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Small Geometry Device Physics and Technology

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High field transport of small geometry devices is reviewed placing main emphasis on the drift velocity overshoot effect and device simulation techniques. Monte Carlo simulation was used to investigate the overshoot effect. Experimental results of the overshoot are reviewed. Device simulation techniques for MOSFETs and MESFETs are briefly reviewed. Monte Carlo simulation of quantized two-dimensional electrons in Si inversion layers and in quantum well structures is also reported. Monte Carlo simulation shows that the drift velocity overshoot is very large in HEMT.

§1. Introduction

VLSI technology has made a remarkable progress in recent years and MOSFETs processed in the region of submicron rule are available. When the size of semiconductor devices is reduced in the region of submicrons and the mean free path of the carriers becomes comparable with the device size, new effects are expected, such as drift velocity overshoot, ballistic transport and quantum size effect.[1] In view of device technology, these effects are very attractive because of improvement of the high speed operation and of possibility to fabricate new devices based on mechanisms different from existing devices. In this paper we deal with hot electron effects in very small devices placing main emphasis on drift velocity overshoot.

§2. Drift Velocity Overshoot in GaAs

Drift velocity overshoot has been investigated by the following methods.

(a) Monte Carlo simulation[2]

(b) quantum transport equation[3]

(c) kinetic equation with a temperature model[4-6]

(d) Boltzmann equation[7]

All the results indicate drift velocity overshoot at high electric fields. Among the methods Monte Carlo simulation is the most conventional and gives a detailed picture of the electron transient. In this paper we report some important results of the drift velocity overshoot effect obtained by Monte Carlo simulation, where we deal with the screening of the polar phonon field by electrons and electron-electron scattering.

In the present analysis we are interested in GaAs and thus we used the parameters of Littlejohn et al.,[8] but we took into account anisotropy of the upper valleys, four L-valleys with m_t=0.082m and m_l=1.58m and six X-valleys with m_t=0.19m and m_l=0.98m.

It is well known that the field induced by long wavelength polar optical phonons is screened by free electrons.[1] The screening reduces the polar optical phonon scattering and increases the intervalley transfer of hot electrons from the valley to the higher valleys. Figure 1 shows time evolution of the drift velocities in Γ, L and X valleys and average drift velocity with (solid curve) and without screening (dashed curve) for $n = 1X10^{17}cm^{-3}$, T = 300K and E = 10kV/cm. Note that overshoot velocity is about $5X10^7$cm/s at t = 0.5ps.

From Monte Carlo simulation we found a quite anisotropic distribution of electrons in the region where the electron drift velocity exhibits overshoot.[1] In Fig. 2 the time evolution of the electron drift velocity is plotted for the case with (solid curve) and without electron-electron scattering (dashed curve) at E = 10kV/cm for $n= 1X10^{17}cm^{-3}$. It is found in Fig. 2 that e-e scattering affects the drift velocity in the overshoot region, but the effect is quite weak for the steady state value because of the increase in the electron temperature.

§3. Experiments on Drift Velocity Overshoot

It is very difficult to observe drift velocity overshoot because of the fact that it occurs only for a very short time interval and in a very narrow region near the cathode or in a very short sample. This is the reason why a quantitative result has not yet been reported on the effect. Here we will summarize the experimental methods and the results on the overshoot effect;

(a) electro-absorption[9]

(b) laser impulse response of high speed GaAs photodetector[10]

(c) infrared absorption measurement and Fourier transform analysis[11]

(d) measurements and analysis of current-voltage characteristics[1,12]

(e) measurements of FET characteristics and their analysis.[13]

The methods (a) and (b) are "time resolved" and reveal an existence of overshoot. The method (c) is to obtain time dependence of the conductivity by Fourier transform of frequency dependent conductivity and shows overshoot of conductivity in Si. The methods (d) and (e) are based on the analysis of the steady state current-voltage characteristics assuming a drift velocity field curve which gives the maximum drift velocity in the specimens. The methods (a) to (c) do not taken into account the field distribution but time evolution is obtained. The methods (d) and (e), on the other hand, takes into account the non-uniform field distribution in a very short devices but time evolution is not resolved. Our results on n-GaAs are shown in Fig. 3, where the normalized donors n_o, electron density n, potential u, and drift velocity v_d for eV/kT=75 are plotted as a function of normalized distance for $n^+ n\, n^+$ structure, where we find maximum drift velocity $3X10^7$cm/s.

§4. Device Simulation

Modeling of semiconductor devices is made by the following approaches;

(A) Two-dimensional device simulation

(B) Solve kinetic equations using a temperature model

(C) Many particle Monte Carlo simulation.

Two-dimensional device simulator is shown to work in MOSFET with submicron channel length. The method is based on numerical analysis of Poisson and current continuity equations with a proper assumption for the drift velocity-field relation. The following formulae are usually adopted.

