FLICKER NOISE OF HOT HOLES IN SILICON AT 78 K

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From flicker-noise data versus applied voltage and current–voltage measurements on a $p^+\pi p^+$ planar silicon device at 78 K we calculated Hooge's parameter α for flicker noise as a function of the electric field strength E_0 applied along the ⟨1, 0, 0⟩ crystallographic direction. We found that $\alpha(E_0)$ decreases with increasing field. For $E_0 \leqslant 3 \times 10^4$ V/m the following relation holds: $\alpha(E_0) = \alpha(0)/[1 + (E_0/E_{c\ell})^2]$. $E_{c\ell}$ is the field where the drift velocity of the light holes is within 10% of the sound velocity. This particular $\alpha(E_0)$ dependence indicates the connection between $\alpha(E_0)$ and the scattering of light holes by acoustic phonons.

The origin of flicker or $1/f$ noise is still being debated. There is substantial evidence, however, in support of Hooge's view that flicker noise is a bulk effect, and that for a homogeneous conductor the following relation holds [1,2]:

$$S_G/G^2 = \alpha/Nf, \tag{1}$$

where G is the conductance, N the total number of free charge carriers, f the frequency and α a parameter.

In a previous paper [3] we reported on the influence that high electric fields have on the flicker noise of electrons in silicon. The electric field was applied along the ⟨1, 1, 1⟩ crystallographic direction of silicon at a lattice temperature of 78 K. The results were interpreted in terms of the bulk hypothesis. It was found that

$$\alpha(E_0)/\alpha(0) = [1 + (E_0/E_c)^2]^{-1},$$

where E_0 is the dc applied electric field and E_c the field where $\alpha(E_0) = \frac{1}{2}\alpha(0)$.

It turned out that $\mu(0) \cdot E_c = v_s$, where v_s is the sound velocity of longitudinal waves propagating along the ⟨1, 1, 1⟩ direction. This was not suprising since the predominant scattering mechanism at this temperature is long wavelength acoustic phonon scattering. The results provide the first direct evidence for the relation between flicker noise and the scattering mechanism.

We now report results obtained on holes in silicon. We used $p^+\pi p^+$ planar silicon devices. The room temperature resistivity of the π-region was 100 Ω m. The basic material was obtained from Wacker Chemitronic. The devices were provided with plane parallel contacts with a cross-sectional area of 10^{-6} m^2; the contact spacing was 40 μm. The field was applied along the ⟨1, 0, 0⟩ crystallographic direction of silicon.

In fig. 1 we show the mobility μ and Hooge's parameter α as a function of the electric field strength applied along the ⟨1, 0, 0⟩ crystallographic direction in silicon at 78 K. The values for the mobility were calculated from a measurement of the current–voltage characteristic. The α-values were calculated from measurements of the spectral intensity of the ac open circuited voltage fluctuations versus the applied voltage. Machine calculations were applied in a manner described before [3,4].

There is a statistical error of 10% in the measured value of the spectral intensity of the ac open circuited voltage fluctuations. This in turn introduces a statistical error of 5% in α at fields below 10^4 V/m. Above 10^4 V/m the error increases with increasing field, reaching 25% at $E_0 = 7 \times 10^4$ V/m.

The mobility data are in good agreement with those obtained by the application of a time-of-flight technique [5].

Note that α, which is a measure of the magnitude of the flicker noise, is independent of the field at low

