Electrical Properties of Nickel-Low-Doped n-Type Gallium Arsenide Schottky-Barrier Diodes

REUBEN HACKAM AND PETER HARROP

Abstract—The forward current characteristics of nickel-low-doped n-type gallium arsenide Schottky-barrier diodes are measured over the temperature range 90.5–434 K. The ideality factor and its temperature dependence is determined and found to decrease with increasing temperature according to the relationship $n(T) \approx 11.4T^{-1/2} + 0.444$ to within ± 4 percent. This is in agreement with the theoretical analysis of Strikha, who predicted a temperature dependence law between T^{-1} and $T^{-1/2}$. The barrier height is determined from both the saturation current and the capacitance methods. A modification is made to the forward current expression, which results in good agreement between the values of the barrier height obtained from both methods over a wide temperature range. The barrier height is found to decrease with increasing temperature at a rate of 5.8×10^{-4} V/K. Comparison with the dependence of the energy gap on temperature in GaAs suggests that the observed change in the barrier height is equal to that of E_g.

I. Introduction

IN RECENT YEARS there has been considerable interest in the study of metal–semiconductor Schottky-barrier diodes, primarily for their superior performance as microwave mixers and also because they are increasingly being used to improve the fast switching of high-frequency transistors. The study of the dependence of the Schottky diode characteristics on ambient temperature is important for practical applications and for understanding the current conduction mechanisms involved.

A careful survey of the literature reveals that there are conflicting measurements concerning the dependence on temperature of both the ideality factor n and the barrier height ϕ_B in Schottky diodes. Padovani and Sumner [1] reported that in Au n-type GaAs Schottky diodes n decreased with increasing temperature, while the measurements of the barrier height from the capacitance method and the saturation current yielded values in agreement with each other and independent of temperature. In order to reconcile the modified Richardson constant obtained from the activation energy plots with the accepted literature value, Padovani [2] concluded in a later publication that ϕ_B should decrease linearly with increasing temperature, while Crowell and Rideout [3] theoretically predicted that n values in GaAs Schottky diodes should be strongly dependent on temperature. Spitzer and Mead [4[did not observe a dependence on temperature in the measured values of ϕ_B. For Cr and Ni–GaP, Nannichi and Pearson [5] found that the ideality factor was constant at $n=1.1$ in the range 25–500°C, while ϕ_B decreased with increasing temperature. In silicon, Cowley and Zettler [6] found that both ϕ_B and n had the same values at 77, 196, and 289 K. Cowley [7] also observed a small change in ϕ_B with increasing temperature that is considerably less than that observed by Arizumi and Hirose [8], Crowell, Sze, and Spitzer [9], and Saxena [10], who observed very strong dependence on temperature. Kahng [11] reported that the capacitively determined ϕ_B has negligibly small temperature dependence, while a large dependence on the temperature was found when the barrier height was determined from photoelectric techniques. Yu and Snow [12], on the other hand, observed that, in silicon, n depends on the forward bias voltage. At low voltage, n decreased with increasing temperature while at higher bias n was independent of temperature [12]. Levine [13] also suggested that both ϕ_B and n should depend on the bias voltage. In both nickel–silicon and gold–silicon Schottky diodes, Padovani [14] found that the values of the barrier height determined from the capacitance method were higher at 300 K than the corresponding values at 77 K, suggesting a positive temperature dependence in ϕ_B with increasing temperature. This is in disagreement with the negative temperature dependence reported for ϕ_B [3], [8], [9] and the energy gap E_g [9] in silicon. The activation energy plots in Au–Si and Ni–Si were straight lines yielding a value of ϕ_B, independent of temperature, which was considered [14] in good agreement with the values deduced from the capacitance measurements. Padovani [14] found that a temperature dependence in ϕ_B similar to that of the energy gap must be invoked to reconcile the Richardson constants obtained from the plots with the accepted literature values.

In the present contribution, new measurements are reported concerning the temperature dependence of both the barrier height and the ideality factor in nickel-low-doped n-type gallium arsenide. As far as it is known no such study is available either in Ni n-type GaAs or in any metal–gallium arsenide barrier diodes. The present results lead to a modification of the forward current equation. This modification enables the measurements of the barrier height from both the capacitive method and the saturation current to be reconciled at all ambient temperatures.

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II. Theory

A. Forward Current Conduction

For low-doped Schottky-barrier diodes the dependence of the forward current I on the applied voltage V is given by the expression [15]

$$I = I_s\left[\exp\left(\frac{eV}{nkT}\right) - 1\right] \tag{1}$$

where n is a dimensionless factor introduced in order to allow for deviation from ideality. This deviation arises from the presence of an interfacial dielectric layer between the metal and the semiconductor and from surface charges and image force effects; e is the electronic charge, k is Boltzmann's constant, T is the absolute ambient temperature at which the diode is held, and I_s is the saturation current represented by [15]

$$I_s = A^{**}ST^2 \exp\left(-\frac{e\phi_B}{kT}\right) \tag{2}$$

where A^{**} is the modified Richardson constant, S is the area of the diode, and ϕ_B is the barrier height. The ideality factor n is determined, at each temperature, from the slope of the linear plots of $\log_e I$ against V using (1). The slope of the forward characteristics is measured for $V \gg 3nkT/e$. I_s is determined by the extrapolation from higher forward bias voltage to zero voltage of the $\log_e I$ versus V plots.

