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REAL-SPACE TRANSFER IN HETEROJUNCTION FET's : MONTE-CARLO SIMULATION AND ANALYTICAL MODEL

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Résumé - Nous analysons les résultats d'une simulation Monte-Carlo du NERFET, dispositif à effet de champ où le transfert spatial des électrons du canal au dessus d'une hétérojonction permet d'obtenir un effet de résistance différentielle négative (RDN) sur le courant de drain. Sur la base de cette simulation, nous établissons une expression analytique du courant de transfert spatial. Les résultats obtenus sont en bon accord avec les résultats de la simulation Monte-Carlo sans qu'il soit nécessaire d'introduire de paramètre ajustable.

Abstract - We present the results of a Monte-Carlo simulation of the NERFET, a field effect transistor where the real-space transfer of channel electrons over a heterojunction barrier gives rise to a negative differential resistance (NDR) effect on drain current. An analytical expression of the real-space current is built upon our simulation results. By this way, we construct an analytical model of the NERFET which shows good agreement with Monte-Carlo results without the need of adjusting any parameter.

1-Introduction:

Field-effect devices using conduction along a heterojunction are of growing interest for high speed integrated circuits. They combine two advantages: the high electron density which can be obtained in an accumulation or inversion layer, and a high electron mobility which can be achieved both because of the high purity of the active layer and because of the high quality of the heterojunction interface. However, the confining potential barrier is lower than in classical MISFET's. In heterojunction FET's (HFET's), this barrier is equal to the conduction band discontinuity at the interface and is of the same order of magnitude as the kinetic energy of hot electrons in short devices. Thus, hot electrons can transfer from the channel into the barrier semiconductor. This real-space transfer (RST) can be used in order to obtain a negative differential resistance (NDR) effect on drain current as it is the case in the NERFET [1,2].

2-The model:

The active region of the NERFET is shown in figure 1-a, drawn on the basis of the data in reference 1. The assumed band discontinuity between GeAs and $\text{Ge}_x\text{Al}_{1-x}\text{As}$ ($x=0.34$) is 0.3eV. The mid-gap Fermi level pinning at the GeAs surface is taken into account using the convenient surface charge. The source to drain distance is $L = 1\mu\text{m}$.

As it has been pointed out by several authors [2,3,4], electrons in the channel of submicron devices are strongly out of equilibrium. Furthermore, real-space transfer is governed both by the energy and angular distributions of channel electrons and by the local conditions allowing transmission over the heterojunction conduction band discontinuity. A 2D Monte-Carlo simulation is then very well suited for studying real-space transfer, since it accurately describes non stationary transport phenomena and two-dimensional effects. We used the many-particle Monte-Carlo model which was presented in a previous paper [5]. The motion of each electron is divided into a succession of random free-flights in the 2D self-consistent electric field and of interactions with lattice phonons, ionized impurities and alloy disorder. For each electron impinging on the interface, the transmission probability is calculated with a quantum mechanical model which ensures the continuity of the parallel component of the wave-vector, the continuity of the total (kinetic+potential) electron energy and the continuity of the probability current [6]. However, we do not account yet for a possible tunneling of electrons with an energy lower than the conduction band discontinuity.

In figure 1-b, we present the source, drain and substrate characteristics versus drain and gate voltages. As expected, a substrate current (due to RST) appears for a given V_{DS} value. For bias voltages where source current saturates, the increase in substrate current leads to a symmetrical decrease in drain current. This induces the NDR effect. The electron flux through the heterojunction is especially important at the drain end of the channel, where electrons are hot. However, the substrate current which arises from RST is not just related to heating phenomena: it is shown in figure 2 that the evolution of the electron energy along the channel for a given V_{DS} is not dependent on substrate voltage, whereas I_{sub} is (fig 1-b). Several mechanisms are involved and will now be detailed.

