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ANALYTICAL MODEL OF ELECTRIC FIELD IN HETEROJUNCTION REGION OF HFET STRUCTURE

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A new analytical model of electric field in heterojunction region of heterostructure field effect transistor (HFET), is presented. Electric field dependences on surface density of two-dimensional electron gas and surface density of ionized acceptors in buffer layer are included in developed model. The expression of the electric field intensity is given by using the new correction coefficient. The new coefficient emphasizes more precisely extremely asymmetric spreading of the electric field in the vicinity of a heterojunction. Proposed model is simple and it can be straightforwardly implemented. It can be applied to quite different types of HFETs. The results derived from simulations based on the exposed model are in very good agreement with the already known ones, available in literature.

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1. Introduction

Heterostructure electron devices, realized with thin crystalline layers of different semiconductor materials, are spearheading the drive toward faster, smaller and lower-power electronics [1]. The mentioned layers can be as thin as a several lattice parameters, thus quantum effects become dominant. In the Heterostructure Field Effect Transistor (HFET), quantum effects are responsible for confinement of carriers [1-6]. Block diagram of HFET structure is presented in Fig. 1.

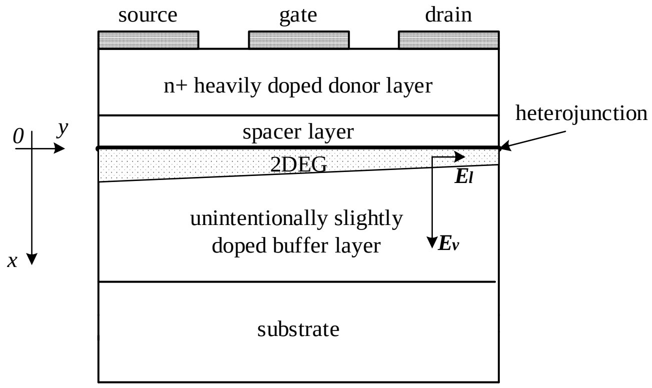

Fig. 1. Block diagram of HFET structure.

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Heavily doped donor layer is made of a semiconductor material with larger band gap, while unintentionally doped buffer layer is made of a semiconductor material with smaller band gap. As a consequence, a quantum well is formed at the buffer side of the heterojunction. Electrons confined in a quantum well form a Two-Dimensional Electron Gas (2DEG). Due to the spacer layer, which is between the donor layer and the buffer layer, electrons mobility, or in fact the speed of HFET, is increased because scattering on donor impurities is decreased [1-6].

In the process of HFET electric field model developing, it is started from the theory of usual silicon electron devices modeling, taking into account all specifics which are referred to heterostructure devices. Bearing in mind significant unisotropic nature of HFET structure, it is usefull to consider separately vertikal E_v and lateral E_l component of the efective electric field (Fig. 1).

2. Model

Electrons in a HFET observe real electric field as well as band structure of the device. To describe this, quasi–electric field concept is introduced. Effective vertical quasi-electric field E_v, which corresponds to the effective vertical quasi–potential ϕ, is:

$$E_v(x) = \frac{1}{q_e} \cdot \frac{d\phi(x)}{dx} . \tag{1}$$

In equation (1), $q_e>0$ is the electron charge and x is the normal distance from the heterojunction (Fig. 1).

If the quasi–potential is modeled in the following form:

$$\phi(x) = \begin{cases} \phi(x) = \infty & ; \quad x < 0 \\ \phi(x) = \phi_0 \cdot (1 - \exp(-a \cdot x)); & x \geq 0 \end{cases} , \tag{2}$$

with a and ϕ_0 being adjustable parameters, the model for the vertical effective quasi–electric field will be:

$$E_v(x) = a \cdot \phi_0 \cdot \exp(-a \cdot x); \quad x \geq 0 . \tag{3}$$

From Mc Laurent′s expansion of equation (3), by neglecting all but the first two series terms, it is obtained:

$$E_v(x) = a \cdot \phi_0 \cdot (1 - a \cdot x); \quad x \geq 0 . \tag{4}$$

The first term in equation (4) is constant, or better to say it does not depend on distance from the heterojunction x. It means that in the area close to the heterojunction (when $x \rightarrow 0$) vertical quasi–electric field becomes constant.

$$E_v = a \cdot \phi_0 ; \quad x \rightarrow 0 . \tag{5}$$

Bearing in mind that HFET layers are very thin, it can be assumed that vertical component of the effective quasi–electric field is constant in the transistor channel. This coresponds to the assymetric triangular aproximation for the quantum well: $\phi(x)=+\infty$ for $x<0$ (in the donor, or in fact spacer layer) and $\phi(x)=q_e K x$ for $x \geq 0$ (in the buffer layer), instead of real potential $\phi(x)$. That is the crudest approximation in this model, but it turns out to be sufficient in CAD (computer aided design).

