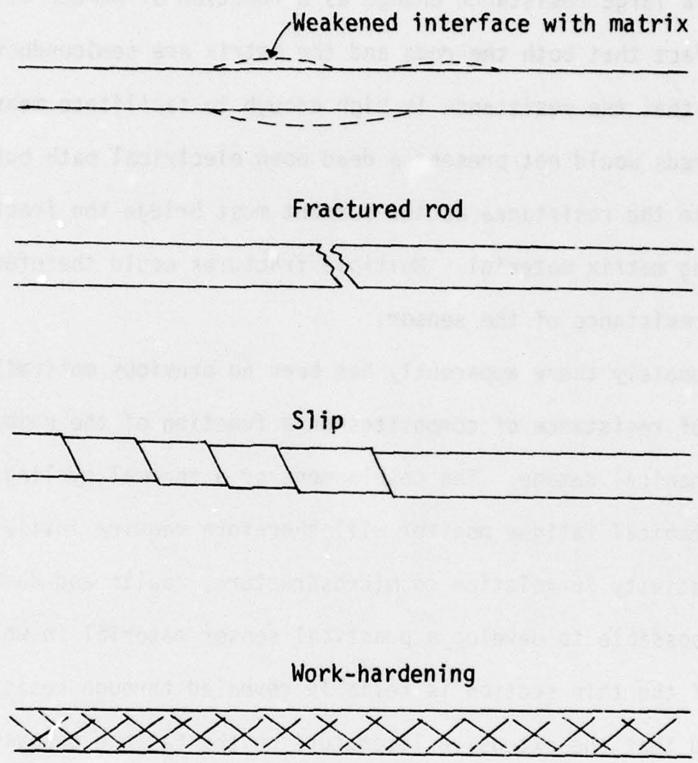


Figure 9. Factors which will Increase Electrical Resistance in Composites

material has a resistance measured perpendicular to the rods which is approximately 1000 times greater than that measured parallel to the rods. Therefore a thin section of this material having its long axis parallel to these rods might exhibit a large resistance change as a function of number of mechanical cycles. The fact that both the rods and the matrix are semiconductors is advantageous in that the resistance is high enough to facilitate measurements. Fractures in rods would not present a dead open electrical path but should simply increase the resistance as the current must bridge the fracture through the neighboring matrix material. Multiple fractures would therefore steadily increase the resistance of the sensor.

Unfortunately there apparently has been no previous motivation for measurements of resistance of composites as a function of the number of fatigue cycles or mechanical damage. The development of a thermal cycling monitor as well as a mechanical fatigue monitor will therefore require initial investigations of resistivity in relation to microstructure, faults and damage mechanisms. It should be possible to develop a practical sensor material in which the mechanical damage of the thin section is reliably revealed through resistance change. It is expected that the extensive literature on the fatigue behavior of eutectic composite gas turbine blades will provide a great deal of guidance and insight in a program to develop a thermal fatigue monitor.

III.D. Pumping Device for Gas (CO_2) Laser

III.D.1. Introduction

Field effect electron emitters based on eutectic alloys have been developed which have potential advantages over present technology for several device applications including electron tubes of various types and high voltage rectification. With current densities near one ampere/cm^2 in oxide-metal composites, applications to laser technology are also of great interest.

Current technology permits controlling emitter tip shape which allows the current density at a given field strength to be predetermined. As the emission is quenched effectively below an electric field value determined by the emitter tip shape, current flow is stopped when the laser energy source is discharged below some design level. In this manner the characteristics of the emitter lend themselves to a simpler and more efficient energy supply.

Typical geometry for an exposed pin emitter will employ a thin foil adjusted to a potential that allows emitted electrons to pass through the foil and ionize the gas in the laser cavity. Through careful design, all accelerated electrons will have sufficient energy to penetrate the foil leaving no low energy electrons to heat and damage the foil.

Other potential advantages for these emitters are an exceptionally long life, uniform excitation over the gas volume, and suitability for use with a lighter, smaller, and cheaper power supply.

III.D.2. Suggested Device Configurations

A program leading to a low cost demonstration of this technology is the recommended approach. This means construction of a very small CO_2 laser. In addition to serving as a working model showing technical feasibility and the potential for much larger systems, a small CO_2 laser has many applications. Some of these are (1) use as a local oscillator (LO) in 10.6 μm heterodyne receivers and radiometers, (2) as a pump for a LO at much longer wavelengths, (3) as a small compact source suitable for use in an active seeker or similar system, or (4) as a base for a phase and frequency locked standard for field use.

Several possible configurations could be considered for device construction. The use of a thin foil anode has already been described. As an alternative, it may be feasible to eliminate the foil and accelerate the electrons directly into the gas. This means the cathode could draw positive ion current. The effect of this current on cathode characteristics and life should be considered.

Gases contained in the laser tube would consist approximately of 14% N_2, 70% He, 14% CO_2, and a small amount of X_e at a pressure near 1 Torr. The gases should be compatible with a long cathode life. The initial systems would use a flowing gas stream to avoid any buildup of CO_2 by-products. Later systems could use sealed gases to search for possible degradation effects. The existence and magnitude of possible contamination and ion current effects on laser performance and cathode life should be carefully examined.

Other possible configurations may be useful using the buried emitter geometry. With this emitter the metal pins are recessed below a surface anode. Very close spacing is achievable permitting large field gradients at potentials between 10 volts and 100 volts. A small waveguide configuration may be useful here. The laser could be pulsed by switching the low voltage (i.e., 20 volts) accelerating source potential, leaving the high voltage across the body of the laser unchanged. This arrangement may be particularly useful where a small compact pulsed CO_2 laser is required.

Recent work on CO and CO_2 lasers using a waveguide configuration has indicated feasibility for the device concept discussed here. The thickness of the waveguide would be one or two mm typically, and the length from five to twenty cm. Excitation potentials near two kV and gas pressures between ten and one hundred Torr should be used initially.

The use of field emitters in small waveguide lasers as suggested here would demonstrate the laser application with a simple and low cost example. Moreover, a small efficient waveguide laser with a compact power supply would be a useful step toward availability of very small lasers for use in receivers or as pump sources for compact long wavelength systems.

III.E. New Magnetic Recorder Pickup Sensors

Recent attempts to advance the technology of tape recorder pickups have involved the use of thin film magneto-resistive elements. The magnetic field induced change in electrical conduction is used to sense the local magnetic field in a tape or disc. The use of thin film elements of such materials as permalloy makes possible high dimensional resolution. A thin film "write" element inductively megnetizes the recording medium for storage of information. Most significant is the fact that magneto-resistive pickup heads sense local field independent of tape speeds.

Because of the quoted 20:1 magneto-resistive sensitivity advantage of certain composites over conventional magnetic alloys the in-situ composite materials should be carefully considered for recorder pickup applications. Although the dimensions of composite materials are likely to be larger than a thin film device, the signal levels produced using small composites should be much greater. In addition, the directional effects associated with the strong anisotropy occurring with magneto resistivity in the composites offers advantages in discriminating against other recorded signals, i.e., it may be possible to vectorially read two independent channels on the same section of material, in analogy to stereo record techniques. One could superimpose two magnetic "tracks", instead of using the current side-by-side track geometry. This would permit a two-fold increase in information density on magnetic tape of a given size, leading to more compact airborne equipment.

The potential increased sensitivity of a eutectic magneto-resistive magnetic tape unit could permit precision magnetic storage elements which would perform accurately in spite of disturbances such as mechanical shock or electric power transients which an airborne electronic system might experience.

To date, prototype thin film sensors have been fabricated and tested;[1,2] the reported performance is sufficient to suggest that the characteristics of a eutectic magnetic recorder pickup sensor should be given a preliminary evaluation.

Materials consisting of a semiconducting matrix with aligned conducting filaments exhibit the large magneto-resistive effect needed here. The effect is directional because it essentially results from a shorting of the induced Hall emf within the semiconductor matrix.

The InSb-NiSb eutectic exhibits an 18-fold resistance change with the application of large fields. The ultimate sensitivity for recorder pickup applications must be evaluated. This material is understood to be commercially available because of its current application to power control.

III.F. Plasma Display Device

Device: High contrast, high resolution miniature plasma display.

System application for device: Aircraft instrument and other display systems.

Basic physical phenomena: Visible radiation from electrical discharge in noble gases.

Material property required (e.g., photo-voltaic): Insulated pins of electrically conductive material.

Superior or unique composite characteristics: Uniformly spaced conductor pins at micron dimensions; matrix which may be selectively etched away. Composite makes possible thin, rugged display concept. Uranium atoms prime the plasma.

Candidate materials and property values: $Mo\text{-}Gd_2O_3$ and $W\text{-}UO_2$.

Comments: It appears that the plasma display could exploit unique properties of a eutectic material. The concept for this device is shown in Figure 10. A plasma is confined to small apertures etched into the composite surface. The size of the apertures may be so small as to include only one metal pin at the bottom. By confining the plasma to small finite areas, the luminence ("contrast") is higher.[3] Combined with the generally high brightness of plasma displays, one obtains a sharp contrast between adjacent bright photo elements. The general concept of contrast enhancement by use of apertures has long been used in commercial plasma displays (large numerical); however, it is

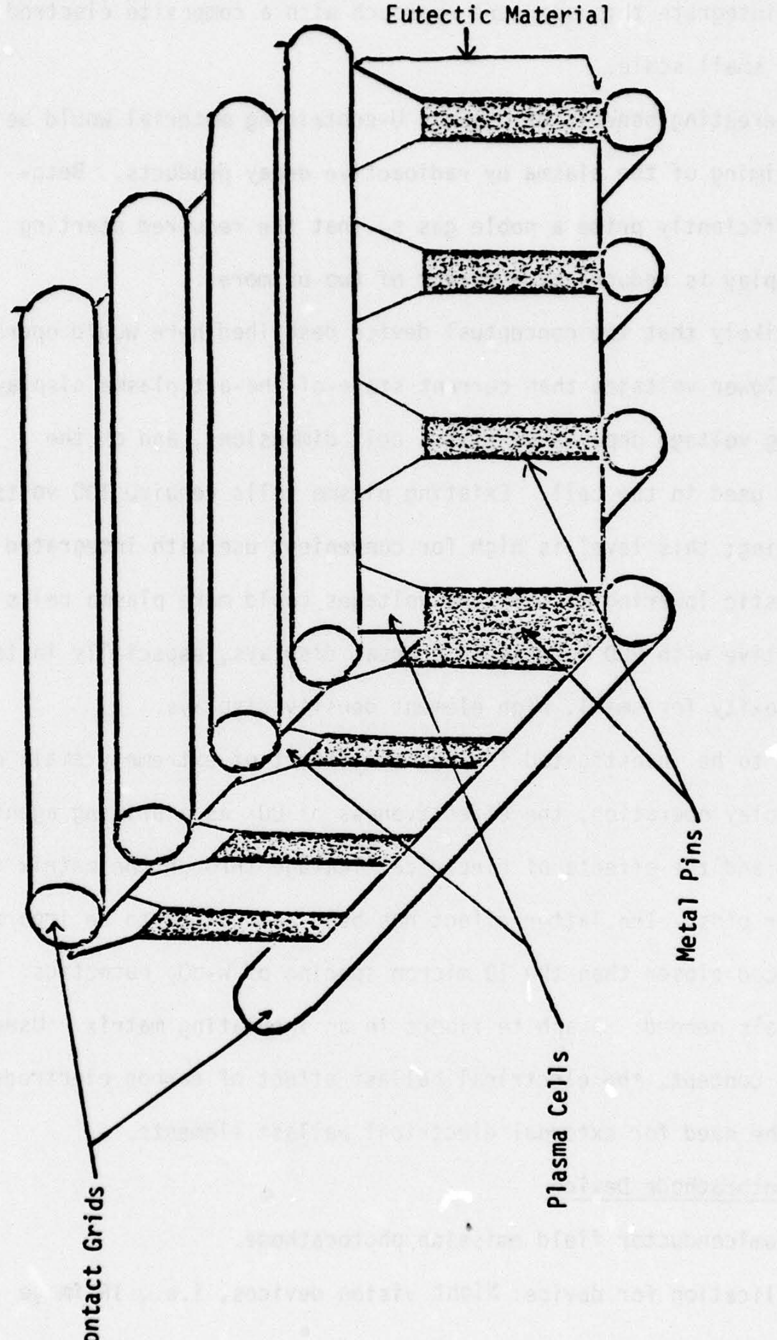


Figure 10. Schematic of Plasma Display Based on Eutectic Material

here proposed to integrate this aperture approach with a composite electrode surface on a very small scale.

A most interesting benefit of using a U-containing material would be the "inherent" priming of the plasma by radioactive decay products. Beta-emissions very efficiently prime a noble gas so that the required starting voltage for a display is reduced by a factor of two or more.

It seems likely that the conceptual device described here would operate at significantly lower voltages than current state-of-the-art plasma displays, since the starting voltage depends on plasma cell dimensions, and on the priming mechanism used in the cell. Existing plasma cells require 100 volts or more for starting; this level is high for convenient use with integrated circuitry. A drastic lowering of starting voltages could make plasma cells much more competitive with LED and liquid crystal displays, especially in terms of cost and complexity for small, high element density displays.

Parameters to be investigated include the effect of extremely small cell dimensions of display operation, the effectiveness of UO_2 as a priming agent for plasma cells, and the effects of electrical leakage through the matrix from adjacent conductor pins. The latter effect has been calculated to be important only for pins spaced closer than the 10 micron spacing of W-UO_2 eutectics.

New materials needed: Graphite fibers in an insulating matrix. Used in the above display concept, the electrical ballast effect of carbon electrodes would eliminate the need for external electrical ballast elements.

III.G. Photocathode Device

Device: Semiconductor field emission photocathode.

System application for device: Night vision devices, i.e., IR image detector.

Basic physical phenomena: Photocathode incorporating field emission.

Materials property required: Photosensitive p-type semiconductor rods responsive to electric field gradients.

Superior or unique composite characteristics: An array of small pins potentially all crystallographically aligned in a direction which maximizes field-aided photoemission.

Candidate materials and property values: Si and Ge have been shown to have a good photo-response when needle-like structures are placed in an electric field.[1,2]

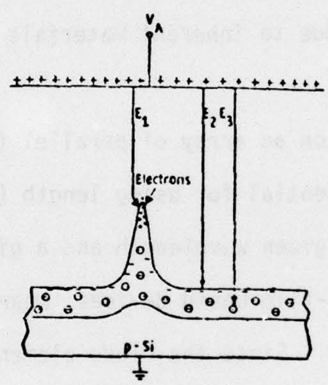


Figure. 11. Model of the Field Emitter

Comments: It is suggested that (1) either a composite with photosensitive rods of a semiconductor such as GaAs or Si be operated as shown in Figure 11, or (2) a field of metallic pins extending from a composite surface be "coated" with a film of a photosensitive semiconductor. The resolution potential is good in this concept, as it is in the optical display concept.

<u>III.H. I.R. and X-Ray Detectors</u>

Device: Image-sensor arrays for I.R. and x-ray detectors with good resolution and high sensitivity.

System application for device: "T.V. camera" to generate images from x-ray and I.R. radiation patterns.

Basic physical phenomena: Photoconduction in semiconductors.

Materials property required: Photoconduction in presence of I.R. or x-rays.

Superior or unique composite characteristics: An array of parallel plates or pins may be fabricated to dimensions of a few microns in one operation. Reduced cross-talk if matrix addressing or readout is used.

Candidate materials and property values: Si would be suitable; other materials should be satisfactory due to inherent materials flexibility of the device concept.

Comments: Detectors based on an array of parallel (p) and (n) semiconductor plates or rods have the potential for using length (or depth) to overcome the lack of absorption for a given wavelength and a given material. Greater depth, especially compared to thin-film based devices, means that more absorption (∴ better sensitivity) occurs. Since the diode elements extend through the depth of the composite slice, the absorbed radiation is always near a p-n junction and directly under the surface where radiation entered. Therefore, resolution will be good. In addition, cross-talk is reduced as with other composite-based concepts which put the matrix-addressing electrode on opposite sides of the device, rather than on the same side.

III.I. Summary

The preceding brief summaries represent the more promising concepts which were identified and given a preliminary technical evaluation during this research effort. Other concepts were suggested, but effort was not available for a preliminary evaluation. Examples of such concepts are (1) composites containing thermally conductive graphite fibers for directional heat transfer, and (2) piezoelectric/"light valve" for use as page composer for storing data in a laser hologram memory system. Others include use of suitable eutectics as photocatalytic materials for the photoreduction of water to hydrogen fuel. Layered semiconductor structures have demonstrated such a catalytic effect.

Complementary uses of in-situ materials involve either extracting the rod structures for separate use or extracting the matrix as a porous plate for separate applications, e.g., it has been suggested that the geometry of Mg or Al fibers would be ideal for use in a liquid phase shifter device for phase-shifted microwave systems. The composite matrix with pins removed would serve as a precision filter or a "container" for liquids or powders. A liquid might be uniquely subjected to a magnetic field while confined to the channels of the matrix material.

A further suggestion has been made to the effect that aircraft might be made "invisible" to microwave detection by coating with suitable materials. Due to the capability for generation of unique and enhanced properties, it is suggested that a material with microwave absorbing or other properties could be developed making use of the in-situ composite approach.

In the future, until eutectic materials are better characterized, it may be useful to select a higher performance level for a device or material and then seek an appropriate composite material for use. By proceeding from well-defined performance criteria, it may be possible to exploit the unique properties and flexibility of this class of materials.

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IV. Display Devices Based on In-Situ Composites

IV.A. Introduction

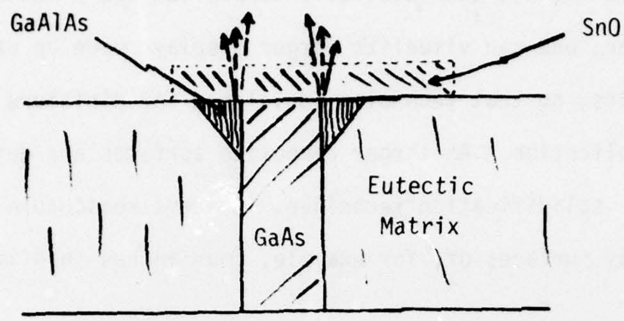
The Air Force has a need for higher performance display systems that surpass the current state-of-the-art with respect to display legibility, compactness, and ability to withstand severe environmental conditions. Reliable, graphic presentation of large quantities of information is vital for effective functioning of military command and control systems.

