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PHOTOEMISSION IN THE 1-2 MICRON RANGE

QUARTERLY REPORT

L. S. ESOFER
H. P. GOSSENBERGER

1972 AUGUST

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NIGHT VISION LABORATORY
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FORT BELVOIR, VA. 22060

CONTRACT NO. DAAR02-72-C-0412

RLA ELECTRONIC COMPONENTS
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QUARTERLY REPORT NO. 1

1972 April 17 - 1972 July 31

PHOTOEMISSION IN THE 1-2 MICRON RANGE

Contract No. DAAK02 -72 -C -0412

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Principal Investigator: John S. Escher

Phone Number: 609-452-2700, Ext. 3283

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Materials Research Laboratory

RCA Laboratories

Sponsored by

NIGHT VISION LABORATORY

U.S. ARMY ELECTRONICS COMMAND

Fort Belvoir, Va. 22060

and

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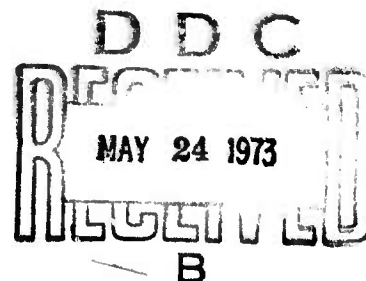
Washington, D. C. 20301

1972 August 16

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SUMMARY

Research has begun on a GaAs/Ge device designed to have photoemission sensitivity into the 1-2 micron range. The device consists of a thin GaAs epitaxial layer vapor-phase grown on a p-n Ge junction. The p-n junction is reverse biased, and the GaAs is vacuum activated to negative electron affinity (NEA) in operation. The p⁺-GaAs provides an effective biasing contact for the Ge p-n junction and allows the n-Ge region to be very thin optimizing the performance of this device.

Good quality GaAs epitaxial growth on Ge has been achieved. A one-micron thick GaAs layer on a Ge p-n junction has been activated to almost 1000 $\mu\text{A}/\text{lm}$. Four p-n junctions were fabricated at 800°C diffusion temperature for four different diffusion times. An experimental diffusion depth versus diffusion time plot was made. This plot was then fit to the one-dimensional diffusion equation resulting in an estimate of the diffusion coefficient for As into Ge at 800°C which is in good agreement with reported values.

Some calculations were made of the photoexcited electron energy losses in the depletion region and the flat band region of the Ge p-n junction. Results of these calculations indicate that our present substrate material ($4 \times 10^{17}/\text{cm}^3$ p-Ge) is much too highly doped for optimal device performance. Much lighter doped material is on order. Also, these calculations show that junction depths must be made very thin, no more than a few tenths of a micron for lightly doped p-Ge substrate material. Two complete devices constructed and tested in this first quarter had junctions of 3.5 and 1.8 microns thick, much too thick to have any 1-2 micron emission.

Overall, the experimental results on GaAs and the calculations on the Ge p-n junction show that this device still looks most promising for 1-2 micron emission. Recommendations for further work are included.

FOREWORD

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Work done and
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Report approved by: B. F. Williams, Manager
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The research in this report was carried out in the Electro-Optics Laboratory, RCA Electronic Components, under the direction of Dr. B. F. Williams, Manager, Electro-Optics Laboratory, and in the Materials Research Laboratory, RCA Laboratories, under the direction of Dr. J. J. Tietjen, Director, Materials Research Laboratory. Key research personnel include Dr. J. S. Escher, Project Engineer, and Dr. F. Gossenberger. This report covers the period 1972 April 17 - 1972 July 31.

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I. INTRODUCTION

The research conducted under this contract has been directed toward extending the spectral sensitivity of photoemitters into the 1-2 micron wavelength range. Work during this first quarter has focused on a field-assisted device with a reverse biased Ge p-n junction and a thin activated surface layer of GaAs. Photoemission sensitivity of this device is designed to extend to the band gap of Ge, approximately 1.8 microns.

II. TECHNICAL DISCUSSION

A. The Electron Transparent Contact and the GaAs/Ge Device

Recent years have seen a great deal of work on activated III-V materials and silicon to achieve higher quantum sensitivities and longer wavelength response. Present theories of activation and experimental results strongly suggest that quantum efficiencies of .1% or greater from a non-field-assisted surface for wavelengths much greater than 1.2 microns will be practically impossible.¹ Previous photoemitter devices designed for greater than one micron sensitivity have suffered from such limitations as very low quantum efficiency (less than 10^{-4}), high dark current (thermionic emission on the same order as the signal level), or non-reproducible results. Two of the most common design types are the reverse biased p-n junction emitter and the tunneling emitter. The reverse biased junction emitter is basically a hot electron emitter. Problems with this device are that, if a metal film is used to make large-area electrical contact on the emitting surface, the photoexcited hot electrons are severely attenuated in the metal film before reaching the metal-vacuum interface. If, however, the surface n-region is made thicker and thereby becoming the electrical contact, the photoexcited electrons are again severely attenuated in the long flat-band n-region.² Tunneling emitter designs have suffered from high-field breakdown in the insulator region and poor quality (poor minority carrier diffusion length) of the emitting layer.³

Work during this first quarter has been on a GaAs(p⁺)/Ge(n)/Ge(p) field-assisted device which offers the possibility of relatively high sensitivity out to the band gap of Ge, approximately 1.8 microns. The Ge p-n junction is reverse biased to near breakdown in operation. The GaAs surface is activated with Cs-O to achieve negative electron affinity (NEA). An electron energy band diagram for this device is shown in Fig. 1. The details of this figure will be discussed in the Appendix where we calculate the various energy losses suffered by photoexcited electrons in crossing the depletion region and the n-Ge region. The presence of the GaAs allows the n-Ge region to be very thin (on the order of a tenth of a micron). The highly doped GaAs (approximately $1 \times 10^{19}/\text{cm}^3$ Zn) is about one micron thick and provides an effective electrical contact for biasing the Ge p-n junction. Because of the excellent lattice match and coefficient of thermal expansion