The expression for the vertical electric field can be determined starting from the Gauss Low, bearing in mind that the carriers are confined in a very thin region, practically flat, located very close to the heterojunction [3-6]. Gauss Law suggests the following expression $E_v(n_s)=q_e n_s/\varepsilon_b$ (assuming that the field exists only on one side of the heterojunction), or $E_v(n_s)=q_e n_s/2\varepsilon_b$ (assuming that the field exists on the both sides of the heterojunction), where n_s is the 2DEG surface density of the carriers that are confined in the potential well and ε_b is the permittivity of the buffer semiconductor. With the correction for surface density of ionized acceptors in the buffer layer $n_b=x_b N_b$, where N_b is ionised acceptors cocentration in the buffer layer, following model can be used for the vertical electric field:

$$E_v = q_e \cdot \frac{\alpha \cdot n_s + n_b}{\varepsilon_b} . \tag{6}$$

The correction for surface density of ionized acceptors in the buffer is important if this density is to high or if 2DEG surface density is to low.

In equation (6) adjusting coefficient $\alpha \in [1/2;\ 1]$. Obviously, for $\alpha=1/2$ the value of the electric field would be underestimated, and for $\alpha=1$ the value of the electric field would be overestimated. The actual value falls between these two limits. The vertical electric field is dominantly spread in the buffer layer, and can be expressed as:

$$E_v = q_e \cdot \frac{0.88 \cdot n_s + n_b}{\varepsilon_b} . \tag{7}$$

The expression of the electric field intensity in the potential well is given by a new correction coefficient $\alpha=0.88$. The new coefficient emphasizes more precisely extremely asymmetric spreading of the electric field in the vicinity of a heterojunction, or in fact in the channel. As a consequence, this model appears to be more accurate than the other existing ones.

Table 1. Different models of the HFET vertical effective electric field obtained for the case of trangular quantum well approximation.

HFET vertical effective electric field model	Comment	Reference
$E_v = q_e \cdot \frac{n_s}{\varepsilon_b}$	Electric field spreads only in the buffer	Stern, Sarma 1984. [7] Sen et al. 2000. [8]
$E_v = q_e \cdot \frac{n_s + n_b}{\varepsilon_b}$	Electric field spreads only in the buffer and buffer dopants are taken into account	Stern, Sarma 1984. [7]
$E_v = q_e \cdot \frac{0.5 \cdot n_s + n_b}{\varepsilon_b}$	Electric field spreads equaly on the both sides of the heterojunction, and buffer dopants are taken into account	Byun et al. 1990. [9] Šašić, 1996. [10] Karm., Ramesh 2000. [11]
$E_v = q_e \cdot \frac{0.75 \cdot n_s + n_b}{\varepsilon_b}$	Average solution	Lukić, 2003. [3] Ramović, Lukić 2004. [4]
$E_v = q_e \cdot \frac{0.88 \cdot n_s + n_b}{\varepsilon_b}$	This paper, improoved average solution	

In Table 1 different HFET vertical electric field models are presented. All solutions are based on the Gauss Law, but with different corrections which are taken into account for 2DEG distribution and concentration of impurities in the buffer layer. The vertical electric field model given by the equation (7), as well as the other models in Table 1 are taken as a constant values in the channel (they are not distance dependent), because the shape of the potential-well is assumed to be triangular (parameters can be obtained by using self-consistent procedure).

For the nitride based HFETs, polarisation should be introduced:

$$E_v \sim E_{pol} + q_e \cdot \frac{0.88 \cdot n_s + n_b}{\varepsilon_b} . \tag{8}$$

Lateral HFET effective electric field E_l is aproximately constant except in the drain region, but anyway that region is depleted. Following model is proposed:

$$E_l = \frac{V_{DS}}{L} . \tag{9}$$

In equation (9), V_{DS} is drain to source voltage and L is the channel length. Using equations (7) and (9), general model for the HFET electric field can be written:

$$\vec{E} = q_e \cdot \frac{0.88 \cdot n_s + n_b}{\varepsilon_b} \cdot ort\vec{x} + \frac{V_{DS}}{L} \cdot ort\vec{y} . \tag{10}$$

The lateral component of HFET electric field is much smaller than the vertical component, and is usually neglected. The exception is in the drain region.

3. Results

In Table 2 typical values of donor concentration in the donor layer N_d, 2DEG surface density n_s, unintentionally introduced acceptors concentration in the buffer layer N_b and surface density of ionized aceptors in the buffer layer n_b, for the GaAs based HFET, are shown.

