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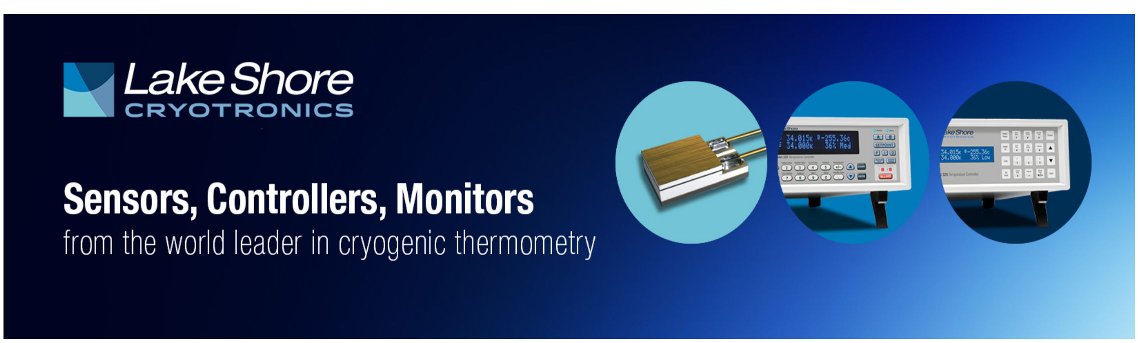

FORWARD CURRENT-VOLTAGE CHARACTERISTICS AND DIFFERENTIAL RESISTANCE PEAK OF A SCHOTTKY BARRIER DIODE ON HEAVILY DOPED SILICON

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An analysis of the forward current–voltage data for a temperature range of 77.2° to 423°K on a Cr–Si ($N_D = 7 \times 10^{18}$ cm^{-3}) Schottky barrier diode is given. The $I-V$ behavior of such a diode, which obviously does not follow the simple Schottky theory, is not explained by the more recent calculations of Padovani and Stratton, and of Crowell and Rideout in which field emission is taken into account. It is observed that the peak in differential resistance and its variation with voltage on such a diode is in reasonable agreement with the theories of Stratton and Padovani, and of Crowell and Rideout.

The purpose of this paper is to present an analysis of forward current–voltage data for a temperature range of 77.2° to 423°K for Schottky barrier diodes made by depositing Cr on heavily doped ($N_D = 7 \times 10^{18}$ cm^{-3}) n-type Si. The experimental data give the following results when compared with the various theoretical calculations:

(a) The calculations of Padovani and Stratton[1] and Crowell and Rideout[2] assuming field and thermionic-field (T-F) emission in Schottky barriers do not explain the forward current–voltage ($I-V$) data obtained on our diode for the temperature ranged 77.2° to 423°K.

(b) The calculation of Stratton and Padovani[3] on the differential resistance peaks in Schottky barrier diodes is in reasonable agreement with the $I-V$ data of our diode at 77.2°K.

The method of fabricating the Schottky barrier diode and analyzing the $I-V$ plots at various temperatures has been described in detail elsewhere.[4] Therefore, only a very brief account will be given here.

The diode was fabricated on (111), n-type Si having a doping of $N_D = 7 \times 10^{18}$ cm^{-3} using standard planar technology. The diode had circular geometry with a diameter of 0.8 mil. The metal, Cr, was evaporated from an electron gun in a vacuum system at a pressure of about 2×10^{-7} Torr. After appropriate photoresist steps, the diodes were encapsulated in hermetically sealed TO-18 packages.

The Schottky equation[4,5] describing $I-V$ behavior of the diode can be written as,

$$I = I_s[e^{V/V_0} - 1]\,. \tag{1}$$

For the voltage range of interest, $V/V_0 \gtrsim 3$, when comparing the experimental $I-V$ data with the theories of Padovani and Stratton[1] and Crowell and Rideout,[2] Eq. (1) can be written as,

