dundancy inherent in the analysis may be used to reduce the effects of measurement noise, connector scatter, and imperfect descriptions of the calibrating standards.

It is suggested that, in practice, the standards be four short circuits offset by approximately 90°, and a near match. These standards are convenient because of their availability, and beneficial in that their distribution is likely to avoid the accuracy degradation which can occur when measuring in areas of the Smith chart remote from a calibrating standard. Results are presented which demonstrate the viability of the calibration method.

A BASIC listing of the calibration algorithm is available from the authors.

Appendix

Expressions [5] for the constants F_i, G_i, and H_i in terms of the q_i and A_i, and for γ_i are given here in compact programmable form:

$$F_i = \frac{(-1)^i}{2q_i}\left[|A_j|^2(b_k - b_l) + |A_k|^2(b_l - b_j) + |A_l|^2(b_j - b_k)\right]$$

$$G_i = \frac{(-1)^i}{2q_i}\left[|A_j|^2(a_k - a_l) + |A_k|^2(a_l - a_j) + |A_l|^2(a_j - a_k)\right]$$

$$H_i = \frac{(-1)^i}{q_i}\left[|A_j|^2(a_k b_l - a_l b_k) + |A_k|^2(a_l b_j - a_j b_l) + |A_l|^2(a_j b_k - a_k b_j)\right]$$

$$\gamma_i = (c_j - c_k)\left[(s_i - s_j)(c_k - c_l) - (c_i - c_j)(s_k - s_l)\right] + (c_k - c_l)\left[(s_l - s_i)(c_j - c_k) - (c_l - c_i)(s_j - s_k)\right]$$

where

$$i = 1, 2, 3, \text{ and } 4,$$
$$j = i+1,\ k = i+2, \text{ and } l = i+3,$$
$$A_i = A_{i+4} = a_i + jb_i,$$
$$q_4 = 1, \text{ and}$$
$$\gamma_i = \gamma_{i+4}.$$

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Letters

Comments on "Theory and Measurement of Back Bias Voltage in IMPATT Diodes"

S.C. TIWARI

In the above paper,[1] back bias voltage in IMPATT diodes has been discussed in detail; however, some previous work on this problem has gone unnoticed. Bracket [1] first pointed out that RF-induced negative resistance was responsible for low-frequency instability which was ten times or so higher in GaAs as compared to Si diodes. Using sinusoidal RF voltage, he considered rectification in the avalanche region which showed that the dc operating voltage decreased with increasing RF voltage amplitude. Lee *et al.* [2] first discussed anomalous rectification in dc current when second-order terms in voltage were considered in their analysis. We have also independently found [3], [4] the existence of abnormal rectification in our self-consistent nonlinear avalanche region analysis. It is the purpose of this paper to briefly report relevant results.

The standard nonlinear integro-differential Read equation is solved self-consistently based on a functional relation between avalanche generated current density $J_{ca}(t)$ and the avalanche region electric field $E_a(t)$ under simplifying assumptions discussed in [3] and [5]. Although the effect of reverse saturation current has also been considered, we write the expressions for $J_s = 0$ given by

$$J_{ca}(t) = J_{ca}(0)\exp(K_i \sin \omega t / \tau_i \omega) \quad (1)$$

$$E_a(t) = b/(\ln(ax_a) - \ln(1 + K_i \cos \omega t))^{1/m} \quad (2)$$

where $J_{ca}(0)$ is $J_{ca}(t)$ at $t = 0$, τ_i is the intrinsic response time, K_i is the injection parameter which determines the RF voltage amplitude, a, b, and m are ionization rate parameters, and x_a is the avalanche region width. The Fourier components of J_{ca} and E_a can be calculated using (1) and (2), and the standard drift region analysis (e.g., [5]) is used to calculate various quantities of interest. The results of calculation for GaAs diodes using ionization rate parameters measured by Salmer *et al.* [6] are presented

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[1] L. H. Holway, Jr., and S. L. G. Chu, *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 916–922, 1983.

0018-9480/85/0100-0072$01.00

TABLE I
RECTIFICATION EFFECT IN GaAs DIODES AT ROOM TEMPERATURE

Frequency = 12GHz	Drift Transit Angle = π	Bias Current Density = 500 A/Cm^2			
$x_a = 0.2$ μm		$x_a = 0.4$ μm		$x_a = 1.0$ μm	
V_{RF}(V)	V_0(V)	V_{RF}(V)	V_0(V)	V_{RF}(V)	V_0(V)
4.61	51.47	1.91	57.12	2.64	70.47
10.25	52.12	4.13	57.1	4.0	70.31
16.4	53.26	6.5	57.07	8.5	69.34
22.96	54.94	9.0	57.03	12.1	68.0
37.63	60.2	24.22	55.55	18.0	64.23

in Table I. The change in voltage due to temperature rise and space charge resistance is not included. It can be seen that for $x_a = 0.2$ μm the abnormal rectification occurs. The value of ax_a determines whether rectification due to the harmonics of E_a is additive or subtractive. The avalanche voltage $E_a x_a$ is nonsinusoidal, and this is primarily responsible for abnormal rectification for appropriate values of ax_a. Using effective ionization rates for Si, it is found that even for $x_a = 0.1$ μm normal rectification occurs. Since a increases with increasing temperature, the abnormal rectification should depend upon the temperature also. If Hall and Leck [7] ionization rate parameters for GaAs are used, an interesting case is found for $x_a = 0.2$ μm. V_0 increases with increasing V_{RF} and starts decreasing after 45-percent modulation. Thus, it is clear that the value of the ionization rate parameters and the avalanche region width critically determine whether the recitification is normal or abnormal. This seems to be the reason that Holway and Chu have found abnormal rectification for x_a between 0.1 and 0.5 μm.