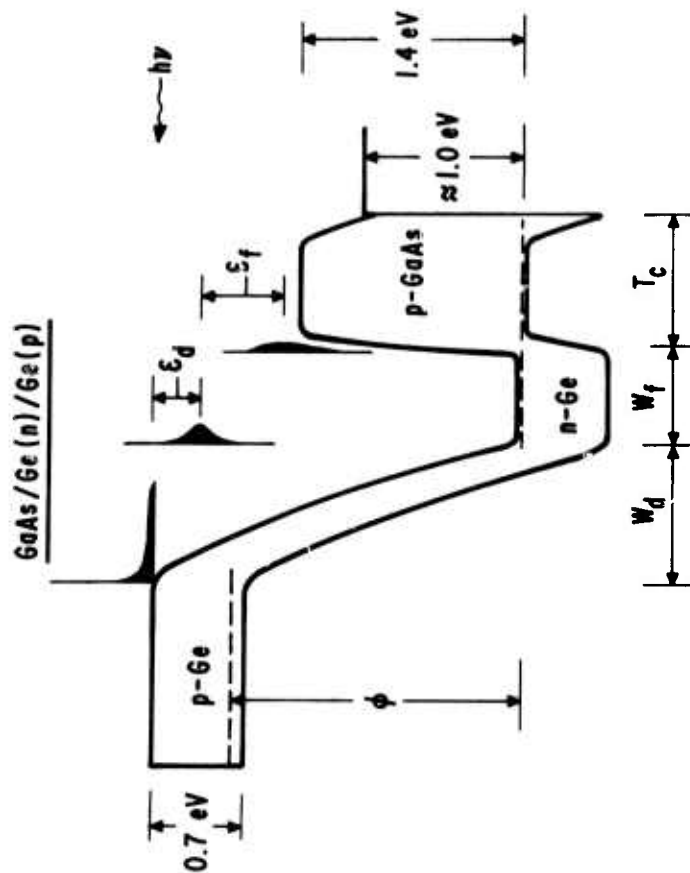


Fig. 1. Energy band diagram for the GaAs/Ge device. ϕ is the applied reverse bias to the junction. W_d is the width of the depletion region. W_f is the width of the flat band n-Ge region. T_c is the thickness of the GaAs. ϵ_d is the energy lost in the depletion region and ϵ_f is the energy lost in the flat band region of the Ge.

match between GaAs and the quality of the GaAs should be sufficiently good so that photoexcited electrons reaching the GaAs from the Ge will have a reasonable probability of diffusing to the GaAs surface and being emitted. Hence, the GaAs acts as an electron transparent contact for this device and is designed to avoid the problems faced by previous reverse biased p-n junction emitters. For incident light of wavelength greater than about 0.9 micron, the GaAs becomes optically transparent (except for reflection losses at the GaAs vacuum interface, 32%, and the GaAs-Ge interface, $\approx 4\%$). Greater than 0.9 micron light then travels into the Ge where it photoexcites electron-hole pairs. Photoexcited electrons in the p-Ge diffuse to the depletion region of the reverse biased p-n junction where the field sweeps them into the GaAs and finally into vacuum. Hence, this device should have a very broad band of sensitivity from cut-off wavelength of the vacuum window used for the device to the band-gap-limited emission of the Ge.

B. Vapor-Phase Growth of GaAs on Ge

We have developed a technique for the epitaxial growth of GaAs on chemically polished single-crystal Ge wafers. The wafers are oriented 30° off the $\langle 100 \rangle$ direction, which has been our standard orientation for epitaxial growth of GaAs on GaAs. In order to prepare a Ge substrate for subsequent growth of GaAs, the wafer is first vapor etched using a gaseous mixture of H_2 and HCl at a temperature of approximately $825^\circ C$. This vapor etching is very important and serves to remove the surface oxide and any work damage remaining after chemical polishing. The Ge p-n junction is formed by diffusing arsenic into the surface of the Ge by exposing the wafer to a mixture of H_2 and As vapor at a temperature of approximately $800^\circ C$. The thickness of the resulting n-region is controlled by the exposure time to the As. Then a one-micron epitaxial layer of GaAs is grown on the Ge substrate. Growth temperature for the GaAs has been $725^\circ C$. The epitaxial growth results from the gas phase reaction of GaCl and As vapor. The GaCl is formed by the reaction of Ga with gaseous HCl while the arsenic results from the thermal decomposition of arsine. The GaAs is doped to approximately $1 \times 10^{19}/cm^3$ with Zn acceptors. Zinc is introduced into the system by passing H_2 over a heated quartz bucket containing Zn. The doping level is set by the temperature of the Zn bucket ($450^\circ C$). The thickness of the epitaxial growth is set by the length of time in the growth zone region (approximately 2 minutes).

A great deal of progress has been made in the preparation and growth of epitaxial GaAs on Ge. Initial growth attempts of GaAs on Ge looked very poor in appearance. However, through improved substrate material and especially in substrate preparation, we have been able to grow GaAs on Ge that looks bright and shiny with few (less than 6) pits on the surface. The pits develop after preparing the Ge substrate and are not due to the GaAs growth. Examination of even the best looking GaAs/Ge, however, in strong light, such as sunlight, still shows a slight haze. The exact reason for the haze and its ultimate effect on the performance of this device is not as yet known. The excellent activation result discussed in Section II-C on one of these materials strongly suggests that the haze is not seriously

degrading the quality of the epitaxial growth of the GaAs. Nevertheless, further work will be continued toward improving the looks of the GaAs. The parameters of Zn doping level and GaAs thickness will be optimized later in the program.

C. Experimental Activations of GaAs on Ge

We have Cs-O vacuum activated two GaAs/Ge samples during this first quarter. One of these, 5-24-72:1, was from an early growth period when the GaAs looked rather poor. The other, 7-6-72:2, was a more recent growth which benefited from improved substrate preparation and growth techniques. Although 7-6-72:2 looked much better than 5-24-72:1, it still had a slight but definite haze. Both samples had $1.0 \pm .1$ micron of GaAs as determined by angle-lapping and staining techniques on similar samples.

5-24-72:1 activated to a peak reflection sensitivity of $440 \pm 40 \mu\text{A/lm}$. 7-6-72:2 activated to a peak reflection sensitivity of $980 \pm 80 \mu\text{A/lm}$.⁴ An experimental yield curve is shown in Fig. 2 for 7-24-72:2. The activation system used in both experiments is a relatively new all-metal VacIon system. The system volume is approximately 14 l, and it has a 60 l/sec VacIon pump and a 300 l/sec Ti sublimation pump. After a 10-12 hour 250°C bake, the system pressure bottoms out in the low 10^{-11} range as measured on a nude ion gauge. The Cs-O activation procedure proceeds exactly as if the sample were a standard GaAs grown on GaAs. The Ge substrate does not seem to present any new problems to the activation procedure.

Realistic estimates of the diffusion length L in the GaAs and the surface escape probability B can be made from these results. The analysis follows from a comparison of the yield curve shape near threshold, where emission is predominately from thermalized electrons, with a theoretical yield curve shape computed from a solution of the one-dimensional diffusion equation. Results of these computer calculations are shown in Figs. 3 and 4. Fig. 3 shows the total integrated white-light sensitivity possible from GaAs (i.e., surface escape probability B set to unity) versus electron diffusion length in the GaAs for a given GaAs thickness. Infinite surface recombination is assumed at the GaAs-Ge interface. Fig. 4 is the diffusion model solution to the quantum yield curve for a one-micron thick GaAs layer for various diffusion lengths. Again, unity surface escape probability and infinite surface recombination at the GaAs-Ge interface is assumed. Reasonable estimates for B and L are the following:

Sample No.	B	L (microns)	Sensitivity ($\mu\text{A/lm}$)
5-24-72:1	$0.35 \pm .05$	$0.25 \pm .05$	440 ± 40
7-6-72:2	$0.50 \pm .05$	$0.75 + 1.0 - 0.2$	980 ± 80