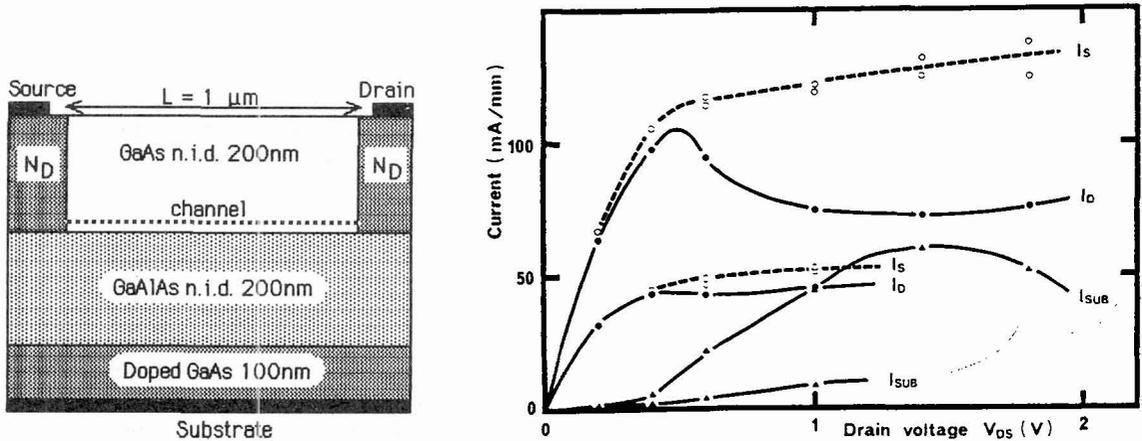


Fig.1- Device geometry and current-voltage characteristics deduced from Monte-Carlo simulation.

Let us note firstly that increasing V_{sub} results naturally in a higher confining field E_{\perp} at the upper GaAs/GaAlAs interface. This implies modifications both in the current saturation mechanism and in the amount of real-space transfer. Figure 2 shows the evolution of the transverse electric field along the interface for two values of V_{sub} under bias conditions leading to source current saturation ($V_{DS} = 1V$). For the low substrate voltage ($V_{sub} = 1V$), E_{\perp} becomes negative near the drain, causing channel pinch-off and moving hot electrons away from the interface. For a higher substrate voltage, ($V_{sub} = 2V$), E_{\perp} has a confining influence all along the channel and current saturation is due to another mechanism. From the electron concentration, we find that a dipolar domain is trapped at the drain N^+ region boundary, clearly indicating a velocity saturation mechanism [7,8]. In the accumulated region of the domain, population inversion of the electrons from the Γ valley and the lateral valleys occurs. This allows the presence of hot electrons, pertaining to the L valleys, near the interface.

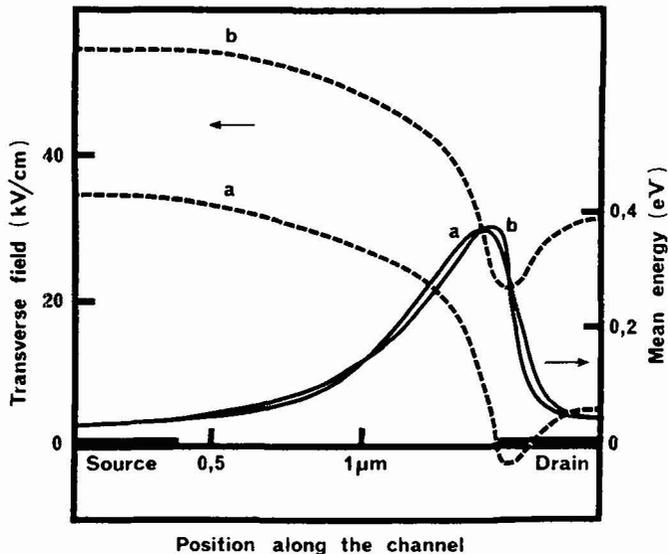


Fig.2- Evolution of the electron energy and of the transverse electric field along the channel; V_{sub} =a) 1V, b) 2V.