We have noted earlier [4] that "the nonlinearity of the ionization process gives rise to a new rectification effect termed as abnormal rectification for small values of the avalanche region widths which should make such diodes to be free from RF tuning induced burn out." Since we were unaware of the work of Goedbloed [8], indirect support to our prediction of abnormal rectification was sought from the result of Iglesias *et al.* [9] that the diodes with $x_a = 0.2$ μm were less susceptible to RF tuning induced burn out. Further, without rederiving the Read equation to a higher order, our nonlinear solution admits the possibility of anomalous back bias voltage in IMPATT diodes.

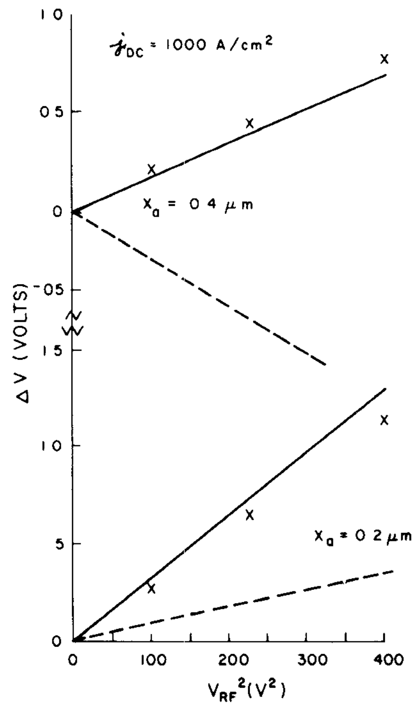

Fig. 1. $\Delta V = V_{dc} - V_0$ versus V_{RF}^2 for $x_a = 0.2$ μm and 0.4 μm. The dc current density is 1000 A/cm^2; V_0, which includes space charge resistance, is 46.5 and 40.5 V, respectively, in the two cases. The crosses are finite difference calculations, the solid lines are (1) and the dashed lines are the classical Read result where $c_2 = 0$.

Reply[2] by L. H. Holway, Jr., and S. L. G. Chu[3]

We clearly state in our paper[1] that the classical Read equation gives positive back bias voltages for avalanche widths less than 0.25 μm. The calculations in Tawari's "Comments" above do no more than verify this fact. However, our experiment showed a positive ΔV for an avalanche width x_a of 0.37 μm, a thickness at which both the classical result and Tiwari's calculations predict a negative back bias. In our paper,[1] by including second-order terms in the derivation of the Read equation in an expansion in powers of $\delta = \alpha x_a - 1$, we derived an equation for the back bias

$$\Delta V = (c_1 + c_2) w_T E_{RF}^2 \tag{1}$$

where $c_1 = -\alpha''/4\alpha'$ is the term from the classical Read equation and $c_2 = x_a \alpha'/10$ is a new term, always positive and usually larger in magnitude than c_1. With this new term, (1) predicted a ΔV in agreement with our measurements.

[2]Manuscript received June 14, 1984.
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Recently, we verified (1) in another way, by comparison with a finite-difference computer program, which solves the continuity equation directly, neglecting diffusion and using the values for α and saturated velocity given at 200°C in our paper.[1] The results shown in Fig. 1 are for $x_a = 0.2$ μm and 0.4 μm so that comparisons can be made with both Table II of our paper[1] and with Tiwari's calculations. All calculations were for a symmetric double-drift diode of width $w_T = 2$ μm. The spikes are 2.42×10^{12} cm^{-2} and 2.07×10^{12} cm^{-2}, respectively, and drift region dopings are 3×10^{15} cm^{-3}. However, the results are essentially independent of doping spike magnitudes and drift region dopings, provided the diodes are punched-through at all times and the spikes are large enough to prevent significant drift region ionization.

