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Generation-recombination noise in submicron semiconductor layers: Influence of the edges

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In highly doped thin semiconductor layers one often observes generation-recombination (g-r) noise with a broadened Lorentzian-like spectrum. In a theoretical analysis we have shown that such a spectrum can be ascribed to g-r processes between conduction band and monoenergetic traps in the edge of the layers. © *1995 American Institute of Physics.*

One often observes generation-recombination (g-r) noise in highly doped submicron semiconductor layers. This is somewhat surprising. In such a material the Fermi level is close to the conduction band, so that traps are almost completely filled. It is well known that filled or empty states do not produce g-r noise. Further, the observed g-r spectra are often found to have a broadened Lorentzian-like shape. Examples of such a g-r spectra can be found in the literature.[1–3] They are obtained from AlGaAs transmission line method test structures and from GaAlAs/GaAs heterojunction bipolar transistors.

In this communication we show that g-r noise with a broadened Lorentzian-like spectrum in highly doped layers can be ascribed to g-r processes in the edge of the layers. The broadening of the g-r spectrum is a result of the position dependence of the relaxation time in the depletion region near the edge of the layers. The possibility of such a broadening for monoenergetic traps in the depletion region of a semiconductor resistor was already shown by Folkes.[4]

Consider a GaAs layer as sketched in Fig. 1. The n-type layer is provided with two ohmic contacts. The electric current I is flowing as indicated by the arrows. The n layer is doped with shallow donors, the concentration is N_D. The dope of the p layer is $N_A=N_D$. The n layer has monoenergetic traps, concentration N_t, that produce g-r noise. The metallurgic junction between the n and p layer is located at $x=\lambda$.

The band bending of the conduction band for $0<x<\lambda$ is given by

$$V(x)=\tfrac{1}{2}V_D(x/\lambda)^2 \tag{1}$$

with $\lambda=(\epsilon V_D/qN_D)^{1/2}$, ϵ the dielectric constant, and V_D almost equal to the band gap (1.4 V).

If $N_D \ll N_A$, then the band bending for $0<x<\lambda'$ is given by

$$V(x)\approx V_D(x/\lambda')^2 \tag{2}$$

with $\lambda'=(2\epsilon V_D/qN_D)^{1/2}$. For $N_D \gg N_A$ we obtain

$$V(x)\approx V_D(2x\lambda''-x^2)/\lambda''^2 \tag{3}$$

with $\lambda''\approx(2\epsilon V_D/qN_A)^{1/2}$. Here λ' and λ'' are the junction widths.

The spatial cross-correlation spectral density of the electron density for unit length $n(x)$ is given by[5]

$$S_n(x,x',\omega)=\frac{4\tau(x)n(x)n_{t,\mathrm{eff}}(x)}{[n(x)+n_{t,\mathrm{eff}}(x)][1+\omega^2\tau^2(x)]}\,\delta(x-x'), \tag{4}$$

with

$$n_{t,\mathrm{eff}}(x)=n_tf_t(x)[1-f_t(x)], \tag{5}$$

$$f_t^{-1}(x)=1+\exp[(E_t-E_F)(x)/kT]=1+\exp(\gamma x^2-b), \tag{6}$$

$$\tau^{-1}(x)=\beta[n(x)+n_{t,\mathrm{eff}}(x)]/f_t(x), \tag{7}$$

$$n(x)=n\exp[-qV(x)/kT]=n\exp(-\gamma x^2), \tag{8}$$

$$\gamma=q^2N_D/2\epsilon kT,\quad \beta=v_{\mathrm{th}}\sigma_t/A. \tag{9}$$

Here, τ is the relaxation time, $n_t=N_tA$ the trap density for unit length, $\omega=2\pi f$ the frequency, δ the Dirac-delta function, f_t the Fermi–Dirac distribution function of the traps, v_{th} the thermal velocity of the free electrons, σ_t the capture cross section of the traps, and A the cross section of the layer perpendicular to the x axis. At the end of this section some remarks will be made about expression (7) for τ. With the help of Eqs. (1), (4)–(9) we can calculate a number of relevant parameters.

