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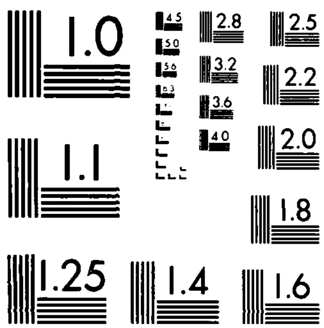

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ADVANCED ELECTRONIC SYSTEMS REVIEW

SEPTEMBER 1978

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SCIENCE APPLICATIONS, INC.

ADVANCED ELECTRONIC SYSTEMS REVIEW

SEPTEMBER 1978

SAI-79-813-WA

by

Jan A. Rajchman

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TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

FORWARD

The Information Processing Techniques Office of the Defense Advanced Research Projects Agency has conducted a small research effort aimed at evaluating the state-of-the-art and potential usefulness of various new advanced technologies in the electronic, circuits display and other hardware areas allied to the information processing disciplines.

Dr. Jan A. Rajchman, Staff Vice President and Director of Research for RCA Laboratories until his retirement, conducted a series of visits to various organizations, companies and laboratories during the Fiscal Year 1978 in order to ascertain the state of on-going research projects which were of interest to DARPA. Dr. Rajchman reported his findings in a series of meetings, briefings and reports to the project office in IPTO:

Dates and places visited are listed below.

December 12-13, 1977 - California Institute of Technology
December 14, 1977 - University of Southern California, Information Sciences Institute
December 14, 1977 - Aerojet Electro Systems Corporation
December 15, 1977 - Hewlett-Packard Corporation
February 13, 1978 - Westinghouse Electric Laboratories
March 2, 1978 - Philips Laboratories
April 13, 1978 - Xerox Corporation Research Laboratories
April 14, 1978 - University of California at Berkeley
April 17-18, 1978 - Stanford University
April 18-20, 1978 - Society for Information Display International Symposium, San Francisco, California
June 25-28, 1978 - IEEE/CE Workshop "Computer Elements for the 80's", Vail, Colorado
August 10, 1978 - IBM Research Center, Yorktown Heights, New York
September 25-27, 1978 - EASCON '78 Conference, Washington, D.C.

The items included in this review represent visit reports, memorandums and letters prepared by Dr. Rajchman for use by the Defense Advanced Research Projects Agency in evaluating the various technologies surveyed during the year.

The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either expressed or implied of the Defense Advanced Research Projects Agency or the United States Government.

SECTION 1

REPORT ON VISIT TO CALIFORNIA INSTITUTE OF TECHNOLOGY - COMPUTER SCIENCE DECEMBER 12 AND 13, 1977

1.1 INTRODUCTION

Ivan Sutherland articulates well some of the essential aspects of the ungoing integrated circuits revolution. He emphasizes the major role of connections and the necessity for a fundamental geometric and topological approach. He attacks frontally with realistic examples the widely talked about possibility of a greater mix of logic and memory. He asks afresh how to build and how to use LSI computers in a manner that is reminiscent of the early thinking at the time when electronics was first applied to computers. These explicit rationales, of which is the principal exponent, have helped to give direction, spirit and cohesion to a research team at Computer Science Department of CalTech. Of course many in the team, particularly Carver Mead, have contributed to these rationales. One feels the exhilarating spirit for exploration of new potentialities through constructive examples, as well as the humility and the discipline that results from attempts at their experimental implementation.

The focus on smart memories, as well explained in the ARPA contract proposal, is a concrete approach in a fertile area with significant direct promise as well as with wider implications for computer systems. The CalTech/Industry Integrated Circuit Design Project for the development of software tools for LSI design will provide the University with hardware and practical guidance and may help industry in a increasingly critical area.

In short, my general impressions after this initial two-day visit, are very favorable. What needs to be done and how to go about it are well thought out. The concreteness and coherence of the approach are unusual for an academic group.

1.2 PROJECTS

1.2.1 Introduction

The group concentrates on circuit layouts. The chips are made by various manufacturers. Arrangements are being made to reduce the present turn-around time of several months through "a chip per month club" and hopefully through the goodwill generated by the CalTech/Industry cooperative project.

The layout is to proceed through strict rules and is to be aided by a good notation. The working out of the rules and the notation is part of the research. These will evolve mostly through the working out of specific examples.

Most projects are centered on making memories "smarter." This is a good strategy. This area is a natural extension of present trends and ought to be very fertile for innovations. As pointed out in the ARPA contract proposal, it is likely to lead to a general understanding of the LSI potentialities and also have some immediate practical spin-offs.

1.2.2 RAM's (Random Access Memories)

1. Carver Mead is working on hierachy levels, splitting the memory in n blocks of k each. When k increases the propagation time and required power increase, hence it pays to increase the number of levels n. This requires the addition of appropriate amplifiers that

that increase the cost only negligibly. He is working out the optimum split between k and n. It turns out that the situation is more advantageous in associative memories. This is an interesting straight-forward study.

2. The "high bandwidth primary stores" described in the ARPA contract proposal of 7/28/77, has three interesting modifications of conventional RAM's. Also addressing to blocks seems very interesting. Work in these areas seems to have a good start.

3. The memory without word boundaries is particularly interesting. It exploits the freedom of addressing each memory chip differently, a freedom that is ignored in conventional designs.

