QUANTUM THEORY OF 1/f NOISE IN IRRADIATED SEMICONDUCTOR SAMPLES AND DEVICES

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We have performed an investigation of electronic 1/f noise in materials, devices and systems, excluding MOSFETs, but focusing on the effects of irradiation with γ-rays, neutrons, β and α particles. The investigation used the author’s quantum 1/f formulas. An increase of 1/f noise was obtained for junction-type devices. Our calculations indicate that low dose levels can under certain conditions lower the quantum 1/f noise of FET-type devices in which the mobility of the carriers is large and limited by electron-phonon scattering. Analytical expressions and graphical representation have been obtained, showing the dependence of 1/f noise on the absorbed radiation dose.

1. Introduction

Noise in irradiated materials is of importance for military and civillian applications, also in space where natural high radiation levels are present and man-made irradiation is an additional concern. The quantum 1/f noise theory allows the calculation of all forms of fundamental 1/f noise. In MOSFET, this fundamental quantum 1/f noise is usually masked by a much larger non-fundamental 1/f-like noise caused by traps in the oxide. Therefore, until the oxide is replaced by a better material, MOSFETs will not reach their quantum limit, and are thus excluded from this study. 1/f noise in MOSFETs is the subject of other papers [1]-[2], including references therein.

For the case of homogeneous compound semiconductor samples, or FETs and HFETs, of high mobility, it is interesting to note that when the sample is allowed to reach equilibrium, a lowering of 1/f noise through irradiation is predicted by the quantum 1/f theory (Sec. 2). This 1/f noise reduction is limited to very small samples, for which the conventional quantum effect is not masked by the coherent quantum 1/f noise. It will be particularly noticeable in good samples and FET/HFET devices, that had a relatively high mobility, limited by lattice scattering, and become more defect-scattering-limited after the irradiation. The effect is observed only in stable samples or devices, i.e., at sufficient time after the irradiation. To verify the effect, the 1/f noise is measured at low temperature before irradiation. The sample is brought to room temperature, is irradiated, and kept at room temperature for a week. It is then returned to the same low temperature, and measured under the same conditions as before, to determine the 1/f noise in stable condition after the irradiation.

For junction devices, a linear increase of 1/f noise with the absorbed dose is obtained in Sec. 3. Junction-type devices contain p-n junctions perpendicular to the current density vector. In this case, the current is determined either by diffusion, or, particularly at lower temperatures, by recombination in the space charge region of the junction (or by both, in the transition interval of temperatures). Quantum 1/f fluctuations in the diffusion constant (related to mobility fluctuations through the Einstein relation) and in the recombination rates, both at the surface and in the bulk, are causing the 1/f noise in this case. Not all carriers are involved, but only those emerging from the scattering or recombination process mentioned. Their number is $N=I/e\tau$, where τ is the lifetime of the carriers, I the current through the junction, and e the elementary charge. Since the number of carriers enters in the denominator, the noise power is proportional to the first power of the current I for forward bias larger than kT/e, whereas it goes like I^2 in samples and FET/HFET devices. The main radiation effect comes now from the drastic reduction of the lifetime τ in the denominator, causing an increase of 1/f noise with irradiation in junction devices. For flash transients see Sec. 4.

2. Permanent Conventional Quantum 1/f Noise Reduction in Semiconductor Samples and FET/HFET-Type Devices Through Irradiation

Introduction. This 1/f noise reduction is limited to very small samples, for which the conventional quantum effect is not masked by the coherent quantum 1/f noise; see [3] for both, including theory and experiment. It will be particularly noticeable in good samples and FET/HFET devices, that had a relatively high mobility before irradiation, limited by lattice scattering, and become more defect-scattering-limited after the irradiation. The effect is observed only in stable samples or devices, i.e., at sufficient time after the irradiation. To verify the effect, the 1/f noise is measured at low temperature before irradiation. The sample is brought to room temperature, is irradiated, and kept at room temperature for a week. It is then returned to the same low temperature, and measured under the same conditions as before, to determine the 1/f noise in stable condition after the irradiation. The renewed cooling is necessary, because normally, even after a week the irradiated samples/devices are not stable enough to avoid the superposition of a dominant $1/f^2$ component caused by linear drift.

