FLICKER NOISE OF HOT ELECTRONS IN SILICON AT $T = 78$ K

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From flicker-noise and current–voltage measurements performed on an n^+nn^+ silicon planar device at $T = 78$ K we calculated Hooge's parameter α as a function of the electric field strength, E_0. We found that $\alpha(E_0) = \alpha(0)/[1 + (E_0/E_c)^2]$. E_c is a critical field where the drift velocity equals the sound velocity, indicating the connection of the observed effect with acoustical phonon scattering.

The origin of flicker or $1/f$ noise is still being debated. Hooge and his coworkers [1] consider it as transport noise residing in the volume rather than as carrier density fluctuations due to surface effects [2]. Experimental evidence in favour of Hooge's interpretation is considerable and is still growing, leading to an interpretation in terms of mobility fluctuations [3,4]. The present paper gives the first experimental results on $1/f$ noise of hot electrons.

We studied the noise developed across the terminals of an n^+nn^+ silicon device as a function of applied voltage. The frequency range considered in our measurements extended from 1 Hz to 1 MHz. The $1/f$ frequency dependence was observed for at least two decades in frequency, depending on the applied voltage. The frequency exponent was -1 within the accuracy of our measurements (5%). Since flicker noise is essentially a low frequency effect we used dc bias. Consequently the voltage range has an upper limit that is determined by the onset of excessive Joule heating, which changes the lattice temperature. By comparing the dc current voltage characteristic with the characteristic obtained by pulse bias with a low duty cycle we could determine the dc voltage below which no excessive Joule heating occurred. Yet by cooling the device down to 78 K we could still operate the device in the hot carrier regime. The resistance of the n-region was 22 Ω m at room temperature, and the field was applied in the ⟨111⟩ crystallographic direction. The contact spacing was 78 μm, and the cross sectional area was 10^{-6} m^2. The geometry warrants a one-dimensional treatment.

Based on Hooge's view Kleinpenning gave a description of $1/f$ noise of *thermal carriers* in such a device taking space charge into account, which was subsequently vindicated by experiments on silicon diodes [5]. Zijlstra calculated the spectral intensity of the ac open circuited voltage fluctuations due to $1/f$ noise taking *hot carrier effects* and space charge injection into account. Kleinpenning's results were retained as a special case. For frequencies small with respect to the reciprocal transit time of the charge carriers [6] he found

$$S_V(f) = -\frac{\epsilon q A}{f I_0^2}\int_0^{E_L}\frac{\alpha(E_0)(E_L - E_0)^2 v_d^2(E_0)\,dE_0}{[1 + q n_d v_d(E_0) A/I_0]^3}, \tag{1}$$

where $\alpha(E_0)$ is Hooge's parameter, I_0 is the current, q the permittivity of the material, A the cross sectional area, n_d the density of the fully ionized donors, v_d the drift velocity and E_L the electric field at the collecting contact at $x = L$, and $-q$ is the electron charge.

The current–voltage dependence is given by the parametric formulas [6,7]

$$V_0 = \frac{\epsilon A}{I_0}\int_0^{E_L}\frac{E_0^2\mu(E_0)\,dE_0}{1 + q n_d v_d(E_0) A/I_0}, \tag{2a}$$

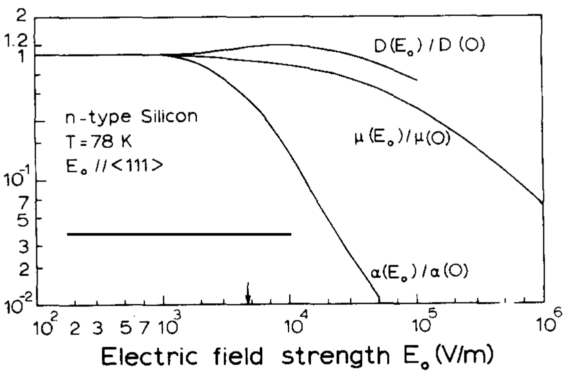

Fig. 1. The normalized diffusion coefficient, mobility and α as a function of the electric field strength. The arrow indicates the value of $E_c = 4.68 \times 10^3$ V/m.

$$L = -\frac{\epsilon A}{I_0} \int_0^{E_L} \frac{E_0 \mu(E_0)\, \mathrm{d}E_0}{1 \cancel{+ q n_\mathrm{d} v_\mathrm{d}(E_0) A}/I_0} . \tag{2b}$$

The sign convention chosen for the different physical quantities is as follows: $I_0 < 0$ and $E_0 < 0$, whereas $V_0 > 0$. The formulas are equally valid for holes provided appropriate sign changes are made.

Eqs. (2) can be used to calculate by computer the mobility as a function of E_0 from a measurement of the current–voltage characteristic [8]. In addition, from a measurement of $S_V(f)$ as a function of V_0 one can calculate α as a function of E_0 in the same way as the diffusion coefficient of hot carriers was calculated from a measurement of thermal noise versus applied voltage [9].

In fig. 1 we present the results for the normalized mobility $\mu(E)/\mu(0)$, the normalized diffusion coefficient $D(E)/E(0)$ and $\alpha(E_0)/\alpha(0)$, at $T = 78$ K. We used $\mu(0) = 2\ \mathrm{m^2/V\,s}$ and calculated $\alpha(0) = 7.52 \times 10^{-4}$ and $D(0) = 1.33 \times 10^{-2}\ \mathrm{m^2/s}$.

The maximum value of electric field strength that we could use without bringing about excessive Joule heating was 5×10^4 V/m. This value limits our $1/f$-noise experiments and therefore the calculation of $\alpha(E_0)$.

The normalized mobility at higher field strengths was obtained from pulse $I_0 - V_0$ measurements on the same device [9], whereas $D(E)/D(0)$ was obtained from pulsed thermal noise data [9].

From $D(E_0)$ and $\mu(E_0)$ curves we conclude that carrier heating effects become apparent at an electric field strength E_c, given by $E_c \mu(0) = v_s$, where v_s is the sound velocity in the appropriate crystallographic direction. For n type silicon and the $\langle 111 \rangle$ direction $v_s = 9.36 \times 10^3$ m/s [9]. The arrow in fig. 1 indicates the value of $E_c = 4.68 \times 10^3$ V/m.

Since the predominant scattering mechanism at this temperature is long wavelength acoustical phonon scattering, this result is not surprising. It should be noted that the field dependence of α also begins in the neighbourhood of the electric field strength E_c. This seems to indicate that $\alpha(E_0)$ is a physical quantity related to the acoustic phonon scattering mechanism in the bulk of the device. In fact in the range of electric fields considered the normalized value of α could be described by $\alpha(E_0)/\alpha(0) = [1 + (E_0/E_c)^2]^{-1}$.

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