Extraction of Schottky diode parameters from forward current-voltage characteristics

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It is shown that by using the forward current density-voltage (J-V) characteristics of a Schottky diode, a plot of $d(V)/d(\ln J)$ vs J and a plot of the function $H(J)$ vs J, where $H(J) \equiv V - n(kT/q)\ln(J/A^{**}T^2)$, will each give a straight line. The ideality factor n, the barrier height ϕ_B, and the series resistance R of the Schottky diode can be determined with one single I-V measurement. This procedure has been used successfully to study thermal annealing effects of W/GaAs Schottky contacts.

The forward current-voltage (I-V) characteristics of a Schottky diode obeying the thermionic emission model are given by

$$I = I_S[\exp(qV_D/kT) - 1]. \tag{1}$$

Most practical Schottky diodes show deviations from ideal thermionic emission behavior. A dimensionless parameter called the ideality factor, n, is usually included in the I-V relationship to take into account nonideal diode behaviors[1]

$$I = I_S[\exp(qV_D)/nkT) - 1], \tag{2}$$

where q is the electronic charge, V_D the voltage applied across the diode, k the Boltzmann constant, and T the absolute temperature. I_S can be expressed by

$$I_S = A_{\text{eff}}A^{**}T^2\exp(-q\phi_B/kT), \tag{3}$$

where A_{eff} is the effective area of the diode, A^{**} ($= 8.6\,\text{cm}^{-2}\,\text{K}^{-2}\,\text{A}$) is the Richardson constant, and ϕ_B is the Schottky barrier height of the diode.

The effect of the diode series resistance R is usually modeled with a series combination of a diode and a resistor with resistance R through which the current I flows. The voltage V_D across the diode can then be expressed in terms of the total voltage drop V across the series combination of the diode and the resistor. Thus, $V_D = V - IR$, and for $V_D > 3kT/q$ Eq. (2) becomes

$$I = I_S\exp[q(V - IR)/nkT]. \tag{4}$$

A method to extract the series resistance R of ideal Schottky diodes (i.e., $n = 1$) was first proposed by Norde.[2] For the $n > 1$ cases, Sato and Yasumura[3] had modified Norde's approach to extract the values of n, ϕ_B, and R from the forward I-V data of a Schottky diode. Their approach requires, for a given Schottky diode, two experimental I-V measurements conducted at two different temperatures and the determination of the corresponding minima to the modified Norde's function. In this letter, we present an alternate approach to determine the values of n, ϕ_B, and R from a single I-V measurement. The proposed technique was applied to characterize W/GaAs Schottky diodes subjected to various annealing temperatures and the Mo/Si Schottky diode presented by Sato and Yasumura.[3]

Equation (4) can be rewritten in terms of current density $J(= I/A_{\text{eff}})$. Thus,

$$V = RA_{\text{eff}}J + n\phi_B + (n/\beta)\ln(J/A^{**}T^2), \tag{5}$$

where

$$\beta = q/kT. \tag{6}$$

Differentiating Eq. (5) with respect to J and rearranging terms, we obtain

$$\frac{d(V)}{d(\ln J)} = RA_{\text{eff}}J + \frac{n}{\beta}. \tag{7}$$

Thus, a plot of $d(V)/d(\ln J)$ vs J will give RA_{eff} as the slope and n/β as the y-axis intercept. To evaluate ϕ_B, we can define a function $H(J)$:

$$H(J) \equiv V - (n/\beta)\ln(J/A^{**}T^2). \tag{8}$$

For Eq. (5) we can deduce

$$H(J) = RA_{\text{eff}}J + n\phi_B. \tag{9}$$

Using the n value determined from Eq. (7), a plot of $H(J)$ vs J will also give a straight line with y-axis intercept equal to $n\phi_B$. The slope of this plot also provides a second determination of R which can be used to check the consistency of this approach. Thus, performing two different plots [Eqs. (7) and (9)] of the J-V data obtained from one measurement can determine all the three key diode parameters: n, ϕ_B, and R.

