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ELECTRIC FIELD DEPENDENCE OF GaAs SCHOTTKY BARRIERS*

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Abstract—The bias dependence of the photoelectric barrier energy of *n*-GaAs–Al diodes has been measured. The devices were fabricated by cleavage of the GaAs in an evaporating stream of metal in a vacuum of 10^{-8} torr. The barrier energies at various bias levels were determined by extrapolation of the photoresponse vs. photon energy plots. The electric field dependence of the photoresponse was also measured at constant photon energy. The calculated change in barrier energy from the latter method was then compared with the changes in extrapolated values of barrier energy. A small systematic disagreement was observed and attributed to the effects of collection efficiency in the GaAs. The field dependence of Schottky barriers on 5×10^{16} GaAs was found to be in good agreement with that expected from the exponential charge distribution associated with the surface states which determine the barrier energy.

Résumé—La dépendance de polarisation de l'énergie de barrière photoélectrique des diodes *n*-AsGa–Al a été mesurée. Les dispositifs ont été fabriqués par le clivage de l'AsGa dans une vapeur évaporante de métal dans un vide de 10^{-8} torr. Les énergies de barrière à divers niveaux de polarisation ont été déterminées par extrapolation des courbes photoréponse/énergie de photon. La dépendance de champ électrique de la photoréponse a aussi été mesurée à une énergie de photon constante. Le changement calculé de l'énergie de barrière par la dernière méthode a été comparé aux changements dans les valeurs extrapolées d'énergie de barrière. Un petit désaccord systématique a été observé et a été attribué aux effets du rendement de collection dans l'AsGa. La dépendance de champ des barrières Schottky sur le AsGa à 5×10^{16} s'est accordée avec celle prédite par la distribution de charge exponentielle associée aux états de surface qui déterminent l'énergie de barrière.

Zusammenfassung—Die Abhängigkeit der photoelektrischen Sperrschichtenergie von *n*-GaAs–Al-Dioden von der angelegten äusseren Spannung wurde gemessen. Die Bauelemente wurden durch Spalten von GaAs in einem Strahl verdampfenden Metalls unter einem Vakuum von 10^{-8} torr hergestellt. Die Sperrschichtenergien bei verschiedenen Vorspannungen wurden durch Extrapolation der Kurven gewonnen, welche den Photostrom als Funktion der Photonenenergie zeigen. Die Abhängigkeit des Photostroms von der äusseren Spannung bei konstanter Photonenenergie wurde ebenfalls gemessen. Die daraus berechnete Änderung der Sperrschichtenergie mit der Vorspannung wurde dann verglichen mit dem durch die erwähnte Extrapolation gewonnenen Wert. Dabei ergab sich eine kleine systematische Unstimmigkeit, die dem Verhalten der Sammeleffektivität im GaAs zugeschrieben wurde. Die Feldabhängigkeit von Schottky-Sperrschichten auf 5×10^{16} dotiertem GaAs wurde in guter Übereinstimmung mit dem auf Grund der Oberflächenzustände und der zugehörigen exponentiellen Ladungsverteilung erwarteten Wert gefunden.

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THE VACUUM work function at a clean metal surface is known to be lowered by an electric field terminating on the metal. For a microscopically homogeneous surface the principal effect is due to the electron image charge in the metal. It has been generally assumed that a similar effect should be present at the interface between a metal and a semiconductor or insulator. However, only indirect or inconclusive evidence has been available until recently. In 1964 SZE *et al.*[1] reported the field dependence of gold barriers on a chemically prepared Si surface. Their results were in quantitative agreement with the image model if the Si dielectric constant of 12 was used. More recently, measurements on the Al–SiO_2 interface[2] showed an image lowering consistent with the optical dielectric constant of the SiO_2 and an additional contribution due to the penetration of the electric field into the Al.

Surface barriers on GaAs are of considerable interest, since, in contrast to the cases noted above, the barrier energies are dominated by a high density of surface states.[3] It might be expected that the presence of these states would have considerable influence on the field dependence of the carrier energy.[4]

The Schottky barriers reported here consisted of approx 150 Å of Al on *n*-type GaAs with a donor concentration of $5 \times 10^{16}/cm^3$. The GaAs was cleaved on the 110 plane in an evaporating stream of aluminum at 10^{-8} torr in an ion pumped vacuum system.

