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NOISE IN DEVICES.

n-TYPE SILICON AT 77 K : HOT CARRIER NOISE AND NOT GENERATION RECOMBINATION NOISE

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Résumé. — Le courant de bruit mesuré dans Si-n à 77 K est comparé au bruit de génération-recombinaison (G-R) théorique. Le désaccord entre la théorie et l'expérience montre que la formulation habituelle du bruit G-R n'est plus valable dans le cas de porteurs chauds. Le bruit observé est soit du bruit de diffusion de porteurs chauds, soit du bruit G-R de porteurs chauds, c'est-à-dire du bruit G-R dont les paramètres dépendent du champ électrique.

Abstract. — The experimental excess noise current in n-Si at 77 K is compared with the theoretical generation-recombination (GR) noise. The discrepancy between the theory and the experiment shows that the usual formalism describing the GR noise is not valid in that case. The observed noise is either hot carrier diffusion noise, either hot carrier GR noise, that is GR noise with electric field dependent parameters.

1. Introduction. — The knowledge of the noise sources, that is of the physical processes responsible for the noise, is of great importance : it allows modelling and predicting the noise of the devices, and gives informations on the improvement to be expected on the noise concerning the device fabrication and technology.

A few years ago, the noise of the n-type silicon channel of junction gate field effect transistors (J FET) at 77 K was found [1] [2] to be 40 to 100 times greater than predicted by the theory. Some authors suggested that this excess noise could be due to hot carrier effect [2] [3], other authors attributed it to generation-recombination (G-R) processes [1]. Besides its interest on the fundamental point of view, the answer to this question has practical consequences on the J FET properties and technology. If the increase in noise is due to hot carrier effect, it likely cannot be further reduced, conversely if it is due to G-R processes, one may expect the possibility to lower it by modifying the dopant or the doping process of the wafer.

A more refined theory was recently developed [4], taking into account the variation versus the electric field E of both the mobility $\mu(E)$ and the noise temperature $T_n(E)$: these variations, measured on homogeneous samples and carried in the model used for the J FET, gave a theoretical noise in agreement with the experimental one within a factor 2. Although the noise spectrum of the homogeneous samples was white in the range 200 MHz - 1GHz, it was argued [5] that it could be the plateau of a G-R noise, due to the thermal fluctuations of the number of carriers between the donor level and the conduction band, with

very high cut-off frequency due to short lifetimes because the energy level of the boron is relatively shallow.

We shall investigate in this paper the noise of homogeneous bars, where the electric field is uniform, and see whether it is possible to interpret the experimental results using the G-R theory.

2. Thermal G-R noise of hot carriers. — Diffusion noise is due to the fluctuation of the velocity of the carriers. Conversely G-R noise is due to the fluctuation of the number of carriers.

Let us consider a homogeneous bar of semiconductor of length L and cross section A , with a d.c. current I passing through :

$$I = q \frac{Nv}{L} \quad (1)$$

where $N = nAL$ is total number of carriers inside the bar, v is the drift velocity. In G-R noise, N fluctuates around its average value, with a spectral density S_N . This results in a noise current with spectral density S_{IGR} :

$$S_{IGR} = \frac{q^2 v^2}{L^2} S_N \quad (2)$$

this gives, combined with eq. (1)

$$S_{IGR} = \frac{I^2}{N^2} S_N \quad (3)$$

It is well known [6] that $S_N = 4 \Delta N^2 \tau / (1 + \omega^2 \tau^2)$ where ΔN is the root mean square deviation of N . When the fluctuation is governed by the transition

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between the conduction band and the impurity level, ΔN^2 is proportional to N [6] : $\Delta N^2 = \alpha N$, therefore :

$$S_{IGR} = \frac{4 \alpha I^2}{N} \frac{\tau}{1 + \omega^2 \tau^2} \quad (4)$$

where α and τ are constants depending on the donor energy level, on the lattice temperature, and on the concentrations of the free carriers and of the impurities [6].

At high electric field, the quantity usually measured [7] is the noise temperature $T_n(E)$ defined as

$$S_I = 4 k T_n(E) \operatorname{Re} \{ \delta I / \delta V \} \quad (5)$$

where k is the Boltzmann constant, δV is the complex sinusoidal voltage superimposed to the d.c. voltage, produced by a complex sinusoidal current δI through the device, superimposed to the d.c. current I . Re means the real part.

