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Temperature Dependence ot Ionization Rates in Ge

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Abstract

The ionization rates of electron and hole in germanium have been measured from 200°K to 300°K and were fit to the modified Baraff theory, in which the optical phonon mean free path is temperature dependent and can be fit to the formula: $\lambda = \lambda_o \tanh \frac{E_p}{2KT}$, where E_p is the average optical phonon energy.

The asymptotic optical phonon mean free paths wherin deduced from experiments are $\lambda_{oe} = 73 \pm 4$ Å and $\lambda_{ob} = 84 \pm 4$ Å for electron and hole respectively which are in good agreement with that of Miller's data obtained at room temperature.

A simiplified approach to calculate the ionization rates from the photomultiplication data has also been deduced for the one sided abrupt junction.

Theory

The ionization rate in semiconductor plays an important role in its operational characteristics such as breakdown phenomena in p n junction[1] and high field transport in the bulk semiconductors, e.g. in IMPATT, TRAPATT and avalanche photodetectors.[1]

The temperature dependence of the ionization rates in Si and in GaAs has been measured recently[3,4]. In the present report, the ionization rates of electrons and holes in Ge are measured herein over the temperature range from 200°K to 300°K using photomultiplication method. The results are then compared with the modified Baraff theory[2,3], so as to establish a functional dependence of the ionization rates on temperature.

In the Baraff theory[2], the rates are correlated with three material parameters: E_I the ionization thresholc energy; the average carrier mean free path due to phonon scatterings; and $\langle E_P \rangle$, the average energy loss per phonon scattering. The value of E_I is approximately three-halves of the band gap energy[5]. However in the modified Baraff theory, the calculation of the ionization rates still follows the Baraff theory but with the additional information on the temperature dependence of optical phonon mean free path λ, which is given in the following,

$$\lambda = \lambda_o \tanh \left(E_p / 2KT \right) \tag{1}$$

and

$$< E_p > = E_p \tanh \left(E_p / 2KT \right) \tag{2}$$

where λ_o is the high-energy low-temperature asymtotic phonon mean free path, and E_p is the optical phonon energy. For Ge the value[4] of E_p is 0.037eV which is only slightly greater than the room-temperature thermal energy ($KT = 0.026eV$). Thus a large variation of the ionization rates upon temperature is expected in Ge. According to Baraff theory[2], the ionization rates are then related with the optical phonon mean free path.

The multiplication fators of holes M_p, which is related to the electron and the hole ionization rates α_n, α_p for a p^+n junction, is shown as follows,

$$1 - \frac{1}{M_p} = \int_O^W \alpha_p \exp \left[-\int_O^X \left(\alpha_p - \alpha_n \right) dx' \right] dx \tag{3}$$

whereas for electrons,

$$1 - \frac{1}{M_n} = \int_O^W \alpha_n \exp \left[\int_O^X \left(\alpha_p - \alpha_n \right) dx' \right] dx \tag{4}$$

Where W is the width of the depletion layer.

Multiplying Eq. (3) by $\exp \left[-\int_O^X \left(\alpha_p - \alpha_n \right) dx \right]$ and combining with Eq. (4), leads to.

$$\exp \left[\int_O^X \left(\alpha_n - \alpha_p \right) dx \right] = \frac{M_n}{M_p} \tag{5}$$

Since W is related to the maximum junction field E_m. Differentiating Eqs. (3) and (5) with respect to W, then we obtained after some manipulations that,

$$\alpha_p \left(E_m \right) = \frac{M_p}{M_n} E_m \frac{d \left(1 - \frac{1}{M_p} \right)}{dv} \tag{6}$$

and

$$\alpha_n \left(E_m \right) = M_n E_m \frac{d}{dv} \left(1 - \frac{1}{M_n} \right) - \left(M_n - 1 \right) \alpha_p \left(E_m \right) \tag{7}$$

thus we can get the values of α_n and α_p from the above two equations. When $M_p = M_n = M$, Eqs. (6) and (7) automatically reduce to that of GaAs p-n junction[4], $\alpha_n = \alpha_p = E_m \frac{d}{dv} \left(1 - \frac{1}{M} \right)$.

Table I

Temperature °K	Doping* $N(cm^{-3})$	Breakdown Voltage V_B (Volts)	Optical Phonon mean free path λ(Å)		λ_o(Å)	
			electron	hole	electron	hole
300	$4.3\ 10^{15}$	47	47	50	77	82
250	–	44	53	58	77	84
200	–	38	61	69	77	87

* measured from C–V curve.

Experimental

The Ge p–n–p junctions are fabricated by diffusion process, the breakdown properties of Ge diodes are listed in Table I. The background doping was obtained from the capacitance measurement, and then E_m can be calculated from the following equation, $E_m = E_m[2qN(V+V_{bi})/\varepsilon_s]^{1/2}$ where N is the background doping, V the applied reverse bias and V_{bi} the built in potential. The photomultiplication setup is similar to that described by Lee et al[7]. A Tenney Temperature chamber has been employed to perform the temperature effect experiments. Once the dependence of the multiplication factor on applied voltage is determined, the ionization rate can be computed from Eqs. (6) and (7) for abrupt junctions.

In order to measure α_n and α_p respectively, the photo response measurement was made on the collector and base terminals. When the chopped light illuminate on the collector junction, the electron multiplication factor M_n was measured, whereas when the chopped light illuminate on the emitter region, the injected holes transpose through the base–collector junction and thus the hole multiplication factor M_p was obtained. Finally the electron and the hole ionization rates were evaluated by using Eqs. (6) and (7).