It is proposed here that the ideality factor n should also be included in the expression for the saturation current. This is because the effects that cause deviation from $n=1$ at higher bias voltage are also present at zero bias voltage. In particular, the interfacial layer that has by and large the strongest effect on n, but also the image force and surface charges that will be present at zero voltage. The mere reduction of the applied voltage to zero does not result in the elimination of these effects. The expression for the forward current should now read

$$I = A^{**}ST^2 \exp\left[-\frac{e\phi_B}{n(T)kT}\right] \cdot \left[\exp\left(\frac{eV}{n(T)kT}\right) - 1\right]. \tag{3}$$

$n(T)$ is temperature dependent. The barrier height is determined, at each temperature, from I_s according to

$$\phi_B = \frac{n(T)kT}{e}\log_e\left[\frac{A^{**}ST^2}{I_s}\right]. \tag{4}$$

It will be shown later that the argument for inclusion of n in the expression of I_s is also supported by: 1) the agreement in the measured values of ϕ_B using both the capacitive method and the saturation current obtained from (4); and 2) the resultant ϕ_B following a temperature dependence law nearly equal to that of the energy gap in GaAs.

B. Determination of the Barrier Height from the the Capacitance Measurements

The dependence of the barrier capacitance C on the applied bias voltage is given by [16]

$$\frac{1}{C^2} = \frac{2}{S^2 \cdot e \cdot \epsilon_0 \cdot \epsilon_r (N_d - N_a)}(V_d - V) \tag{5}$$

where ϵ_0 is the permitivity of free space, ϵ_r is the dielectric constant of gallium arsenide, N_d is the donor concentration, N_a is the acceptor concentration, and V_d is the diffusion voltage. It will be observed that V_d can be determined from a plot C^{-2} versus V. Extrapolation of the linear plot, in accordance with (5), to the horizontal axis where $1/C^2 \rightarrow 0$, at each temperature, yields the diffusion potential. The barrier height, at various temperatures, is determined from [15]

$$\phi_B = V_d + \phi_F \tag{6}$$

where ϕ_F is the position of the Fermi level relative to the bottom of the conduction band and is given by

$$\phi_F = \frac{kT}{e}\log_e\left(\frac{N_c}{N_d}\right). \tag{7}$$

N_c is the electron density in the conduction band. The change in N_c with temperature variation is calculated assuming a dependence law of $T^{3/2}$ [17]. A more rigorous analysis by Sze *et al.* [15], [16] for the barrier height expression, which is used in the present work, gives

$$\phi_B = V_d + \phi_F + \frac{kT}{e} - \Delta\phi \tag{8}$$

where $\Delta\phi$ is the image force lowering of the barrier, equal to about 20 mV [18].

III. Details of the Schottky-Barrier Diodes and Experimental Procedure

Nickel is deposited under high vacuum on n-type epitaxial GaAs wafer, oriented in the ⟨100⟩ crystallographic directions and doped to a concentration of 1×10^{16} cm^{-3}. The n$^+$ layer is doped to 10^{18} cm^{-3}.

The forward current–voltage characteristics are measured using a stabilized power supply (stability better than ± 0.01 percent) and a current-limiting resistance of 500 Ω. The applied voltage is measured using either a digital voltmeter having an input resistance of 5×10^9 Ω and an accuracy of ± 0.05 percent; or when very low currents ($<10^{-10}$ A) are monitored, an electrometer is used having a very high input resistance of 10^{14} Ω and an accuracy of better than ± 1 percent. The current flowing in the diode is monitored with an accuracy of better than ± 2 percent. The ambient temperature of the diode is measured to an accuracy of ± 0.2°C. In order to eliminate photoelectrically excited currents all measurements are taken with the diode in complete darkness. The capacitance of the diode is measured at different frequencies at an estimated maximum error of about ± 2 percent.