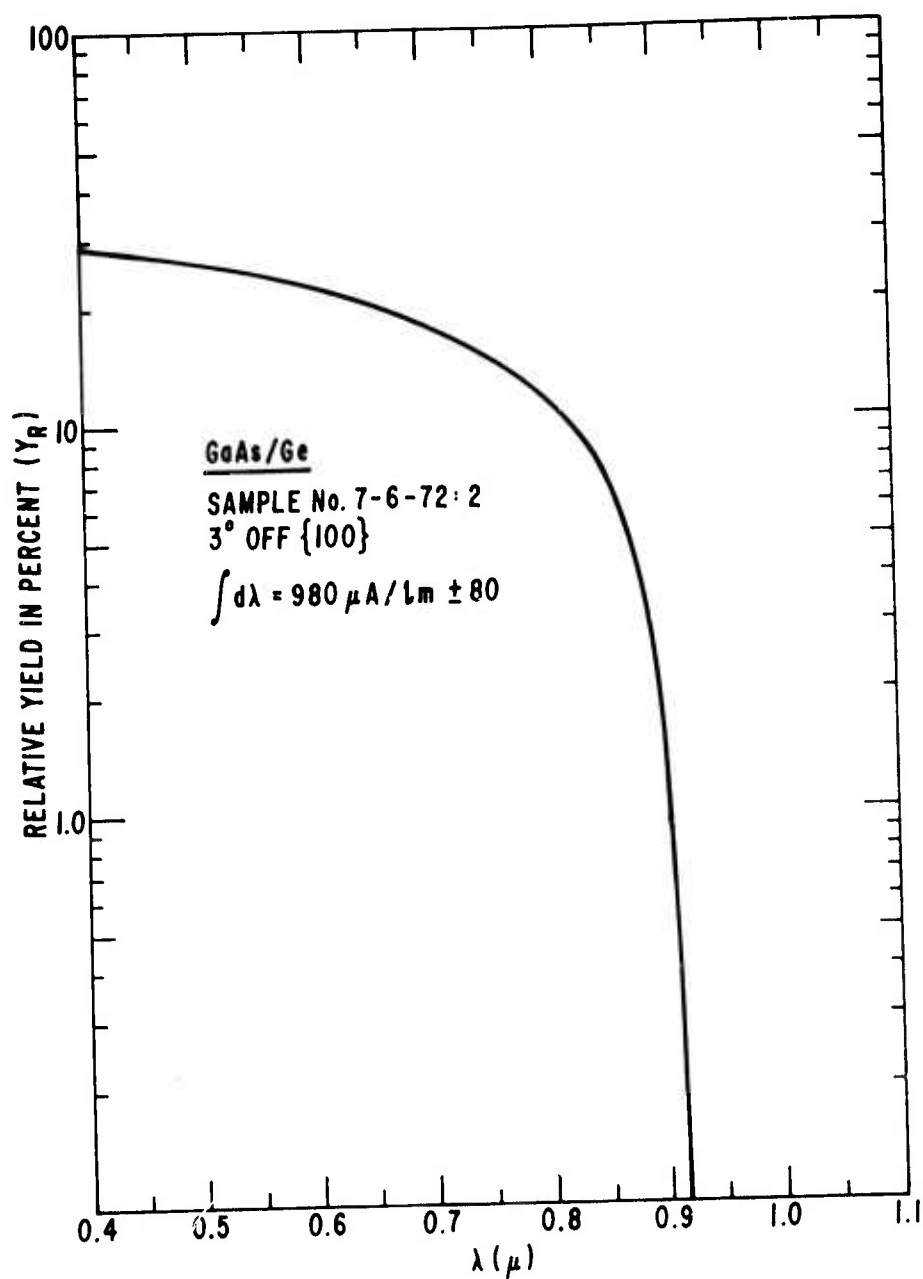


Fig. 2. Experimental activation yield curve from sample No. 7-6-72:2. The integrated white-light sensitivity is 980 $\mu\text{A/lm}$ (no glass). Note that the vertical scale in this figure is only relative.

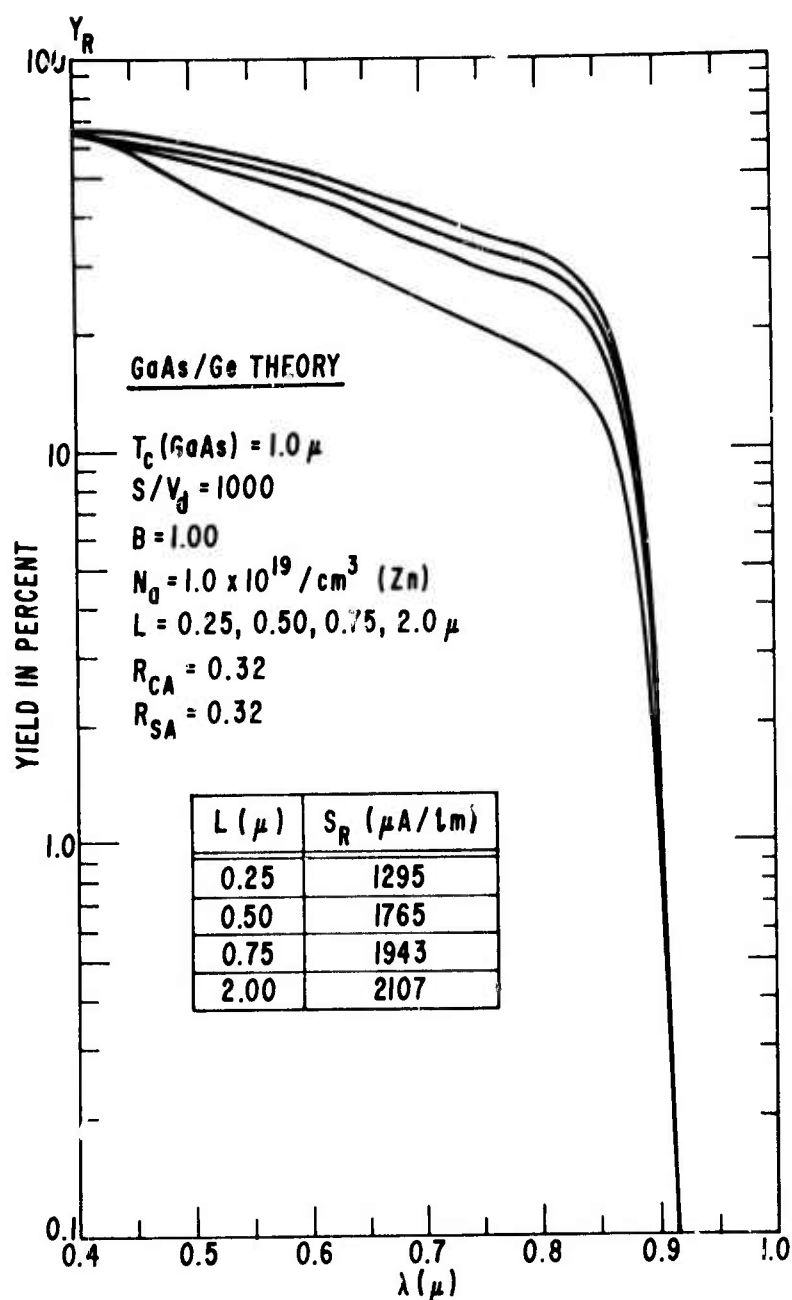


Fig. 3. Theoretical yield curve for GaAs of thickness 1.0 micron and infinite surface recombination at the GaAs-Ge substrate interface. Four different diffusion lengths are shown, 0.25, 0.50, 0.75, and 2.00 microns. A unity escape probability B is assumed here for convenience. Also, for reference, is a table of the integrated white-light sensitivity in $\mu\text{A}/\text{lm}$ for the four diffusion lengths considered here. R_{CA} and R_{SA} are reflection coefficients. S/V_d is the relative surface recombination velocity.