Derivation. In general, Matthiessen's rule allows us to write for the resulting carrier mobility μ

$$1/\mu=\Sigma_i(1/\mu_i), \qquad (2.1)$$

where μ_i is the mobility that would be observed if only scattering process "i" would act. The quantum fluctuations

$$\delta\mu/\mu^2=\Sigma_i(\delta\mu_i /\mu_i^2), \qquad (2.2)$$

are multiplied by μ, squared, averaged (quantum expectation value) and referred to the unit frequency interval to obtain the spectral density of fractional fluctuations

$$S_{\delta\mu/\mu}(f) = \Sigma_i(\mu/\mu_i)^2 S_{\delta\mu i/\mu i}(f). \qquad (2.3)$$

This is based on the statistical independence of fluctuations in the cross section or rate of the scattering process i from all others. All $S_{\delta\mu i/\mu i}$ decrease ~1/N, with N the total number of carriers.

In particular, let n_o be the total concentration of all types of impurity and defect scattering centers, and n' the additional concentration of defect scattering centers introduced by the irradiation. Then Eq. (2.1) yields

$$1/\mu_o = 1/\mu_{od} + 1/\mu_l \qquad (2.4)$$

for the initial mobility, and

$$1/\mu = 1/\mu_d + 1/\mu_l = (1+r)/\mu_{od} + 1/\mu_l, \qquad (2.5)$$

where $r=n'/n_{od}$ is the ratio between the additional defect concentration n' created by the irradiation and the pre-existing defect concentration n_{od}. We have assumed that if lattice scattering would be absent, the mobility μ_d expected after the irradiation would be reduced by a factor 1+r when compared with its initial value μ_{od}, present before irradiation. This is to be expected, since the frequency of scattering is proportional to n' and therefore with the absorbed dose of radiation J in Sv (sieverts)

$$n'=\kappa J; \quad \kappa=\rho\sigma_d/E(\sigma_{tot}-\sigma_s), \tag{2.6}$$

where κ is a coefficient defined for the given semiconductor material of density ρ as the product of the atomic cross section for defect creation σ_d in bn (barns) with ρ in Kg/m^3, divided by the energy of the particles E in joules and by the total atomic effective absorption cross section σ_{tot} -σ_s. Here σ_s is the scattering cross section, while σ_{tot} is the total attenuation cross section, both in bn. Note that 1Sv is 100 rad, and 1 rad =100 erg/g. n' is obtained in m^{-3}. Note that σ_d is dependent on the temperature of the lattice through a Debye-Waller factor for the part involving displacement of lattice points with creation of interstitials. For neutrons, σ_d includes the nuclear capture cross section, etc.

Initially, for the noise measurement before irradiation, we can thus write

$$S_{\delta\mu/\mu}(f) = (\mu_o/\mu_{od})^2 S_d + (\mu_o/\mu_l)^2 S_l = (1-\mu_o/\mu_l)^2 S_d + (\mu_o/\mu_l)^2 S_l \tag{2.7}$$

where $S_d= S_{\delta\mu d/\mu d}(f)$ and $S_l= S_{\delta\mu l/\mu l}(f)$ are the quantum 1/f spectral densities of fractional mobility fluctuations calculated for the elementary act of defect scattering of a current carrier, and for the elementary act of lattice scattering, respectively. On the other hand, after the irradiation, at the same temperature, in stable (in fact, metastable) conditions, we obtain

$$S'_{\delta\mu/\mu}(f) = (1+r)^2(\mu/\mu_{od})^2 S_d + (\mu/\mu_l)^2 S_l = (1-\mu/\mu_l)^2 S_d + (\mu/\mu_l)^2 S_l. \tag{2.8}$$

We neglect now that both S_d and S_l decrease like 1/N. From Eqs. (2.7) and (2.8) we derive the ratio

$$\boxed{R = S'/S = [(\mu_l-\mu)^2 S_d+\mu^2 S_l]/ [(\mu_l-\mu_o)^2 S_d+\mu_o^2 S_l]} \tag{2.9}$$

between the 1/f noise power after and before irradiation. Since $\mu<\mu_o$ and $S_d<<S_l$, this ratio is less tan unity. Neglecting S_d, (because conventional quantum 1/f effect is proportional to the square of the scattering angle, and defect scattering is mainly small angle scattering), we obtain

$$\boxed{R\approx\mu^2/\mu_o^2;} \quad R\approx 1/[1+r(1+\mu_o/\mu_l)]^2; \quad R\approx 1/[1+(\kappa J/n_o)(1-\mu_o/\mu_l)]^2 =1/(1+AJ)^2, \tag{2.10}$$

where $A=(\kappa/n_o)(1-\mu_o/\mu_l)$ is a constant (see Fig. 1). **Rms Q1/f noise is thus reduced like μ..** On the other hand, if defect scattering was negligible before irradiation, $n_{od}=0$ and $\mu_o=\mu_l$. This yields

$$R= \mu^2/\mu_o^2 + (1-\mu/\mu_o)^2(S_d/S_l). \tag{2.11}$$

This prediction of the quantum 1/f theory is remarkable, because it is counterintuitive. It is usually masked in the short run by the transient effects discussed in Sec. 3 below, and by relaxation of the defect concentration towards the equilibrium concentration. This relaxation contributes a large temporary $1/f^2$ noise spectral component, as does any linear drift, present during the noise measurement. Note that