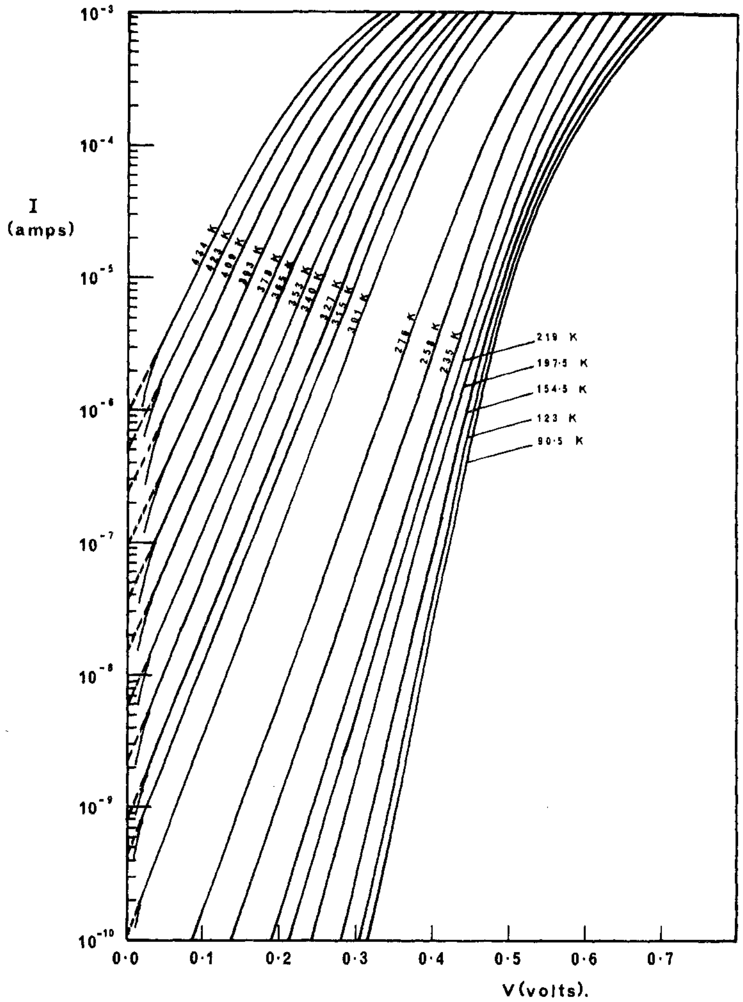

Fig. 1. Dependence on temperature of the forward characteristics of Ni-low-doped n-type GaAs diodes.

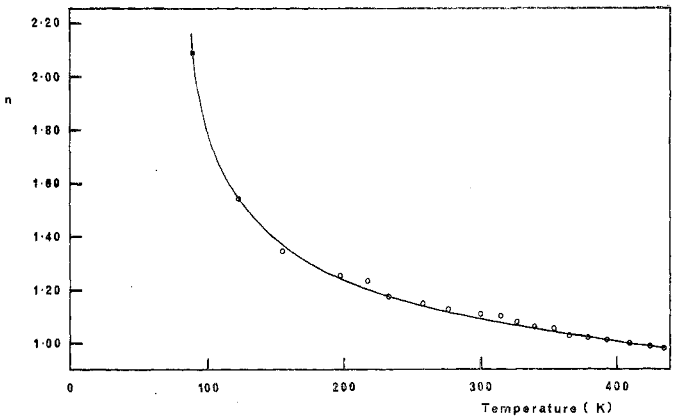

Fig. 2. Variation of the ideality factor with temperature.

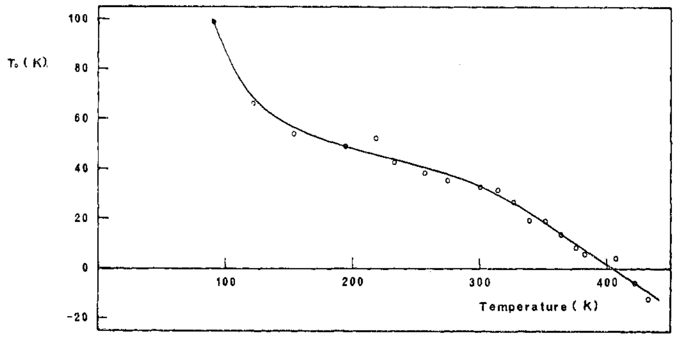

Fig. 3. T_0 versus temperature.

IV. Results and Discussions

A. The Ideality Factor n

Fig. 1 shows semilog plots of the forward current–voltage characteristics of a Ni-low-doped n-type GaAs Schottky-barrier diode. These measurements are repeated in different diodes and the characteristics are reproducible to within the experimental errors.

It will be observed that the plots are linear over a wide range of current values. Typically, at 301 K, the plot is linear over six decades of current. At high current values, the plots are curved slightly downward where a presence of the finite resistance of the diode becomes noticeable and causes a reduction in the current through the diode for a particular applied voltage. It will be observed that the curving in the plots is more pronounced, and appears at gradually decreasing currents, as the temperature is decreased. At very low temperatures (<200 K) it is observed that the experimental I–V characteristics tend to become independent of temperature, in good agreement with the studies in Au-n GaAs reported by Padovani and Sumner [1]. This suggests that at low temperatures there is a strong tendency towards quantum-mechanical tunneling [19].

