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Comparison between theoretical and experimental results for energy states of two-dimensional electron gas in pseudomorphically strained InAs-HEMTs

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Abstract

Comparison between theoretical and experimental results for energy states of the two-dimensional electron gas has been made for pseudomorphically strained InAs-HEMTs. Not only the threshold voltage but the transconductance of HEMTs calculated using the non-parabolic energy band model agreed fairly well with those obtained experimentally. In addition, the effect of composition of the $In_xGa_{1-x}As$ barrier layer on energy states of 2DEG was investigated. It was found that V_{TH} does not depend on the structure of the buffer layer used.

1. Introduction

In InP-based high electron mobility transistors with a pseudomorphically strained InAs channel (InAs PHEMTs), a current-gain cutoff frequency f_T of 688 GHz has been reported [1]. In addition, the operating characteristics of InAs PHEMTs have been analyzed experimentally for future logic applications [2].

According to Kane [3], the non-parabolicity of the conduction band should be taken into account when a semiconductor has an energy gap as small as that in InAs. Recently, we have used the energy dependent effective mass and the standard perturbation to determine the energy states of two-dimensional electron gas (2DEG) in the InAs channel of PHEMTs by solving both the Schrödinger and Poisson equations self-consistently [4]. In addition, we have clarified that the threshold voltage of PHEMTs V_{TH} is given by the effective conduction band offset-energy ΔE_C between the barrier and channel layers [5].

The purpose of this paper is to compare between theoretical and experimental results for energy states of 2DEG and to show that our theory is effective in analyzing device characteristics of PHEMTs. In addition, the effect of composition of the $In_xGa_{1-x}As$ barrier layer on energy states of 2DEG is investigated.

2. Device structure

Figure 1 shows a schematic cross section of PHEMTs assumed in the calculation. The epitaxial layers of InAs PHEMTs under calculation consist of an undoped InAlAs layer, an undoped $In_xGa_{1-x}As/InAs/In_xGa_{1-x}As$ composite channel layer (10 nm), and an InAlAs barrier layer with a Si-doping density of 2 x 10^{12} cm^{-2} (4 nm) [2]. The thickness of InAs was set to be 5 nm within the critical thickness.

3. Results and discussion

The gate metal was assumed to be the same Ti/Pt/Au as used in Ref. 3, so the surface potential energy at the gate-to-source voltage V_{GS} of 0 V (i.e., the Schottky barrier height) was assumed to be 0.655 eV [6]. Figure 2 shows the dependences of n_s on the V_{GS} for InAs PHEMTs, where the curve (a) corresponds to the non-parabolic energy band case and (b) to the parabolic energy band case. The V_{TH} for both cases were estimated by interpolating in such a way that $n_s \rightarrow 0$ in the n_s-V_{GS} curve. The value of V_{TH} was -0.10 V for the case (a) and-0.02 V for the case (b). The change of V_{TH} from cases (a) to (b) is ascribed to the effect of the non-parabolicity of conduction band for InAs [5]. There is another difference in the slope of the cases (a) and (b), i.e. the former is greater than the latter. This implies that the value of the transconductance G_m calculated for the parabolic energy band case is less than that calculated for the non-parabolic conduction band. Since the thickness of InAlAs layer under the gate is as thin as 4 nm, the dependence of V_{TH} on the gate length, i.e. the short channel effect, is thought to be small (Fig. 3 in Ref. 3). Therefore, it is possible to compare V_{TH} values obtained by the theory and the experiment. Figure 3 (b) shows the drain current I_{DS} versus V_{GS} for InAs PHEMTs with a gate length of 40 nm at the drain voltage V_{DS} of 0.5 V obtained by Kim et al. (Fig. 4 in Ref. 3). The theoretical results for I_{DS} (Fig. 3 (a)) were obtained using the following equation based on the velocity saturation model, which holds for HEMTs with a short gate length [7]:

$$I_{DS} = n_s q v_s \qquad [A/\mu m],$$

where v_s is the saturation velocity of electrons and n_s is the sheet concentration of 2DEG. The v_s was estimated from the experimental data on f_T to be 2.53x10^7 cm/sec by using the following relation:

$$f_T = \frac{v_s}{2\pi\left(L_g + \Delta L_g\right)},$$

where ΔL_g was deduced from the result obtained by Monte Carlo simulation (43 nm) [8]. The data plotted in Fig. 2 were used as n_s. As shown in Fig. 3, the V_{TH} at a V_{DS} of 0.5 V was about −0.09 V, which was obtained by extrapolating the drain current to zero. Figure 4 shows the dependence of G_m on V_{GS}, where the curve (a) corresponds to the theoretical results calculated using the non-parabolic energy band model and the curve (b) to experimental

results for InAs PHEMTs with a gate length of 40 nm at the drain voltage V_{DS} of 0.5 V obtained by Kim et al. (Fig. 5 in Ref. 3). As seen from Figs. 3 and 4, not only V_{TH} but G_m calculated using the non-parabolic energy band model agrees fairly well with those obtained experimentally. On the other hand, in the parabolic band case, neither V_{TH} nor G_m coincides with experimental results.

The dependences of n_s on the V_{GS} for $In_{0.53}Ga_{0.47}As$/ InAs/$In_{0.53}Ga_{0.47}As$ PHEMTs (structure A) and $In_{0.75}Ga_{0.25}As$/InAs/$In_{0.75}Ga_{0.25}As$ PHEMTs (structure B) were calculated and the V_{TH} for both kinds of HEMTs were estimated. These results are shown in Fig. 5, where the curve (a) corresponds to the structure A and the curve (b) to the structure B. No noticeable difference between V_{TH} for both structures was observed. This is a proper result because V_{TH} is given by the effective conduction band offset-energy ΔE_C between the barrier and channel layers as we have clarified [5]. And the slope for the structure B is slightly larger than for the structure A, indicating that G_m for the former is slightly higher than that for the latter. This is because that 2DEG distributes near the upper interface between InGaAs and InAs in the structure B rather than the structure A.

