Design and Simulation of Enhancement-mode N-polar GaN Single-channel and Dual-channel MIS-HEMTs

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Abstract

GaN HEMTs have demonstrated higher power density and efficiency over existing technologies such as silicon and gallium arsenide (GaAs) based RF and microwave transistors [1]. Until recently, improvements in the design of GaN semiconductor device had focused on Ga-polar GaN based HEMTs. Lately, N-polar GaN shows the advantage over Ga-polar device in making enhancement-mode (E-mode) device with low access resistance, and in particular, for low voltage operation. An E-mode N-polar GaN MISFET device was demonstrated to achieve a threshold voltage of 1 V and a record-high drive current 0.74 A/mm at a gate length of 0.62 [2]. Unfortunately, there are few analytical and simulation models developed for E-mode N-polar GaN HEMT. Moreover, the drive current under low voltage bias for N-polar GaN HEMT is smaller than the state-of-the-art Ga-polar GaN HEMT. In this work, by 2-D simulations in Synopsys TCAD [3], we, for the first time, (1) investigated N-polar E-mode single channel GaN MIS-HEMT through simulations; (2) designed an E-mode N-polar GaN dual channel MIS-HEMT and identified the mechanism of the drive current enhancement.

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Design and Simulation of Enhancement-mode N-polar GaN Single-channel and Dual-channel MIS-HEMTs

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GaN HEMTs have demonstrated higher power density and efficiency over existing technologies such as silicon and gallium arsenide (GaAs) based RF and microwave transistors [1]. Until recently, improvements in the design of GaN semiconductor device had focused on Ga-polar GaN based HEMTs. Lately, N-polar GaN shows the advantage over Ga-polar device in making enhancement-mode (E-mode) device with low access resistance, and in particular, for low voltage operation. An E-mode N-polar GaN MISFET device was demonstrated to achieve a threshold voltage of 1 V and a record-high drive current 0.74 A/mm at a gate length of 0.62 μm [2]. Unfortunately, there are few analytical and simulation models developed for E-mode N-polar GaN HEMT. Moreover, the drive current under low voltage bias for N-polar GaN HEMT is smaller than the state-of-the-art Ga-polar GaN HEMT. In this work, by 2-D simulations in Synopsys TCAD [3], we, for the first time, (1) investigated N-polar E-mode single channel GaN MIS-HEMT through simulations; (2) designed an E-mode N-polar GaN dual channel MIS-HEMT and identified the mechanism of the drive current enhancement.

As shown in Fig. 1(a), a 20 nm unintentionally doped N-polar GaN layer was deposited on a 2 nm AlN back barrier. On top of the GaN layer, we put a 2 nm AlN polarization-neutralization cap, then a 5 nm SiN gate dielectric layer to build an E-mode MIS-HEMT. Source and drain region were heavily doped and we assumed perfect electrode contact condition since 0.027 $\Omega\cdot$mm contact resistance was reported for non-alloyed ohmic contact of the experimental N-polar GaN device [2]. The gate length was set to be 0.62 um as the experimental device structure and the gate workfunction was adjusted for threshold voltage calibration. Polarization charge was automatically simulated by spontaneous and piezoelectric polarization model. Fixed charge was inserted at the SiN/AlN interface to mimic passivation effect. Traps were introduced in the GaN buffer layer for threshold voltage and leakage current fine tuning.

Fig. 1(b) depicts the simulated device characteristics, which are in agreement with the experimental results [2]. The slightly higher simulated drain current may be due to the smaller access region compared to the experimental structure [2].The simulated energy band diagrams and electron density distribution below the gate region are shown in Fig. 1(c), whereas V_{gs} is set to be 2 V close to the threshold voltage and the 2DEG is induced with a density of $1.87 \times 10^{12}/\mathrm{cm}^{-2}$. The threshold voltage is obtained as 1.37 V. Suggested by the simulated band diagram shown in Fig. 2(a), further conduction band bending of GaN channel layer will introduce an inversion carrier channel in addition to 2DEG sheet. Because of the natural polarization direction property of N-polar GaN, the inversion carrier channel is developed close to the surface interface and separated from the 2DEG sheet induced close at the back. Considering the MOSFET threshold voltage analytical model, to induce significant electron density in inversion carrier channel to form dual channels in N-polar GaN layer, the gate controllability need to be strengthen. In this design, the single channel device structure is further modified with a stack consisting of 1 nm SiN and 2 nm AlN virtually grown on the GaN. The simulated band diagrams in Fig. 2(b) depict the development of two "wells" at the front and back interfaces as the gate bias increases. The simulated output characteristic of the dual channel MIS-HEMT in Fig. 3(a) shows almost 2X on-state current as the single channel device. The I_d-V_{ds} group curve indicates that the current through the inversion carrier channel will become a significant or larger component of the total drive current as the gate bias increases. This increased current carrying capability is due to the presence of dual channels as illustrated in Fig. 3(b), where two comparable electron densities are induced close to their interfaces respectively under a 5 V gate bias.

In conclusion, we have demonstrated a design method of E-mode N-polar GaN single channel and dual channel MIS-HEMT. The mechanism for the creation of the additional inversion carrier channel has been identified. We have shown that the N-polar GaN is suitable for dual channel MIS-HEMT because the location of natural 2DEG induced at the back barrier interface helps reduce the dual channel overlap. Significant increase in on-state current simulated by TCAD suggests that the E-mode N-polar GaN dual channel MIS-HEMT can be a promising device structure for RF/power amplifier application. The authors would like to acknowledge the valuable suggestions provided by Dr. Prasanta Ghosh in paper review.