Many military display systems still rely on cathode ray tubes (CRT). Various forms of CRT have been devised, but all suffer from the fundamental limitations of vacuum tube devices—fragility, warm-up delay, heater burn-out, etc. The need for improved display capability for Air Force needs is apparent if one reviews the extensive past and current research activity aimed at improving the CRT, a device with limited resolution and contrast capability.

Two promising concepts of a display device—based on a eutectic composite—have been given a preliminary evaluation by the project staff. These solid state devices have the potential for resolution, ruggedness and lifetime much greater than current CRT capability. These concepts are referred to as diode displays (Figure 1). Their primary virtues would be high resolution in a flat, solid state device. Such a device could improve the performance of extremely small "head up" type display systems. Since eutectic composites are known to have at least a million contacts per cm^2, these materials may be capable of more directly transferring information to airborne personnel via a "contact lens" or other miniature device.

The latter phase of display effort of this project had the goal of demonstrating technical feasibility of conceptual and/or engineering designs for eutectic-based devices. Miniature high resolution displays offer potential for improved or new capabilities for current and projected Air Force command and control activities. Therefore, after developing conceptual designs,

DIODE DISPLAY DEVICE



POSITIVE AREAS

A. CONTROL GRIDS OF 25uM (1000 LINES PER INCH) ARE CURRENTLY DEPOSITED ON CIRCUITS.

B. SnO IS VERY WORKABLE: TRANSMISSION IS 95%.

C. CIRCUIT SWITCHING (ANALOGY TO CRT) FOR RASTER AND SIGNAL CIRCUIT; MULTIPLEX CIRCUITS ON ADJACENT CHIP: 500 TO 1000 CONTACT STRIPS.

UNKNOWN AREAS

A. IMPURITIES IN RODS (SEMICONDUCTOR GRADE NEEDED).

B. GROWTH OF POLYCRYSTAL AT INTERFACE/JUNCTION.

C. DIFFERENT GROWTH RATES AROUND PERIMETER OF ROD.

Figure 1. Diode Display Device

fabrication techniques were reviewed only for miniature displays. This decision seemed realistic since the then-available composites had a maximum diameter of 1-2 inches. However, one can visualize larger displays made up of a mosaic of small display modules, so that technology developed for miniature devices could have a wider application. As larger composite surfaces are developed using the directional solidification technique, it seems reasonable to project that monolithic display surfaces of, for example, four inches in diameter could be fabricated.

In the early stages of this study, the project staff presented display concepts utilizing the micron-dimension fibers of eutectic composites. It was tentatively concluded that several display devices could be formed by a union of existing display technology with a eutectic substrate. LED, liquid crystal, plasma, and thin-film luminescent display modes were considered. In order to evaluate these concepts in greater depth, a study/experimentation effort was conducted by the project staff at Georgia Tech.

After an initial study period, device feasibility evaluation was concentrated on LED and liquid crystal device concepts, both using eutectic composites containing insulated metal pins. Device options included (a) composites containing pins of an appropriate semiconductor material (for LED device), and (b) composites containing insulated metal pins (diodes or luminescent sites would be formed on the tip of the pin by various techniques). The choice of a specific design for feasibility evaluation was determined by the availability of specific eutectic materials and other engineering considerations. For example, thick film luminescent-type displays were less attractive due to the rather complex and unpredictable optical processes involved. Composites containing pins of a LED-compatible semiconductor were not available. (See Table I for list of known materials.) This phase of the work involved study of engineering designs, identification of areas requiring experimental data, and

TABLE I

Eutectics with Semiconductor Component

System[1]	Composition, Wt. % Vol. % or at % (X)	Microstructure (i.e., rods or plates etc. of material (Y))	Reference Code[2]
Ag-Bi	3% Ag by Vol.	Broken Lamellae of Ag	9 23 4 67 HTJ 69 DTG 71 DTG 72 UC
Ag-Ge	78% Ag by Vol.	Abnormal	2
Ag-Si	90% Ag by Vol.	Abnormal	3
Al-Ge	66% Al by Vol.	Abnormal	6 70 FVA 74 TCC 75 JWL
$Al-Mg_2Si$	88% Al by Vol.	Abnormal	24

1 The only reported conductivity data (p-type or n-type) was for InSb-MnSb (p-type, 73 AMIA) and for $SnSe-SnSe_2$ (p-type SnSe, n-type $SnSe_2$, 70 AW).

2 (a) Numeric Reference Codes refer to the codes at the end of this section.

(b) Alpha-Numeric Codes refer to the Bibliography at the end of this report. The codes give: year, author's last initial, author's first and second initials.

TABLE I (Continued)

System[1]	Composition, Wt. % Vol. % or at % (X)	Microstructure (i.e., rods or plates etc. of material (Y))	Reference Code[2]
Al-Si	88% Al by Vol.	Abnormal and rods of Si	22 12 1 3 74 CC 75 JWL 75 KJ 70 FVA
Au-Ge	69% Au by Vol.	Abnormal interconnected flakes	10 70 FVA
Au-Si	82 at % Au		70 FVA
Be-Si	62 at % Be		74 TCC
$Bi-Pb_2-Bi$	27% Bi by Vol.	Abnormal pyramid L/S interface	7 8 26 5 65 DVL 67 LJD 66 LSA 67 GFSB 68 GDE 72 SCA
$Bi-Bi_2$ Tl	63 wt. % Bi	Abnormal	70 GJE

TABLE I (Continued)

System[1]	Composition, Wt. % Vol. % or at % (X)	Microstructure (i.e., rods or plates etc. of material (Y))	Reference Code[2]
Cd_3As_2-NiAs	2.2% NiAs by Vol.	Rods NiAs	69 HSER 72 UC 70 GFS 72 UC
Co-Co_3 Si	77 at % Co	Lamellar	73 JRE 74 LJD 74 LJD 75 LJD
CrP-InP	1.6 Mole % Cr	Rods at CrP	74 SBW
Ga-Ge	90 at % Ge		74 TCC
GaAs-CrAs	35.4 Wt. % CrAs	Rod and lamellar	17 67 HDTJ 67 GFSB
GaAs-GaP		Lamellar	70 BN
GaAs-MoAs	9.4% MoAs by Wt.	Rectangular rod and lamellar	17 20 67 HDTJ 67 GFSB
GaAs-VAs	8.4% VAs by Wt.	Rectangular rod and lamellar	17 20 67 GFSB 67 HDTJ 70 GFS

TABLE I (Continued)

System[1]	Composition, Wt. % Vol. % or at % (X)	Microstructure (i.e., rods or plates etc. of material (Y))	Reference Code[2]
GaSb-$CoGa_{1.3}$	7.9% $CoGa_{1.3}$ by Wt.	Rods of $CoGa_{1.3}$	14 67 HDTJ 67 GFSB
GaSb-CrSb	13.4% CrSb by Wt.	Rods of CrSb	14 67 HDTJ 67 GFSB
GaSb-$FeGa_{1.3}$	7.9% $FeGa_{1.3}$ by Wt.	Rods of $FeGa_{1.3}$	14 67 HDTJ 67 GFSB
GaSb-GaV_3Sb_5	4.9% GaV_3Sb_5 by Wt.	Square and rectangular rods of GaV_3Sb_5	15 67 HDTJ 67 GFSB
GaSb-V_2Ga_5	4.4% V_2Ga_5 by Wt.	Square and rectangular rods of V_2Ga_5	15 67 HDTJ 67 GFSB
Ga-Si	90 or 50 at % Si		74 TCC
Ge-Ge_2Ti	98.1 Wt. % Ge	Rods of Ge_2Ti	73 HNJ
Ge-$HfGe_2$	96 Wt. % Ge	Irregular	73 HNJ 75 JWL
Ge-In	10 or 70 at % In		74 TCC
Ge-Sb		Lamellar	70 FVA

TABLE I (Continued)

System[1]	Composition, Wt. % Vol. % or at % (X)	Microstructure (i.e., rods or plates etc. of material (Y))	Reference Code[2]
Ge-Sn	30 at % Ge		74 TCC
Ge-$Th_{0.9}Ge_2$	85 Wt. % Ge	Poorly aligned rods of $Th_{0.9}Ge_2$	73 HNJ
Ge-Tl	30 at % Ge		74 TCC 75 JWL
InAs-CrAs	1.7% CrAs by Wt.	Rods of CrAs	14 67 HDTJ 67 GFSB
InAs-FeAs	10.5% FeAs by Wt.	Rods of FeAs	14 67 HDTJ 67 GFSB
InSb-CrSb	0.6% CrSb by Wt.	Rods of CrSb	13 67 HDTJ 75 WH 67 GFSB
InSb-FeSb	0.7% FeSb by Wt.	Rods of FeSb	13 67 DTJ 67 GFSB 64 PB 70 BMB 73 AMIB
InSb-Mg_3Sb_2	2.2% Mg_3Sb_2 by Wt.	Lamellae of Mg_3Sb_2	17 67 GFSB

TABLE I (Continued)

System[1]	Composition, Wt. % Vol. % or at % (X)	Microstructure (i.e., rods or plates etc. of material (Y))	Reference Code[2]
InSb-MnSb	6.5% MnSb by Wt.	Rods of MnSb	13 19 67 HDTJ 67 GFSB 64 PB 70 BMB 73 AMIA 73 AMIB
InSb-NiSb	1.8% NiSb by Wt.	Rods of NiSb	25 16 18 67 HDTJ 64 PB 68 PB 67 GFSB 71 WH 70 GFS 70 BMB 75 WH 69 AYA 68 EAGR 68 EAGR 70 MH 72 UC 73 AW 73 AMIB 73 VEV 76 VVS

TABLE I (Continued)

System[1]	Composition, Wt. % Vol. % or at % (X)	Microstructure (i.e., rods or plates etc. of material (Y))	Reference Code[2]
In-Si			75 JWL
Mg-Mg_2Si	96.6% Mg by Vol.	Faceted Rods of Mg_2Si	27
Pb-Ge	2,5,10,70 at % Pb		74 TCC 75 JWL
Pb-Si			75 JWL
Sb-InSb	35% Sb by Vol.	Triangular rods of Sb	11 19 67 HDTJ 67 DNM 75 WWG
Si-$CrSi_2$	72% Si by Vol.	Rods $CrSi_2$	72 LLM
Si-$NbSi_2$	92 Wt. % Si	Rods $NbSi_2$	73 HNJ
Si-Sn			75 JWL
Si-$TaSi_2$	94 Wt. % Si	Rods $TaSi_2$	73 HNJ
Si-Tl			75 JWL
Si-VSi_2	95 Wt. % Si	Irregular	73 HNJ
Si-WSi_2	95 Wt. % Si	Highly faceted	71 HNJ
SnSe-$SnSe_2$	61 at % Se	Lamellar	70 AW 70 GFS

TABLE I (Continued)

System[1]	Composition, Wt. % Vol. % or at % (X)	Microstructure (i.e., rods or plates etc. of material (Y))	Reference Code[2]
UO_2-W	96 Wt. % UO_2	Rods W	70 CAT 72 CAT 75 RCM 75 FRK 72 CAT
V-V_3 Si	75% V by Vol.	Rod and lamellar	21
ZnO-Zn_2SiO_4	~30 mol % SiO_2	Abnormal	75 WL

conduct of key experiments to assess feasibility.

In Table II a list of general milestones in the development of a prototype display device is given. The design philosophy was based upon use of mature display technology combined with available composite substrates. The intent was to confine the effort primarily to study of interfacing of proven display modes (LED junctions for example) with the surface of well-characterized eutectic materials.

IV.B. Display Device Concepts

IV.B.1. Diodes Based on Composite with Semiconductor Pins (e.g.,GaAlAs)

Diode junctions would be formed at the tips of the fiber phase by epitaxial deposition of a second semiconductor material. In order to fabricate such a display, several potential problem areas must be experimentally reviewed. For efficient diodes, the composites must contain rods with low levels of impurity. The mutual solubility of composite phases must be determined; possibly compensating dopants, etc., may be required for some eutectic materials. The ability to grow quality epitaxial material and thereby obtain functional diode junctions must be experimentally developed. Also, the natural growth directions of junction material must be examined. It would be most desirable, for example, if junctions could be induced to grow symmetrically around the tip of the semiconductor rod. It is believed that one or more junctions currently used for light-emitting diodes (LED's) may be suitable for a diode display device. For example, GaAs is known to form rod-like eutectics with several metals. If an insulating matrix can be found (possibly a non-metal element), then a composite containing rods of GaAs would be epitaxially layered with GaAlAs to form a field of red-emitting diodes. If possible, a matrix should be selected which can act as dopant for the semiconductor rods; in this way, limited mutual solubility of phases would be a positive factor in the operation of the diodes.

Composites with a suitable combination of semiconductor fibers and

Table II

Milestones in LED Display Evaluation Effort

1. Develop conceptual design for LED deposited on metal/insul. composite
   (a) Identify composite material required
   (b) Identify design elements which must be evaluated experimentally

2. Initiate experimental evaluation of key design elements
   (a) Show feasibility of depositing "semiconductor-grade" films on a specific eutectic composite, using GaAs as a model
   (b) Show feasibility of depositing "semiconductor-grade" LED component (GaP or GaAsP) on a specific composite
   (c) Demonstrate formation of P-N junction suitable for LED purposes
   (d) Show that functional electrical contacts can be made to the diodes
   (e) Demonstrate technique for electrical isolation of diodes on the monolithic display face

3. On the basis of (2), develop engineering designs for LED display prototype (<u>or</u> alternative displays based upon a semiconductor/semiconductor composite or a "plasma tube" concept which would use a composite as a low voltage electron emitter).

4. Prototype LED display fabrication
   (a) Develop capability to deposit "device grade" semiconductor films on composite substrate
   (b) Fabrication of one or more functional LED's on the surface of the eutectic composite
   (c) Fabrication of one or more functional LED's with acceptable emission intensity, and dimensions suitably small for a miniature display

5. Alternative displays
   (a) If LED display problems appear to be insurmountable, initiate design effort on alternative displays and phase out LED display effort.

insulating matrix were not available during this study. When materials are developed, it will be of great interest to examine their potential for use in diode displays.

IV.B.2. Diode Display with Diodes on Tips of Conductive Pins (Insulating Matrix)

In this concept, both layers of the LED junction would be epitaxially deposited on a conductive fiber tip of the composite. The micron-dimension "dot-size" and physical separation of "dots", permitting high resolution and contrast, are known to exist in composites with metal (conductive) fibers and in systems with semiconductor fibers.

The key to the function of the diode display lies in the array of addressable diode junctions (see Figure 2), formed at the ends of low electrical resistivity fibers. The fibers are distributed in an insulating matrix. To form a complete device, the eutectic with diode junctions would be connected to multiplexing i.c. chips (see Figure 3). Conventional masking/vapor deposition techniques would permit use of sufficient control grids to give $\sim$1000 lines per inch in resolution.

In order to achieve high resolution using existing thin-film technology, it was concluded that a monolithic design with matrix addressing should be used (references 28 to 37). Of the several LED junctions reported in the literature, GaP or GaAsP were selected by the staff as most promising candidates for use with a composite substrate; the technology for making both these junctions is in widespread commercial use. (Note also Figure 4.) In order to demonstrate concept feasibility, only a small number of diodes needed to be fabricated and tested—a matrix of perhaps 5×5 diodes would have been sufficient to verify the potential for high density of optical elements.