The actual diodes were then made by isolating areas approx 10^{-4} cm^2 on the freshly cleaved surface. Only those with leakage currents less than 10^{-9} A at -1 V were considered acceptable. The photoresponse was determined by focusing a beam of 50 c/s chopped monochromatic light onto the barrier area and using a phase sensitive detector to measure photocurrent.

Two methods[1] for determining the shifts in the barrier energies with electric field were employed. The first involves plotting the square root of the photocurrent normalized to the incident photon flux vs. energy of incident photons and extrapolating the curves thus obtained to the energy axis thereby obtaining a measure of the barrier energy. The general relation is of the form

$$I = C(h\nu - \varphi)^2 \quad (1)$$

where I is the photocurrent, C a constant of proportionality, $h\nu$ the energy of incident photons and φ the barrier energy. Several such extrapolations at different bias voltages can be used to measure the actual barrier energy as a function of electric field. Figure 1 illustrates this technique.

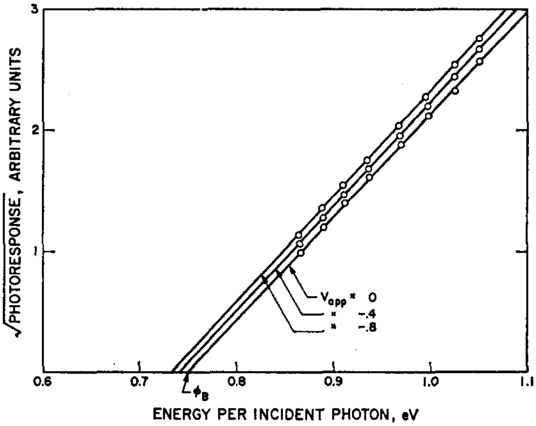

FIG. 1. Photoresponse vs. incident photon energy for various sample bias conditions (sample temperature = 300°K).

In order to achieve the required accuracy, all data reduction was done numerically and plotted directly by the IBM7094/40 computer system.

In the second approach the photon energy is held constant and the photocurrent is measured as a function of bias voltage. From the dependence of the photocurrent on the bias voltage the change in barrier energy can be inferred provided that C, the proportionality constant in equation (1), is not field dependent. The results of the two measurements are shown in Fig. 2.

It can be seen that the barrier lowering calculated from the bias dependence of the photocurrent differs only slightly from that obtained by the extrapolation of the square root of the photocurrent vs. photon energy. It may be inferred from this result that the collection efficiency over the range investigated is only slightly field dependent.

Samples with excess leakage current gave apparent lowering considerably larger than those reported here, and only by the exercise of extreme care in the sample preparation could reproducible results be obtained.

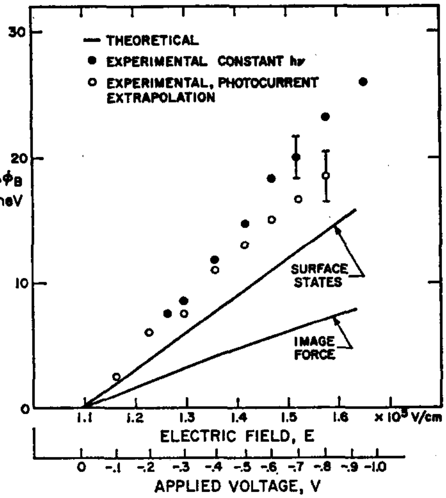

FIG. 2. Shift in barrier energy vs. maximum electric field in the barrier depletion region.

Larger field dependence of the barrier energy as measured by both techniques was observed in the case of forward bias and in reverse bias when appreciable increase in the leakage current was evident. The constant $h\nu$ method was more sensitive to errors of this nature than the extrapolation procedure. These effects were much larger than could be accounted for by changes in sample impedance, and are not at present understood. However, it may be remarked that a very small modulation of the d.c. leakage current by the chopped light could give apparent photoresponse of the same order as that due to photoinjection from the metal.

Of the possible sources of field dependence of the barrier energy which have been discussed,[1,2,4] the major contribution in the present case should arise from the penetration of charge in the GaAs surface states into the crystal,[4] as illustrated in Fig. 3.

The average volume charge density[4] of these states can be written

$$\rho = \frac{qN}{d}\exp(-x/d) \tag{2}$$

where q is the electronic charge, N the number of surface states per unit area, and d the penetration distance of the surface state. PADOVANI and STRATTON[5] have measured the electron energy vs.

