Current Transport in Large-Area Schottky Barrier Diodes

G. S. VISWESWARAN AND R. SHARAN

Abstract—**The conventional method used to determine the mechanism of current transport in a Schottky barrier diode can lead to erroneous inferences if a fluctuation of parameters, such as that which would occur in a large area diode, is present. This has been illustrated by taking a Gaussian variation of a parameter in case of diodes showing T_o anomaly.**

Methods for determining the mechanism of current transport in small-area Schottky barrier diodes are rather well-known [1]. Commonly, one considers that the current flow across the barrier is due to thermionic emission (TE), thermionic field emission (TFE), or field emission (FE) [2]. To determine which one of these three is the operative mechanism in a given diode, it is customary to use the method suggested by Saxena [1]. The method consists of obtaining the current-voltage (I-V) characteristics in the forward region at different temperatures (T), and thereby plotting V_T versus T, where V_T is the inverse of the slope of the ln I-V characteristics at a constant current. The typical nature of the resulting plot is shown in the inset of Fig. 1, where the curves I, II, and III represent the cases where TE is the mechanism of current transport with unity ideality factor, with ideality factor greater than unity, and with T_o anomaly [3], [4], respectively. Curves IV and V correspond to TFE and FE, respectively.

In recent years, due to their application in photovoltaic [5] and power devices [6], it has become necessary to fabricate large-area Schottky barrier diodes. To determine the mechanisms of current transport in these cases, the method suggested by Saxena [1] has also been utilized [7], leading to ambiguous results as already pointed out [8]. The ambiguity has arisen from the fact that the experimental plot of V_T versus T for large-area Schottky diode has shown the mechanism to be field emission [7] in a low-doping and high-temperature range where field emission is not possible [8]. The purpose of the present communication is to demonstrate that even though the mechanism of current transport in a large-area Schottky diode is TE with T_o anomaly, the fluctuations of parameters can create a situation so that the experimental plot of V_T versus T would show FE to be the mechanism of transport.

Before proceeding further, we note two important observations regarding the Schottky diodes which show T_o anomaly. The first is in the work of Levine [3] and Crowell [4], where it is established that T_o anomaly is due to a surface charge distribution [4, eq. (5)],

$$Q_{ss} = Q_f\left[\exp\left(-(\phi - \phi^*)/E_o\right) - 1\right] \quad (1)$$

where ϕ^* defines the neutral level at the surface, ϕ is the barrier height, E_o is a characteristic energy, and Q_f is the fixed ion surface charge that balances the interface state charge at the flat-band configuration. It has also been predicted that T_o is uniquely related to E_o [3]. The second observation is due to Padovani [2] who has noted that different Au-n-GaAs Schottky diodes made on the same wafer showed different values of T_o. Guided by these observations, we have assumed that for a large-area diode the value of E_o fluctuates. It has been further assumed that the variation of areas ΔAi of patches with values of E_o between E_{oi} and $E_{oi} + \Delta E_{oi}$ has a Gaussian distribution, i.e.,

$$\frac{\Delta Ai}{A} = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left\{-\frac{(E_{oi} - \bar{E}_o)^2}{2\sigma^2}\right\} \Delta E_{oi} \quad (2)$$

where $\bar{E}_o$ is the mean value of E_{oi}'s, σ is the standard deviation, and A is the total area of the diode. The total current (I) flowing in the diode can then be written as:

$$I = AJ = A^* T^2 \int_{E_{oi1}}^{E_{oi2}} \left(\frac{dA_i}{dE_{oi}}\right)\left\{\exp\left(-\frac{\phi_i}{kT}\right)\right\}\left\{\exp\left(\frac{qV}{kT}\right) - 1\right\} dE_{oi} \quad (3)$$