Two concepts have been formulated by staff members. In both of these, a photodiode is deposited at the tip of conductive eutectic fibers. These concepts meet the general criteria of (1) making greatest use of thin film

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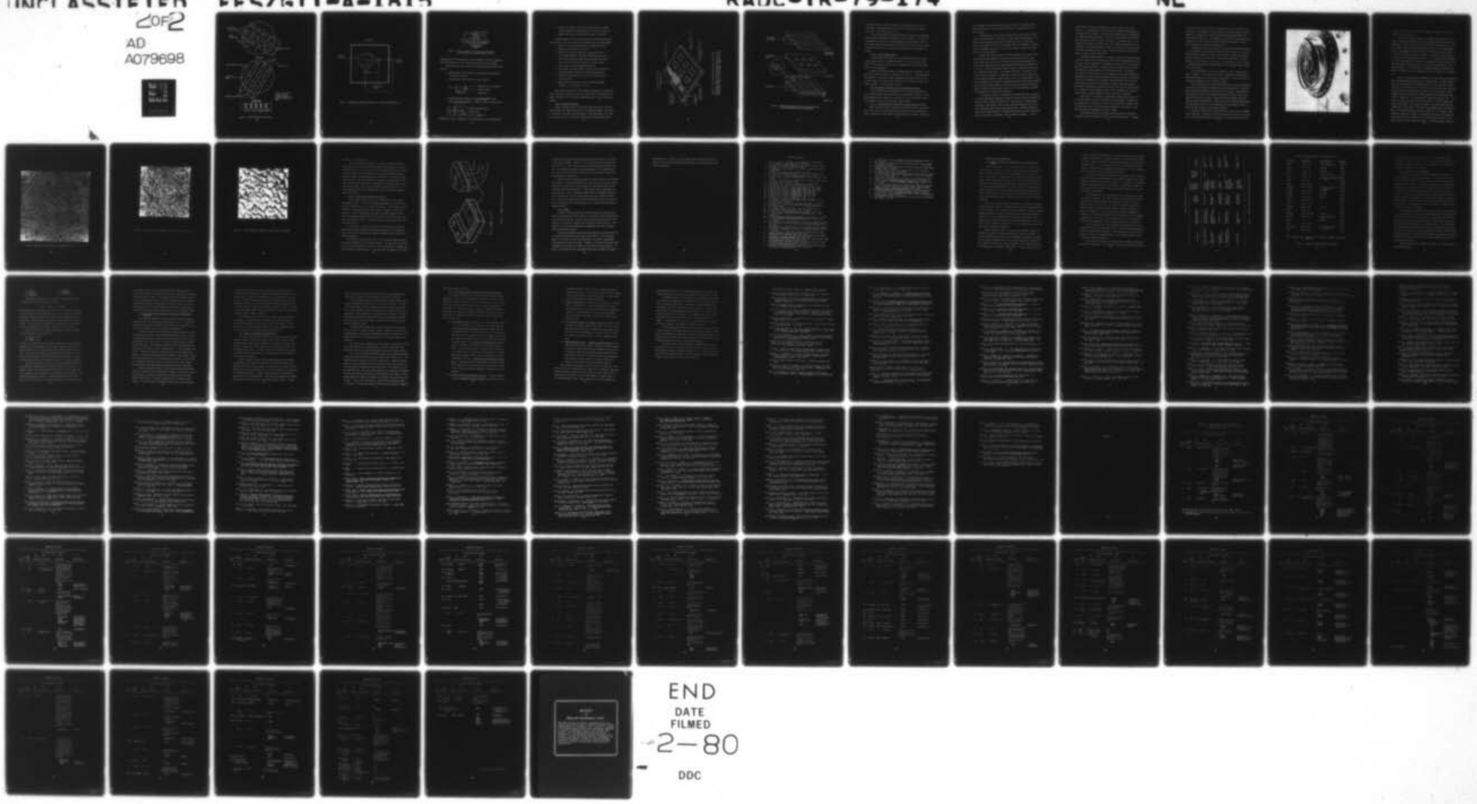

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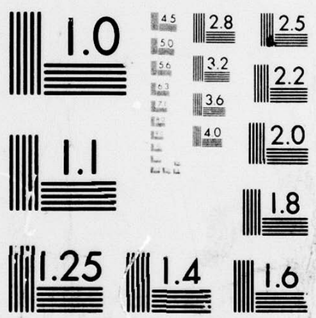

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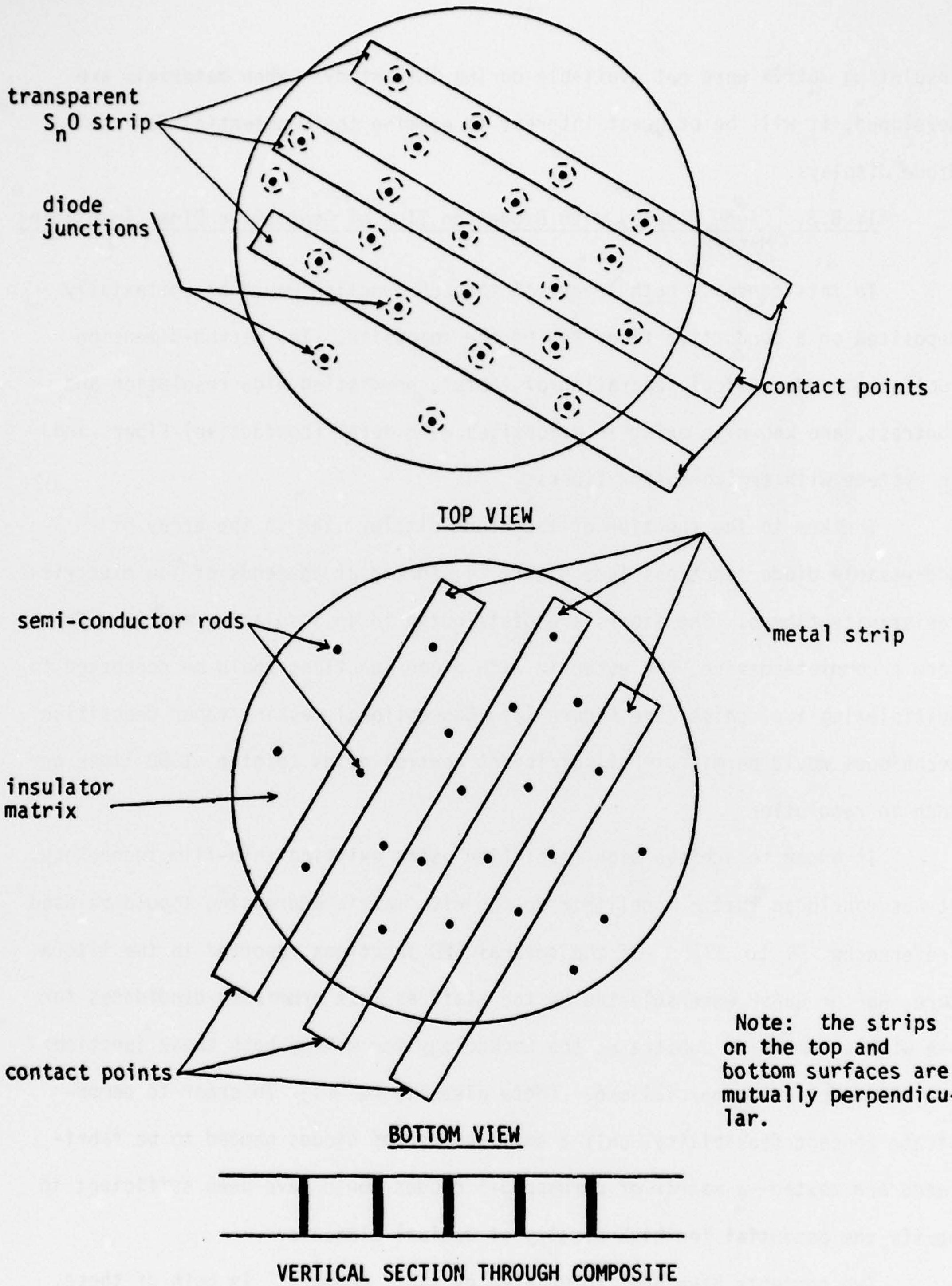


Figure 2. Composite-Based Diode Display

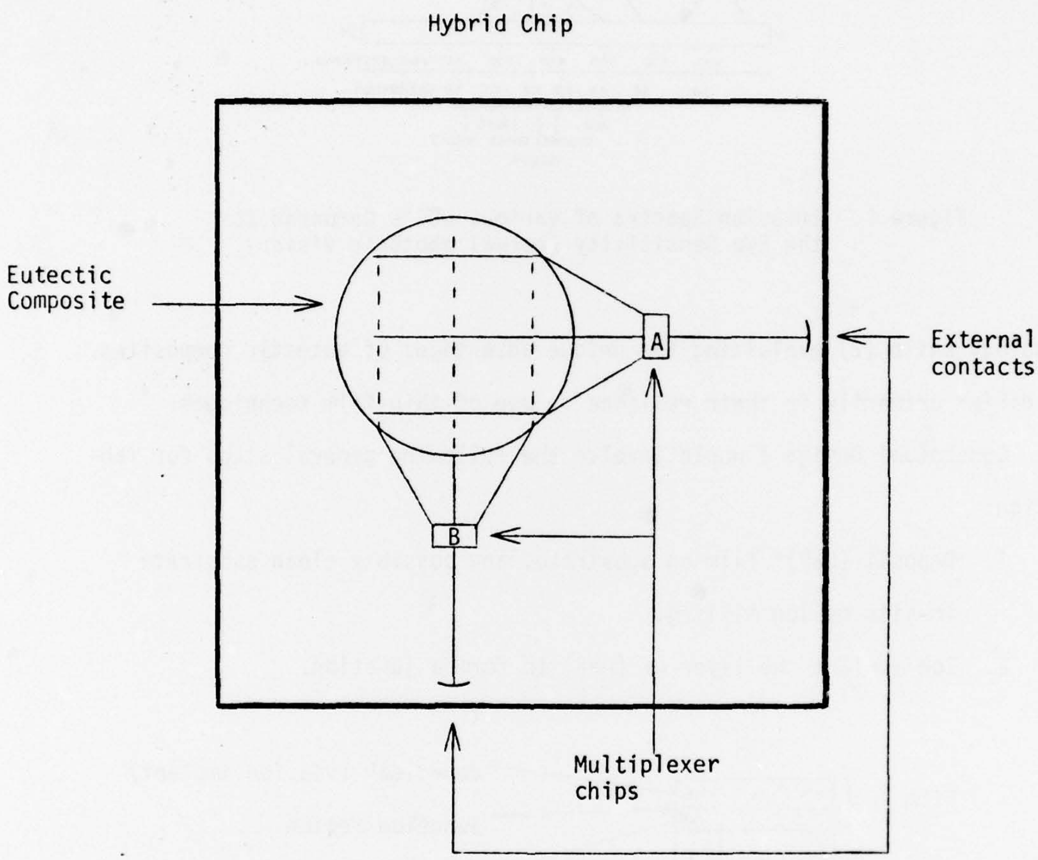


Figure 3. Addressing (Scanning) Technique for a Eutectic Display Device.

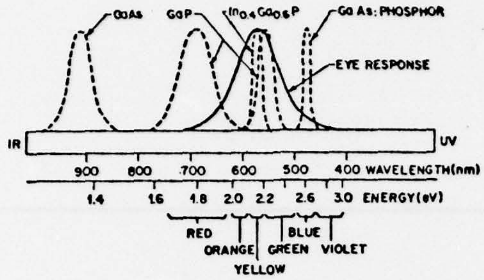
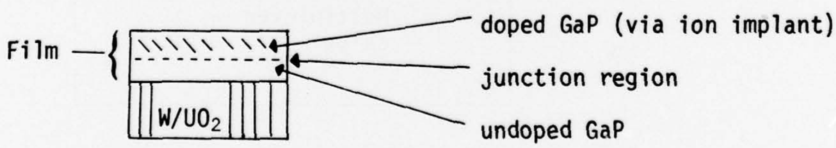


Figure 4. Emission Spectra of Various LED's Compared to the Eye Sensitivity (normal photopic vision)

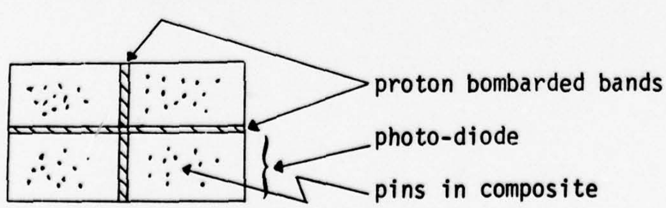
technology while (2) exploiting the unique advantages of eutectic composites. They differ primarily in their reliance on use of thin-film techniques.

Conceptual Design I would involve the following general steps for fabrication:

1. Deposit (GaP)* film on substrate, and possibly clean substrate in-situ by ion milling.
2. Ion implant the layer of (GaP) to form a junction.



3. Isolate photodiode elements by <u>proton bombardment</u>[4] which creates <u>high resistance</u> zones. (Figure is view of display face.)



*Either GaP or other 2-component (III-V) semiconductor for LED base material.

4. Deposit SnO_2 contact grid on top surface (note that a smooth surface, conducive to good deposition, is left after step (3)).
5. Deposit metal contact grid on bottom surface of composite.

Conceptual Design II would be fabricated by the following procedure (see Figure 5). This design would not require the use of ion implantation.

1. Deposit a film of insulating SiO_2 onto composite surface.
2. Mask and etch out holes in SiO_2 film.
3. Deposite film of GaAs, then GaAsP in same step (turn on 'P' oven in MBE apparatus). Note that semiconductor material on the SiO_2 would be polycrystalline and relatively high resistance, so that each hole in the SiO_2 film would contain electrically isolated semiconductor material.
4. Form junction in GaAsP material, either by zinc diffusion or during the growth process with a controlled dopant oven.
5. Deposit transparent SnO_2 (or ITO) film in a strip pattern over the surface.
6. Deposit metal strip pattern on back surface of composite substrate. (See references 38 to 41.)

Both concepts require that "device grade" semiconductor films be grown either directly or indirectly on the metal contact array of the eutectic substrate. Therefore, it is essential to determine how or if such films may be prepared.

IV.B.3. Plasma Tube Display

Another conceptual device is the plasma tube display which uses a low voltage emitter (of composite material) as the switching element. (See Figure 6). Currently, the plasma tube type display is being developed for a variety of Air Force uses, including several relatively small area devices such as

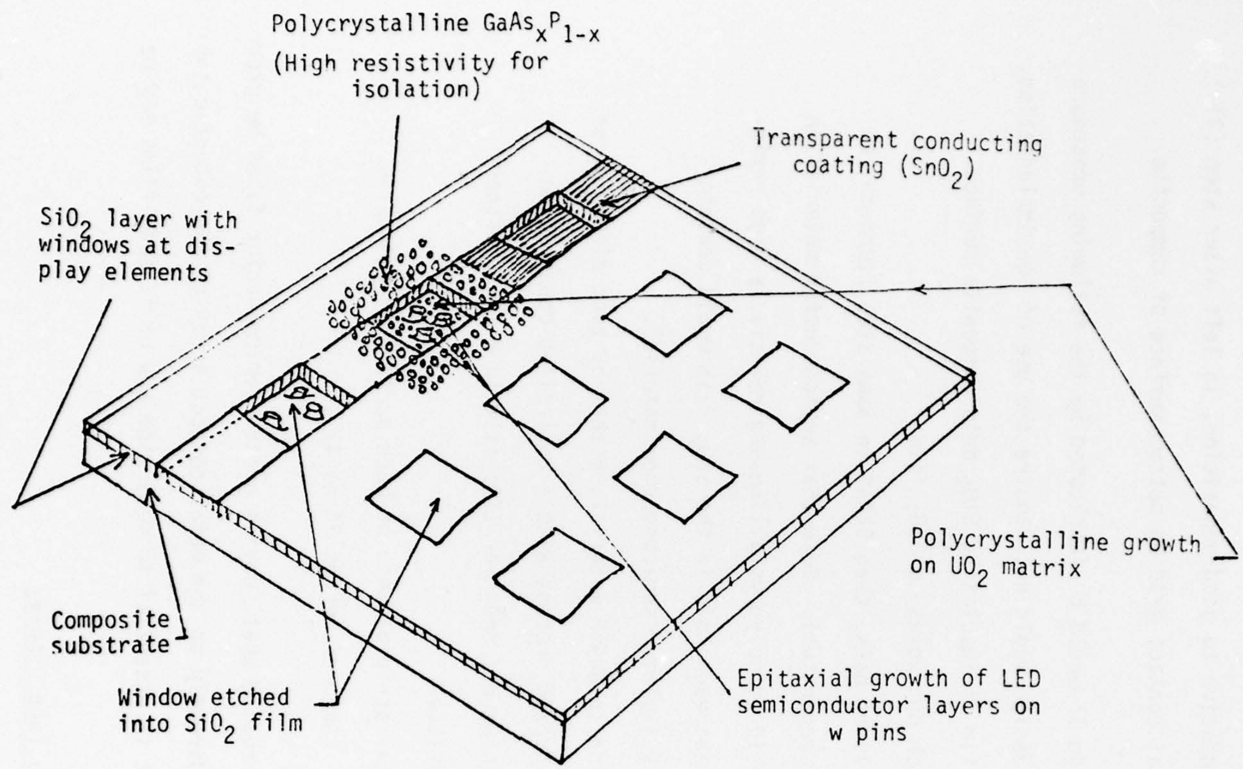


Figure 5. Front Surface Construction of LED Display

NOTE: Back contact strips are perpendicular to front surface SnO_2 contact strips and each strip makes contact with the W pins in each display element of a row.

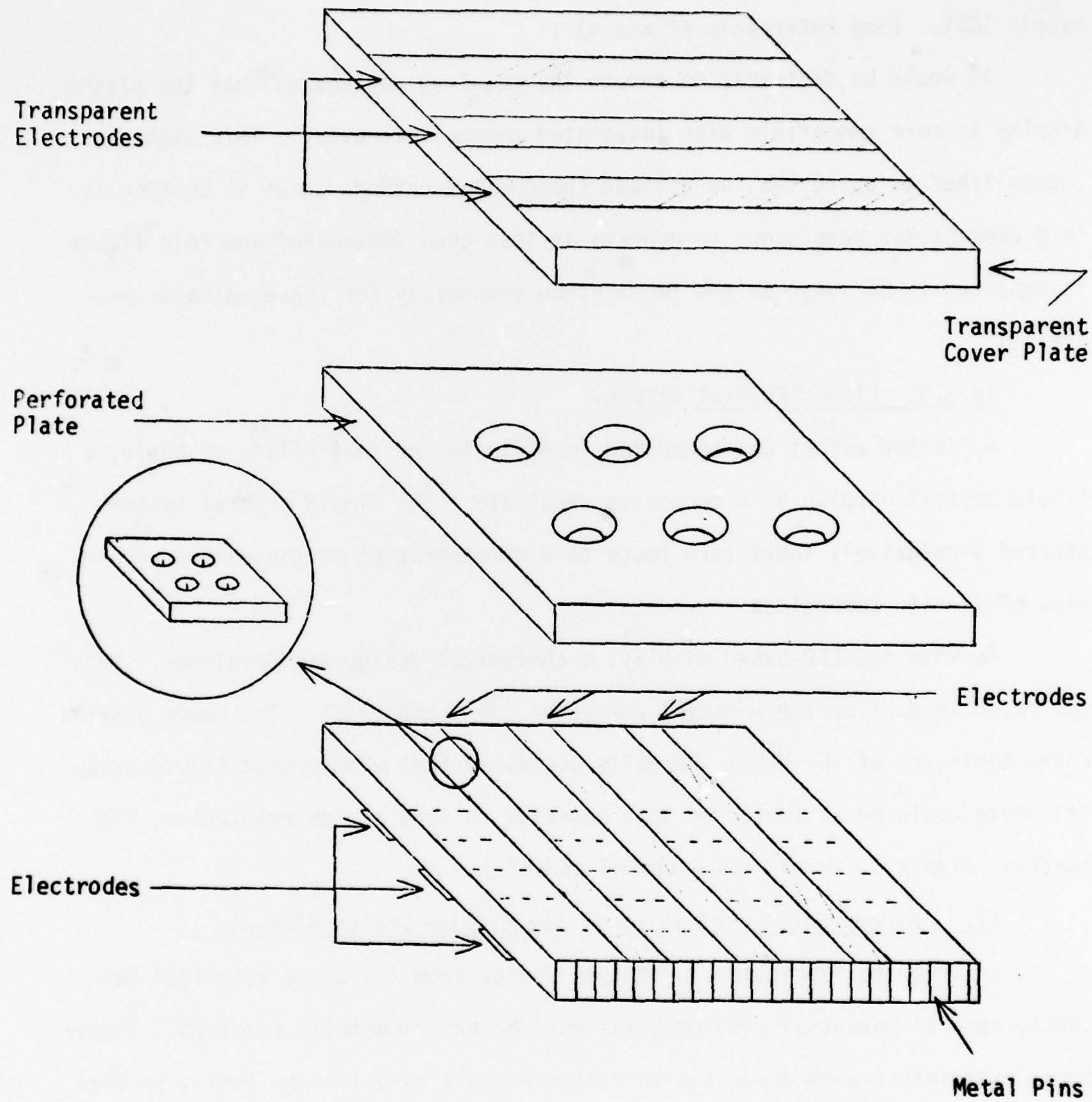


Figure 6. Composite-Based Display: Flat Plasma Tube Using Low Voltage Emitter as Electrode Element

instrument displays. Working voltages for plasma displays now in use are around 300V. Experimental devices have recently been operated at approximately 100V. (See references 42 and 43.)

