Extended Abstracts of the 19th Conference on Solid State Devices and Materials, Tokyo, 1987, pp. 383-386

Significance of Low Field Mobility and Its Carrier Concentration Dependence in Characteristics of High Electron Mobility Transistors

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We clarify the influences of low field mobility and its carrier concentration dependence on drain current and transconductance g_m of high electron mobility transistors and other heterostructure FETs. In particular, high mobility ($>10^5 cm^2/Vs$) is shown to be effective in achieving and maintaining the intrinsic limit of $g_m(=\varepsilon_2 v_s/d^*)$ irrespective of bias conditions, where v_s is the saturation velocity, and ε_2 and d^* are the dielectric permittivity and the effective thickness of gate insulator, respectively. The carrier concentration dependence of mobility is found to affect greatly the gate-voltage dependence of g_m and leads to the appreciable increase of g_m even beyond its intrinsic limit.

1. Introduction

Much attention has been paid to high electron mobility transistors (HEMTs) and other heterostructure field effect transistors (HS-FETs) because of their excellent characteristics both in high speed digital and low noise microwave application. A number of studies have been made on the modeling of HEMTs[1)-5)] to clarify optimum device parameters and to attain higher performances. So far, an emphasis has been focused on the field-velocity relationship, because it is believed that velocity saturation of carriers is thought to dominate the FET performance, especially in short channel devices. It has been shown, however, that, in the vicinity of the source, the electric field is not always high enough for carriers to drift at saturation velocity v_s and pointed out the importance of low field mobility in the modeling of HEMTs[6)]. Hence, a accurate modelings of mobility is quite significant.

The low field mobility μ of two dimensional electron gas (2DEG) in HEMT is known to depend on the concentration N_s of 2DEG[7)]. In this work, we present a new model of HEMT which takes into account not only the velocity saturation effect but also the N_s dependence of μ [8)]. We clarify the influences of μ and its dependence on N_s on drain characteristics and transconductance g_m.

2. A New Model for HEMT

Let us consider the HEMT structure with gate length L, gate width W, doped and spacer AlGaAs layer thickness w_d and w_{sp}, respectively. The following analysis, however, remains valid for any HS-FETs, including MOSFETs. Our model is based on the charge control model[1)2)] and the following field-velocity characteristic:

$$v=\frac{\mu E_x}{1+\frac{\mu}{v_s}E_x}, \tag{1}$$

where $E_x=dV_c(x)/dx$, $V_c(x)$ is the potential at x in the channel. The 2DEG concentration $N_s(x)$ at x in the channel linearly increases as the increase of gate voltage V_g, which is expressed as

$$N_s(x)=(\varepsilon_2/qd^*)(V_g'-V_c(x)), \tag{2}$$

where $V_g'=V_g-V_{th}$, V_{th} is the threshold voltage, q the electron charge, ε_2 and d^* the dielectric permittivity and effective thickness of AlGaAs, respectively. In general, d^* in Eq. (2) is larger than the metallurgical total thickness $d=w_d+w_{sp}$ of AlGaAs by about 80A, because of the field-induced change of the Fermi energy and the quantum level of 2DEG[2]. Although in actual HEMT structures N_s begins to saturate as the increase of V_g[9], the model can be easily extended to include this saturation effect.

Here we consider HEMT and assume that μ depends on N_s as

$$\mu=\mu_0(N_s/N_{s0})^{\gamma}, \tag{3}$$

where the exponent γ is known to be in the range of 0.3~2, depending on the operating temperature and the structure of HEMTs[7]. The model, however, can be applied to the arbitrary μ-N_s relationship. For simplicity, we neglect the source and drain resistance and assume that $V_c(0)=0$ and $V_c(L)=V_d$. From Eqs. (1)-(3) and the drain current equation $I_d=qN_s(x)v(x)W$, the drain current can be expressed as

$$I_d=K_0\frac{\frac{1}{1+\gamma}\frac{1}{V_{g0}{}^{\gamma}}[V_g'^{\,2+\gamma}-(V_g'-V_d)^{2+\gamma}]}{1+\frac{1}{1+\gamma}\frac{1}{V_0V_{g0}{}^{\gamma}}[V_g'^{\,1+\gamma}-(V_g'-V_d)^{1+\gamma}]}, \tag{4}$$

where $K_0=\varepsilon_2\mu_0W/Ld^*$, $V_0=Lv_s/\mu_0$, $V_{g0}=qd^*N_{s0}/\varepsilon_2$. Note that V_0 is the drain voltage that would be required to accelerate electrons up to the saturation velocity if the acceleration were linear.