$$I = I_s e^{V/V_0}\,. \tag{2}$$

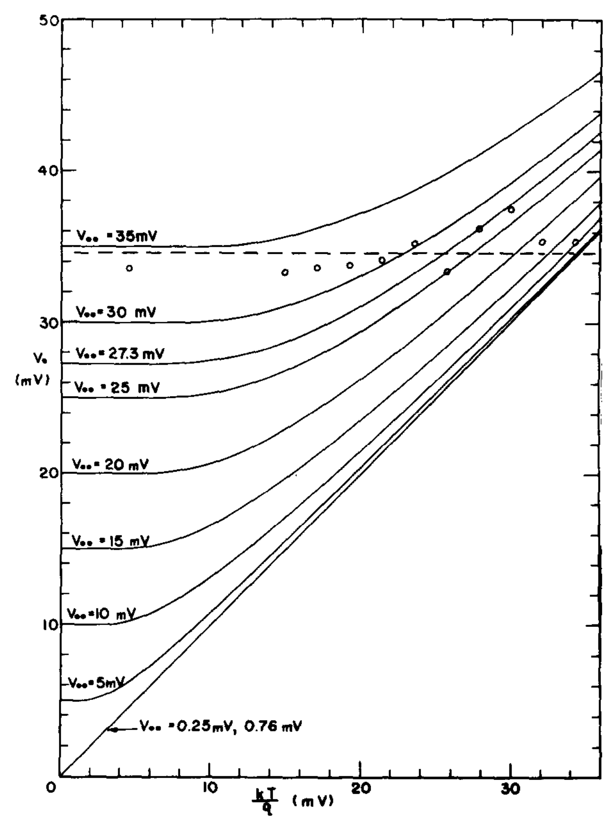

Fig. 1. Plot of V_0 vs kT/q according to Padovani and Stratton's theory shown by solid lines for various V_{00} (Ref. 1) and the experimental data on Cr–Si (n-type, $N_D = 7 \times 10^{18}$ cm^{-3}) diode for the temperature range 77.2°–423°K. The theoretical curve according to this theory for the diode studied here is the one labeled as V_{00} = 27.3 mV. A dashed line parallel to abscissa has been drawn arbitrarily through the data to illustrate that they are more or less temperature-independent.

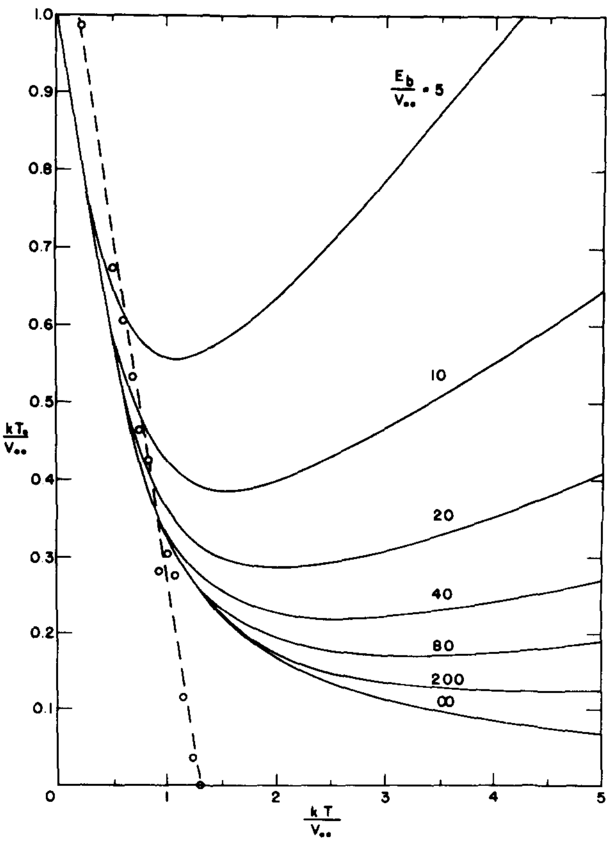

Fig. 2. Plot of kT_0/V_{00} vs kT/V_{00} for various values of E_b/V_{00} according to Crowell and Rideout's theory (Ref. 2). The experimental data are plotted as circles through which a dashed line is drawn.

