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Net Acceptor Type Trap Density in Semi-insulating GaN layers

Taketoshi Tanaka, Norikazu Ito, Minoru Akutsu, Kentaro Chikamatsu, Shinya Takado, and Ken Nakahara

ROHM Co., Ltd.
21, Saiin Mizosaki-cho, Ukyo-ku, Kyoto 615-8585 Japan
Phone: +81-75-321-4318 E-mail: taketoshi.tanaka@dsn.rohm.co.jp

Abstract

A new method is proposed to estimate net acceptor type trap density (N_T-N_D, where N_T is gross acceptor type trap density, and N_D is donor density) in semi-insulating GaN layers widely used as the electron channel layer in AlGaN/GaN HFETs. Current-voltage characteristics obtained from the stacked structure of GaN and AlGaN epitaxially grown on a Si wafer have the multiple thresholds where current exponentially increases. Band diagram simulation reveals that the thresholds relate to N_T-N_D, and thereby the N_T-N_D in GaN and AlGaN films are experimentally determined to be 5.3×10^{16} cm^{-3} and 3.4×10^{17} cm^{-3},respectively.

1. Introduction

The AlGaN/GaN heterojunction field-effect-transistor (HFET) has the high potential in high frequency switching, because of high electron mobility of two dimensional electron gas (2DEG) generated by spontaneous and piezoelectric polarization in AlGaN/GaN combinations. In fact, Kashiwagi *et al*. reported 10-MHz switching of a recessed gate AlGaN/GaN HFET [1].

AlGaN/GaN HFET structures usually include an AlGaN barrier layers epitaxially grown on a GaN layer with high resistivity for 2DEG generation. This GaN layer must be semi-insulting to achieve low parasitic capacitance and low leakage drain current during off state. Epitaxial GaN films are usually unintentionally doped by donors and thus carrier compensation by the kind of acceptor type traps that capture electron is necessary to achieve semi-insulating. In addition, a certain acceptor type trap density (N_T) is reportedly essential to suppress punch-though in short channel [2], while current collapse, a common problem of AlGaN/GaN HFETs, is caused by negatively charged acceptor type traps through hole emission or electron capture [3].

Deep levels in GaN layers have been measured by deep level transient spectroscopy (DLTS) [4] and deep level optical spectroscopy (DOLS) [5]. On the other hand, DLTS cannot deal with semi-insulating layers [6], and DOLS do not measure donor density (N_D) of semi-insulating layers [5]. In addition, many types of impurity and their complexes with defects can be candidates for deep level in GaN, and therefore N_T cannot be determined by impurity density measurement. Accordingly no highly practical and simple method exist to measure net acceptor type trap density, N_T-N_D, in semi-insulating materials.

The team proposes here the measurement procedure to estimate N_T-N_D quantitatively in semi-insulating GaN layers. This method is based on the assumption that the density of negative charges in an electrically biased semi-insulating film originate from N_T-N_D.

2. Simulation and Experiments

The one dimensional simulation were carried out by device simulator, Sentaurus Device from Synopsys Incorporation in this study. N_D and N_T were set in a GaN and AlGaN stacking structure so that N_T was set larger than N_D for reproducing semi-insulating behavior, as shown in Fig.1. N_T-N_D of 3×10^{16} cm^{-3} and 2×10^{17} cm^{-3} were put in GaN and AlGaN layers, respectively. The anode and cathode were put on GaN and AlGaN, respectively. Carbon is one of major candidates for acceptor type traps, and thus we set the energy level of acceptor type trap, E_T, in GaN layer to be 0.9eV above the valence band edge (E_V). However, note that E_T of trap plays no significant role in the following discussion.

Experimental counterparts were prepared that 0.2-μm unintentionally n-type doped AlN nucleation layer, 0.2-μm AlGaN buffer, and 1.5-μm intentionally undoped GaN were sequentially grown by metal organic chemical vapor deposition on a Si substrate. Ti/Al anode were formed on GaN and Al cathode on the backside of a Si wafer. The positive DC were biased to the anode in both simulation and experimental samples.

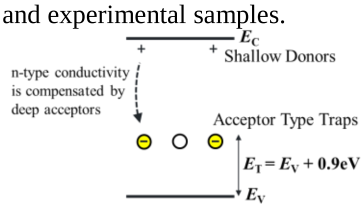


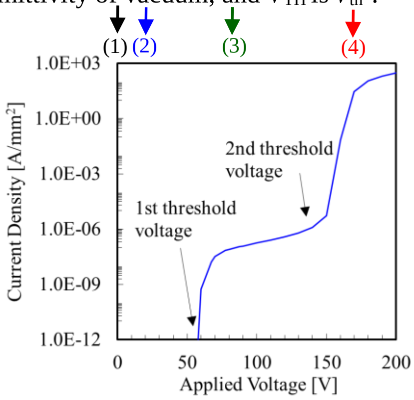
Fig.1 The simulation model of a semi-insulating GaN.