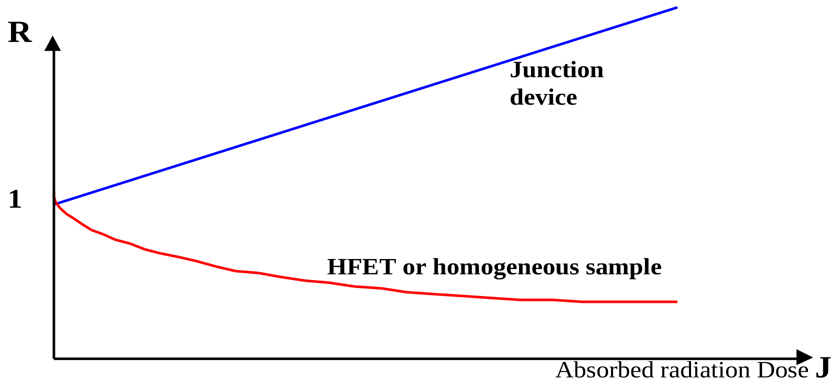

Fig. 1. Dependence of the Noise Modification Ratio R on the absorbed radiation dose J

the decrease can be stronger, since N is likely to go up.

3. Permanent Quantum 1/f Noise Increase in Junction-Type Devices

Introduction. Junction-type devices contain pn junctions perpendicular to the current density vector. In this case, the current is determined either by diffusion, or, particularly at lower temperatures, by recombination in the space charge region of the junction (or by both, in the transition interval of temperatures). Quantum 1/f fluctuations in the diffusion constant (related to mobility fluctuations through the Einstein relation) and in the recombination rates, both at the surface and in the bulk, are causing the 1/f noise in this case. Not all carriers are involved, but only those emerging from the scattering or recombination process mentioned. Their number is $N=I/e\tau$, where τ is the lifetime of the carriers, I the current through the junction, and e the elementary charge. Since the number of carriers enters in the denominator, the noise power is proportional to the first power of the current I for forward bias larger than kT/e, whereas it goes like I^2 in samples and FET/HFET devices. The main radiation effect comes now from the drastic reduction of the lifetime τ in the denominator, causing an increase of 1/f noise with irradiation in junction devices. There is also a small shift in the current limiting mechanism (mainly in the transition region) and a change in the quantum 1/f coefficient for diffusion/mobility fluctuations as mentioned in the previous Sec. 1, but that is usually a much smaller effect here. On top of everything are, of course, the large transient radiation effects to be discussed in Sec. 3.

Derivation. The lifetime of the carriers decreases with the radiation dose J

$$1/\tau = 1/\tau_o + \sigma v n' = 1/\tau_o + \sigma v \kappa J, \qquad (3.1)$$

where κ is the factor of proportionality introduced in Eq. (2.6) above, v is the rms speed of the electrons in the semiconductor, and σ is the well-known Conwell-Weisskopf cross section if the defects are ionized. The 1/f noise is calculated below first for a pn junction.

For a diffusion limited n^+-p junction the current is controlled by diffusion of electrons into the p - region over a distance of the order of the diffusion length $L = (D_n\tau_n)^{1/2}$ which is shorter than the length w_p of the p - region in the case of a long diode. If N(x) is the number of electrons per unit length and D_n their diffusion constant, the electron current at x is

$$I_{nd} = - eD_n dN/dx, \tag{3.2}$$

where we have assumed a planar junction and taken the origin x = 0 in the junction plane. Diffusion constant fluctuations, given by kT/e times the mobility fluctuations, will lead to local current fluctuations in the interval Δx

$$\delta\Delta I_{nd}(x,t) = I_{nd}\Delta x\delta D_n(x,t)/D_n. \tag{3.3}$$

The normalized weight with which these local fluctuations representative of the interval Δx contribute to the total current Id through the diode at x = 0 is determined by the appropriate Green function and can be shown to be (1/L)exp(-x/L) for $w_p/L >> 1$. Therefore the contribution of the section Δx is

$$\delta\Delta I_d(x,t) =(\Delta x/L)\exp(-x/L)I_{nd}\delta D_n(x,t)/D_n, \tag{3.4}$$

with the spectral density

$$S_{\Delta Id}(x,f) = (\Delta x/L)^2 \exp(-2x/L)\, I_{nd}^2\, S_{Dn}(x,f)/D_n^2. \tag{3.5}$$