where T is the temperature, A^* is the Richardson constant, q is the charge on the electron, k is the Boltzmann constant, ϕ_i is the barrier height of the ith patch, and V is the applied voltage. To evaluate the value of current at different temperatures from (3), one needs the values of $\bar{E}_o$, σ, ϕ_i, E_{oi1}, E_{oi2}, A^*, and the area A which is taken to be 1 cm^2. To obtain the value of $\bar{E}_o$, several Au-nSi Schottky barrier diodes were made which showed T_o anomaly, and there was a variation of T_o among the diodes made on the same wafer. Corresponding E_o values were calculated using (19) of [3] and the average value obtained was taken as $\bar{E}_o$ and is given in Fig. 1, where a plot of V_T versus T with σ as a parameter is shown. The value of ϕ_i is calculated from (1) which needs the value of Q_{ss}, ϕ^* and Q_f/qE_o. From charge neutrality, one obtains $Q_{ss}(T) = Q_{sc}(T)$, where Q_{sc} is the space charge under depletion approximation [9]. The value of $\phi^*(T)$ is equal to $[E_g(T) - \phi_o]$ where the band-gap $E_g(T)$ of silicon and the value of neutral level ϕ_o (0.27 eV as measured from the valence band) are taken from Sze [9]. Using in (1) the measured values of the barrier height and the characteristic energy E_o for several diodes, an average value of $|Q_f/qE_o| = 1.48 \times 10^{11}$ cm^{-2}/eV has been obtained. The value of A^* is taken to be 42 A/cm^2/K^2 [10]. The limits of integration E_{oi1} and E_{oi2} are taken to be 2σ away from E_o. Using these values, the I-V characteristics at different temperature and the corresponding V_T have been calculated.

As already mentioned, a plot of V_T versus T is given in Fig. 1 for a fixed value of $\bar{E}_o$ and four different values of σ. The following features

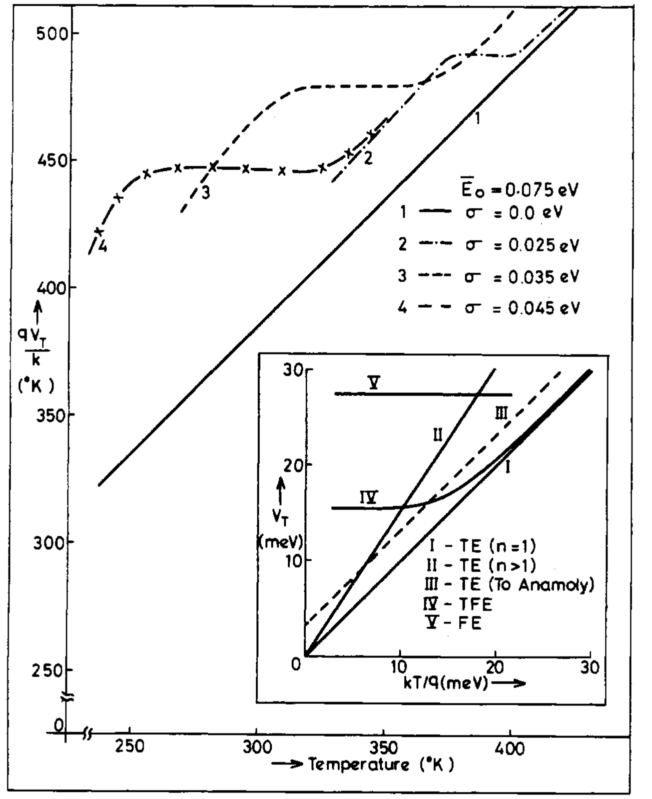


Fig. 1. Plot of qV_T/k versus T with σ as a parameter. The donor density is 2.5×10^{15} cm^{-3}. The inset shows Fig. 2 of Saxena [1].

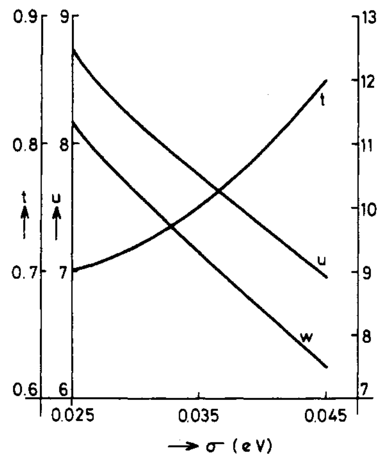


Fig. 2. Plot of u, w, and t, versus σ with $\bar{E}_o = 0.075$ eV. Other parameters are as in Fig. 1.

