DRIFT AND DIFFUSION OF HOT HOLES IN SILICON

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Received 5 December 1978

The mobility and the diffusion coefficient versus electric field strength were calculated from current and noise data on Si hole injection diodes. The results were interpreted in terms of the structure of the valence band.

In an anisotropic semiconductor diffusion can be described by a diffusion tensor $\bar{D}$. This quantity is related to the spectral intensity tensor S_v of the velocity fluctuations of the charge carriers [1] as follows:

$$4\bar{D} = S_v(f) = S_v(0)\,, \tag{1}$$

for frequencies f smaller than the reciprocal correlation time of the velocity fluctuations. In cartesian coordinates the tensor elements of S_v are then given by

$$S_{\alpha\beta}(0) = 4\int_0^\infty \langle \Delta v_\alpha(t)\,\Delta v_\beta(t+\tau)\rangle\,\mathrm{d}\tau\,, \tag{2}$$

where Δv is a velocity fluctuation. Eq. (1) is the basis for the determination of diffusion coefficients from noise measurements. In the past this technique has been applied to semiconducting samples without space charge [2]. In this paper we show how diffusion coefficients can be obtained from noise measurements on single injection diodes [3], when the current flow is limited by space charge.

If the electric field is applied along a symmetry direction (x-axis) of the crystal the spectral intensity of the ac open circuited voltage fluctuations due to carrier velocity fluctuations is, for electrons, given by [4]

$$S_V(f) = -\frac{4\epsilon qA}{I^2}\int_0^{E_L} \frac{D(E)\,(E_L-E)^2\,\mathrm{d}E}{(1-qn_\mathrm{d}E\mu(E)A/I)^3}\,, \tag{3}$$

where A = cross sectional area, I = electric current, E = electric field strength, E_L = field at $x = L$, n_d = density of fully ionized donors and $-q$ = electron charge. The injecting contact is at $x = 0$, whereas the collecting contact is at $x = L$. Eq. (3) holds for geometries where a one dimensional description is warranted and for frequencies small with respect to the reciprocal transit time of the carriers.

In addition the current voltage dependence is given by the parametric formula [4]

$$V = \frac{\epsilon A}{I}\int_0^{E_L} \frac{E^2\mu(E)\,\mathrm{d}E}{1-qn_\mathrm{d}E\mu(E)A/I_0}\,, \tag{4}$$

$$L = -\frac{\epsilon A}{I}\int_0^{E_L} \frac{E\mu(E)\,\mathrm{d}E}{1-qn_\mathrm{d}E\mu(E)A/I_0}\,. \tag{5}$$

For eqs. (3)–(5) the following sign convention is appropriate $V > 0; I, E < 0$.

These equations are equally valid for holes provided the right-hand sides change sign and the sign convention is $V < 0; I, E > 0$. Then of course n_d represents the density of fully ionized acceptors. Conversely, eqs. (3)–(5) can be used to calculate μ and D as a function of E from measured data on S_V and I as a function of applied voltage. In order to do this numerically we consider small field intervals ΔE so that μ and D do not change appreciably within such an interval. Accordingly we rewrite (3)–(5) as follows:

$$S_{V_i} = -\frac{4\epsilon qA}{I_i^2}\int_0^{E_{L_i}-\Delta E} \frac{D(E)\,(E_{L_i}-E)^2\mathrm{d}E}{(1-qAn_\mathrm{d}E\mu(E)/I_i)^3} - \frac{4\epsilon qAD_i}{I_i^2}\int_{E_{L_i}-\Delta E}^{E_{L_i}} \frac{(E_{L_i}-E)^2\,\mathrm{d}E}{(1-qAn_\mathrm{d}E\mu_i/I_i)^3}\,, \tag{3a}$$

$$V_i = \frac{\epsilon A}{I_i} \int_0^{E_{L_i}-\Delta E} \frac{E^2 \mu(E)\, dE}{1 - q n_d A E \mu(E)/I_i} + \frac{\epsilon A \mu_i}{I_i} \int_{E_{L_i}-\Delta E}^{E_{L_i}} \frac{E^2\, dE}{1 - q n_d A E \mu_i / I_i}, \qquad (4a)$$

$$L = -\frac{\epsilon A}{I_i} \int_0^{E_{L_i}-\Delta E} \frac{E \mu(E)\, dE}{1 - q A n_d E \mu(E)/I_i} - \frac{\epsilon A \mu_i}{I_i} \int_{E_{L_i}-\Delta E}^{E_{L_i}} \frac{E\, dE}{1 - q A n_d E \mu_i / I_i}. \qquad (5a)$$

