Final Quarterly Report — Covering the Period 11 November 1965 to 11 February 1966

RESEARCH ON COLD CATHODES

By: ... LEPPERT B. V. DORE

Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

CONTRACT NAS 5-9581

STANFORD RESEARCH INSTITUTE

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SRI Project 5511

Approved: J. D. NOE, EXECUTIVE DIRECTOR
ENGINEERING SCIENCES AND INDUSTRIAL DEVELOPMENT

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ABSTRACT

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GaP/Pd surface-barrier diodes have been fabricated and tested for possible application to the surface-barrier cathode. Barrier heights of about 1.4 eV were measured by plots of $1/C^2$ as a function of V and photothreshold plots. The data suggest, however, that the barriers are not of uniform height, some regions having lower barrier heights than the nominal value. The current-voltage characteristics of the diodes also deviated from Schottky theory. The current at low forward-bias voltages was too high, which is again indicative of low-barrier regions.

The photothreshold responses of W/BaO and Pd/BaO with a small amount of free Ba deposited on the surface have been studied. In both cases a reduction of work function was obtained by the addition of a small amount of Ba onto the surface. In the case of W/BaO/Ba a work function of 1.375 eV was obtained. The system Pd/BaO/Ba produced a work function of 1.42 eV, compared to about 1.7 eV for the Pd/BaO alone (measured after over-activation).

The effects of a heated substrate were studied during the deposition of BaO on Pd and on Ni. In the case of Pd held at about 600°C during the BaO evaporation, a double intercept was obtained on a Fowler plot (square root of photoresponse vs. $h\nu$), the lower intercept corresponding to a work function of 1.22 eV.

Emission tests were conducted on the system GaP/Pd/BaO. In the first test (for unknown reasons) the vacuum was not good and good BaO activation could not be obtained. On the second test the I-V characteristics of the GaP/Pd diode indicate low-barrier regions, and no emission was observed.

Preliminary steps have been taken to evaluate the transistor cathode using p-n junctions of GaAs, InP, or Si.

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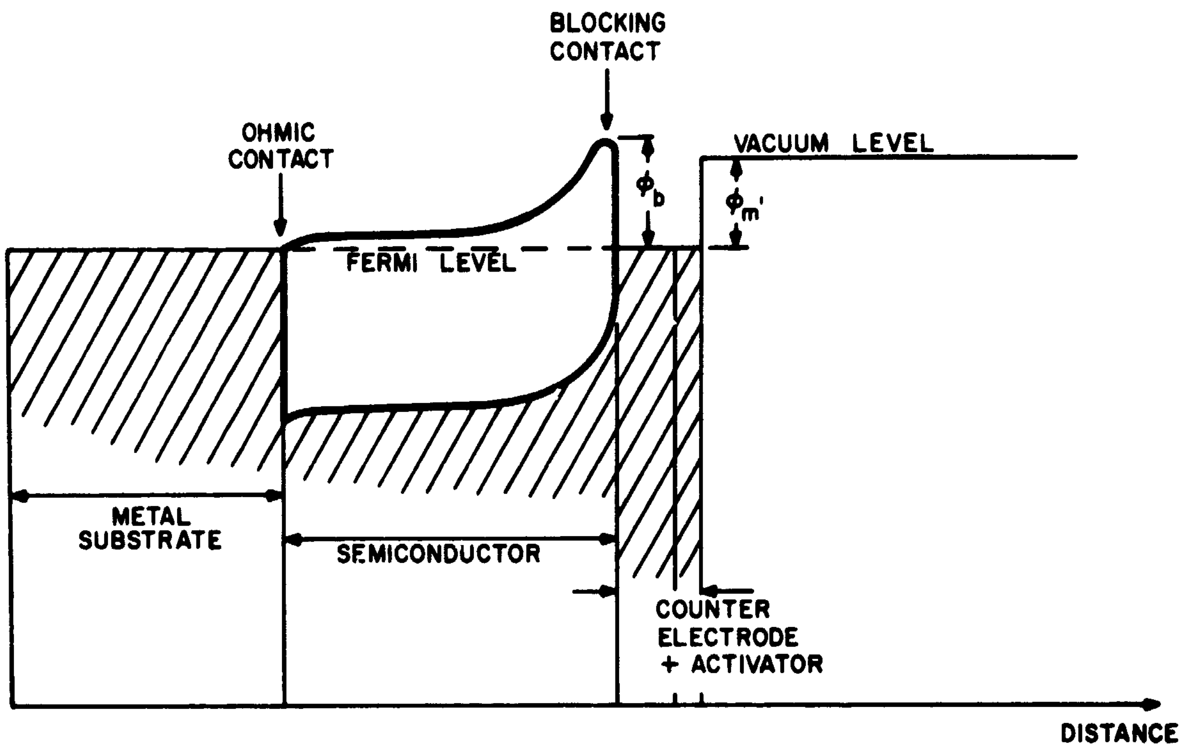
I INTRODUCTION

The objective of this program is to perform research on semiconductor/metal, hot-electron cold cathodes. The hot electrons are generated in a thin metal surface film by forward-biasing a rectifying semiconductor/metal diode. The metal film is on the order of 50-to-100 Å in thickness and is activated by a low-work-function coating to reduce the vacuum barrier below the semiconductor/metal barrier. Energy diagrams for the cathode, with and without bias, are shown in Figs. 1(a) and 1(b). (The dimensions of the structure are not drawn to scale and the thickness of the metal film is exaggerated for clarity.) Referring to Fig. 1(b), a portion of the hot electrons emitted over the top of the barrier into the metal film traverse the film ballistically and enter the vacuum. Most of the electrons that become scattered in the metal film are lost however, and these electrons create a bias current for the device.

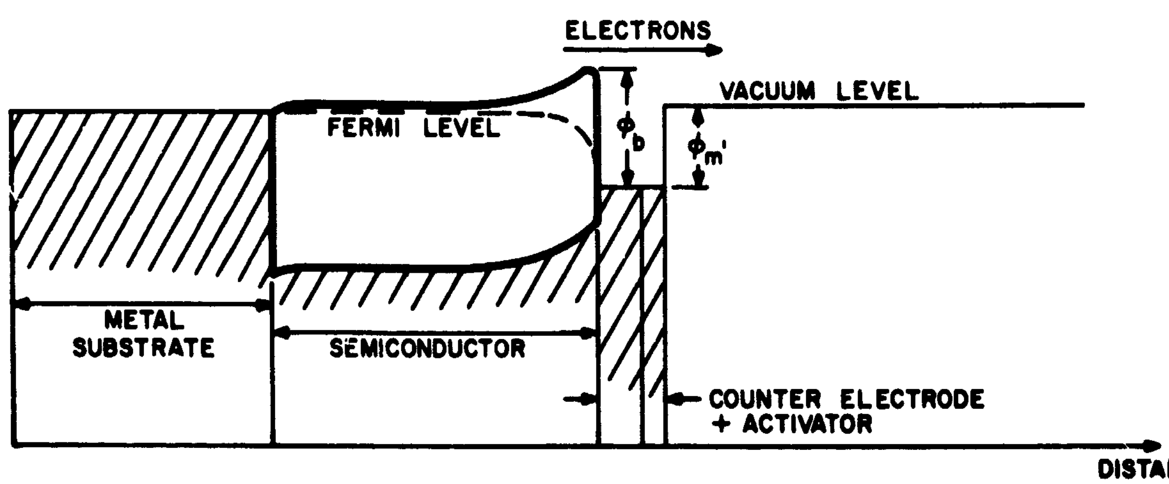
Since the initiation of the contract, an alternative cold cathode has been suggested, as indicated in the Second Quarterly Report.[1*] The energy diagrams for the new cathode, shown in Fig. 2, resemble those of an n-p-n transistor, and the operation of the cathode is similar to that of the transistor. The vacuum constitutes the collector for the transistor cathode, as it is called. The transistor cathode promises higher efficiency than the surface-barrier cathode.

In our previous report it was concluded that the system GaP/W/BaO is marginal because the GaP/W barriers are about 1.42 eV, whereas the W/BaO work functions are about 1.45 eV. Difficulties in evaporating W during the past quarter have led to an investigation of the system GaP/Pd/BaO for the surface-barrier cathode. This report will present

[*] References are given at the end of this report.



(a) ENERGY AS A FUNCTION OF DISTANCE FOR SURFACE-BARRIER CATHODE WITHOUT BIAS.



(b) ENERGY AS A FUNCTION OF DISTANCE FOR SURFACE-BARRIER CATHODE WITH BIAS.