1.2.3 Associative Memories

1. Content addressable or more generally associative memories have a long history in research but so far have found use only in relatively small storage capacities for the administration of addresses in a hierachy of random access memories. The cost of the necessary logic within such memories made them prohibitively expensive. The advent of LSI, with its cheap logic capability, and the fact that it uses the same technology for logic and storage, radically changes the situation.

   Now that associative memories may have become economically feasible, the question of just how useful they really are, has become very timely. It is generally thought, and Ivan Sutherland concurs, that straight content addressable - key matching - memories with no other attributes then the delivery of bits associated with the key, are of no great value, because the same function can be accomplished with random access memories and the proper hashing software techniques. This is probably so, although I am not sure that the situation has been fully analyzed. The software approach is operationally slower and involves overhead expense in programming that also preempts some of the storage space. One could well ask just how inexpensive a straight key matching content addressable memory would have to be to beat the hashing techniques in use today.

2. In any case the CalTech group believes, and probably rightly so, that other than straight key matching attributes are necessary to make associative memories truly useful. Just what these attributes should be is being studied by Bert Locanthi. He is doing this by designing a memory to be used in an otherwise conventional computer system but having an instruction portfolio of generality sufficient to test various applications. The design of the memory hardware follows the practical rules advocated by the group.

He proposes to store words in circulating shift registers, or data loops, and to perform the associative logic one bit of the word at a time as it passes through some bit-location of the loop. Associations are with immediately adjacent loops, with broadcasting buses communicating with all loops, and also with distant loops that can be reached through a carry tree structure. The memory is made of packages containing four loops and associated logic, as well as packages for the carry tree. The set of instruction is still being studied but will include up and down shifts, matchings of various sorts, propagation, etc.

3. The idea of making an associative memory out of circulating word loops and with logic on the "passing bits," has appeared in the literature I believe. In any case I was considering it for some time. It provides for great economy in logic with respect to a "static" type of associative memory in which there is association logic at every bit. One could ask whether in these days of cheap logic it makes sense to use serial loops that have inherently slower access. The answer is probably yes, as we concluded in a short discussion, because there is economy not only in logic gates but more importantly in connections, and the lesser speed may be tolerated in a memory with enhanced capabilities. Still the case for a purely static associative memory does not seem to be closed.

1.2.4 The Wiring Layout Machine

The recognition of the importance of the layout problem and the shortcomings of todays computer aided design used conventionally are very pertinent. Hence attacking the special problem of wire routing by a dedicated system within the framework of smart memories, is a very good idea.

I was particularly impressed by the combination of analog and digital technique proposed. It leads to great simplicity and yet apparently there is sufficient flexibility in programming the system. For example, instructing to favor certain chosen wire direction is relatively easy.

1.3 OTHER PROJECTS

I had a short discussion on essentially all projects. Besides the ones mentioned above, these included the following:

1. Discussion with Martin Rem on his theoretical work on "Associons."
2. Display device by Jim Rawson.
3. Sorting problem. Ivan Sutherland and Martin Rem explained the sorting device proposed by Philip Armstrong.
4. I was informed of the interesting work of Henry S. Baird on the design of a family of algorithms for LSI circuits. (Baird works at RCA Laboratories).
5. Chuck Seitz and Charles Molnar gave me a short discussion on non-synchronous systems and their merits. I was interested on their comments on the length of time bistable circuits, such as conventional flip-flops, stay in their metasable state and the resulting errors rates in strictly synchronousely controlled machines.

1.4 JOINT INTEGRATED CIRCUIT BOARD

There is a joint enterprise between CalTech and a number of industrial firms for the development of software tools for designing LSI circuits.

The design of LSI circuits is expensive and time consuming, and matters are worsening as the chips become larger and denser. Many months are required from the concept of a desired circuit function to the actual LSI layout for it, even when the design is aided by specially programmed computers. Once the layout is made, it takes only a week to a month to obtain actual chips (if the circuit has sufficient priority in the particular shop where it is being manufactured).

The problem can be helped through a cooperative effort between an academic group with a fresh outlook (economy of connections not devices, regularity of design, etc.) and industrial firms with practical know-how and experience. As I understand it, as early as mid-1976, Ivan Sutherland has discussed this possibility with various interested parties. He found a positive response at CalTech and various firms.

Each industrial participant contributes one resident at CalTech as well as $100 K a year. The results of the esearch are available to all participants on a non-exclusive ro[illegible] free basis. The results will be in the public domain and pu[illegible]shed. The participants are so far: DEC, Burroughs (verbal [illegible]pproval) Hewlett-Packard, Xerox, Intel and possibly IBM.

As it happens I met briefly Burroughs and Hewlett-Packard representatives who were at CalTech to discuss the early part of their participation.

"universal" tool for displays, so that the real question to ask is not whether it is the only one possible, but just how good it really is.

5.2 TECHNOLOGY

The array is made by some thirty vacuum evaporations, successively, of metals, semi-conductors, insulators, and dopants. Although the layers are very thin, ranging from 5 A to 7000 A, reproducible and reliable arrays are obtained. Electroluminescent powders and also liquid crystals have been successfully applied on the arrays and adequate methods for sealing the whole package have been found. The final demonstration of working panels is indeed convincing.

The technology is well documented in many reports and papers.* It is based on the original work on TFT, esp. of P. K. Weimer of RCA in the early sixties. Brody explains that no essential breakthroughs were or are necessary to obtain the systems benefits for displays. Only very careful and methodical work. I believe that significant contributions were made at Westinghouse. Among interesting points are: x-y mask method for making universal masks and substrate, the use of Cd Se (as contrasted with CdS or CdTe), the use of Al, Cr/Au or In/Au metals, the use of Al_2O_3 for insulation, and the necessity of ultra clean substrates. Annealing for 10 hours is an essential step, yet its fundamentals are unknown.

