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Two-Dimensional Simulation of Interface States Effect on AlGaAs/GaAs HEMT

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Abstract The influence of interface states on a two-Dimensional Electron Gas (2DEG) in an AlGaAs/GaAs High Electron Mobility Transistor (HEMT) has been studied. In this paper a two-dimensional quantum model of the HEMT is first presented by considering the interface states effect on the channel electrons of the HEMT. The electron concentration in the channel of the HEMT is obtained by solving Schrödinger and Poisson equations self-consistently. The simulated results reveal that the distribution of 2DEG changes with the interface state density. Our analysis has also shown that the additional scattering centers increase with the interface state density. Therefore, the channel electron mobility and the transconductance of HEMT decrease with increasing interface state density.

PACC: 2560S, 2560B

1 Introduction

In most heterostructures there are various interface states due to lattice mismatch or imperfections at the interface. The properties of an AlGaAs/GaAs interface are intimately related to the device performance. The existence of interface states in an $Al_xGa_{1-x}As$/GaAs heterostructure grown by MBE or MOCVD technology has become one of the important problems during development of the HEMT. It is known that a 2DEG in the AlGaAs/GaAs HEMT is formed in an approximate triangular quantum well in the high-purity GaAs layer at the AlGaAs/GaAs heterointerface. Therefore, the interface states have a large influence on the 2DEG.

Although a very low interface state density can be predicted for epitaxial heterostructures, no direct measurement has yet been reported to date. Several authors have measured the interface state densities using a few indirect methods[1~6]. The interface states can cause additional scattering by trapping electrons from 2DEG. It has been shown that

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the interaction of the electrons with interface may be one of the sources of low-frequency noise in GaAs MESFETs[7].

A number of two-dimensional numerical models for HEMT's have been developed based on the drift-diffusion approach[8~12]. The velocity overshoot effect and surface Fermi-level pinning effect in the AlGaAs/GaAs HEMT have been studied by using the two-dimensional models[9,12,13]. At first, we present a new quantum model for the HEMT and then study the effect of interface states on the 2DEG of the AlGaAs/GaAs HEMT. The electron distributions in the channel are derived with a two-dimensional numerical simulation by solving the Schrödinger and Poisson equations self-consistently. Finally, the influence of interface states on the electron mobility is also discussed in detail.

2 Two Dimensional Numerical Model

The structure of the $Al_{0.3}Ga_{0.7}As$/GaAs HEMT for our simulation is shown in Fig. 1. A quantum model presented in this paper is based on two-dimensional Poisson and Schrödinger equations. The quantum model including the interface state effect is described as follows. The electrons in the channel of the AlGaAs/GaAs HEMT, which are confined in a quasi-triangular potential well, form a quantized 2DEG. The electron energy states in the quantum well are described by Schrödinger equation. In Schrödinger equation, the electrostatic potential is given by the solution of Poisson equation, and the electron concentration in Poisson equation depends on the electron wave function in Schrödinger's equation. Therefore, the potential $V(x,y)$ and the electron wavefunctions are determined by solving self-consistently the two-dimensional Schrödinger equation

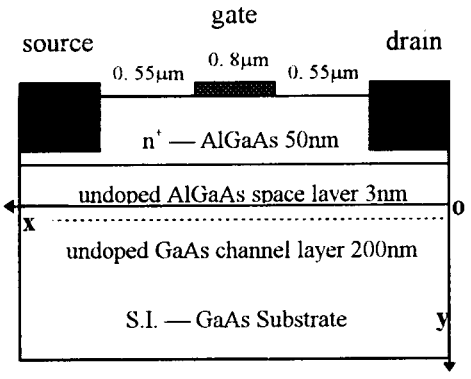

Fig. 1. The structure used in the simulation of AlGaAS/GaAs HEMT

$$-\frac{\hbar^2}{2m^*}\frac{d^2\Psi_i(x,y)}{dy^2}+V^*(x,y)\Psi_i(x,y)=E_i(x)\Psi_i(x,y) \tag{1}$$

and the two-dimensional Poisson equation

$$\frac{d^2V(x,y)}{dx^2}+\frac{d^2V(x,y)}{dy^2}=-q[N_D-n(x,y)]/\varepsilon \tag{2}$$

where m^* is the electron effective mass; N_D is the impurity doping level; $\Psi_i(y)$ is the wavefunction corresponding to the eigenvalue $E_i(x)$ for the i-th subband; the effective potential energy $V^*(x,y)$ is defined as[14]

$$V^*(x,y)=-qV(x,y)+V_h(y)+V_{xc}(y)+V_{im}(y) \tag{3}$$

$V(x,y)$ is the electrostatic potential to be found from the Poisson equation; $V_h(y)$ is the

band offset in the conduction band; $V_{xc}(y)$ is the exchange-correlation potential energy; and finally $V_{im}(y)$ is the classical image force energy; $V_{xc}(y)$ and $V_{im}(y)$ are not considered in our simulation. In the Poisson equation (2), the electron concentration is given by

$$n(x,y) = \sum_i N_i |(\Psi_i(x,y)|^2 \tag{4}$$

here N_i is the two-dimensional mobile electron gas concentration corresponding to the i-th subband level in the channel,

$$N_i = \frac{m^* k_b T}{\pi \hbar^2} \ln\left[1 + \exp\left(\frac{E_F - E_i}{k_b T}\right)\right] \tag{5}$$

where k_b is the Boltzmann constant; T is absolute temperature; E_F and E_i are the Fermi level and the i-th subband energy level, respectively. The lowest subband E_0 is taken into account in our simulation. The boundary conditions are that the wavefunctions vanish at GaAs base and AlGaAs layer.