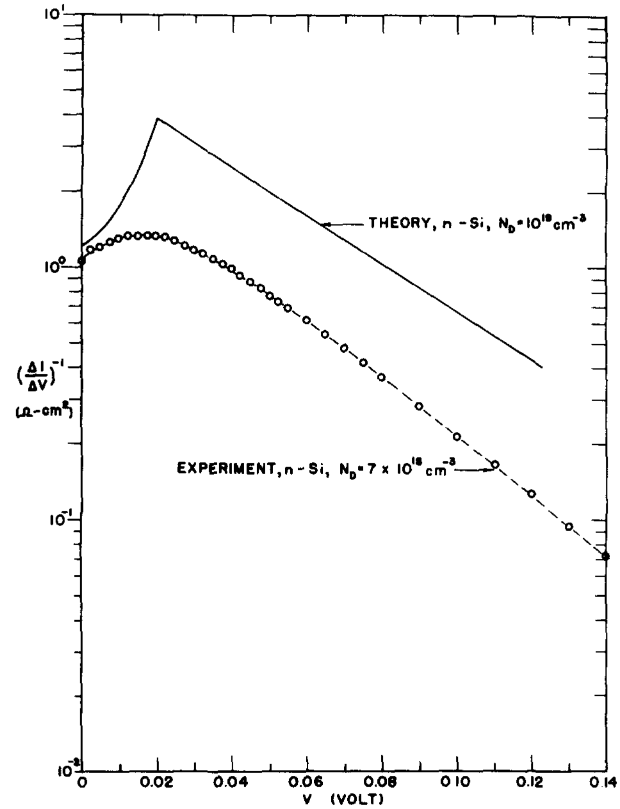

Fig. 3. Plot of the differential resistance $(\Delta I/\Delta V)^{-1}$ vs voltage V according to Stratton and Padovani's theory shown by solid line (Ref. 3) for a Schottky barrier on n-type Si with a doping $N_D = 10^{19}$ cm^{-3}. The experimental data of $(\Delta I/\Delta V)^{-1}$ vs V at the temperature 77.2°K are also plotted for a Cr-Si Schottky barrier diode with $N_D = 7 \times 10^{18}$ cm^{-3}.

The term V_0 in Eqs. (1) and (2) is defined as follows:

(1) If the diode obeys ideal Schottky theory,[5] then

$$V_0 = kT/q \ . \tag{3}$$

(2) If the diode obeys the T-F theory of Padovani and Stratton,[1] then

$$V_0 = V_{00} \coth(V_{00}/kT) \ , \tag{4}$$

where

$$V_{00} = (\hbar/2)[N/m^*\epsilon_0\epsilon]^{1/2} \ . \tag{5}$$

(3) If the diode obeys an empirical equation proposed first by Padovani and Sumner,[6] and verified further by Saxena,[4] then

$$V_0 = k(T + T_0)/q \ , \tag{6}$$

where T_0 is a constant > 0.

From the $I-V$ data at various temperatures, V_0 was calculated at each temperature by fitting the $\ln I$ vs V plots with a straight line. When $\ln I$ vs V plots could not be fitted accurately with a straight line at high temperatures due to the series resistance effects, the procedure of Saxena and Varady[7] was used to calculate V_0. The accuracy of determining V_0 was $\pm$ 1 mV. Figure 1 shows a plot of V_0 vs kT/q using the experimental data (shown as circles) and the theory of Padovani and Stratton[1] using Eqs. (4) and (5) (shown by solid lines). This theory is not valid near zero bias. A dashed straight line parallel to abscissa is drawn arbitrarily through the data to illustrate that they are more or less temperature insensitive. If the effective mass of the electrons in the Si used here is assumed to be $m^* = 0.26\, m_e$, then Padovani and Stratton's theory[1] gives V_{00} = 27.3 mV. Therefore, if the Cr-Si diode would have followed Padovani and Stratton's theory, then the experimental V_0 vs kT/q data would have followed the curve labeled with V_{00} = 27.3 mV in Fig. 1. However, as is evident from Fig. 1, the data do not follow the above-mentioned theoretical curve. Therefore, the theory of Padovani and Stratton does not explain the experimental data on our diode. At low temperatures, between 77.2°K and about 223°K, the diode behavior could be explained by Padovani and Stratton's theory[1] if it were assumed that the effective carrier concentration in the Si used was about 1×10^{19} cm^{-3} instead of $7 \times$