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*In particular, two recent comprehensive reports:

"Thin film transistor-addressed display device", T. P. Brody et al. Final Report 77-9F9-DSPLA-R3, Sept. 1977

"Large scale integration of displays through thin film transistor technology", T. P. Brody & P. R. Malmberg Scientific Paper 77-1F9-DESPL-P2, Nov. 28, 1977

SECTION 5

MEMORANDUM ON VISIT TO WESTINGHOUSE ELECTRIC COMPANY RESEARCH AND DEVELOPMENT CENTER CHURCHILL BORO PITTSBURGH, PENNSYLVANIA FEBRUARY 14, 1978

5.1 INTRODUCTION

The rationale of T. P. Brody for a solid state display device is that "wiring" and "addressing" the matrix is the essential problem rather than finding better phenomena or materials for the control of emission of light. He has articulated his point very eloquently in many publications, including Westinghouse and government reports. His point is that the thin film deposition technique and the thin film transistor provide a viable approach for all required addressing functions. The technology provides the necessary non-linearity and uniformity of threshold for full contrast x-y addressing, element storage, means for delivery of power to the light controlling or emitting element, all circuitry necessary for driving the x and y lines, as well as all connections. He argues further that only the thin film technology is capable of supplying such all-embracing functions.

His rationale has merit. Years of work on electroluminescent powders and films as well as on liquid crystals have resulted in materials that only marginally operate in the xy mode. Furthermore, in that mode they are less efficient in emitting or controlling light than they are when energized directly. Hence the idea of a separate addressing means by the best available switch - the transistor - is very appealing. On the other hand, he introduced a technology which in many ways is more complex than that of the displaying material. There is some doubt as to the perfection attainable and also how suitable it is for large size. It is neverless an

4.4.2 Thin Film Magnetic Heads

Hewlett-Packard have Magnetic disc and tape products. There is a research effort in thin film heads. I had only a very short discussion on the subject with Dr. Kurzig.

4.4.3 Superconductivity and Josephson Effect

In this area I had only a very short discussion with Jim Opfer, and some explanations from Len Cutler. The interest of the group is mostly scientific. Applications for very accurate standards of voltage are more likely than for logic switching and storage devices.

I have the impression that Hewlett-Packard is extremely good on knowing what they need in semi-conductor logic and memory devices and also very good at the design. They are now seeking to have more of their own manufacturing capability.

4.4 PHYSICAL RESEARCH LABORATORY (LEN CUTLER, HEAD)

4.4.1 Magnetic Bubble Memory

Research on Magnetic Bubble Memories started in 1970 gradually increased in scope to peak at a manpower of seven or eight professionals. Recently some have left and the group is reduced to 3 or 4.

I was shown a million bit bubble memory in operation. As I understand it, it has been in operation since August 1977. The memory has 128 bytes and is byte oriented. Each channel provides one bit of the byte. Each channel is made of 32 loops in each of which circulate 4096 bits. Effective rate of access is 54 kilobytes/sec.

I was quite impressed by the achievement of this memory, which obviously required very sophisticated material and processing of the wafers and thorough circuit design. Unfortunately there was not enough time to go into details. That demonstration was somewhat overshadowed by a discussion of competitive efforts. For example, it was mentioned that IBM has a group of fifty working on Bubbles and that TI has recently introduced a Bubble Memory on the market.

4.3 SEMI-CONDUCTOR DEVICES DIVISION

Unfortunately, I had only a short discussion with Dr. Paul Stoft, Head of the Division. As I understand it, this unit is responsible for most of the logic and memory devices used in Hewlett-Packard products. They are responsible for the original development of hand-held calculators, notably the Hewlett-Packard 35, the first of the series. The staff includes 80 professionals.

There is considerable work with memory systems. At this time, the chips themselves are specified by Hewlett-Packard but most are manufactured by others. I had a brief but interesting conversation with Zvonko Fazrinc, Head of a 4 man advanced group on memories. Among other subjects, we discussed the question of volatility. He believes that CMOS memories with batteries for holding stand-by information are quite adequate. However, he is meeting resistance in product designers who are wishing for a memory with intrinsic non-volatile characteristics.

I understand that the group is developing an LSI liquid crystal display having 40 characters formed by 5 x 8 matrices ¼" high.

Later I was shown (by James Sansbury and Josef Berber) the beginnings of a new IC facility. It is intended for LSI memories, and hopefully will make it possible to make part (or all) of the presently purchased chips ($10 million per year). They are aiming at a pilot line of 64 k chips in two years. I saw also relatively standard design and testing facilities.

of the division are LED's. They are GaAs and GaP light emitting diodes. Total annual sales are about $40 million and constitute about 25% of the free world market.

Simple lamps or single LED's are produced at the rate of 5 million a month, and constitute a surprising (to me) large part of the business. There is a great deal of cleverness in extracting as much light as possible through various optical tricks (e.g., total reflections on the edges of the crystal). Still, efficiencies are only about 1%.

There is a variety of digital displays. Some are made by assembling separate segments, each being an elongated LED. Others are monolithic. Plastic lenses are used. All of these products are well known of course. Some 5 x 7 matrix arrays are made also.

Although we have not discussed explicitly the possibility of large matrix LED displays, I do not think this is a realistic possibility due to the low efficiency and relatively high cost.