The number of free electrons in the two depletion regions, $-(W+\lambda)<x<-W$ and $0<x<\lambda$, is given by

$$N_{\mathrm{depl}}=2\int_0^\lambda n\exp(-\gamma x^2)dx=n\lambda(2\pi kT/qV_D)^{1/2}$$
$$\approx n\lambda/3. \tag{10}$$

The number of free electrons in the bulk region, $-W<x<0$, is given by $N_{\mathrm{bulk}}=nW$. Therefore, the conductance is dominated by the bulk if $N_{\mathrm{bulk}}/N_{\mathrm{dep}}=3W/\lambda>1$, thus $W>\lambda/3$. The spectral noise density of the fluctuations ΔN_{bulk} is

$$S_{N_{\mathrm{bulk}}}(\omega)=\int_{-W}^0\int_{-W}^0 S_n(x,x',\omega)dx'dx$$
$$=4\langle\Delta N_{\mathrm{bulk}}^2\rangle\tau_0/(1+\omega^2\tau_0^2), \tag{11}$$

with τ_0 the relaxation time in the bulk. The variance $\langle\Delta N_{\mathrm{bulk}}^2\rangle$ is

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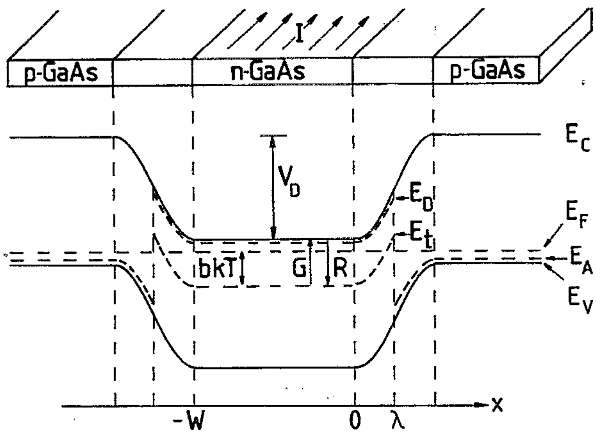

FIG. 1. Energy band diagram of the layer ($N_D=N_A$).

$$\langle \Delta N^2_{\text{bulk}} \rangle = \int_0^\infty S_{N_{\text{bulk}}}(\omega)df = \frac{n_t W}{(1+e^{-b})(1+e^{b})+n_t/n}. \tag{12}$$

For the depletion regions we obtain

$$S_{N_{\text{depl}}}(\omega)=2\int_0^\lambda \int_0^\lambda S_n(x,x',\omega)dx'dx \tag{13}$$

and

$$\langle \Delta N^2_{\text{depl}} \rangle = \frac{2n_t\lambda}{a}\int_0^a \frac{dz}{(1+e^{z^2-b})(1+e^{-z^2+b})+(n_t/n)e^{z^2}} \tag{14}$$

with $a=\lambda\gamma^{1/2}=(qV_D/2kT)^{1/2}\approx 5$.

Remark. The expression for the relaxation time, Eq. (7), needs some explanation. The relaxation time τ for a two-level system is given by [See Eq. (24) of Ref. 5]

$$1/\tau = a[n_1N_2/n_2+N_1(N_2-n_2)/(N_1-n_1)] \tag{15}$$

with n_i the number of carriers in level i, N_i the number of states, and a the capture probability of electrons by level 2. For a nondegenerate n-type semiconductor with traps this leads to

$$1/\tau = a[nN_t/n_t+N_t-n_t]=a[n+N_t(1-f_t)f_t]/f_t \tag{16}$$

with $n=n_1 \ll N_c=N_1$, $n_t=n_2$, and $N_t=N_2$. Here n is the number of free electrons, N_c the number of states in the conduction band, N_t the number of trap states, and $f_t=n_t/N_t$ the trap occupancy factor. The capture probability is given by $a=v_{\text{th}}\sigma_t/\Omega$, with Ω the sample volume. If n, n_t, and N_t are densities then we have $a=v_{\text{th}}\sigma_t$. It should be noted that this formula for τ can also be derived from Sah's results.[6] For a single level Shockley–Read–Hall center the regression of a fluctuation of the trapped electron concentration is given by Eq. (5) in Ref. 6

$$\frac{\partial \Delta n_t}{\partial t} = -[c_n(n+n_1)+c_p(p+p_1)]\Delta n_t + c_n(N_t-n_t)\Delta n - c_p n_t \Delta p. \tag{17}$$

