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Theoretical simulation of DC and RF performance for AlInN/InGaN/AlInN double-heterojunction FET using a Monte Carlo approach

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Abstract: A theoretical prediction of beyond-THz frequency operation is demonstrated for a III-nitride heterojunction FET with a gate length of sub-100 nm. The calculation is based upon an ensemble Monte Carlo simulation coupled with a 2D Poisson equation. The simulation results suggest that a current gain cutoff frequency of more than 1 THz is achieved by an AlInN/InN/AlInN or AlInN/InGaN/AlInN double-heterojunction FET with a gate length of less than 50 nm or 30 nm, respectively, which are fabricated on a non-polar GaN substrate. The importance of high-mobility InN and InGaN used as a channel material for high-speed and high-frequency applications is numerically verified.
Keywords: current gain cutoff frequency, double-heterojunction, FET, InN, InGaN, Monte Carlo simulation
Classification: Electron devices, circuits, and systems

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1 Introduction

A III-nitride heterojunction FET is attracting considerable attention as a high-frequency and low-loss device with improved breakdown characteristics [1]. By scaling-down the device dimension to a nanometer scale range in AlGaN/GaN heterojunction FETs, a current gain cutoff frequency of 190 GHz has already been reported [2]. Since the emerging applications, such as Giga-bit wireless transmission and high-resolution wireless imaging systems, require a new frequency band that is far beyond the millimeter-wave frequency range, it is strongly demanded to further improve the frequency performance of nitride-based FETs. The most straightforward approach to enhance the operation frequency of FET devices is the use of ultra-short gate lengths on a channel material with improved transport characteristics. InN is well-known to exhibit excellent transport properties, such as high electron mobility and high peak electron velocity [3]. However, the difficulty in growing high quality InN or InGaN with high In composition has hindered experimental approaches for developing an optimized device structure with a channel layer composed of these materials. It is therefore of great importance to investigate the possibility of THz frequency operation using these heterojunctions composed of In-rich nitride materials.

In this paper, we describe theoretical prediction of high-frequency performance in AlInN/In(Ga)N/AlInN double-heterojunction FETs based on an ensemble Monte Carlo device simulation. A comprehensive study on the effects of structural and material parameters on the device performance indicates that InN or InGaN with high In composition is promising as a channel material for high frequency operation. Velocity overshoot and short-channel effects are discussed in terms of gate length and material parameters. The first theoretical prediction of over 1 THz in the current gain cutoff frequency is demonstrated with 50 nm and 30 nm gate length double-heterojunction FETs with a channel material made of InN and $In_{0.75}Ga_{0.25}N$, respectively.

2 Calculation method

Calculations were made using an ensemble Monte Carlo algorithm to solve Boltzmann transport equation coupled with 2D Poisson equation [4]. Our device model incorporates an analytical 3-vallay band structure with non-

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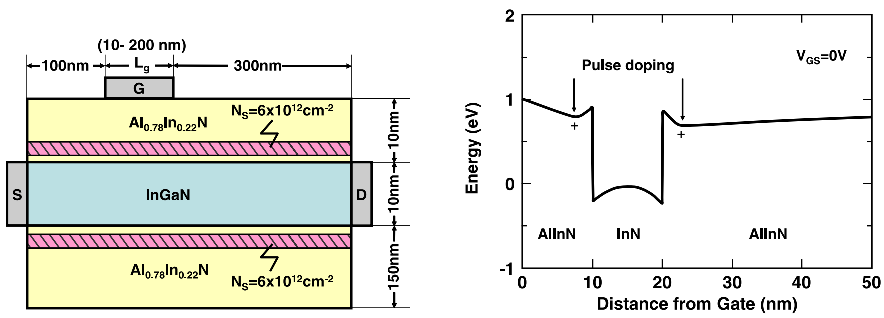
parabolicity for all nitride materials. For simplicity, physical parameters for ternary materials were derived from linear interpolation between binary materials [5]. The scattering mechanisms considered were acoustic phonon scattering, polar optical phonon scattering, equivalent and non-equivalent intervalley phonon scattering, and impurity scattering [6].

