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X-9. Avalanche Multiplication in Ge and GaAs *p-n* Junctions

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The ionization rates of holes (α_p) and electrons (α_n) have been measured in Ge and GaAs *p-n* junctions. In GaAs, $\alpha_p \simeq \alpha_n$, whereas in Ge, $\alpha_p=(2.2\pm0.2)\alpha_n$, the latter in good agreement with Miller's result. The mean free paths for scattering of electrons (λ_n) and holes (λ_p) with optical phonon emission have been determined by comparison of the measured ionization rates to Baraff's theory and the values obtained ranged from 42 to 50Å in GaAs and from 77 to 88Å in Ge. These values are higher than previously measured; the increase is attributed to improved crystalline perfection. The measured ionization rates (and Miller's data in Ge) predict breakdown voltages of *p-n* junctions which are in good agreement with experimental results whereas the previous GaAs data predict considerably higher breakdown voltages than are obtained experimentally.

Extensive measurements of the ionization rates have been made by Lee *et al.* in Si[1] and by Logan and White in GaP[2] where the results for holes (α_p) and electrons (α_n) were compared to Baraff's theory[3] to determine λ_n and λ_p, the mean free path for scattering of hot electrons and holes respectively. In Si $\alpha_n \gg \alpha_p$ and $50\text{Å} \leq \lambda_n \leq 70\text{Å}$, $30\text{Å} \leq \lambda_p \leq 45\text{Å}$, whereas in GaP $\alpha_n \sim \alpha_p$ and $\lambda_n=\lambda_p=38\pm3\text{Å}$. The available data on GaAs[4] has two deficiencies: (1) the geometrical structure of the junctions precluded the separation of the ionization properties of the electrons and the holes and (2) the junction used were so narrow that difficulties arise in the interpretation of the data. In Ge[5] ionization rates were obtained by analysis of complimentary junction pairs (p^+n and n^+p) with equal field dependence upon bias. It was found that $\alpha_p \sim 2\alpha_n$ in the field range 1.7–2.5×10^5 V/cm. It is of interest to evaluate these data by fitting the ionization rates to Baraff's theory and to obtain new data to assess the assumption used in Miller's derivation: that the scattering environment is identical from junction to junction and that the effects of field inhomogeneities or microplasmas are negligible. With scattering by optical phonons, variations in λ by 10% are common,[1,2] and λ has been observed to decrease by as much as 35% in junctions made on highly imperfect crystals.[1]

It is thus of interest to study relatively wide junctions, with well defined field distributions, whose construction permits generation of photocurrent due to either injection of holes or of electrons into the junction space-charge. Using diffusion techniques, junctions have been made in both Ge and GaAs where the diffused layer may be either *p* or *n*-type. The junctions studied in this work are listed in Table I where their pertinent electrical characteristics and details of fabrication are briefly summarized. The bias de-

Table I. Junctions properties

Breakdown voltage (volts)	λ(Å)	Capacitance law	Diffusion impurity	Background doping (cm^{-3})	Diffusion temp. °C	Diffusion time (HR)	Junctions depth (μ)
GaAs							
38	50	$V^{-1/3}$	Zn	10^{16}	825	4	8
38	51	$V^{-1/3}$	Zn	10^{16}	825	4	8
19	42	$V^{-1/2}$	Zn	6×10^{16}	650	16	3
10	42	$V^{-1/2}$	Sn	2×10^{17}	900	1	1
Ge							
75	83	$V^{-1/2}$	Zn	3×10^{15}	650	16	3
40	77	$V^{-1/2}$	Sb	4×10^{15}	600	16	1.5
36	88	$V^{-1/2}$	Sb	4×10^{15}	600	16	1.5

pendence of the junction capacitance was either square law or cube law, as noted, with built-in voltage of 1.4 ± 0.1 V in GaAs and 0.6 ± 0.1 V in Ge. It is noted that for a square law junction formed by diffusion;[1] the maximum field, E_m, is given by

$$E_m = \frac{2V}{W}\left(1 - \frac{L}{W}\right), \tag{1}$$

where V is the total junction bias, W is the junction width and L is the characteristic decrement of the diffusion profile. L was estimated by approximating an exponential distribution to the erfc diffusion profile at the junction and $L \sim 0.1$ W in the GaAs junctions and $L \ll W$ in the relatively wide Ge junctions.

With normal incident illumination of light whose wavelength is short enough to be highly attenuated in the diffused layer, the generated photocurrent, I_p, is due mainly to minority carrier injection from the diffused layer. From the variation of I_p with E_m, one obtains the field dependence of M, the ratio of the collected to the injected charge. The ionization rate, α, associated with the injected carriers, either electrons or holes, may then be determined as a function of E_m using procedures previously described.[1] Since microplasmas appeared only when $M > 5$, their effects and the effects of the field inhomogeneities which produced them, could be minimized by keeping M in the range 1-2. The multiplication, M_{np}, obtained with penetrating radiation is initiated by both electrons and holes, and may be compared to that obtained at the same field with non-penetrating light, either M_n or M_p associated with either electrons or holes, respectively. In a uniform field at low multiplication,[6]

$$\frac{\alpha_p}{\alpha_n} = 2\left(\frac{M_{np}-1}{M_n-1}\right) - 1, \quad \frac{\alpha_n}{\alpha_p} = 2\left(\frac{M_{np}-1}{M_p-1}\right) - 1. \tag{2}$$

In the GaAs junctions $M_{np} \approx M_n \approx M_p$, implying $\alpha_n \approx \alpha_p$. However in the Ge junctions $M_{np}/M_n \approx M_p/M_{np} \approx 1.2$, and evaluating the observed data with eq. (2), one estimates that $\alpha_p/\alpha_n = 2.2 \pm 0.2$, in good agreement with Miller's result.[5]

