Study of forward I-V plot for Schottky diodes with high series resistance

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The current-voltage characteristics for Schottky barrier diodes with series resistance are discussed. It is shown that by using Norde's function $F(V) = V/2 - (kT/q)\ln(I/SAT^2)$ at two different temperatures, barrier height, n-value or ideality factor, and series resistance can be determined even in the case $1 < n < 2$.

For the simple theory of a Schottky diode the current-voltage characteristic is given by, neglecting image-force-lowering,

$$I = I_s[\exp(qV_D/kT) - 1],$$

where q is the electronic charge, V_D the applied voltage across the junction, k the Boltzmann constant, and T the absolute temperature. The saturation current I_s is expressed by

$$I_s = SAT^2 \exp(-q\phi/kT),$$

where S is the diode area, A is the Richardson constant, and ϕ is the barrier height.

One can determine the value of barrier height by making a $\ln I$ vs V plot under forward bias. For voltages larger than a few kT/q this plot will be a straight line whose extrapolated intercept with the current axis gives I_s. From this I_s value ϕ can be calculated.

However, departures from the theory of the forward I-V characteristic have been previously reported for practical Schottky diodes.[1] These departures have been usually described in terms of a dimensionless ideality parameter n, that is, the forward I-V relationship is assumed proportional to $\exp(V/nkT)$.

Difficulties will arise if the diode has a series resistance R. The straight-line part of the plot will then be confined to the voltage interval $kT/q \ll V <$ departing point from the straight line due to the voltage drop across the resistance R. And when R is large, this interval will be too small to get a reliable value of barrier height ϕ. Furthermore, since one is forced to use an interval where V is small, excess current may be significant in the total current, the extrapolation making the value of I_s more unreliable. Norde[2] has developed the method to be able to determine ϕ and R for the diode with a large series resistance in case of $n = 1$.

In this communication we wish to present a method capable of determining n, ϕ, and R. The proposed procedure is checked by experimental results for a Mo–n-Si Schottky diode.

We assume that the forward I-V characteristic is expressed as

$$I = SAT^2 \exp(-q\phi/kT)\exp(qV_D/nkT), \tag{1}$$

where n is the ideality parameter which is smaller than 2 because of the empirical values in most experimental situations, and that n is independent of the temperature and biasing voltage. We adopt the function

$$F(V) = V/2 - (kT/q)\ln(I/SAT^2) \tag{2}$$

proposed by Norde.[2] The voltage across the diode V has a relationship with V_D,

$$V_D = V - IR. \tag{3}$$

From Eqs. (1)–(3),

$$F(V) = (1/2 - 1/n)V + \phi + IR/n. \tag{4}$$

For the ideal case $R = 0$, $F(V)$ will be a straight line with slope $(n-2)/2n(<0)$. In most practical cases this slope is expected to be close to $-1/2$ because usual n is slightly larger than unity. If, on the other hand there is only a resistance, we will get

$$F(V) = F_R(V) = V/2 - (kT/q)\ln(V/SAT^2R).$$

For large voltages this will approach a straight line with slope 1/2. Between these extremes $F(V)$ will have a minimum point which is important to determine the desired unknowns. In Fig. 1 are shown calculated $F(V)$ curves for different values of series resistance and temperature in the case of $n = 1.5$. The barrier height and junction area were arbitrarily chosen to be 0.67 eV and 3.14×10^{-2} cm^2, respectively.

Differentiating Eq. (4) with respect to voltage gives

$$\frac{dF(V)}{dV} = \frac{1}{2} - \frac{1}{n} + \left(\frac{R}{n}\right)\left(\frac{dI}{dV}\right).$$

Since, from Eqs. (1)–(3), we obtain

$$\frac{dI}{dV_D} = \frac{\beta I}{n}$$

and

$$\frac{dI}{dV} = \left(\frac{dI}{dV_D}\right)\Bigg/\left[1 + R\left(\frac{dI}{dV_D}\right)\right],$$

the derivative becomes

$$\frac{dF(V)}{dV} = \frac{n - 2 + \beta RI}{2(n + \beta RI)},$$

where $\beta = q/kT$.