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FIG. 1 ENERGY DIAGRAM OF SURFACE-BARRIER CATHODE

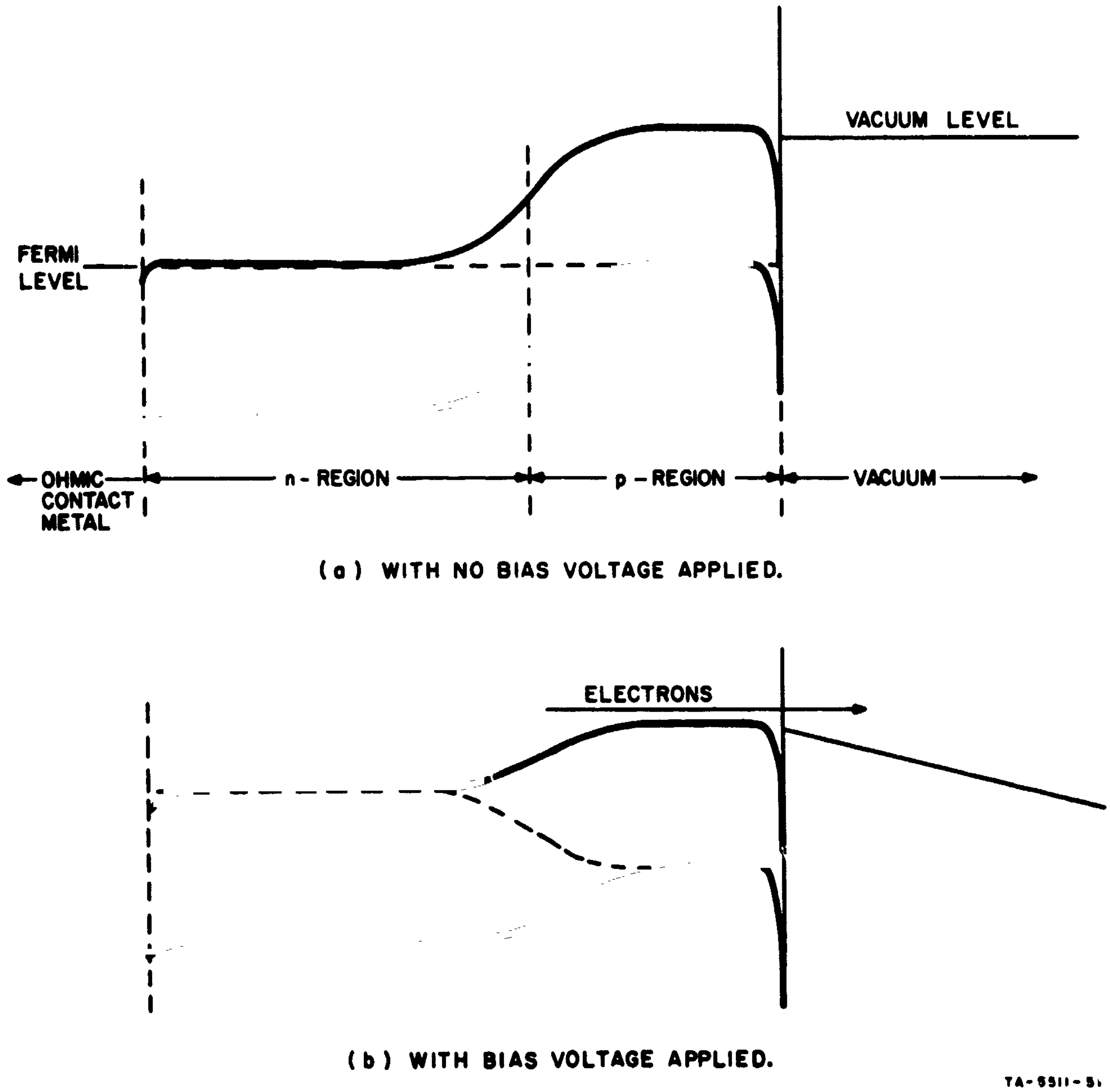

FIG. 2 ENERGY DIAGRAMS FOR TRANSISTOR CATHODE

results obtained on the electrical measurements on GaP/Pd diodes and on Pd/BaO and Ni/BaO photoelectric work functions.

II DISCUSSION

A. GaP/Pd Diodes

1. I-V Characteristics

Considerable difficulties have been experienced in evaporating tungsten for fabricating GaP/W surface barrier diodes (and for fabricating W/BaO photo-surfaces). These difficulties can all be attributed to the very low vapor pressure of tungsten and consequently to the extremely high temperatures required for rapid evaporation. The commercial electron-beam gun which has been purchased and installed in the oil-free high-vacuum system is designed, according to the manufacturer, for evaporating refractory materials, specifically including tungsten. However, there were a number of gun failures during attempts to evaporate W. Only occasionally were the deposition runs satisfactory. A technical representative of the manufacturer was called in, and small changes were made following his suggestions. Since difficulties in tungsten evaporati have persisted, it was decided that the gun design is marginal for this use.

The excellent results being obtained with BaO activation have suggested that a number of other metals should be suitable for the metal surface film. Hence, it was decided to discontinue the investigation of W, at least temporarily, and to examine other metals for the surface film. Among the metals considered was palladium. Based on the theory developed by Geppert, Cowley, and Dore,[2] a GaP/Pd barrier height of about 1.4 eV could be predicted. This should be high enough if a reasonable Pd/BaO work function could be obtained. (See Sec. II-B-2 for discussion of Pd/BaO work-function studies.)

In order to check these predictions, Pd was evaporated either from a tungsten basket or by means of electron bombardment through suitable masks onto GaP crystals. The crystals had previously been prepared with ohmic contacts. The crystals had been freshly etched and placed in the evaporator wet with methanol, as discussed in previous reports. Approximately 200 Å of palladium was evaporated at a pressure of about 10^{-8} torr.

The resulting GaP/Pd surface-barrier diodes were first examined for I-V characteristics on a curve tracer. Figure 3 is a photograph of the trace obtained on one of the diodes. Good rectification

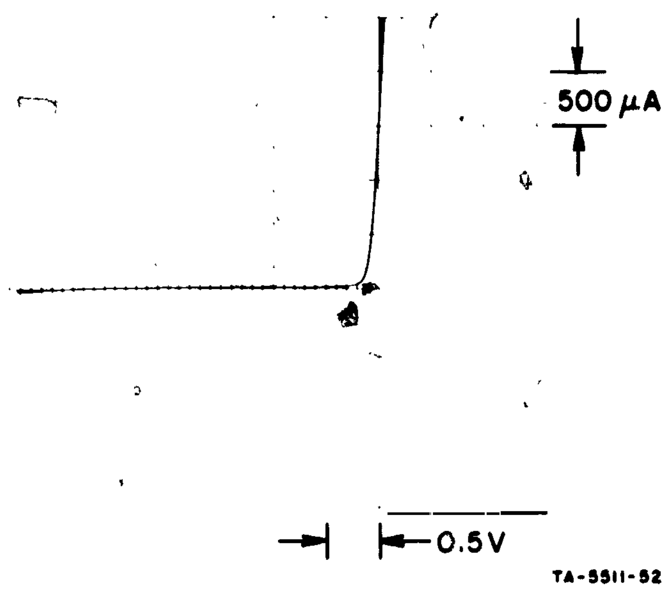

FIG. 3 PHOTOGRAPH OF I-V CHARACTERISTICS OF GaP/Pd DIODE ON CURVE TRACER

is observed, although the break voltage is slightly under one volt, indicating a barrier of perhaps slightly more than one volt, or a somewhat higher barrier with some barrier nonuniformity (see Appendix A).

Figures 4(a), 4(b), 4(c), and 4(d) are semilog I-V plots for four GaP/Pd diodes. None of these characteristics are in accord with simple Schottky theory. The currents at low voltages are too high, indicating regions of low barrier height.

2. <u>Measurements of $1/C^2$ as a Function of V</u>

Data on $1/C^2$ as a function of V were taken and plotted for several of the diodes, as shown in Figs. 5(a) and 5(b) for two of the diodes. The intercepts indicate diffusion potentials of 1.3 and 1.4