The results of Baraff's theory[3] relating α to E_m are a family of curves with two adjustable parameters, ε_i, the threshold ionization energy and λ, the mean free path for scattering where an optical phonon of energy ε_r is emitted. With $\varepsilon_r = 0.036$ eV for both Ge[7] and GaAs[8] the experimentally observed data on the diodes of Table

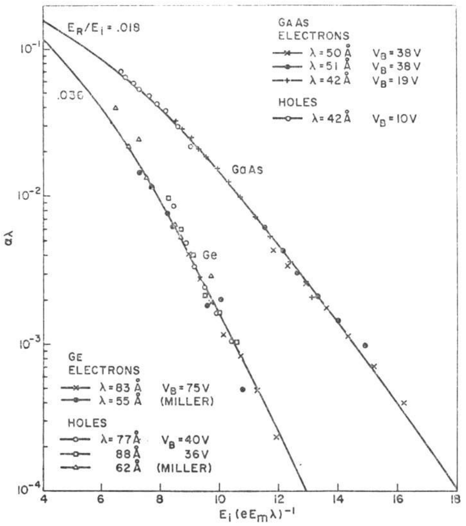

Fig. 1

I are best fitted to the two appropriate Baraff curves in Fig. 1 with $\varepsilon_1 = 1.5\,\varepsilon_g$, where ε_g is the band gap and $42\text{Å} < \lambda < 51\text{Å}$ for GaAs and $77\text{Å} < \lambda < 88\text{Å}$ for Ge.[9] Poorer agreement is obtained with $\varepsilon_i = \varepsilon_g$ or $2\varepsilon_g$ and λ adjusted by $\pm 20\%$ from the above values to fit the data to the appropriate curves. Also shown in Fig. 1 is the data of Miller[5] fitted to the Ge curve with $\lambda_n = 55$Å and $\lambda_p = 62$Å. These values are lower than those obtained in the junctions studied here and may indicate greater crystalline perfection in the presently available Ge. This effect may also explain the higher values of λ for GaAs than $\lambda = 15 \pm 2$Å reported in earlier work.[4] Since the junctions used in the previous study were relatively narrow ($\sim$400Å) one might expect significant corrections due to the distance $x_0 \approx \varepsilon_i/eE$ that the carriers must travel before they achieve the energy distribution characteristic of the junction field. For $\alpha_n = \alpha_p$ and a uniform yield, this effect reduces the effective junction width[6] by a factor $F = 1 - \dfrac{\varepsilon_i}{EW}\left(2 - \dfrac{1}{M}\right)$. Application of this correction to the earlier work, increases the measured α by a factor 1.25 ± 0.02 over the entire field range but leaves λ unchanged to within experimental error.

Using the measured ionization rates to predict the breakdown voltages of p-n junctions,[10] one finds that Miller's data[5] and the present Ge and GaAs data give good agreement with experimental results whereas the previous GaAs data[4] give considerably higher breakdown voltages than are obtained experimentally.

The p-n junctions used in this study were made by Mrs. D. Ketchow, R. A. Furnanage and D. V. Speeny. We are indebted to G. A. Baraff and C. R. Crowell for valuable discussions about this work, and to H. G. White for assistance with the experiments.

References

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DISCUSSION

Tauc, J.: I should like to mention some recent papers (Czech. J. Phys., in print) of Dr. Antončík from the Institute of Solid State Physics in Prague who is interested in similar problems. These papers represent a cotinuation of a former paper on the quantum efficiency in covalent semiconductors, delivered at International Conference on Semiconductor Physics in Paris, in the high energy region where multiple Auger transitions take place. The band structure is taken into account in a proper way both in the primary absorption process and in the secondary relaxation processes. The general formulation of the problem leads to the solution of a system of functional integral equations whose number is given by the number of energy bands considered. Figure 1 represents the spectral dependence of the quantum

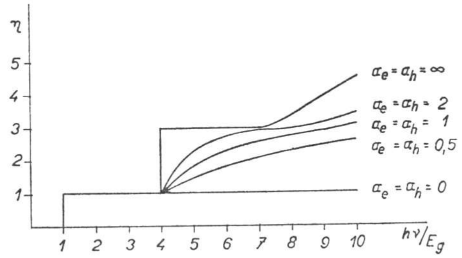

Fig. 1.

efficiency for a two band model with equal effective masses. Parameters α_e, α_h respectively represent the relative probability of the impact ionization process and the electron-(hole-) phonon interaction. When calculating the probability of the impact ionization and electron-(hole-) interaction Dr. Antončík considers several typical band structures and different approximations. It can be shown, that Shockley's and van Roosbroeck's approximation respectively represent a very special case of this general formulation.

Rose, A.: Have you made any attempt to estimate the optical phonon coupling constants needed to fit your mean free path results?

Sze, S. M.: No, we did not study.

Conwell, E. M.: It is quite unlikely that optical phonon scattering is actually the dominant scattering process for the energy range cocerned. In n-Ge that process is likely to be intra- or inter-valley acoustic scattering. In GaAs it is almost certainly not optical mode scattering and most likely to be intervalley scattering. Further, it is by no means certain that there is actually a mean free path independent of electron energy in the range concerned.

Davies, L. W.: The Baraff diagram relates to uniform electric field conditions, whereas your measurements on diffused junctions relate to a strongly non-uniform electric field in the region where avalanche multiplication is occuring. Have you estimated the possible effects of this situation on your measured values of λ?

Sze, S. M.: The effect of the field distribution has been considered.