It would be desirable to reduce the required voltage so that the plasma display is more compatible with integrated control circuitry. This might be accomplished by using the low voltage (composite) cathode shown in Section II. This element has been shown to operate at less than 100 volts, and this figure is expected to be lower as the fabrication technology for these cathodes progresses.

IV.B.4. Liquid Crystal Display

A limited effort was conducted to evaluate the feasibility of basing a liquid crystal display on a composite substrate. The liquid crystal system offered a relatively short-term route to a demonstration of the unique properties of in-situ composites.

As with the LED-based display, a conceptual design was developed. This was based in part on the works of reference (44) and (45). The known general characteristics of the W-UO_2 composite suggested that widely-used liquid crystal media could be activated by this material to form a high resolution, high contrast display. (See references 46 and 47.)

IV.C. Experimental Evaluation of Key Display Design Elements

In order to fabricate a prototype device from the above described concepts, several potential problem areas must be experimentally resolved. Therefore, experiments were conducted to evaluate, on a very limited basis, several design elements of LED and liquid crystal display designs.

IV.C.1. Diode Deposition via MBE (Molecular Beam Epitaxy) on (W-UO_2)

After review of available literature on LED device function and fabrication, it was found that some preliminary experiments had to be conducted if a realistic evaluation of the proposed display device was to be made. Therefore, it was decided to proceed through the sequence in Table I, conducting experiments when necessary in order to obtain properties or characteristics not in the literature.

The feasibility of fabricating a display device using an array of LED's formed in the neighborhood of the rods of a $W-UO_2$ composite was examined. The technique that seems most promising for forming the LED's is the epitaxial growth of semiconductor films onto the exposed rods of the composite. Molecular beam epitaxy (MBE) is being used in the initial stages to explore the growth features of GaAs on tungsten.

Several other eutectic material have been synthesized, but many of their characteristics were unknown or specimens could not be obtained for study. $W-UO_2$ contains one micron pins, up to 200 microns long and approximately 10 microns apart with resistivity of approximately 200-500 ohm-cm, perpendicular to pin axis. $CrSi_2$-Si (Levinson at General Electric) contains 10 micron $CrSi_2$ pins, spaced 30 microns apart. Pins are 50 microns long. Electrical resistivity of the Cr/Si material is comparable to that of W-U-O; the lattice size of Cr/Si would be expected to match closely that of III-V semiconductors. However, specimens of Cr/Si could not be obtained, and tests with it were postponed until a source could be located. $Mo-Cr_2O_3$ and $Cr-Cr_2O_3$ also meet the general material criteria of metal/insulator matrix; little information was available on the properties of these eutectic materials.

The epitaxial growth of a semiconductor from the vapor onto a substrate of the same semiconductor theoretically would be easier than the case where the substrate differs from the epitaxial film. Factors such as crystallographic orientation, contamination, lattice match, substrate temperature and arrival rate of deposited atoms influence the growth process. Gallium arsenide has been used to provide efficient infrared-emitting diodes; to obtain a diode that emits in the visible a band gap of 1.8eV or greater is needed. This is accomplished in the ternary compounds such as $Ga_xAl_{1-x}As$, $Ga_xIn_{1-x}P$ and $GaAs_xP_{1-x}$. The consideration is then the lattice parameter match between the constituent binary compounds. In the GaAs-AlAs system the lattice parameters are 5.65Å and 5.62Å, respectively; in GaP-InP they are 5.45Å and 5.87Å; and in GaAs-GaP they are 5.65Å and 5.45Å. For $GaAs_xP_{1-x}$, therefore, there is a requirement to minimize lattice distortion, for a graded region where the P concentration is increased from zero to slightly less than 0.45, where the direct-to-indirect band-gap transition occurs. A practical composition profile for $GaAs_xP_{1-x}$ diodes is given in Gooch.[29]

The feasibility experiments are designed to compare the epitaxial growth of GaAs onto the micron-size tungsten rods with the more common growth of GaAs on larger area GaAs substrates. The deposition technique that is being used is molecular beam epitaxy (MBE). MBE employs molecular beams to supply the main constituents and doping impurities to the growing surface. The process is carried out in an UHV system and has the advantage of low growth temperatures, good thickness control, junction formation by varying the dopant concentration, cleanliness and adaptability to characterization techniques such as electron diffraction and AES which can be employed at various stages during growth. While much of the MBE work has been concerned with the growth of GaAs and other III-V compounds or mixed compounds on GaAs, there is evidence that epitaxial growth of GaAs on other substrates, especially W and Mo, is possible.

Specifically, the feasibility of depositing "semiconductor-grade" films on a W-UO_2 composite surface with exposed W rods was examined, using GaAs as the epitaxial film. Evaluation of the films by SEM and other analytical techniques was done before a decision was made to proceed to the growth of "semiconductor-grade" LED component films (GaP or GaAsP).

The UHV/MBE system had a quadrupole mass spectrometer for monitoring residual gases and the spectrum of arsenic vapor during deposition. Ion pumps, titanium sublimation pump feedthru and heating mantle are on the lower half of the system. An arrangement of flanges includes an ionization guage, liquid N_2 feedthrus, thermocouples for measuring the Ga and As oven temperatures and power leads for these ovens. The chamber includes two ports, one equipped with a sputter ion gun for substrate cleaning and the other containing a rotary motion feedthru and thermocouple and power leads.

The substrate holder was attached to the rotary motion feedthru enabling it to be rotated to a shutter position with substrate facing up, to a cleaning position with the substrate facing the ion gun, and to a deposition position with the substrate facing the ovens. The substrate, (100) GaAs or the W-UO_2 composite, is held onto a beryllia plate by liquid gallium or indium. Heating is accomplished by passing a current through a Ta film sputtered onto the back side of the beryllia.

The configuration of the ovens surrounded by a liquid nitrogen trap is shown in Figure 7. The Ga oven in the center is maintained at approximately 900°C during deposition and the As oven at about 300°C. Provision is made for an additional phosphorus oven to grow GaP or GaAsP.

Initial deposition runs to verify the conditions for depositing epitaxial GaAs substrates were made and compared with results obtained with a large MBE system that has been operated successfully for over one year. GaAs substrates were chemically cleaned; the oxide which was present after such cleaning was removed by heating in the system to about 530°C and any residual carbon was removed by Argon ion sputtering. Confirmation of this cleaning procedure would have been possible later on in the program since it was planned to install a device for Auger analysis of the substrate surface.

Preparation of the W-UO_2 surface proceeded in parallel with the UHV/MBE system development. Mechanically polishing the composite specimen and cleaning with trichloroethylene followed by methanol in an ultrasonic bath left a poly-

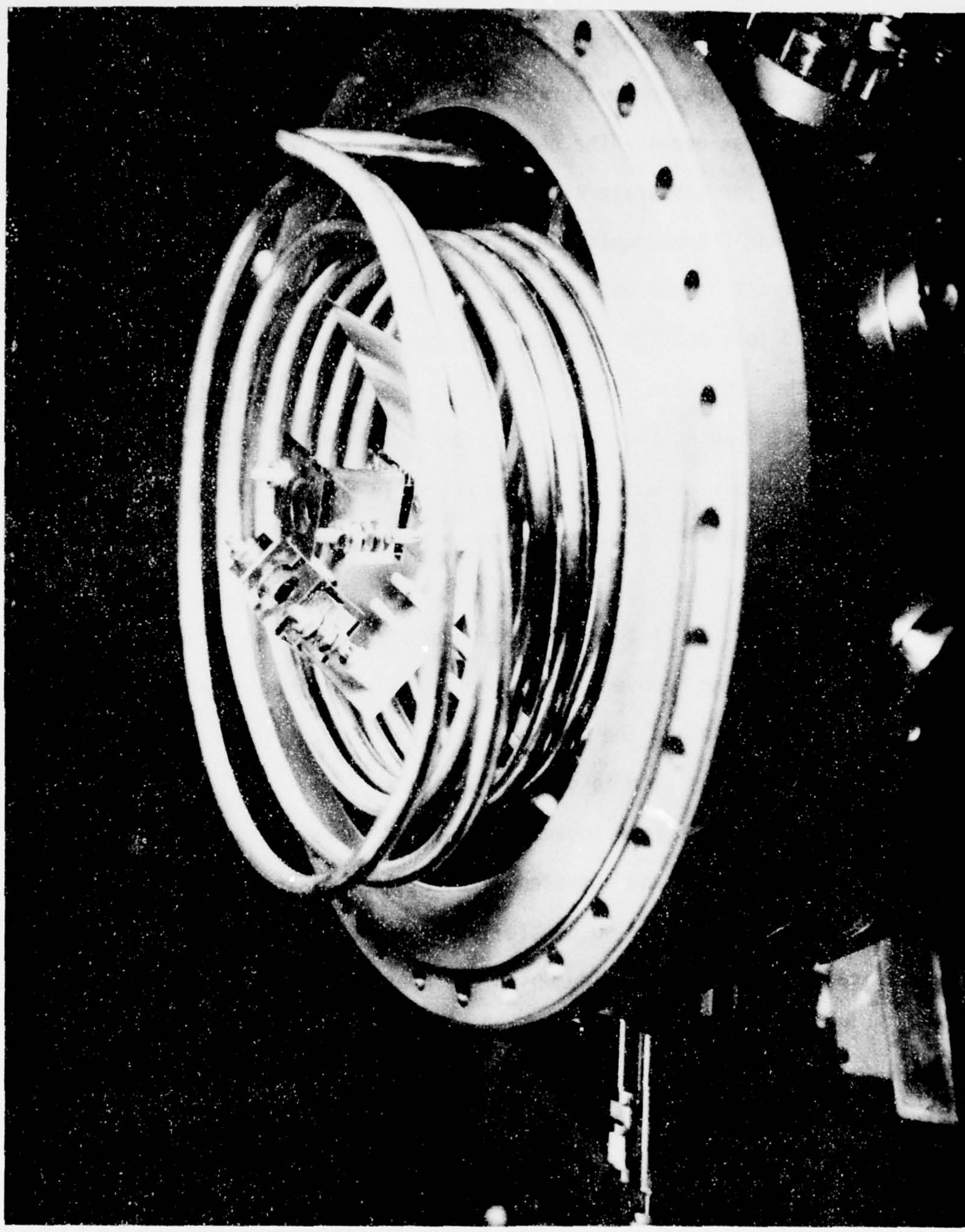


Figure 7. View of MBE Apparatus: Ovens and Nitrogen Coil

crystalline layer of UO_2 over the entire specimen as indicated by reflection electron diffraction patterns.

Etching for 30 seconds removes UO_2 and exposes the tunsten pins; a spot pattern is obtained by RHEED (reflection high energy electron diffraction) indicating the single crystal nature and orientation of the tungsten pins. Figure 8 shows an SEM micrograph (magnification 10,000X) of the etched composite surface. Measurements on the pins indicate a pin diameter of approximately 0.5 micron and a height of about 0.33 micron. Scratches on the UO_2 matrix are a result of the final mechanical polish step. It is expected that refinements in the polishing procedure will improve the smoothness of the UO_2 surface. Controlling the etch time would enable us to obtain pin heights greater or less than that shown. It would be possible with Auger techniques to determine the extent of contamination on the tungsten surface and its removal by ion sputtering.

A series of experiments were conducted at two GaAs deposition temperatures after the MBE equipment was tested using a GaAs substrate. The MBE set-up was shown to be performing well for depositing GaAs on a GaAs substrate. Smooth surfaces (at SEM magnifications of 5-6000X) with small etch pits were seen when GaAs was deposited on GaAs substrate at 575°C. As a starting point, a W-UO_2 substrate was next substituted in the MBE apparatus and films deposited again at 575°C. Growth rate in all experiments was about one micron per hour. SEM views of the resulting surface are shown in Figure 9. The films appeared to attach to both phases of the composite; however, the growth surface was very irregular and of poor quality. Now the substrate temperature was increased to 650°C. The resulting growth may be seen in Figure 10. Films formed at this temperature seemed not to adhere to the tungsten (pin) phase of the composite, while growth on the matrix appears to be of better quality (surface of film appears smoother, grains appear to be larger). Microprobe analysis showed the

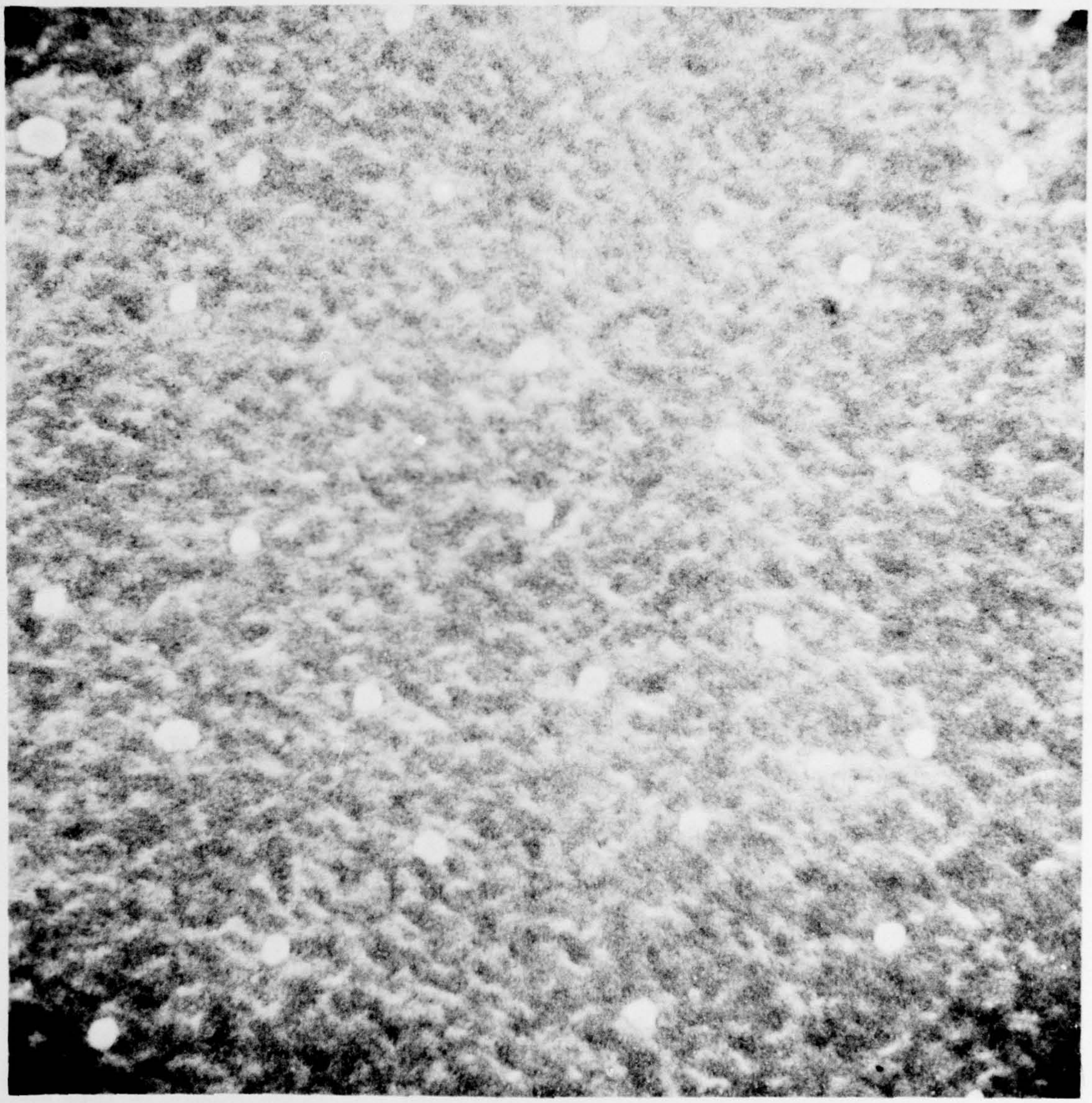


Figure 8. SEM View of $W-UO_2$ Surface. Pin Diameter is 0.5 μ.