The ideality factor n is calculated from the slope of these plots, at each temperature, using (1). In Fig. 2 n is plotted against temperature where it can be observed that n decreases with increasing temperature. At 301 K, the n value is about 1.09. The ideality factor increases from $n=0.97$ at 434 K to $n=2.08$ at 90.5 K. From Fig. 2 it is clear that such a constant is unsuitable for specifying the characteristics. Having observed generally similar temperature dependence in Au n-type GaAs, Padovani and Sumner [1] found that their results could be explained by replacing n by T_0 as follows:

$$n = 1 + \frac{T_0}{T} \tag{9}$$

where T_0 is a constant $=46 \pm 8$ K. Fig. 3 shows a plot of T_0 against T in accordance with (9). This graph demonstrates that T_0 is also inappropriate for defining the characteristics of this Schottky diode since it is also temperature dependent. It should be noted that in the temperature range 200–300 K our value of $T_0 = 40 \pm 8$ K (Fig. 3) is close to that reported by Padovani and Sumner [1]. However, outside the temperature range 200–300 K the variation in T_0 is much too large to be taken as constant. Recent work by Saxena [10] in n-type silicon Schottky diodes suggests that the observed dependence of T_0 on temperature may be due to an abnormally high field around the periphery of the

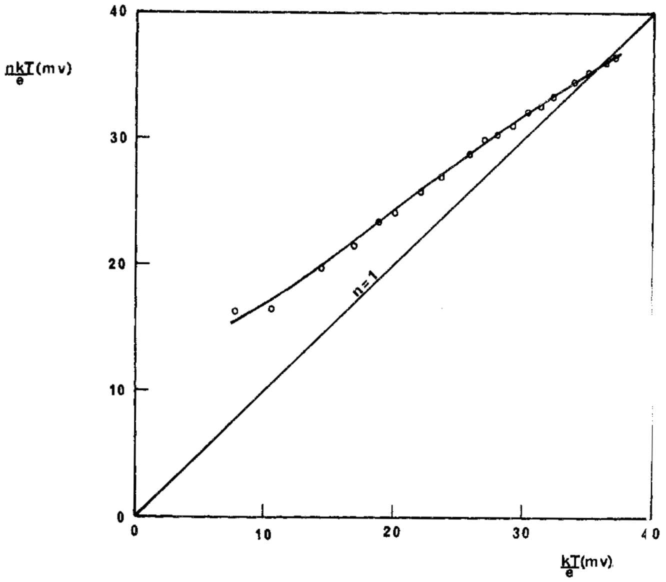

Fig. 4. nkT/e versus kT/e.

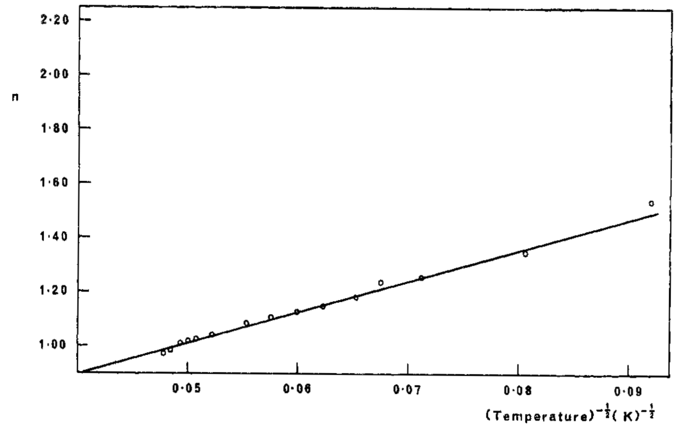

Fig. 5. n versus $T^{-1/2}$.

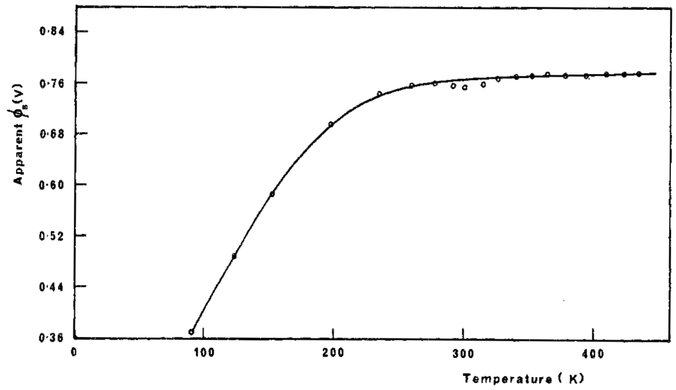

Fig. 6. Apparent ϕ_B from the uncorrected saturation-current equation versus temperature.

device which gives rise to thermionic-field emission [3], [20], [21] in this region.

The ideality factor is further analyzed by plotting nkT/e against kT/e, which is shown in Fig. 4.

