A modified forward I-V plot for Schottky diodes with high series resistance

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It is shown that by plotting the function $F(V) = V/2 - (kT/q)\ln(I/AA^{**}T^2)$ a reliable value of the barrier height can be obtained even if there is a series resistance which would hamper the evaluation of the standard $\ln I$-vs-V plot. A theoretical examination of $F(V)$ is followed by experimental plots for some common Schottky-barrier diodes.

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For an ideal Schottky-barrier diode the I-V characteristic is given by (neglecting minor effects)

$$I = I_s(\exp(\beta V_D) - 1),$$

where V_D is the voltage across the diode,

$$I_s = AA^{**}T^2\exp(-\beta\phi_B),$$

$$\beta = q/kT.$$

A well-established method of determining the barrier height ϕ_B is to make a ln I vs. V plot. For voltages larger than a few kT/q this plot will be a straight line whose extrapolated intercept with the zero voltage axis gives I_s. From this I_s value ϕ_B can be calculated.

Difficulties will arise, however, if the base material presents a series resistance R to the diode. The straight-line part of the plot will then be confined to the voltage interval

$$kT/q << V << IR$$

and if R is large, this interval will be too small to give a reliable value of I_s. Furthermore, since one is forced to use an interval where V is small, recombination current[1] in the diode may be a significant part of the total current, making the extrapolated I_s value still more unreliable.

The problem with a series resistance can in many cases be avoided by using a plot of the function

$$F(V) = \frac{V}{2} - \frac{1}{\beta}\,ln\left(\frac{I}{AA^{**}T^2}\right). \tag{1}$$

For a diode with a series resistance R, the current is given by

$$I = I_s[\exp(\beta V_D) - 1] = I_s\{\exp[\beta(V - IR)] - 1\}. \tag{2}$$

If we assume that $V_D \gg kT/q$, Eq. (2) and (1) will give

$$F(V) = \phi_B + IR - \tfrac{1}{2}V.. \tag{3}$$

For the ideal case $R = 0$, $F(V)$ is a straight line with slope $= -\frac{1}{2}$ and the extrapolated intercept with the F(V) axis gives the barrier height ϕ_B. If, on the other hand there is only a resistance, we will get

$$F(V) = F_R(V) = \frac{V}{2} - \frac{1}{\beta}\ln\left(\frac{V}{RAA^{**}T^2}\right).$$

For large voltages this will approach a straight line with slope $= +\frac{1}{2}$. Evidently the actual $F(V)$ will be close to the ideal case for small current values and will approach the $F_R(V)$ curve for large currents. Somewhere between these two extremes $F(V)$ will have a minimum, which is the point of interest. In Fig. 1 are shown calculated $F(V)$ and $F_R(V)$ curves for different values of series resistance. The barrier height ϕ_β was arbitrarily chosen to be 0.79 eV.

Differentiating Eq. (3) with respect to voltage gives

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

Since

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

and

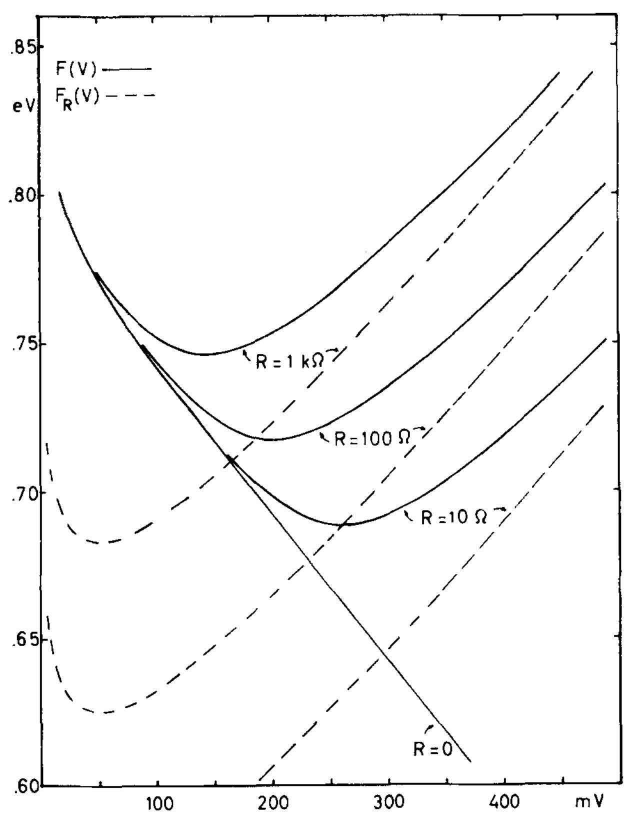

FIG. 1. Calculated plots of $F(V)$ and F_R(V) with $\phi_B = 0.79$ eV, A = 1 cm², $A^{**} = 120$ A (°C cm²)⁻¹, T = 20 °C.

