# TEMPERATURE DEPENDENCE OF AVALANCHE MULTIPLICATION IN SEMICONDUCTORS

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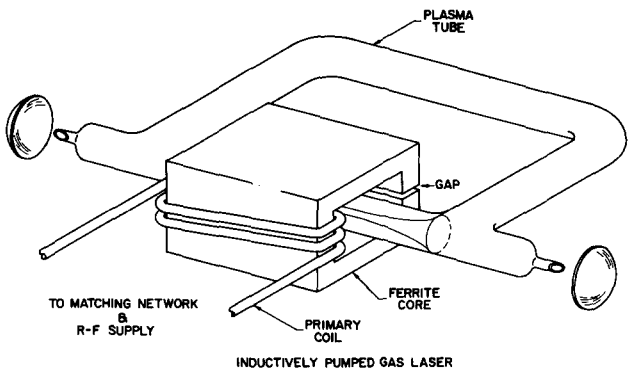


**Fig. 1. Inductively-pumped gas laser.**

The assistance of Clentis K. Williams was of immeasurable aid in this experimental work and the identifications were made with the aid of a computer program by J. B. Davis.

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# TEMPERATURE DEPENDENCE OF AVALANCHE MULTIPLICATION IN SEMICONDUCTORS

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Expressions for the temperature dependence of the carrier mean free path for optical phonon scattering and the mean energy loss per collision are presented which predict avalanche multiplication as a function of electric field for any operating temperature once the appropriate parameters have been determined at a single temperature. This has been verified for electrons in Si by the correlation of measurements at 300°K, 213°K, and 100°K. The temperature dependence of the breakdown voltages of a variety of abrupt and linear-graded Si and Ge *p-n* junctions has also been predicted. The fractional change in breakdown voltage with increasing temperature is predicted to decrease with increased doping concentration and, for the same breakdown voltage, to be less for linear-graded junctions than for abrupt junctions.

Room-temperature secondary ionization rates for electrons and holes have been measured by Miller in Ge,[1] Lee et al. in Si,[2] Logan and White in GaP,[3] and Logan and Sze in GaAs and Ge.[4] The dependence of charge carrier ionization probability per unit distance traveled, $\alpha$, on the electric field, $E$, can be described in terms of Baraff's theory[5] using three parameters, $\epsilon_r$, the Raman optical phonon energy, $\epsilon_i$, the ionization energy, and $\lambda$, the carrier mean free path for optical phonon generation. $\epsilon_i$ values $\approx 3E_g/2$ where $E_g$ is the band gap energy appear most appropriate.[2-4,6] The remaining adjustable parameter is $\lambda$. Average values of $\lambda$ obtained from Baraff's original approach are given in Table I as $\lambda_{(\text{uncorrected})}$. A more rigorous approach would include the effects of both optical phonon generation and absorption rather than generation alone. As a first approximation, the average energy lost per collision, $\langle\epsilon_r\rangle$, can be used in place of $\epsilon_r$ in Baraff's theory. This is important for Ge and GaAs because both semiconductors have $\epsilon_r$ (refs. 7 and 8) values not much larger than $kT$ for $T \sim 300$°K (cf. Table I).

For electrons with an energy $\epsilon > \epsilon_r$, and a density of states at energy $\epsilon$ which does not vary rapidly over an energy increment $\pm\epsilon_r$,

$$\langle\epsilon_r\rangle/\epsilon_r = (2N+1)^{-1} = \tanh(\epsilon_r/2kT) = \lambda/\lambda_0 , \qquad (1)$$

**Table I. Optical Phonon Mean Free Paths.**

| | Ge | Si | | GaAs | GaP |
|---|---|---|---|---|---|
| | | Hole | Electron | | |
| $\epsilon_r$(eV) | .036 | .063 | | .036 | .05 |
| $\lambda$(uncorrected) (Å) | 80 | 40 | 65 | 45 | 38 |
| $\lambda$(300°K) (Å) | 65 | 38 | 62 | 35 | 32 |
| $\lambda_0$(Å) | 105 | 47 | 76 | 58 | 42 |