Although a negative value of γ leads to infinitely high mobility at $N_s=0$ and appears to be unacceptable, I_d dose not diverge and can be still calculated formally from Eq. (4) as long as $\gamma>-1$. Hence, this model is valid also in describing the room temperature operation of Si-MOSFET, where γ is -1/3 due to the electron-phonon coupling.

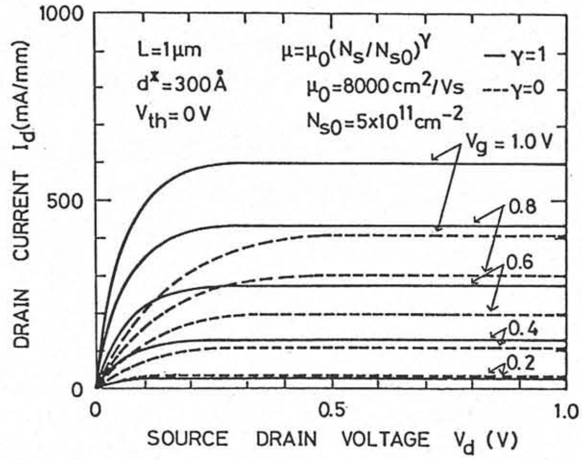

Fig. 1. I_d-V_d characteristics calculated with L=1μm and d^*=300A. The solid lines show the case of γ=1, whereas the dashed lines show the case of γ=0.

The drain current of a HEMT with L=1μm and d^*=300A is calculated by using Eq. (4). The result is shown in Fig. 1 for the case where μ_0=8000cm^2/Vs, and $N_{s0}=5\times10^{11}$cm^{-2}. Here I_d is normalized by the gate width W. Solid lines show the result for γ=1, whereas dashed lines for γ=0. Note the I_d characteristics are greatly affected by the γ value. It is expected that g_m-V_g characteristics are also strongly affected as will be discussed in Sec. 4.

3. Low Field Mobility Dependence of g_m

In order to clarify the effect of low field mobility on the transconductance g_m, we examine first the simple case that μ is constant and independent of N_s. By setting γ to be zero in Eq. (4), we find that I_d is given by[3,4]

$$I_d=\begin{cases} K_0(V_dV_g'-V_d{}^2/2)/(1+V_d/V_0) \\ \quad\text{(before quasi pinch-off:}V_d<V_{sat}\text{)} & (5.a) \\ K_0V_{sat}{}^2/2 \\ \quad\text{(after quasi pinch-off:}V_d>V_{sat}\text{)} & (5.b) \end{cases}$$

where $V_{sat}=V_0(\sqrt{2V_g'/V_0+1}-1)$. Equation (5.a) is derived for the case of "before the quasi pinch-off", whereas Eq. (5.b) is obtained for the case of "after the quasi pinch-off". Here the word "quasi pinch-off(QPO)" is used to emphasize the difference from the normal pinch-off. In this case, electron concentration at the drain edge is not zero but remains at a finite value ($=I_d/qv_s$) even "after the quasi pinch-off."