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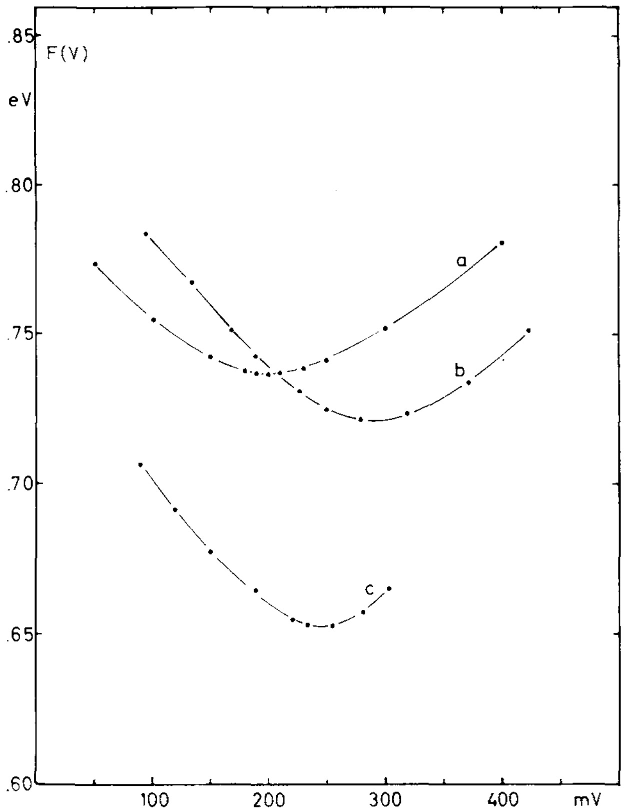

FIG. 2. Experimental plots of $F(V)$ for three different Schottky diodes: (a) Au on CP6-etched n-Si; (b) PtSi on n-Si; (c) Pd_2Si on n-Si. The minimum point gives the following values of barrier height and series resistance: (a) $\phi_B = 0.81$ eV, R = 4.9 kΩ (b) $\phi_B = 0.84$ eV, R = 580 Ω; (c) $\phi_B = 0.75$ eV, R = 107 Ω.

$$\frac{dI}{dV_D} = \frac{d}{dV_D}[I_s \exp(\beta V_D)] = \beta I,$$

the derivative becomes

$$\frac{dF}{dV} = \frac{\beta RI}{1+\beta RI} - \frac{1}{2}. \tag{4}$$

Putting $dF/dV = 0$ will thus give the current I_0 at the minimum point of $F(V)$. From Eq. (4) we obtain

$$I_0 = \frac{1}{\beta R} = \frac{kT}{qR}. \tag{5}$$

The corresponding voltage V_0 is, using Eq. (2),

$$V_0 = I_0 R + V_D(I_0)$$

$$= \frac{1}{\beta} + \ln\left(\frac{I_0}{AA^{**}T^2}\right) \tag{6}$$

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

$$F(V_0) = \frac{V_0}{2} - \frac{1}{\beta}\left(\frac{I_0}{AA^{**}T^2}\right). \tag{7}$$

Using the measured values of I_0, V_0, and $F(V_0)$ and Eqs. (5)–(7), we finally obtain

$$R = \frac{kT}{qI_0},$$

$$\phi_B = F(V_0) + \frac{V_0}{2} - \frac{kT}{q}. \tag{8}$$

Experimental $F(V)$ plots for different Schottky diodes are shown in Fig. 2. The ϕ_B values obtained from these plots are in good agreement with the expected values.

Once the V_0 value is established, the assumption that $V_D \gg kT/q$ can be checked since at $V = V_0$ we have

$$V_D = V_0 - kT/q.$$

It should be noted that a series resistance is not the only cause of an $F(V)$ plot with a minimum. If the back contact to the diode is not an "Ohmic" contact, it can be a reverse-biased diode when the main contact is forward biased. Even if the barrier of the back contact is low, it can seriously affect the current. Using subscripts 1 and 2 to denote the front and the back contact, respectively, the I-V characteristic of the structure will be (now assuming there is no series resistance)

$$I = \frac{I_{s1} I_{s2}}{I_{s2} + I_{s1}\exp(\beta V)}[\exp(\beta V) - 1].$$

If we assume that both diodes have the same area A, this can be expressed as

$$I = AA^{**}T^2 \frac{\exp[-\beta(\phi_1 + \phi_2)]}{\exp(-\beta\phi_2) + \exp(-\beta\phi_1)\exp(\beta V)} \times [\exp(\beta V) - 1].$$

Assuming that $V >> kT/q$ and using formula (1), the $F(V)$ function is

$$F(V) = \phi_1 - \frac{V}{2} + \frac{1}{\beta} ln\{1 + \exp[\beta(V - \phi_1 + \phi_2)]\}.$$

By differentiation it is easily seen that this function has a minimum at

$$V = V_0 = \phi_1 - \phi_2,$$

and that

$$F(V_0) = \frac{\phi_1 + \phi_2}{2} + \frac{kT}{q} ln2.$$

The two barriers are then given by

$$\phi_1 = F(V_0) + \frac{V_0}{2} - \frac{kT}{q} ln2, \tag{9}$$

$$\phi_2 = F(V_0) - \frac{V_0}{2} - \frac{kT}{q} ln2.$$

From the $F(V)$ plot only it is difficult to tell whether the minimum is caused by a series resistance or a non-Ohmic back contact. However, in most experimental situations one of these possibilities can be ruled out. If the front contact barrier height is the only point of interest, it does not matter what model is used since they both give essentially the same barrier value, as can be seen comparing Eqs. (8) and (9).

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[1]E.H. Rhoderick, *Metal-Semiconductor Contacts* (Clarendon, Oxford, 1978).