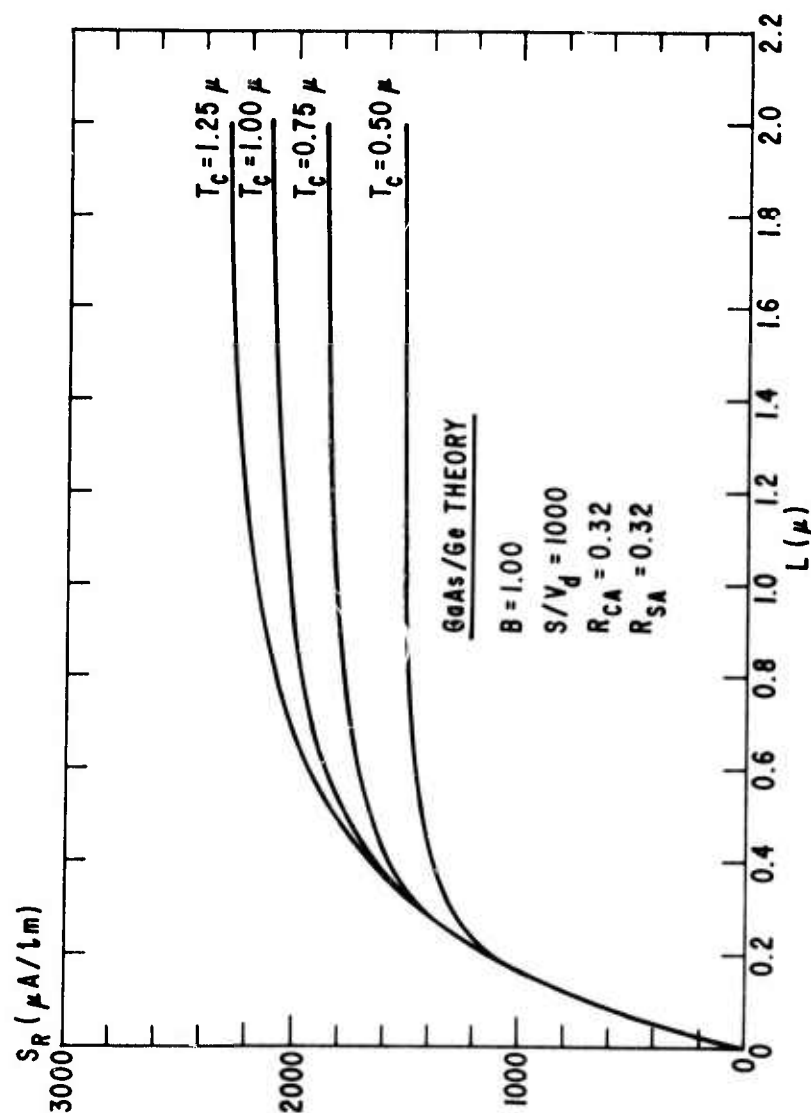


Fig. 4. Theoretical integrated white-light reflection sensitivity in $\mu A/lm$ versus electron diffusion length in microns for GaAs thicknesses of 0.50, 0.75, 1.00, and 1.25 microns. A unity escape probability B is assumed in these calculations. Infinite surface recombination at the GaAs-Ge substrate interface is assumed.

Sample 5-24-72:1 was GaAs grown on p-Ge. However, sample 7-6-72:2 was GaAs grown on a Ge p-n junction (substrate was 4×10^{17} p-Ge; surface was exposed for three minutes at 800°C to As). The present experimental vacuum activation system has not been modified yet to allow junction testing during activations. Hence, the ability of the junction to withstand the activation cycling remains to be evaluated. Sample 7-6-72:2 will, however, be removed from the system and its junction characteristics tested and evaluated.

Before a complete device can be vacuum tested, two more questions need to be answered. First of all, these two activation results were obtained on "as-grown" samples. They were not handled or treated in any unusual way. The real device, however, requires that the GaAs surface be waxed down and mesa diodes be etched into the substrate. The effect of this waxing down and etching cycle on the activation needs to be evaluated. Second, ohmic contacts need to be made to the GaAs surface and the p-Ge substrate for reverse biasing purposes. The effect of these contacts on the activation also needs to be evaluated. Fortunately, these questions do not need to be answered immediately to test the operation and feasibility of this device. Section II-F describes an on-the-bench technique that allows testing of these devices.

D. P-N Junction Formation in Ge

Formation of the p-n junction in Ge is probably the most critical step in the successful operation of this device. Maximum sensitivity requires the device to be biased to near the breakdown voltage of this junction. There are many factors such as doping levels, junction width and area, and device geometry that can affect the reverse breakdown voltage, V_R .⁵ Close attention to these factors has already been seen to be important.

Initial attempts to see diode characteristics as measured by I-V measurements were frustrated in two ways. First, areas larger than about 5 mm x 5 mm had shorted junctions, probably due to inclusions of localized defects within the area causing breakdown. Second, steel probes were used initially whose pressure on the surface tended to cause permanent breakdown of a previously good junction.