Manuscript received July 6, 1978.

The authors are with the Department of Electrical Engineering, the Indian Institute of Technology, Kanpur 208016, India.

0018-9219/79/0300-0436$00.75

of this plot should be noted: 1) For a given $\bar{E}_O$ when $\sigma = 0$, one gets a plot which is typical of T_O anomaly, i.e., a straight line parallel to unity ideality factor line, but not passing through the origin. As the value of σ becomes finite, a flat region appears which is typical of FE in the conventional interpretation. Thus, although the mechanism of current transport in the diode is TE, the fluctuations of parameters have brought in the characteristics of FE if attention is restricted to a limited range of temperature. This suggests that caution should be exercised while inferring the mechanism of current transport in Schottky diode from V_T versus T plots. 2) Let the flat regions obtained for nonzero σ in Fig. 1 be bounded by temperatures T_1 in the lower limit and T_u in the upper limit. It would be advantageous to express T_1 and T_u in terms of geometrical and material parameters of the diode so that if desired the range $T_u - T_1$ and the mean position $(T_1 + T_u)/2$ can be controlled. It has been found that $(T_1 + T_u)/100°K = u - t$ and $(T_1/100°K) \times (T_u/100°K) = w/t$, where u, w, and t are dimensionless quantities and are, inter alia, dependent upon $\bar{E}_O$ and σ. The calculation of u, w, and t has been done by analytically differentiating $\ln I$ from (2) with respect to V, then again taking a derivative of its inverse with respect to temperature and equating it to zero. This results, with some approximations, in a cubic equation in temperature of the form $T'^3 - uT'^2 + vT' - w = 0$ where $T' = (T/100°K)$. The three roots of this equation are t, T_1, and T_u. Our interest is in the plots of u, w, and t versus σ which is given in Fig. 2 for the same values of parameters as in Fig. 1. The correlation between the values T_1 and T_u calculated from the plot of Fig. 2 and those obtained in Fig. 1 has been found to be good.

In conclusion, it has been shown that the methods which are commonly utilized to determine the mechanism of current transport in Schottky diodes can lead to erroneous conclusions if the fluctuation of some of the parameters are present. This has been illustrated by taking the case of diodes with T_O anomaly and by using a Gaussian nature of fluctuation of parameters. It is obvious, of course, that this is only a particular case and has been used to illustrate the point. In actual practice, more complicated situations can arise which would need further systematic study.

References

[1] A. N. Saxena, "Forward current-voltage characteristics of Schottky barriers on n-type silicon," *Surface Sci.*, vol. 13, pp. 151–171, 1969.

[2] F. A. Padovani, *Semiconductors and Semimetals*, vol. 7A, R. K. Willardson and A. C. Beer, Eds. New York: Academic Press, 1971, p. 75.

[3] J. D. Levine, "Schottky barrier anomalies and interface states," *J. of Appl. Phys.*, vol. 42, pp. 3991–3999, 1971.

[4] C. R. Crowell, "The physical significance of the T_O anomalies in Schottky barriers," *Solid-State Electron.*, vol. 20, pp. 171–175, 1977.

[5] H. J. Hovel, *Solar Cells, Semiconductors and Semimetals*, vol. 11, R. K. Willardson and A. C. Beer, Eds. New York: Academic Press, 1975.

[6] D. Cooper, B. Bixby, and L. Carver, "Power Schottky diodes—a smart choice for fast rectifiers," *Electron.* (USA), vol. 49, no. 3, pp. 85–89, 1976.

[7] S. M. Vernon and W. A. Anderson, "Temperature effects in Schottky barrier silicon solar cells," *Appl. Phys. Lett.*, vol. 26, pp. 707–709, 1975.

[8] B. Bhaumik and R. Sharan, "Temperature effects in Schottky barrier solar cells," *Appl. Phys. Lett.*, vol. 29, pp. 257–259, 1976.

[9] S. M. Sze, *Physics of Semiconductor Devices*. New York: Wiley-Interscience, 1969. (Q_{SC} (p. 371), $E_g(T)$ (p. 24), ϕ_O (p. 373).