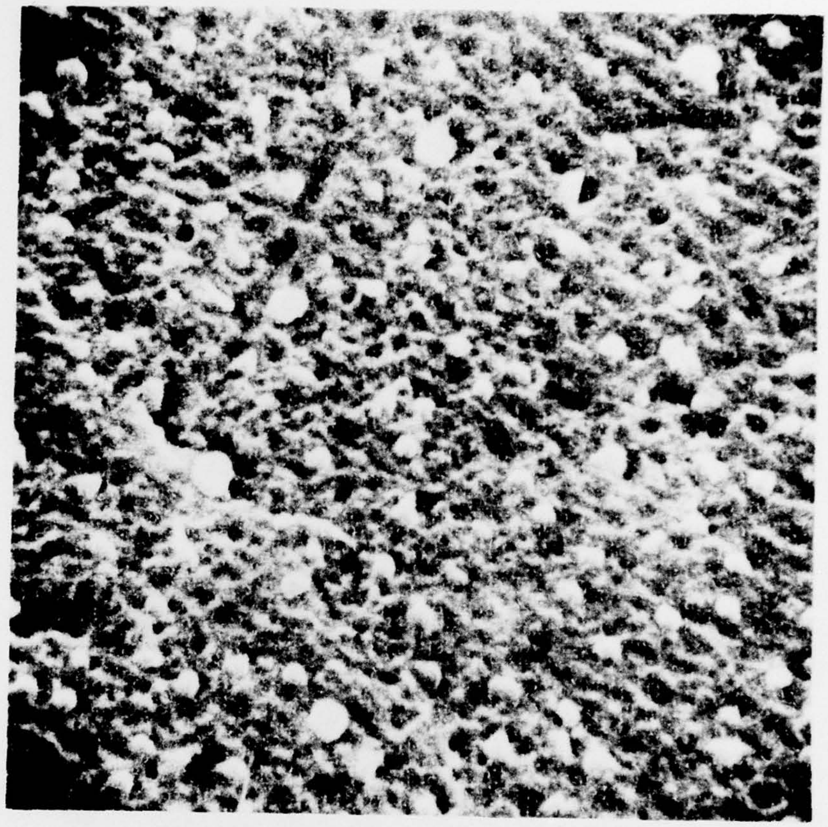


Figure 9. SEM View of Flow Temperature Epitaxial Film (∿10,000X)

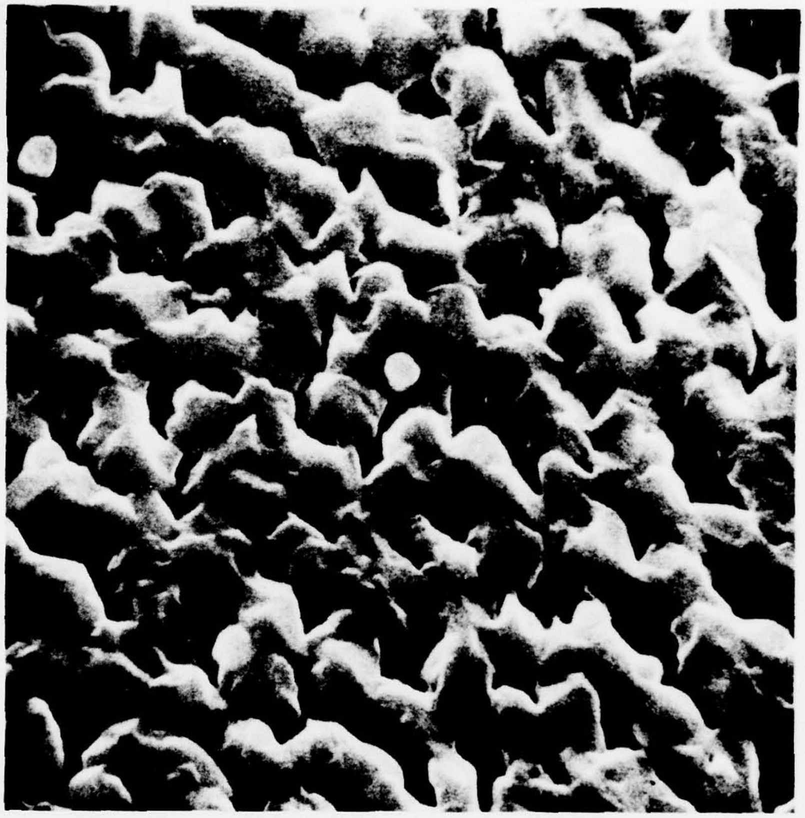


Figure 10. High Temperature Growth of GaAs on $W-UO_2$ (~20,000X)

presence of U in the GaAs films.

From the limited effort expended, it appears that growth of quality semiconductor films on this particular composite should follow one of two experimental paths. First, a series of runs at intermediate temperatures should be made on carefully cleaned substrates to locate conditions where "smooth" growth is obtained, yet temperatures are low enough to avoid reaction between matrix and film. The other experimental route would involve etching back the matrix 10-20 microns, depositing an intermediate film of perhaps Al_2O_3, etching Al_2O_3 off the pins, and finatly depositing the semiconductor filsm. This latter approach would have the advantage of reducing any electrical leakage through the matrix.

IV.C.2. Liquid Crystal Experimental Activity

In the previous section (IV.B.4.), the rationale for liquid crystal experiments is given. At the outset of these experiments, no reliable figure for matrix conductivity of UO_2 in W-UO_2 was available. It was assumed that UO_2 behaved as a reasonably good electrical insulator. However, simple liquid crystal cell tests and subsequent resistivity measurements showed that the matrix UO_2 conducted enough current to activate the entire liquid crystal coating on the composite surface. It was not possible to selectively excite small areas of the LC film.

For the tests, a liquid crystal test cell was constructed and shown to be operational using conventional (coated glass) substrates for electrode surfaces. The test cell exhibited good switching response and good resolution at electrode boundaries.

At this point, W-UO_2 surfaces (circa 1 in^2 area) were prepared by polishing and vapor deposition of metal contact patterns. The substrate was installed in the test cell (see Schematic, Figure 11), and liquid crystal film (MBBA) used as with the glass substrates above. It was shown that the composite will conduct

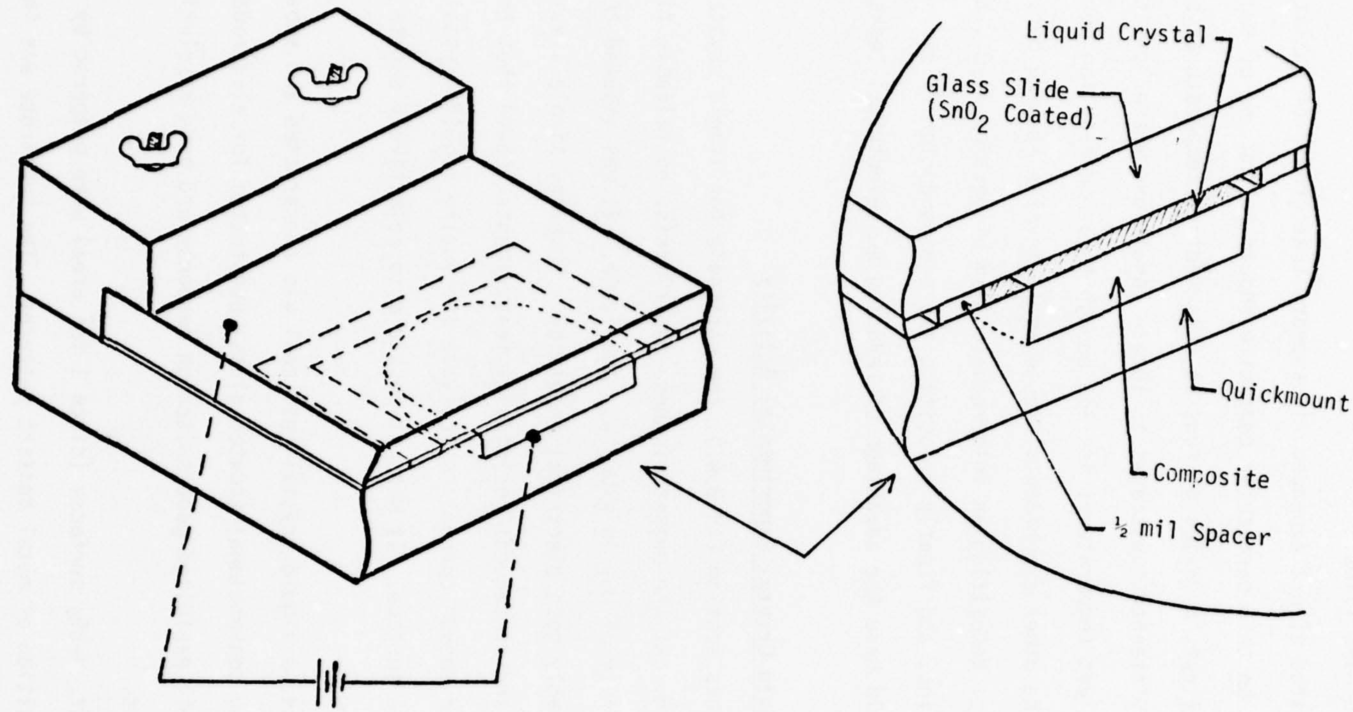


Figure 11. Schematic of Liquid Crystal Test Cell

an applied low voltage and activate the light-scattering effect of the liquid crystal material (MBBA). However, in all cases the entire cell surface area was either "on" or "off"; we were not able to activate specified areas of the cell. We conducted experiments to determine whether (a) the composite matrix (UO_2) had too little electrical resistivity or (b) if electrical "shorts" existed elsewhere in the test cell.

Further testing, including measurement of the resistivity (circa 500 ohm/cm) of W-UO_2 in a direction perpendicular to the W pins, has led to the conclusion that the W-UO_2 material is not suitable for use with available (low conductivity) liquid crystal materials. Liquid crystal cells are extremely low current devices. There is apparently enough electrical "leakage" through the bulk of the eutectic to activate the liquid crystal over the entire display face. Other display types, such as thin-film luminescents, which are high current, non-linear devices should be studied until a high resistivity composite becomes available.

IV.D. Summary

A number of display concepts have been described by the project staff. These include diode (LED) arrays, thin-film luminescent devices, plasma devices, and liquid crystal devices. At least two very promising characteristics seem inherent in such devices: extremely high resolution and sharp contrast. Also, potential for solid state compactness and ruggedness seem likely in designs other than the plasma display.

Preliminary engineering experiments were conducted to assess feasibility of constructing prototype LED and liquid crystal devices. The LED concepts appear still viable in view of the characteristics of several semiconductor films deposited on composite surfaces. However, at this point the project staff recommends that study be first made of the thin-film luminescent display. It appears likely that much less development effort would be required to obtain a prototype device. Liquid crystal tests showed that the matrix electrical conductivity of available insulator/conductor eutectics is too great for use with liquid crystal media.

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V. Conclusions and Recommendations

V.A. General Trends Toward Utilization of In-Situ Composites in Devices

As mentioned briefly in the introduction, eutectic composites hold great promise as a new class of materials with potential for application in a broad range of current and future electro-optic devices. The project staff, in the course of evaluating eutectic materials, has pointed out three general areas in which these composites have unique and desirable features. These are: (a) the potential for engineering a material which may satisfy the several property requirements of a specific device, (b) synergistic or unique combinations of properties may be obtained which are not available in any single phase material, and (c) directional eutectic solidification presents a simple economical means of preparing complex and precision composite structures.

This class of materials offers the opportunity to engineer, by combining many classes of materials, composite structures for the specific demands of various devices. This includes devices with electronic, magnetic, optical, thermal conductivity and other functions which require anistropic material properties. Also, the magnitude of the electrical conductivity or other property may be varied by suitable choice of eutectic components. Thus, the specific set of properties required by a new or more effective device may be supplied by an appropriate composite.

Further reason for interest in the eutectic composites includes the potential for synthesis of unique combinations of material properties. It has been experimentally observed that by combining a component with property A-B (for example, magnetoelectric) with another component with property B-C (for example, electro-optic), then one may obtain a "new" composite material with property A-C (for example, magneto-optic). There is efficient transfer of energy during these interactions due to the interface quality and crystallographic orientation of the eutectic components. Efficient energy transfer may provide a means of amplifying relatively weak properties of some materials to usable levels, i.e., if the optical effect of an electro-optic material were weak, combining with a magneto-electric material could yield a composite with a strong optic effect via magnetic energy input.

Directional solidification enables one to synthesize complex structures containing micron-sized elements which are uniformly dispersed in and crystallographically aligned with the matrix material. It is doubtful if any bonding process or deposition process could compete on an economical basis with the relatively simple technology of single-step composite fabrication by means of directional solidification.

There apparently are a large number of eutectics which would be potentially useful composites. This class of materials has received only limited study, but early research efforts have shown that the number of suitable eutectics number in the hundreds. As a body of information regarding the range of materials becomes available, trends in eutectic properties as a function of composition, etc., and other general data are systematically developed, it is likely that additional device applications will be suggested to researchers in this field. Also, additional data, etc., will speed the evaluation and development of device concepts based on in-situ composites.

At this point only one of the many types of these materials has been carefully evaluated at the experimental level. That work has been essentially confined to the mechanical properties of high temperature gas turbine alloys. Therefore, the eutectic composites appear to be an attractive area in which to search for useful new materials.

In the search to identify device applications, an extensive information base has been established. This includes a current device-oriented literature

Eutectic Device Characteristics

	New Device	Based upon Physical Phenomena & Effect	Material Property Required	Potential Superior or Unique Composite Property	Candidate Materials & Property Values	System Application
1.	V.M.H. photovoltaic cell	Photovoltaic jct. optical absorption	Semiconductors	Radiation resistant high conversion efficiency	InP/cdS	Detector/solar cell
2.	V.M.S.B. photovoltaic cell	Photoelectric effect & Schottkey barrier	Semiconductor and metal	Increased conversion efficiency		Detector/solar cell
3.	M-Josephson detector array	Josephson jct.	Superconductor and insulator	broadband detector	Ta/al	Detect multi-laser WL
4.	Field emission radar tube cathode	Field emission electron source	Array of sharp conductive fibers	Low voltage operation high current density long lifetime	W/UO_2	Radar detection systems
5.	Diode display	Light-emitting diodes	Semiconductor and insulator	Fiber density permits high resolution		Head up display system

Figure 1. Example of Summary Table Used for Device Evaluation

A Survey of Known Semiconductor-Containing Eutectics

EUTECTIC	COMPOSITION	MICROSTRUCTURE	REFERENCE
Ag-Bi	97 vol % Bi	Broken Lamellae Ag	67HDTJ
Ag-Ge	22 vol % Ge	Abnormal	65DVL
Al-Ge	34 vol % Ge	Abnormal	70FVA
Al-Si	12 vol % Si	Abnormal, Rods Si	70FVA
Au-Ge	31 vol % Ge	Abnormal, interconnected flakes	70FVA
Au-Si	18 at % Si	?	70FVA
Be-Si	(62 at % Be)	?	74TCC
Bi-Pb_2Bi	73 vol % Pb_2Bi	Abnormal, pyramid L/S interface	67GFSB
Bi-Bi_2Tl	37 wt % Bi_2Tl	Abnormal	70GJE
Co-Co_3Si	(23 at % Si)	Lamellar	73JRE
CrP-InP	~1.6 mole % CrP	Rods CrP	74SBW
Ga-Ge	(90 at % Ge)	?	74TCC
Ga-Si	(90 at % Si)	?	74TCC
Ge-$HfGe_2$	(96 wt % Ge)	Irregular	71HNJ
Ge-In	70 at % In)	?	74TCC
Ge-$MoGe_2$	(95-98 wt % Ge)	Irregular	71HNJ
Ge-$PrGe_2$	(92 wt % Ge)	Degenerate Lamellar	71HNJ
Ge-Sb	?	Lamellar	70FVA
Ge-Sn	(30 at % Ge)	?	74TCC
Ge-$Th_{0.9}Ge_2$	(85 wt % Ge)	Poorly Aligned Rods $Th_{0.9}Ge_2$	71HNJ
Ge-Tl	(30 at % Ge)	?	74TCC
⋮			

NOTE: Reference Code: year, author's last initial, authors' 1st and 2nd initial.

Figure 2. Example of Tabulated Eutectic Composites

collection, tabular device descriptions for use in evaluation processes (see Figure 1), tables of eutectics with useful properties (see Appendix 1), and tables of specific classes of eutectic composites (e.g., eutectics with semiconductor components, see Figure 2).

V.A.1. Status of In-Situ Composites

There are many unanswered questions regarding the development of eutectic systems for use as composite materials. For example, what is the role of directional solidification parameters in controlling the ultimate spacing precision of fibers in a eutectic? Can eutectics be prepared with fiber spacing more precise than currently observed variations of about 10%? In this case, an affirmative answer would open the door to use of these materials in a variety of interference-grating type systems and applications based on optical/IR birefrengence. As further work is done on a variety of types of systems—metals, ionics, covalents and mixtures—a clearer picture may be formed of the experimental as well as theoretical limitations of the various types of eutectic composites.

As an example of some of the limited information available concerning the in-situ composites, the following generalizations may be made about fiber (rod) and lamellar (plate) type structures. One key factor by which some prediction can be made as to whether a fiber or lamellar type structure will occur for a particular composite is the volume fraction of the minor phase. For fractions greater than 35% the structures will almost certainly be lamellar, while less than 10% will almost invariably yield fibers. Either of the structures may occur for volume fractions between these extremes, with fibers prevailing for fractions less than 25% and plates (lamellar) prevailing for fractions greater than 30%.

Fibers are known to have a number of different cross sections, some of which are listed below:

1) circular
2) square
3) rectangular
4) triangular
5) hexagonal
6) octagonal
7) arrow-feather

The separation distance (λ) is a function of the rate of growth (R) of the solid and obeys quite closely the relation

$$\lambda = AR^{-1/2} \quad \text{where A is a constant.}$$

Rod diameters tend to range from a minimum of .1μ to a maximum of around 5μ. It has been shown for some systems that an increase in the rate of growth by two orders of magnitude results in a decrease in rod diameter by one order of magnitude. However, rod structures will in general deteriorate if this is done. This may indicate that smaller rods are possible for the systems whose rod diameters fall in the typical range from 1 to 2.5 microns.

There seem to be only a few distinct variations on lamellar growth. The ones mentioned in the literature are:

1) parallel plates
2) spiral
3) Chinese script

The separation distance for lamellar growth ranges from 5 to 10μ for metallic systems and may reach maximums of 20μ in ionic systems and even higher for organic materials. Since the minor phase volume fraction ranges from 30 to 50%, it follows that the range on plate thickness will be from 1.5 to 2.5μ. It would be most useful if sufficient information were available to extend this type of generalization to many other properties of eutectic composites.

Previous research efforts suggest that many useful methods remain to be discovered in the technology of directional eutectic solidification. For example, Guinier (73GA) reported that Sn precipitates in the Pb lamallae of a Pb-Sn eutectic could be removed by a suitable anneal of the material. The precipitates apparently diffuse to a thermodynamically more stable area, which in this case results in a more desirable eutectic microstructure. Also in the above study, it was found that a ribbon-like ingot geometry for directional solidification yielded much more regular lamellar microstructures than did cylindrical ingots. This suggests novel ingot geometries may be required for some eutectic systems in order to prepare high quality composites. Other promising avenues for improvement or control of eutectic quality include seeding of the directional growth and also the use of heat pipes to maintain close control of thermal gradients during in-situ composite growth.