By differentiating Eq. (5) by V_g, g_m is given by

$$g_m=\begin{cases} g_{m.int}(V_d/V_0)/[1+(V_d/V_0)] & \text{(before QPO)} \quad (6.a) \\ g_{m.int}[1-1/\sqrt{(2V_g/V_0)+1}] & \text{(after QPO)} \quad (6.b) \end{cases}$$

where $g_{m.int}=\varepsilon_2 v_s/d^*$, the intrinsic limit of transconductance. Note that $g_{m.int}$ is the upper limit of g_m that can be achieved, when all the carriers in the channel are uniformly induced by the capacitor relationship $N_s=(\varepsilon_2/qd^*)V_g'$ and they are accelerated to their saturation velocity v_s. In realistic situations, g_m is reduced considerably from its upper limit $g_{m.int}$ whenever the full acceleration of electrons is hampered in any part of the channel, particularly at the source end. For one case, the acceleration of electrons becomes insufficient if the drain voltage $V_d \lesssim V_0$ (or the average drain field $E_d(=V_d/L) \lesssim v_s/\mu_0$). This effect can be evaluated by Eq. (6.a) and leads to the appreciable drop of $(g_m/g_{m.int})$ as shown in Fig. 2(a). The drop is significant unless low field mobility μ_0 is higher than $10^5 cm^2/Vs$.

It can been seen from Eq. (6.b) that the efficient acceleration of electrons is also prevented when the gate voltage V_g is not much higher than V_0. It is because, if $V_g \lesssim V_0$, a high-field region is inevitably formed in the drain end of the channel and the field in the source end gets low. Figure 2(b) shows the drop of g_m caused by this quasi pinch-off effect. Note that the decrease of V_g results in the drastic drop of g_m unless μ_0 is above $10^5 cm^2/Vs$.

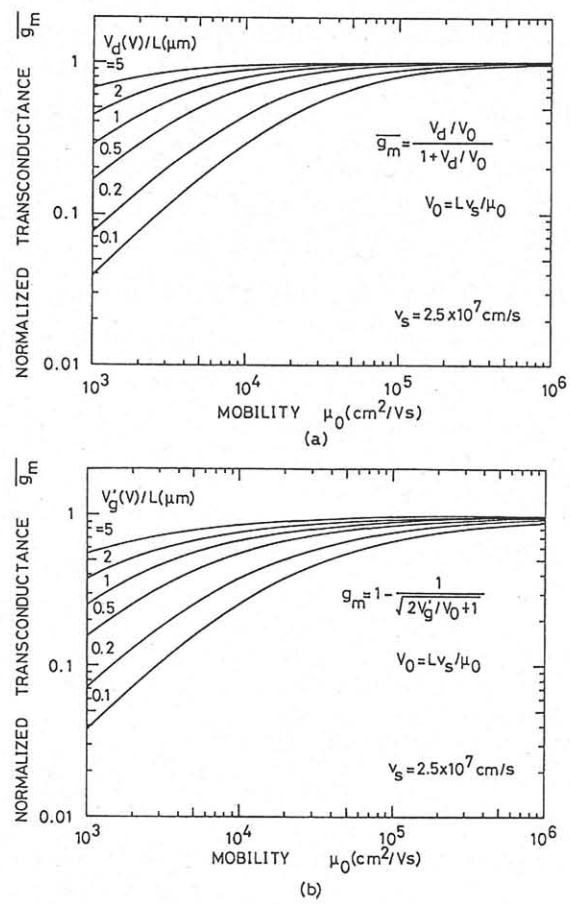

Fig. 2. (a) Dependence of normalized transconductance $\overline{g_m}=g_m/g_{m.int}$ on low field mobility μ with drain voltage per unit gate length as a parameter, which is calculated from Eq. (6.a). (b) Dependence of $\overline{g_m}$ on μ with V_g' as a parameter, which is calculated from Eq. (6.b). The drastic drop of $\overline{g_m}$ can be seen when μ is less than $10^5 cm^2/Vs$, unless sufficiently high drain voltage and gate voltage are applied at the same time.

For given V_g and V_d, g_m is limited by the lower of the two g_m values shown in Figs. 2(a) and (b). If μ_0 is greater than $10^5 cm^2/Vs$, g_m is nearly equal to $g_{m.int}$. Upon the decrease of μ_0 down to $10^4 cm^2/Vs$ or less, g_m deviates appreciably from $g_{m.int}$ unless both the drain voltage (or the average drain field) and the gate voltage are maintained high. In practical applications, particularly in digital circuits, such conditions cannot be maintained.