4. Conclusions

Not only V_{TH} but G_m calculated using the non-parabolic energy band model agreed fairly well with those obtained experimentally. It was found that V_{TH} does not depend on the structure of the buffer layer used, in other word V_{TH} is given simply by the effective conduction band offset-energy ΔE_C between the barrier and channel layers.

References

[1] D. H. Kim, B. Brar, and J. A. del Alamo, IEEE in *IEDM Tech. Dig.,* 11-319 (2011).

[2] D. H. Kim and J. A. del Alamo, IEEE Electron Devices 57, 1504 (2010).

[3] E. O. Kane, J. Phys. Chem. Solids 1, 249 (1957).

[4] Y. Nishio, S. Yamaguchi, Y. Yamazaki, A. Watanabe, T. Tange, T. Iida, and Y. Takanashi, 31st International Conference on the Physics of Semiconductors (ICPS2012), 37.19 (2012).

[5] Y. Nishio, T. Tange, N. Hirayama, T. Iida, and Y. Takanashi submitted to pssc (2013).

[6] Larry P. Sadwick, C. W. Kim, Kin L. Tan, and Dwight C. Streit, IEEE Electron Devices Lett. 12, 11 (1991).

[7] S. M. Sze, Physics of Semiconductor Devices (John Wiley & Sons,New York, 1981) Chap. 6.

[8] T. Takegishi, H. Watanabe, S. Hara, and H. Fujishiro, IEICE Trans. Electron. E93-C (2010).

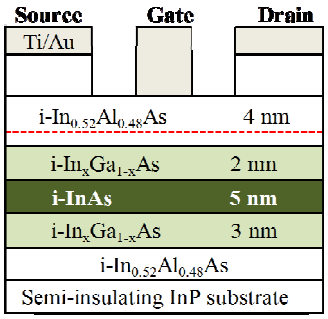

Figure 1: Schematic cross section of pseudomorphically strained InAs HEMTs assumed in the calculation.

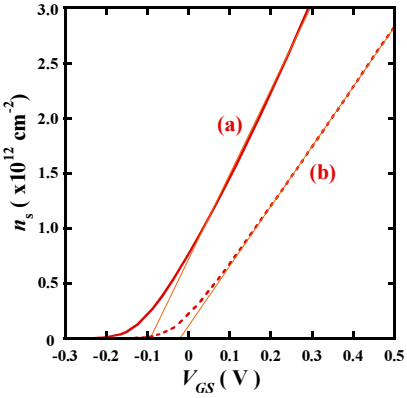

Figure 2: Dependence of the n_s on the V_{GS} for InAs PHEMTs. Solid line corresponds to (a) the non-parabolic energy band case and (b) dashed line to the parabolic energy band case

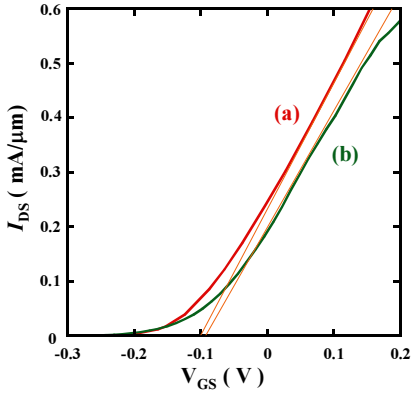

Figure 3: Drain I-V characteristics of InAs PHEMTs with a gate length of 40 nm. The red curve (a) is for the theoretical result and the green curve (b) is for the experimental result.

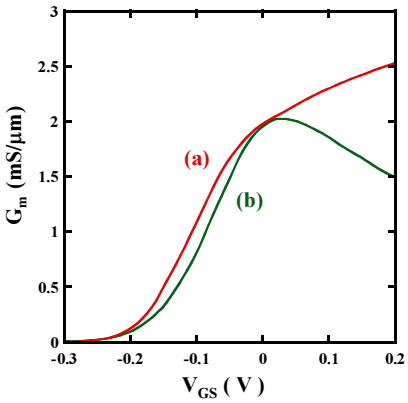

Figure 4: Dependence of G_m on V_{GS}, where the curve (a) corresponds to the non-parabolic energy band case and the curve (b) to experimental results for InAs PHEMTs with a gate length of 40 nm.

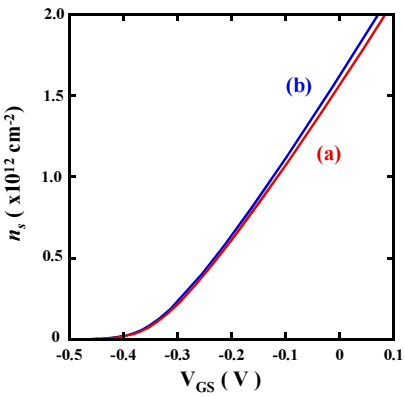

Figure 5: Dependence of n_s on V_{GS}. The red curve (a) is for the $In_{0.53}Ga_{0.47}As$/InAs/$In_{0.53}Ga_{0.47}As$ PHEMTs, and the blue curve (b) is for the $In_{0.75}Ga_{0.25}As$/InAs/ $In_{0.75}Ga_{0.25}As$ PHEMTs.