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A study of the ionization rates of electrons and holes in GaAs using a computer analysis of the properties of GaAs IMPATTs

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Investigations by Stillman *et al.* [Appl. Phys. Lett. **24**, 471 (1974)] and Ito *et al.* [J. Appl. Phys. **49**, 4607 (1978)], mainly based on photomultiplication measurements, suggest that in GaAs the ionization rates of electrons and holes are not identical. Though the results of the two investigations are in qualitative agreement, there is a considerable difference in the numerical values of the ionization rates. A computer study of the dc properties of the linearly graded and high-low type GaAs IMPATT diodes using the ionization rate data of Stillman *et al.* and Ito *et al.* has been carried out, and it has been found that the data of Ito *et al.* are in closer agreement with the experimental breakdown voltage data.

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Investigations on the inequality of the ionization rates of electrons and holes (α and β, respectively) in GaAs have recently aroused considerable interest in view of the increasing importance of GaAs as a semiconducting material for avalanche photodiodes (APD) and IMPATTs. Previously, the ionization rates of the two types of carriers in GaAs were considered to be identical. Photomultiplication measurements of Logan and Sze[1,2] on diffused p^+-n and n^+-p GaAs junctions indicated that $\alpha = \beta$, in all measurements since then equality of ionization rates were reported.[3–6] However, it is interesting to note that the wavelength of incident radiation for carrier multiplication was not varied during these earlier experiments and hence the equality of the ionization rates of the charge carriers could not be vigorously ascertained.

In 1973 Lindley *et al.*[7] studied the noise performance of GaAs APD's and observed that the noise power increased as $M^{2.1}$ for the variation of multiplication factor between 5 and 120. Earlier theoretical analysis by McIntyre[8] indicated that the noise power of GaAs APD's should vary as M^3 if $\alpha = \beta$ and as M^2 if the ionization rates are considerably different. This led researchers to investigate more accurately the ionization rates in GaAs by achieving pure electron and hole injections in the photomultiplication experiments. Thus Stillman *et al.*[9] studied the variation of multiplication factors (M_n or M_p) with bias voltage in Schottky-barrier GaAs APD's in the field range $(2.5–3.3)\times 10^5$ V cm^{-1} and calculated the electron and hold ionization coefficients from the multiplication data. In calculating the ionization rates from the multiplication data they used the expression derived by Woods *et al.*[10] assuming linear variation of electric field in the depletion layer of a Schottky-barrier diode. Stillman *et al.* found that the ionization rate for holes was larger than that of electrons. Sudbury and Laton[11] fitted the data of Stillman *et al.* with an expression

$$\alpha = 1.2\times 10^7 \exp(-2.3\times 10^6/E),$$

and

$$\beta = 3.6\times 10^8 \exp(-2.9\times 10^6/E) \quad (1)$$

in their small-signal analysis of GaAs avalanche diode. In 1978 Ito *et al.*[12] determined the ionization rates of carriers in GaAs from the measurement of photocarrier multiplication. They employed a GaAs p-n junction having a crater mesa structure so that pure injection of holes and electrons could be obtained by illuminating the center of the crater and the annular ring round the crater, respectively. Ito *et al.* also used the formula of Woods *et al.* to evaluate α and β from the multiplication data.

Though the results of Ito *et al.* are in qualitative agreement with those of Stillman *et al.*, still there is a considerable difference in the numerical values of the ionization rates. The ionization rates for holes and electrons can be expressed according to the data of Ito *et al.* as

$$\alpha = 5.6\times 10^6 \exp(-2.41\times 10^6/E)$$

and

$$\beta = 1.5\times 10^6 \exp(-1.57\times 10^6/E), \quad (2)$$

respectively.

In view of the considerable difference in the ionization rate expressions (1) and (2), it is interesting to test the agreement of the data with the breakdown voltage measurements on GaAs diodes of different types of structures.

The purpose of the present paper is to ascertain the validity of the two sets of ionization rate data by applying them to determine the breakdown voltage of (i) linearly graded and (ii) high-low (HL) type GaAs avalanche diodes, and to compare the results with available experimental data. The computation of the breakdown voltage has been obtained by accurate determination of field and current profiles in the depletion layer of the device employing a double-iterative computer method recently reported.[13] Computed values of breakdown voltage have been compared with the breakdown voltage measurements of Kressel and Blicher[14] (linearly graded) and Nishitani *et al.*[15] (high-low type).

The computed values of the breakdown voltage of a

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TABLE I. Computed breakdown voltages for GaAs using different ionization rates.

Structure		Calculated values using Stillman data [a]		Calculated values using Ito data [b]		Measured values of breakdown voltage
	Gradient (m^{-4})	Maximum field (V/m)	Breakdown voltage (V)	Maximum field (V/m)	Breakdown voltage (V)	(V)
Linearly	1×10^{30}	3.73×10^{7}	11.2	4.88×10^{7}	16.8	17 [c]
graded	2×10^{28}	3.00×10^{7}	57.6	3.45×10^{7}	71.0	68 [c]
High-low SDR		4.19×10^{7}	7.1	5.87×10^{7}	22.8	19.5 [d]

[a]Ref. 9.
[b]Ref. 12.
[c]Ref. 14.
[d]Ref. 15.

linearly graded (with different impurity gradients), and an HL GaAs diode using the two sets of the ionization rate data has been presented in Table I along with the experimentally determined breakdown voltages. It is evident from Table I that for both linearly graded and HL structures, the breakdown voltages computed from the data of Ito *et al.* are very close to the experimentally determined breakdown voltage. On the other hand, for identical structures, the breakdown voltages computed from the data of Stillman *et al.* are much less than the experimental values.

The present study thus indicates that a better purity of respective carrier injection was achieved by Ito *et al.* through crater mesa structure. It can be concluded that the ionization rate data of GaAs given by Ito *et al.* are consistent with the noise properties of GaAs APD's as well as the breakdown voltage measurements of GaAs avalanche diodes.

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