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where $N$ is the number of phonons per mode of vibration of energy $\epsilon_r$, and $\lambda_0$ is the low temperature limit of the mean free path.[10] If the density of states is parabolic and nonpolar optical phonons are involved, $\lambda$ is independent of energy for $\epsilon \gg \epsilon_r$. For polar optical phonons, as found in GaAs and GaP, $\lambda$ should increase with energy.[11] The analysis should then determine an average mean free path. Note that

$$\langle \epsilon_r \rangle / \lambda = \epsilon_r / \lambda_0 = \text{constant}. \quad (2)$$

Since $1/\lambda$ is the number of collisions per unit distance traveled by a charge carrier, the energy lost per unit path length is independent of the temperature.

Figure 1 shows Baraff's predicted values of $\alpha\lambda$ as a function of $\epsilon_i/eE\lambda$ for two values of $\epsilon_r/\epsilon_i$. The low temperature value of $\epsilon_r/\epsilon_i$ for Ge is 0.036. When generation and absorption are considered, the Baraff curve for $\epsilon_r/\epsilon_i = 0.022$ should be appropriate at room temperature. The experimental data due to Miller,[1] and Logan and Sze,[4] fit both curves with different electron and hole mean free paths for different junctions. The differences in $\lambda$ for the same $\epsilon_r/\epsilon_i$ have been attributed to crystal imperfections.[4] The $\lambda$ and $\lambda_0$ values [from Eq. (1)] obtained for Ge, Si, GaAs, and GaP are listed in Table I. The $\lambda_0$ values are considerably larger, and the $\lambda$'s smaller than the room temperature uncorrected values.

Once $\lambda_0$ is known, Eq. (1) predicts $\lambda$, $\langle \epsilon_r \rangle$, and thus the Baraff normalizing parameters at any temperature. Figure 2 shows the resultant unnormalized plots of ionization rate vs electric field for electrons in Si at 100°K, 213°K, and 400°K, and experimental ionization rates at 100°K and 213°K.[12] The theoretical predictions use the $\lambda_0$ values in Table I. The agreement at both 100°K and 213°K is satisfactory. This further confirms the fundamental significance of $\lambda$ as a mean free path.

These results may be understood qualitatively as follows. In the low-field region the ionization rate is strongly temperature dependent because the ionizing carriers travel several mean free paths without a collision. In the high-field region a greater fraction of the carriers produces ionization and the energy loss per unit distance traveled is more significant. This is less temperature sensitive because