Table 2. Typical values of impurity concentrations and carriers concentrations in GaAs HFET.

Donor concentration in the donor layer N_d [m^{-3}]	Surface density of 2DEG n_s [m^{-2}]	Concentration of unintentionally introduced acceptors in the buffer layer N_b [m^{-3}]	Surface density of ionized acceptors in the buffer layer n_b [m^{-2}]
10^{24}	10^{16}	10^{19}	1.2×10^{14}
10^{24}	10^{16}	10^{21}	1.3×10^{15}

By using the proposed model (7), simulations were performed. Obtained results for the electric field dependence on 2DEG surface density $E_v(n_s)$ and for the electric field dependence on surface density of ionized acceptors in the buffer layer $E_v(n_b)$ are presented in Fig. 2 and Fig. 3.

In the simulation presented in Fig. 2, 2DEG surface density n_s is varied in the range 10^{15}m^{-2} – 2×10^{16}m^{-2}. For the surface density of ionized acceptors in the buffer layer n_b is accepted 10^{15}m^{-2}.

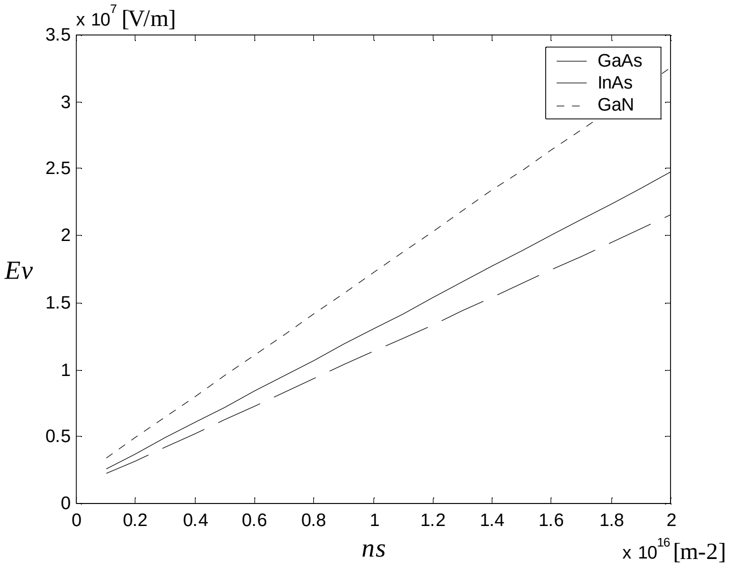

Fig. 2. HFET vertical electric field E_v versus 2DEG surface density n_s.

In the simulation presented in Fig. 3, surface density of ionized acceptors in the buffer layer n_b is varied in the range $12 \times 10^{13} \mathrm{m}^{-2} - 13 \times 10^{14} \mathrm{m}^{-2}$. For the 2DEG surface density n_s is taken $10^{16} \mathrm{m}^{-2}$.

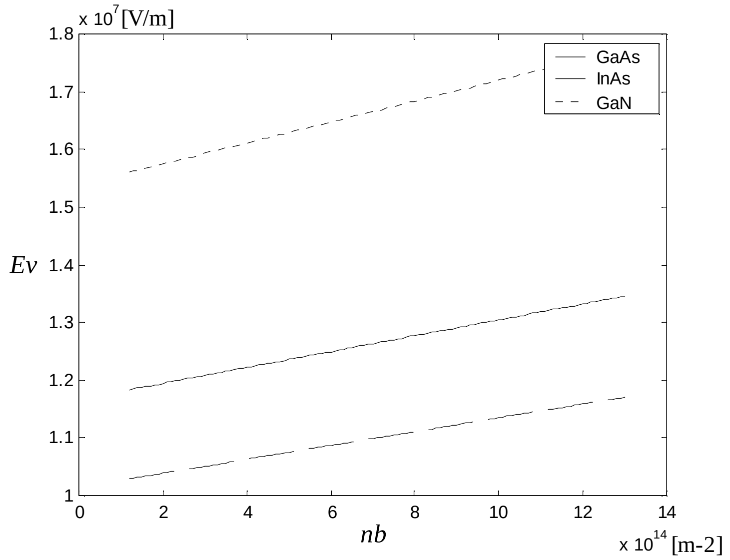

Fig. 3. HFET vertical electric field E_v versus surface density of impurities in the buffer layer n_b.