There is a large line of Optocouplers in which an LED illuminates a PIN diode. These are used for providing high voltage or noise isolation between two coupled circuits. An interesting new development is a pencil like device including an LED and a PIN diode as well as high resolution optics. It is intended for detecting code lines printed on products of supermarkets. The device could be used to read appropriate codes on cards of library catalogues. Also interesting are surveying instruments, the LED and PIN diode being fast enough to allow the determination of distance by simple measurement of the back-and-forth time of light travel. (Cost about $2,500).

SECTION 4

VISIT TO HEWLETT-PACKARD
DECEMBER 15, 1977

4.1 INTRODUCTION

This was a general visit to Hewlett-Packard in the areas of displays and memories which was arranged at my request by Bernard M. Oliver, Vice President of Research and Development.

Hewlett-Packard is strongly R&D oriented. Also it gives great autonomy to its Divisions and Departments. Each unit decides on its own products and its own R&D as long as the return on capital is more than a specified amount (8%). The company spends about 10% of sales on R&D which 8.5% is contributed by the independent units and 1.5% corporate funds. (I was also interested to hear that 10% of Hewlett-Packard business is in medical electronics).

The visit included the following:

1. Optoelectronic Division, Roland H. Haitz, Research & Development Manager
2. Semi Conductor Devices, Dr. Paul Stoft
3. Physical Research Laboratory, Len Cutler
   - Magnetic Bubble Memory
   - Thin Film Magnetic Heads
   - Superconductivity - Josephson Effect

4.2 OPTOELECTRONIC DIVISION

Roland H. Haitz, Manager of R&D, gave me a two hour lecture and a short tour of his operation. The main product

SECTION 3

VISIT WITH KEN O. FUGATE OF AEROJET ELECTRO SYSTEMS
DECEMBER 14, 1977 (EVENING)

Tom Ellis of ISI arranged for me this evening to visit with K. O. Fugate, at his apartment in Marina del Rey.

K. O. Fugate was in the throes of completing a proposal to ONR for a display device using thin film EL. He gave me a thumb-nail sketch of it. He counts on using EL thin films made essentially by the techniques devised by Dr. Mito of Sharp, Japan. With a black layer enhancing contrast, adequate images are obtained with relatively low intensity (35 ft/l). With the lower intensities, life is longer (5000 hr. perhaps) and the required voltages are lower. He counts on the Westinghouse thin film transistors for the driving of the EL array, there being at least one transistor per pixel. He has a scheme for greatly reducing the voltage required to control the transistors. The scheme is proprietary (and he did not disclose it to me).

In the first nine-month phase of the contract, with a team of five, he expects to have a 77 x 227 line display 2.9" x 6.6", requiring 2 or 3 watts for the display and ½ watt for the control circuits. This strikes me as an ambitious goal.

In general, I found K. O. Fugate to be very enthusiastic and quite knowledgeable. At the moment I do not know how he and his group have dealt and will deal with all the exacting nitty-gritty procedures and details that are characteristically involved in the thin film technologies on which the device is based.

work at Mitsibishi in Japan several years ago. I was also quite impressed about the subsequent development of that work there. The fact that relatively large micron-sized particles with relatively small charge are used, fundamentally provides a very efficient control (i.e., large effect on light for small control energy). I will be very interested to see how Philips can obtain the high resolution (100 lines/inch) that Tom Ellis told me they have achieved.

I learned also about the proposal that ISI is making to ARPA relative to a protocol for use in portable terminals with the flat displays being developed.

ordinary typewritten text (on a 1:1 scale) would be very important for desk top use as well as panels on the wall to aid discussions and command and control functions. On this subject, Keith Uncapher has the same views and strong convictions as Robert Kahn.

Unquestionably the problem of a flat display is of great importance. It is one of the outstanding, if not the outstanding, unresolved problems in electronic technology. Industry has already expanded tremendous efforts toward the solution of that problem. Considerable industrial work is still in progress, and I believe most of it is a proprietary nature. I suspect that, in view of many unsuccessful attempts, most industry supported work tends as much as possible to rely on conventional or well proven techniques. And yet, quite novel techniques may well be required for a really satisfying solution of that problem. Here, the government may play a key role in fostering imaginative but risky research for which it is not reasonable to expect industrial support particularly in today's economic climate.

I was gratified to find in a discussion with Tom Ellis that there is indeed considerable government, particularly ARPA, support. We discussed various approaches and the various companies involved. In particular Tom Ellis told me about the effort at Westinghouse (Dr. Peter Brody) on thin film transistors, and the coupling of that effort under the aegis of ARPA and ISI, to the work on the display itself at Xerox (Dr. J. H. Becker).

We discussed also the electrophoretic approach and the Philips work in this area. (Joze Kostelec at Briarcliff and Richard Inciardi at Arlington). I have been very much interested in that approach ever since I saw the realized, have much greater potentialities, potentialities that have and are being widely discussed. Yet in many industries there is much less work toward their implementation than might be believed, despite that fact that the trend is taken as being inevitable. Rather, there is the belief that they will result from a natural evolution. The active advocacy of ISI, in contrast, appears as a very positive force. Efforts at ISI are aimed at DOD uses for which performance is more important then economy. These uses may well usher in wider commercial applications.

I had brief discussions on the following subjects:

- The experience with word processing in the last three years. Evidently a great success. Also, the machines seem to be well liked by the secretarial staff.
- Work of Randy Cole and his group on network secure communications, packet message transmission, voice compression techniques, vocoders, etc.
- I met with Ben Cohen for a few minutes.