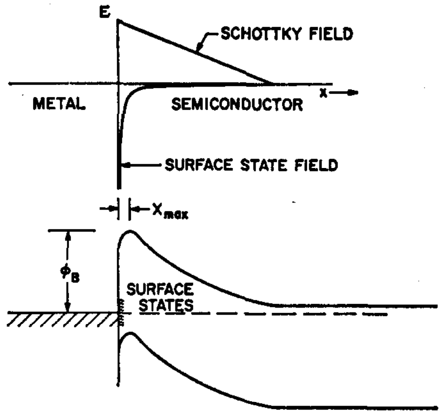

FIG. 3. Electric field and potential resulting from the surface states in the Schottky barrier depletion region.

wave vector (k) and have found k to be 10^{-1} Å^{-1}, nearly constant near the center of the band gap. Using this value of k, $d = 5$ Å in equation (2) since the charge density is proportional to the square of the wave function. Here we have assumed that the bulk of the charge results from surface states with energies near the center of the gap.[3] If states of lower energies were involved, a larger effect would be obtained. For values of electric field, E, less than 10^6 V/cm, the location of the potential maximum, x_{max}, obtained by superimposing the ideal Schottky field and the surface state field is very nearly

$$x_{max} = d \log_e \frac{qN}{\epsilon E} \tag{3}$$

where ϵ is the permittivity of the GaAs. The resulting barrier shift, $\Delta\phi$, is to an excellent approximation

$$\Delta\phi = -Ex_{max}. \tag{4}$$

Since the position of the potential maximum is logarithmic in the field, the effect of the image charge is merely to add a small additional barrier lowering which is nearly independent of field. The effect of field penetration into the metal should be negligible because of the surface states,[6] and even if present would not contribute appreciably at the fields encountered here.

A detailed calculation of the surface state lowering, including the effect of the image charge was done on an IBM7094 computer, using $N = 3 \times 10^{14}$ cm^{-2}. The potential used was that due to the surface states [equation (2)], and the bulk donor charge density assumed constant. For these contributions the static dielectric constant (assumed here to be $E_{static} = 13.5\ E_0$) was used. In addition the standard image potential was computed using the optical value of the dielectric ($E_{opt} = 11.5\ E_0$) and then added to obtain the total potential. Typical values of x_{max} obtained were 45 Å for a donor density of 5×10^{16}. These distances are sufficiently large that the image potential approximation should be valid. The results of this computation were labeled 'Surface State' in Fig. 2. The lowering expected from the simple image force alone is shown for comparison. In all cases the barrier energy at zero applied voltage φ_0 is used as a reference.

CROWELL and SZE[7] suggested that backscattering of electrons by optical phonons in the GaAs can appreciably reduce the collection efficiency of the barrier. Such reduction stems from the scattering of electrons coming from the metal before reaching the potential maximum in the semiconductor.

In their analysis the probability of an electron reaching the potential maximum, x_{max}, is given by

$$P = \exp\left(-\frac{x_{max}}{L}\coth\frac{E_0}{2kT}\right) \tag{5}$$

where L is the mean free path for generation of optical phonons in GaAs and E_0 is the optical phonon energy.

The field dependence of P is thus determined from x_{max} and the photocurrent takes the form

$$I \propto (h\nu-\varphi)^2\exp\left(\frac{d}{L}\coth\frac{E_0}{2kT}\right). \tag{6}$$

By varying the field in the barrier region, the location of the potential maximum is changed, and consequently a change in the collection efficiency will result.

Incorporating this additional field dependence with $L = 58$ Å[8] and $E_0 = 0.035$ eV respectively, the barrier shifts from constant photon energy measurements are reduced approx 20 percent in excellent agreement with the values obtained from the extrapolations.

It can be seen that the results of both methods are in fairly good agreement with the surface state model. The effects of tunneling and surface state filling have been estimated and are small compared to the field dependence observed under the present conditions. The presence of traps or deep levels would tend to increase the field near the interface and possibly account for occasional anomalously greater barrier energy shifts.

For these diodes φ was 0.75 eV as measured by the photoresponse extrapolation (see Fig. 1). Capacitance measurements give a value for the diffusion potential of 0.72 eV and I–V characteristics were similar to those reported by PADOVANI and SUMNER.[9]

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