Figure 1 (a) shows the schematic cross section of an AlInN/InGaN/AlInN double-heterojunction FET simulated by our theoretical calculation. The FET consists of an undoped InGaN channel layer, upper and lower pulse-doped n-type AlInN barrier layers and an undoped GaN substrate (not shown). An aluminum composition of 0.78 was assumed for both AlInN layers so that the AlInN layer is lattice-matched to GaN. The doping concentration for both AlInN barrier layers was assumed to be $3 \times 10^{19}\,\mathrm{cm}^{-3}$ with a doped layer thickness of 2 nm. A spacer layer of 1 nm was inserted between the InGaN channel layer and both AlInN barrier layers. The gate length (Lg) was varied from 10 to 200 nm. For simplicity, source and drain ohmic contacts were placed only on the InGaN channel layer. Other details of the device parameters are shown in Fig. 1 (a). The conduction band energy discontinuity was assumed to be 70% of the bandgap difference. During simulation, the electron population in the device adjusts itself so that the overall charge neutrality is satisfied. The number of sample particles thus varies between 20,000 and 40,000 depending on the bias conditions. Simulations were performed typically for 50 ps. The terminal currents were estimated by the method using cumulative terminal charges [7]. The transconductance (g_{m}) was derived by differentiating the estimated drain current with respect to the gate-source voltage under a constant drain-source voltage of 5 V. Using the calculated g_{m} and the corresponding gate-source capacitance (C_{GS}), estimated by counting the difference in the total mobile charge in the device, a current gain cutoff frequency was defined as $g_{\mathrm{m}}/2\pi C_{\mathrm{GS}}$.

Figure 1 (b) shows the conduction band energy as a function of the distance from the gate for an AlInN/InN/AlInN double-heterojunction structure. Under the existence of polarization effects with a polar material, it is well-known that a double-heterojunction structure gives rise to an acute tri-



(a) (b)

Fig. 1. (a) Schematic cross section of AlInN/InGaN/AlInN double-heterojunction FET and (b) conduction band energy diagram.

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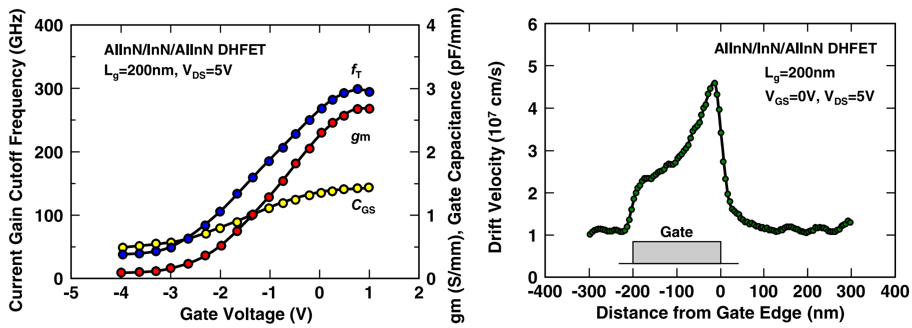
angular potential well due to the positive and negative polarization charges at both AlInN/InGaN hetero-interfaces. As a result, the carrier confinement in the potential well for the polar double-heterojunction gets worse. By using non-polar materials, excellent carrier confinement is expected with a square well of AlInN/InGaN/AlInN in Fig. 1 (b). In this simulation, we thus assume an AlInN/InGaN/AlInN double-heterojunction grown on a non-polar GaN substrate, where any polarization effects are ignored. In order to induce two-dimensional electrons in the square well of non-polar InGaN, we have provided n-type pulse-doping in both upper and lower AlInN barrier layers.

3 Results

We first examined DC performance for AlInN/InGaN/AlInN double-heterojunction FETs (DHFETs) with a gate length of 200 nm. For all channel materials of GaN, $In_{0.5}Ga_{0.5}N$, and InN, an excellent pinch-off and saturation behavior was confirmed. By increasing In composition in the InGaN channel, the device exhibited a dramatic increase in the maximum drain current and the peak transconductance, i.e., 1.9, 3.3, and 5.7 A/mm and 0.87, 1.62, and 2.68 S/mm for a channel material of GaN, $In_{0.5}Ga_{0.5}N$, and InN, respectively. The threshold voltage estimated was about -1.3 V for all devices. It is evident that a channel layer of increased In composition is beneficial for high drain current and high-transconductance operation. Consequently, the maximum current gain cutoff frequency (f_T) was calculated to be 160, 230, and 300 GHz for a channel material of GaN, $In_{0.5}Ga_{0.5}N$, and InN, respectively.