(a) Scharfetter-Gummel's formula[14]

$$v_d=\mu_o E/[1+\frac{N}{N/S+N_r}+\frac{(E/A)^2}{E/A+F}+(\frac{E}{B})^2]^{1/2}$$

(b) Modification of Scharfetter-Gummel's formula[15]

$$v_d=\mu(N,E_G)E_D[1+(\frac{\mu(N,E_G)E_D}{v_c})^2(\frac{\mu(N,E_G)E_D}{v_c}+G)^{-1}+(\frac{\mu(N,E_G)E_D}{v_s})^2]^{-1/2}$$

(c) Thornber's formula[16]

$$v_d=\mu(E_G)E_D/[1+\{\mu(E_G)E_D/v_s(E_G)\}^\beta]^{1/\beta}$$

(d) Schwarz-Russek's formula[17]

$$v_d=\frac{v}{\sqrt{2}}\{-1+[1+(\frac{2\mu_o E}{v}[1+\exp(\frac{-E_{op}}{m^* v\mu_o E})])^2]^{1/2}\}^{1/2}$$

(e) Cooper-Nelson's formula[18]

$$v_d=\mu E_t/[1+(\mu E_t/v_s)^\alpha]^{1/\alpha},\ \mu=\mu_o/[1+(\frac{E_n}{E_c})^c]$$

The simplest one is Thornber's formula and usually β=2 is used. Cooper-Nelson's formula is the same as the Thornber's and the validity of the formula was proved by the time of flight measurement of electrons and holes in MOS inversion layers. Scharfetter-Gummel's formula takes into account the effect of impurity scattering (N), and Yamaguchi's formula takes into account the gate field dependence of the mobility. These formulae are valid for carriers in Si MOSFET's, whereas in GaAs we have to take into account negative differential mobility due to the intervalley transfer of electrons to upper valleys.[12] It should be noted that fitting of the I_D vs. V_D curves using these formulae gives the saturation velocity or the maximum drift velocity and thus we may obtain the overshoot effect as shown in the case of one-dimensional analysis shown in the case of n^+nn^+. An example of the device simulation is shown in Fig. 4, where I_D-V_D curves measured in a short MOSFET with 0.38μm channel length are compared with the curves simulated using Cooper-Nelson's formula.[19] The gate field dependence of the carrier mobility in MOS inversion layers is explained in terms of surface quantization by Schwarz and Russek,[20] Lin,[21] and Hamaguchi,[1] independently, where the electron mobility is shown to depend on the size of spread in the direction normal to the surface. Shirahata and Hamaguchi[19] has shown that Cooper-Nelson's formula is well explained by taking electrons in the lowest two subbands into account as shown in Fig. 5.

The method shown above assumes a uniform temperature distribution. To improve this assumption a temperature model is proposed to solve kinetic equations.[6,22] This model takes into account the overshoot effect and seems to be more accurate. However, we have to note that such a temperature model assumes Maxwell-Boltzmann distribution function and that the assumption fails in hot electron problem. The most reliable results, therefore, will be obtained by using many particle Monte Carlo simulation as done by Hockney et al,[23] Warriner,[24] Pone et al.[25] and Yoshii et al.[26]

§5. Hot Electron Transport in MOS Inversion Layers and in Heterojunction Devices

We reported Monte Carlo simulation of 2D electrons in Si inversion layers, where the subband structure is assumed to be unchanged by the electron repopulation.[27] In this paper we present drift velocity vs. electric field curves obtained by Monte Carlo simulation in Si inversion layer, where self-consistent calculation, calculation of scattering probabilities and Monte Carlo simulation are iteratively performed. The results are shown in Fig. 6, where drift velocity is plotted as a function of electric field for normal field $5\text{X}10^4$, $1\text{X}10^5$ and $5\text{X}10^5$ V/cm. These features are very similar to the experimental results of Cooper and Nelson.[18]

Monte Carlo simulation of 2D hot electrons in a HEMT has been reported.[28,29] Here we present our results in HEMT with electron sheet density of $5\text{X}10^{11}$ cm^{-2} was carried out and the results are shown in Fig. 7 for transient response of the drift velocity. We found from the present simulations that negative differential mobility appears and the maximum drift velocity is higher than that in a bulk GaAs and overshoot of the drift velocity reaches $8\text{X}10^7$ cm/s at 77K. We found that the drift velocity in the Γ-valley subbands is about 10^8 cm/s. In the calculations we assumed 2D subbnands are formed in the L-valley of GaAs-well.[30]

§ 6. Technological Progress

MOSFETs with channel width of 100nm were fabricated by Skocpol et al.[31] by electron beam lithography and 1D conduction was observed. Chou et al.[13] fabricated n-channel MOSFETs with channel length of 75nm in Si using combined x-ray and optical lithographies and observed overshoot effect at 4.2K. Katayama et al.[32] observed gigantic oscillations in mobility in n-channel MOSFETs with channel width 150nm and length around 1.5μm using LOCOS structure. Very recently quasi-1D conduction is observed in periodic parallel inversion lines in Si by Warren et al.[33] These investigations will give a breakthrough to a new field of very small semiconductor device physics.