Neglecting transitions between trap and valence band (thus $c_p=0$ and $\Delta p=0$) and taking into account charge neutrality ($\Delta n=-\Delta n_t$), Eq. (17) reduces to

$$-\frac{\partial \Delta n_t}{\partial t} = \frac{\partial \Delta n}{\partial t} = -c_n[n+n_1+N_t-n_t]\Delta n = -\frac{\Delta n}{\tau}, \tag{18}$$

where n is the free electron density, N_t the trap density, n_t the trapped electron density, $n_1=n_i\exp(E_t-E_i)/kT$, E_i the Fermi level for an intrinsic specimen, $n_i=N_c\exp(E_i/kT)$—the free electron density in an intrinsic specimen, and $c_n=v_{\text{th}}\sigma_t$—the capture probability of electrons by traps. Since $n_1=N_c\exp(E_t/kT)$ the relaxation time τ in Eq. (18) can be written as

$$1/\tau = c_n[n+N_c e^{E_t/kT}+N_t-n_t]. \tag{19}$$

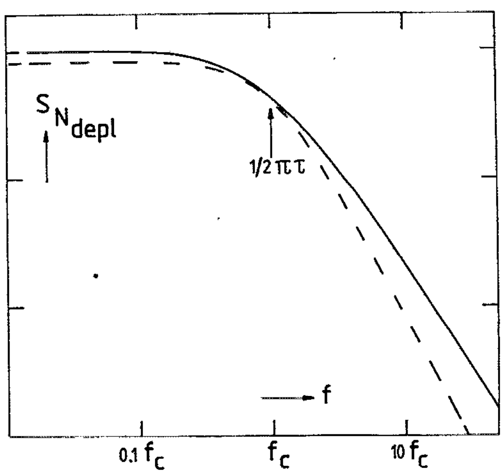

FIG. 2. Spectral density $S_{N_{\text{depl}}}$ vs frequency f on a logarithmic scale. Full line: Eq. (20), dashed line: Lorentzian spectrum.

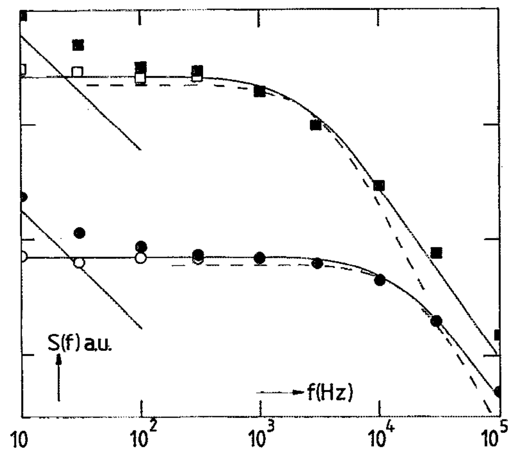

FIG. 3. Lorentzian-like spectra of thin GaAs layers: Pascal *et al.* (Ref. 1) (●), Jarrix (Ref. 3) (■). Full line: Eq. (20), dashed line: Lorentzian spectrum. (Open symbols corrected for $1/f$ noise).

TABLE I. Time constant τ and variance $\langle \Delta N^2 \rangle$ at four situations.

$E_t - E_F \gg kT$ thus $f_t \ll 1$		$E_F - E_t \gg kT$ thus $f_t \approx 1$	
$n^* \gg n_t^*$	$n^* \ll n_t^*$	$n^* \gg N_t - n_t^*$	$n^* \ll N_t - n_t^*$
$1/\tau = v_{\mathrm{th}}\sigma_t N_c \exp(-\lvert E_t\rvert/kT)$	$1/\tau = v_{\mathrm{th}}\sigma_t N_t$	$1/\tau = v_{\mathrm{th}}\sigma_t n^*$	$1/\tau = v_{\mathrm{th}}\sigma_t (N_t - n_t^*)$
$\langle \Delta N^2 \rangle = n_t^* \Omega$	$\langle \Delta N^2 \rangle = n^* \Omega$	$\langle \Delta N^2 \rangle = (N_t - n_t^*)\Omega$	$\langle \Delta N^2 \rangle = n^* \Omega$

As $nN_t/n_t = n[1+\exp(E_t - E_F)/kT] = n + N_c \exp(E_t/kT)$, we find Eq. (19) to be equal to Eq. (16).

Here it should be noted that the capture probabilities a, β, and c_n differ by a geometrical factor. For n,N in densities per unit volume we have $c_n = v_{\mathrm{th}}\sigma_t$, for densities per unit length we have $\beta = v_{\mathrm{th}}\sigma_t/A$, and for total numbers $a = v_{\mathrm{th}}\sigma_t/\Omega$.

Here we present the results for the special case where $n_t < n \exp(-b)$. The formulas for the variance and the g-r noise become more simple then. In the whole depletion region we can use the approximation $n(x) > n_{t,\mathrm{eff}}(x)$. At room temperature the assumption $E_t = -0.15$ eV results in $b \approx 5$ and thus $N_t < N_D/150$. For this case we find $\langle \Delta N^2_{\mathrm{bulk}} \rangle \approx n_t W/150$, $\langle \Delta N^2_{\mathrm{depl}} \rangle \approx n_t \lambda/10$, and $\langle \Delta N^2_{\mathrm{depl}} \rangle / \langle \Delta N^2_{\mathrm{bulk}} \rangle \approx 15\ \lambda/W$.

