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Dependence of backgating on the type of deep centres in the substrate of GaAs FETs

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ABSTRACT

The reduction of the conductance of GaAs FETs by a negative voltage applied to the substrate, termed backgating or sidegating, is numerically modelled to clarify which type of traps is responsible. Modelling is carried out for several sets of deep levels in the substrate. It is observed that deep acceptors are mainly responsible for backgating independently of the shallow level type in the substrate. In this case there is no threshold. When deep donors are present in the substrate, it is observed that backgating is reduced and there is a threshold. The presence of a buffer layer between the channel and the semi-insulating substrate also helps in reducing backgating.

1. Introduction

Backgating (or sidegating) effect has been bothering GaAs integrated circuit (IC) technology for a long time because it is responsible for parasitic interactions between neighbouring IC components, thus lowering the maximum attainable integration density. Backgating is the channel conductance reduction of a GaAs field-effect transistor by a negative voltage applied to the semi-insulating substrate [1]. In some cases, backgating has a threshold voltage V_{th}; that is the channel current is reduced only when the substrate voltage exceeds V_{th}. Several backgating models have been proposed, and in all of them, it is eventually attributed to the widening of the depletion region of the channel–substrate interface (C-S-I). In the model explaining the threshold [2], backgating is due to electron injection into the substrate from the backgate, where V_{th} is the trap-fill-limit (TFL) which is the minimum voltage to make the substrate conducting and hence the applied voltage reaches the (C-S-I). The hot electron model [3] relates backgating to the accumulation of excess electrons in the near-channel region of the substrate, occurring when the electric field in the substrate exceeds the threshold of N-type negative differential conductivity (NDC). Backgating is also related to the Frenkel-Poole hole emission from deep acceptors [4]. In other models [5,6] backgating is associated with the impact ionization of deep traps in the substrate which increases the free electron density, thus changing the voltage distribution between the bulk of the substrate and the (C-S-I). Previous works confirmed that the threshold voltage for sudden increase in substrate leakage current is exactly the same as the threshold voltage for the backgating effect [2]. This correlation shows that this effect depends not only on the properties of (C-S-I) but also on the current transport through the substrate. Recently Murty and Jit reported that GaAs MESFET capacitances are photo dependent and this is due to trapping effects in the substrate which also responsible for backgating [7].

This work is a numerical simulation of the backgating phenomenon observed in GaAs FETs. The main aim of this paper is to show that the threshold for backgating depend, among other factors, on the type of traps located in the substrate.

2. Sample structure

The substrate is assumed to contain shallow and deep levels. The density of deep levels is usually greater than that of shallow levels for typical semi-insulating substrates [8]. Deep acceptors are assumed to be located at the middle of the energy gap ($E_V + 0.7$ eV) which is a typical value for Cr levels in Cr-doped semi insulating GaAs widely used as substrate for GaAs FETs while deep donors are located at $E_C - 0.75$ eV which is a typical value for the well known EL_2 [9]. The channel is n-type with a density of 10^{16} cm^{-3} shallow levels. The channel thickness is $a_c = 0.2$ μm, that of the substrate is $a_s = 10$ μm. The backgating is studied for two types of devices: with and without a high purity buffer layer between the channel and the SI substrate.

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3. The transport equations

The transport in semiconductors is governed by three sets of differential equations. The Poisson's equation relating potential with charge densities:

$$\frac{d^2\psi}{dx^2} = -\frac{q}{\varepsilon}(p - n + N_D - N_A + (1 - f_D)N_{TD} - f_A N_{TA}) \tag{1}$$

where ψ is the potential, $\varepsilon = \varepsilon_0\varepsilon_r$ is the dielectric constant of GaAs; n and p are the free electron and hole densities, $(N_D - N_A)$ is the effective doping distribution, N_{TD} is the deep donor density, N_{TA} is the deep acceptor density and $f_{D(A)}$ is the occupation probability of the deep donor (or acceptor) given by the Shockley-Read-Hall statistics [10] as:

$$f = \frac{C_n n + C_p n_i e^{-\left(\frac{E_T - E_i}{kT}\right)}}{C_n\left(n + n_i e^{\left(\frac{E_T - E_i}{kT}\right)}\right) + C_p\left(p + n_i e^{-\left(\frac{E_T - E_i}{kT}\right)}\right)} \tag{2}$$

E_T is the energy level of the trap, E_i is the intrinsic Fermi level, $C_{n(p)}$ is the trap capture coefficient for electrons (holes), n_i is the intrinsic density, k is the Boltzmann constant and T is the absolute temperature.