If we write the expression for the current, following Padovani and Sumner [1], as

$$I = I_s \exp\left(\frac{V}{V_0}\right) \tag{10}$$

where

$$V_0 = \frac{nkT}{e} \tag{11}$$

and from (9) we have

$$V_0 = \frac{k}{e}(T + T_0). \tag{12}$$

According to (9), if T_0 had been a constant the experimental values of V_0 would have resulted in a plot parallel to $n = 1$ (Fig. 4). It is clear from examination of Fig. 4 that an approximation of constant T_0 is unjustified. It has been shown in Au n-GaAs [20] and Si [10] Schottky diodes exhibiting thermionic-field emission that the plot of (12) can be represented by a curve which asymptotically tends towards the $n = 1$ line at high temperatures. Thus, in view of Fig. 4, there would seem to be reasonable grounds for supporting that, in diodes that do not include a guard-ring structure, there is evidence of a current component due to thermionic-field emission.

A further examination of the dependence of n on temperature is made by plotting n against $T^{-1/2}$. This is represented in Fig. 5. It will be seen that a linear plot is obtained over the whole range of temperature covered in this work. The dependence of the measured value of the ideality factor can be represented by the following expression

$$n(T) = 11.4T^{-1/2} + 0.444 \tag{13}$$

to within ± 4 percent.

This is in excellent agreement with the theoretical analysis of Strikha [22] who predicted a temperature dependence law between T^{-1} and $T^{-1/2}$.

B. Measurements of the Barrier Height

The barrier height value is first calculated from each of the extrapolated values of saturation currents in accordance with (2) using $A^{**} = 4.4\ A\ \text{cm}^{-2}\cdot\text{K}^{-2}$ [16]. The dependence of the effective Richardson constant on temperature is assumed to be negligibly small. This assumption is justified by the measurements of Cardona [23], which showed that the variation in the effective electron mass in GaAs for $N_d = 10^{17}\ \text{cm}^{-3}$ is generally less than 2 percent over the temperature range 100–296 K. Furthermore, Crowell [18] has shown that the effective Richardson constant is proportional to the effective electron mass.

Fig. 6 shows a plot of ϕ_B calculated in accordance with (2), which does not include the proposed ideality-factor

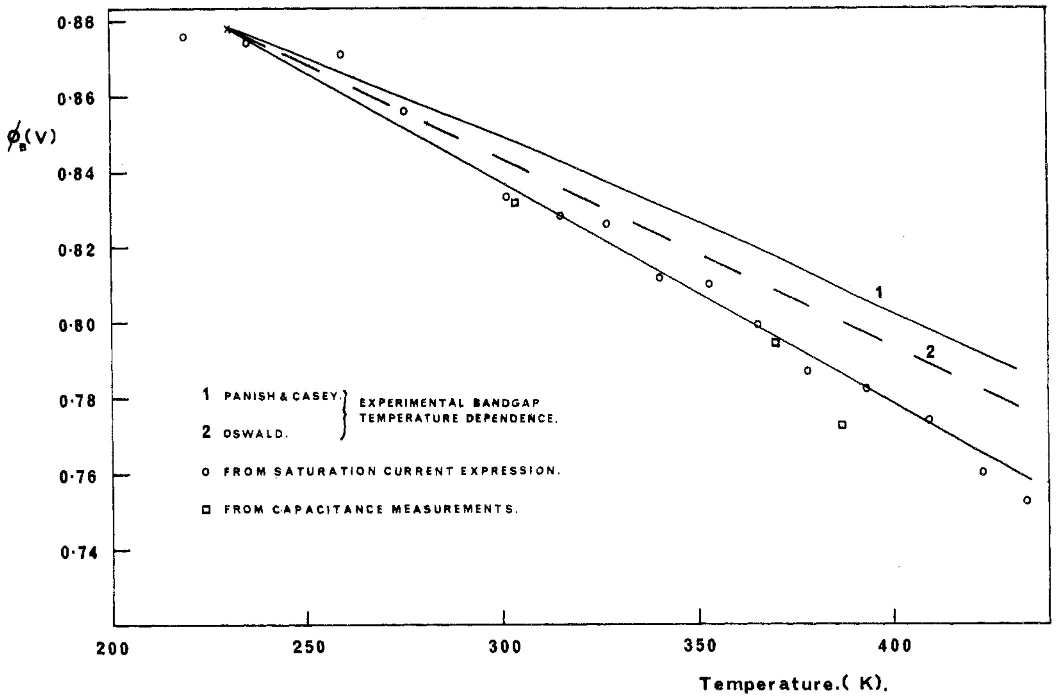

Fig. 7. Correlation of the experimental values of ϕ_B versus T with the experimentally obtained temperature dependence of the bandgap.

correction. It will be observed that such a plot of ϕ_B against T has a positive temperature coefficient that is contrary to the negative dependence measured by Crowell, Sze, and Spitzer [9] in silicon diodes and Mead and Spitzer [24] in InAs and InSb [24], which follows closely the change in the energy gap E_g with T. In order to remedy this contradiction it is necessary to return to the reasons for including n and T_0 in the ideal-diode equation [see (1)].