2.2 DISPLAY DEVICES

One of the areas of greatest priority at ISI, is that of display devices. Keith Uncapher emphasized the need for a small display with reasonably high definition and preferable with small power requirements to allow portability. Such a display is the key to portable personal terminals. One could imagine such terminals used by military personnel, e.g., privates in the army, and eventually, if available at low enough cost, by individuals in the general public. Also large flat displays with sufficient resolution to resolve

SECTION 2

VISIT TO USC/INFORMATION SCIENCES INSTITUTE
DECEMBER 14, 1977

2.1 GENERAL REMARKS

Keith Uncapher, the Director, gave me a rather lengthy overview of the Information Science Institute. Incidentally, I have known Keith ever since the early fifties when he was the principal advocate for the use of the Selectron tube memory, which I developed at RCA, for the "Johnniac" computer of Rand Corporation.

There is no need to recount here many of the general points he covered, as they are well known to ARPA. I was interested in the genesis of ISI and the notion on which it is based: the off-campus group with many professionals to deal with computer science and its applications. Its main areas of work, i.e., digital communication, man-machine communication, quality software, information distribution (e.g., electronic mail), and service as a main nod of the ARPA network, have a large component of software. There is also a considerable amount of thinking in the hardware area in my field of interest, particularly with respect to displays. Before discussing that subject, a few general remarks are in order.

I was particularly impressed by the strong conviction in and advocacy of the computarization or rather "electrolization" of all man-to-man and man-to-machine communications. Keith spoke of the need for personal computers and storage, the use of video and audio communications for conferences between distant conferences, electronic mail, text editing techniques, personal terminals with video and audio, etc. Of course, these possibilities that are only partially the enterprise into being in the first place and helped to acquire the necessary financial support. The real test will occur after some time when unavoidable difficulties will be encountered. I believe that most will be overcome and that significant results are to be expected.

I believe that this enterprise is very important. It combines industrial know-how with academic research to the benefit of both. Perhaps the most important aspect of this combined enterprise is that it provides a natural way to transfer the results of research into actual products. The utilization of the products of research is a difficult problem. Typically many successfully developed ideas in central industrial laboratories are not adapted by their parent companies. Transfer of ideas from the outside is even more difficult.

Incidentally, Merrill Brooks from Hewlett-Packard gave a short talk at lunchtime, about the Hewlett-Packard organization and their way to sponsor research. He stressed the great independence and responsibility of each unit, which is free to decide on its own products and its own research, as long as it earns the right return on equity (more than 8%). This is a way of solving the research-to-product transfer that is direct and yet somehow avoids the danger of concentrating only on short term projects.

1.5 CONCLUDING REMARKS

I learned about some of the managerial, organizational and financial matters of the CalTech group from Ivan Sutherland and Carver Mead. These helped me to gain a perspective.

As indicated in the introduction, my general impressions after this initial two-day visit are very favorable. What needs to be done and how to go about it are very well thought out. There are many interesting ideas.

The work has just started. What I heard are, of course, the naturally optimistic ideas and plans that brought interesting are also the relatively straightforward methods for protecting the thin-film array from the electroluminescent powder or the liquid crystal, for providing for openings in the protective layer to contact the EL or LC, and finally for sealing the whole package.

There do not seem to be any "fundamental" problems. A possible exception is the question of life. Knowledge of the failure mechanisms is scant. Preliminary studies show deterioration does occur in prolonged operation. The indications are that useful life times of 5000 hours or more can be expected. The need for more study of life is realized.

There are, however, serious "engineering" problems. No perfect array has been built. The relation between a given number of imperfections and the overall care, i.e. the required engineering effort, is unknown. There is also the question of attainable size. So far, 6" x 6" displays were made by the movable mask mechanism. The next planned design uses a set of eleven "dedicated" stencil masks supported on a 14" carrousel wheel. During the fabrication these are successively overlaid over the TFT plane. The plane size was reduced to 2" x 2". Larger sizes are possible with the method. However, no matter how the size is extrapolated in future set-ups, really large sizes are out of the question. Hence, a "mosaic" of arrays would have to be used. No serious thought was given to this possibility as far as I know.

5.3 PRESENT PLANS

As Brody sees it, the laboratory feasibility is established. The next step is to show realistic manufacturability, i.e. really come to grips with the "engineering" problems. This is a step on which Brody wants to concentrate, while deemphasizing various improvements and extensions, such as higher resolution, the use of a single buried-gate transistor per pixel, color, or even the simultaneous fabrication of the driving line circuits with those of the array.

This strikes me as a very sensible policy. After all, the whole exercise is one LSI on a grand scale, a scale larger than that reached by the present silicon LSI. Nearly a hundred thousand elements have already been integrated, but much larger numbers are needed. Also much bigger areas are needed. (The only other comparable scale of integration I know of, both in number of elements and physical size, were lead-niobium evaporated superconductive memory planes at RCA Laboratories. More than a quarter million bits on a 4½" x 4½" were made. Near perfection was attained, but full knowledge of it was lacking because of inadequate testing circuits.)