The electron and hole conservation laws can be written as:

$$\frac{1}{q}\cdot\frac{dJ_n}{dx} + G + G_I - U = 0 \tag{3}$$

$$\frac{1}{q}\frac{dJ_p}{dx} - G - G_I + U = 0 \tag{4}$$

where G is the external generation rate, U is the net recombination rate and G_I is the impact ionisation generation rate which may be important for high electric field and current. The external generation rate is obviously negligible. The impact ionisation is given by [11]

$$G_I = \alpha(E)\frac{|J_n| + |J_p|}{q} \quad \text{with } \alpha(E) = \alpha_\infty \exp\left\{-\left(\frac{E_i}{E}\right)^2\right\} \tag{5}$$

$\alpha(E)$ is the field dependent impact ionisation coefficient, $\alpha_\infty = 3.5 \times 10^5\ \text{cm}^{-1}$ and $E_i = 550$ kV/cm. Recombination in GaAs can be direct (from band to band) or via recombination centres located in the energy gap. The first can be negligible if there are high densities of recombination centres. The second mechanism is given by the Shockley-Read-Hall model [10] for a single species of recombination centres as:

$$U = \frac{np - n_i^2}{\tau_p\left(n + n_i e^{\left(\frac{E_T - E_i}{kT}\right)}\right) + \tau_n\left(p + n_i e^{-\left(\frac{E_T - E_i}{kT}\right)}\right)} \tag{6}$$

τ_n and τ_p are the minority carrier lifetimes given by:

$$\tau_n = \frac{1}{C_n N_T} \quad \text{and } \tau_p = \frac{1}{C_p N_T}$$

Since we have considered two deep levels then the net recombination rate is the sum of the two rates.

Although the electric field is high (can reach 200 kV/cm for a substrate bias of 200 V) the currents J_n and J_n are very small ($\approx 10^{-10}\ \text{A cm}^{-2}$ in reverse bias). This gives $G_I \approx 10^{11}\ \text{s}^{-1}\ \text{cm}^{-3}$ which is negligible compared to U which can be as high as $10^{17}\ \text{s}^{-1}\ \text{cm}^{-3}$ since τ_n and τ_n can as low as 10^{-10} s in GaAs with the presence of high density of traps and or recombination centres.

The electron and hole currents are given by:

$$J_n = -\mu_n\left(qn\frac{d\psi}{dx} - kT\frac{dn}{dx}\right) \tag{7}$$

$$J_p = -\mu_p\left(qp\frac{d\psi}{dx} + kT\frac{dp}{dx}\right) \tag{8}$$

where μ_n and μ_p are the electron and hole mobility whose dependence on the electric field E is taken into account by the following empirical relation:

$$\mu_n = \mu_{no}\frac{1 + \left(\frac{v_{ns}}{\mu_{n0}E}\right)\left(\frac{E}{E_0}\right)^4}{1 + \left(\frac{E}{E_0}\right)^4}, \mu_p = \mu_{p0}\frac{1}{1 + \mu_{p0}\frac{E}{v_{ps}}}$$

With $\mu_{n0} = 4500\ \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$ is the low field electron mobility, $\mu_{p0} = 400\ \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$ is the low field hole mobility, $v_{ns} = 8.5 \times 10^6\ \text{cm s}^{-1}$ is the electron saturation velocity, $v_{ps} = 10^7\ \text{cm s}^{-1}$ is the hole saturation velocity and $E_0 = 4000\ \text{V cm}^{-1}$ is the peak electric field [12].

4. Numerical method of resolution

The numerical simulation was carried out using the package Kurata [13]. The three differential Eqs. (1), (3) and (4) together with Eqs. (5)–(8) are numerically solved for the three unknowns: ψ, n and p with appropriate boundary conditions. These are that electrical neutrality holds at the ohmic contact for the space charge while for the potential is zero and the applied voltage at the ends of the channel and the substrate respectively. These gives six boundary conditions which are:

$$n(1) = N_D, p(1) = \frac{n_i^2}{N_D} \text{ at the channel end}$$

$$p(L) = \frac{\left(N_{AS} - N_{DS} - M \times N_T^M\right) + \sqrt{\left(N_{AS} - N_{DS} - M \times N_T^M\right)^2 + 4n_i^2}}{2}$$

$$n(L) = \frac{\left(M \times N_T^M + N_{DS} - N_{AS}\right) + \sqrt{\left(N_{AS} - N_{DS} - M \times N_T^M\right)^2 + 4n_i^2}}{2}$$

at the substrate end

$$\psi(1) = 0, \psi(L) = V_{app}$$

M here indicates the trap charge,– for a deep acceptor and + for a deep donor, N_{DS} and N_{AS} are the densities of the shallow donors and acceptors in the substrate, V_{appl} is the applied voltage to the substrate.