When it was observed that the forward current increased less rapidly with increasing applied voltage than was predicted, parameters n and T_0 were introduced to account for effects due to surface states, or due to the presence of an interfacial layer. The parameter n has been defined usually in terms of the density of surface states and voltage-dependent image force lowering of the barrier [8], [15], [25], or, where $n>1.2$ [27]–[29], at about 300 K, the presence of an interfacial layer has been implicated. Recent work by Levine [13] permits a theoretical calculation of the previously empirical temperature constant T_0 in terms of a surface energy distribution at the metal–semiconductor junction. Usually the calculations of n and T_0 are assumed to be independent of voltage (however, Levine [13] suggested that T_0 should be proportional to the applied voltage) and calculated from the slopes of the $\log_e I$ versus V curves. These same curves also generate the I_s values after extrapolation. It is suggested that the expression for I_s should contain the same ideality factor, since the above phenomena, which are responsible for deviation from $n=1$, are still present at zero voltage bias. Fig. 7 shows the values of ϕ_B determined in accordance with (4). This figure demonstrates that the effect of multiplying ϕ_B by the temperature dependent values of n is to produce a temperature dependence of ϕ_B that is comparable to that obtained from the capacitance measurements. The capacitance measurements are presented in Fig. 8 for various temperatures. Unfortunately, the temperature range is restricted by the large errors incurred in determining n and ϕ_B at very low temperatures. It should be noted that no dependence of the diode capacitance on the operating frequency is observed over the range 30 kHz–1 MHz.

The barrier height in Ni n-GaAs have so far been reported only at room temperature. Our value of $\phi_B = 0.834$ V at 301 K compares favorably with that of 0.89 V, which we calculate from the reported measurement of the diffusion potential by Sato *et al.* [30], in evaporated diodes, but at a much higher donor concentration of $N_d = 10^{17}$ cm^{-3}. The only other known values are due to Rhoderick [25], 0.77 V for chemically etched surfaces, and Genzabella and Howell [31], 0.83 V for ⟨111⟩ and 0.70 V for ⟨100⟩ orientations.

Further justification for the modification of including n in (4) arises when the energy gap is considered. Crowell *et al.* [9] have shown that, in the case of Au n-type Si diodes, the lowering of ϕ_B with increased temperature is entirely due to an accompanying reduction in the energy gap. For Ti n-type Si, Cowley [7] found that $d\phi_B/dT$ is considerably smaller than that expected for the change in the energy gap with temperature.

In Au-GaAs Padovani [2] reported from the slopes

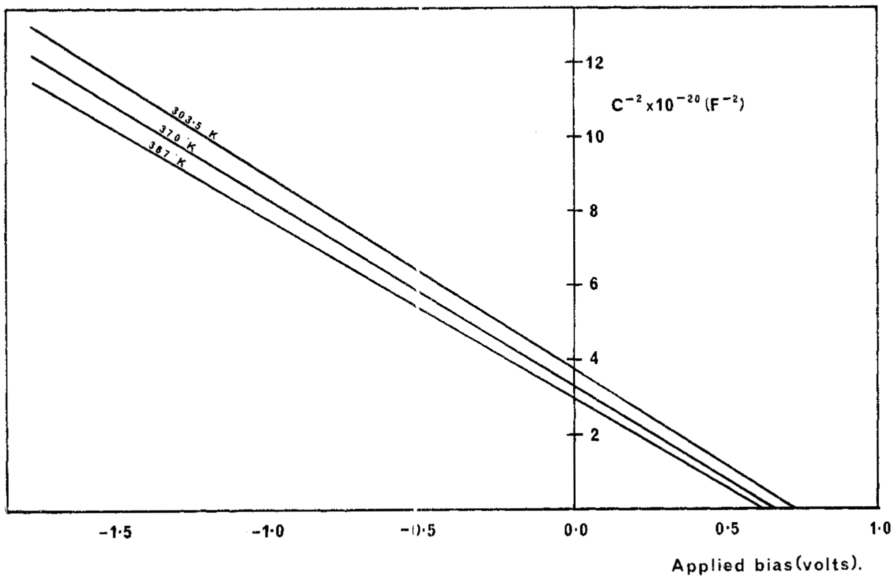

Fig. 8. C^{-2} versus applied voltage at various temperatures.

of the linear Richardson plots of $\ln(I/ST^2)$ versus $e/k(T+T_0)$, where T_0 is the excess temperature given by (9) and (12), a value for the barrier height that was independent of temperature and equal to that obtained from the capacitance measurements. However, Padovani [2] found that a temperature dependence in ϕ_B is needed in order to reconcile the value of the Richardson constant obtained from the intersect of the linear plot with the ordinate to the accepted literature value. In both nickel n-type silicon and gold n-type silicon Schottky diodes, Padovani [14][1] found that the values of the barrier height increased with increasing temperature. This is in disagreement with the negative temperature dependence observed previously for ϕ_B [3], [9], [26] and E_g [9]. Nannichi and Pearson [5] suggested that the dependence of ϕ_B on temperature is slightly smaller than that of E_g in Ni n-type GaP and Cr n-type GaP diodes. Unpublished research (by the present authors) in silicon, using the same equipment, also shows a decrease in ϕ_B with increasing T, and thus confirms the reliability of the experimental method employed here.

