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Principal GaAs FET Parameter Which Most Influences the Transconductance g_{mmax}

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Analysis and comparison with the experimental results reported on doped channel heterojunction(HJ) FETs indicate that the parameter which most influences the maximum transconductance g_{mmax} is the gate-channel spacing (thickness of the depletion or insulating layer) rather than mobility. When the gate-channel spacings are the same, doped channel FETs gave higher g_{mmax}'s than the HEMT structure FETs. Improvement of the mobility from 2000 to 8000 cm^2/Vsec improves the g_{mmax} by only about 20%, but when the drain current is small as so in low noise FETs, the mobility can also influence the g_m.

1. Introduction

The HEMTs or 2DEGFETs are attracting a lot of interest of the device researchers since it utilizes the two dimensional electron gas (2DEG) with very high electron mobility, and great efforts have been devoted to develop high speed FETs. About two years ago, the author gave a suspicion on contribution of the high electron mobility, and claimed that the high g_m of HEMTs can be mostly attributed to decrease of the depletion (insulating) layer separating the gate and the flowing carriers [1,2].

Recently, several papers have been published on high g_m FETs, which have highly doped channels, therefore, low electron mobilities, but with thin depletion (or insulating) layers [3-6]. These results indicate that thickness of the depletion layer is more important than the mobility of the carriers.

The purpose of this paper is to analyze the parameters including the mobility, which determine the g_{mmax}, and compare the analyzed results with the reported experimental results.

2. Expressions of the Drain Saturation Current and the Transconductance

Since the drain saturation current I_{dsat} of FETs can not be expressed exactly by a simple analytical equation, some assumptions must be made for the velocity-field characteristics: mobility constant, velocity constant, and combination of these two. For each case, the drain saturation current I_{dsat} and the transconductance g_m can be expressed by the equations shown in Table 1.

For the constant mobility case, carriers are assumed to flow in infinite velocity at the pinch-off region. The g_m increases proportionally to the mobility as shown in Eq.2, but it also increases with decrease of the gate-channel spacing "d". The proportional constant of Eq.1, $K=\mu\varepsilon/dL_g$, was named K value and defined as a figure of merit of FETs by Abe at al[7]. This K value is now widely used, but it must be noted that this K value depend not only "μ" but also on "d" and is only valid for the constant mobility case.

For constant mobility

$$I_{dsat} = \frac{\mu\varepsilon}{dL_g} \cdot (V_G - V_T)^2 \qquad (1)$$

$$g_{mo} = \frac{2\mu\varepsilon}{dL_g} \cdot V_G \qquad (2)$$

For velocity constant

$$I_{dsat} = \frac{\varepsilon v_s}{d} \cdot V_G \qquad (3)$$

$$g_{mo} = \frac{\varepsilon v_s}{d} \qquad (4)$$

For velocity saturation

$$I_{dsat} \simeq \frac{\mu\varepsilon}{dL_g} V_c (\sqrt{1 + 2U_g} - 1)^2 \qquad (5)$$

$$V_c = \mu E_c$$

$$U_g = (V_G - V_T - I_{dsat} \cdot R_s)/V_c$$

$$\frac{1}{g_m} \simeq R_m = R_s + \sqrt{\frac{dL_g}{2\varepsilon_s \mu I_{ds}}} + \frac{d}{\varepsilon v_s} \qquad (6)$$

notes: all equations are per unit gate width

Table 1, Equations for I_{dsat}s and g_ms, μ; mobility, e; dielectric constant, d; gate channel spacing, L_g; gate length, V_G; gate voltage, V_T; threshold voltage, v_s; saturation velocity, E_c; threshold field (3kV/cm), $R_m = 1/g_m$; transresistance, R_s; source resistance.

Equations 2 & 3 show I_{dsat} and g_m for an ideal FET whose carrier flows in a constant velocity from the source to the drain. The g_m in this case does not depend on the gate voltage V_G or I_{dsat}.

In actual FETs the velocity saturation inevitably occurs since the average field in the channel is much higher than the threshold field (3kV/cm). In that case, the FET is generally analyzed by dividing the channel into two regions; a mobility limited region and a velocity saturation region. The v-E characteristics have been approximated by two straight lines[8] or a curve which gradually approaches the saturation velocity[9]. They are essentially the same, and give almost the same g_m. In this work, Das et al's expressions[9] were adopted. In their expressions, inverse of the g_m (it can be called the transresistance R_m) is sum of the source series resistance, the intrinsic resistance and the resistance of the pinch-off region where the carriers flow in the saturation velocity or in peak velocity. The carrier mobility can mainly influence the intrinsic resistance. Furthermore, the mobility can reduce the intrinsic resistance in square root way, not in a linear way as expected in the mobility constant case.