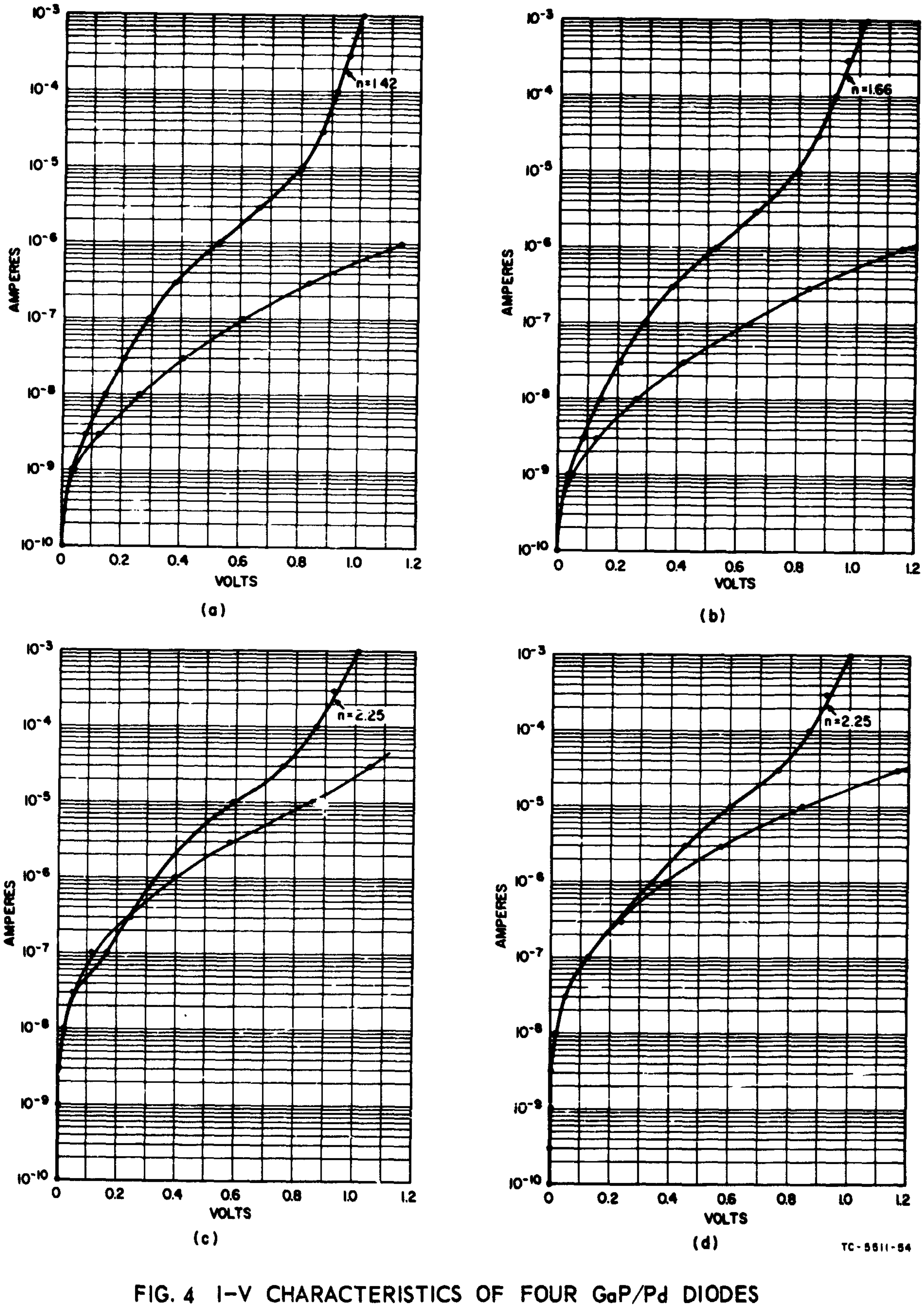

FIG. 4 I–V CHARACTERISTICS OF FOUR GaP/Pd DIODES

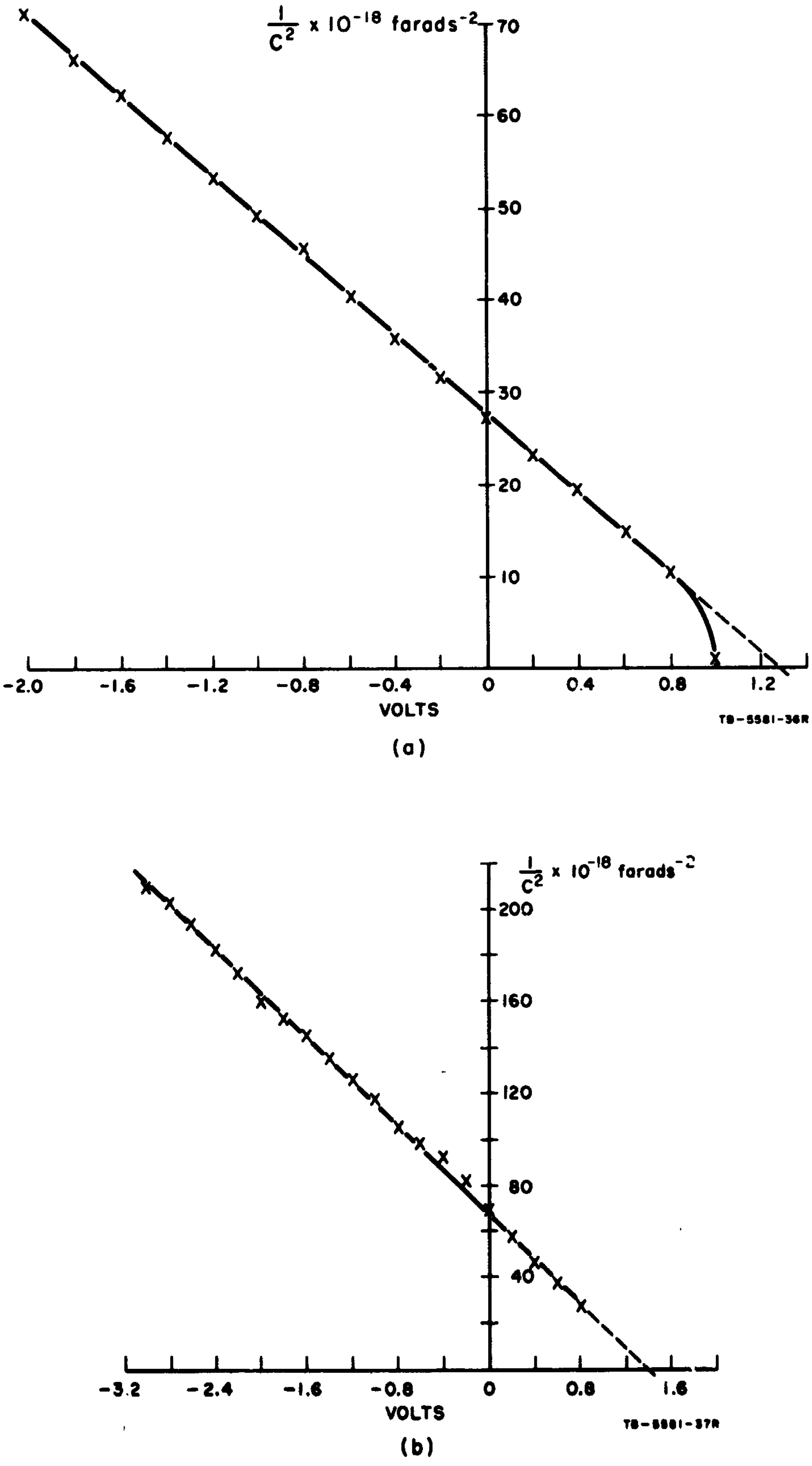

FIG. 5 $1/C^2$ AS A FUNCTION OF V FOR TWO GaP/Pd DIODES volts. The donor densities of the GaP crystals were computed from the slopes of the curves by the equation

$$N = \frac{-2}{\epsilon_o \epsilon_r \, q \, \frac{d\left(\frac{A}{C}\right)^2}{dV}}$$

where ϵ_o is the permittivity of free space, ϵ_r is the relative permittivity of GaP (taken to be 8.46), q is the electronic charge, A is the area of the diode, C is the differential diode capacitance, and V is the applied dc bias voltage.

The results for two diodes on a Monsanto crystal were 1.325×10^{17} cm^{-3} and 2.08×10^{17} cm^{-3}. This compares with a value of 7.2×10^{17} cm^{-3} determined from Hall mobility and resistivity measurements. For a crystal from Stanford University a value of 1.31×10^{16} cm^{-3} for N was obtained, which compares with a value of 1.3×10^{17} cm^{-3} determined from mobility and resistivity.

The drop to zero at 1.0 volt in Fig. 5(a) indicates a low-barrier region (see Appendix).

3. Photoresponse

Hot-electron photothreshold measurements have been taken on the GaP/Pd diodes using the PE 112 spectrometer. Figures 6(a), (b), and (c) are plots of the square root of the response as a function of photon energy for four of the diodes. The intercepts of about 1.5 eV check fairly well with the diffusion potentials of 1.3 and 1.4 eV of Figs. 5(a) and 5(b). If the Fermi level is assumed to lie 0.06 eV below the bottom of the conduction band in the GaP, the barrier heights obtained from Figs. 5(a) and 5(b) would be 1.36 eV and 1.46 eV, respectively.

B. Evaporated-BaO Studies

1. W/BaO/Ba Experiments

In a study of the photoelectric effect from BaO, Dueker and Hensley[3] reported that the application of a partial monolayer of Ba

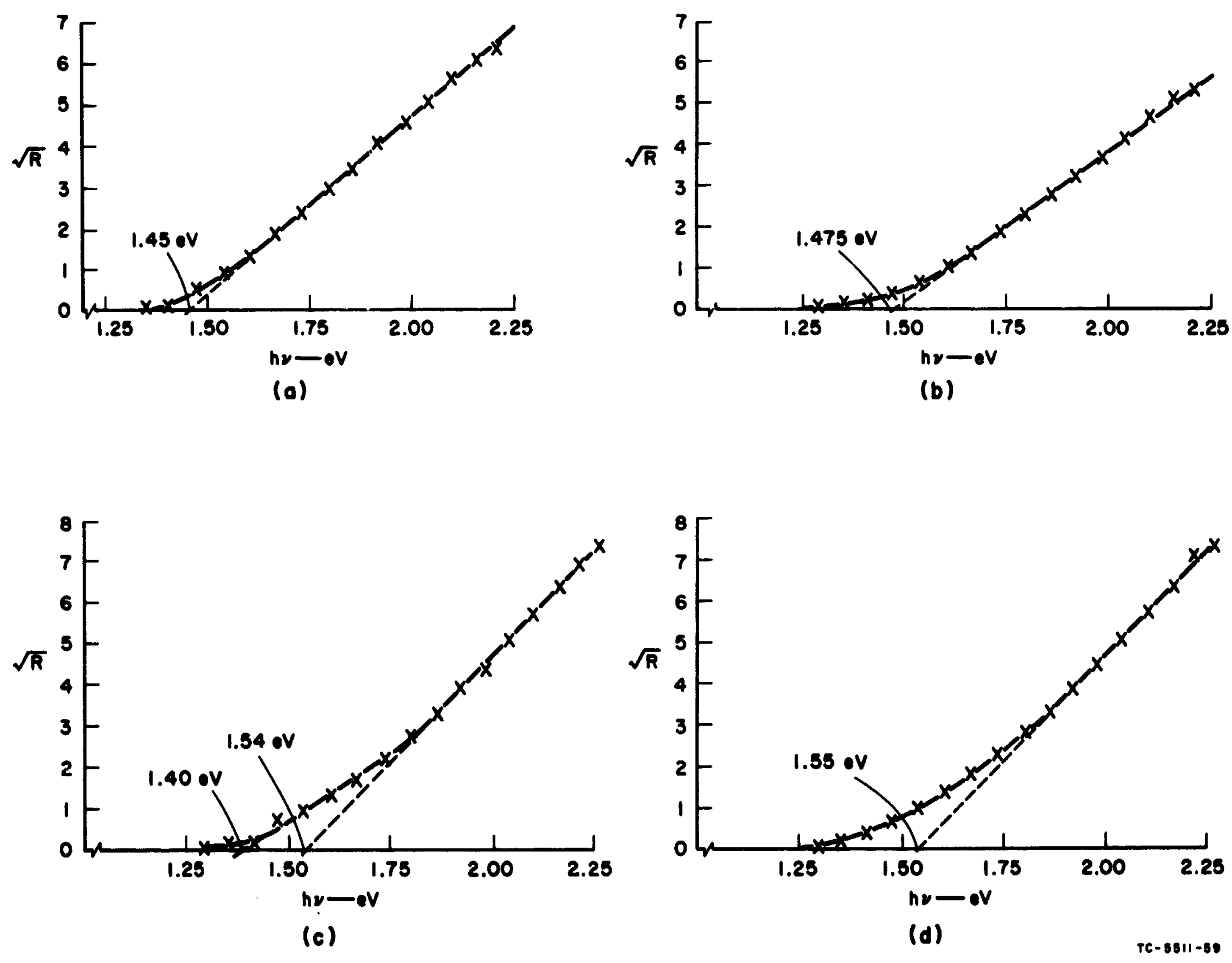

FIG. 6 SQUARE ROOT OF PHOTORESPONSE PER PHOTON AS A FUNCTION OF PHOTON ENERGY FOR FOUR GaP/Pd DIODES

on the surface of the BaO reduced the electron affinity of the BaO by several tenths of an eV. A similar effect was observed by Smirnov and Nikonov[4] with bulk BaO. They measured the emission characteristics of a BaO cathode in a constant stream of Ba. In a dynamic equilibrium corresponding to two to three tenths of a monolayer of Ba on the surface of the BaO, the thermionic work function was reduced by 0.3 to 0.4 eV. An experiment was set up to verify this effect using a conventional getter as a source of Ba. Tungsten was evaporated onto a sheet Mo substrate, followed by the usual BaO activation using a Pt source. Some difficulty was experienced in evaporating the W, so the results obtained cannot be attributed to W alone.

2. Pd/BaO/Ba Experiments

Some of the difficulties encountered in depositing W films have been described in Sec. II-A. The decision to try Pd in place of W was based upon ease of evaporation and the expectation of obtaining a vacuum barrier lower than the GaP/Pd barrier by using BaO plus Ba. The results of the first experiment are shown in Fig. 7. High-purity Pd metal was evaporated from a helical W basket onto a sheet Pt substrate. Curve A was plotted from the response obtained after evaporating BaO for 5 minutes. When more BaO was evaporated, the work function increased. After 7 more minutes of evaporating BaO with no improvement, it was decided to liberate a small amount of Ba. The work function immediately improved, but a fault developed in the spectrometer which prevented optimizing the effect.

The work function of 1.42 eV from curve B in Fig. 7 represents the combination of BaO and Ba on the Pd. Considering the fact that the BaO application was not optimum, and that the work function before the Ba deposition was started was in the vicinity of 1.7 eV, it should be possible to obtain values down to 1.25 eV on the Pd.

3. Heated-Substrate Depositions

For the next experiment it was decided to use a heated substrate during the deposition of the BaO.. This was done for two reasons.