Putting $dF(V)/dV = 0$ will give the current I_0 at the minimum point of $F(V)$, and thus

$$R = (2 - n)/\beta I_0. \tag{5}$$

The corresponding voltage V_0 is

$$V_0 = V_D(I_0) + RI_0,$$

and the minimum value of $F(V)$ becomes

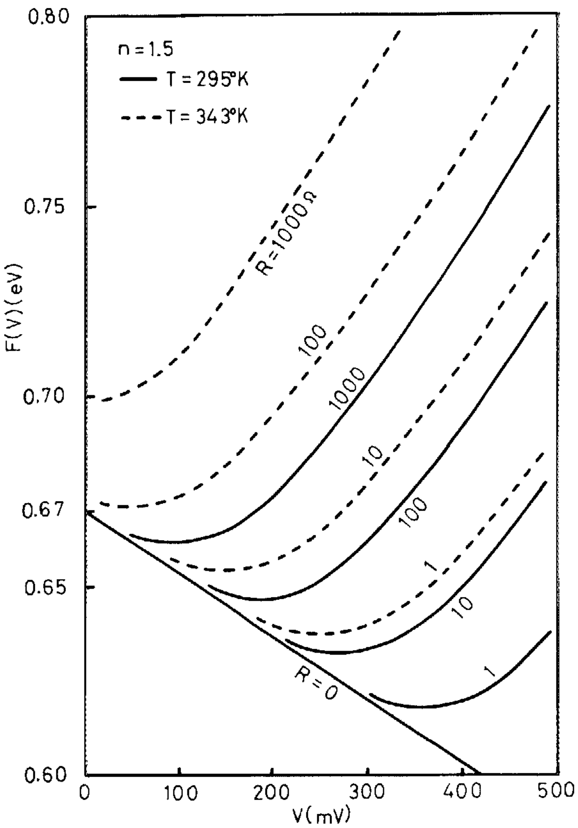

FIG. 1. Calculated plots of $F(V)$ with $\phi = 0.67$ eV, $S = 3.14 \times 10^{-2}$ cm^{-2} $A = 120$ A/°K cm^2.

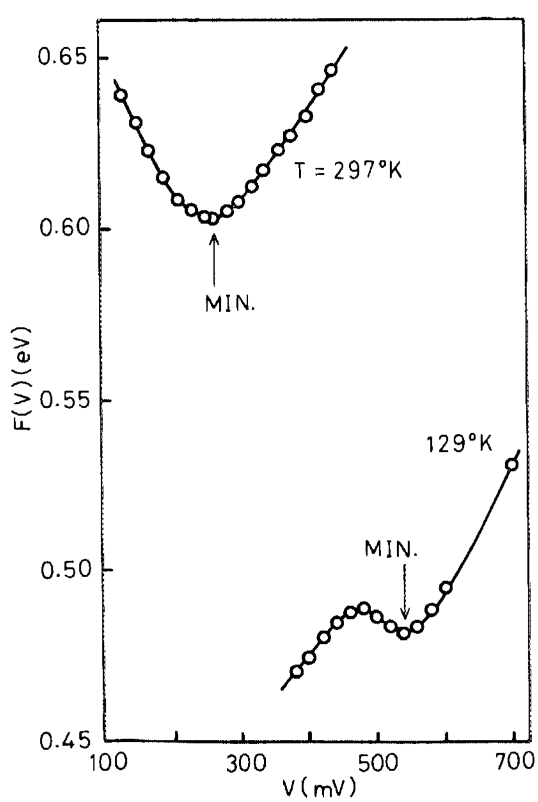

FIG. 2. Experimental plots of $F(V)$ for a Mo–n-Si Schottky diode.