In both cases, expected values for HFET electric field are obtained. Minimal value for $E_v(n_s)$ is about 50 kV/cm for all three HFET types. Maximal value for $E_v(n_s)$ is about 180kV/cm for InAs based HFET, about 220 kV/cm for GaAs based HFET and about 300 kV/cm for GaN based HFET. It should be noticed that for GaN HFET model (7) has to be expanded by introducing polarization term like in (8). Obtained values for $E_v(n_b)$ are from about 100 kV/cm to about 110 kV/cm for InAs based HFET, from approximately 120 kV/cm to approximately 135 kV/cm for GaAs based HFET and from approximately 155 kV/cm to approximately 170 kV/cm for GaN based HFET.

It is clear that the concentration of unintentionally introduced impurities is for several orders of magnitude smaller than donor concentration. Thus, surface density of ionized acceptors in the buffer layer is for the order of magnitude smaller than surface density of carriers which are confined in a quantum well. It can be concluded that the correction n_b in the model is important only for threshold voltage operating regime, because n_s is than approximately of the same order of magnitude like n_b.

By using the proposed model for the electric field, HFET carrier mobility dependence on 2DEG surface density was obtained, instead of standard carrier mobility dependence on elcetric field which can be find in literature. The GaAs based HFET carrier mobility μ dependence on surface carrier density n_s, at room temperature, is shown in Fig. 4. For low surface carrier densities, the carrier mobility is constant. For higher surface carrier densities, this mobility decreases, because the frequency and intensity of collisions between carriers increase. In this case (GaAs HFET at T=300 K) mobility decrease starts for the surface density concentrations $n_s=5 \times 10^{15} 1/\mathrm{m}^2$.

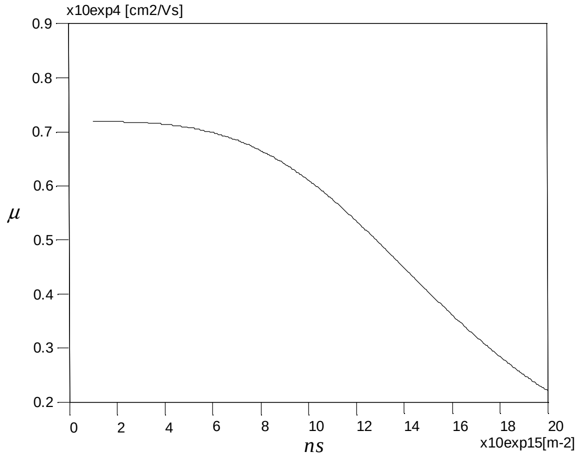

Fig. 4. HFET carrier mobility μ dependence on 2DEG surface density n_s.

For a given temperature, the value of mobility is found to be a function of an average vertical electric field only [5].

Mobility is strongly influenced by scattering on ionized impurities. Surface state density and the quantity of ionized impurities can not be easily exactly determined. This affects the accuracy of simulations results.

4. Discussion

There is no special physical explanation why this particular correction coefficient should be α=0.88, but it is sure that with this coefficient electric field is modeled more accurate in comparison with the other similar models (given in Table 1).

We found out that the best fit for the value of the critical electric field in HFET is much higher than expected. The value accepted in literature is about 4 kV/cm, and the best fit for this value is found to be 200 kV/cm. Our investigations led to the conclusion that this value corresponded to the normal electric field and should express its influence on carriers' mobility in the channel. The point is that its value (E_0 = 200 kV/cm) far exceeds the value accepted in literature (E_0 = 4 kV/cm) which corresponds only to the lateral electric field.

The way in wich electric field in HFET quantum well is described is very important for solving Schrödinger's and Poisson's equations. By using model (7) Schrödinger's equation could be analytically solved. Eigen energies and Fermi energy dependences on electric field could be obtained explicitly. For accepted electric field dependence on 2DEG surface density, eigen energies and Fermi energy dependences on 2DEG surface density could be determined. The value of the electric field at the spacer layer – buffer layer interface is due to boundary condition used for solving Poisson's equation, and holds for donor layer.

5. Conclusions

By using Gauss Law, HFET electric field model is developed. In this model electric field is supposed to be uniform. Thus, the model proposed in this paper holds for the case of electric field in the very thin area located close to the heterojunction, or better to say in the channel. The model is extremely usefull and applicable, bearing in mind that the channel is the most important region of HFET.

Vertical electric field is significantly higher then lateral, thus lateral component can be neglected. This is not valid only in the drain region, but anyway this region is depleted.

The model is more accurate than the other existing, thanks to the new correction coefficient which emphasizes more precisely asymmetric electric field spreading in the HFET heterojunction region.

Proposed model is applicable for different HFET types: for the GaAs based devices which have been used for a long time and which are the best studied, as well as for the devices with strained lattices wich are less known. The model is also applicable to the newest GaN based HFETs.

The point is that the proposed model is very simple, and at the same time it describes complex HFET physics very good. This can be concluded because the results obtained by using this model are in very good agreement with the expected and the known published ones.

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