So far no perfect samples were obtained, although some had very few defects. There is no question that the attainment of perfection (or very near perfection perhaps) will determine whether solid state panels will or will not really make it. The degree of perfection achieved in the laboratory is in fact remarkable, considering the innumerable steps and parameters involved and the length of the processing (tens of hours). As I understand it, 2 nearly perfect panels were made out of 50 starts, or an "yield" of 4% in finished panels. I understand also that imperfections were always shorts or opens but not mysterious intermittents. Their cause was always rationally explained and most often was a deleterious deposition of some "particle" during evaporations. The particles originated from peelings of the vacuum chamber or originated from the evaporant source. Hence, cleaner rooms and vacuum systems, a more homogenous source of evaporated material, greater precautions, computer control, on line tests are all called for. In short, a demanding manufacturing approach is essential.

Manufacturing has also to be reasonably efficient. For example, the time required to complete a panel from start to finish has to be greatly reduced from the tens of hours used in the laboratory process. Eventually, the efficiency of manufacturing will determine yields and cost and hence acceptability.

The success of a manufacturing enterprise is not, unfortunately, a clear cut issue. The success is highly dependent on the scale of support. Cleanliness, computer controls, on line and off line tests, materials, preparation, accuracy of masks and their registration, etc. are all "open" variables in the sense that any criterion for being "sufficient for the job" is hard to define. The result is that a given approach to manufacturing may easily be deemed "right" or "wrong" depending on the level of its support.

As I understand it, the total effort at Westinghouse at the moment is that of 13 men. It is contemplated that a large portion of the effort will be devoted to manufacturing and will be under the aegis of a Product Division (Tube Division) and not the Laboratory. Though some men will be transferred, specialists in manufacturing will join the project. Funding is from the government (Army, first phase 300 K and ARPA) and also from Westinghouse. Although I don't know the exact facts, I believe that the manufacturing enterprise is to be funded at less than a million a year.

For a convincing demonstration that thin film arrays for displays can actually be manufactured, the effort seems somewhat modest. It reflects more what is affordable than what is needed. Incidentally, this is a conclusion that I did not discuss with Brody.

5.4 WESTINGHOUSE-XEROX ADDRESSED EP DISPLAY (ISI AND ARPA SPONSORED)

Electrophoretic displays have many attractions for portable units of the kind ISI and ARPA are interested in. Very low power, image retention, high contrast, and large viewing angle are among them.

In their simplest form, electrophoretic cells do not have the necessary non-linearity for xy addressing. Also, to allow reasonably fast scans, some local means for the retention of video is required. Clearly, arrays of TFT's provide the missing "addressability" properties. Hence, the TFT-EP combination is potentially very attractive.

The combined Westinghouse-Xerox enterprise will provide a real test of this potentiality. Fortunately, the contemplated size of the portable display is small enough to be fabricated out of a single array - though the diameter of the carrousel for the "dedicated" masks will require a much larger vacuum system than presently available.

5.5 CONCLUSION

Important innovations are almost always due to the conviction, determination, and hard work of a man. This is the case of the thin film transistor array for solid state displays. It is principally due to the strong conviction and determination of T. P. Brody. The accomplishments at Westinghouse are indeed impressive.

However, there is no question that it would be preferable to have a simpler display device in which the light emitter or controller has the required properties for x-y addressing, without the added complexity of the TFT's. The electrophoretic Philips display is an example of such a device. The EL and LC displays may still make it. Other approaches should be encouraged. My own bias is that the real answer will be such a simpler device. Yet, it is not available today and the proposed approaches for its realization are still quite uncertain.

In conclusion, in the present state of the art, it is advisable to do the utmost to ensure the success of the TFT arrays - were it only to determine whether they are really capable of being manufactured. This is precisely the area on which Westinghouse is planning to concentrate.

SECTION 6

LETTER CONCERNING STATE OF THE ART OF DISPLAY TECHNOLOGY MARCH 13, 1978

In our initial discussions I expressed some pessimism with regard to the possibility of a desk size matrix display of high resolution. Since then I visited with Information Science Institute, Westinghouse and Philips and had a short encounter with Aerojet. As a result, I learned more about the state of the art in solid state matrix displays. You asked me to summarize my position as of the moment.

The thin film transistor array of Westinghouse* is an "universal" addressing solution for an EL, LC, or EP display. There is nothing wrong with it in principle. The results I witnessed at WE are indeed impressive. However, the engineering and manufacturing problems are extremely difficult. Some thirty exacting successive evaporations through high precision perfectly registered masks, ultra clean processing, rigorous controls, exacting annealing procedures are all required. While imperfect laboratory displays of six inches in size have been demonstrated, the planned realistic manufacture is aimed at two inch sizes. (Using a dozen or so "dedicated" masks mounted on a 14" diameter wheel.) Even if the size could be extended to 12" - a rather ambitious size - a desk size unit would require the juxta-position of many arrays. There are various ideas for such modular construction. For example, full size masks could be made from smaller masks by a step-and-repeat method, and then the full sized masks thus made would be used to make the display in a gigantic vacuum system containing the appropriate mechanism for moving the masks for the successive evaporations. Alternatively, complete small

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*My visit to Westinghouse is more fully described in the Memorandum dated February 14, 1978.

arrays can somehow be patched. Perhaps, the modular TFTs could be first assembled and connected and then the EL or EP material applied on the whole surface. Essentially no serious work was done to really appraise these or other possibilities, although Brody seems to favor the large mask approach in one of his publications. Present efforts are justly addressed to the sine-qua-non question whether reasonable sized planes can be fabricated at all. Until that question is realistically answered, there is very little incentive and insufficient experimental knowledge to consider the problem of modular construction.