3. Comparison of Analyzed Results with Reported Experimental Results

In order to see which expression is most appropriate one, analyzed results were compared with reported experimental results. Figure 1 shows transfer characteristics replotted from the output characteristics of 2DEGFET reported by Baba et al[10]. The broken lines show the curves calculated with Eq.1 by normalizing at $V_G - V_T = 0.3V$. It is clear that the I-V curve of 2DEGFET does not follow Eq.1. Furthermore, the g_m at 77K is only twice of that of 300K, even though the mobility at 77K (89000 $cm^2/V.s$) is 10 times larger than that at 300K. These results indicate that the transfer characteristics of

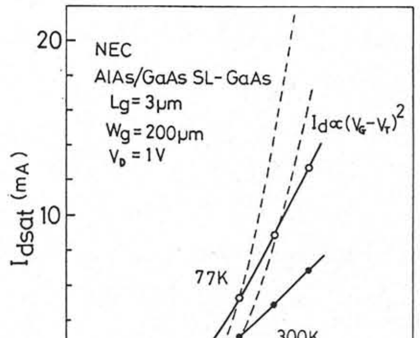

Fig.1, Transfer characteristics of 2DEGFET[10] Broken lines represent Eq.1 normalized at $V_G - V_T = 0.3V$.

2DEGFETs do not follow Eq.1, but rather follow Eq.6, since g_m is doubled if the second term is neglected as shown in Fig.2.

To see how much the each term of Eq.6 contributes the total R_m, absolute values of three terms were calculated by changing the gate-channel spacing "d" for a FET with following device parameters:

$Rs=0.4\ \Omega mm$, $Lg=0.5\ \mu m$,

$I_{dsat}=200$ mA/mm, $v_s=2x10^7$ cm/sec.

$\mu=2000$ or 8000 $cm^2/Vsec$.

The calculated results are shown in Fig.2. It should be noted that the calculated values are the maximum transconductance g_{mmax} (R_{mmin}) because the maximum I_{dsat} of 200 mA/mm, which is common for all reported normally-off FETs, was taken. The point of $R_m=0$ ($g_m=\infty$) is taken at the top line of the figure, and the R_m goes down linearly so that the Eq.6 can be understood visually.

The first term is the source resistance R_s, and is independent of "d". Reported R_s's are scattered form 0.2 to 1.0 Ωmm, so $R_s=0.4$ Ωmm was adopted here. The second term is almost the same as so called intrinsic resistance R_i of FET, which is the resistance(V_G/I_{dsat}) of the channel whose field is low and the carrier velocity is limited by the mobility. Therefore, it depends on the carrier concentration and the mobility, but it also depend on "d" and increases with increase of "d". However, the maximum value is less than 2.0 Ωmm even for $\mu=2000$ $cm^2/V.s$.

The third term is a resistance of the pinch-off region (R_p). Since the depletion layer spread over whole channel and the field is very high, carriers flow in the saturation velocity v_s, so this term depend on only "v_s" and "d". The R_p increases linearly with increase of "d" as shown by broken line, and reaches to 3 Ωmm for d=600A.

Sums of those three terms are shown by

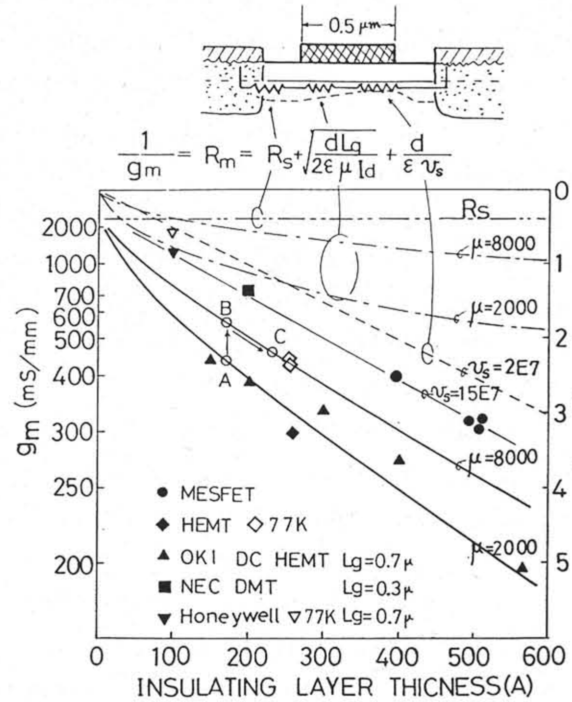

Fig.2, Dependence of the transresistance R_m on the gate-channel spacing. $R_m=0$ ($g_m=\infty$) is at the top line. Reported g_{mmax}es are also plotted as a function of "d".

solid lines. It should be noted that even though the mobility increases from 2000 to 8000 $cm^2/V.s$, the g_m increases only about 20% (from 400 to 500 mS/mm for d=200A). Furthermore, since depletion layers of HEMT structure FETs are larger than those of MESFETs, this improvement of g_m is canceled by increase of "d". For example, "d" for a HEMT with $N_D=2x10^{18}$ cm^{-3} is 240A (point C), whereas that of a GaAs MESFET with the same N_D is 170A (point A) due to absence of a depletion layer at the hetero interface. Therefore, the g_m improves only from point A to point C, not to point B in the figure.