These initial problems were solved by first evaporating approximately 1 mm diameter, 1000 Å thick gold ohmic contacts onto the top GaAs surface. Then, small pieces of Hard Wax W were melted over the gold ohmic contacts. The wax is allowed to melt into roughly circular areas of 1-5 mm diameter. Four to six such areas separated by GaAs can be formed onto a single wafer. The wafer is then etched in a 97% HNO_3 , 3% HF solution at room temperature for 30 minutes. The etch is successful in etching back about 20 microns of the exposed wafer. The Hard Wax W is then washed away in TCE. The resulting mesa structure consists of islands of GaAs/Ge(n)/Ge(p) separated by p-Ge substrate material. The mesa diodes are initially tested for I-V characteristics using a Tektronix Type 575 curve tracer using a steel probe into the p-Ge substrate material and a 10-mil gold wire probe with a rounded end

onto the ohmic gold GaAs contact. Good I-V characteristics are seen on about 50% of all mesa diodes tested in this way. Typical reverse breakdown voltages are 1.5 to 2.0 volts, which is what is expected for an abrupt Ge p-n junction with a doping level of our substrates ($4 \times 10^{17}/\text{cm}^3$ Ga).⁶

After testing a junction for I-V characteristics, the good ones of largest area are then tested for internal photoemission characteristics as described in detail in Section II-E. The final testing of a junction is made when it is 5° angle-lapped and stained with a $\text{H}_2\text{O}_2:\text{HF}:\text{H}_2\text{O}$ solution. The junction is then photographed at 200X, and the thicknesses of the n-Ge and the GaAs epitaxial layers are measured. From this measurement technique, we have generated the data for Fig. 5. Fig. 5 is a plot of the depth of the n-Ge diffusion into the p-Ge versus the time of diffusion at 800°C for four wafers that we have studied in this way. Also shown in Fig. 5 are three theoretical curves which we will now describe.

The arsenic diffusion into the p-Ge can be simply described by the one-dimensional diffusion equation for atomic diffusion,

$$\frac{\partial C(x,t)}{\partial t} = D \frac{\partial^2 C(x,t)}{\partial x^2} \quad , \quad (1)$$

where C is the impurity concentration and D the diffusion coefficient for As into Ge at 800°C.⁷ Taking the boundary condition of "constant surface concentration" of concentration C_s , the solution to Eq. (1) is given by

$$C(x,t) = C_s \text{erfc}(x/\sqrt{Dt}) \quad (2)$$

where x is distance below the surface and t is time of diffusion. Taking the p-n junction boundary as seen in the angle lap staining technique to be when $C/C_s \approx 0.1$, Eq. (2) can be solved to give an expression for the depth of diffusion versus time of diffusion given approximately by

$$x \approx 3\sqrt{Dt} \quad . \quad (3)$$

Eq. (3) was then plotted in Fig. 5 for three different diffusion coefficients, $D = 1.5 \pm .5 \times 10^{-3} \mu^2/\text{sec}$. The fit to the data is not too bad considering the variability of angle-lapping techniques. This range of values for the diffusion coefficient of As in Ge at 800°C is in good agreement with reported values.⁸ Knowledge of the diffusion coefficient and the junction depth versus time is clearly important for optimizing device performance and analyzing results. We will use Fig. 5 in discussing our internal photoemission results of Section II-E.

In the Appendix, we calculate that the depth of the n-region must be $< .1 \mu\text{m}$. Hence, it is clear that we need to form much thinner junctions by either shorter diffusion times and/or lower diffusion temperatures. Work has begun to achieve the thinner junctions. Also, our calculations in the

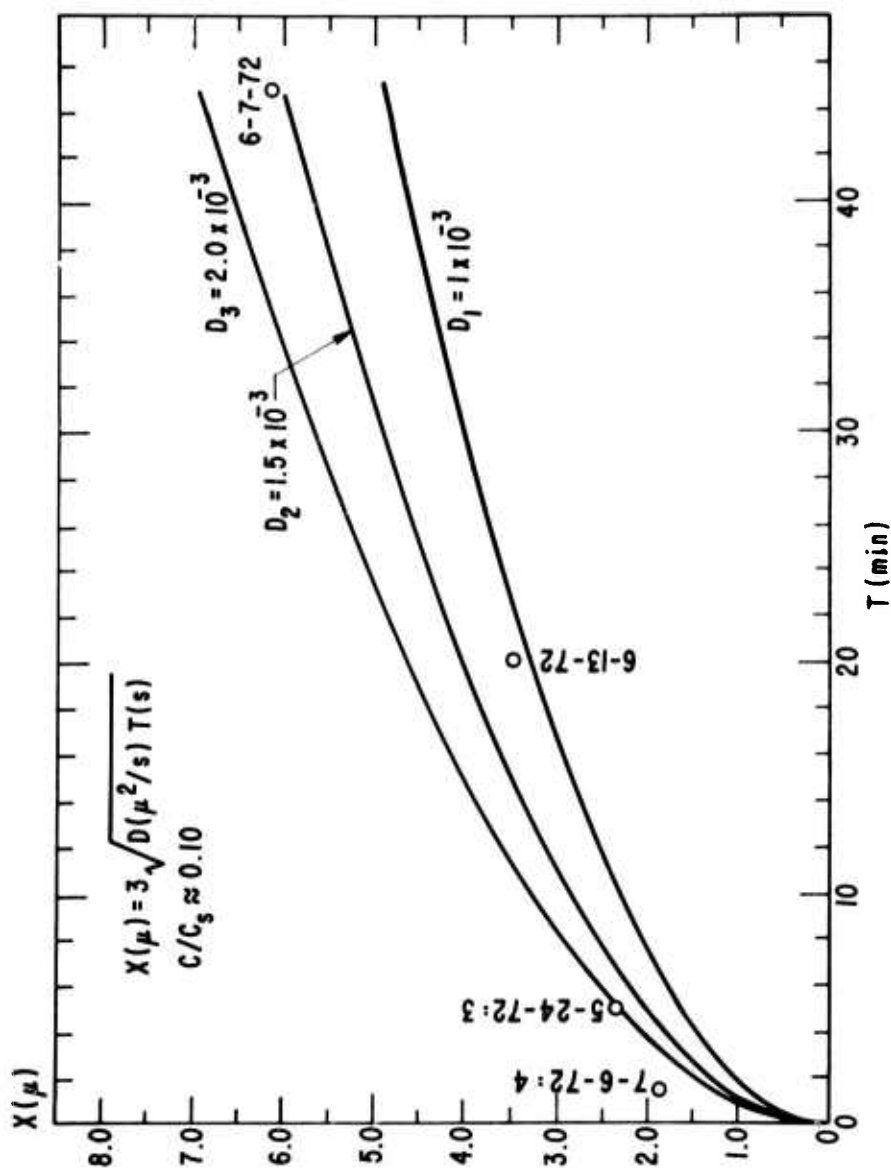


Fig. 5. Depth of As diffusion into p-Ge versus time of diffusion at 800°C. The four data points are shown as circles on this plot. The three curves are theoretical diffusion depth curves for three different diffusion coefficients, $D = 1.5 \pm 0.5 \times 10^{-3} \text{ microns}^2/\text{sec}$. The "constant surface concentration" boundary condition was assumed in these calculations and the boundary of the p-n junction was assumed to be seen in the angle lap photographs when the boundary concentration to surface concentration ratio C/C_s was taken to be approximately 0.10.

Appendix show that we will optimize our emission by using much lighter doped p-Ge wafer material. The lighter doped p-Ge material should support a much higher reverse bias (~100 volts). The lighter doped material will have a deeper depletion region, but the higher reverse bias more than makes up for the increased electron energy losses in the deeper depletion region. Lighter doped material is on order from Nucleonics Products Company, Inc., Canoga Park, California.