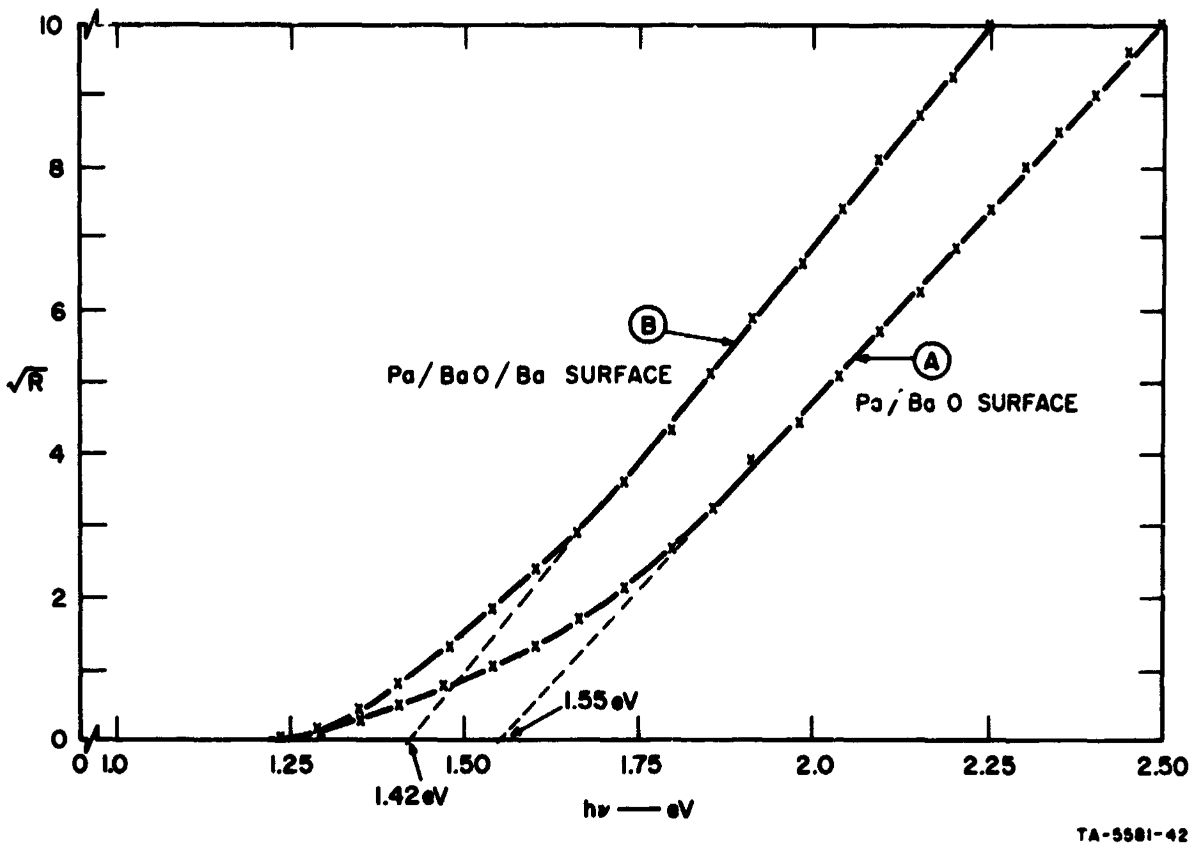

FIG. 7 SQUARE ROOT OF PHOTORESPONSE PER PHOTON AS A FUNCTION OF PHOTON ENERGY FOR Pd/BaO AND Pd/BaO/Ba SURFACES (BaO deposited on substrate at room temperature)

First of all, Russell and Eisenstein[5] report that BaO deposited below 500°C is amorphous, but is crystalline above that temperature. Also Noga[6] reports that above about 700°C there is considerable surface migration of the depositing BaO molecules, resulting in a more uniform coverage. It was reasoned that these two factors together might produce a lower work function for a thinner BaO film.

About 100 Å of Pd was first evaporated from an electron-beam gun onto a Ni substrate held at room temperature. The substrate was then heated to about 600°C and BaO was evaporated until maximum photosensitivity was obtained. Figure 8 is a plot of the square root of the photoresponse as a function of photon energy. A double intercept is observed, the lower intercept corresponding to a work function of 1.22 eV. Then Ba was slowly liberated from a Ba getter. The magnitude

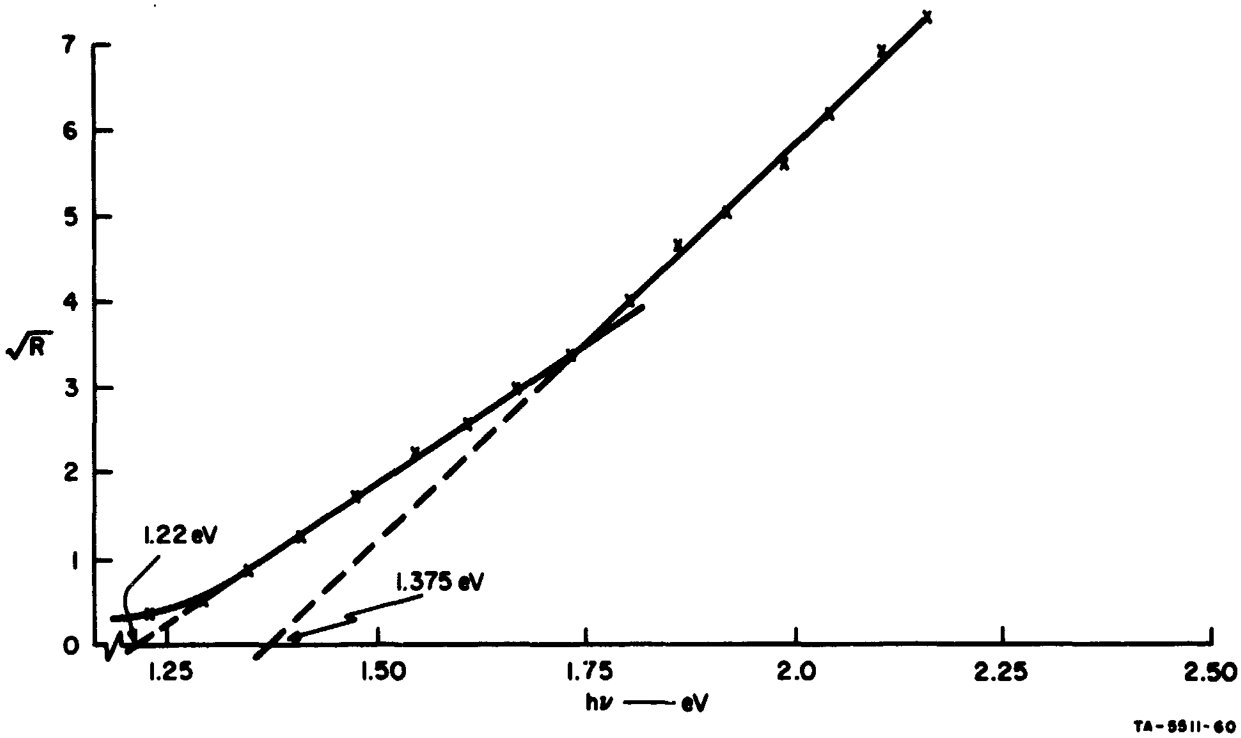

FIG. 8 SQUARE ROOT OF PHOTORESPONSE PER PHOTON AS A FUNCTION OF PHOTON ENERGY FOR Pd/BaO SURFACE
(BaO deposited on heated substrate)

of the photoresponse was observed to increase, but when the threshold data were taken, the work function was found to have increased somewhat, as can be seen in Fig. 9. It may be that a little too much barium was deposited.

It was thought that the double intercept of Fig. 8 might be due to the fact that the Pd was too thin, and some photoemission might be coming from the underlying nickel substrate. On the next experiment, therefore, the Pd evaporation step was omitted. The Ni was held at about 600°C during the BaO deposition, which was continued until a maximum photosensitivity was obtained. Figure 10 is a Fowler plot of the photoresponse indicating a work function of 1.825 eV. It was observed that the photoemission increased very rapidly with temperature about about 400°C. Figure 11 is a threshold plot for the cathode held at 785°K, indicating essentially no change in work function with temperature. The rather high work function obtained with Ni alone suggests that the 1.22 eV obtained with Pd on Ni was due to the Pd.

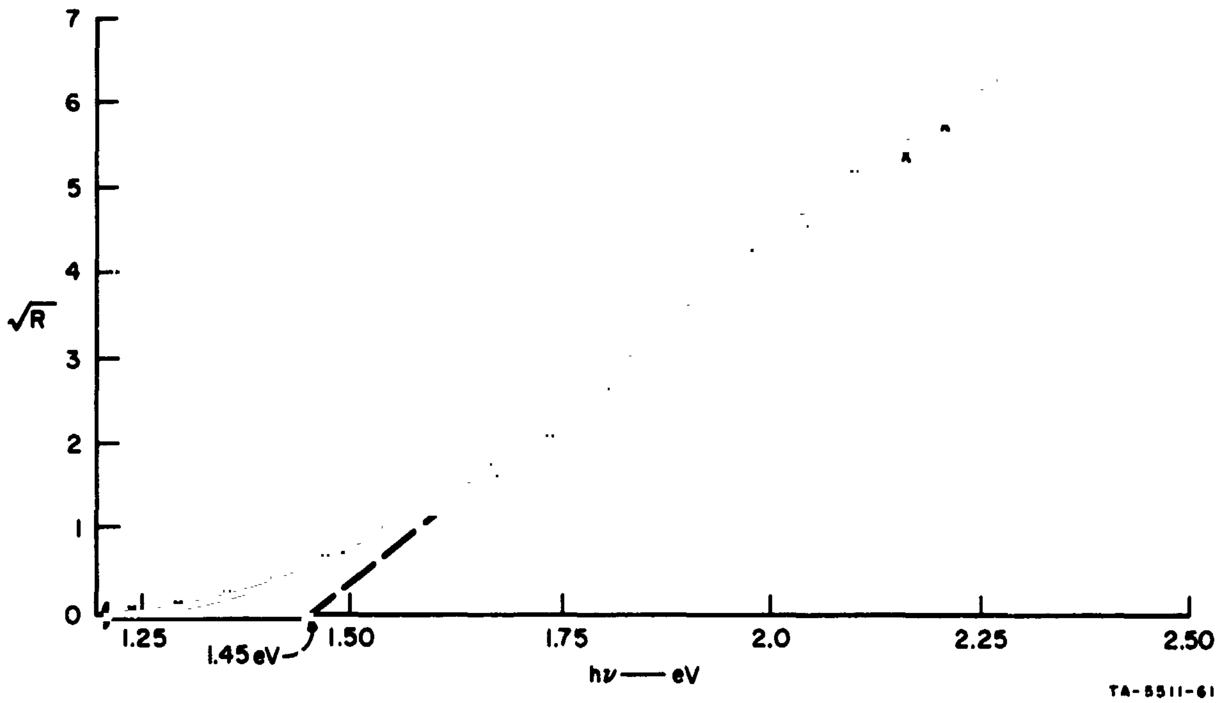

FIG. 9 SQUARE ROOT OF PHOTORESPONSE PER PHOTON AS A FUNCTION OF PHOTON ENERGY FOR Pd/BaO/Ba SURFACE
(BaO deposited on heated substrate)

C. Emission Tests

Pellets of GaP 0.070-inch in diameter were cut from a single crystal obtained from Stanford University. Ohmic contacts of Ag-Te alloy were formed on the phosphorus side of the pellets. A thick Pd grid and connecting annular deposit were then evaporated onto the polished and etched gallium side of the crystals. The technique for applying the thick Pd deposit on the small pellets was developed in the earlier work on Ti/TiO_2 structures. An I-V characteristic of the structure at this stage is shown in Fig. 12.

