

Simulation and analysis of metamorphic high electron mobility transistors

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Abstract

In this paper, the metamorphic high electron mobility transistors (mHEMTs) are investigated numerically and compared with pseudo-morphic high electron mobility transistors (pHEMTs). The two-dimensional device simulator, MEDICI, is used to solve the Poisson's equation and the electron/hole current continuity equations. The influences of δ -doping concentration and position, gate width, spacer thickness, etc. on the performances of HEMTs are explored. It shows clearly that mHEMTs have higher transconductances, drain currents and DC voltage swings than pHEMTs.

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1. Introduction

The low field mobility and some characteristics of GaAs pseudo-morphic high electron mobility transistors (pHEMTs) have been improved by increasing the quantities of indium elements in the channel layer of $\text{In}_x\text{Ga}_{1-x}\text{As}$ [1,2]. However, there is a larger lattice mismatch between the $\text{In}_x\text{Ga}_{1-x}\text{As}$ layer and the GaAs layer resulting from the increasing of the quantities of indium elements. To solve the problem, a HEMT structure with InP substrate which promotes the Indium mole fraction in $\text{In}_x\text{Ga}_{1-x}\text{As}$ channel layer from 0.15 to 0.25 to 0.53 is widely adopted. Such a HEMT with InP substrate shows better noise characteristics and can be fabricated in a smaller size than GaAs pHEMTs in the microwave applications. However, it suffers a higher cost and a brittle feature. Hence, a GaAs metamorphic HEMT (mHEMT) structure with a GaAs substrate is proposed. By increasing the quantities of indium

elements in the channel layer, higher electron mobility and higher two-dimensional electron gas (2DEG) density can be obtained. In addition, δ -doping structures are used in the structure design for its better gate control capability and higher electron mobility [3,4] compared with modulation-doping structures. The merits and drawbacks of the pHEMTs and mHEMTs are simulated and analyzed in this paper.

2. Numerical simulation

Poisson's equation and continuity equations for electrons and holes are solved to find the various electrical characteristics of the devices self-consistently. By Poisson's equation, the electrical potential energy and electronic band structures can be calculated. Continuity equations for electrons and holes are used to get the densities of electrons and holes. In the process of solving these two equations, Boltzman transport theory is also applied. It shows the relationship between the current density of electrons/holes and carrier concentration as well as quasi-Fermi potential. The self-consistent process calculates the electrostatic potential and the concentration of carriers. The

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recombination behaviors between electrons and holes are described with Auger equation, Shockley–Read–Hall equation and direct-recombination equation. Since a pseudomorphic HEMT is a unipolar device, the correlation model among carrier mobility and the mole fractions, concentration, temperature, and the electrical field can be described as the empirical equations presented in Refs. [5,6]. Under the low electrical fields, the carrier mobility can be expressed as Eq. (1)

$$\mu_{no}(x, T) = \mu_n^{\min}(x) + \frac{\left[\mu_n^{\max}(x) \left(\frac{T}{300} \right)^{\text{NUN}} - \mu_n^{\min}(x) \right]}{\left[1 + \left(\frac{T}{300} \right)^{\text{XIN}} \left[\left(\frac{N_{\text{total}}}{\text{NREFN}} \right)^{\text{ALPHAN}} + \left(\frac{N_{\text{total}}}{\text{NREEN2}} \right)^3 \right] \right]}, \quad (1)$$

where NUN, XIN, NREFN, NREEN2, ALPHAN are ANALYTIC model parameters in MEDICI tool [7], N_{total} the local impurity concentration, χ mole fractions, and T the absolute temperature (in K).

Under high electrical fields, the effect on the mobility caused by the electric field is more than that by the Coulomb force between impurities. The relation between carrier mobility and electric field is shown below,

$$\mu_n(x, T, E_{||}, n) = \frac{\mu_{no}(x, T) + \frac{v_n^{\text{sat}}(x)}{E_{||}, n} \left(\frac{E_{||}, n}{E_o(x)} \right)^4}{1 + \left(\frac{E_{||}, n}{E_o(x)} \right)^4}, \quad (2)$$

where $\mu_{no}(x, T)$ is electrons mobility under a low electrical field, $E_{||}$ the electric field in the direction of parallel currents, $v_n^{\text{sat}}(x)$ the saturated drift velocity, and $E_o(x)$ the critical electrical field.

3. Simulation results and discussions

Fig. 1 shows the cross-section view of GaAs mHEMTs and GaAs pHEMTs studied in this paper. An offset-gate design [8,9] is adopted here to reduce the source resistance and the influence of high electric field from drain to gate and, therefore, to increase the breakdown voltage.