Obviously the quantities, J_n, J_n and U involve nonlinear functions which are linearised by Taylor expansion neglecting higher order terms. According to Scharfetter and Gummel [14], the current equations are rewritten in integral forms by assuming that the current is constant between adjacent points and a linear variation of the electrostatic potential.

5. The backgating

The backgating is studied by calculating the space charge induced by the partial depletion of the channel by the applied substrate voltage to reduce its effective thickness and hence the conductance. Since the channel is n-type, then the conductance is given by

$$G = \frac{I}{V} = \frac{q\mu_n E Z_c}{El}\int_{-a_c}^{0} n\,dx = \frac{q\mu_n Z_c}{l}\int_{-a_c}^{0} n\,dx \tag{9}$$

Where I is the current, V is the applied voltage and E is the electric field in the channel. Z_c and l are the length and the width of the channel, respectively. The integral boundaries are at the contact with the gate ($x = -a_c$) and the interface with the substrate ($x = 0$). The normalised conductance is then G/G_0. G and G_0 are the conductance under an applied bias and under zero bias, respectively.

6. Results and discussions

6.1. The effect of deep acceptors

First we consider that only a deep acceptor is present in the substrate. The normalized calculated conductance is presented in Fig. 1. The conductance decreases with increasing density of the deep acceptor. It is reduced at a voltage smaller than the one in the case of their absence. This is evident since acceptors give the substrate a p-type like semiconductor, with a high density than in previous case (without traps). Hence an applied negative voltage to the substrate is a reverse bias. The depletion region at the channel–substrate interface widens causing a decrease in the channel width and hence in its conductance.

6.2. The effect of the deep donors

Adding deep donors to substrate make the conductance reduction have a threshold. So increasing the deep donor density increases the threshold as shown in Fig. 2. At high deep donor density the conductance remains constant, but beyond a certain value of the applied voltage it drops rapidly. A higher voltage is then required to reach the channel–substrate interface to cause a reduction in the channel conductance. This is the case of backgating with threshold voltage. So, the donors reduce backgating. When the donors are larger than the acceptors their effect becomes more apparent. Hence to reduce the effect of deep acceptors (responsible for backgating), they are compensated by deep donors. This increases the electron density and lowers that of holes in the substrate.

6.3. The presence of a buffer layer

Adding a buffer layer can have an effect on backgating and this is shown in Figs. 3 and 4 in the presence of deep acceptors and donors respectively. A buffer layer reduces the effect of deep centers in the substrate on the space charge region at the channel–substrate interface, which is responsible for backgating. Deep acceptors enhance backgating, and thus reducing their effect by adding a buffer layer will reduce backgating too (Fig. 3 is compared with Fig. 1). As to deep donors, they reduce backgating, and thus

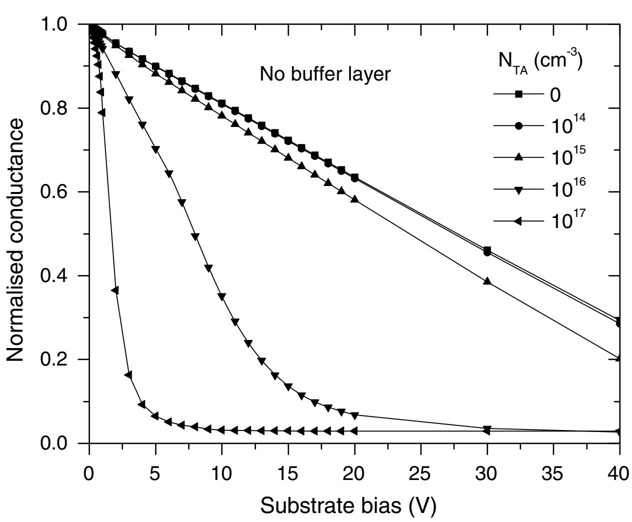

Fig. 1. The normalised conductance as a function of the reverse voltage applied to the substrate of the MESFET without a buffer layer with the deep acceptor density increasing from 0 to 10^{17} cm^{-3}.