Figure 2 (a) shows transconductance, gate capacitance, and current gain cutoff frequency as a function of gate voltage for an AlInN/InN/AlInN DHFET. The maximum cutoff frequency was obtained at a gate-source voltage of around 0.8 V. Figure 2 (b) shows the electron drift velocity plotted as a function of the distance from the gate edge in the drain side for an AlInN/InN/AlInN DHFET with a gate length of 200 nm. The drift velocity is



(a) (b)

Fig. 2. Simulated results for AlInN/InN/AlInN DHFET. (a) Transconductance, gate capacitance, and current gain cutoff frequency as a function of gate-source voltage. (b) Drift velocity versus distance from gate edge.

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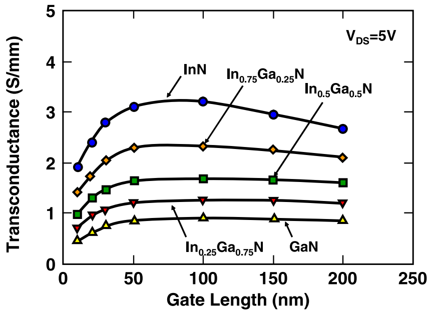
accelerated under the gate and the peak velocity reaches 4.6×10^7 cm/s. In the same device geometry, the peak drift velocity reached 3.6 and 4.1×10^7 cm/s for a channel material of GaN and $In_{0.5}Ga_{0.5}N$, respectively. These values are about 10–20% larger than those of the corresponding steady-state peak electron drift velocity. Therefore, it was found that the velocity overshoot effect became significant when the gate length is reduced to less than 200 nm.

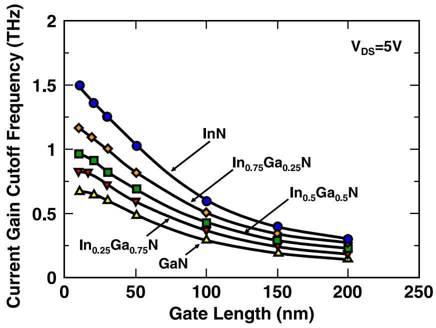
Figure 3 (a) shows the calculated transconductance as a function of the gate length for AlInN/InGaN/AlInN DHFETs with different In compositions in the channel. By scaling down the gate length in the sub-100 nm range, all the devices demonstrated the short-channel effects, where the threshold voltage exhibited a negative shift with a decrease in the gate length. In the gate length range between 100 and 200 nm, a slight increase in the transconductance was observed for FETs with a channel material of InN and $In_{0.75}Ga_{0.25}N$. Since the variation is more intense for the InN channel that has higher electron mobility, the increased transconductance is predominantly due to the velocity overshoot effect. Detailed analysis for devices with a gate length of 10 nm revealed that the peak drift velocity for a channel material of GaN, $In_{0.5}Ga_{0.5}N$, and InN was 4.6, 5.3, and 6.4×10^7 cm/s, respectively. These values are more than 1.5 times larger than those of the steady-state peak drift velocity.

Figure 3 (b) shows the current gain cutoff frequency as a function of the gate length for AlInN/InGaN/AlInN DHFETs with various values in the In composition. It is clear that the calculated cutoff frequency is dramatically improved with a reduction in the gate length. Since the gate-source capacitance reduces almost linearly with decreasing the gate length, the cutoff frequency still improves despite the decrease in the transconductance in the sub-50 nm gate length regime. Note that the AlInN/InN/AlInN DHFET with a 10 nm gate length exhibited a maximum current gain cutoff frequency of as high as 1.5 THz. The results in Fig. 3 (b) indicate that a current gain cutoff frequency of 1 THz can be achieved by choosing a gate length of 50 and 30 nm for a channel material of InN and $In_{0.75}Ga_{0.25}N$, respectively.

From the above simulation results, it is confirmed that an InN or In-



(a)



(b)

Fig. 3. (a) Transconductance and (b) current gain cutoff frequency as a function of gate length.

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rich InGaN channel DHFET is promising as a high-frequency device that is capable of operating in the THz frequency range.

4 Conclusion

An ensemble Monte Carlo 2D simulation was performed for AlInN/InGaN/AlInN DHFETs. The simulation results indicated that a device with a channel In composition of more than 75% together with a sub-50 nm gate length was expected to show a current gain cutoff frequency in the THz range. This report is the first theoretical prediction of THz operation using a III-nitride heterojunction FET.

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