We have applied our proposed procedure to characterize W/GaAs Schottky diodes annealed at temperatures ranging from 100 to 700 °C. The diameter of the tungsten metal dots ranges from 0.02 to 0.12 cm. We have observed that the reverse leakage current of the as-deposited and annealed diodes at a given voltage is directly proportional to the geometrical area of the metal dots, indicating that the edge effect of the diodes is insignificant. Hence, we have taken the geometrical area of the diodes to be A_{eff}. Figure 1(a) shows the plots of $d(V)/d(\ln J)$ vs J and $H(J)$ vs J for the as-deposited W/GaAs diode. As expected, both plots give straight lines. The values of R obtained from the two different plots agree with each other within 10%. The values of n and ϕ_B also agree well with those values obtained from the simple consideration of the linear region of experimental $\ln J$ vs V plot.[4] Figure 1(b) shows the calculated and the corresponding experimental $\ln J$ vs V plots of the as-deposited W/GaAs diode. Figures 2(a) and 2(b) show similar plots for

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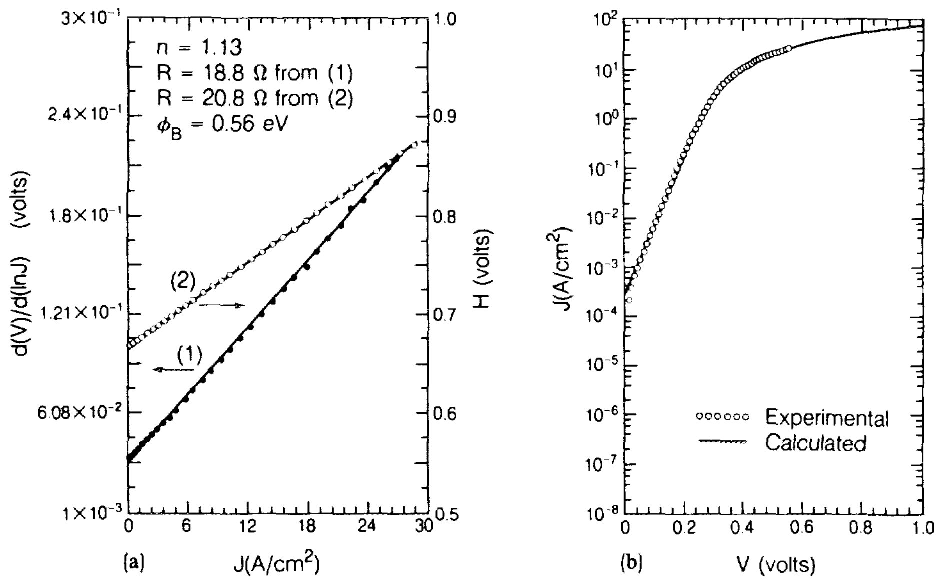

FIG. 1. As-deposited W/GaAs Schottky diode. (a) Plots of $d(V)/d(\ln J)$ vs J and $H(J)$ vs J. (b) Experimental and calculated $\ln J$ vs V plots.

the 700 °C annealed W/GaAs diode. Except for low voltages (<0.05 V), the good agreement between calculated and experimental $\ln J$ vs V plots as seen in Figs. 1(b) and 2(b) implies that the Schottky diode indeed can be modeled quite accurately by the series combination of a diode and a resistor. For the low voltage regime, however, other current conduction mechanisms (e.g., recombination current) dominate and a different model has to be invoked to explain the diode behaviors. The parameters extracted by the proposed procedure for W/GaAs diodes annealed at different temperatures are summarized in Table I.

As a further test for the proposed procedure, we analyzed the J-V data of the Mo/Si diode measured at 297 °C by Sato and Yasumura.[3] The results are shown in Fig. 3. The values of the three diode parameters derived from Fig. 3 ($n = 1.1$, $\phi_B = 0.68$ eV, and $R = 3.2\ \Omega$) are in good agreement with those determined by Sato and Yasumura ($n = 1.12$, $\phi_B = 0.68$ eV, and $R = 3.3\ \Omega$). The advantages of the proposed procedure include: (i) only one I-V measurement is needed, (ii) it is convenient to check the validity of the diode-series resistor model because deviations from straight lines can easily be detected, (iii) the procedure also eliminates the task of determining the minimum of the Norde's function. We have estimated that a few percent uncertainty in the determination of the Norde's function minimum can lead to as much as a 40% error in the evaluation of the series resistance R.

From Table I we note that the value of R of the 700 °C annealed W/GaAs diode is much higher than the values obtained for the low-temperature annealed ones. We have used other analytical techniques to characterize the diodes. Our Rutherford backscattering spectrometry (RBS) analysis[4] shows the diffusion of W atoms into the GaAs substrate to a depth of about 500 Å below the metal/semiconductor interface after annealing at 700 °C. Bright field transmission electron micrographs indicate a flat diode interface up to an annealing temperature of 700 °C. We have attributed the increase in the series resistance of 700 °C annealed diode to the