The M(V) functions are obtained from curve fitting technique. However, for a first order approximation, the M versus V curves can be fitted by the following empirical formula,

$$1-\frac{1}{M} = \left(\frac{V}{V_B}\right)^n \qquad (8)$$

Where V_B is the breakdown–voltage, for electron or hole, one just adds subscript e or h into M and n for the corresponding terms. Substituting this equation into Eqs. (6) and (7) we get the ionization rates at maximum junction field E_m,

$$\alpha_p(E_m) = \frac{M_p}{M_n} E_m \frac{n_h}{V_B}\left(\frac{V}{V_B}\right)^{n_h-1} \qquad (9)$$

and

$$\alpha_n(E_m) = M_n E_m \frac{n_e}{V_B}\left(\frac{V}{V_B}\right)^{n_e-1} - (M_n-1)\,\alpha_p(E_m) \quad (10)$$

Now, we represent an example as follows: from the photomultiplication factor versus voltage curve we obtain[8], $M_n=5.7$, $M_p=6.4$, $n_e=4.5$, $n_h=2.6$ under the reverse bias of 32V which is corresponding to a maximum junction field of 5.8×10^5 V/cm, then applying Eqs. (9) and (10) we obtain $\alpha_p=5.5\times10^2\,\mathrm{cm}^{-1}$ and $\alpha_n=3\times10^3\,\mathrm{cm}^{-1}$.

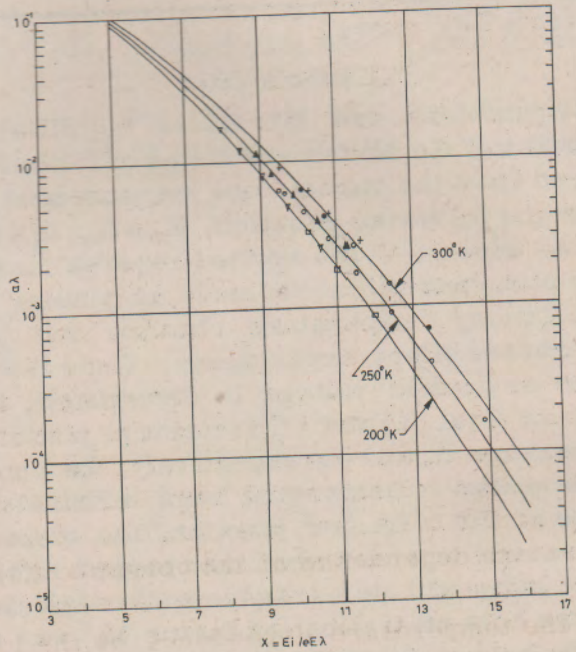

Fig. 1. Temperature dependence of ionization rates in Ge versus reciprocal electric field.

Result

A typical set of the measured ionization rates is shown in Fig. 1. We note that the ionization rate at a given field decreases as the temperature increases. The experimental data are plotted on the modified Baraff curves shown in Fig. 2. At a given temperature the only adjustable parameter to fit a particular curve is the average optical mean free path λ. From the value of λ obtained from the best fit, one can duduce the asymotic mean free path λ_{oe}, λ_{oh} from Eq. (1). It has been found that λ_{oe} and λ_{oh} are essentially independent of temperature or the impurity doping profile.

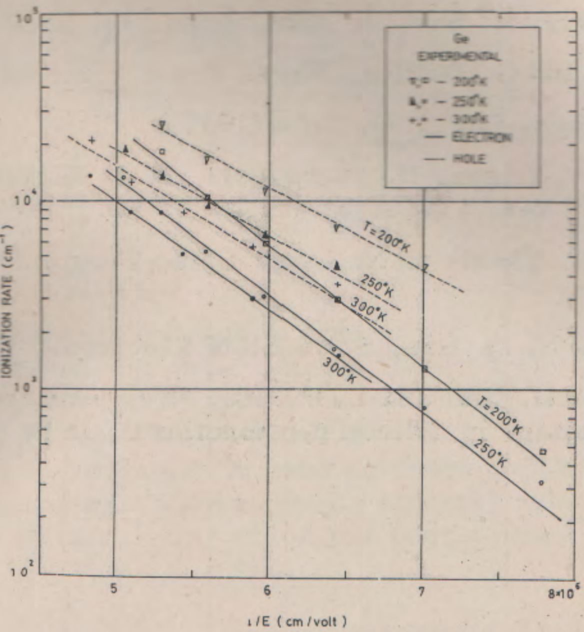

Fig. 2. Temperature dependence of $\alpha\lambda$ versus $x=E_I/qE_m\lambda$.

In summary, the temperature dependence of the ionization rate, α's, in Ge have been obtained over the range 200°K to 300°K. For a given electric field, α's are found to be decreasing with increasing temperature. It is established again that the modified Baraff theory can adequately describe the functional dependence of α's on temperature. The value of λ_{oe} is 73 ± 4 Å and λ_{oh} is 84 ± 4 Å which are in good agreement with the λ_0's value of 70 Å and 81 Å deduced by Miller from room-temperature measurement.

The calculation of the breakdown voltage based on the modified Baraff theory at various temperatures for Si abrupt junction have also been done by one of the authors[9,10].

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