Furthermore, RST is easier for these L valleys electrons. This comes first from the local conditions which allow the transmission of an electron over the conduction band discontinuity. The transmission is impossible unless the kinetic energy associated with the transverse wave-vector component ($\hbar^2 k_{\perp}^2 / 2m^*$ neglecting non-parabolicity) exceeds a minimum value. In other words, an electron from GaAs impinging on the interface with a kinetic energy ϵ will surmount the interfacial potential discontinuity only if the incidence angle is lower than a maximum angle $\theta_{lim}(\epsilon)$ defined by $\sin^2 \theta_{lim} = (1 - \Delta \epsilon_c / \epsilon) m^*(GaAlAs) / m^*(GaAs)$. Due to the barrier heights differences, the maximum incidence in the L valleys is higher than in the Γ

valley. Moreover, in submicron devices, the velocity distribution of hot electrons in the Γ valley is known to be very anisotropic, with a main orientation parallel to the channel interface [4,9]. On the contrary, in the L valleys, the velocity distribution of electrons is randomized by the frequent interactions between equivalent satellite valleys. This again favours the real-space transfer of previously k-space transferred electrons.

To sum up, for the low or medium substrate voltages, the current saturation mechanism is involved in the amount of real-space transfer: we have shown that thermoionic injection is facilitated by electron velocity saturation and by k-space transfer, whereas channel pinch-off induces an antagonist transverse field.

3-Analytical model for the real-space current:

The basis of our analytical model are derived directly from the Monte-Carlo results. We saw that the amount of RST is strongly enhanced when k-space transfer occurs. Therefore, we will only investigate the case where the source current saturation is due to velocity saturation of electrons and is associated with the formation of a dipolar domain trapped near the drain. The substrate current is mostly carried by electrons from the accumulation region of the domain which obey the transmission conditions. Electrons in the domain all belong to the L valleys of the conduction band. Due to the frequent intervalley interactions, they are supposed to obey a Maxwellian distribution (with a temperature T_e).

The substrate current is calculated by adding the contributions of electrons, according to their energy and to the direction of their velocity. With Boltzmann statistics, the number of electrons in a range of $d\epsilon$ in the L valleys is:

$$dn(\epsilon) = \frac{n_0}{kT_e} \exp\left(-\frac{q\epsilon}{kT_e}\right) d\epsilon \quad \text{where } n_0 \text{ is the electron density in the accumulation domain.}$$

Within this population, the electrons which have their velocity directed within a differential solid angle around θ contribute to the substrate current in the ratio of $v_{\perp} = \sqrt{2q\epsilon/m_L^*} \cos \theta$. The resulting differential current is:

$$dI_{sub} = qZ L_d^a \left\{ \frac{n_0}{kT_e} \exp\left(-\frac{q\epsilon}{kT_e}\right) \right\} \left\{ \sqrt{\frac{2q\epsilon}{m_L^*}} \cos \theta \right\} \left\{ \frac{2\pi \sin \theta d\theta}{4\pi} \right\} d\epsilon$$

Here, Z is the device length and L_d^a is the length of the accumulated region of the domain.

Continuity equations in the heterojunction plane (with equal effective masses for electrons in the L valleys of GaAs and GaAlAs) show that an electron can be injected in GaAlAs if its energy ϵ is greater than the band discontinuity in the L valleys ($\Delta\epsilon_{cl}$) and if the velocity is directed within a solid angle which is defined by $\sin^2 \theta_{lim} = 1 - \Delta\epsilon_{cl}/\epsilon$. Integrating over θ and ϵ leads to:

$$I_{sub} = \frac{q n_0 L_d^a Z}{4} \sqrt{\frac{2q\Delta\epsilon_{cl}}{m_L^*}} f\left(\frac{1}{x}\right) \quad \text{with} \quad x = \frac{kT_e}{q\Delta\epsilon_{cl}}$$

$$f\left(\frac{1}{x}\right) = \sqrt{\pi} \sqrt{\frac{x}{2} - 1} \operatorname{erfc}\left(\frac{1}{\sqrt{x}}\right) + \exp\left(-\frac{1}{x}\right)$$