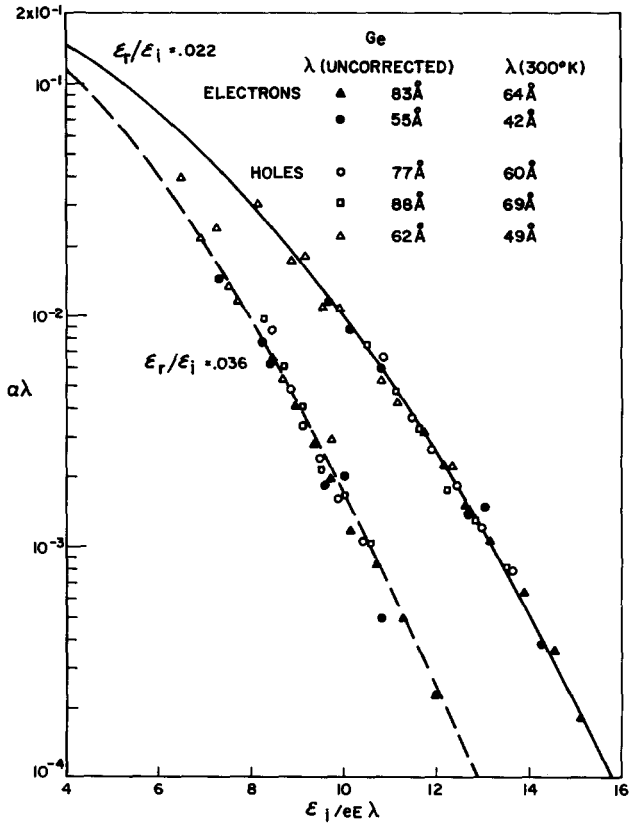


Fig. 1. Ionization rate $\alpha$, as a function of electric field $E$. Legend: ▲,○,□—Logan and Sze[4]; ●,△—Miller[1]; --- Baraff (low temperature approx.); —— present approach.

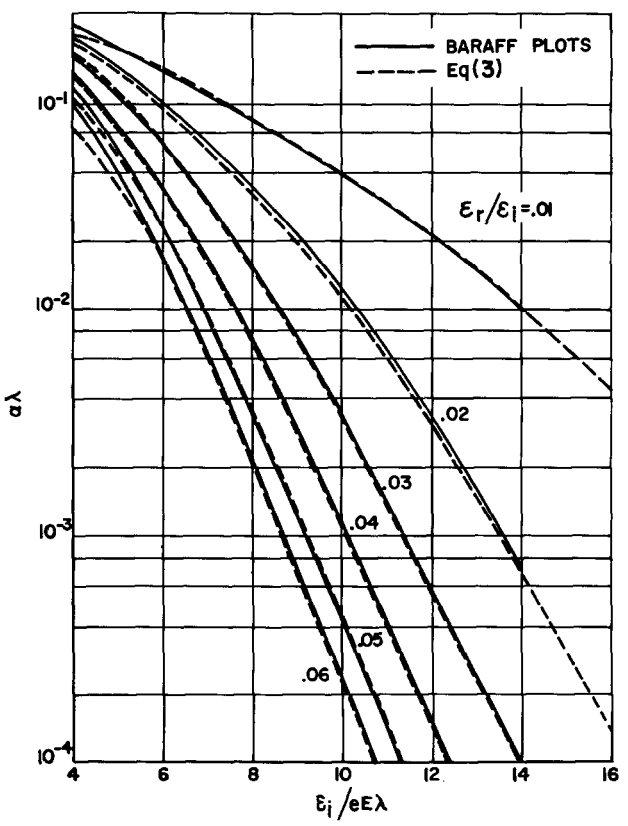


Fig. 2. $\alpha$ vs $1/E$ for electrons in Si at selected temperatures. The data points are experimental.[11] The curves are derived from the room temperature data.

the energy lost per unit path length along the random walk of the carrier is independent of the temperature [cf. Eq. (2)].

To facilitate numerical analysis, Baraff's curves can be represented by the following approximation:

$$\alpha\lambda = \exp\begin{Bmatrix}(11.5r^2 - 1.17r + 3.9\times10^{-4})x^2\\(46r^2 - 11.9r + 1.75\times10^{-2})x\\-757r^2 + 75.5r - 1.92\end{Bmatrix} \qquad (3)$$

where

$$r \equiv \langle\epsilon_r\rangle/\epsilon_i, \text{ and } x \equiv \epsilon_i/eE\lambda\ .$$

Errors in fitting Baraff's curves are within ±2% over the range $0.01 < r < 0.06$ and $5 < x < 16$ (cf. Fig. 3).

Predicted values of $V_B/V_{B(300°K)}$ for abrupt junctions in Ge and Si are shown in Fig. 4. The values of $V_B$ at 300°K have been published previously.[13] Also shown in Fig. 4 are predicted values of $V_B/V_{B(300°K)}$ for Si and Ge linear-graded junctions which have the same room temperature breakdown voltage as abrupt junctions with doping of $10^{15}$ cm$^{-3}$. For the same doping profiles, the predicted percentage change in $V_B$ with temperature is about the same for GaAs and Ge or GaP and Si junctions.