C. Correlation of the Dependence on Temperature of the Barrier Height and the Energy Gap

Fig. 7 compares variations in the experimentally observed values of ϕ_B with temperature with those calculated on the assumption that the variation in ϕ_B is entirely due to the dependence of E_g on temperature. Two such plots are shown and both are normalized to the measured values of ϕ_B at 230 K. The first is a plot following the results of Panish and Casey [32], which gives the following dependence of E_g:

$$E_g = 1.522 - 5.8 \times 10^{-4}T^2/(T + 300), \quad \text{in V.} \quad (14)$$

The second is that due to Oswald [33], who reported

$$E_g = 1.55 - 5.0 \times 10^{-4}T, \quad \text{in V.} \quad (15)$$

It will be observed (Fig. 7) that the dependence of ϕ_B on temperature, as predicted by (4), follows generally that of E_g, where it decreases with increasing temperature. The decrease in ϕ_B with increasing temperature, as observed in the present experiment, is about -5.8×10^{-4} V/K, in the temperature range 230–434 K. It will be noted that this change of $d\phi_B/dT$ is in good agreement with that reported in E_g by Panish and Casey [32] and Oswald [33]. At temperatures below 230 K, both the capacitive and the saturation current methods are unsatisfactory due to the large errors present in determining the measured quantities of C and n.

V. Conclusions

Both n and T_0 have been found to be considerably temperature dependent in the Ni n-type GaAs Schottky-barrier diodes used, which have no guard rings. The deviation in the plot of V_0 against kT/e is interpreted in terms of a small current component due to thermionic-field emission around the periphery of the device.

A number of authors, among them Mead and Spitzer [34] and Broom [35] have experienced difficulty when comparing values of ϕ_B obtained from the I–V characteristics with those calculated from the capacitance and photoresponse methods. It is concluded that, in this work, a better result has been possible simply by including the temperature dependent values of n in the expression for saturation-current density. This is analogous to the inclusion of T_0 in the saturation current

[1] The expression used by Padovani [14] yields only the diffusion potential and not the barrier height. When his values are corrected for the Fermi level, the image force lowering of the barrier, and kT/e [in accordance with (8)], an even larger rate of increase in ϕ_B with increasing temperature is obtained.

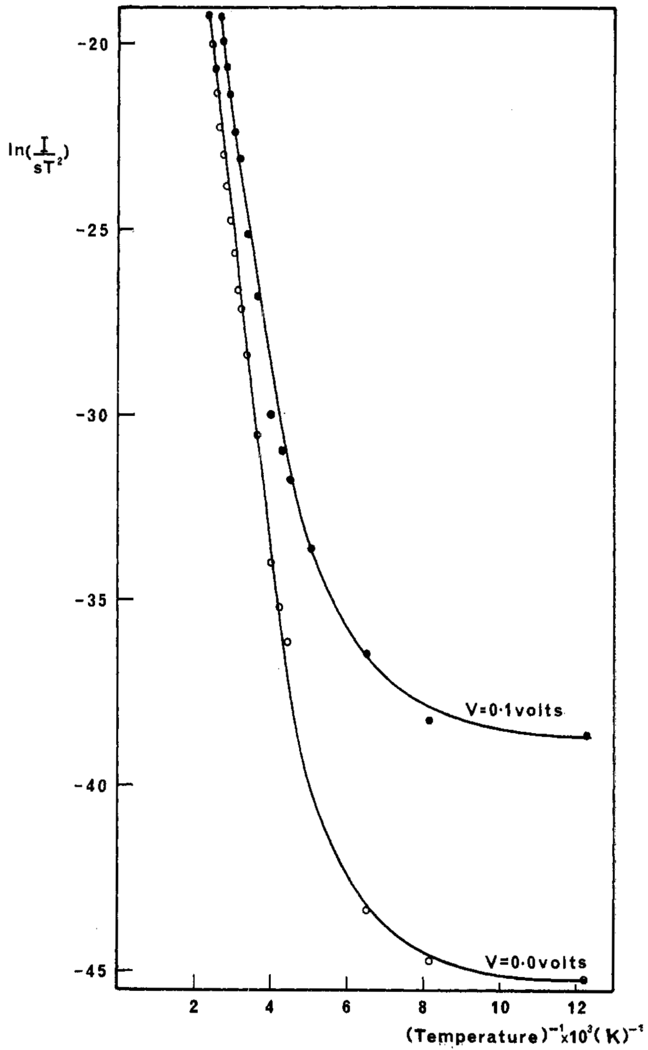

Fig. 9. Richardson plots of $\ln(I/ST^2)$ versus T^{-1}.

suggested previously by Padovani and Sumner [1]. However, since T_0 is not constant, it cannot be applied in our case. The validity of including n in the expression of I_s is demonstrated by comparing the corrected values of the barrier height with the values obtained from the capacitance measurements and by checking the temperature dependence of ϕ_B against that of E_g. Reasonable agreement is found in both cases.