Fig. 2 shows the simulation results of mHEMTs. Fig. 2(a) appears the relationship of transconductance versus gate-source voltage ($g_m - V_{gs}$) under various spacers d_d , the distances between δ -doping layer and channel layer. A short spacer d_d results in a strong supplement of the free carriers from δ -doping layer, and, hence, a smaller source resistance as well as a small threshold voltage (in absolute value) that causes a larger transconductance and a larger DC voltage swing. Fig. 2(b) demonstrates the $g_m - V_{gs}$ relations under various gate-channel distances (d_g). Clearly, a smaller distance d_g results in a curve right-shifting and a larger maximum value of g_m because of the enhancement of channel sensitivity to the gate control. Fig. 2(c) shows the corresponding relations between channel length (gate width) and transconductance. In a short channel, the ballistic effect and carrier velocity overshoot take place, and hence, the transconductance decreases. Fig. 2(d) demonstrates the calculated results of threshold voltages under various δ -doping concentrations and positions. Increasing δ -doping concentration induces a strong normally on channel. In addition, closing δ -doping position to the gate enhances the gate control on the carriers of the δ -doping layer.

On the other hand, the electrical characteristics of mHEMTs are compared with those of pHEMTs. In the Figs. 3(a) and 3(b), the solid lines show the drain current

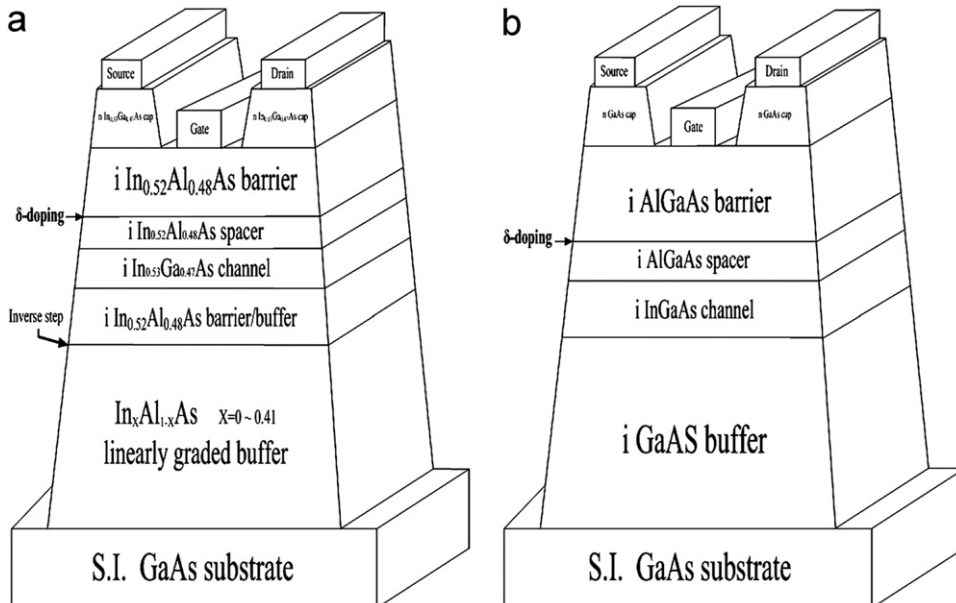


Fig. 1. Cross sections of (a) GaAs mHEMT and (b) GaAs pHEMT.