For mobility and diffusion fluctuations the fractional spectral density is given by $\alpha_{Hnd}/fN\Delta x$, where α_{Hnd} is determined from quantum 1/f theory. With Eq. (8.1) below we obtain then

$$S_{\Delta Id}(x,f) = (\Delta x/L^2)\exp(-2x/L)(eD_n dN/dx)^2\alpha_{Hnd}/fN. \tag{3.6}$$

The electrons are distributed according to the solution of the diffusion equation, i.e.

$$N(x) = [N(0) - N_p] \exp(-x/L); \qquad dN/dx = -\{[N(0) - N_p]/L\} \exp(-x/L). \tag{3.7}$$

Substituting into Eq. (3.6) and simply summing over the uncorrelated contributions of all intervals Δx, we obtain

$$S_{Id}(f) = \alpha_{Hnd}(eD_n/L^2)^2 \int[N_o-N_p]^2 e^{-4x/L}dx/\{[N(0) -N_p]\, e^{-x/L} + N_p\}. \tag{3.8}$$

We note that $eD_n/L^2 = e/\tau_n$. With the expression of the saturation current $I_o = e(D_n/\tau_n)^{1/2}N_p$ and of the current $I = I_o[\exp(eV/kT) - 1]$, we can carry out the integration

$$S_{Id}(f) = \alpha_{Hnd}(eI/f\tau_n)\int du/(au + 1) = \alpha_{Hnd}(eI/f\tau_n)\, F(a). \tag{3.9}$$

Here we have introduced the notations

$$u = \exp(-x/L), \quad a = \exp(eV/kT) - 1,$$

$$F(a) = 1/3 - 1/2a + 1/a^2 - (1/a^3)\ln(1+a). \tag{3.10}$$

Eq. (3.9) gives the diffusion noise as a function of the quantum 1/f noise parameter α_{H}nd. A similar result can be derived for the quantum 1/f fluctuations of the recombination rate r in the bulk of the p - region, the only difference being the presence of α_{Hnr} instead of αH_{nd} in Eq. (3.9). The total noise is the given by Eq. (3.9) with α_{Hnd} replaced by the sum $\alpha_{Hnd} + \alpha_{Hnr}$

$$\boxed{S_{Id}(f) = (\alpha_{Hnd} + \alpha_{Hnr})(eI/f\tau)F(a).} \qquad (3.11)$$

From Eq. (3.1) we obtain and substitute $1/\tau$

$$\boxed{S_{Id}(f) = (\alpha_{Hnd} + \alpha_{Hnr})(eI/f)F(a)(1/\tau_o + \sigma v \kappa J).} \quad \boxed{R \approx (1/\tau_o + \sigma v \kappa J).} \qquad (3.12)$$

This clearly displays a linear increase of 1/f noise with the applied dose (Fig. 1).

The radiation-induced increase in the 1/f noise power of the emitter junction is the most important, because it appears increased by the square of the amplification factor β in the collector circuit. However, the noise increase in the collector junction yields also a considerable contribution. The overall increase will be given by a linear equation similar to what we have in Eq. (22) for a single junction. We conclude that according to the Q1/f theory, the junction devices will show a much larger noise increase. In the long run, as we noticed above, even a decrease of 1/f noise is likely in good FET/HFET devices.

4. Transient Radiation Effects in Semiconductor Devices

These effects are mainly caused by a large flood of current carriers produced by γ-rays through internal photoelectric effect (e.g., excitation of electrons from the conduction band and from localized energy levels), by Compton effect and, if they have more than 1 MeV, also by pair formation. Just as we saw above for noise, this affects junction devices again more than FET/HFET devices.

Measures suggested here by us to prevent large damaging transients from BJTs and HBTs, would consist of inclusion of a sufficiently large, normally reverse-biased, pn junctions *both* before the emitter connection, *and* after the collector connection of a bipolar transistor. Both diodes are made particularly radiation sensitive, and have the other end grounded. The same effect mentioned above will occur then also in the diodes, and will provide a temporary shunt, thereby exactly compensating the extra currents to be expected from the transistor.

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