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TRANSPORT PROPERTIES OF DELTA DOPED FIELD EFFECT TRANSISTOR

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Abstract—The first calculation of mobility and conductivity between source and drain as function of gate voltage in a δ-doped Field Effect Transistor is presented. The calculation was performed with a model for the δ-FET that was shown in [1]. The mobility was calculated using a phenomenological expression that was presented in [2]. That expression does not have empirical form, neither empirical parameter. For the first time a phenomenological expression of the conductivity is presented, which is derived from the mobility expression. The conductivity shows three different regions: a parabolic region and two linear regions. The parabolic region represents the region at which the conduction channel begins to close. On the other hand, the mobility shows a more different behavior. In the mobility there are four regions. These regions correspond to the disappearance of the different conduction channels that form the subbands of the delta-doped quantum well. The different behavior between mobility and conductivity relies on the depletion of the delta-doped quantum well as the gate potential grows.

1. INTRODUCTION

The system we are interested in is the δ-FET in $GaAs$ proposed originally by Schoubert, Ploog and collaborators [3, 4]. They made a field effect transistor in which the channel is formed by growing an n type Si delta-doped well located between the terminals of the source and the drain of a regular $GaAs$ field effect transistor (see Figure 1). The presence of this n type quantum well produces a localized two-dimensional electronic gas ($2DEG$), which participates directly in the conduction channel. The use of this type of doping in semiconductor

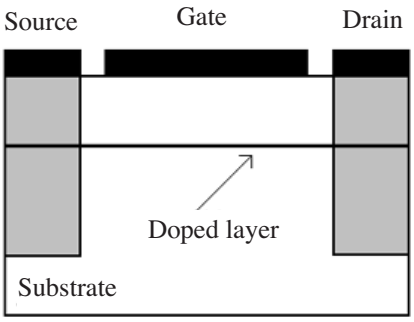

Figure 1. Schematic representation of a δ-FET en GaAs.

devices yields a great improvement in the performance of ultra high frequency optoelectronic devices [5]. The δ-FET is also expected to exhibit a higher transconductance [4] than a high electron mobility transistor due to the proximity of the delta channel to the gate.

2. THEORETICAL BACKGROUND

The δ-doping technique allows one to obtain an extremely sharp doping profile and a high-density-doped layer. Potentials of this system is formed by a metal-semiconductor contact (Schottky barrier), followed by the n-type delta-doped quantum-well system. The presence or not of a confined electronic gas depends on the parameters used in the construction of the system.

If there is electronic confinement, our model for describing the conduction band of the semiconductor in the δ-FET system has, as its main assumptions, that the potential profile is described by the depletion region approach in the proximity of the metal-semiconductor contact.

$$V_{dep}(z) = \frac{2\pi e^2}{\epsilon_r} N_d (z + d - l)^2 \tag{1}$$

where N_d is the background impurity density, ϵ_r is the electric permittivity constant of GaAs, and l is the screening distance for the electric field:

The second assumption is that, in the region not too close to the interface, the delta-doped well potential is described within a self-consistent Thomas-Fermi approach [6] by:

$$V_n(z) = -\frac{\alpha_n^2}{(\alpha_n |z| + z_{0n})^4} \tag{2}$$

$\alpha_n = 2/(15\pi)$ and $Z_{0n} = (\alpha_n^3/\pi N_{2de})^{1/5}$, is the distance at which the n-type delta-doped well is positioned, N_{2de} is the two-dimensional impurity density of the n-type delta-doped quantum-well. The entire potential is mathematically presented by the following expression [7]:

$$V(z) = V_{dep}(z)\theta(l - z - d) + V_n(z) \tag{3}$$

where θ is the unit-step function.

The starting parameters for n-type δ-FET in GaAs are:

m*=0.067, ϵ_r =12.5, $n_{2D} = 7.5 \times 10^{12}\text{cm}^{-2}$

(Figure 2) shows the confining potential and the sub-band energies with their envelope wave functions $n_{2D} = 7.5 \times 10^{12}\text{cm}^{-2}$, the background impurities is of $N_d = 10^{18}\text{cm}^{-3}$ at $T = 0$K. Here, n-type delta-doped quantum-well is located at 300 Å from the interface. The dashed curve represents the obtained confining potential profile and the solid curves represent the wave functions, potential profile, eigenvalues and eigenfunctions. Eigenfunctions have a antisymmetric form (extension to right direction) this phenomena due to Schottky potential contact, (Figure 2) presents for $V_c = 500\,\text{meV}$, eigenvalues $E_f - E_1 = 248.18\,\text{meV}$, $E_f - E_2 = 228.88\,\text{meV}$, $E_f - E_3 = 191.15\,\text{meV}$ and $E_f - E_4 = 97.77\,\text{meV}$, with E_f (Fermi level) is taken to be at the bottom of conduction band.