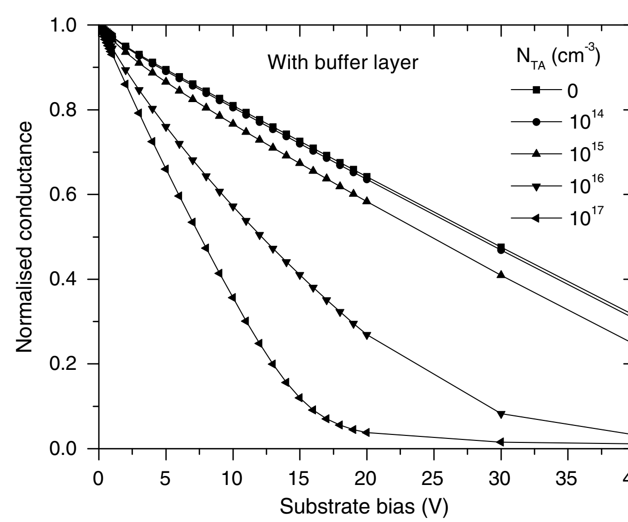

Fig. 3. The normalised conductance as a function of the reverse voltage applied to the substrate of the MESFET with a buffer layer with the deep acceptor density increasing from 0 to 10^{17} cm^{-3}.

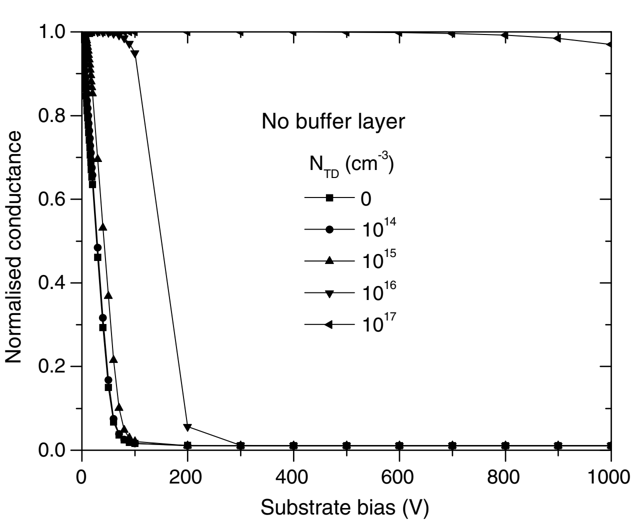

Fig. 2. The normalised conductance as a function of the reverse voltage applied to the substrate of the MESFET without a buffer layer with the deep donor density increasing from 0 to 10^{17} cm^{-3}.

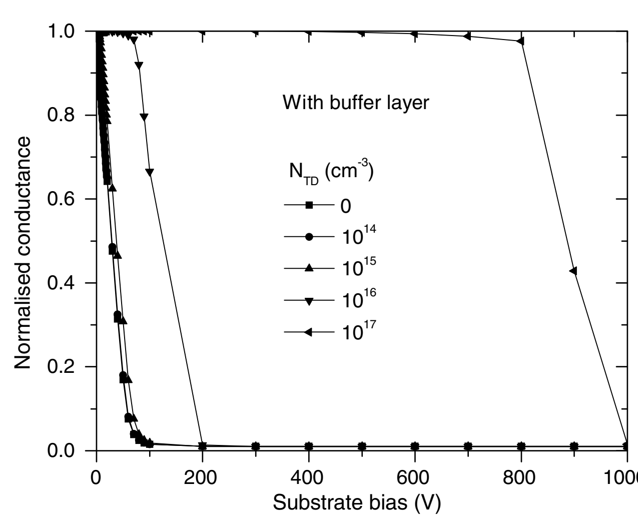

Fig. 4. The normalised conductance as a function of the reverse voltage applied to the substrate of the MESFET with a buffer layer with the deep donor density increasing from 0 to 10^{17} cm^{-3}.

when their effect is reduced by adding a buffer layer, backgating is enhanced (compare Fig. 4 with Fig. 2).

7. Conclusions

The backgating effect in GaAs Field Effect Transistors was numerically modelled as a function of the density of deep acceptors and donors and the presence of a buffer layer. The presence of deep acceptors in the substrate increases the backgating. The donors reduce the backgating since they make the substrate less p-type hence the depletion region inside the channel decreases. The buffer layer reduces backgating in the presence of deep acceptors but enhances it in the presence of deep donors. As a suggestion and in order to reduce backgating, is adding high density of deep donors to compensate deep acceptors.

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