E. Schottky Diode Testing of NEA Devices

We have developed a simple on-the-bench method of testing the operation of the GaAs/Ge(n)/Ge(p) device.¹⁰ The method uses an internal photoemission Schottky barrier technique to generate yield curves from .4 to 2.0 microns.

The method uses distilled water to form a Schottky diode contact to the emitting semiconductor surface, GaAs in our case. An ohmic gold contact is also needed to the GaAs surface. Pt or gold is used to make contact to the water. No bias is applied between the ohmic gold GaAs contact and the water contact. Photons incident through the water contact photoexcite electron-hole pairs in the bulk which then diffuse toward the surface as in a vacuum photoemission experiment. The photoexcited electrons which reach the surface before recombination are collected by the water contact. A simple sample holder with three x-y probes was built to function with our Cary 14 Spectrophotometer which has been electronically modified to generate quantum yield curves. Two of the x-y probes are used to make contact to the ohmic gold GaAs contact and the water, the other is a steel probe to make ohmic contact to the p-Ge substrate in order to apply a reverse bias to the p-n junction. Hence, the complete device can be tested using this on-the-bench method without having to add the additional complications of vacuum, activation, and high temperature contacts.

Two complete devices have been tested for greater than 0.9 micron sensitivity, 6-13-72:1 and 7-6-72:4. These devices had the relatively high p-doping level of $4 \times 10^{17}/\text{cm}^3$ substrate material and both had much too thick an n-region, 3.5 and 1.8 microns, respectively. Neither device showed any internal photoemission beyond the GaAs threshold. This is to be expected, however, since the n-region was so thick and noting our calculations in the Appendix, Fig. 8. Both devices had a reverse bias breakdown voltage of about 1.5 volts. Over 10 volts could be applied to the junction without permanent breakdown of the junction; however, no photoemission beyond 0.9 micron was measured.

The Schottky diode testing of these devices is expected to aid greatly in optimizing the many parameters to achieve maximum 1-2 micron sensitivity. The testing procedure is relatively fast and should save valuable activation time in the long run.

III. RECOMMENDATIONS

A number of important steps have been made this first quarter. The vapor-phase growth of epitaxial GaAs on Ge substrates has come a long way. The quality of the GaAs from appearance and from activation standards is good. It is recommended, however, that additional work be done on substrate preparation and other growth techniques to try to completely eliminate the slight haze in the GaAs that still remains.

The p-n junction formation in Ge has been shown to fit reasonably well the one-dimensional diffusion model. The results of our calculations on the Ge p-n junction show that we must do two things. (1) Junctions formed to date have all been much too thick. Therefore, there is further work needed to form and evaluate much thinner junctions. (2) Much lighter doped substrate material is needed. The lighter doped p-Ge is on order. The lighter doped material will allow a deeper junction than heavier doped substrate material and a much higher reverse bias. The results of our calculations in the Appendix and our estimate of the diffusion coefficient from our measurement of junction depths in Section II-D have given us the necessary information and tools to better design an optimal device.

Modifications to the vacuum activation system are underway to allow biasing and operational testing of the device. The effect of the etching and waxing cycle on the GaAs activation needs to be evaluated. Also, high temperature contacts and procedures need to be evaluated for this device. Finally, the device area, GaAs thickness, GaAs doping level, and device geometry remain to be optimized. Therefore, a great deal of work remains to be done.

Overall, however, from the experimental results on GaAs/Ge and from our calculations, the potential of 1-2 micron emission looks very promising.

IV. APPENDIX

Calculation of Photoexcited Electron Losses and Optimal Doping Levels

In this section we describe some calculations on the photoelectron transport and energy losses in the Ge p-n junction region. Results of these calculations show that our present $4 \times 10^{17}/\text{cm}^3$ p-Ge substrate material is very likely too highly doped.

Consider once again Fig. 1. There are two important energy loss regions that we wish to consider. Photoexcited carriers in the p-Ge that diffuse to the depletion region of the p-n junction must first suffer energy losses in crossing this region. There has not been a great deal of work to indicate how hot electrons lose energy. Williams and Simon⁹ have shown that it is possible to describe the electron energy distribution by

$$J(E) = (W_d/\ell)^{E/E_p} e^{-W_d/\ell/(E/E_p)!} \quad (\text{A-1})$$

where E is the energy relative to the conduction band edge, ℓ is the mean free path for hot electron losses, W_d is the width of the depletion layer, and E_p is the energy lost for each hot electron-phonon interaction. The peak of this distribution goes as

$$\mathcal{E}_d = (W_d/\ell)E_p \quad (\text{A-2})$$

where $\mathcal{E}_d$ is the mean energy loss from the top of the conduction band in crossing the depletion region. This depletion layer loss is schematically shown in Fig. 1. Williams and Simon's work⁹ was done on activated GaP. Parameters appropriate for Ge are $\ell = 65 \text{ \AA}$ and $E_p = .037 \text{ eV}$.¹¹ The width of the depletion layer depends on the doping level of the most lightly doped side of the p-n junction, the p-Ge substrate side in our case. W_d has been calculated for Ge p-n junctions as a function of the doping by Sze.¹² Also, the reverse breakdown voltage V_B for Ge p-n junctions versus doping level has been calculated by Sze and Gibbons.¹³ Therefore we have enough information to calculate the energy loss in the depletion of Ge and compare this with the reverse breakdown voltage as a function of doping level in the Ge. Fig. 6 is a plot of $\mathcal{E}_d$, V_B , and $V_B - \mathcal{E}_d$ versus doping N_B of the p-Ge substrate material. Having crossed the depletion region, the electrons must then cross the n-region. Here we make the assumption that the applied voltage drop occurs in the lightest doped side, i.e., the p-Ge side. Hence, the depletion is assumed for these calculations to be entirely within the p-Ge side and the n-Ge is assumed to be essentially flat band. (Note that the nature of the n-dopant As diffusion into the p-Ge substrate is such that the doping level of the n-Ge is always greater than the p-Ge doping level.) Hot electron losses in the flat band n-region are assumed to be from a random walk isotropic electron-phonon scattering process. The energy loss in the flat band region is simply the number of interactions necessary to random walk across the flat band width, W_f , times the energy loss per interaction, .037 eV. The number of random walk steps needed to cross a