The relatively small (e.g. 4" x 6") display for portable army use that I heard about at ISI, and of which you later showed me a mock-up, strikes me as a very reasonable vehicle for demonstrating the capabilities of TFT arrays. While I have as yet not visited Xerox, the Westinghouse-Xerox enterprise for electrophoretic TFT driven display seems to be do-able and to have a well defined need. Military and other uses can readily be envisaged for a portable flat display unit requiring low power, having image retentivity, linear graphic precision, and simple clear black-white (or two distinct colors) on-off capability for characters and lines.

While an array of TFTs is a straightforward solution to display addressability, it adds a complexity to the display that is generally greater than that of the displaying mechanism it serves. Thereby it renders more difficult the attainment of reasonable perfection and reasonable yields. My own bias favors a display where the displaying element is endowed with the necessary matrix addressing properties.

The electrophoretic image display, EDIP, with grid control described to us at Philips on March 2 is such a display and achieves addressability in a straightforward fashion. It is only slightly more complicated than would be a device with only x and y buses. The scheme is very appealing also in that the x-y addressability depends only on the geometry of the device but not on material properties. The question of the required geometrical accuracy was not discussed during our visit. However, thinking about it afterwards, I believe it to be not severe. Indeed the shape and appearance of the dot corresponding to a pixel depends on the relatively gross widths of the row and column metalizations and not on the uniformity of the minute wells. The uniformity of the well sizes, as well as the uniformity of the anode spacing, will determine the tolerances of coincident addressing which ultimately affect contrast. This problem is somewhat analogous to the half-select problem in core memories, where it is generally analyzed by so-called "shmoo" diagrams.

On the whole the Philips scheme seems very good. My reservations would center around the material problem. I was impressed by the approach explained to us by Beverly Fitzhenry as it seems to be really based on first physical and chemical principles. For example, the nagging formation of agglomerates is analyzed in terms of van der Waals' attractive and electrostatic repulsive forces and is found to be inhibited by the use of attached polymer chains. However, I believe that this is an open ended situation in which the processing of dyes and suspended particles will always present problems and will have to be researched perenially.

It seems to me that the grid controlled EDIP of Philips is well suited for the portable unit of interest to ISI. It can provide all the desirable properties mentioned earlier, including particularly good image retentivity. Also it happens that the required size of about 4" x 6" is a natural extension of the 1" x 1" sized laboratory unit. Admittedly it cannot accept video as fast as a TFT-EP display a la Westinghouse-Xerox but should this be necessary, it could be obtained by an auxiliary LSI memory storing a frame. The applications of a small flat matrix display unit of this sort could be many. It could be used by the police, in hospitals, schools, offices, remote locations such as oil drill stations, etc. The many possible commerical applications could change the attitude of the Philips management toward the project. I would recommend sponsoring such a project in addition to the Westinghouse-Xerox one. Both are risky and the same demonstration vehicle would facilitate a comparison between the two approaches. Also, having two exercises in relatively large scale integration would add to the needed experience for truly large matrix displays.

The task of making a display for the portable unit of ISI would be more ambitious than the Phase I proposed by Philips (525 x 480 elements, 6 lines/mm 7 x 9 cm) but less ambitious than Phase II (2000 x 2000 elements, 6 lines/mm 12" x 12"). Perhaps it could be accomplished in the two years that Philips believed would be required for Phase I alone, if adequate funding were provided.

As far as the desk size is concerned, the grid controlled EDIP is a possible candidate. However, I believe there are many difficulties even if I cannot spell out all of them at this time. For example, the question of geometrical tolerances alone is significant. The spacing of the anode to the grid structure is 50 microns or 2 mils. Sufficient flatness in the grid structure and face plate to insure spacing tolerances needed for reasonable operating tolerances (perhaps 10 microns or less than half a mil) over areas of several meter square is already a very severe problem. Maybe another "tetrode" electrode made as an integral part of the grid-well structure could be the solution to that tolerance problem since the anode spacing would then have no influence on addressing. Some ideas of operating tolerances and "shmoo" diagrams obtained with smaller sizes would be of great help in knowing whether the required tolerances for a large size can realistically be obtained.

A consideration of the factors involved in the extrapolation to large size may be useful concurrently with the work aimed at a 4" x 6" display. It would guide the choice of techniques so that they could be as adaptable as possible to larger sizes, as you indicated during the discussion at Philips on March 2. However, I would envisage only a very short cursory study, as it seems to me to be unrealistic to extrapolate from a laboratory 1" x 1" size to a desk-top size without the benefits of experience with an intermediate size.

In summary, I would favor: (1) The ungoing Westinghouse-Xerox project for a portable six inch TFT driven electrophoretic display. The TFT manufacturability project at WE is a good plan though somewhat undermanned (see memo). (2) A companion Philips grid controlled electrophoretic display for the same portable unit.

I would like to conclude with an appeal to ARPA for general support of flat solid state matrix displays. Many have tried for years to develop such displays. Yet the CRT remains effectively unbeatable, particularly with respect to color, TV speeds, grey scale, resolution, and cost. Industry feels justified to support only token efforts to alternatives that appear more complex, less effective, and more costly. But the aspirations of many imaginative researchers remain undaunted. They have an aesthetic liking for a flat display with faithful geometrical rendition free of analog distortions. They believe it is the ultimate answer. Admittedly, their beliefs have no clear-cut justification, and all ideas proposed so far are both risky and without promise of an ideally performing display. Just the same they are probably right. This is precisely the situation in which the government can provide great leverage. For one thing, it can spell out military uses for which matrix displays are uniquely needed as well as uses for which they could be very useful, though not absolutely indispensable. For another, it can provide sufficient financial support, not available in industry, to bring any reasonable approach to the level at which it can be really appraised.

