Theoretical Analysis of Transconductance Enhancement due to Electron Concentration Dependent Screening in Heavily Doped Systems

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The transport mechanism in heavily doped systems is dominated by ionized impurity scattering involved with electron polarization. The objectives of this paper are to present a new mobility model which incorporates the quantum mechanical screening effect and to introduce a concept of effective mobility to reveal the possibility of transconductance enhancement. It is also demonstrated for the first time that heavily doped and short channel devices actually induce the enhanced characteristics.

The transport equation is based on the Boltzmann equation using a constant relaxation approximation at a quasi-Fermi level and Thomas-Fermi theory is introduced to analyze the screening effect on relaxation time caused by ionized impurity scattering. The new screen mobility μ_s is given by

$$1 / \mu_s (n,Ni) = 1 / \mu_{el} (Ni) * F(n) / F(Ni) + 1 / \mu_{ie}$$

$$F(n) = [\, \ln \{ (3\pi^5)^{1/3} a_B n^{1/3} + 1 \} - (3\pi^5)^{1/3} a_B n^{1/3} / \{ (3\pi^5)^{1/3} a_B n^{1/3} + 1 \} \,] / n$$

μ_s is dependent both on electron (n) and doping (Ni) concentration. μ_{el} and μ_{ie} represent bulk mobility of the ionized impurity scattering and inelastic scattering such as phonon, where bulk means the system has neutral charge. F(n) is defined as a scaling factor of impurity scattering strength and a_B is the effective Bohr radius.

First, dependence of mobility on electron concentration is shown in Fig. 1, illustrated with a GaAs MESFET type structure with heavily doped channel. Experimental data is observed by Hall measurement, while a cap layer of intrinsic GaAs is wet-etched. Because acceptor like impurities exist on the GaAs surface, the depletion region extends into the heavily doped channel and decreases electron concentration as the cap layer becomes thinner. It is shown that theoretical analysis using a screen mobility model is in excellent agreement with experimental results and the strength of ionized impurity scattering is modulated by the screening effect which depends on electron concentration. Transport properties such as current-voltage characteristics, therefore, are determined by the screen mobility. It should be pointed out that advantages of the screening mobility model are analytical based on the constant relaxation approximation and predictable without fitting parameters in any materials only if the bulk mobilities are given experimentally.

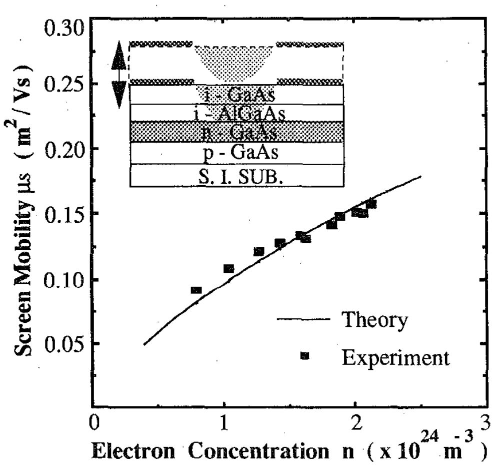

Fig. 1 Dependence of Mobility on Electron Concnetration (Doping Concentration : $3\text{x}10^{24}$ m^{-3})

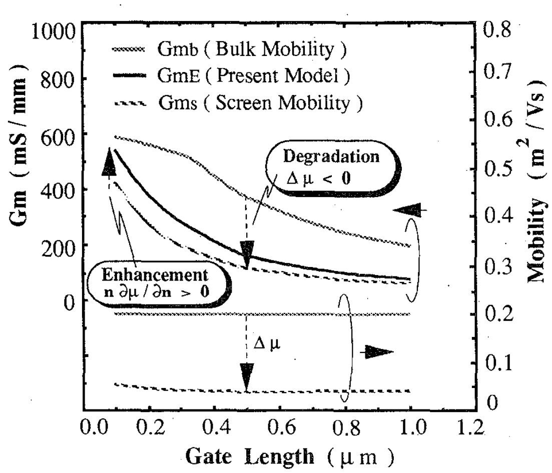

Fig. 2 Dependence of Transconductance and Mobility on Gate Length

To investigate the screening effect on transport characteristics, transconductance is analyzed using the present model. Dependence of transconductance and mobility on gate length are shown in Fig. 2. Transconductance Gm_b, assuming bulk mobility, increases as the gate length becomes shorter but gradually saturates at about 0.3 μm. This means the whole channel under a gate electrode becomes a hot region where electrons are accelerated to a saturation velocity. On the other hand, transconductance Gm_s, assuming screen mobility, degrades due to decrease in mobility at low electron concentration but increases steeply as the gate length becomes shorter. This is because the low mobility reduces the saturation region and transport mechanism is changed to be diffusive conductivity. Transconductance Gm_E, corresponding with actual systems, shows further increase caused by the enhancement effect which becomes strong at high electron concentration. At an extremely short channel of 0.1 μm, the increase in electron concentration due to the short channel effect causes enhancement resulting in a compatible characteristic with Gm_b. Consequently, the transport mechanism in heavily doped and short channel devices is governed by diffusive conductivity on account of screen mobility but the enhancement which eliminates the degradation of transconductance is induced by modulation of electron concentration.