The indices i are introduced to explain the following procedure. We start the calculation with a small value for the voltage V_1; S_{V_1} and $I_1(V_1)$ are supposedly known from experiments. Then we take $\Delta E = E_{L_1}$ and subsequently calculate E_{L_1}, μ_1 and D_1 from eqs. (3a), (4a) and (5a). The next step is to take a larger value for the voltage, V_2 and to choose $\Delta E = E_{L_2} - E_{L_1}$; then E_{L_2}, μ_2 and D_2 can be calculated, and so on. By decreasing the voltage steps $V_i - V_{i-1}$ the convergence of the results can always be ascertained.

We tested the procedure by generating values for I, V and S_V using equations (3)–(5) and by choosing μ and D values independent of E and taking appropriate values for L, A and n_d. Thereupon with our retrieval procedure we reproduced the μ and D values independent of E (within 2%).

Subsequently this procedure was applied to experimental data obtained by Gisolf and Zijlstra [5] on voltage noise of silicon single injection diodes at 100 K. The devices were thin $p^+-\pi-p^+$ silicon slabs (boron doped, 100 crystal plane, cross section 10^{-6} m^2) with sputtered Ti–Au contacts over the entire p^+ surfaces. The π-region has a thickness of 40 μm and bulk resistivity of 100 Ωm at 300 K.

The results for D and μ as a function of E, applied in the ⟨100⟩ direction, are plotted in fig. 1. The mobility results are in agreement with those obtained by Canali et al. [6] using a time of flight technique. The diffusion curve shows a pronounced structure which we ascribe to the effect of light and heavy holes.

In this interpretation the observed diffusion coefficient is given by $D = (n_\ell D_\ell + n_h D_h)/(n_\ell + n_h)$ were subscripts ℓ and h stand for light and heavy, respectively, and n for effective density of states at low fields. At low fields D is independent of E and equal to the generally accepted value which in turn is related to the low field mobility through an Einstein relation at 100 K. With increasing field strength, D increases, supposedly because of long wavelength acoustical phonon scattering of light holes in a parabolic band [7].

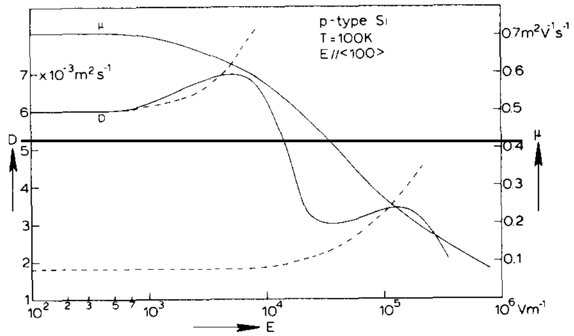

Fig. 1. Mobility μ and diffusion coefficient D versus electric field strength E. Dashed curves represent theoretical D values for light holes (upper curve) and heavy holes (lower curve). We calculated these on the basis of the parabolic band model taking only long wavelength acoustical phonon scattering into account.

If the field strength increases still further, then a sharp decline of the curve sets in which can be explained by the non-parabolicity of the light-hole band at higher energies [8]. Then a second bulge occurs, which is tentatively ascribed to the heavy-hole band where intraband acoustical phonon scattering is responsible for a slight increase in D whereas the subsequent decrease is again due to the nonparabolicity of the heavy-hole band. In order to substantiate this interpretation we calculated D as a function of E assuming a parabolic light- and heavy-hole band with spherical energy surfaces [7], using $m_\ell^*/m_e = 0.19$ and $m_h^*/m_e = 0.43$ [9], where effective masses are denoted by an asterisk and m_e is the free electron mass. The results are shown by the upper dashed curve. Note that the initial increase in D is correctly described.

In addition we calculated $n_h D_h/(n_\ell + n_h)$ with the help of the same model [7]. The results are shown by the lower dashed curve. A more detailed calculation which takes into account the non-parabolicity of the bands is being undertaken at present.

The general behaviour as observed at 100 K is also seen at 145 K. At 210 K, however, this behaviour is hardly perceptible.

In our interpretation we ignored the influence of the spin–orbit band because of its activation energy [10]. We also neglected the occurrence of interband transitions [11]. The latter would have resulted in a strong increase in D with increasing E, which was not observed.

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