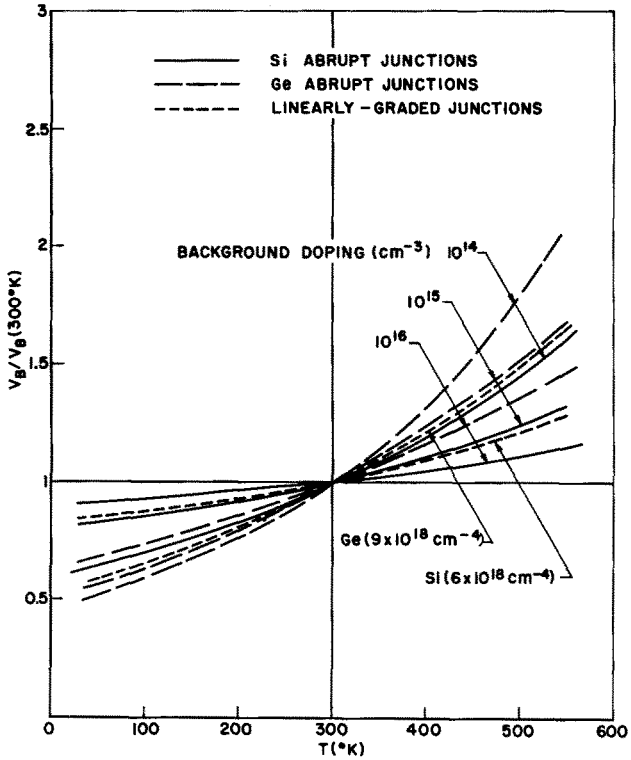


**Fig. 4. Breakdown voltage vs temperature for Si and Ge *p-n* junctions. $V_B$(300°K) is 2000, 330, and 60 V for Si and 950, 150, and 25 V for Ge for dopings of $10^{14}$, $10^{15}$, and $10^{16}$ cm$^{-3}$ respectively. The linear-graded junctions have $V_B$(300°K) the same as those for doping of $10^{15}$ cm$^{-3}$.**

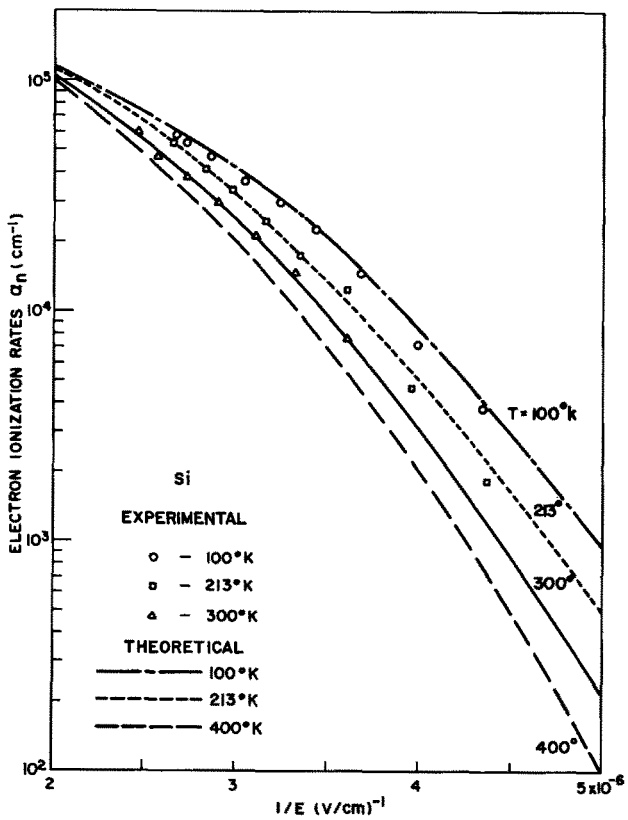


**Fig. 3. Universal Baraff curves (solid lines) and analytical approximations thereto (dashed line).**

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