We assumed interface state's existence at the AlGaAs/GaAs heterointerface. The following interface condition is considered [12,15]

$$\varepsilon_A \frac{dV(x,y)}{dy}\Big|_{int-} - \varepsilon_B \frac{dV(x,y)}{dy}\Big|_{int+} = qN_s \tag{6}$$

where ε_A and ε_B are the dielectric constants of AlGaAs and GaAs layers, respectively. N_s is the interface state density.

The device equations are discretized in space by using a finite difference scheme. An nonuniform mesh spacing is used to optimize speed accuracy of the solution. The iteration method is used to obtain wavefunction of electron for the finite difference equation of Schrödinger. For the finite-different Poisson equation, the successive-over-relaxation (SOR) method can be used to increase the rate of convergence.

3 Results and Discussions

Interface traps formed at the AlGaAs/GaAs heterointerface are due to the existence of interface states. These states locating at the AlGaAs/GaAs interface are considered to be donor like. The interface states, with U-shaped density distribution, are a series of electron energy levels at heterointerface. The existence of the interface states can influence on the electrostatic potential distribution in the heterojunction[15]. The electron distributions of the different interface state's density are given in Fig. 2 at zero gate voltage. It can be clearly seen from figure 2 (a)～(d) that the distributions of electrons are almost unchanged if interface states density is less than $1.0\times10^{11}\text{cm}^{-2}$. The influence of interface states on 2DEG's distribution is no longer negligible when interface states density is more than $5.0\times10^{11}\text{cm}^{-2}$. The results of simulation reveal that the electron concentration near the gate edge reduces with the increasing of the interface state density. The electron distribution changes with the interface state density. If the heterostructure interface is not perfect, then additional scattering centers form at the interface. These scattering centers can strongly affect the transport of the carriers along the channel. The scattering centers or

charge centers lead to a perturbation on potential well, so the distribution of the electrostatic potential is changed. Therefore the distribution of electrons changes due to interaction of the interface state's charge and 2DEG in the channel.

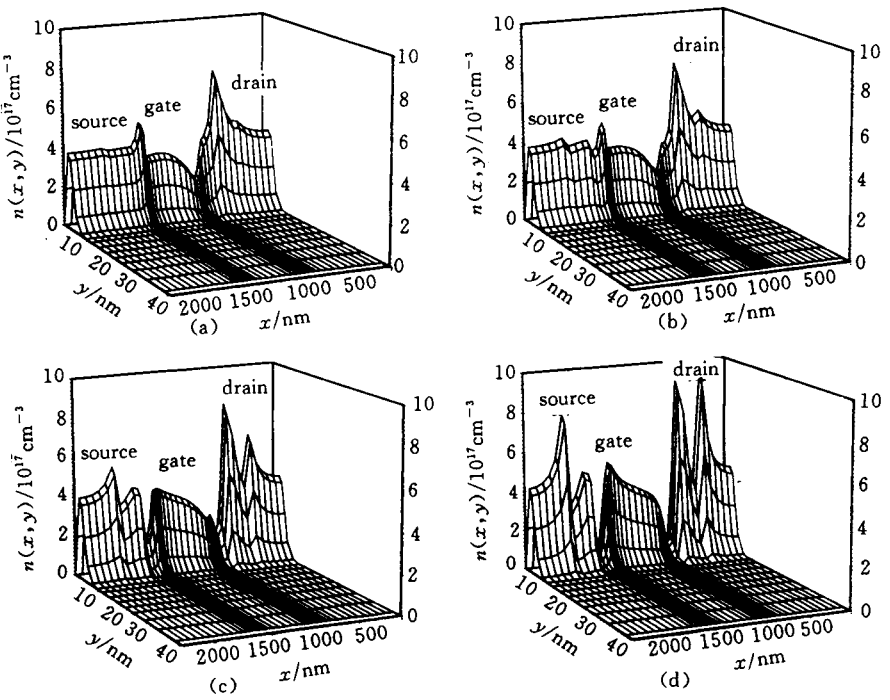

Fig. 2 The electron distributions in the undoped GaAs channel of the HEMT with a gate voltage of 0.0V and drain voltage of 1.0V and the interface state's density of (a) $1.0\times10^{10}cm^{-2}$, and (b) $1.0\times10^{11}cm^{-2}$, and (c) $5.0\times10^{11}cm^{-2}$, and (d) $1.0\times10^{12}cm^{-2}$.

The interface states charge residing in the electron energy levels of the heterointerface varies with the gate voltage[3]. The interface states charge also changes with the capture of electrons at the interface. Hence the interface state's charge can influence the electron concentration.

4 Conclusion

In conclusion, we have presented a two-dimensional quantum model in which the interface states of the AlGaAs/GaAs heterostructures HEMT are taken into account. The simulated results have indicated that the influence of interface states on the electron distribution in the channel of the AlGaAs/GaAs HEMT may play an important role in controlling the performance of the device. Because the distribution of electron concentration in the channel is changed due to existence of the interface states, the interface states cause additional scattering by trapping electrons. The additional scattering has influence upon the electron mobility. When the density of interface states is large enough, these states can

participate in pinning to the Fermi level. Therefore, the mobility of electrons decreases, and the transconductance of AlGaAs/GaAs HEMT's decreases too. The influence of interface states on 2DEG in the channel must consider if the electron concentration in channel has the same order of magnitude as that of the interface states.

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