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Ionization Rates in $(Al_xGa_{1-x})As$*

S. N. SHABDE AND C. YEH

Electron Physics Laboratory, Department of Electrical Engineering, The University of Michigan, Ann Arbor, Michigan 48104

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The ionization rates of $(Al_xGa_{1-x})As$ have been measured as a function of the Al content and the results are presented here. Values of both A and b are found to increase with Al content. It is also found that for low values of Al content, the ionization rates of $(Al_xGa_{1-x})As$ are consistent with Baraff's theory.

The mixed III–V compound $(Al_xGa_{1-x})As$ has recently received considerable attention especially as a potential material for electroluminescent devices[1] and microwave devices such as avalanche diodes.[2] In this correspondence we report ionization rate measurements in this material. Ionization rates have been studied in detail for Si,[3,4] Ge,[5,6] GaAs,[6,7] and GaP.[8,9] The earlier studies which were based on the assumption that the ionization rates of electrons and holes are equal, served to establish the field dependence of these rates. In relatively recent studies,[4,6,9] an experimental refinement of injecting one type of carrier was introduced which made it possible to determine the ionization rates of electrons and holes separately. It is now established that the field dependence of the ionization rates in Si and Ge agrees with the low-field theory of Shockley,[10] while the data on GaAs and GaP are consistent with the high-field theory of Wolff.[11] The results in all four materials are in good agreement with the generalized theory of Baraff[12] which covers both the high- and low-field regions.

The samples available for measurement were junctions formed in $(Al_xGa_{1-x})As$ over a p-type substrate by a single-step liquid epitaxy process.[13] The Al content of the samples were determined from the weight ratio of Al and Ga in the melt.[1] The samples were diced from the wafers and mounted in varactor-diode packages with windows. The typical diode area was 25×10^{-6} in.^{2}.

Several diodes of each composition were tested first to determine the reverse-breakdown characteristic. The ones which showed a sharp breakdown characteristic were selected for ionization rate measurements. Capacitance–voltage measurements were then taken to within 1 V of the breakdown voltage. A square-law relationship between voltage and capacitance was noted for all the diodes. This indicates that the diode junction is an abrupt one.

Multiplication data was obtained by the usual method of measuring the photocurrent generated by a chopped light source in a reverse-biased junction. The multiplication factor M was obtained from this data as a function of electric field. The ionization rate α was then determined as a function of the maximum electric field E_m using the formula

$$1-M^{-1}=\int_0^W \alpha(E)\,dx=mW\alpha(E_m), \qquad (1)$$

where W is the junction width and mW is the effective junction width in which the multiplication takes place if a constant electric field equal to E_m is assumed. The above relation is based on the assumption of equal ionization rates for electrons and holes, i.e., $\alpha_n=\alpha_p$. Since α_n and α_p are equal in both the III–V compounds studied so far (viz., GaAs and GaP), they are not expected to differ significantly in $(Al_xGa_{1-x})As$ with small percentages of Al.

To obtain correct values of $\alpha(E_m)$ from Eq. (1) a method of successive approximation was employed. The field dependence in all the samples studied was found to be of the form

$$\alpha=A\exp-(b/E_m)^2 \qquad (2)$$

which is consistent with Wolff's high-field theory.

The values of A and b for the different compositions studied are shown in Table I. There is a clear trend of an increase in both A and b with the Al content. Table I also shows the measured and the predicted breakdown voltages obtained from the condition

$$\alpha(E_m)W_{\text{eff}}=1. \qquad (3)$$

Although the predicted voltages tend to be somewhat higher than the measured values, the agreement is quite reasonable.

A comprehensive explanation of the ionization results can only be obtained in terms of Baraff's three-parameter theory. The data may be fitted into the Baraff plots by varying two adjustable parameters E_i, the threshold energy for ionization and λ_R, the mean-free path for phonon scattering. A third parameter E_R, the optical phonon energy, must be known in order to determine a particular Baraff curve.

Figure 1 shows Baraff plots for various Al concentrations including the data for pure GaAs. The values of the parameters λ_R and E_i used to obtain the best fits are shown in Table II. E_R is assumed to be equal to 0.036 eV which is the value for pure GaAs. It is seen that with $E_i=1.5E_G$ a value of $\lambda_R=63$ Å is obtained for pure GaAs. This is in agreement with Logan and Sze's[6] data. For low percentages of Al it is found that λ_R decreases with increasing Al concentration. This may be attributed to imperfections introduced by the increasing impurity concentration. It is also seen that E_i obtained for the best fit increases with Al content. This is consistent with the fact that the bandgap energy of the material increases with the Al content. The values of E_i

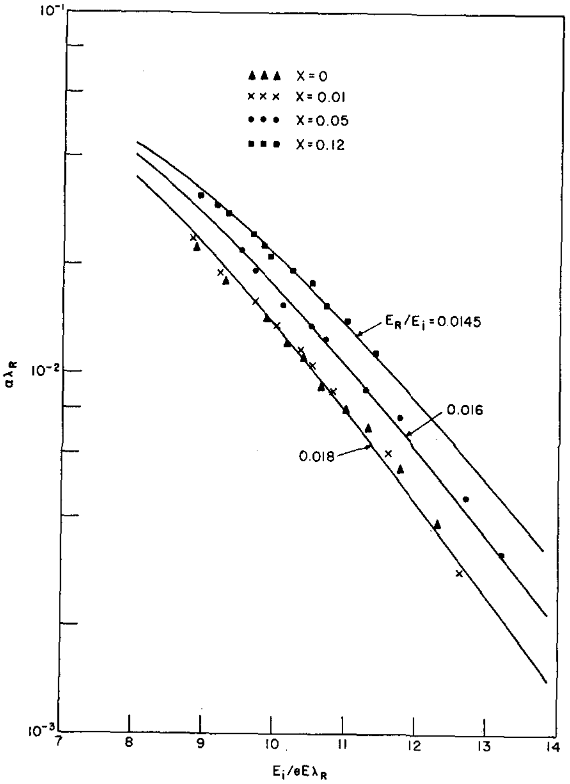

FIG. 1. Baraff plots for various concentrations of Al in $(Al_xGa_{1-x})As$.

TABLE I. Ionization data for $(Al_xGa_{1-x})As$.

x	b (V/cm)	A (cm^{-1})	Breakdown voltage (measured) (V)	Breakdown voltage (predicted) (V)
0	7.2×10^5	3.7×10^5	13.6	14.0
0.01	7.8×10^5	3.1×10^5	15.5	16.5
0.05	9.05×10^5	3.35×10^5	17.0	18.0
0.12	9.3×10^5	3.8×10^5	18.0	19.0
0.24	10.7×10^5	4.3×10^5	25.0	26.5

are found to be somewhat higher than $1.5E_G$ if E_G is obtained from the previously established data.[14,15] Attempts to fit the data for samples with high Al contents become increasingly difficult. This is not surprising considering that the assumptions made (viz., equal ionization rates for electrons and holes and an optical phonon energy equal to that in pure GaAs) are of doubtful validity for samples with higher Al concentrations.

TABLE II. Physical parameters used in Baraff plots.

x	E_i (eV)	λ_R (Å)
0	2.0	63
0.01	2.0	40
0.05	2.25	35
0.12	2.5	40

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