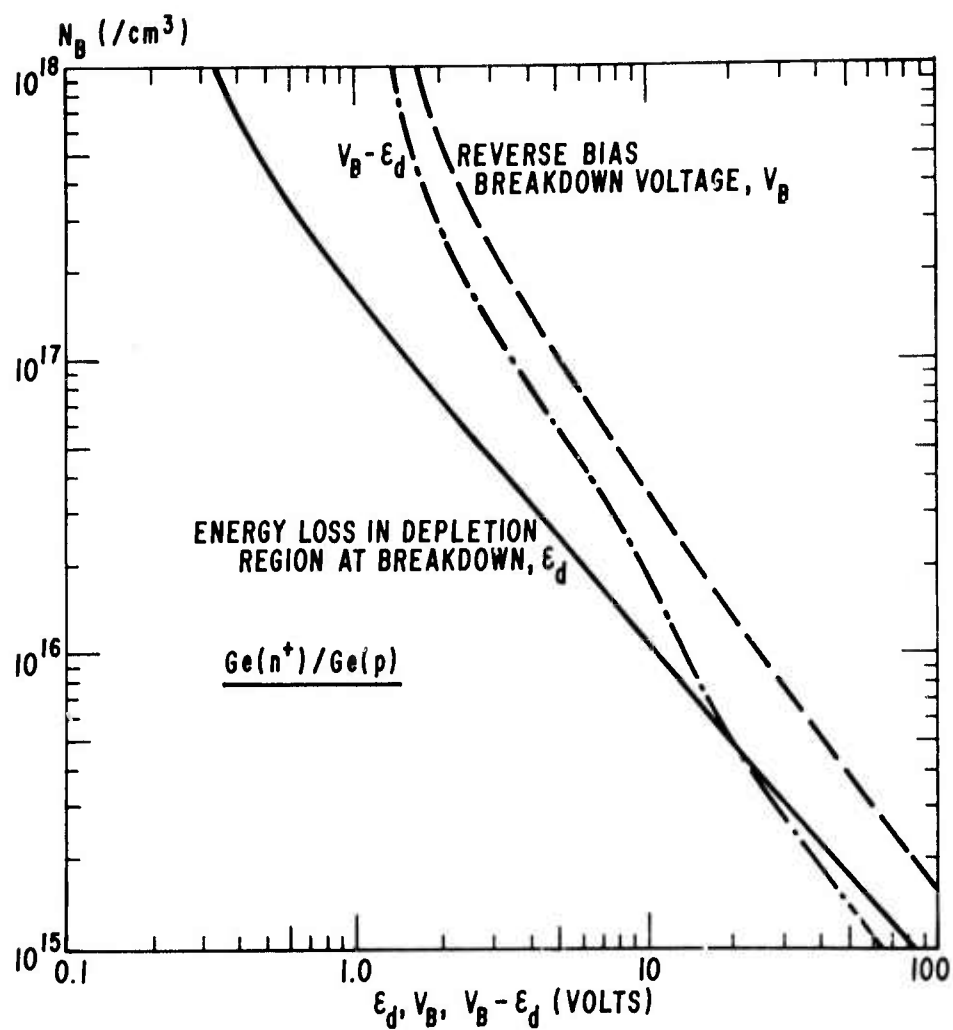


Fig. 6. Theoretical calculation of the p-Ge substrate doping level versus energy loss in the depletion region ϵ_d , the reverse bias breakdown voltage V_B , and the difference $V_B - \epsilon_d$.

width W_f with a mean step size, $\ell = 65 \text{ \AA}$, is given by

$$\mathcal{E}_f = (1/4pq)(W_f/\ell)^2 E_p \quad (\text{A-3})$$

where $p = 1/6$, the probability of walking in the right direction, and $q = 5/6$, the probability of walking in the wrong direction.¹⁴ Fig. 7 is a plot of the total energy loss in the flat region versus the width of the flat band region. One thing that is very clear from this figure is that, for flat band thicknesses much in excess of a few tenths of a micron, the energy losses are disastrous to this device. Hence, a most important requirement will be to minimize this region as much as possible. The limiting thickness, of course, will occur when premature junction breakdown occurs. The minimum thickness will need to be determined experimentally. Fig. 1 shows this flat band energy loss $\mathcal{E}_f$ schematically. Finally, one can combine our calculation results to help design a more optimal device. Fig. 8 is a plot of reverse bias voltage near breakdown V_B minus depletion width losses $\mathcal{E}_d$ minus flat band losses $\mathcal{E}_f$ as a function of the doping level in the p-Ge substrate material N_B for a given thickness of n-Ge region W_f . Fig. 8 tells us that we should be working with very lightly doped p-Ge substrate material. The lightly doped material allows very much higher reverse biases to be applied before breakdown. The higher biases therefore allow much thicker n-Ge regions and still have sufficient energy to enter the GaAs and diffuse out into vacuum. For example, a $5 \times 10^{15}/\text{cm}^3$ p-Ge substrate should be able to be fabricated with a 40-volt reverse bias p-n junction breakdown. If the n-region thickness can be made 1000 $\text{\AA}$ thick, Fig. 8 says that the photoexcited electrons should enter the GaAs with about 4.0 volts, more than enough to overcome the GaAs energy barrier at the Ge(n)/GaAs interface. Our calculations show that, for a fixed n-region thickness, the advantage is definitely with the lighter doped material. Since the hot electron mean free path and the electron-phonon energy loss are not all that well established for Ge, the absolute number results for these calculations are probably subject to some modification. However, we feel that two important facts remain out of all of this: (1) one should try very hard to avoid or at least minimize the n-Ge thickness, and (2) use lightly doped p-Ge substrate material. Fortunately, these two recommendations are feasible. We have recently ordered some lightly doped p-Ge material. The lightly doped p-Ge substrate material means that we do not have to dope the n-region so heavily. Hence, there is now the additional beneficial possibility of the depletion region extending over into the n-region, at least partly. Since the energy losses/micron in the depletion region are much much less than in the flat band region, the lighter doped material may even be better than our calculations show.