A simplified mounting was designed to make electrical contact to the GaP and to expose the gridded surface for a final Pd evaporation, followed by the BaO activation. A number of small Au wires were bonded to the Ag-Te alloy area; this involved heating the pellet to 200°C for 20 minutes in an inert atmosphere. This heating cycle resulted in a certain amount of degradation of the diode characteristic. When it was found that the bonds would not hold, this step was eliminated by using a pressure contact to the ohmic region.

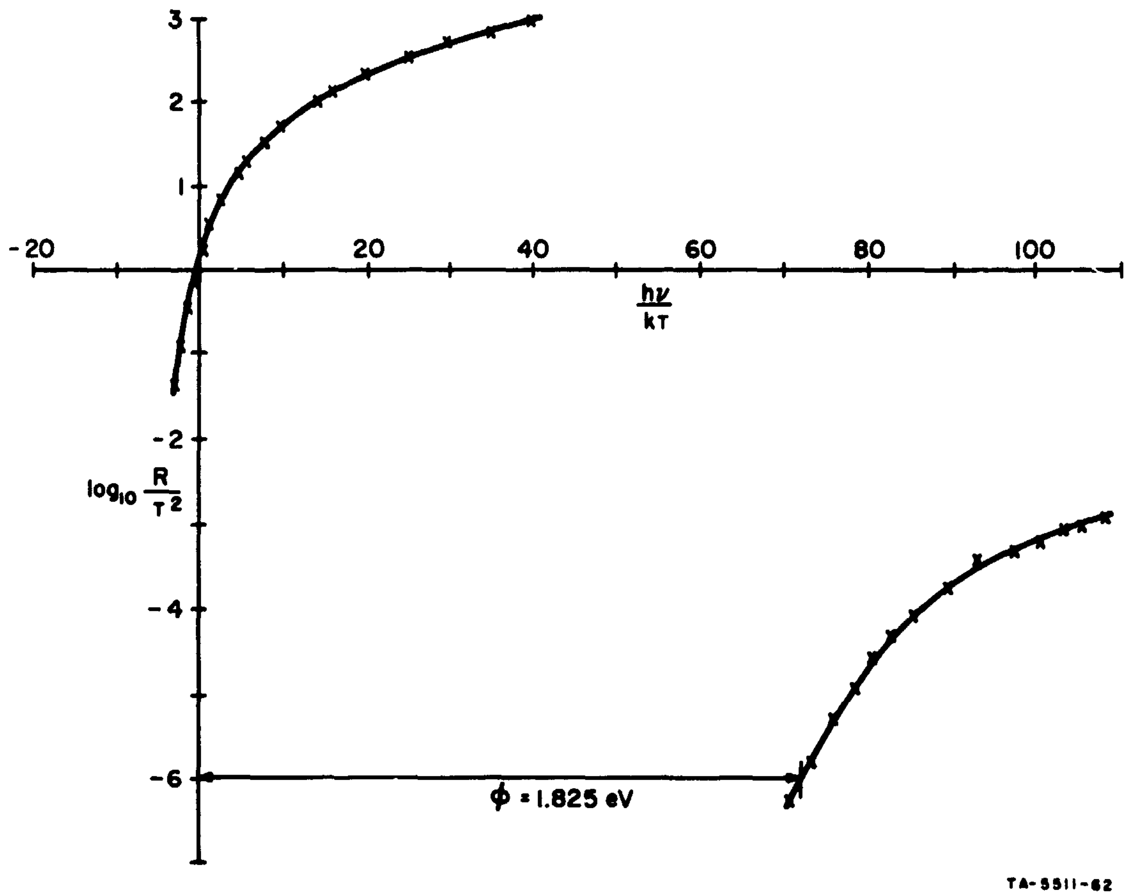

FIG. 10 FOWLER PLOT OF PHOTORESPONSE OF Ni/BaO CATHODE AT 293°K

The experiment was set up in the Vac-Ion system and baked out overnight at 150°C. The I-V characteristic following this operation (Fig. 13) indicates a considerable change in the forward current. Comparing Figs. 12 and 13, it will be seen that the metal/semiconductor barrier has apparently decreased by at least 0.2V. The addition of approximately 75 Å of Pd over the thicker Pd grid on the GaP increased the diode current slightly. The amount of Pd deposited was determined from a previous calibration which provided a thickness-time relationship for a constant level of electron beam power. The Pd surface was activated with BaO for optimum photosensitivity but the vacuum in the system was not sufficient to maintain this condition and it deteriorated within a few minutes.

No vacuum emission was observed with various levels of forward bias. When a 100 mA diode current was reached, a permanent change

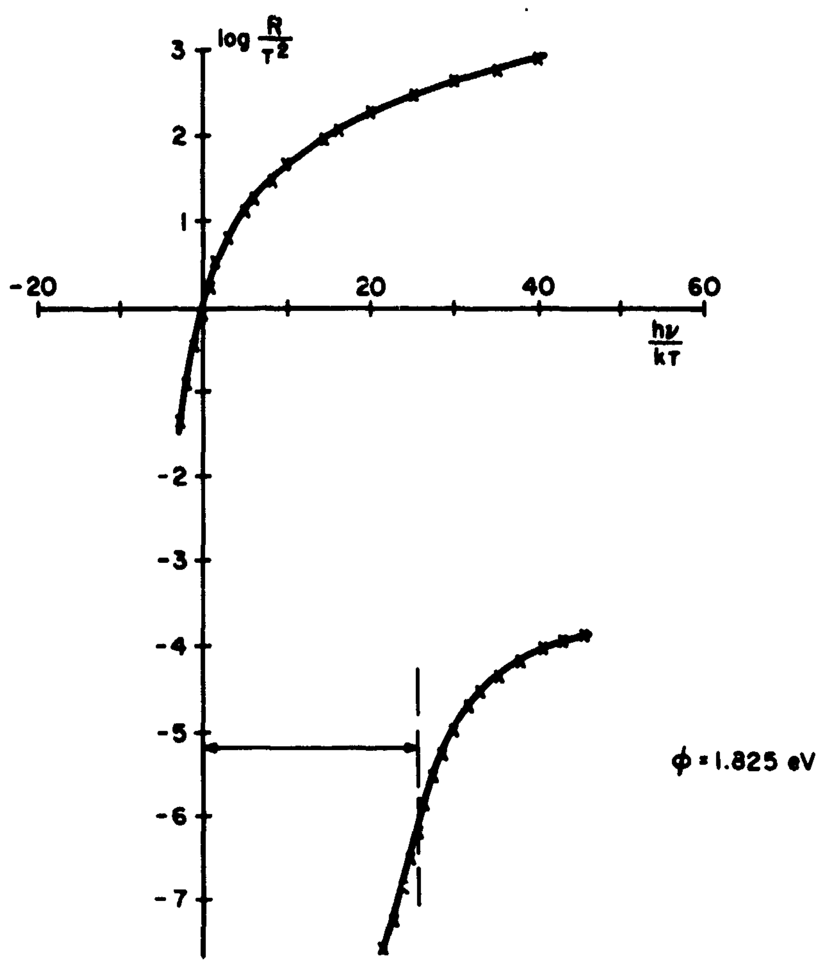

FIG. 11 FOWLER PLOT OF PHOTORESPONSE OF Ni/BaO CATHODE AT 785° K

occurred in the characteristic. A barrier height measurement was made at the termination of the experiment. The curvature of the photoelectric response in Fig. 14 suggests a nonuniform barrier (see Appendix), with some areas as low as 1.23 eV. As reported in Sec. II-A, values in the vicinity of 1.45 eV were obtained in earlier experiments. Some of the degradation was due to the heating produced by the high current, but part of it could be related to the bake-out and the bonding operation.

In a second experiment with another pellet, the bonding operation was omitted and a better vacuum was obtained following activation. The initial characteristic of this diode was not as good as the one in the first test, and again the overnight-bake-out had a deleterious effect.