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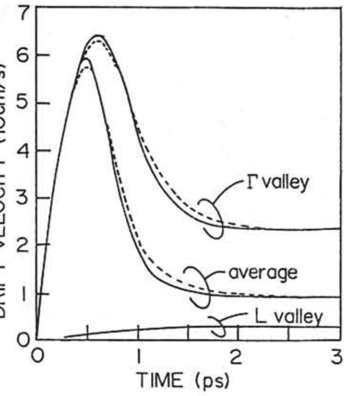

Fig. 1 Time evolution of the drift velocities with (solid curve) and without screening (dashed curve) for $n=1X10^{17}$ cm^{-3}, T=300K and E=10kV/cm.

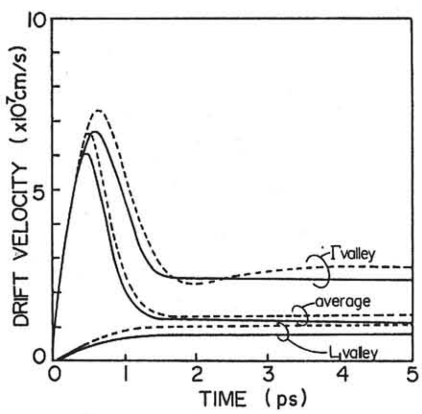

Fig. 2 Time evolution of the drift velocities with (solid curve) and without e-e scattering (dashed curve) for $n=1X10^{17}$ cm^{-3}, T=300K and E=10kV/cm.

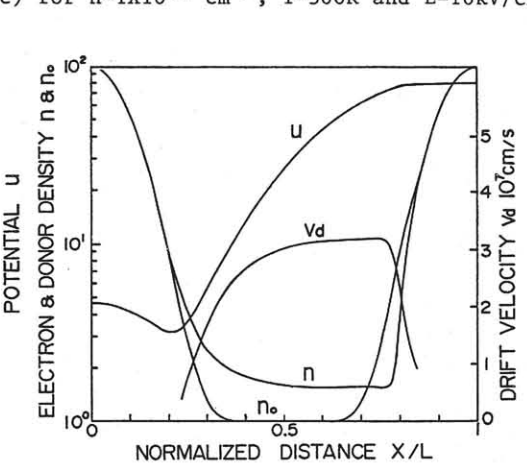

Fig. 3 Normalized donor density n_o, normalized potential u, normalized electron density n and drift velocity v_d for $eV/k_BT=75$ in n^+n n^+ G_aA_s.

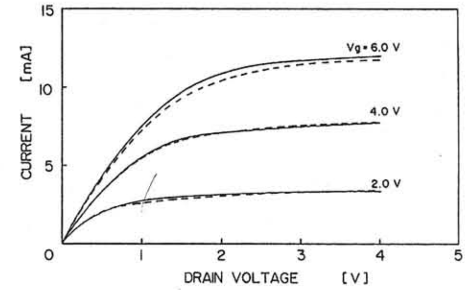

Fig. 4 I_d-V_d characteristics of very short channel (0.38μm) MOSFET at 300K. Dashed curves represent experimental data and solid curves are calculated by 2D device simulation.

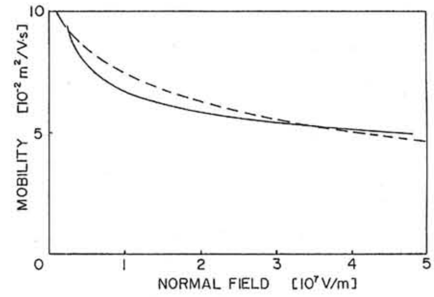

Fig. 5 Electron mobility as a function of (effective) normal field in Si MOS inversion layer. The dashed curve is the experimental data of Cooper and Nelson, and solid curve is calculated by assuming that mobility is limited by 2D electrons in E_o and E_o' subbands.

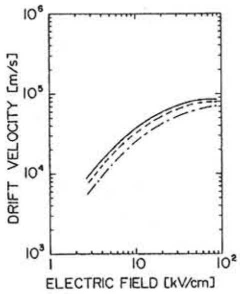

Fig. 6 Drift velocity vs. electric field for 2D electrons obtained by Monte Carlo simulation in Si MOS inversion layer for normal field $5X10^4$, $1X10^5$ and $5X10^5$ V/cm.

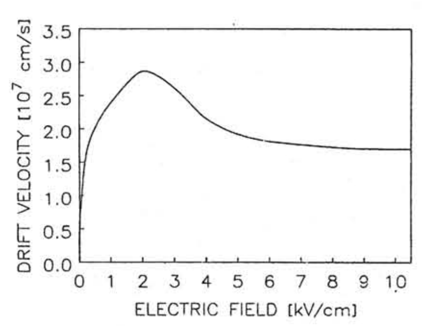

Fig. 7 Transient response of the drift velocity in HEMT with electron sheet density of $2X10^{11}$ cm^{-2}.