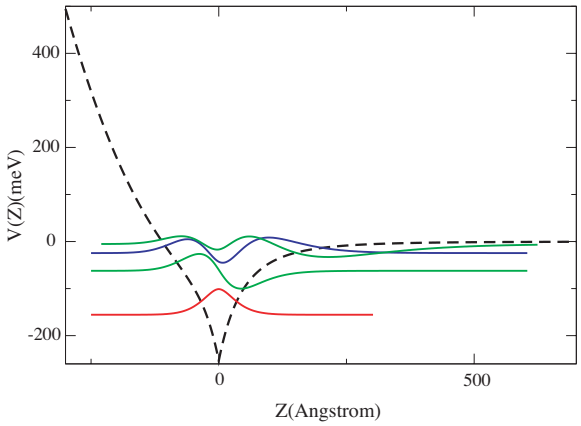

Figure 2. Conduction band, eigenvalues and eigenfunctions for $V_c = 500\,\text{meV}$.

Based on the Thomas Fermi approximation to this δ-FET, we study the electron transport properties of the system. This method also allows us to study the transport properties of the system. We only consider the ionized donor scattering mechanism, because it is the most

important at low temperature. The Coulomb scattering potential due to the ionized impurities is considered as distributed randomly in the doped layer. Finally, we take the ratio of the mobility of ($V_c = 0\,\text{meV}$) to ($V_c \neq 0\,\text{meV}$) the potential contact of the gate.

$$\mu_{rel} = \frac{\mu_{V_c \neq 0}}{\mu_{V_c=0}} = \frac{\iint_{IR^2} \rho_e^{V_c=0}\left(z'\right).\rho_{imp}^{V_c=0}\left(z\right).|z|.dz.dz'}{\iint_{IR^2} \rho_e^{V_c\neq 0}\left(z'\right).\rho_{imp}^{V_c\neq 0}\left(z\right).|z|.dz.dz'} \tag{4}$$

$\rho_e^{V_c\neq 0}\left(z'\right)\left(\rho_e^{V_c=0}\left(z'\right)\right)$ is the electron density where the potential contact of the gate is $V_c \neq 0\,\text{meV}\,(V_c = 0\,\text{meV})$ and $\rho_{imp}^{V_c\neq 0}\left(z\right)\left(\rho_{imp}^{V_c=0}\left(z\right)\right)$ is the impurity density where the potential contact of the gate is $V_c \neq 0\,\text{meV}\,(V_c = 0\,\text{meV})$. The former expression can be put in the following form:

$$\mu_{rel} = \frac{\Sigma_1^{ne}\int_{IR} |F_e^{V_c=0}(z')|^2.\left(k_F^{V_c=0} - E_i^{V_c=0}\right).|z'|.dz'}{\Sigma_1^{ne}\int_{IR} |F_e^{V_c\neq 0}(z')|^2.\left(k_F^{V_c\neq 0} - E_i^{V_c\neq 0}\right).|z'|.dz'} \tag{5}$$

where $F_e^{V_c\neq 0}(z')$, $k_F^{V_c\neq 0}$ and $E_i^{V_c\neq 0}$, ($F_e^{V_c=0}(z')$, $k_F^{V_c=0}$ and $E_i^{V_c=0}$) are the envelope function, the Fermi level and the ith level respectively of the $V_c = 0$ ($V_c \neq 0$), the former expression is valid for $T = 0\,\text{K}$.