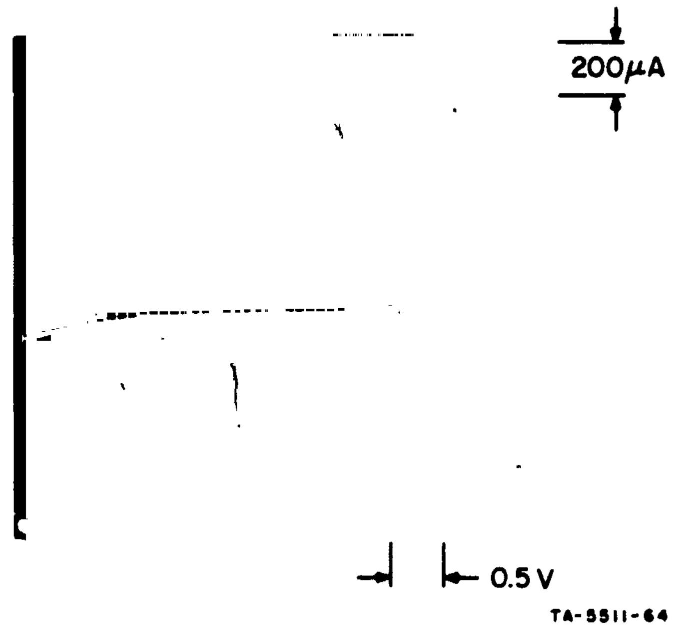

FIG. 12 I-V CHARACTERISTICS OF GaP/Pd GRID STRUCTURE PRIOR TO ASSEMBLY FOR EMISSION TEST

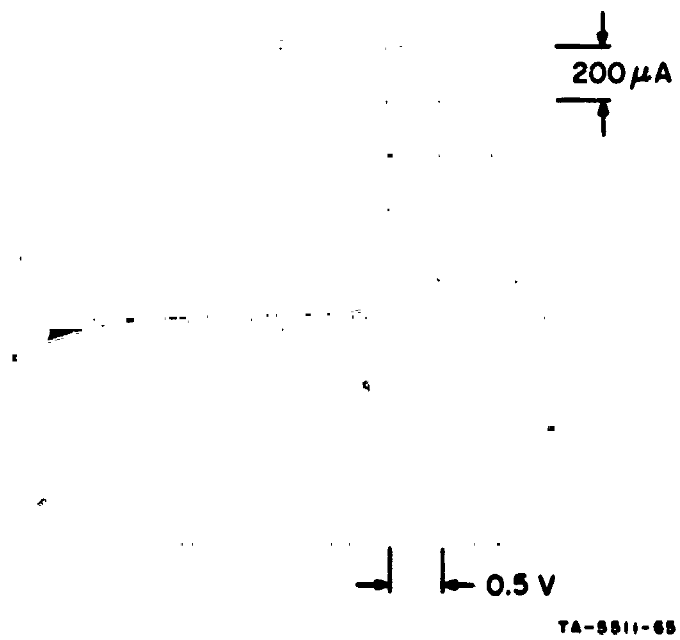

FIG. 13 I-V CHARACTERISTICS OF COMPLETED GaP/Pd STRUCTURE FOLLOWING VACUUM BAKE-OUT

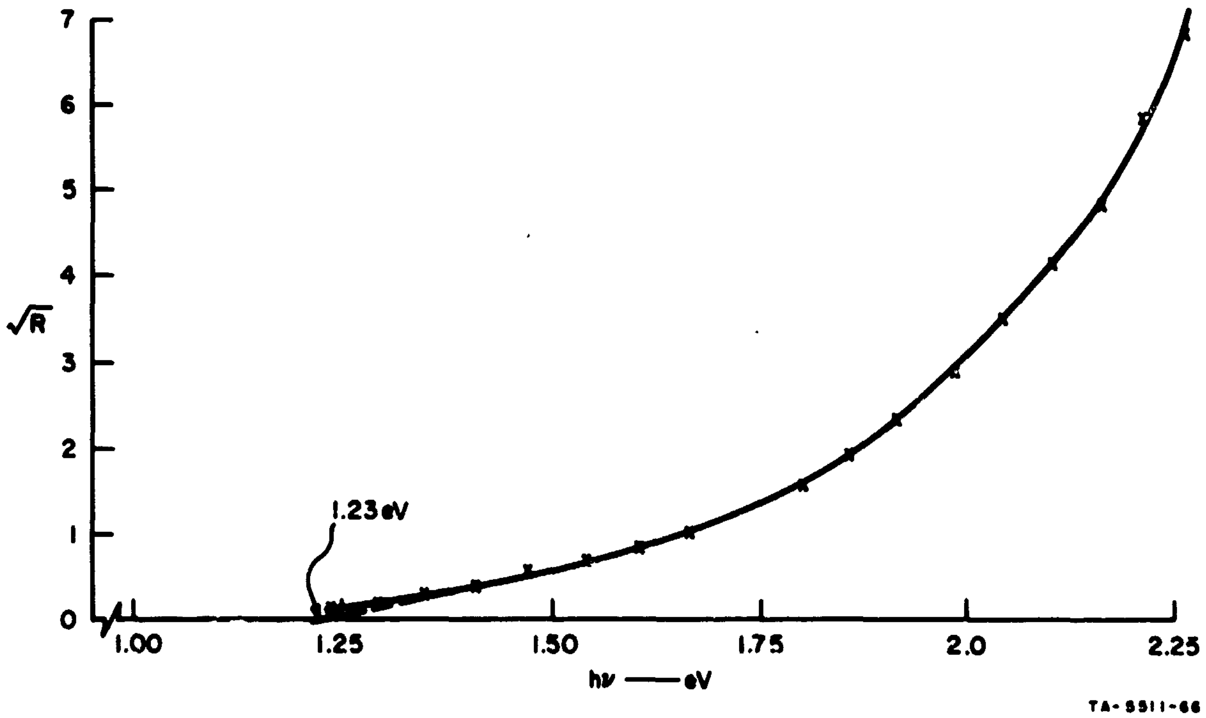

FIG. 14 SQUARE ROOT OF PHOTORESPONSE PER PHOTON AS A FUNCTION OF PHOTON ENERGY FOR GaP/Pd/BaO CATHODE STRUCTURE FOLLOWING EMISSION TESTS

No vacuum emission was obtained and it was concluded that the metal/semiconductor barriers in both tests were not uniform, having low spots which dominated when the bias was applied.

D. Transistor Cathode

A very limited amount of effort has been expended in the area of the transistor cathode. It has been decided that the first thing to do is to perform an experiment similar to that reported by Scheer and van Laar[7] but using BaO activation instead of cesium. A heavily-doped GaAs wafer has accordingly been procured, and a vacuum cleaving apparatus is being designed for the experiment. The plan is to cleave the crystal in an evaporating stream of BaO, and continue the BaO evaporation until maximum photoresponse is obtained. At this point the BaO evaporation would be discontinued, and the absolute quantum efficiency as a function of hν would be measured. If the high quantum efficiencies reported by Scheer and van Laar[7] are obtained, BaO activation would then have been proven satisfactory for the transistor cathode, at least for a heavily-doped GaAs structure.

From the standpoint of electron diffusion length, GaAs is actually a poor choice of material for the transistor cathode, L_D being only about one micron. Much longer diffusion lengths have been reported for InP. However, InP has a slightly smaller forbidden gap, 1.29 eV as compared to 1.4 eV for GaAs. Therefore lower vacuum work functions would be required for InP. It is not certain if a value equal to or less than 1.29 eV can be obtained, at least with BaO. Also, InP crystals are very limited in availability as compared to GaAs crystals. We have on hand a few InP crystals grown and supplied by Monsanto Chemical Co., St. Louis, Missouri.

Silicon would be an even better choice than InP if sufficiently low work functions could be obtained. It might be possible to obtain a work function of 1.1 eV or lower through activation with Cs_2O, although this material is not as stable as BaO.

It is interesting to speculate that the large degree of band-bending at the surface obtained with Cs activation of GaAs might not occur with BaO (or Cs_2O). In such a case the scattering near the surface might be decreased or eliminated, permitting lower doping densities to be used. This would permit higher emitter injection efficiencies to be obtained without having to resort to a large-bandgap heterojunction emitter. On the other hand, it is not clear whether the band-bending is required to obtain a low vacuum barrier. If it is, and BaO or Cs_2O do not produce band-bending, then these materials could not be used as activators. If high quantum efficiencies with GaAs/BaO are obtained with the heavily-doped GaaAs, the next step would then be to reduce the doping level of the GaAs and determine whether scattering is detrimental to the quantum efficiency. It not, then band-bending does not take place and is not required. This would be an ideal situation.

E. Life Tests

1. GaP/Pt Diode

One diode was operated for 4300 hours with 1.5V applied bias. No apparent change was observed in its characteristics during this period, but the test was terminated when a probe contact to the Pt film became intermittent. A second diode on the same GaP crystal was placed on test; after 1500 hours with 1.0V applied bias, the I-V characteristic became "soft." The current with 4.0V reverse bias increased from 50 to 700 μA. There is no obvious explanation for this degradation in performance, particularly since the test on the initial diode has been resumed with very little change in its characteristics (Fig. 15).

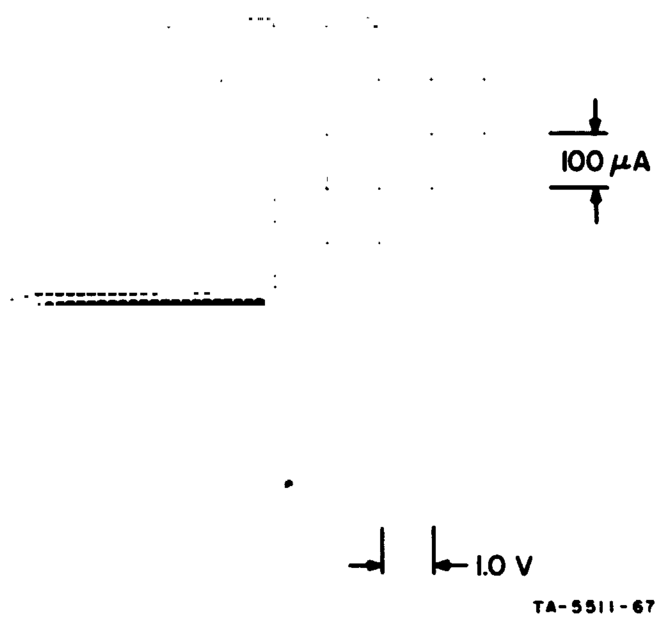

FIG. 15 I-V CHARACTERISTICS OF GaP/Pt DIODE ON LIFE TEST

2. GaP/Pd Diode

At the present time Pd appears to be a better choice for the cathode structure than Pt. Accordingly, a GaP/Pd diode has been placed on test, and will be run concurrently with the GaP/Pt test.

3. Ag/BaO Phototube

The photoelectric work function of a glass Ag/BaO phototube has been measured several times over a period of 16 months. The most recent measurement after 11,500 hours of shelf life is 1.51 eV. This value is about 0.10 eV higher than the average of reported values from previous measurements. However, the method of obtaining threshold values from the photoresponse has been modified slightly. Previous plots of $\sqrt{R}$ as a function of $h\nu$ have not been normalized with respect to energy. All such plots now represent the square root of the response per incident photon. As a result the slope of the linear portion of the plot is increased and the intercept moves to a higher value of $h\nu$. A Burroughs 5500 computer has been programmed to do the calculation and plot the results on a line printer.

The previous measurements on this tube have been analyzed by this means and the results obtained are as follows:

Initial Measurement	1.45 eV
Second Measurement	1.50 eV
Third Measurement	1.50 eV
Fourth Measurement	1.40 eV
Fifth Measurement	1.50 eV
Sixth Measurement (Current)	1.51 eV

The average of these measurements is 1.48 eV and it is interesting to note that there is less variation in these values than in those obtained by the original process.

III CONCLUSIONS

GaP/Pd surface barriers are between 1.4 and 1.5 eV high. However, the diodes we have fabricated do not follow Schottky theory. For unknown reasons, there seem to be low-barrier regions. The cause might be a nonuniform contamination at the GaP/Pd interface; such contamination could presumably arise as the result of improper preparation of the GaP surface prior to insertion in the vacuum system. Alternatively, it could arise in the vacuum system prior to the deposition of the Pd. The problem of obtaining a clean semiconductor surface in a vacuum is a severe one, as conversations with Profs. William Spicer and John Moll at Stanford University have revealed. This problem is currently under active investigation at Stanford University and elsewhere.

It has been confirmed that the deposition of a small amount of free Ba onto a metal/BaO surface reduces the work function by a few tenths of an eV. Work functions of 1.375 eV and 1.4 eV have been obtained on the structures W/BaO/Ba and Pd/BaO/Ba, respectively. It is believed that still lower work functions can be obtained by means of this technique.

The use of a heated substrate during the evaporations of the BaO has also been demonstrated to be beneficial in obtaining low work functions. In the case of Pd held at about 600°C during the BaO deposition, a work function of 1.22 eV was obtained. Unfortunately, this technique might be difficult to apply to the complete surface-barrier cathode. GaP will dissociate in a good vacuum above about 500°C, and GaP/metal surface barrier diodes would probably deteriorate at even lower temperatures. Some degradation has been noted at moderate bake-out temperatures.