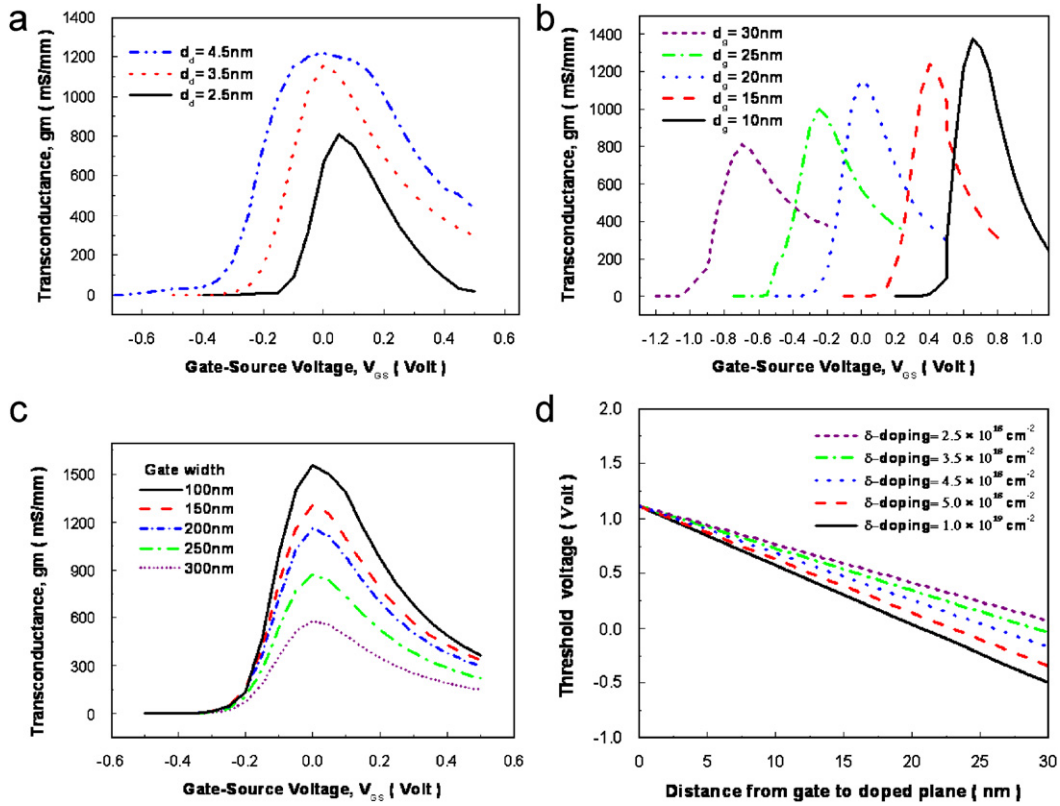


Fig. 2. (a) Transconductance versus gate-source voltage under various spacers between δ -doping layer and channel layer. (b) Transconductance versus gate-source voltage under various distances between channel layer and gate layer. (c) Transconductance versus gate-source voltage under various gate widths (channel lengths). (d) Threshold voltages under various δ -doping concentrations and positions.

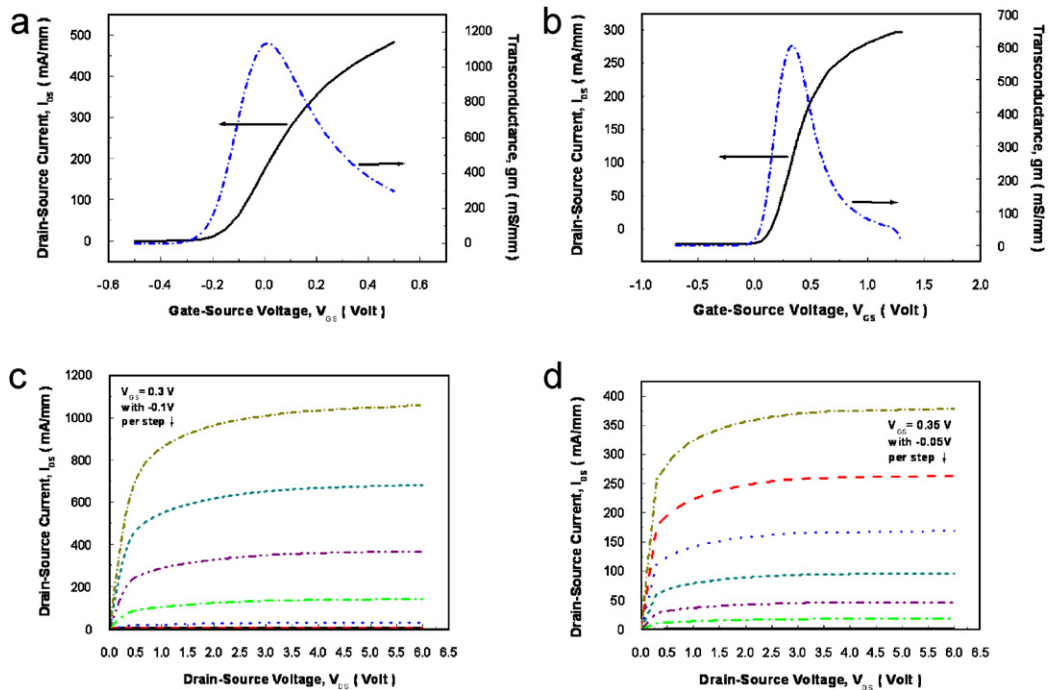


Fig. 3. Drain current (I_{DS}) and transconductance (g_m) versus gate voltages (V_{GS}) of (a) GaAs mHEMTs and (b) GaAs pHEMTs. Drain current (I_{DS}) versus drain-source voltages (V_{DS}) of (c) GaAs mHEMTs and (d) GaAs pHEMTs.