3. RESULTS AND DISCUSSION

The (Figure 3) contains the curve of relative mobility *vs.* V_c. The mobility shows two different behaviors. The first is between 0 meV and 1200 meV where we have the mobility ratio is rising from 1 to 2.06. The second is between 1200 meV and 1500 meV where the mobility is rising also from 2.06 to 4.52. In the first interval, the mobility ratio creases mildly but in the second, it increases rapidly, we can see the potential contact affect more the mobility ratio when V_c superior 1200 meV. In the mobility ratio characteristic there are four regions, in other words there are three transitions, the first from 150 meV to 200 meV, the second from 600 meV to 650 meV and the last one from 1200 meV to 1250 meV, the responsible of this transitions is the change in the number of state in δ-doped quantum well.

$$\sigma_{rel} = n_{rel}.\mu_{rel} \tag{6}$$

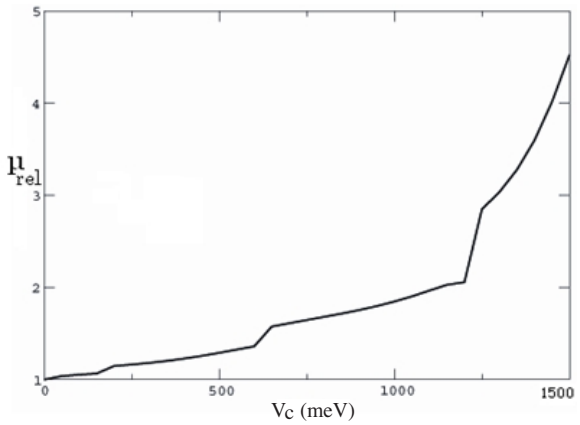

Figure 3. Mobility calculations versus the contact potencial (V_c) in meV.

$$n_{rel} = \frac{\Sigma_1^{ne}\left(k_F^{V_c=0} - E_i^{V_c=0}\right)}{\Sigma_1^{ne}\left(k_F^{V_c\neq 0} - E_i^{V_c\neq 0}\right)} \tag{7}$$

σ_{rel}: Relative conductivity, n_{rel}: Relative electronic density of the delta-doped quantum well, μ_{rel}: Relative mobility.

Relative conductivity *vs.* V_c characteristic shows fluctuation of conductivity ratio as a function of V_c, there are two zones type, the first zone type is linear, it is in [200 meV, 600 meV] and [1250 meV, 1500 meV]. The second zone type is parabolic, it is in [650 meV, 200 meV].

The conductivity ratio has a mild growth when V_c is in [0 meV, 650 meV] because the mobility ratio rise slowly from 1 to 1.57, in other word the interaction of impurities and free electrons are not low and the variation of electron density in δ-doped quantum well is practically constant. On the contrary, when $V_c \geq 650$ meV the (Figure 4) shows that the conductivity decreases, the reason being that the conduction channel begins to close, due to the strong decrease of confined electrons in the delta-doped well.

The δ-FET permits to have a negative differential resistance (NDR), NDR is seen in intervals [650 meV, 1200 meV] and in [1250 meV, 1500 meV], In electronics we learn that an amplifier coupled with a properly designed positive feedback circuit can be made into an oscillator. We find the optimum $V_c = 650$ meV Contact potential to achieve the maximum conductivity.

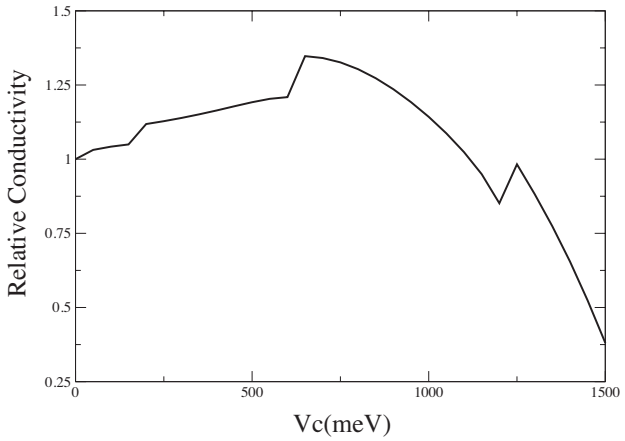

Figure 4. Conductivity calculations versus the contact potencial (V_c) in meV.

4. CONCLUSIONS

In Summary, we have presented an expression to calculate the relative electronic mobility. In this way it is possible to compare in a reasonable way the mobilities of $V_c = 0\,\text{meV}$ and $V_c \neq 0\,\text{meV}$. This phenomenological formula for the mobility ratio allows us to study the range of parameters governing this problem and to get the best choice of them.

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