The emission tests were inconclusive because of a poor vacuum in one case and a poor diode characteristic after bake-out in another case. Further emission tests are required to establish feasibility of the surface-barrier cathode approach.

IV PROGRAM FOR NEXT INTERVAL

(1) Continue investigation of GaP/Pd structures using improved techniques.

(2) Study methods of making ohmic contact to ZnS crystals.

(3) When ohmic contact problem is solved, fabricate and test various ZnS/metal diodes.

(4) Continue study of BaO activation processes.

(5) Study activation of GaAs with BaO for application to the transistor-cathode.

(6) Continue life testing of BaO phototubes and GaP diode structures.

APPENDIX A

NONUNIFORM METAL/SEMICONDUCTOR SURFACE BARRIERS

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NONUNIFORM METAL/SEMICONDUCTOR SURFACE BARRIERS

The usual theoretical treatments of metal/semiconductor surface barriers assume a constant barrier height over the entire area of the junction. In some cases the observed dependence of current and differential capacitance upon applied dc bias voltage is very close to that predicted by such a theory. We have observed cases, however, where marked deviations from theory occur. It will be shown that such deviations can be accounted for on the basis of a nonuniform barrier height over the junction area.

Consider the plot of Fig. A-1, in which the square root of the photoresponse of a GaP/W diode is plotted against the incident photon energy. The extrapolated intercept of the straight-line portion of the curve indicates a barrier height of 1.45 eV. There is an extended tail, however, down to lower photon energies. The simplest explanation for this is the existence of a distribution of barrier heights extending down to values well below 1.45 eV.

Consider next the $1/C^2$-vs.-V plot of Fig. A-2 for the same diode. The voltage-axis intercept of the straight-line portion of the curve is 1.5 eV, in close agreement with the value obtained from the photoresponse method. For forward biases, however, the differential capacitance approaches infinity at bias voltages well below that corresponding to the "barrier height." Again, the simplest explanation is that some areas of the diode have barrier heights well below 1.5 eV, and these areas dominate the measured capacitance for bias voltages approaching the lower barrier heights.

Finally, consider the current-voltage characteristics of the same diode (Fig. A-3). The current increases with voltage as $\exp(qV/nkT)$, where n is about 1.7, until series resistance begins limiting the current above about 1.0 volt. Again, this is consistent with a nonuniform barrier height, wherein the current at low bias voltages is too high

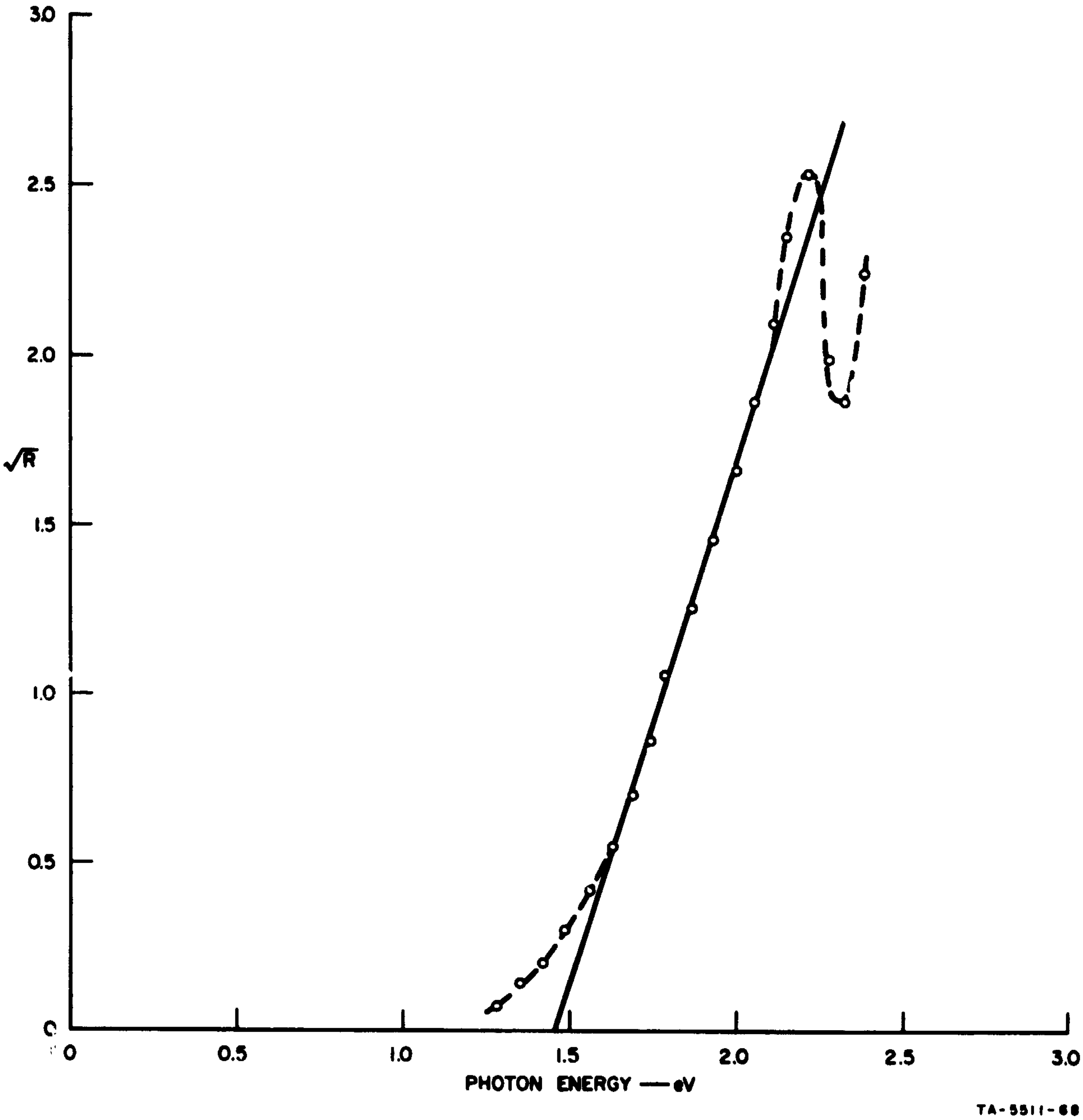

FIG. A-1 SQUARE ROOT OF PHOTORESPONSE AS A FUNCTION OF PHOTON ENERGY FOR GaP/W DIODE

because of the areas having barrier heights well below the maximum. (Series resistance would limit the current to the low-barrier areas for large forward biases.)

In an attempt to construct a theoretical model that would explain the experimental results, we have considered a diode with a continuous distribution of barrier heights. The distribution of barrier heights

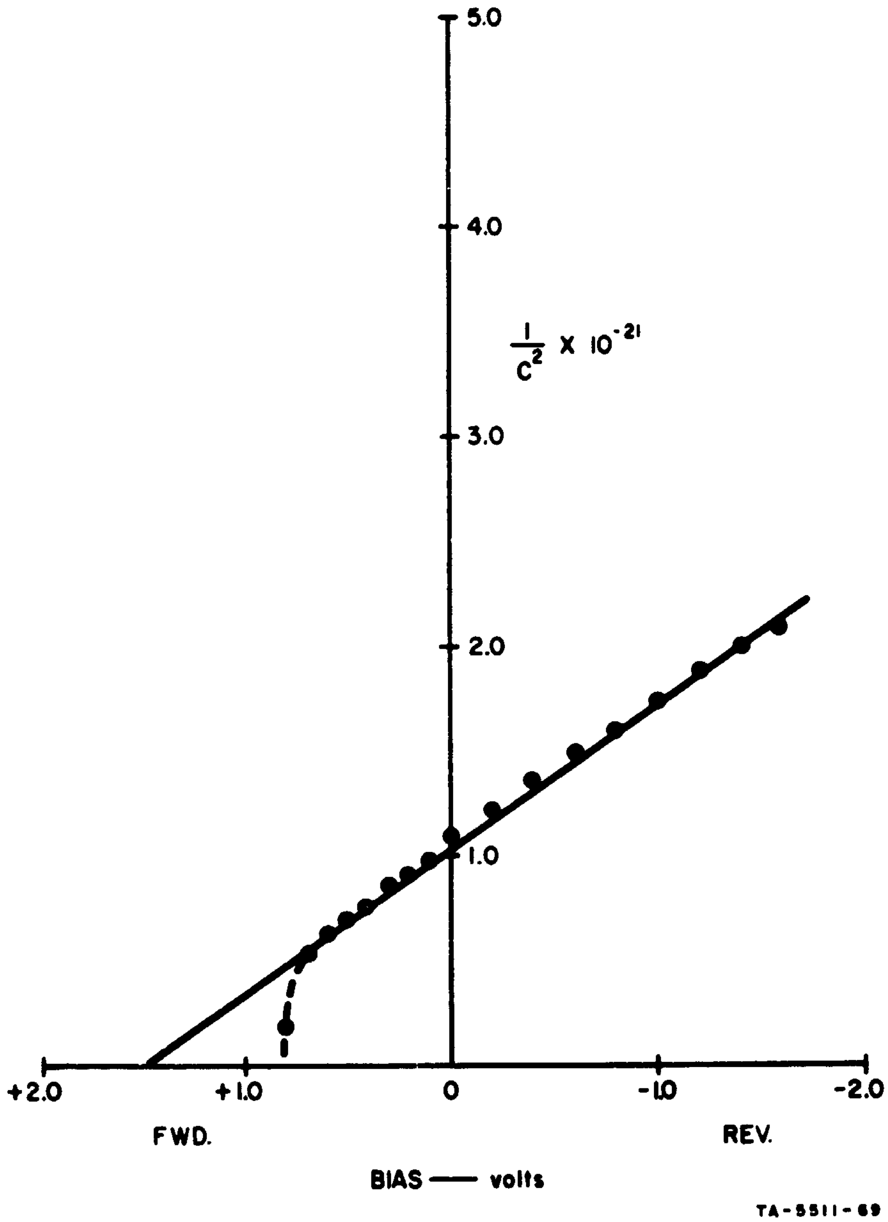

FIG. A-2 PLOT OF $1/C^2$ AS A FUNCTION OF V FOR GaP/EVAPORATED-W DIODE

is characterized by the barrier height distribution function $\Phi(\varphi)$ which is defined as follows.