V.B. Cold Cathode Devices Based on Field Emission from Composite Materials

Field emission cathodes for microwave tubes offer the advantages of instant warm-up, high current (power) density and long life. Initially the prototype tubes would be developed for applications such as magnetron transmitters where cathode noise would not affect tube operation.

Preliminary experiments were performed to determine whether the favorable geometry afforded by an annular cathode would lead to total current from a composite field emission cathode which would satisfy the needs of a medium or high power traveling wave tube. The results obtained strongly indicated that further study of this component might well lead to the development of a successful cold cathode for use in microwave tubes. At currents greater than 0.5 mA, a visible glow appeared to emanate from most of the cathode circumference. The project staff tentatively concluded that they achieved a reasonably uniform hollow field emission beam with an intensity of at least 4-5 mA. It is considered significant that this first device did, in fact, operate even though fabrication and assembly techniques were not well developed.

The second experimental phase of this study was concerned with demonstration of relatively large stable emission currents. To this end, a series of experiments was conducted to identify key variables which limit total current output and also to identify variables which contribute to stable currents. It was shown that a hollow type field emission cathode design can be operated CW for periods of days at currents on the order of 15 mA and current densities (approximately 500 mA/cm^2) comparable to operational microwave cathodes. The device was operated with low frequency (60 Hz) at 5 mA currents. Uniform average emission over the relatively large array of pins (approximately 0.03 cm^2) was observed; emission uniformity also was implied by the distribution of rounded pin tips after experiments. Use of a constant-current power supply markedly reduced the amplitude of current transients and associated damage to composite emitters.

The performance obtained in this work suggests that, with additional development, the composite-based field emitter could form the basis for a high performance cathode or high intensity "cold" electron beam. There is particularly a need for better quality materials and for studies of the behavior of arrays of pins emitting electrons simultaneously.

V.C. Compact, High Resolution Display Devices

In order to address the continuing Air Force need for improved—greater resolution, greater contrast, more compact, more reliable—devices, several promising eutectic-based display concepts were analysed in some depth. These concepts included diode arrays, plasma tubes, liquid crystal, and thin-film luminescent display types. In general, the effort was focused toward combining developed display technology (e.g., LED technology) with the microstructure of eutectic composites.

Detailed designs for composite-based display devices were developed and experiments were conducted in the areas of light emitting diode (LED) technology and liquid crystal displays. In the course of this work, the staff identified two very promising designs for an LED type display, and constructed an excellent research tool, a molecular beam epitaxy unit, for evaluating appropriate thin-film LED technology. Experiments were conducted that suggest good quality films may be grown on a two-phase composite surface. If good films can be grown on this substrate, then there is a good probability of fabricating a successful LED type display on the eutectic composite.

In the LED designs there are common key design elements which must be evaluated experimentally since data is not otherwise available. This work must be done before a realistic attempt to fabricate a device can be made. The critical experiment facing the staff was one to examine the quality of semiconductor films deposited on the available W-UO_2 substrate. An advanced MBE (molecular beam epitaxy) deposition device was constructed, since MBE promised to give rapid, "best chance" deposition on the relatively uncharacterized composite surface.

These experiments suggest that one could successfully deposit good quality films on a two-phase surface. However, cleaning one or both of the exposed materials for epitaxy, and temperature selection to obtain best film quality both may call for unique approaches or for a careful compromise of conditions.

The liquid crystal experiments were conducted as a supplementary effort which might provide a quick demonstration of the useful properties—high resolution, high contrast effects—obtainable from a eutectic-based display.

A test cell was constructed and the available W-UO_2 composite electrode surface was found to efficiently activate a MBBA liquid crystal mixture. The display was easily switched on and off at normal low L.C. operating voltages. However, it was not possible to activate specified areas of the display, due to the relatively low resistivity of the UO_2 matrix. This experience led to the conclusion that, until other eutectic materials are available, development of electrical display devices should be directed toward LED, plasma, or other display modes which respond non-linearly to relatively large currents and low voltages. In such cases, the electrical resistance of the composite matrix is much less critical and the potential contrast and resolution of a composite display device may be realized.

V.D. Other New or Improved Devices Utilizing In-Situ Composites

In the course of this study, a number of device concepts have been suggested by members of the project staff in addition to the cold cathode and display concepts (see Sections II & III). These concepts have been reviewed by the staff from the point of view of several academic and engineering disciplines, i.e., Physics, Metallurgy, Electronics, Material Science, etc. Listed below are concepts which appear particularly interesting; these concepts have been subjected to preliminary technical/economic analysis and deserve further study.

(a) Photovoltaic devices for application as either radiation detector (e.g., laser radiation) or as solar cells for power generation. The vertical multiheterojunction device would combine two semiconductor materials in a composite structure to form photovoltaic junctions which are inherently tolerant of damaging radiation and are capable of high power output for a given surface area exposed to radiant energy. The vertical multi-Schottky Barrier would be based on a composite of semiconductor matrix containing metal fibers. This device should have increased detector sensitivity (or increased solar cell output) due to the presence of closely-spaced metal conductors which collect the photoelectrons before recombination can occur. Polycrystalline film/multiple Schottky device. The unique feature of this detector or solar cell would be the potential for using a polycrystalline semiconductor material while retaining efficiency comparable to single crystal semiconductors.

(b) Eutectics containing superconductor phases. It appears possible to develop broad-band visible/IR detectors by forming an array of

Josephson junctions at the surface of a composite containing superconducting fibers. Also, a similar array of contacts appears capable of generating far infrared wavelengths. Current sources for these wavelengths have severe limitations.

(c) Thermal Fatigue Monitor. This device is visualized as a "mileage meter" to indicate at any time the accumulated cyclic stress—due to thermal cycling in service—that an electronic device has undergone. The fatigue monitor would be based upon composite materials which have predictable microstructural changes when thermally cycled.

(d) Field Emission Exitation for Stable CO_2 lasers would offer a means of pumping an extremely compact laser system. The small low voltage power supplies required and reliable efficient pumping source would facilitate the development of a modular laser unit useful, for example, in secure multi-laser air-to-air communication systems.

(e) Magnetic Recorder Sensors. A magnetic recorder pickup based on a composite magneto-resistive material potentially would be capable of vectorially reading super-imposed independent channels which—in analogy to stereo record technique—would be recorded on the same section of material. The insensitivity to tape speed would permit precision recorder operation in spite of mechanical or electrical disturbances which an aircraft might encounter.

Other concepts were suggested, but effort was not available for a preliminary evaluation. Examples of such concepts are (1) composites containing thermally conductive graphite fibers for directional heat transfer, and (2) piezoelectric/"light valve" for use as page composer for storing data in a laser hologram memory system. Others include use of suitable eutectics as photocatalytic materials for the photoreduction of water to hydrogen fuel. Layered semiconductor structures have demonstrated such a catalytic effect.

Complementary uses of in-situ materials involve either extracting the rod structures for separate use or extracting the rods leaving a porous plate for separate applications. For example, it has been suggested that the geometry of Mg or Al fibers would be ideal for use in a liquid phase shifter device for phase-shifted microwave systems. It is understood that some preliminary work is now underway. The composite matrix with pins removed would serve as a precision filter or a "container" for liquids or powders. A liquid might, for example, be uniquely subjected to a magnetic field while confined to the channels of the matrix material.

A further suggestion has been made to the effect that aircraft might be made "invisible" to microwave detection by coating with suitable materials. Due to the capability for generation of unique and enhanced properties, it is suggested that a material with microwave absorbing or other properties could be developed making use of the in-situ composite approach.

In the future, until eutectic materials are better characterized, it may be useful to select a higher performance level for a device or material and then seek an appropriate composite material for use. By proceeding from well-defined performance criteria, it may be possible to exploit the unique properties and flexibility of this class of materials.

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APPENDIX I

Appendix I. Microstructure, Crystallography and Functional Properties of Unidirectionally Solidified Eutectics*

A - Binary Eutectic Alloys

Number	I System α+β	II vol%α	III Microstructure	IV References(1)	V Properties
1	Ag-Bi	~3	Broken lamellae of Ag	H. W. Kerr and W. C. Winegard. *Crystal Growth*. Pergamon. New York. 1967. 179. M. R. Taylor. R. S. Fidler and R. W. Smith. *J. Crystal Growth*. 3. 4. 666 (1968). T. Digges. Ph.D. Thesis. Lehigh Univ. 1969.	
				67HTJ 69DTG	semiconductor galvanothermomagnetic
				71DTG 72UC	electrical analog thermomagnetic
2	Ag-Cu	~74	Lamellar and rod	E. C. Ellwood and K. Q. Bagley. *J. Inst. Metals* 76. 631 (1949). F. D. Lemkey and M. Nichols. United Aircraft Res. Labs. East Hartford. Conn., unpublished. H. E. Cline and D. F. Stein. *Trans. AIME*. 245. 841 (1969).	
				75FGA 75FGB	elect. conductivity thermoelectric
3	Ag-Ge	~78	Abnormal	V. deL Davies. *J. Inst. Metals*. 93. (1964-65). 10.	
4	*Ag-Pb	~15	Broken lamellae	H. W. Kerr and W. C. Winegard. *Can. Met. Quart.*. 6. 67 (1967).	
			Rods and broken lamellae. abnormal at high R	A. Moore and R. Elliot. *J. Inst. Metals*. 96. 62 (1968).	
				66LSA 67LJD,67GFSB	superconductor superconductor
5	Ag-Si	~90	Abnormal	M. G. Day and A. Hellawell. *Proc. Roy. Soc.*. Ser. A, 305. 473 (1968).	

(*) This appendix is partially derived from the work of Hogan (71 HLM).

(1) Reference Code: year, author's last initial, author's first and second initials. (See Bibliography)

A - Binary Eutectic Alloys

Number	I System α+β	II vol%α	III Microstructure	IV References	V Properties
6	$Al-Ag_3Al_2$	~40	Lamellar	E. C. Ellwood and K. Q. Bagley, *J. Inst. Metals*, 76, 631 (1949).	
				R. W. Kraft, F. D. Lemkey, D. L. Albright, and F. D. George, United Aircraft Res. Labs. Rep. A-110069-5, 1962.	
				D. J. S. Cooksey, D. Munson, M. P. Wilkinson and A. Hellawell, *Phil. Mag.* 10, 745 (1964).	
7	$Al-Al_4Ca$	69	Lamellae and rods of $CaAl_4$	K. N. Street, C. F. St. John and G. Piatti, *J. Inst. Metals* 95, 326 (1967).	
8	$Al-Al_4Ce$	88	Lamellar and rod	Ibid.	
9	$Al-Al_9CO_2$	~98	Lamellae of Al_9CO_2	F. D. Lemkey, W. Tice, and E. Bartholomew, unpublished.	
10	$Al-CuAl_2$	54	Lamellar	V. deL. Davies, *J. Inst. Metals*, 93, 10 (1964-65).	
				R. W. Kraft and D. L. Albright *Trans. AIME* 221, 95 (1961).	
				R. W. Kraft, *Trans. AIME* 221 704 (1961).	
				R. W. Kraft, *Trans. AIME* 224 65 (1962).	
				I. G. Davies and A. Hellawell *Phil. Mag.* 19, 1285 (1969).	
			Fibrous	I. M. Hogan, *J. Aust. Inst. Metals*, 10, 78 (1965).	
				73GG	thermal cycling
				75BBN	thermal transport
11	$Al-Al_9Fe$	97	Abnormal	R. W. Kraft, F. D. Lemkey, D. L. Albright, and F. D. George, United Aircraft Res. Labs. Rept. A110069-5, 1962.	
12	Al-Ge	66	Abnormal	A. Hellawell, *Trans. AIME*, 239, 1049 (1967).	
				74TCC	elect. resistivity superconductor
				75JWL	superconductor
13	$Al-Al_3Ni$	89	Hexagonal rods and broken lamellae of Al_3Ni	F. D. Lemkey, R. W. Hertzberg, and J. A. Ford, *Trans. AIME* 233, 334 (1965).	
				W. K. Tice, W. R. Lasko and F. D. Lemkey in "*Fifty Years of Progress in Metallographic Techniques*," ASTM STP 430, 239 (1968).	
				69MRG	thermal conductivity
				70 BMB	electrical conductivity
				73KYP	thermal stability
				73GG	thermal cycling
				74SR	resistivity

A - Binary Eutectic Alloys

Number	I System α+β	II vol%α	III Microstructure	IV References	V Properties
14	Al-Al_3Pd	67	Lamellar	F. D. Lemkey, United Aircraft Res. Labs., unpublished.	
15	Al-AlSb	99	Abnormal	V. deL. Davies, *J. Inst. Metals* 93, 10 (1964-65). G. Lesoult, Ecole des Mines, Centre de Materiaux, Corbeil, France.	
16	Al-Si	88	Abnormal and "rods" of Si	W. Straumanis and N. Brakes, *Z. Phys. Chem.* 38B, 140 (1937). R. A. Meussner, U.S. Naval Res. Lab. Rept. 5341, 1959. J. A. E. Bell and W. C. Winegard, *J. Inst. Metals* 93, 318 (1964-65). M. G. Day and A. Hellawell, *Proc. Roy. Soc.*, Ser. A, 305, 473 (1968).	
				74CC	elect. resistivity/ superconductor
				75JWL	superconductor
				75KJ	elect. resistivity
17	Al-Sn	1.5	Lamellar and rod	J. D. Hunt, Oxford Univ., England, unpublished. A. Moore and R. Elliott, Univ. Manchester, Manchester, England.	
18	Al-Al_3Th		Spiral lamellar	R. E. Fullman and D. L. Wood, *Acta Met.* 2, 188 (1954).	
19	Al-Al_3Y	84	Lamellar and rod	K. N. Street, C. F. St. John, and G. Piatti, *J. Inst. Metals* 95, 326 (1967).	
20	Al-Zn	26-30	Lamellar	D. J. S. Cooksey, D. Munson, M. P. Wilkinson and A. Hellawell, *Phil. Mag.*, 10, 745 (1964). D. D. Double, P. Truelove and A. Hellawell, *J. Crystal Growth*, 2, 191 (1968).	
20.1	Au-Co		Rods Co	70GFS 70LJD	ferromagnetic magnetic
21	Au-Ge	69	Abnormal interconnected flakes	R. W. Kraft, F. D. Lemkey, D. L. Albright, and F. D. George, United Aircraft Res. Labs. Rep. A-110069-5, 1962.	
21.1	Au-PbTe	~23	Rods Au	75DH	thermo-elect.power/ Hall coeff./ elect. resistivity
21.2	Be-Si			74TCC	magnetic, elect. resistivity/ superconductor
				75JWL	superconductor

A - Binary Eutectic Alloys

Number	I System α+β	II vol%α	III Microstructure	IV References	V Properties
22	Bi-Au_2Bi	~78	Broken lamellar	R. S. Fidler, J. A. Spittle, M. R. Taylor, and R. W. Smith, "Solidification of Metals, ISI, 173 (1968).	
23	Bi-Cd	57	Lamellar and/or abnormal with pyramid *L-S* interface	W. Straumanis and N. Brakss, *Z. Phys. Chem.* 38B, 140 (1937). V. deL. Davies, *J. Inst. Metals* 91, 127 (1963). V. deL. Davies, *J. Inst. Metals* 93, 10 (1964-65). E. P. Whelan and C. W. Haworth, *J. Aust. Inst. Metals* 12, 77 (1967). S. Musikant, Ph.D. Thesis, Lehigh Univ., 1967.	
				67FRE	superconductor
				70GFS	thermoelectricity
23.1	Bi-Cu		Rods Cu	75WWG	elect. resistivity
24	Bi-MnBi	96	Rods of MnBi	W. M. Yim and E. J. Stofko, *J. Appl. Phys.* 38, 5211 (1967).	
				70GFS,72GCD,73BJC	magnetic
				76GCD	ferromagnetic
25	*Bi-Pb_2Bi	27	Abnormal, pyramid *L/S* interface	J. D. Hunt, Ph.D. Thesis, Cambridge Univ., Cambridge, England, (1963). H. W. Kerr and W. C. Winegard, *Can. Met. Quart.* 6, 67 (1967). E. P. Whelan and C. W. Haworth, *J. Aust. Inst. Metals* 12, 77 (1967). C. W. Haworth and King Smith, Univ. of Sheffield, Sheffield, England, unpublished.	
				65DJL,67HDTJ	semiconductor
				67LJD	superconductor
				66LSA	superconductor
				67GFSB,68GDE	superconductor
				MF72SCA	supercond./ elect.,thermal
25.1	Bi-Sb			72UC	thermomagnetic
26	Bi-Sn	40	Abnormal, pyramid *L/S* interface	J. D. Hunt, Ph.D. Thesis, Cambridge Univ., Cambridge, England, (1963). H. W. Kerr and W. C. Winegard, *Can. Met. Quart.* 6, 67 (1967). E. P. Whelan and C. W. Haworth, *J. Aust. Inst. Met.* 12, 77 (1967).	
				67LJD,70GFS	superconductor
				66LSA	superconductor
				67GFSB,68GDE	superconductor

Appendix I (cont'd)

A - Binary Eutectic Alloys

Number	I System α+β	II vol%α	III Microstructure	IV References	V Properties
27	Bi-Bi_2Tl		Abnormal	H. W. Kerr and W. C. Winegard, *Can. Met. Quart.*, 6, 67 (1967).	
28	*Bi-Zn	96	Broken lamellae and rods of Zn	E. P. Whelan and C. W. Haworth, *J. Aust. Inst. Metals* 12, 77 (1967). S. Musikant, Ph.D. Thesis, Lehigh Univ., 1967.	
29	*Cd-Pb	19	Lamellar	J. D. Hunt and J. P. Chilton, *J. Inst. Metals* 91, 338 (1962-63). G. A. Chadwick, *J. Inst. Metals* 91, 298 (1962-63). G. A. Chadwick, *J. Inst. Metals* 92, 18 (1963-64).	
				67LJD,70GFS	superconductor
				66LSA,70GJE	superconductor
				67FSB	superconductor
30	Cd-CdSb	81	Abnormal	R. W. Kraft, F. D. Lemkey, D. L. Albright and F. D. George, United Aircraft Res. Labs. Rept. A110069-5, 1962.	
31	*Cd-Sn	25	Lamellar	J. D. Hunt and J. P. Chilton, *J. Inst. Metals* 91, 338 (1962-63). J. E. Gruzleski and W. C. Winegard, *J. Inst. Metals* 96, 301 (1968). W. Straumanis and N. Brakss, *Z. Phys. Chem.* 38B, 140 (1937). J. E. Gruzleski and R. W. Kraft, to be published.	
				67LJD,70GFS	superconductor
				66LSA	superconductor
				67GFSB	superconductor
				70DL	RF surface permeability
32	*Cd-Zn	83	Lamellar	W. Straumanis and N. Brakss, *Z. Phys. Chem.* 30B, 117 (1935). J. D. Hunt and J. P. Chilton, *J. Inst. Metals* 91, 338 (1962-63). B. J. Shaw, *Acta Met.* 15, 1169 (1967).	
33	Co-CoAl	65	Lamellae and rods of Co	(C) H. E. Cline, *Trans. AIME* 239, 1906 (1967).	
34	Co-CoBe	77	Lamellar	S. Shapiro and F. D. Lemkey, United Aircraft Res. Labs., East Hartford, Conn., unpublished.	