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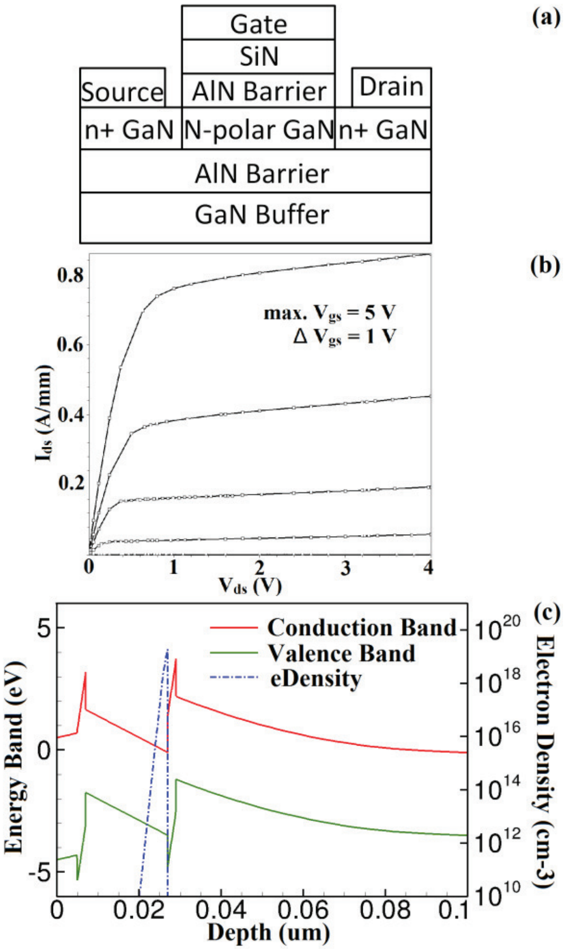

Fig. 1 (a) Structure schematic, **(b)** output characteristics and **(c)** energy band diagrams and electron density of the calibrated simulations of a single channel MIS-HEMT.

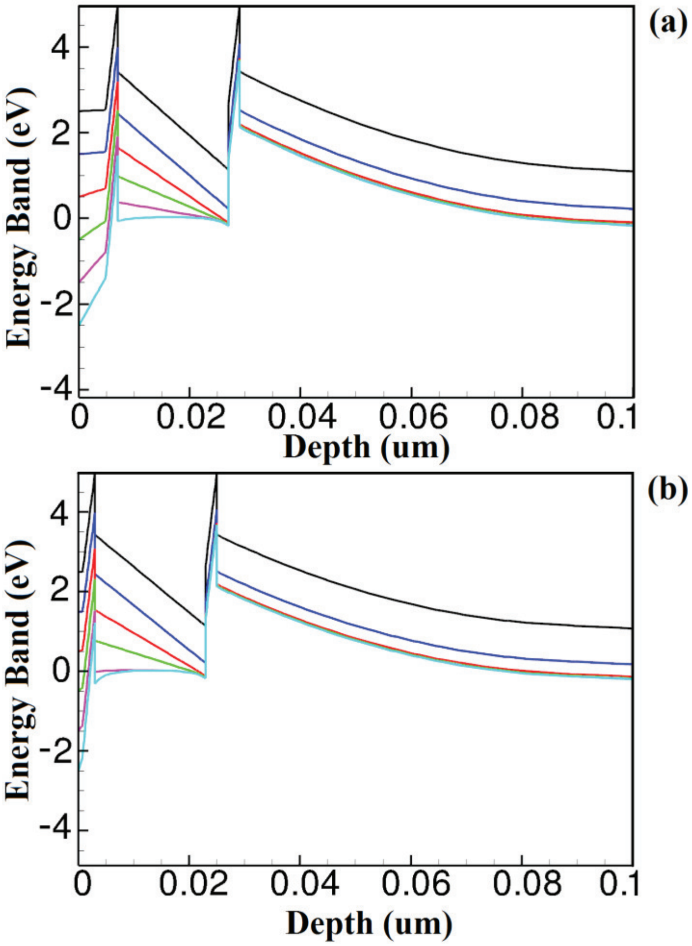

Fig. 2 Energy band diagrams under gate region versus gate bias for **(a)** single channel and **(b)** dual channel MIS-HEMT.

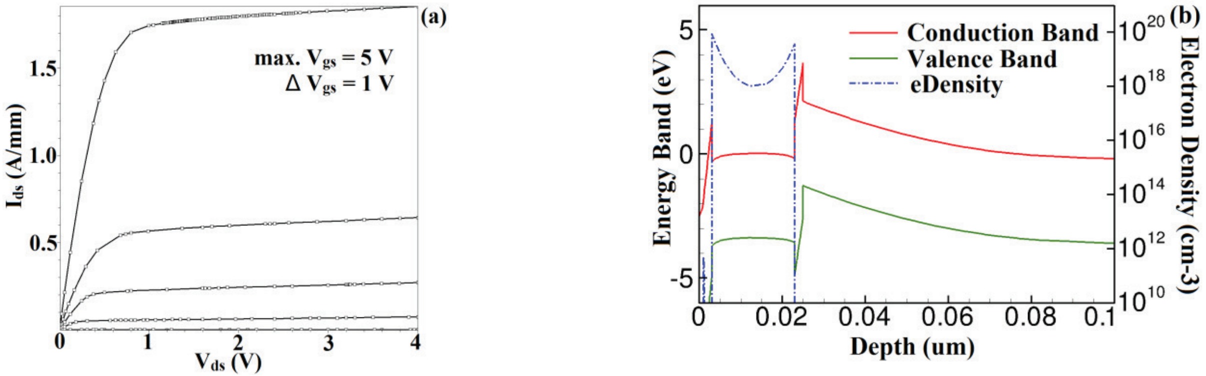

Fig. 3 (a) Output characteristics and **(b)** energy band diagrams of the dual single channel MIS-HEMT.