4. Effects of N_s Dependence of Mobility

Next we consider the effect of carrier concentration dependence of μ. When $\gamma > 0$ as in HEMT, the increase of V_g causes not only the increase of N_s but the enhancement of μ. Hence, the drain current will increase at a faster rate than in the case of constant mobility, leading to the enhancement of g_m. When $\gamma < 0$ as in Si-MOSFET, the opposite phenomenon takes place, leading to lower g_m. To quantify this expectation, g_m is calculated and plotted in Fig. 3 as a function of V_g for the case when L=1μm and d^*=300A. Note that g_m value calculated for $\mu=\mu_0(N_s/N_{s0})^\gamma$ depends sensitively on γ and in some cases exceeds its intrinsic limit $g_{m.int}$.

Since the mobility is assumed here as $\mu=\mu_0[\varepsilon_2(V_g'-V_c(x))/qd^*N_{s0}]^\gamma$, μ is always smaller than 2×10^5cm^2/Vs in case $0<\gamma<2$, $V_g'<1$V, and μ_0=8000cm^2/Vs. In some region of Fig. 3, however, the calculated g_m exceeds the g_m value that is predicted for the case of $\mu_0=2\times10^5$cm^2/Vs independent of N_s. From these results summarized in Fig. 3, the importance of considering the N_s dependence of mobility is clearly seen in understanding the drain characteristics and g_m of HS-FETs.

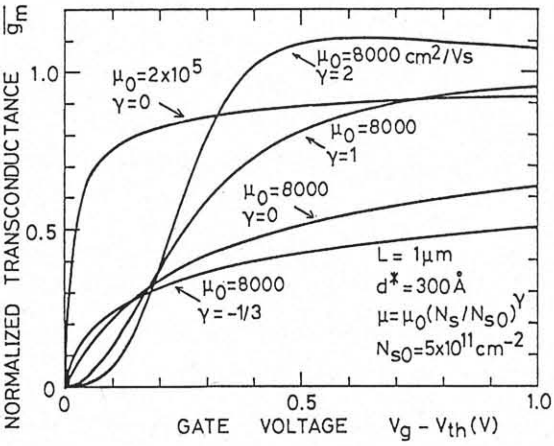

Fig. 3. The gate voltage dependence of $\overline{g_m}$ calculated for some cases of mobility model given by Eq. (3). Note that g_m value depends sensitively on γ value.

5. Conclusion

A new and simple model of HEMTs and HS-FETs is presented, which takes into account the carrier concentration dependent mobility. High mobility at low electric fields in excess of 10^5cm^2/Vs is shown indispensable to obtain high g_m irrespective of bias conditions, indicating that velocity saturation dose not always dominate the FET performance. Carrier concentration dependent mobility is found to give a strong influence on drain current characteristics and transconductance.

Acknowledgment

The authors are grateful to Professor J. Hamasaki, T. Matsusue, and T. Noda for useful discussions. This work is supported in part by the Grant-in-Aid from the Ministry of Education, Science, and Culture, Japan.

References

1) D. Delagebeaudeuf and N. T. Linh: IEEE Trans. Electron Devices **ED-29**(1982) 955.
2) T. J. Drummond, H. Morkoc, K. Lee, and M. Shur: IEEE Electron Device Lett. **EDL-3**(1982) 338.
3) M. H. Weiler and Y. Ayasli: IEEE Trans. Electron Devices **ED-31**(1984) 1854.
4) C. Z. Cil and S. Tansal: IEEE Electron Device Lett. **EDL-6**(1985) 434.
5) see also, "Special issue on heterojunction field effect transistors," IEEE Trans. Electron devices, **ED-33**(1986).
6) K. Yokoyama and H. Sakaki: IEEE Electron Device Lett. **EDL-8**(1987) 73.
7) K. Hirakawa and H. Sakaki: Phys. Rev. B **B33**(1986) 8291.
8) H. Sakaki, J. Motohisa, and K. Hirakawa: submitted to IEEE Electron Device Lett.
9) K. Hirakawa, H. Sakaki, and J. Yoshino: Appl. Phys. Lett. **45**(1984) 253.