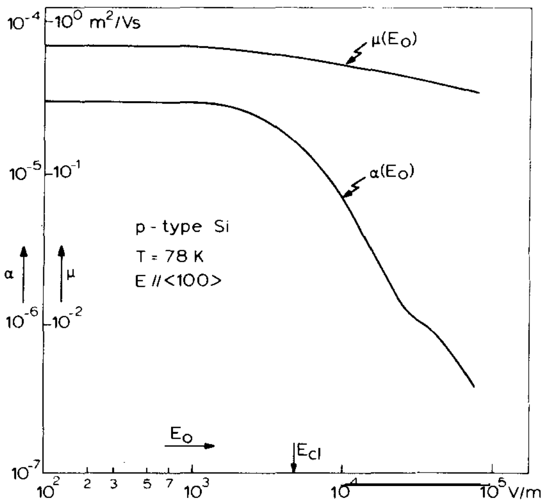

Fig. 1. The mobility and Hooge's parameter α as a function of the electric field strength E_0. The arrow indicates the field $E_{c\ell}$ where $\alpha(E_{c\ell}) = \frac{1}{2}\alpha(0)$. The statistical error in $\alpha(E_0)$ ranges from 5% at fields below 10^4 V/m to 25% at $E = 7 \times 10^4$ V/m.

fields, as expected, whereas at higher fields it decreases inversely proportional to the square of the field. At still higher fields some structure is observed. The arrow at $E_{c\ell} = 5.2 \times 10^3$ V/m indicates the field where α is one half of its low-field value.

As in the case of n-type silicon, acoustic phonon scattering is predominant at $T = 78$ K and at moderate fields. By analogy one would expect that $\mu(0) \cdot E_{c\ell} = v_s$, where for p-type silicon v_s is the weighted average of the longitudinal ($v_{s\ell}$) and the transverse (v_{st}) sound velocity. If one takes $v_s^2 = \frac{1}{3}v_{s\ell}^2 + \frac{2}{3}v_{st}^2$, $v_{s\ell} = 9.0 \times 10^3$ m/s and $v_{st} = 5.3 \times 10^3$ m/s [6], then one finds $v_s = 6.8 \times 10^3$ m/s. However, it turns out that the product $\mu(0) \cdot E_{c\ell}$ is substantially smaller than v_s.

In considering charge transport in p-type silicon, however, one should distinguish between light and heavy holes and take inter- and intra-band acoustic phonon scattering into account. Inter-band scattering occurs because of the degeneracy of two valence bands at $k = 0$ [7].

It so happens that $E_{c\ell}$ is the field where the drift velocity of the light holes is within 10% of the sound velocity. Consequently the interpretation of the curve becomes clear. When the electric field increases, the light holes become heated. This heating is characterized by a field $E_{c\ell}$, where the drift velocity of the light holes approach the sound velocity.

Hooge's parameter $\alpha(E_0)$ decreases strongly in the region of $E_{c\ell}$ and can be described by $\alpha(E_0) = \alpha(0)/[1 + (E_0/E_{c\ell})^2]$. From this decrease we conclude that $\alpha(E_0)$ is strongly affected by the scattering of light holes by longitudinal and transverse acoustic phonons, involving inter- and intra-band transitions.

A possible explanation for the structure observed at $E_0 = 3 \times 10^4$ V/m could be that at this field the contribution of the heavy holes to $\alpha(E_0)$ becomes apparent. Then, we expect the scattering processes of heavy holes with acoustic phonons to cause a decrease in $\alpha(E_0)$ at a field E_{ch}, where $E_{ch} = v_s/\mu_h(0)$. $\mu_h(0)$ is the low-field mobility of the heavy holes. Unfortunately, however, the statistical error in $\alpha(E_0)$ in this range of fields (cf. fig. 1) prevents any accurate quantitative check of this assertion.

In the foregoing it was assumed that the effective masses of light and heavy holes are given by $m_\ell^* = 0.20\,m$ and $m_h^* = 0.55\,m$, respectively [5], where m is the free electron mass. In addition it was assumed that the low-field mobilities and the effective density of states were proportional to m^{*-1} and $m^{*3/2}$ respectively where m^* is the effective mass of the particle [7]. Therefore in view of the observed value for $\mu(0) = 0.70\ m^2V^{-1}s^{-1}$, we have $\mu_\ell(0) = 1.47\ \mathrm{m^2V^{-1}s^{-1}}$ and $\mu_h(0) = 0.53\ \mathrm{m^2V^{-1}s^{-1}}$.

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