Consequently, for the special case $N_A = N_D = 10^{17}\ \mathrm{cm}^{-3}$ where $\lambda = 0.1\ \mu$m, the g-r noise in the depletion region dominates when $W < 1.5\ \mu$m. Note that the conductance in the depletion region dominates for $W < 0.03\ \mu$m.

For the same situation, $b=5$ and $N_t < N_D/150$, the spectral noise density of ΔN_{depl} is calculated to be approximately equal to

$$S_{N_{\mathrm{depl}}}(\omega) = \frac{8 n_t \lambda}{a} \int_0^a \frac{dz}{[e^b + e^{z^2}][(e^{-b} + e^{-z^2})^2 + \omega^2 \tau_0^2]}, \tag{20}$$

with $a \approx 5$. The results are plotted in Fig. 2. Here we observe an obvious broadening of the ideal Lorentzian spectrum. The corner frequency is about $\omega_c \approx e^{-b}/\tau_0$, which results in an effective time constant

$$1/\tau_{\mathrm{eff}} = \omega_c = \beta n \exp[(E_t - E_F)_0/kT]$$
$$\approx v_{\mathrm{th}} \sigma_t N_c \exp(-\lvert E_t \rvert/kT). \tag{21}$$

Here, N_c is the effective density of states in the conduction band.

In Fig. 3 we have plotted two experimentally observed broadened Lorentzian-like spectra. The data are from thin GaAs layers and have been published in Ref. 1 and in Ref. 3 (Fig. I47). Here we see that the experimentally observed deviations from the ideal Lorentzian spectrum are similar to the calculated deviations presented in Fig. 2.

It is common practice to determine the trap energy E_t from the temperature dependence of the relaxation time τ. This energy is evaluated from Arrhenius plots, i.e., $\log(\tau T^2)$ vs $1/T$. According to Eq. (21) we have

$$1/\tau = v_{\mathrm{th}} \sigma_t N_c \exp(-\lvert E_t \rvert kT) \sim T^2 \exp(-\lvert E_t \rvert/kT), \tag{22}$$

where $v_{\mathrm{th}} \sim T^{1/2}$, $N_c \sim T^{3/2}$, and σ_t is assumed to be independent of the temperature. If the g-r noise is determined by the bulk of the semiconductor, then Eq. (22) only holds for very special cases, and one has to be careful using this equation. According to Eqs. (7) and (12) for homogeneous devices we have

$$1/\tau = v_{\mathrm{th}} \sigma_t [n^*/f_t + N_t(1-f_t)] \tag{23}$$

and

$$\langle \Delta N^2 \rangle = \frac{N_t \Omega}{(1+e^{-b})(1+e^b) + N_t/n^*}$$
$$= \frac{\Omega}{1/(N_t - n_t^*) + 1/n_t^* + 1/n^*}, \tag{24}$$

where n^* is the density of free electrons, n_t^* the density of trapped electrons, Ω the device volume, and $f_t = n_t^*/N_t = (1 + e^{-b})^{-1}$, thus $e^{-b} = (N_t - n_t^*)/n_t^*$.

We can have several situations, which are summarized in Table I.

Considering Eq. (22) and the results in Table I, the conclusion is obvious. Equation (22) can be used for the special case where:

(1) $E_t - E_F \gg kT$, thus the trap has to be situated at a level more than kT above the Fermi level.
(2) density of free electrons has to be much larger than density of trapped electrons $(n^* \gg n_t^*)$
(3) temperature dependence of $v_{\mathrm{th}} \sigma_t N_c$ has to be $\sim T^2$, thus σ_t is independent of T.

Here it should be noted that Eq. (22) is often used for III-V semiconductors with a donor concentration N_D such that $E_c - E_F = kT \ln N_c/N_D < 0.2$ eV. With the help of Arrhenius plots activation energies, $\lvert E_t \rvert$, have been determined with values higher than 0.2 eV, thus $E_F - E_t \gg kT$. Such an analysis can be correct provided that the edges determine the g-r noise and Eq. (21) applies.

In thin highly doped layers the g-r noise is mainly determined by the edges of the layer, whereas the conductance is determined by the bulk. In such layers we can expect deviations from the ideal Lorentzian shape.

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