[10] C. R. Crowell, "Thermionic Field Emission in Schottky barrier diodes," *Solid-State Electron.*, vol. 12, pp. 55–59, 1969.

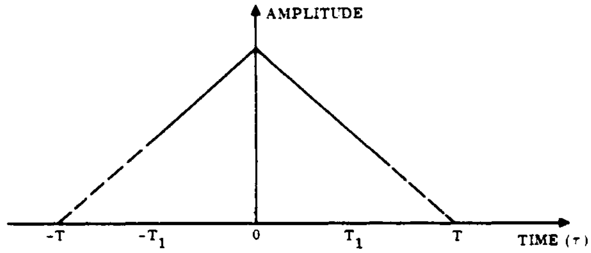
Spectral Estimation: An Impossibility?

RAMON NITZBERG

***Abstract*—Many methods of estimating the power spectrum are based upon the autocorrelation function. As the data is finite in duration, only a portion of the autocorrelation function can be directly estimated. An example of the insufficiency of using only a portion of the autocorrelation function for spectral estimation is discussed.**

Manuscript received July 24, 1978.

The author is with General Electric Company, Syracuse, NY 13221.



$(\tau) = 1 - \frac{|\tau|}{T}$; $|\tau| \le T_1$

$R(\tau)$ = Unspecified; $|\tau| > T_1$

Fig. 1.

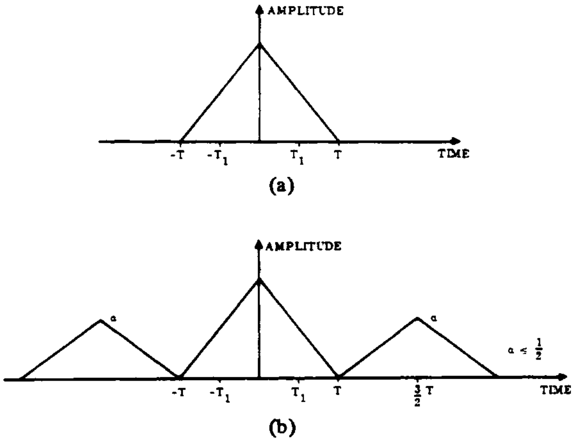


Fig. 2.

I. Introduction

The literature on techniques for spectral estimation is extensive. Recently, emphasis has been placed upon spectral estimation by maximum entropy [1] and associated techniques. This technique was developed to overcome the poor frequency resolution associated with short duration data streams. The finite-duration estimated autocorrelation function is extended over all time by the maximum entropy algorithm. It has been shown that the maximum entropy technique is equivalent to assuming the data stream has been generated by an all-pole network [2]. Alternate techniques that are based upon other network assumptions, such as all-zero networks, or mixed poles, and zeroes networks, have also been suggested and evaluated.

A recent paper by Gutowski *et al.* [3] reported the results of generating three random time sequences by using three different models: autoregressive (AR), moving average (MA), and autoregressive-moving average (ARMA). These models correspond to a recursive feedback digital filter (all-pole network); feed-forward digital filter (all-zero network), and a mixed feed-forward-feedback digital filter (both poles and zeroes network). For each case they estimated power spectra using techniques appropriate to each of the three models. They show that spectral estimates obtained when using the inappropriate models tended to differ significantly from the true spectrum. It is shown in the next section that model mismatch is a fundamental problem and the spectral estimation error is not primarily due to random errors involved in the estimation procedures.

II. Truncated Autocorrelation Functions

Most spectral estimation procedures initially estimate an autocorrelation sequence, sometimes in a disguised form, and then use this sequence to estimate the spectrum. Spectral estimation difficulties are often "blamed" upon errors in this initial autocorrelation estimate. We will assume that in some unspecified manner, the *exact* autocorrelation *function* (not just the sequence) is known over the time interval $(-T_1, T_1)$. An example is shown in Fig. 1. Two candidates for the complete autocorrelation function are shown in Fig. 2. It is clear that many other candidates exist. The specific values and even the functional form of the power spectra of the various candidates differ in a gross