The solid lines in Fig. 1 were calculated from (1), using Table II of our paper[1] and assuming $V_{RF} = w_T E_{RF}$; the dotted lines were the classical result in which c_2 was eliminated from (1). For $x_a = 0.4$ μm, both the classical results and Tiwari's calculation show the dc voltage decreasing with V_{RF} while (1), the computer calculations, and our experiment all agree that the dc voltage increases. This verifies the correctness of our mathematical dem-

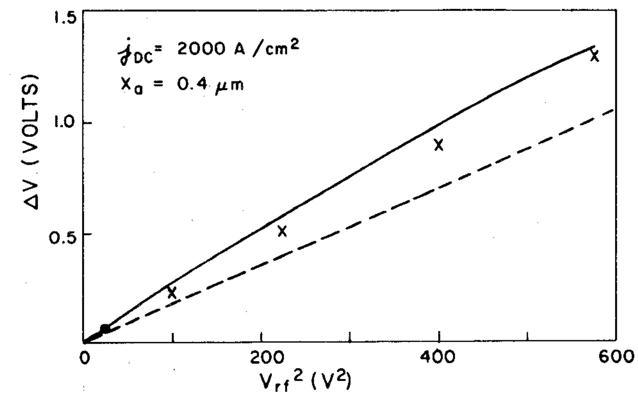

Fig. 2. ΔV versus V_{RF}^2 for $x_a = 0.4$ μm when $j_{DC} = 2000$ A/cm^2. The solid curve includes the effect of space charge on γ while the dashed line assumes $\gamma = 1$.

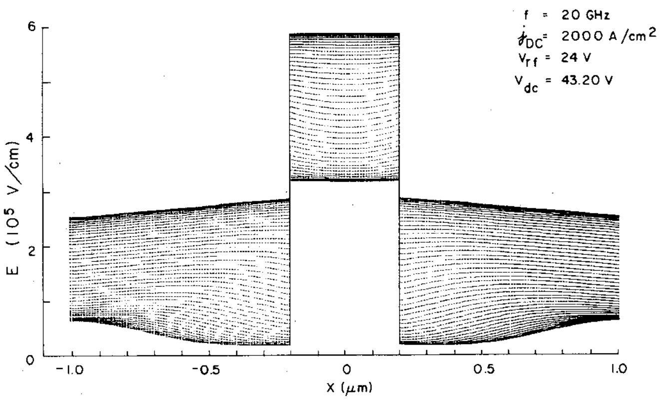

Fig. 3. Electric field versus distance at successive instants of time. The curves for $V_{RF} = 24$ V and the conditions of Fig. 2 are shown as the phase changes from 90° to 270° in steps of 4°.

onstration[1] that the classical Read equation must be modified in order to predict ΔV. Apparently, Tiwari thinks an inaccuracy results from using only the first two terms in the Taylor's expansion. The close agreement of (1) with the computer calculations demonstrates that the Taylor's expansion is adequate if the modified Read equation is used. We should point out that the modification of the classical Read equation, while it is crucial in calculating ΔV, has only a very small effect on the calculation of the negative conductance of the diode.

At larger currents, we must take $E_{RF} = V_{RF}/\gamma w_T$, where γ, which takes into account space-charge effects, is defined in our paper.[1] The solid curve in Fig. 2, in which the dc current has been increased to 2000 A/cm^2, includes the effects of γ in (1), and replaces the dotted straight line which assumes $\gamma = 1$. The electric field values for this current density and $V_{RF} = 24$ V are shown in Fig. 3. Here the curves show the spatial value of E at specific instants of time as the phase of the external voltage increases from 90° to 270° in steps of 4°. The space charge moving into the drift region when the phase is near 180° causes the field lines to curve upward.

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Corrections to "Theory and Application of Coupling Between Curved Transmission Lines"

MOHAMED ABOUZAHRA, MEMBER, IEEE AND LEONARD LEWIN, FELLOW, IEEE

In the above paper,[1] the following corrections should be made. On page 1990, (8) should read

$$i_1(-\infty) = (\Delta\beta)^2 \left\{ \frac{\pi R}{h} e^{-R\beta_0^2/h} - j\frac{2R\sqrt{\pi}}{h} \cdot e^{-R\beta_0^2/2h} \mathrm{Daw}\left[\beta_0 \sqrt{\frac{R}{2h}}\right] \right\} + 0(\Delta\beta)^4.$$

Equation (9) should read

$$i_2(-\infty) = j\Delta\beta \sqrt{\frac{\pi R}{h}}\, e^{-R\beta_0^2/h} + 0(\Delta\beta)^3.$$

On page 1993, (A11) should read

$$b(s) = \frac{1}{2\beta_0} \frac{d}{ds}\left[\frac{a'(z)}{a^2(z)}\right] + \frac{1}{4\beta_0^2}\left[\frac{a'(z)}{a^2(z)}\right]^2.$$

The sentence that follows (A12) should read, "With $\beta_0 L \gg 1$ and then $\cdots$."

On page 1994, (A14) should read

$$U''_1 + U_1 = \frac{U_0}{2} \frac{d}{ds}\left[\frac{a'(z)}{a^2(z)}\right].$$

Equation (A15) should read

$$U_0(s) = Ae^{-js} + Be^{+js}.$$

Equation (A19) should read

$$U_1(s) = C_1 e^{-js} + C_2 e^{+js} + \frac{e^{-js}}{4j}\int_{r_1}^{s} e^{js'} U_0(s') \frac{d}{ds'}\left[\frac{a'(z')}{a^2(z')}\right] \cdot dz' - \frac{e^{+js}}{4j}\int_{r_2}^{s} e^{-js'} U_0(s') \frac{d}{ds'}\left[\frac{a'(z')}{a^2(z')}\right] ds'.$$

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[1] M. Abouzahra and L. Lewin, *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 1988–1995, Nov. 1982.