Considering that any increase in V_{DS} above the saturation value V_{DSsat} has the effect of reinforcing the dipolar domain, we obtain the relative length of the domain (L_d^a/L) by solving Poisson equation. On the other hand, kT_e/q can be determined using the energy relaxation equation. The only unknown quantity is then $n_0 L_d^a$, which accounts for the domain geometry. This geometry can be specified for the NERFET: the domain is confined on an almost constant thickness between the heterojunction plane and the surface space-charge layer resulting from the Fermi-level pinning at the GaAs surface. The whole set of equations can then be expressed only in terms of x and of constant parameters:

$$Q_0 = q n_0 L_d^a a Z = x \frac{3\epsilon_0 \epsilon_r a Z}{v_{sat} \tau_e} \Delta\epsilon_{cl} \quad (\text{eV}) \quad (v_{sat} \text{ is the saturation velocity and } \tau_e \text{ the energy relaxation time})$$

$$\frac{L_d^a}{L} = \frac{2 \epsilon_0 \epsilon_r a Z}{L} \frac{V_{DS} - V_{DSsat}}{Q_0} \frac{1}{x} - \frac{Q_0}{q N_D a Z L} x \quad \text{where } Q_0 = \frac{3\epsilon_0 \epsilon_r a Z}{v_{sat} \tau_e} \Delta\epsilon_{cl}$$

$$I_{sub} = \frac{Q_0}{4a} \sqrt{\frac{2q\Delta\epsilon_{cl}}{m_L^*}} x f\left(\frac{1}{x}\right)$$

On the other hand, the drain current is obtained as the ratio of the stored charge Q_D over the transit time in the accumulation domain (L_d^a/v_{sat}) whereas the source current is a saturated current controlled by V_{sub} with a transconductance g_m . Therefore:

$$I_D = \frac{Q_D v_{sat}}{L} \frac{x}{L_d^a/L} \quad \text{and} \quad I_S = g_m (V_{sub} - V_T) \frac{1}{1 - L_d^a/L}$$

Current conservation allows the determination of x . Figure 3 shows the characteristics obtained by using the electrical parameters deduced from the simulation ($Z = 100\mu\text{m}$, $g_m = 6.2\text{mS}$, $V_T = 0.28\text{V}$, $V_{DSsat} = 0.4\text{V}$). Remembering that these characteristics are valid for V_{DS} lying in the range $[V_{DSsat}, V_{GS} - V_T]$, we show the Monte-Carlo characteristics for comparison. The maximum error in drain and source currents is less than 15%. This is quite satisfying since there is no adjustable parameter. Furthermore the intermediate results of the analytical model (T_e , L_d^a , Q_D ...) are found also to correlate well with the Monte-Carlo results.

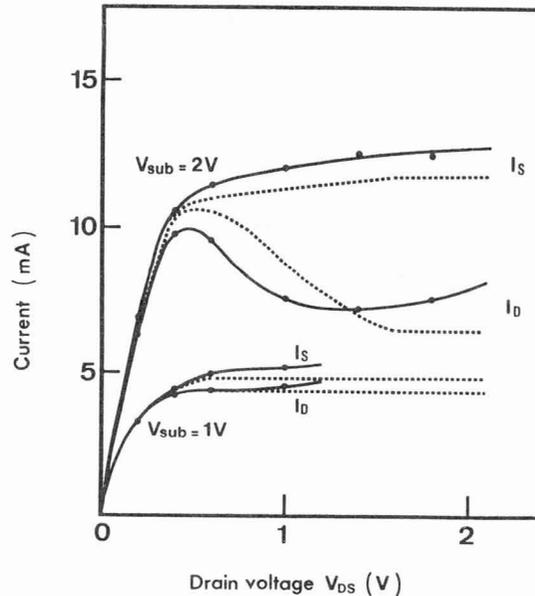


Fig.3- Comparison between the analytical (dashed lines) and the Monte-Carlo (solid lines) characteristics for two values of the substrate voltage ($V_{sub} = 1\text{V}$ and 2V)

4-Conclusion

We have studied real-space transfer in the NERFET using a self-consistent Ensemble Monte-Carlo simulation which accurately describes the thermionic injection range. Based on these results, we propose an analytical expression for the RST current which is well correlated with our Monte-Carlo results.

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