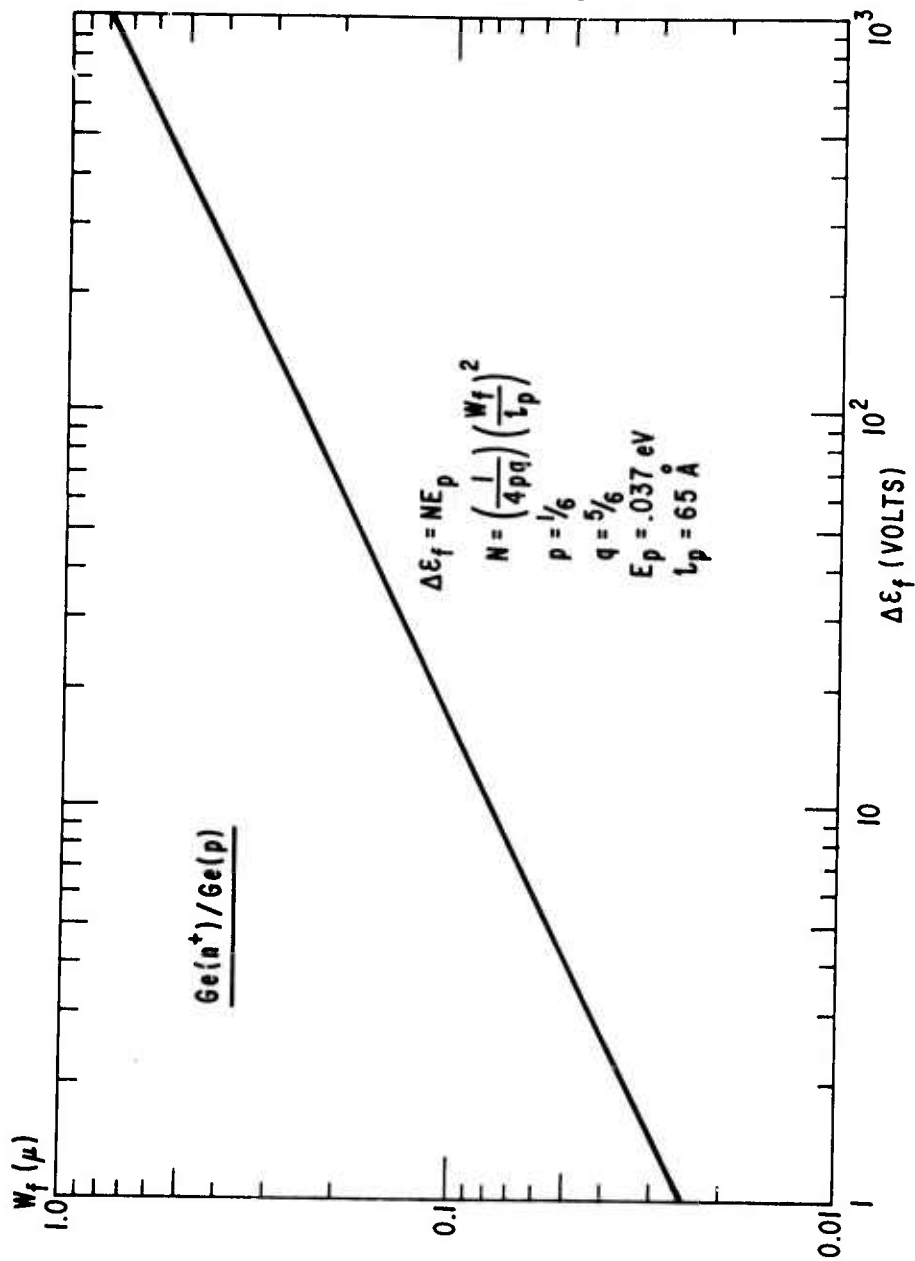


Fig. 7. Theoretical energy loss of photoexcited electrons in crossing the flat band n-Ge region. Width of the flat band region W_f in Angstroms versus energy loss ϵ_f in volts. An isotropic random walk process is assumed in these calculations for the flat band region.

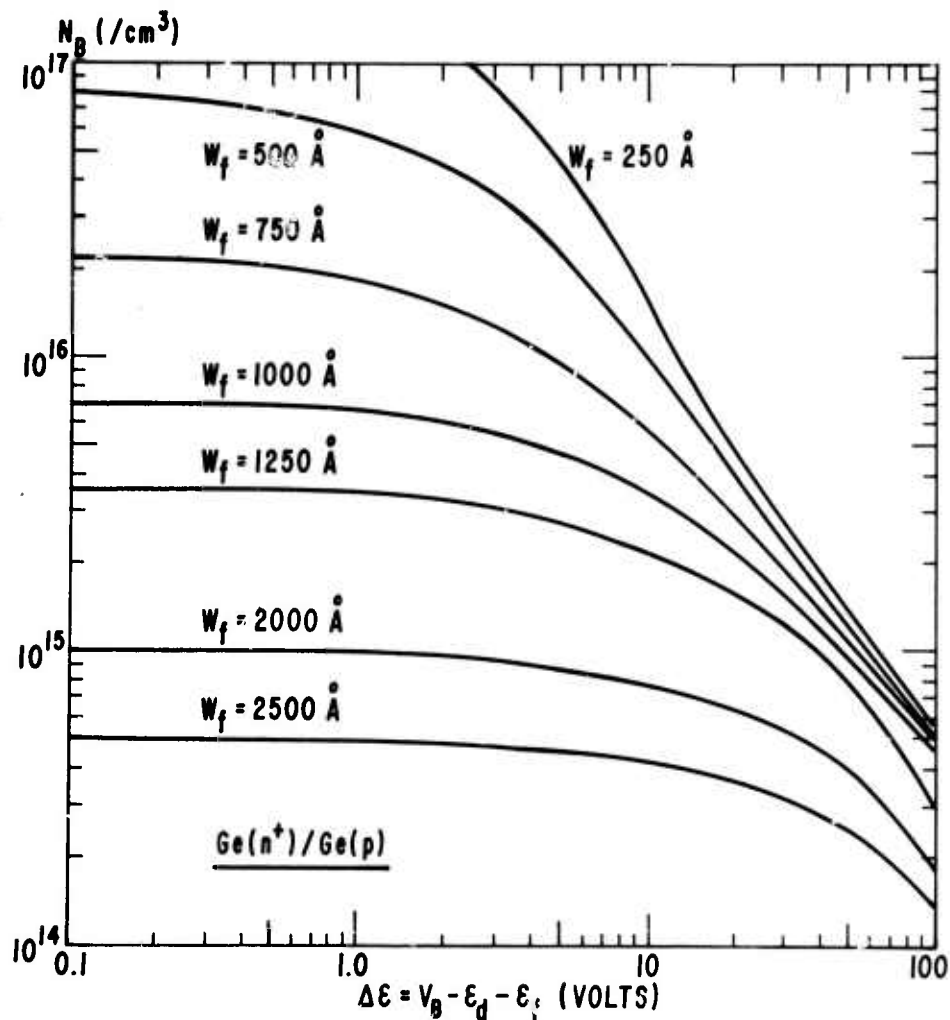


Fig. 8. Combined results of Figs. 6 and 7. Reverse bias voltage near breakdown minus energy loss in the depletion region minus the energy loss in the flat band region, $V_B - \epsilon_d - \epsilon_f$ versus doping level of the p-Ge substrate material for a given width of the flat band region, $W_f = 250 \text{ \AA}$, $500 \text{ \AA}$, $750 \text{ \AA}$, $1000 \text{ \AA}$, $1250 \text{ \AA}$, $2000 \text{ \AA}$, and $2500 \text{ \AA}$.

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13. ABSTRACT Research has begun on a GaAs/Ge device designed to have photoemission sensitivity into the 1-2 micron range. The device consists of a thin GaAs epitaxial layer vapor-phase grown on a p-n Ge junction. The p-n junction is reverse biased, and the GaAs is vacuum activated with Cs-O to negative electron affinity in operation. The p ⁺ -GaAs provides an effective biasing contact for the Ge p-n junction and allows photo-excited electrons to diffuse through into vacuum. Work during this first quarter has resulted in good quality epitaxial growth of GaAs on Ge. A one-micron thick GaAs/Ge sample has been vacuum activated to almost 1000 μ A/lm. The nature of As diffusion into Ge has been studied for the purpose of fabricating optimal Ge p-n junctions. Results of this experimental work combined with theoretical calculations indicate that our present substrate material is too highly doped for optimal device performance. Overall, the experimental results on GaAs and our calculations show that this device still looks most promising for 1-2 micron photo-emission.			

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