Comparison between eqs. (4) and (5) show that

$$T_{nGR}(E) = \frac{\alpha I^2}{k N \operatorname{Re} \{ \delta I / \delta V \}} \frac{\tau}{(1 + \omega^2 \tau^2)}. \quad (6)$$

In the white spectrum range ($\omega \tau \ll 1$), $\delta I / \delta V$ is equal to the slope dI/dV of the static characteristic $I(V)$, so that eq. (6) becomes, since $I = qnvA$ and $V = EL$:

$$T_{nGR}(E) = \frac{q}{k} \frac{\alpha \tau v^2}{(dv/dE)}. \quad (7)$$

The knowledge of v versus E gives T_n versus E . Indeed eq. (7) gives a variation of T_n always steeper than E^2 . This can be seen using the empirical expressions often used for the mobility : at low field [8], $\mu = \mu_0(1 - \gamma E^2)$, and at higher fields

$$\mu = \mu_0 \left[1 + \left(\frac{E}{E_c} \right)^\beta \right]^{-1/\beta}$$

With β comprised between 1 [9] and 1.2 [10]. All these expressions, carried in eq. (7), give :

$$T_{nGR}(E) = \frac{q}{k} \alpha \tau \mu_0 E^2 f(E) \quad (8)$$

where $f(E) = \frac{v^2}{\mu_0 E^2 (dv/dE)} \geq 1$ ($f(E)$ is dimensionless). The measurements performed on n type silicon [4] at 77 K show that the slope of $T_n(E)$ versus E is much less steep than E^2 , which indicates that the noise is not thermal generation recombination.

Of course measurements of the noise temperature $T_n(E)$ and of the differential resistance dV/dI allow determining the noise current S_I using eq. (5), and comparing it with the theoretical G-R noise expression given by eq. (4). This has been performed on figure 1 where the experimental excess noise current

$$S_I(I) - S_I(0)$$

has been plotted versus I at 77 K for a n-type silicon

FIG. 1. — Excess noise current $S_I(I) - S_I(0)$ versus the d.c. current I , in n-type silicon at 77 K ($N_D = 8.2 \times 10^{14} \text{ cm}^{-3}$). The dots are experimental points measured in the frequency range 250-850 MHz. The full line is the theoretical G-R noise current given by eq. (4).

bar, the characteristics of which are given in table I. The noise was found to be white within the range of frequencies measured (250-850 MHz). The full straight line on figure 1 is the theoretical G-R noise described by eq. (4) : the constant α can be computed by [6] :

$$\alpha = (N_D - n) / (2 N_D - n) \quad (9)$$

which, using table I, gives $\alpha = 0.242$. The constant τ cannot be determined using the G-R statistics, and is an adjustable parameter. The value

$$\tau = 7.1 \times 10^{-11} \text{ s}$$

has been chosen so as to fit eq. (4) with the experimental result

$$\{ I = 0.365 \text{ A}, S_I - S_I(0) = 1.12 \times 10^{-22} \text{ A}^2/\text{Hz} \}.$$

TABLE I

Characteristics of the sample used in figure 1

Quantity	Symbol	Value	Unit
Length	L	0.99	mm
Cross section	A	0.148	mm ²
Ohmic resistivity at 300 K	ρ_{300}	6.0	$\Omega \text{ cm}$
Ohmic resistivity at 77 K	ρ_{77}	0.75	$\Omega \text{ cm}$
Impurity concentration (from [12])	N_D	8.2×10^{14}	cm^{-3}
Free carrier ohmic concentration at 77 K (deduced from [11])	n_{77}	$0.68 N_D$	
Ohmic mobility at 77 K (deduced from ρ_{77} and n_{77})	μ_{077}	1.5×10^4	cm^2/Vs

Figure 1 clearly shows that the theoretical and the experimental variations of $S_I(I) - S_I(0)$ are in disagreement, which rejects the hypothesis that the noise is purely thermal G-R noise in n-type silicon bars.

Therefore, using this theory, for modeling the noise in the channel of JG FETS, leads to results in disagreement with the experiments.

3. Electric field assisted G-R noise. — Indeed in eq. (4) some *constants* actually depend on the electric field. This is obviously so for N . The free carrier concentration n depends on E for two reasons :

a) Poole Frenkel effect : the electric field lowers the potential barrier of the carriers not yet thermally ionized, and therefore trapped on the impurity level, so that more and more carriers jump in the conduction band as the field increases.

b) Impact ionization : the electric field increases the energy of the free carriers, so that some of them can ionize the impurities when colliding with them, thus increasing the concentration of the free carriers.

The increase of N diminishes S_I according to to eq. (4), but of an amount not exceeding $1/0.68$,

which is not sufficient to get a good fit between experimental and theoretical results. For example, due to the Poole Frenkel effect, at $I = 1$ A, S_{IGR} is lowered only by a factor 1.22.

Furthermore, the variation of N versus E produces a variation of α (see eq. (8)), and also of τ . Therefore it comes out that all the factors involved in eq. (4) depend on the electric field, so that, if the noise is due to a G-R process, this process is *not* a thermal one but is strongly influenced by the electric field, so as to get *hot carrier G-R noise*, to which the formulas of the usual thermodynamic G-R noise do not apply. Indeed it seems that G-R noise modified taking into account the Poole Frenkel effect gives a *possible* explanation of the noise observed in n-type silicon bars at 77 K [13], using only one adjustable parameter which is the zero field lifetime τ . However the experimental data now available do not allow to make sure that this explanation is the right one, rather than impact ionization noise or hot carrier diffusion noise : additional experiments must be performed at much higher frequencies to see whether the cut-off frequency associated with the life time does exist.

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