Preliminary measurements with Au and Al n-type low-doped GaAs corroborate this work and also show a reduction in ϕ_B with increasing T.

Appendix

Dependence of ϕ_B on Temperature

The activation energy plots of $\log_e(I/ST^2)$ against $1/T$ in accordance with (1) and (2) are shown in Fig. 9 for applied bias voltages $V=0$ and $V=0.1$ V.

It will be observed that these plots do not yield straight lines in agreement with similar plots reported previously [1]. The curving in these plots is due to the temperature dependence of both ϕ_B and n. The latter

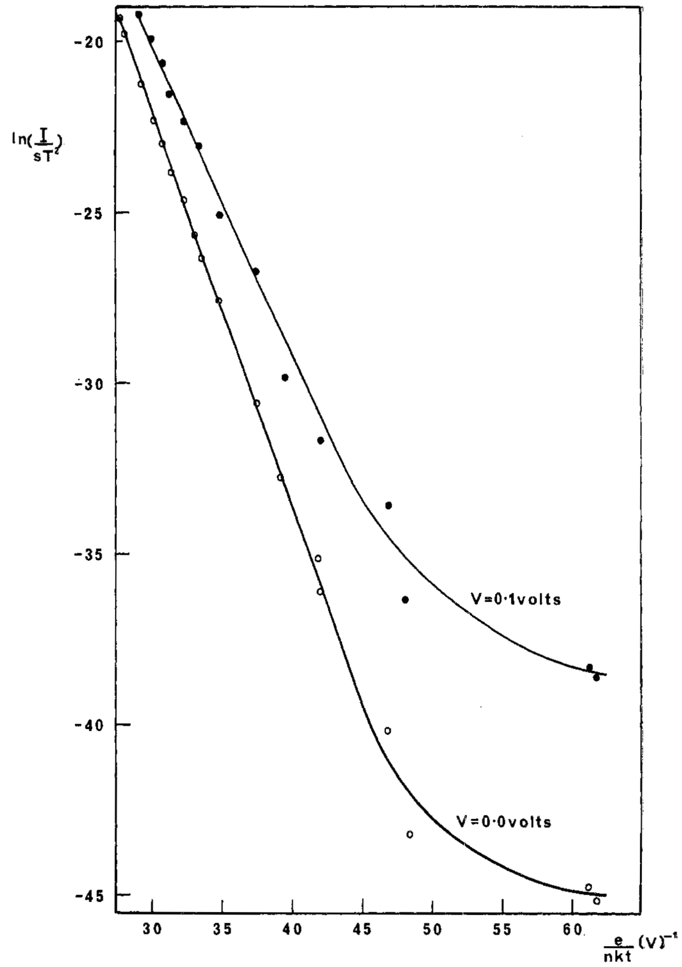

Fig. 10. Richardson plots of $\ln(I/ST^2)$ versus e/nkT.

should be included in the current expression as shown in Section II. Padovani [14], [19] has shown that the Richardson plots of $\log_e(I_s/ST^2)$ versus V_0^{-1} give straight lines having slopes of $V-\phi_B$ when $V>3(nkT/e)$. In Fig. 10 such plots are shown for $V=0$, and $V=0.1$ V, where it can be seen that these plots are also nonlinear. It should be mentioned that, unlike Padovani's suggestion [19], if ϕ_B is assumed to decrease linearly with increasing T, the Richardson plots will not be straight lines. This can be seen from the following. Assuming

$$\phi_B = \phi_{B_0} - \gamma T \tag{16}$$

where ϕ_{B_0} is the barrier height at $T=0$ and γ is a positive constant, substituting (16) into (3) and after rearrangements

$$\log\left(\frac{I_s}{ST^2}\right) = \log_0 A^{**} - \frac{e\phi_{B_0}}{nkT} + \frac{e\gamma}{nk}\,. \tag{17}$$

Since n is temperature dependent, a plot of $\log(I_s/ST^2)$ versus $V_0^{-1}=e/nkT$ will not be linear, as was, indeed, observed experimentally (Fig. 10).

Inserting the expression of n [see (9)] proposed by Padovani and Sumner [1] into (17) gives

$$\log_e\left(\frac{I_s}{ST^2}\right) = \log_e A^{**} - \frac{e\phi_{B_0}}{k(T+T_0)} + \frac{e\cdot\gamma\cdot T}{k(T+T_0)}. \quad (18)$$

This also shows that the Richardson plot of $\log_e (I_s/ST^2)$ versus $e/k(T+T_0)$ will not yield a straight line since the third term on the right-hand side of (18) is temperature dependent.

Acknowledgment

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