3. Results and Discussion

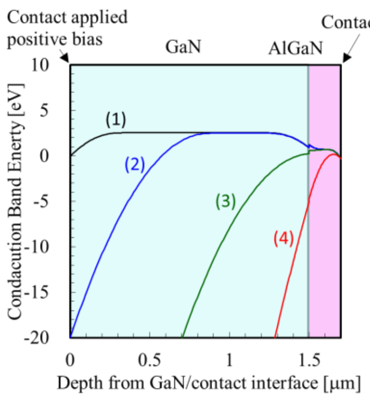
Simulated current-voltage (*I*-*V*) curves exhibit two threshold voltages as shown in Fig.2 (a). The band diagrams in Fig.2 (b) correspond to the *I*-*V* state (1)-(4) in Fig.3 (a). The band bends downward only in the GaN layer below the first threshold voltage (V_{th}^1). The band bending reaches the AlGaN layer just at V_{th}^1 denoting (3), and extends to the other-side contact at the second threshold voltage (V_{th}^2). In the voltage region blow V_{th}^1, no current flows, meaning no mobile electrons, because N_T-N_D in the GaN has a capacity enough to capture electrons. This happens in all volume of the GaN layer, and therefore, assuming that negative charges in the GaN layers only originates from N_T-N_D, this value is given by Poisson's equation

$$N_T - N_D = \frac{2\varepsilon_0 \varepsilon V_{TH}}{qd^2} \qquad (1)$$

where q denotes elementary charge, d the thickness of the GaN layer, ε relative dielectric constant of GaN, ε_0 is permittivity of vacuum, and V_{TH} is V_{th}[1].



(a) Simulated *I-V* characteristics



(b) Conduction band edge bending

Fig.2 *I-V* characteristics and corresponding band diagrams

Our experimental sample produces a very similar *I-V* curve to the one in Fig. 2(a), as shown below in Fig. 3. Eq. (1) determines the N_T-N_D of the GaN layer of the sample to be 5.3×10^{16} cm^{-3}. The same discussion can be applied to the AlGaN layer, and thus N_T-N_D of AlGaN layer are calculated to be 3.4×10^{17} cm^{-3} by V_{th}[2].

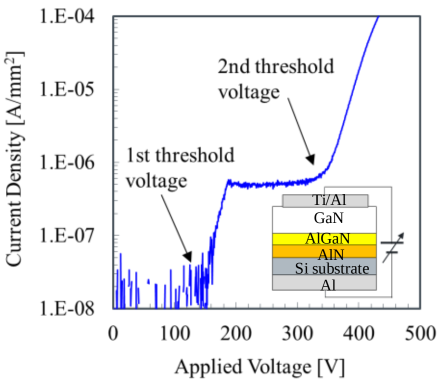


Fig.3 *I-V* characteristics of semi-insulating GaN and AlGaN stacked layers on Si substrate.

Photoluminescence (PL) measurement excited by He-Cd laser was also performed to our AlGaN/GaN samples. Thus, as shown in Fig.4, N_T-N_D calculated by this method clearly correlates to PL strength ratio denoting for YL/NBE, namely yellow luminescence (YL) strength divided by near-band-edge luminescence (NBE) strength. YL generally relates to deep levels in GaN [7], and therefore our proposed method to estimate N_T-N_D provides a simple and practical measure to estimate deep levels.

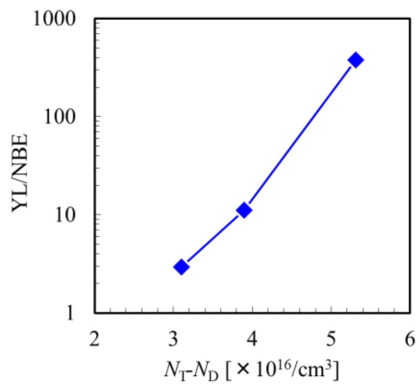


Fig. 3. Correlation between YL / NBL and N_T-N_D calculated by Eq. (1).

4. Conclusion

Band diagram simulation for a AlGaN/GaN stacking structure sandwiched by electrodes reveals that *I-V* curve have current increasing threshold at the voltage determined by N_T-N_D in a semiconductor and its thickness. This means that simple *I-V* measurement can determine N_T-N_D by use of Poisson's equation. Experimental *I-V* curve shows very similar to this simulation one, and N_T-N_D determined by this procedure correlates well to YL/NBE. Therefore our proposed method to estimate N_T-N_D provides another measure to estimate deep levels in semiconductors.

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