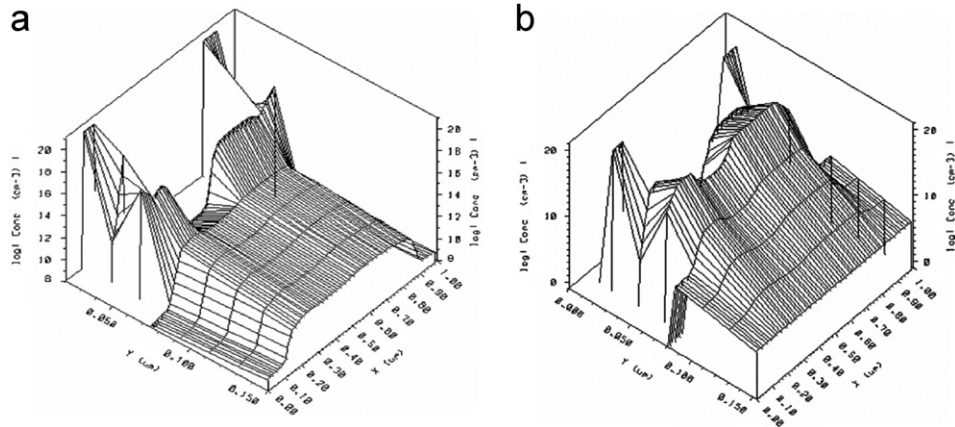


Fig. 4. Three-dimensional distribution of electron concentrations of (a) mHEMTs and (b) pHEMTs under thermal equilibrium.

(I_{DS}) versus gate voltages (V_{GS}) and the dash lines show the transconductance (g_m) versus gate voltages (V_{GS}) of HEMTs. Remarkably, as illustrated in Fig. 3, mHEMTs have higher drain currents and DC voltage swings than pHEMTs. Also, the transconductance of mHEMTs (1160 ms/mm) is far higher than that of pHEMTs (609 ms/mm). Besides, the three-dimensional distribution of electron concentrations of mHEMTs and pHEMTs under thermal equilibrium are demonstrated in Fig. 4(a) and Fig. 4(b), respectively.

4. Conclusions

GaAs mHEMTs and pHEMTs are designed and analyzed in this paper. The simulation results show that both of the mHEMTs and pHEMTs are significantly determined by the structure parameters, such as δ -doping position and concentration, gate width, and spacer layer thickness. 2D simulator—MEDICI, obtains optimal designs of GaAs mHEMTs. It reveals that the transconductance may go up to 1160 ms/mm and channel carrier concentration under thermal equilibrium may go up to 10^{18} cm^{-3} . The comparisons between mHEMTs and

pHEMTs are also presented. It is found that mHEMTs have much better performances than pHEMTs.

References

- [1] C. Ladner, C.B. Aupetit, A. Nezzari, J. Decobert, J.C. Harmand, G. Post, P. Vigier, J. M. Dumas, in: Proceedings of the 10th International Conference on Indium Phosphide and Related Materials IEEE, Japan, 1998, pp. 505.
- [2] G. Meneghesso, A. Neviani, R. Oesterholt, M. Maloubian, T. Liu, J.J. Brown, C. Canali, E. Zanoni, IEEE Trans. Electron. Devices 46 (1999) 2.
- [3] C.E.C. Wood, G. Metzger, J. Berry, L.F. Eastman, J. Appl. Phys. 51 (1980) 382.
- [4] E.F. Schubert, A. Fischer, K. Ploog, IEEE Trans. Electron. Devices 33 (1986) 625.
- [5] Z. Yu, R.W. Dutton, SEDAN III-A Generalized Electronic Material Device Analysis Program, Stanford Electronics Laboratory Technical Report, Stanford University, 1985.
- [6] W.B. Joyce, R.W. Dixon, Appl. Phys. Lett. 31 (1977) 354.
- [7] MEDICI, Two-Dimensional Device Simulation Program, Version 4.1, Users Manual, Avant! Corporation, TCAD Business Unit, 1998, pp. 127 (Chapter 2).
- [8] D. Geiger, J. Dickmann, C. Wölk, E. Kohn, IEEE Electron. Device Lett. 16 (1995) 30.
- [9] K. Higuchi, H. Matsumoto, T. Mishima, T. Nakamura, IEEE Trans. Electron. Devices 46 (1999) 1312.