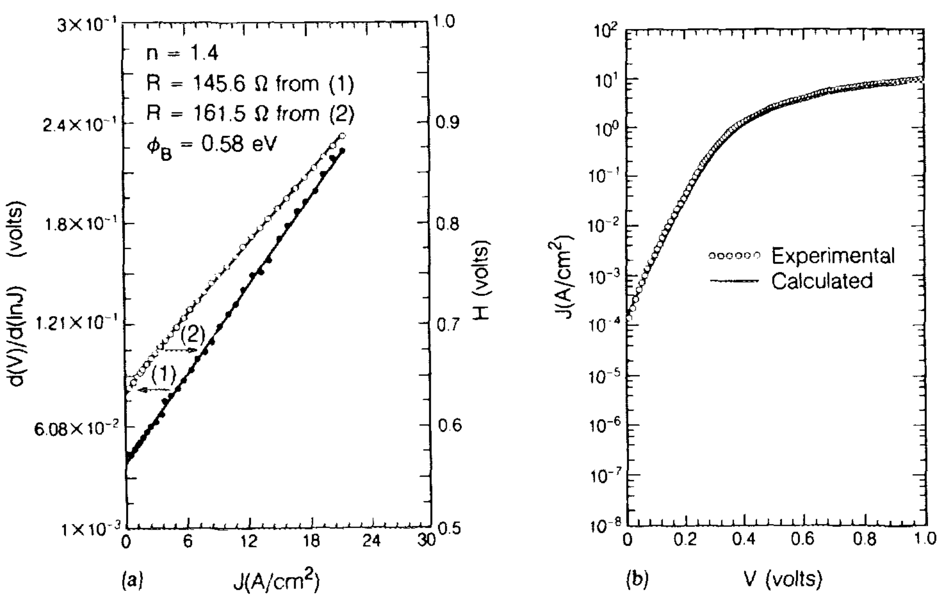

FIG. 2. 700 °C annealed W/GaAs Schottky diode. (a) Plots of $d(V)/d(\ln J)$ vs J and $H(J)$ vs J. (b) Experimental and calculated $\ln J$ vs V plots.

TABLE I. Extracted diode parameters for W/GaAs Schottky diodes.

Annealing temperature (°C)	n	R^a (Ω)	R^b (Ω)	ϕ_B (eV)
As deposited	1.13	18.8	20.8	0.56
100	1.14	4.9	5.4	0.57
300	1.12	3.8	4.3	0.63
600	1.24	6.9	7.6	0.56
700	1.40	145.6	161.5	0.58

[a] From $d(V)/d(\ln J)$ vs J.
[b] From $H(J)$ vs J.

electrical compensation of the substrate dopants by the in-diffused W atoms, leading to the formation of a diffused and highly resistive layer at the W/GaAs interface and the observed deviations from ideal Schottky diode behavior of the 700 °C annealed diode ($n = 1.4$).[4] According to our RBS results, the onset of W in-diffusion occurs at temperatures around 600 °C. The initial reduction in series resistance when the as-deposited diode is subjected to annealing may be attributed to the thermal removal of an interfacial native oxide.

In summary, it is shown that by using the forward I-V data of a given Schottky diode with known area, two linear plots, namely, $d(V)/d(\ln J)$ vs J and $H(J)$ vs J, can be generated. From the slopes and y-axis intercepts of these two plots, the values of the ideality factor, barrier height, and series resistance of the Schottky diode can be determined. These extracted diode parameters can then be used to generate a calculated $\ln J$ vs V plot for comparison with the experimental $\ln J$ vs V plot of the Schottky diode. The good agreement between the calculated and experimental plots observed for different diodes confirms the validity of this approach.

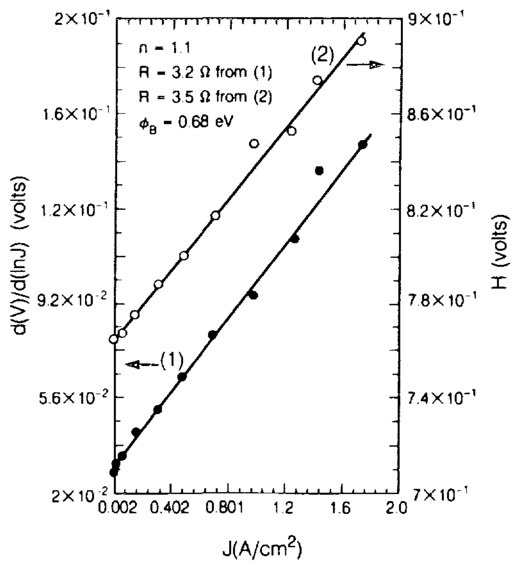

FIG. 3. Plots of $d(V)/d(\ln J)$ vs J and $H(J)$ vs J for the Mo/Si Schottky diode measured at 297 °C by Sato and Yasumura (see Ref. 3).

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