Gm_E, Gm_b and the experimental results of transconductance dependent on gate voltage in a 0.3 μm device are shown in Fig. 3. It is found that Gm_E is in good agreement with experimental results and a crossover region occurs in the two theoretical characteristics. At low voltage, the decrease in screen mobility degrades Gm_E. At high voltage, however, the increase in electron concentration causes a strong enhancement effect, so Gm_E actually exceeds Gm_b. It is demonstrated that transconductance in the heavily doped system can be enhanced by the screening effect.

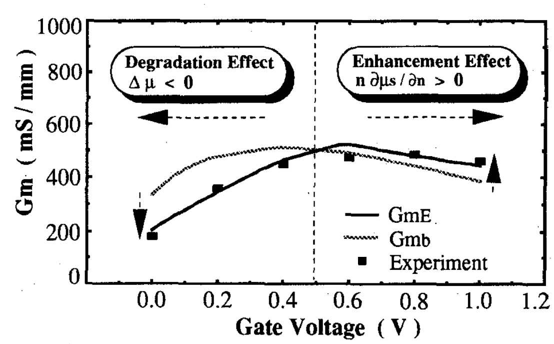

Fig. 3 Dependence of Transconductance on Gate Voltage

Finally, effective mobility μ_E ($= \mu_s + n\partial\mu_s/\partial n$) is introduced to explain the transconductance characteristics shown in Fig. 3. Dependence of screen and effective mobility on doping concentration as a function of electron concentration are shown in Figs. 4 and 5. Because devices are generally operated at lower electron concentration than the doping concentration, μ_s always becomes lower than μ_b. However, the effective mobility μ_E including the enhancement effect $n\partial\mu_s/\partial n$ can exceed μ_b as shown in the shaded region. In fact, at high voltage, μ_s is evaluated as 0.12 m^2/Vs which is lower than μ_b 0.2 m^2/Vs but μ_E reaches into the shaded area resulting in high transconductance. It is found that transconductance is determined by the effective mobility, so Gm_E exceeds Gm_b in practice.

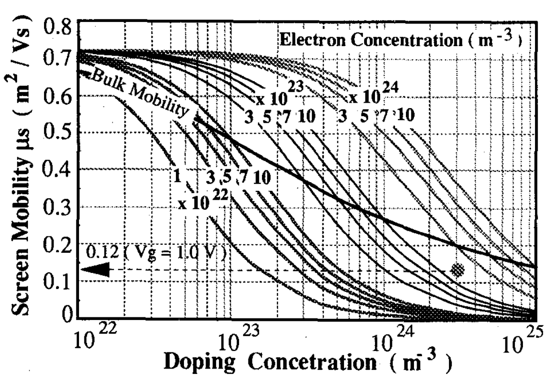

Fig. 4 Dependence of Screen Mobility on Doping Concentration as a Functon of Electron Concentration

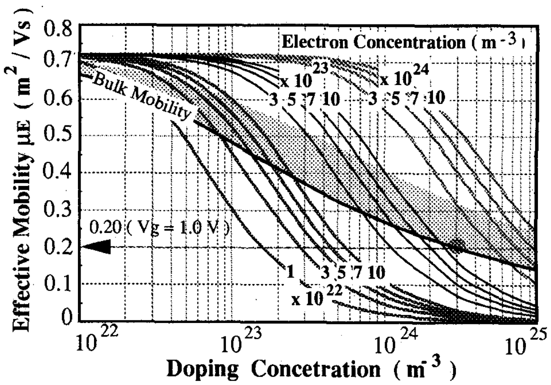

Fig. 5 Dependence of Effective Mobility on Doping Concentration as a Functon of Electron Concentration

To summarize, we proposed a mobility model that takes into account the screening effect on ionized impurity scattering. It is revealed that the transport mechanism in heavily doped and short channel systems has diffusive conductivity due to the screen mobility. It is also demonstrated theoretically and experimentally that the effective mobility incorporating the enhancement effect caused by modulation of electron concentration can exceed the bulk mobility and provide high transconductance.