10^{18} cm^{-3}. Such a concept that the surface carrier concentration of the semiconductor was greater than the otherwise-known bulk carrier concentration has been used earlier by Landsberg.[8]

The term T_0 can be evaluated from the experimental data by using Eq. (6). Figure 2 shows a plot of kT_0/V_{00} vs kT/V_{00} for various E_b/V_{00} in which the solid lines represent the theoretical calculations of Crowell and Rideout.[2] The curve labeled as ∞ corresponds to Padovani and Stratton's curves shown in Fig. 1 when they are normalized with V_{00}. Also, the ordinate (kT_0) of Fig. 2 is related to that (V_0) of Fig. 1 by Eq. (6). E_b is the band bending related to the barrier height ϕ_{MS} as,

$$E_b = \phi_{MS} - \phi_F \,, \tag{7}$$

ϕ_F being the energy difference between the Fermi level and the bottom of the conduction band. For Cr–Si Schottky barrier, ϕ_{MS} was found to be 0.61 eV. The circles in Fig. 2 represent the experimental data. A dashed line has been drawn through the data to illustrate their temperature variation. The theoretical value of E_b/V_{00} for the diode studied here should be about 22. The experimental data, as is evident from Fig. 2, do not follow the theory of Crowell and Rideout.[2] However, if it were assumed as before that the effective carrier concentration in the Si used was higher than 7×10^{18} cm^{-3}, then the experimental points will move toward the theoretical curve labeled as ∞ in the temperature range of 77.2° to 273°K.

Stratton and Padovani[3] calculated the tunneling current in a Schottky barrier made on a heavily doped semiconductor. This theory[3] is valid near zero bias. It was found that at sufficiently low temperatures, a peak should occur at a bias corresponding to the Fermi energy of the semiconductor when the differential resistance $(dI/dV)^{-1}$ is plotted vs V. Figure 3 shows a plot of $(dI/dV)^{-1}$ vs V as calculated by Stratton and Padovani[3] (shown by solid line) for n-type Si having a carrier concentration of 10^{19} cm^{-3}. Also shown are the experimental data (dashed line) obtained on the Cr–Si diode studied here at the liquid-nitrogen temperature (77.2°K). For a quantitative comparison of the experiment and the theory,[3] measurements at temperatures lower than 77.2°K (e.g., liquid-He temperature, 4.2°K) should be made. The peak in the experimental data is observed to occur at a voltage slightly less than the voltage where the theoretical peak occurs. This is probably due to the fact that a carrier concentration of 10^{19} cm^{-3} was used in the theoretical calculation[9] and the experimental data was taken on the diode in which the carrier concentration was 7×10^{18} cm^{-3}. The higher doping shifts the voltage at which the peak occurs to a larger value of the voltage.

The experimental peak in Fig. 3 is not as sharp as the theoretical one because the measurements were made at 77.2°K. For a quantitative comparison with the theory, the measurements should be made at least at liquid-He temperature, 4.2°K.

The theoretical curve in Fig. 3 is higher than the experimental curve by a factor of about 2.5. A part of this factor can be explained by the fact that WKB approximation was used by Stratton and Padovani.[3] Their theoretical curves were larger by a factor of about 1.8 when compared with those of Conley *et al.*[10] Such a discrepancy was not considered to be a serious one since the results of the former[3] were analytically tractable, whereas the latter[10] used numerical methods to calculate the tunneling current from the exact theory as a function of applied bias.

The decrease in $(\Delta I/\Delta V)^{-1}$ vs V beyond the peak in Fig. 3 is about the same for both the theoretical and the experimental curves. Such agreement is not found when the experimental data of Conley *et al.*[10] obtained on "In on n-type Ge (10^{19} cm^{-3}) Schottky barrier" are compared with either their theoretical curve or that of Stratton and Padovani.[3]

While revising the manuscript, a study paper by Crowell and Rideout[11] was brought to the attention of the author. Their theory fits the data at 77°K presented in this paper fairly well. A detailed comparison of the experimental data with theories of Stratton and Padovani,[3] Conley *et al.*,[10] and Crowell and Rideout[11] will be published elsewhere after the measurements of 4.2°K and other temperatures have been made.

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