The fractional area of the junction with a barrier height between φ and $\varphi + d\varphi$ is given by

$$dA = \Phi(\varphi)\, d\varphi \quad .$$

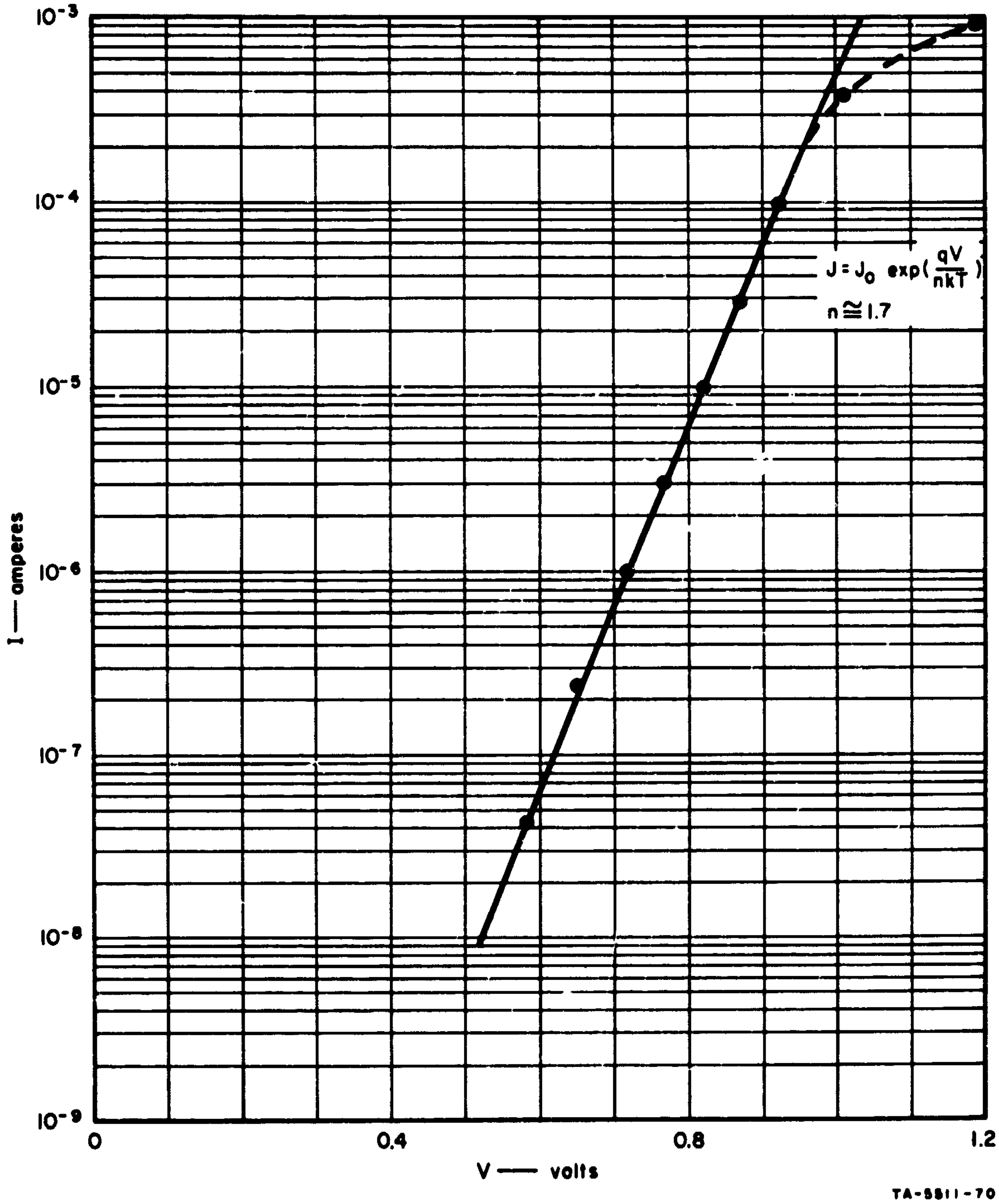

FIG. A-3 PLOT OF LOG I AS A FUNCTION OF V FOR GaP/EVAPORATED-W DIODE

Defined in this way, the function $\Phi(\varphi)$ is simply a probability density function on φ and is normalized so that

$$\int \Phi(\varphi)\, d\varphi = 1 \quad .$$

We now consider a junction in which the current density, as a function of barrier height and applied voltage, is given by the solution of the transcendental equation

$$J = A\,T^2\, e^{\frac{-e\varphi}{kT}}\, e^{\frac{e}{kT}(V - \rho\Delta J)} - 1$$

where

ρ = Resistivity of semiconductor

Δ = Effective thickness of semiconductor

V = Applied voltage.

If we express the solution of this equation as

$$J = J(V,\varphi)$$

then the average current density of the junction is given by

$$\bar{J}(V) = \int J(V,\varphi)\ \Phi(\varphi)\ d\varphi \quad .$$

We have computed $\bar{J}$ as a function of applied voltage V for the case where the barrier-height distribution function $\Phi(\varphi)$ is gaussian, with the form

$$\Phi(\varphi) = (2\pi\sigma^2)^{-1/2}\ \exp -(\varphi - \varphi_o)^2/2\sigma^2$$

where

φ_o = Average barrier height

σ^2 = Variance of barrier height distribution.

In Fig. A-4 we have plotted J_{ave} as a function of applied voltage for a sequence of cases with the same average barrier height but with varying variance. It is clearly apparent from these curves that a diode with even a very narrow distribution of barrier heights will have a current-voltage characteristic that differs substantially from the

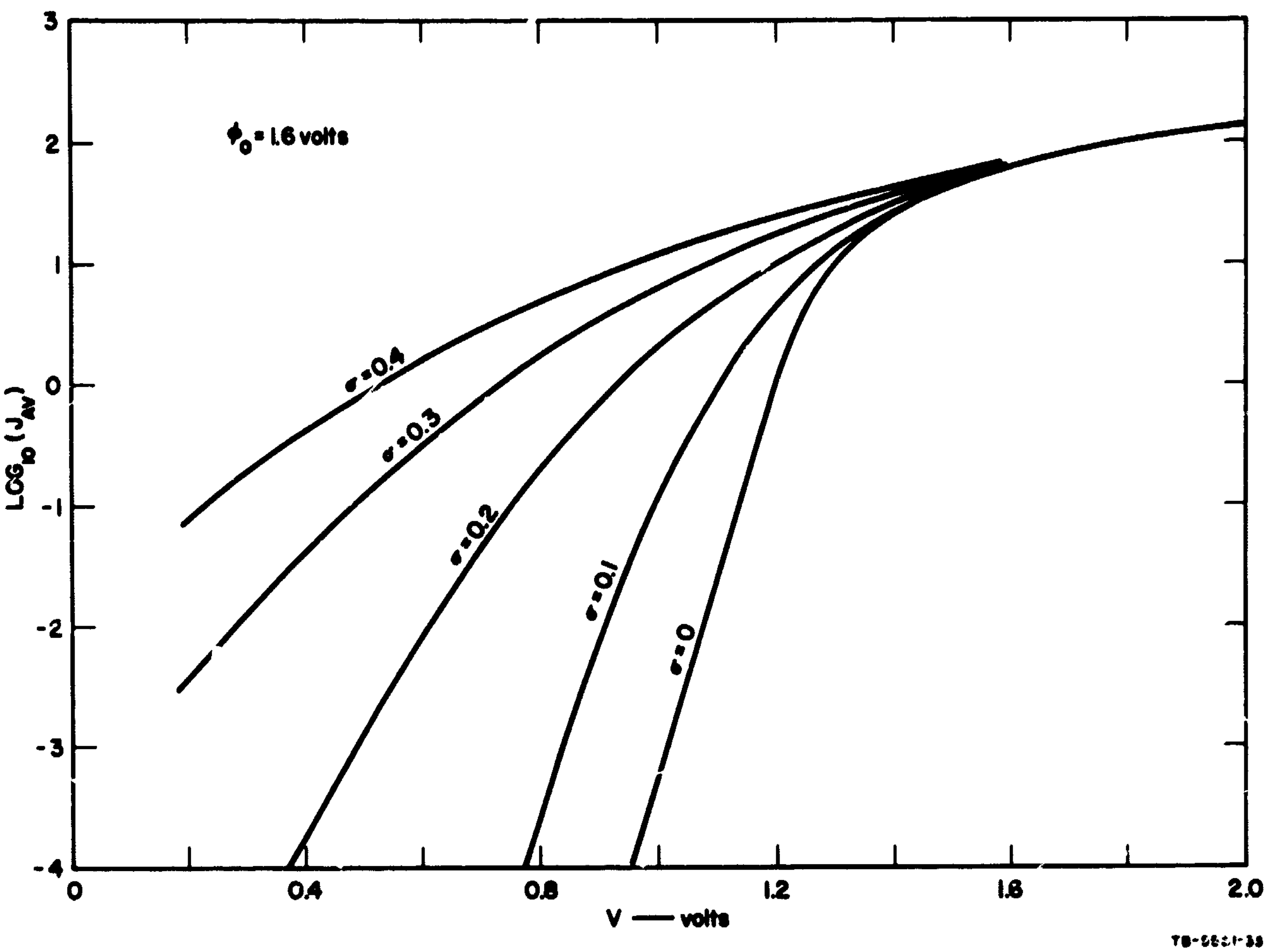

FIG. A-4 PLOTS OF J_{av} AS A FUNCTION OF APPLIED VOLTAGE FOR DIFFERENT VALUES OF VARIANCE

current-voltage characteristic of a diode with uniform barrier height. In particular, the current increases more slowly with bias voltage than for the case of a uniform barrier.

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GaP/Pd surface-barrier diodes have been fabricated and tested for possible application to the surface-barrier cathode, Barrier heights of about 1.4 eV were measured by plots of $1/C^2$ as a function of V and photothreshold plots. The data suggest, however, that the barriers are not of uniform height, some regions having lower barrier heights than the nominal value. The current-voltage characteristics of the diodes also deviated from Schottky theory. The current at low forward-bias voltages was too high, which is again indicative of low-barrier regions.

The photothreshold response of W/BaO and Pd/BaO with a small amount of free Ba deposited on the surface have been studied. In both cases a reduction of work function was obtained by the addition of a small amount of Ba onto the surface. In the case of W/BaO/Ba a work function of 1.375 eV was obtained. The system Pd/BaO/Ba produced a work function of 1.42 eV, compared to about 1.7 eV for the Pd/BaO alone (measured after over-activation).

The effects of a heated substrate were studied during the deposition of BaO on Pd and on Ni. In the case of Pd held at about 600°C during the BaO evaporation, a double intercept was obtained on a Fowler plot (square root of photoresponse vs. hν), the lower intercept corresponding to a work function of 1.22 eV.

Emission tests were conducted on the system GaP/Pd/BaO. In the first test (for unknown reasons) the vacuum was not good and good BaO activation could not be obtained. On the second test the I-V characteristics of the GaP/Pd diode indicate low-barrier regions, and no emission was observed. Preliminary steps have been taken to evaluate the transistor cathode using p-n junctions of GaAs, InP, or Si.

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surface barrier						
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