A - Binary Eutectic Alloys

Number	I System $\alpha+\beta$	II vol% α	III Microstructure	IV References	V Properties
34.1	Co-Mo			67HJ	permamagnetic
35	Co-Co_2Nb	61	Lamellar	F. D. Lemkey. United Aircraft Res. Labs.. East Hartford, Conn.. unpublished.	
				70GFS,70KRC,71CDA	magnetic
				74AHL	magnetic
36	Co-CoSb	38	Lamellar	F. S. Galasso. *J. of Met.* 19. 17. June (1967).	
				70GFS,67GFSB	ferromagnetic
36.1	Co-Co_3Si	77at%	Lamellar	73JRE 74LJD,MF74LJD	magnetic
37	Co-Co_2Ta	65	Lamellar and rod	S. Shapiro. J. Ford and F. Lemkey. United Aircraft Res. Labs.. East Hartford. Conn.. unpublished.	
38	Co-Co_7W_6	77	Lamellar	F. D. Lemkey and E. R. Thompson. United Aircraft Res. Labs.. East Hartford. Conn.. unpublished.	
				67HJ	permamagnetic
39	Co-$Co_{17}Y_2$	19	Rods of Co	F. S. Galasso. *J. of Met.* 19. 6. 17 (1967).	
				67FSB,70GFS	ferromagnetic
40	Cr-$Cr_{23}C_6$	39	Rods of Cr	J. Westbrook. *J. Metals*. 9. 1277 (1957). F. D. Lemkey and J. A. Ford. United Aircraft Res. Labs.. East Hartford. Conn.. unpublished.	
41	Cr-Cr_2O_3	~ 19	Rod	C. O. Hulse. United Aircraft Res. Labs.. East Hartford. Conn.. unpublished.	
41.1	CrP-InP (Cr doped InP)	~1.6mole%		74SBW	semiconductor

A - Binary Eutectic Alloys

Number	I System $\alpha+\beta$	II vol% α	III Microstructure	IV References	V Properties
42	Cu-Cr	~98	Rods of Cr	R. W. Hertzberg and R. W. Kraft. *Trans. AIME* 227. 580 (1963). M. J. Salkind, F. D. Lemkey and F. D. George. *Whisker Technology*. Wiley, New York. 1969. Chap. 10.	
43	$Cu-Cu_2O$	~90	Rods of Cu_2O	L. W. Eastwood. *Trans. AIME*. 111. 181 (1934). D. N. Williams, J. W. Roberts and R. J. Jaffee. *Met. Prog.* 108 (1960).	
44	$Fe-Fe_2B$	55	Square rod	A. R. T. deSilva and G. A. Chadwick. Univ. Cambridge. Cambridge. England. 1968.	
44.1	$Fe-FeBe_2$		Rods Fe	70GFS	ferromagnetic
45	$Fe-Fe_3C$	41	Lamellar and rod	M. P. Wilkinson and A. Hellawell. *Brit. Cast Iron Res. Assoc. J.*, 11. 439 (1963). M. Hillert and H. Steinhäuser. Särtryck *Ur Jernkoforets Annaler*. 144. 520 (1960).	
46	Fe-C	~92	Abnormal	K. D. Lakeland. *BCIRA J.*, 12. 634 (1964). R. J. Brigham. G. R. Purdy and J. S. Kirkaldy. *Can. Met. Quart.*, 3. 239 (1964). R. J. Brigham. G. R. Purdy and J. S. Kirkaldy. *Crystal Growth*. Pergamon. New York. 1967. p. 161. I. Minkoff. "Solidification of Metals." *ISI*. 251 (1968).	
47	$Fe-Fe_xO$	~10	Rod	B. J. Bayles. United Aircraft Res. Labs., East Hartford, Conn., unpublished.	
48	Fe-FeS	9.5	Rods of Fe (hexagonal)	D. L. Albright and R. W. Kraft. *Trans. AIME*. 236. 999 (1966). S. Marich. G. Brinson. *J. Aust. Inst. Metals*. 13. 195 (1968). 67GFSB, 70BMB, 70GFS 71WH	ferromagnetic electromagnetic
49	$Fe-Fe_xSb$	18	Hexagonal rods of Fe	F. S. Galasso. F. C. Douglas. W. Darby and J. A. Batt. *J. Appl. Phys.* 38. 3241 (1967). 67GFSB, 70BMB, 70GFS 70GJK 71WH	ferromagnetic magnetic electromagnetic

A - Binary Eutectic Alloys

Number	I System $\alpha+\beta$	II vol%α	III Microstructure	IV References	V Properties
49.1	$Fe-Fe_2Ti$		Rods Fe	70GFS 74TK	ferromagnetic magnetic
49.2	$Fe-Fe_2Zr$		Rods Fe	70GFS	ferromagnetic
49.3	Ga-Ge (?) Ga-Si (?)			74TCC 74TCC	superconductor elect.,magnetic resistivity
49.4	Ge-In (?)			74TCC	elect.,magnetic resistivity
	$Ge-HGe_2$	(96wt%Ge)	Irregular	71HNJ 75JWL	superconductor
49.5	Ge-SB		Lamellar		
49.6	Ge-Sn			74TCC	superconductor/ elect.,magnetic resistivity
49.7	$Ge-Ge_2Ti$	93.2	Rods $TiGe_2$	71HNJ	superconductor
49.8	Ge-Tl			74TCC	superconductor/ elect.,magnetic resistivity
				75JWL	superconductor
49.9	Hg-Tl	70wt%		70GJE	superconductor
50	$In-BiIn_2$	~30	Lamellar	S. A. Levy, Y. B. Kim and R. W. Kraft, *J. Appl. Phys.* 37, 3659 (1966).	
				66LSA,70GJE 67GFSB,68GDE 75FJJ	superconductor superconductor superconductor
50.1	In-Si			75JWL	superconductor
51	β. $\overline{InSn}$-γ. $\overline{SnIn}$	~25	Lamellar and rod	R. W. Kraft, F. D. Lemkey, D. E. Albright and F. D. George, United Aircraft Res. Labs. Rept. A11069-5, 1962. S. A. Levy, Y. B. Kim and R. W. Kraft, *J. Appl. Phys.* 37, 3659 (1966).	
				66LSA 67GFSB,68GDE 75FJJ	superconductor superconductor superconductor

Appendix I (cont'd)

A - Binary Eutectic Alloys

Number	I System $\alpha+\beta$	II vol%α	III Microstructure	IV References	V Properties
52	$Mg-Mg_{17}Al_{12}$	32	Lamellar	A. S. Yue. *Trans. AIME*. 224. 1010 (1962).	
				70GFS	thermoelectrical
53	$Mg-Mg_2Cu$	~60	Lamellar	F. D. Lemkey. United Aircraft Res. Labs.. East Hartford. Conn.. unpublished. R. Zukowski. M. S. Thesis Lehigh Univ.. 1967.	
54	$Mg-Mg_2Ni$	72	Lamellar and rod	F. D. Lemkey. United Aircraft Res. Labs.. East Hartford. Conn.. unpublished. R. Zukowski. M. S. Thesis. Lehigh Univ.. 1967.	
55	$Mg-Mg_2Si$	96.6	Faceted rods	A. S. Yue. Lockheed. Palo Alto Res. Lab.. Palo Alto. Calif.. to be published.	
56	$Mg-Mg_2Sn$	76	Lamellar "Chinese Script"	R. W. Kraft. *Trans. AIME*. 227. 393 (1963).	
57	$Mo-Mo_2C$	63	Lamellar	F. D. Lemkey. United Aircraft Res. Labs.. East Hartford. Conn.. unpublished.	
58	$Nb-Nb_2C$	69	Rectangular rod	F. D. Lemkey and M. J. Salkind. *Crystal Growth*. Pergamo New York. 1967. p. 171. F. D. Lemkey and M. J. Salkind. *Proc. 11th Refractory Composites. AFML-TR-66-179*. 1027 (1966).	
59	Nb-Th	10	Rod	H. E. Cline. R. M. Rose. and J. Wulff. *J. Appl. Phys*. 34. 1771 (1963).	
60	Ni-C	90	Abnormal	R. J. Brigham. G. R. Purdy and J. S. Kirkaldy. *Crystal Growth*. Pergamon. New York. 1967. p. 161.	
			Flakes	K. D. Lakeland. *BCIRA J.*. 12. 63 (1964). D. D. Double and A. Hellawell. *Acta Met*. 17. 1071 (1969). B. Lux. W. Kurz and M. Grages. *Pract. Metall.*. no. 8 (1969).	
61	$Ni-Ni_3B$	35	Lamellar	S. Shapiro and J. A. Ford. *Trans. AIME*. 236. 536 (1966).	
62	Ni-NiBe	60-62	Lamellar	F. D. Lemkey. B. J. Bayles and M. J. Salkind. Final Rept.. Contract DA-19-020-AMC-00434(X). Dept. of Army. 1965.	

A - Binary Eutectic Alloys

Number	I System α+β	II vol%α	III Microstructure	IV References	V Properties
63	Ni-Ni_3Cb	~74	Lamellar	R. T. Quinn, R. W. Kraft and R. W. Hertzberg, *Trans. Quart. ASM*, 62, 38–44 (1969).	
64	Ni-Cr	77	Lamellar and rods of Cr	R. Kossowsky, W. C. Johnston, and B. J. Shaw, *Trans. AIME*, 245, 1219 (1969). 70KRA 70KRB 70KRD	
65	Ni-$Ni_{15}Gd_2$	~40	Rods of Ni	F. Galasso and W. Darby Hulse, United Aircraft Res. Labs., East Hartford, Conn.	
65.1	Ni-In	74at%	Lamellar	72LJD	structure
66	Ni-NiMo	50	Lamellar	E. R. Thompson, *Proc. 12th Refractory Composites*, Denver, Colo., 1966.	
67	Ni-Ni_3Sb	40	Lamellar	F. Galasso and W. Darby Hulse, United Aircraft Res. Labs., East Hartford, Conn.	
68	Ni-Ni_5Si_2	35	Lamellar	A. R. T. deSilva and G. A. Chadwick, Cambridge Univ., Cambridge, England, 1968.	
69	Ni-Ni_3Sn	38	Lamellar	F. S. Galasso, *J. of Met.*, 19, 17 (1967). 67GFSB,70GFS	ferromagnetic
70	Ni-Ni_3Ti	61	Lamellar	K. D. Sheffler, R. W. Kraft, and R. W. Hertzberg, *Trans. AIME*, 245, 227–231 (1969).	
71	Ni-Ni_7Th_2	38	Rod and lamellae of Ni	M. J. Salkind, F. D. George, F. D. Lemkey and B. J. Bayles, Final Rept., Contract NOw 65-0384-d, 1966.	
72	Ni-W	93	Rod	F. D. Lemkey and E. R. Thompson, United Aircraft Res. Labs., East Hartford, Conn. W. Kurz and B. Lux, to be published, *Rev. de Metall.* 75WH	multi-needle cathode
73	Pb-$AuPb_2$	~52	Lamellar	R. W. Kraft, F. D. Lemkey, D. L. Albright and F. D. George, United Aircraft Res. Labs. Rept. A-110069-5, 1962. S. A. Levy, Y. B. Kim, and R. W. Kraft, *J. Appl. Phys.* 37, 3659 (1966). 66LSA 67GFSB	superconductor superconductor

A -- Binary Eutectic Alloys

Number	I System α+β	II vol%α	III Microstructure	IV References	V Properties
73.1	Pb-Ge			74TCC	elect.,magnetic resistivity
				75JWL	superconductor
73.2	Pb-In			MF72SCA	superconductor
73.3	Pb-Na	~80at%	Lamellar	75GAD	superconductor
74	Pb-Sb	88	Abnormal, pyramid *L/S* interface	J. D. Hunt, Ph.D. Thesis, Cambridge Univ., Cambridge, England, 1963. V. deL. Davies, *J. Inst. Met.* 93, 10 (1964-65).	
				66LSA,67LJD,70GFS	superconductor
				67GFSB	superconductor
74.1	Pb-Si			75JWL	superconductor
75	Pb-Sn	37	Lamellar	J. P. Chilton and W. C. Winegard, *J. Inst. Met.* 89, 162 (1960-61). W. C. Winegard, S. Majka, B. M. Thall, and B. Chalmers, *Can. J. Chem.* 29, 320 (1951). R. H. Hopkins and R. W. Kraft, *Trans. AIME* 242, 1627 (1968). C. W. Haworth, private communication.	
				66LSA,73GA	superconductor
				67DL	supercond./mag RF permeability
				73YAS,MF72SCA	superconductor
				75FJJ	superconductor magnetization
				75RPL	superconductor
76	$Sb-Ag_3Sb$	~ 28	Abnormal, with pyramid *L/S* interface	J. D. Hunt, Ph.D. Thesis, Cambridge Univ., Cambridge, England, 1963. V. deL. Davies, *J. Inst. Met.* 93, 10 (1964-65).	
77	Sb-CdSb	13	Abnormal	R. W. Kraft, F. D. Lemkey, D. L. Albright and F. D. George, United Aircraft Res. Labs. Rept. A110069-5, 1962.	

A - Binary Eutectic Alloys

Number	I System α+β	II vol%α	III Microstructure	IV References	V Properties
78	*Sb-InSb	~35	Triangular rods of Sb	W. K. Liebman and E. A. Miller, *J. Appl. Phys.* 34, 2653 (1963). S. Muskam, Ph.D. Thesis, Lehigh Univ., 1967.	
				67HDTJ 67GFSB 69DNM 75WWG	semiconductor thermoelectric IR polarization elect. resistivity
79	Sb-MnSb	71	Circular rods of MnSb	M. R. Jackson, R. N. Tauber and R. W. Kraft *J. Appl. Phys.* 39, 4452 (1968).	
				68JMR,70GFS 70BMB	magnetic ferromagnetic
80	$Sb-Sb_2Tl_7$	12	Abnormal	S. A. Levy, Y. B. Kim, and R. W. Kraft, *J. Appl. Phys.* 37, 3459 (1966).	
				66LSA 67GFSB	superconductor superconductor
80.1	$Si-CrSi_2$	(?)	Rods $CrSi_2$	72LLM	elect. resistivity/ semiconductor
80.2	$Si-NbSi_2$	92wt%	Rods $NbSi_2$	71HNJ	semiconductor
80.3	Si-Sn			75JWL	superconductor
80.4	$Si-TaSi_2$	94st%	Rods $TaSi_2$	71HNJ	semiconductor
30.5	Si-Tl			75JWL	superconductor
80.6	$Si-VSi_2$	95wt%	Irregular	71HNJ	semiconductor
80.7	$Si-WSi_2$	95wt%	Highly Faceted	71HNJ	semiconductor
81	$*Sn-Ag_3Sn$	~97	Abnormal/lamellar	V. deL. Davies, *J. Inst. Met.* 93, 10 (1964-65). A. Moore and R. Elliott, *Solidification of Metals*, ISI, London 1967, p. 167.	
81.1	Sn-AuSn	~94at%	Lamellar	75FJJ	superconductor

Appendix I (cont'd)

A - Binary Eutectic Alloys

Number	I System $\alpha+\beta$	II vol%α	III Microstructure	IV References	V Properties
82	Sn-η Cu_6Sn_5	98.4	Rod	G. J. Davies. *High Strength Materials*. Victor Zackay. Ed., Wiley. New York. 1965. p. 603.	
83	Sn-Zn	91	Broken lamellae and rods of Zn	W. Straumanis and N. Brakss. *Z. Phys. Chem.* 38B. 140 (1937). D. Jaffrey and G. A. Chadwick. Cambridge Univ., Cambridge. England. J. D. Hunt and J. P. Chilton. *J. Inst. Metals* 91. 338 (1962–63). W. A. Tiller. R. Mrdjenovich. *J. Appl. Phys.* 34. 3639 (1963). P. J. Taylor. H. W. Kerr and W. C. Winegard. *Can. Met. Quart.* 3. 235 (1964). D. Jaffrey and G. A. Chadwick. *Phil. Mag.* 18. 573 (1968).	
				70GFS	superconductor
				67GFSB,67LJD	superconductor
				66LSA	superconductor
				65LOS	superconductor
84	Ta-Ta_2C	71	Rectangular rods of Ta_2C and lamellae	F. D. Lemkey and M. J. Salkind. *Crystal Growth*. Pergamon. Oxford. 1967. p. 171. F. D. Lemkey and M. J. Salkind. *Proc. 11th Refractory Composites Working Group*. AFML-TR-66-179. 1966. p. 1027.	
85	TaFe-$TaFe_2$		Lamellar/abnormal	K. Wetzig. *Phys. Stat. Sol.* 19. K71 (1967). K. Wetzig. *Phys. Stat. Sol.* 27. K7 (1968).	
86	Te-Bi_2Te_3	73	Lamellae of Bi_2Te_3	F. Galasso and W. Darby Hulse. United Aircraft Res. Labs.. East Hartford. Conn.	
				67GFSB,70GFS	thermoelect.
87	Th-Ti	75	Rod	M. J. Salkind. F. D. George. F. D. Lemkey. and B. J. Bayles. Final Rept.. Contract NOw 65-0384-d. 1966.	
88	Ti-TiB	~90	Abnormal	F. D. Lemkey. B. J. Bayles. and M. J. Salkind. Tech. Rept. AMRA CR-64-0514. Dept. of Army Contract DA-19-020-AMC-00434(X). 1965.	
88a	Ti-Ti_5Si_3	~75	Rods of Ti_5Si_3	A. S. Yue. Haifa Conference. July 1969.	
				71CFW	structure/ mechanical