SECTION 7

VISIT TO XEROX COMPANY, PALO ALTO RESEARCH CENTER
APRIL 13, 1978

7.1 ELECTROPHORETIC DISPLAYS AT XEROX

7.1.1 Materials

Dr. J. H. Becker pointed out that Xerox was working on electrophoretic displays since the 1960's (US Patents: Morton Silverberg - 3,607,256 June '68; Paul Evans - 3,612,758 Oct. '69).

White particles of Titanium dioxide (T_1O_2) suspended in a hydrocarbon liquid with a blue dye are used. The composition of the liquid is proprietary. Titanium dioxide is used because of its high index of refraction (2.5) and hence high scattering power. White scattering results from particles .1 to .2 um in particle aggregates whose diameter, following a gaussian distribution, has a mean diameter of 1.5 um. (No selection to avoid the distribution is used.)

The particles are heavier than the suspending liquid. Density matching consisting in embedding the particles in a plastic, used by all other groups, is not used by Xerox. Becker believes this to be unnecessary because the particles stick firmly to one or the other wall and are in transit only a short time. Plastic coatings reduce contrast and speed.

Cell characteristics for given materials, particle size, surfactants, etc. are tested in one inch square 3 mil thick cells. Cells switch typically in 15 milliseconds. This is measured as a transition from white to 10% white switching to deeper black (or blue) is several times that switching time. The longer time is due to "straggler" particles. Switching involves hydrodynamic effects. There is no x-y addressability.

Material work is done by Ann Wang with whom I had only a short conversation. Much of the material work at Xerox is proprietary, although Ann Wang is to publish some of the results shortly. As I understand it, the T_1O_2 particles are charged positively (as opposed to the negatively charged particles used by Philips). With the proper surfactants reproducible results are obtained.

7.1.2 Arrays

Tests are made with 10 mm square elements spaced 2 mm apart in 3 mil thick cells. Because of fringing electric fields (and related hydrodynamic effects) control is not limited to the energized cell. Some reduction in spreading is obtained by letting float the electrodes of adjacent elements, i.e. connect them through high impedence when not selected. However spreading is serious enough that actual walls between elements seem necessary. Work is in progress to ascertain how such partitioned displays operate. It seems that eventually the walls will make it difficult to fill a sealed display sandwich with the necessary liquid suspension.

7.1.3 Work Status

As I understand it, Xerox support at its present level of one person (Dr. Becker almost full time and some support from Ann Wang) will continue pending resolution of possible contract from ISI (ARPA). The contemplated contract would consist of:

Phase I (6 months 40 K)

Would demonstrate that lateral spreading can be controlled and the electrophoretic technology is compatible with TFT's. Work would be with elements size compatible with resolution of 80 to 90 lines per inch. - The materials work would have no support from the government as Xerox wishes to keep results proprietary.

Phase II (12 months 40 K for Xerox)

Would consist of a display 3" x 5½" with 2000 characters, 5 x 7, that is 100 K pixels with spacing arranged on 400 columns and 25 rows. With a write time of 100 microseconds per column, the row time is 40 milliseconds and frame time about one second.

(Dr. Becker believes that it may be better to start with a panel of lower resolution.)

This phase would also comprise a study of long range life.

Dr. J. H. Becker said that Xerox signed a contract a year ago but that contractual delays have occurred and the contract is still not in force. He also believes that a companion TFT project will require about 200 K. In addition he believes that Westinghouse working now with resolution of 20 to 30 lines-inch is more anxious to develop fabrication techniques than to work on higher resolution.

7.1.4 Discussions with Management

Dr. J. H. Becker reports to B. Kazan, who in turn reports to R. Ulbrich.

As I understand it from discussions with B. Kazan and R. Ulbrich, Xerox has considerable interest in displays for office terminals. Its main effort is on improving CRT terminals although there are no efforts in improving the cathode ray tube itself. A very small effort (4 persons) is devoted to alternative display technologies in B. Kazan group. Xerox is very unlikely to continue to support research in electrophoretic displays without government support. The support is mostly needed to justify the utility of the work rather than to provide financial relief.

7.2 OTHER WORK AT XEROX (SEEN IN MY SHORT VISIT)

7.2.1 Mechanical balls display

N. K. Sheridon is in B. Kazan group and is well-known for his work on the "Ruticon" (based on elastomers and photoconductive sandwiches). He has conceived a new display using 25 um rotating balls imbedded in a transparent elastomer. The balls are made out of T_1O_2, are black on one side, are electrically polarized, and are coated with a thin film of oil. The techniques for making the display are simple and very ingenious. However, the fastest reversal time is 30 milliseconds. It requires 75 volts. There are no thresholds of switching. The contrast is at best 4 to 1.

7.2.2 Solid State Lasers

Dr. William Striefer, research fellow at Xerox, has a considerable group working on gallium arsenide lasers. The effort is considerably greater than the total effort in Kazan's group on the electrophoretic and mechanical ball displays. The work is with devices, not display arrays. I saw a very well equipped laboratory but had no time for detailed discussions.

7.2.3 Integrated Circuits

W. Gunning (formerly engineer at Rand) who designed circuits for electrostatic memory tubes, Selectrons (which I developed at RCA in the forties) considers the implications of LSI to Xerox business. He is convinced of the future of electron beam lithography. He works closely with Sutherland's group at CalTech and has a broad perspective on the subject.

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