Experimentally obtained g_m's reported on GaAs MESFETs, HEMT structure FETs, and doped channel HJFETs are also plotted in Fig.2. Solid triangles ▲ are g_ms of OKI's HEMT structure FETs with differently doped (therefore, different thickness "d") AlGaAs layers with the same pattern and same process. The channels are unintentionally (due to diffusion from doped AlGaAs) and intentionally doped, therefore, the mobility is higher for thicker "d". They follow the simply analyzed curve of g_m very well. Solid circles ● (GaAs MESFETs from NTT), solid square ■ (NEC doped channel MISFET) and solid inverted triangle ▼ (Honeywell inverted HEMT) follow another curve with $v_s=1.5\times10^7$ cm/s very well.

It is very interesting that the latter (GaAs MESFET, NEC-DMT etc.) gives much higher g_ms than HEMT structure FETs. The reason is not known well, but it seems that when a doped AlGaAs layer is on the top of the channel, the HJFET gives lower a g_m.

Above discussions are on the maximum transconductance g_{mmax} for I_{dsat}=200 mA/mm. They are valid for switching devices whose drain current swings from zero to the maximum, but situation is different for low noise FETs whose drain current at the operation is about 1/10 of the maximum I_{dsat}. Figure 3 shows drain current dependence of g_m (or R_m) for different mobilities. Insulator thickness "d" is assumed to be 200A. Other parameters are R_s=0.4 Ωmm, L_g=0.5 μm. When I_{dsat} is 20 mA/mm, g_m greatly depends

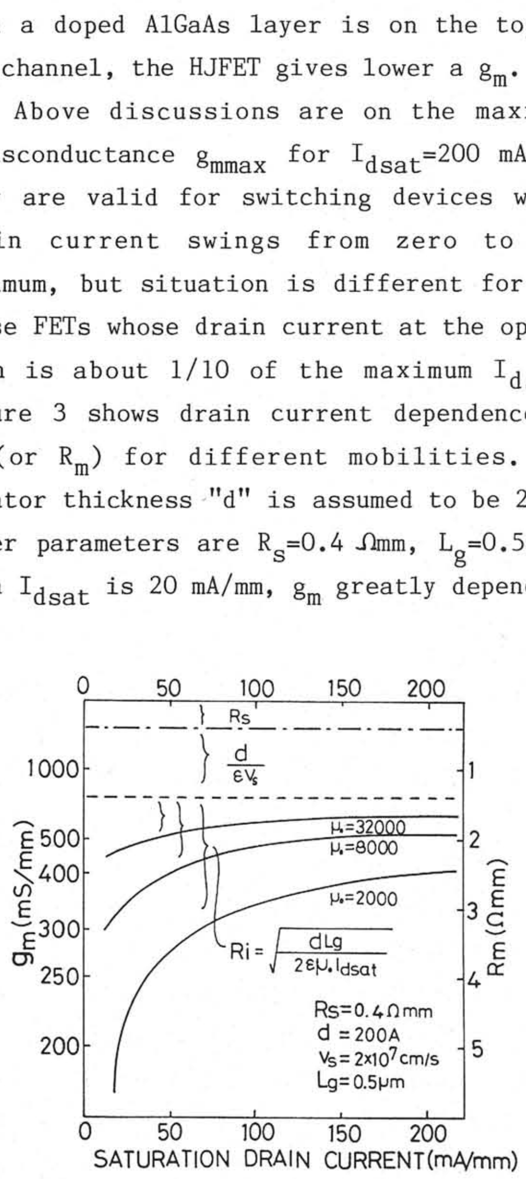

Fig.3, Drain current dependence of g_m for d=200A with different mobility.

on the mobility. However, these results are for I_{dsat}=200A. If I_{dsat}=350A, resistance of the pinch-off region R_p is doubled, deterioration due to R_i decreases very much.

4. Summary

Comparison between simple analysis of g_m and reported experimental results indicates that principal FET parameter which most influences g_{mmax} is gate-channel spacing. However, the analysis also indicates that mobility also greatly influence the g_m, if the drain current is very small, in such the case of low noise FET.

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REFERENCES

1) F.HASEGAWA; IEEE Trans. Electron Devices, ED-32 (1985) 2528.
2) F.HASEGAWA; Digest of Technical Meeting of IECE, Japan, ED85-73
3) H.INOMATA et al; Japan. J. Appl. Phys., 25 (1986) L731.
4) H.HIDA et al.; IEEE Electron Device Letters, EDL-7 (1986) 625.
H.HIDA et al.; 1986 IEDM Technical Digest, p759.
5) N.CIRILLO,Jr et al.; IEEE Electron Device Letters, EDL-7 (1986) 71.
6) U.K.MISHRA et al.; 1986 IEDM Technical Digest, p829 (Late News).
7) M.Abe et al., IEEE Trans. Electron Devices, ED-29 (1982) 1088.
8) K.Lee et al.; IEEE Trans. Electron Devices, ED-30 (1983) 207.
9) M.B.DAS et al.; Solid State Electronics, 28 (1985) 997.
10) T.Baba et al., Japan. J. Appl. Phys., 23 (1984) L654.