Appendix I (cont'd)

A - Binary Eutectic Alloys

Number	I System α+β	II vol%α	III Microstructure	IV References	V Properties
89	$V-V_3Si$	75	Rod and lamellar	M. J. Salkind, F. D. George, F. D. Lemkey, and B. J. Bayles, Final Rept., Contract NOw 65-0384-d, 1966.	
89a	$V-V_2C$	66	Lamellar	H. H. Jaker, Ames Lab., Iowa State Univ., Ames, Iowa.	
90	$Zn-MgZn_2$		Spiral lamellar	R. L. Fullman and D. L. Wood, *Acta Met.* 2, 188 (1954). J. D. Hunt and J. P. Chilton, *J. Inst. Met.* 94, 146 (1966).	
91	$Zn-Mg_2Zn_{11}$	~50	Lamellar and rod with pyramid L/S interface	J. D. Hunt and J. P. Chilton, *J. Inst. Met.* 94, 146 (1966). R. R. Jones and R. W. Kraft, *Trans. AIME* 242, 1891 (1968).	
91a	$Zn-Zn_5Ti$	~96	Rods of Zn_5Ti	K. Esashi and B. S. Koda, Haifa Conference, July 1969.	
92	$Al-Mg_2Si$	88	Abnormal	F. R. Thompson, United Aircraft Res. Labs., East Hartford, Conn.	
92.1	Cd_3As_2-NiAs	~91mole%	Rods NiAs	69HSER 72UC 70GFS	electro-thermo-magnetic semiconductor/magnetoresistance
93	Co-HfC	85	Rod "arrow feather"	F. D. Lemkey and F. R. Thompson, United Aircraft Res. Labs., East Hartford, Conn.	
94	Co-NbC	88	Rod and lamellar	Ibid.	
95	Co-TaC	84	Rod "arrow feather"	H. Bibring and G. Seibel, *Compt. Rend. Acad. Sci. Paris*, 144 (1969).	
96	Co-TiC	84	Rod "arrow feather"	F. D. Lemkey and F. R. Thompson, United Aircraft Res. Labs., East Hartford, Conn.	
97	Co-VC	80	Rod	Ibid.	
97.1	$Fe-Co_3Nb$		Lamellar	70GFS 71CDA	ferromagnetic magnetic
98	Ni-HfC	72-85	Rod "arrow feather"	Ibid.	
99	Ni-NbC	89	Rod "arrow feather"	Ibid.	
100	Ni-TiC	94.5	Rod "arrow feather"	Ibid.	
101	NiAl-Cr	66-67	Rod Lamellar and hexagonal rod	F. D. Lemkey and W. Tice, United Aircraft Res. Labs., East Hartford, Conn. E. R. Stover, *WADC TDR60-184*, Part 7, Vol. 2. 73WJL	

A - Binary Eutectic Alloys

Number	I System α+β	II vol%α	III Microstructure	IV References	V Properties
102	NiAl-Mo	89	Hexagonal rod	E. R. Thompson and W. Tice. United Aircraft Res. Labs., East Hartford, Conn. E. R. Stover. *WADC TDR60-184*, Part 7, Vol. 2. 73WJL	
103	Ni_3Al-Ni_3Cb	56	Lamellar	E. R. Thompson and F. D. Lemkey. *Trans. ASM Quart.* 62. 140 (1969).	
104	$Ni_3Al-Ni_7Zr_2$	58	Lamellar	Ibid.	
105	GaAs-CrAs	35.4	Rod and lamellar	A. Müller and M. Wilhelm. *Z. Naturforsch.*. 21A. 555 (1966). V. B. Reib and I. Renner. *Z. Naturforsch.*. 21A. 546 (1966). 67HDTJ,67GFSB	IR polarizer/ resistivity
105.1	GaAs-GaP (eutectic?)		Lamellar	70BN	non-linear optical
106	GaAs-MoAs	9.4	Rectangular rod and lamellar	A. Müller and M. Wilhelm. *Z. Naturforsch.*. 21A. 555 (1966). V. B. Reib and I. Renner. *Z. Naturforsch.*. 21A. 546 (1966). 67HDTJ,67GFSB	IR polarizer/ magnetoresistivity
107	GaAs-VAs	8.4	Rectangular rod and lamellar	A. Müller and M. Wilhelm. *Z. Naturforsch.*. 21A. 555 (1966). V. B. Reib and I. Renner. *Z. Naturforsch.*. 21A. 546 (1966). 67HDTJ 70GFS	semiconductor magnetoresistivity/ IR polarizer
108	GaSb-CrSb	13.4	Rods of CrSb	A. Müller and M. Wilhelm. *J. Phys. Chem. Solids*. 26. 2029 (1965). 67HDTJ 67GFSB	semiconductor magnetoresistivity/ IR polarizer

Appendix I (cont'd)

A – Binary Eutectic Alloys

Number	I System $\alpha+\beta$	II vol% α	III Microstructure	IV References	V Properties
109	GaSb-$CoGa_{1.3}$	7.9	Rods of $CoGa_{1.3}$	Ibid. 67HDTJ 67GFSB	semiconductor magnetoresistivity/ IR polarizer
110	GaSb-$FeGa_{1.3}$	7.9	Rods of $FeGa_{1.3}$	Ibid. 67HDTJ 67GFSB	semiconductor magnetoresistivity/ IR polarizer
111	GaSb-GaV_3Sb_5	4.9	Square and rectangular rods of GaV_3Sb_5	A. Muller and M. Wilhelm, *J. Phys. Chem. Solids*, 28, 219 (1967). 67HDTJ 67GFSB	semiconductor magnetoresistivity/ IR polarizer
112	GaSb-V_2Ga_5	4.4	Square and rectangular rods of V_2Ga_5	A. Müller and M. Wilhelm, *J. Phys. Chem. Solids*, 28, 219 (1967). 67HDTJ 67GFSB	semiconductor magnetoresistivity/ IR polarizer
113	InAs-CrAs	1.7	Rods of CrAs	A. Müller and M. Wilhelm, *J. Phys. Chem. Solids*, 26, 2029 (1965). 67HDTJ 67GFSB	semiconductor magnetoresistivity/ IR polarizer
114	InAs-FeAs	10.5	Rods of FeAs	Ibid. 67HDTJ 67GFSB	semiconductor magnetoresistivity/ IR polarizer
115	InSb-CrSb	0.6	Rods of CrSb	Ibid. p. 2021. 67HDTJ 75WH 67FSB,70BMB	semiconductor multi-needle cathode magnetoresistivity/ IR polarizer

A – Binary Eutectic Alloys

Number	I System α+β	II vol%α	III Microstructure	IV References	V Properties
116	InSb-FeSb	0.7	Rods of FeSb	Ibid. p. 2021.	
				67DTJ	semiconductor
				67GFSB	magnetoresistivity/
					IR polarizer
				64PB,70BMB	IR polarizer
				73AMIB	
117	InSb-Mg_3Sb_2	2.2	Lamellae of Mg_3Sb_2	A. Müller and M. Wilhelm. *Z. Naturforsch.*, 21. 555 (1966).	
				67HDTJ	semiconductor
				67GFSB	magnetoresistivity/
118	InSb-MnSb	6.5	Rods of MnSb	A. Müller and M. Wilhelm. *J. Phys. Chem. Solids*, 26. 2021 (1965). S. Musikant. Ph.D. Thesis, Lehigh Univ., 1967.	
				67HDTJ	semiconductor
				67GFSB	magnetoresistivity/
					IR polarizer
				64PB,70BMB	IR polarizer
				73AMIA	thermal conductivity
				73AMIB	
119	InSb-NiSb	1.8	Rods of NiSb	H. Weiss and M. Wilhelm. *Z. Physik*, 176. 399 (1963). A. Müller and M. Wilhelm. *Z. Naturforsch.*, 19. 254 (1964). A. Müller and M. Wilhelm. *Z. Naturforsch.*, 22A. 264 (1967).	
				67HDTJ	semiconductor
				64PB,68PB	IR polarizer
				67GFSB,71WH, 71WH,70GFS	
				70BMB	magnetoresistivity/
					IR polarizer
				75WH	multineedle cathode/
					IR polarizer
				69AYA	magnetoresistance
				68EAGR,MFGBEAGR, MF70MH	microwave emission
				72UC	electro-thermo-
					magnetic
				73AW	
				73AMIB	
				73VEV	galvanomagnetic
				76VVS	
119.1	$Mn_{0.6}Ga_{0.4}Sb$			76AMI	elect./ferromagnetic

A - Binary Eutectic Alloys

Number	I System α+β	II vol%α	III Microstructure	IV References	V Properties
120	LiF-NaF	48.7-60	Lamellar	J. W. Moore, Ph.D. Thesis, Univ. Michigan, 1965; Final Rept. ORA Project 05612, Dept. of Navy Contract Nonr-1224(47). D. Penfold and A. Hellawell, *J. Amer. Ceram. Soc.*, **48**, 133 (1965). P. Truelove and A. Hellawell, *Phil. Mag.*, **11**, 1309 (1965). M. Nichols and W. Lasko, U.S. Patent Pending, United Aircraft Res. Labs., 1963. J. G. Loxham and A. Hellawell, *J. Amer. Ceram. Soc.* **47**, 184 (1964). D. J. S. Cooksey, D. Munson, M. P. Wilkinson, and A. Hellawell, *Phil. Mag.*, **10**, 745 (1964). D. Double, P. Truelove, and A. Hellawell, *J. Crystal Growth*, **2**, 181 (1968). J. A. Batt, F. C. Douglas, and F. S. Galasso, *Ceramic Bulletin*, **48**, 622 (1969). 68BJA,70GFS	optical
121	NaF-NaCl	22-23.1	Rectangular rod	J. W. Moore, Ph.D. Thesis, Univ. Michigan, 1965; Final Rept. ORA Project 05612, Dept. of Navy Contract Nonr-1224(47). P. Truelove and A. Hellawell, *Phil. Mag.*, **11**, 1309 (1965). J. G. Loxham and A. Hellawell, *J. Amer. Ceram. Soc.*, **47**, 184 (1964). D. J. S. Cooksey, D. Munson, M. P. Wilkinson, and A. Hellawell, *Phil. Mag.* **10**, 745 (1964). J. A. Batt, F. C. Douglas, and F. S. Galasso, *Ceramic Bulletin* **48**, 622 (1969). 67GFSB,68BJA 70GFS,73SAJ 75YAS	optical far-field IR

A - Binary Eutectic Alloys

Number	I System α+β	II vol%α	III Microstructure	IV References	V Properties
122	NaBr-NaF	83.4	Rectangular rod	J. W. Moore, Ph.D. Thesis, Univ. Michigan, 1965; Final Rept. ORA Project 05612, Dept. of Navy Contract Nonr-1224(47). J. A. Batt, F. C. Douglas, and F. S. Galasso, *Ceramic Bulletin*, 48, 622 (1969). J. G. Loxham and A. Hellawell, *J. Am. Ceram. Soc.*, 47, 184 (1964). 68BJA,70GFS	optical imaging
123	LiF-NaCl	25	Rod	Ibid. J. A. Batt, F. C. Douglas, and F. S. Galasso, *Ceramic Bulletin*, 48, 622 (1969). 67GFSB,68BJA, 70GFS	optical imaging
124	$LiF-CaF_2$	60	Lamellar	M. Nichols and W. Lasko, U.S. Patent Pending United Aircraft Res. Labs., 1963. J. A. Batt, F. C. Douglas, and F. S. Galasso, *Ceramic Bulletin*, 48, 622 (1969). 68BJA,70GFS	optical imaging
124.1	$NaCl-PbCl_2$	~20		75HLA	optical imaging, x-ray detector
125	$NaF-MgF_2$	~20	Rod	M. Nichols and W. Lasko, U.S. Patent Pending, United Aircraft Res. Labs., 1963. 67GFSB	optical
126	$NaF-PbF_2$	~20	Rod	Ibid. 67GFSB	optical
127	MnO-MnS	43.5	Lamellar	J. W. Moore, Ph.D. Thesis, Univ. Michigan, 1965; Final Report ORA Project 05612 Dept. of Navy Contract Nonr-1224(47).	
127.1	FeCo-FeCoB		Rods Fe	70GFS	ferromagnetic

A - Binary Eutectic Alloys

Number	I System $\alpha+\beta$	II vol%α	III Microstructure	IV References	V Properties
128	FeO-FeS	36.1	Rectangular rod	Ibid.	
128.1	SnSe-$SnSe_2$	61at%Se	Lamellar	70AW,70GFS	P-N Heterojunction
128.2	Tl_2Se-As_2Se_3	~75mol%		74RGW	optical
129	$Zn_3B_4O_{11}$-ZnB_2O_{11}	50	Lamellar	D. E. Harrison, *J. Crystal Growth*, 3, 674 (1968).	
129.1	ZnO-Zn_2SiO_4	~30mol% SiO_2	Abnormal	75WL	
129.2	Al-Ni-Cu	(?)		72RMD	
130	$BaFe_{12}O_{19}$-$BaFe_2O_4$	28.6	Abnormal	F. Galasso, W. L. Darby, F. C. Douglas, and J. A. Batt, *J. Amer. Ceram. Soc.* 50, 333 (1967).	
				67GFSB 70BMB,70GFS 67FSA	ferromagnetic permamagnetic
131	$PbMoO_4$-PbO		Rods of $PbMoO_4$	M. Nichols and W. Lasko, U.S. Patent Pending, United Aircraft Res. Labs., 1963.	
				70PDA	acoustooptic
131.1	TiNb-Zr-Ta			75HT	superconductor
131.2	Fe-Co-Ti-Ba-O ($BaTiO_3$-$CoFe_2O_4$)			72SJ,75WH,74RAMJG 74BJ,75BJ 74RAMJG	magneto-electric, magnetic magneto-electric elect. resistivity
132	Carbon tetrabromide-hexachlorethane	91.4	Lamellar	J. D. Hunt and K. A. Jackson, *Trans. AIME*, 236, 843 (1966).	

A – Binary Eutectic Alloys

Number	I System α+β	II vol%α	III Microstructure	IV References	V Properties
133	Camphor-succino-nitrile		Lamellar	Ibid. 66HJD	optical
134	Carbon tetrabrom-ide-succino-nitrile (metastable)		Lamellar	Ibid. 66HJD	optical
135	Azobenzene-benzil		Faceted/faceted	Ibid.	
136	$C_{10}H_{16}O$-$C_{10}H_8$	59	Lamellar	F. D. Lemkey. U.S. Patent Pending. 1963.	
137	$C_{10}H_{16}O$-$(CH_3CO_2)_2C_6H_4$	73	Lamellar	Ibid.	
137.1	Anthracene -PBCl[2]			75WH 72SJ	optical/ x-ray detection optical
138	Mg-50Zn-3Al	Unknown	Lamellar	A. S. Yue and J. B. Clark. *Trans AIME*. 221. 383 (1961).	
139	Sn-32.3Pb-18.3 Cd αSn-βPb-γCd	68. 12	α/β/γ/β/α Lamellar mutually ∥	H. W. Kerr. A. Plumtree. and W. C. Winegard. *J. Inst. Metals* 89. 63 (1964-65). H. W. Kerr. J. A. Bell. and W. C. Winegard. *J. Aust. Inst. Metals*. 10. 64 (1965).	
140	Sn-31.1Pb-3.4Zn αSn-βPb-γZn	65. ~25	α/β. α/γ β not ∥ to γ Lamellar	Ibid.	
141	Al-33Cu-7Mg αAl-θCuAl₂-SAl₂CuMg	38. 21	α/S lamellar θ-rod	D. J. S. Cooksey and A. Hellawell *J. Inst. Metals*. 95. 183 (1967). F. D. Lemkey and A. Hellawell. Oxford Univ.. Oxford. England. unpublished.	
142	Cd-40Sn-48In αCd-βSn-γSnIn	~10. ~20	α/γ lamellar β/γ lamellar Lamellar pairs ⊥	D. J. S. Cooksey and A. Hellawell *J. Inst. Metals* 95. 183 (1967).	
143	Cd-45Sn-37Tl αCd-βSn-γTl	15. 42	α/γ lamellar β rod	Ibid.	
144	Zn-65.5Sn-31.1Pb αZn-βSn-γPb	4. 71	α/β lamellar γ rod	Ibid.	
145	Al-4Cu-89Zn αAl-βZn-εCuZn	22. 66	α/β lamellar α/ε lamellar with nonparallel interface	Ibid.	
146	Al-19Cu-41Ag αAl-θCuAl₂-ζAlAg	30. 33	θ/ζ associated	Ibid.	
147	Al-6.4Ni-0.2Fe αAl-βAl₃Ni-T AlFeNi	88. 10	α/T lamellar β rod	F. D. Lemkey. United Aircraft Res. Labs.. East Hartford. Conn.	

A - Binary Eutectic Alloys

Number	I System α+β	II vol%α	III Microstructure	IV References	V Properties
155	Ni-19.4Ti-5.7Al $\gamma'Ni_3Al$-βNi_2TiAl-ηNi_3Ti	35. 32	γ'/η lamellar η/β_1 lamellar $\gamma' + \beta_1$ Lamellar	E. R. Thompson and F. D. Lemkey *ASM Trans. Quart.*, 62, 140 (1969)	
156	CaF_2-NaF-LiF $10^{mol\%}$-$37^{mol\%}$-$53^{mol\%}$			M. Nichols and W. Lasko, U.S. Patent Pending, United Aircraft Res. Labs., 1963.	
156.1	$Tb_{0.27}Dy_{0.73}Fe_{2-\sigma}$ $0.2\leq\sigma\leq0.3$			75SHT	magneto-mechanical coupling/ magnetoresistive
152	UO_2-W	96wt%	Rods W	70CAT	optical/ electronic
				72CAT	
				75RCM	semiconductor/optics
				75FRK	high-field e^-emission
				MF72CAT	high field e^-emission

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