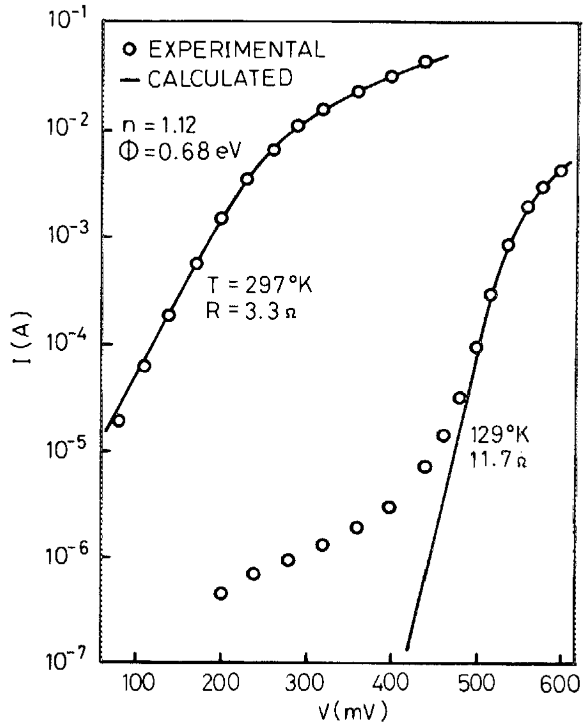

FIG. 3. Experimental and calculated I-V curves for the same diode as in Fig. 2.

$$F(V_0) = (1/2 - 1/n)V_0 + \phi + (2/n - 1)/\beta. \tag{6}$$

First let us consider the simplest case $n = 1$. From Eqs. (5) and (6), R and ϕ will be

$$R = kT/qI_0$$

$$\phi = F(V_0) + V_0/2 - kT/q,$$

which are the same results as derived by Norde.[2]

In order to determine the values of n, R, and ϕ, we need at least two experimental I–V curves measured at different temperatures T_1, T_2. Using Eqs. (5) and (6) at each temperature, we get the following equations,

$$R_i = (2 - n)/\beta_i I_{0i}, \tag{7}$$

$$\phi = F(V_{0i}) + (1/n - 1/2)V_{0i} - (2/n - 1)/\beta_i, \tag{8}$$

where R_i, β_i, I_{0i}, and V_{0i} $(i = 1,2)$ correspond to T_1, T_2, respectively.

Solving these four equations simultaneously,

$$n = (2\Gamma\Delta T - \Delta V)/(\Delta F + \Gamma\Delta T - \Delta V/2), \tag{9}$$

$$R_i = (2\Gamma T_i \Delta F/I_{0i})/(\Delta F + \Gamma\Delta T - \Delta V/2), \tag{10}$$

where $\Gamma = k/q$, $\Delta T = T_1 - T_2$, $\Delta V = V_{01} - V_{02}$, and $\Delta F = F(V_{01}) - F(V_{02})$. From the results of Eqs. (8) and (9) barrier height ϕ can be calculated too. Thus we finally obtain all the unknowns that are desired under the present model. It should be noted that, as far as ideality factor n is smaller than two, the procedure mentioned above is mathematically valid. However, when n is large (<2), the minimum point of $F(V)$ will be unclear, indicating that the graphical determination of V_0 becomes difficult in practical application. Therefore the upper limit of n value would depend on the accuracy of the measurement.

In Figs. 2 and 3 are shown typical experimental $F(V)$ and

I-V plots at temperatures 297 and 129 °K for a sputtered Mo–n-Si Schottky diode together with the calculated I-V curves using the values determined by our procedure. In calculation we used the value $A = 264$ A/°K cm^2 because n on n^+-Si epitaxial wafers with (111) surfaces were used.[3] Except for the difference due to excess current in the voltage region lower than about 0.48 V at 129 °K, good agreement can be seen in Fig. 3. Obtained value $\phi = 0.68$ eV agrees well with the result by Zettler and Cowley[1] and with our capacitance-voltage measurements taking into account experimental errors. When $V_{01} = 0.26$ V(297 °K) and $V_{02} = 0.54$ V(129 °K) are much larger, then kT/q is also satisfied.

The fact mentioned above means that our theory is useful to evaluate the parameters of the diode with a series resistance.

In summary, we discussed a method of determining the barrier height, series resistance, and n value for a Schottky diode. It is shown that: (1) Function $F(V)$ is still applicable to the diode with the ideality parameter larger than unity (<2). (2) The procedure presented here automatically includes the simplest case $n = 1$. (3) Using two I-V curves at different temperatures, our method enables one to determine the key parameters of a Schottky barrier diode, that is, ϕ, R, and n uniquely.

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[1]See, for example, R. A. Zettler and A. M. Cowley, IEEE Trans. Electron. Devices **ED-16**, 58 (1969).

[2]H. Norde, J. Appl. Phys. **50**, 5052 (1979).

[3]S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1969), Chap. 8, p. 380.