INTERFACE ELECTRON TRAPS AND CAPACITANCE CHARACTERISTICS OF ALGAN/GAN

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1. Introduction

HEMT transistors on AlGaN/GaN are still the object of intensive study in recent years. They gave excellent high frequency, high temperature, and high power properties. Its physics and technology is still being developed, but there are, certainly, still question and problems waiting for the solution.

Electron traps and surface states in the structures may have important and detrimental influence on their electrical characteristics. As surface states the states on the AlGaN layer surface are commonly named and on the other hand traps are in the bulk of the semiconductor. Brannick *et al.* [1] studied the traps located at the top of AlGaN layer. The states localized at the AlGaN a GaN layers interface are called interface states. Deep acceptors present in the buffer layer have been found responsible, *e. g.*, for a current collapse in AlGaN/GaN high electron mobility transistors (HEMT) because it is more pronounced when there are deep acceptors present in the buffer layer. It is known from DLTS measurement, that the traps are prevalently located near the AlGaN/GaN interface [2]. Two different deep levels located at AlGaN/GaN interface were observed by deep level optical spectroscopy also by Nakano *et al.* [3]. Interface states at the interface of GaN and AlInN were studied also by photocurrent method. Analysis of frequency dispersion in capacitance and conductance of the AlGaN/GaN structures was used in [4]. There is also the meaning that the interface states and the charge accumulated in these states may cause capacitance hysteresis that is frequently observed in experimental measurement of AlGaN/GaN heterostructures [5]. Fang *et al.* [6] observed hole-like traps at the interface. The continuous distribution of interface states from 56 to 110 meV below the conduction band of GaN has been found and argued that those states are responsible for a gate leakage current. As a reason for their formation, the difference in growth temperatures of 1100 °C and 800 °C for GaN and AlInN, respectively, was supposed.

2. Theory

We simulated the charge transport in heterostructures by well-known drift-diffusion approximation. Continuity equations were solved self-consistently with the Poisson equation and we received the electric potential and the charge concentration in every point of the whole device. The three equations which were solved simultaneously are

$$\Delta\varphi = -(q/\varepsilon_s)(p - n + N_d^+ + N_a^-)$$
$$\frac{\nabla \cdot \mathbf{J}_n}{q} = U, \qquad \mathbf{J}_n = q(-\mu_n n \nabla\varphi + D_n \nabla n) \tag{1}$$
$$\frac{\nabla \cdot \mathbf{J}_p}{q} = -U, \qquad \mathbf{J}_p = q(-\mu_p p \nabla\varphi - D_p \nabla p),$$

where, φ is the electrostatic potential, q is the electronic charge, ε_s is the permittivity of the semiconductor, p and n are the hole and the electron densities, respectively, J_n, J_p are, respectively, the current densities of electrons and holes, μ_n, μ_p, and D_n, D_p are respectively the mobilities and diffusion coefficients, and U is the net recombination rate. Comparing to the semiconductor which has only shallow dopants, in this case where the deep energy levels – traps are present in the structure, we have another source of charge which depends on the position of the Fermi energy that depends vice-versa on the mobile charge doping concentration. It was necessary to include another computing loop to find out the position of the quasi-Fermi energies for electrons and holes since the structure is not in thermodynamic equilibrium by the current flow. The occupancy of the interface trap is determined by probability

$$P(E) = \frac{1}{1 + 2\exp[(E_{DL} - E_{Fn})/kT]}, \tag{2}$$

where E_{DL} is the energy level of the trap, E_{Fn} is the position of the quasi-Fermi level of electron and 2 is the degeneracy factor.

Then equations (1) were discretized and solved by finite difference method using fixed point iteration method [7,8].

We assumed two types of traps, donor-like, which are neutral when occupied and positive if they are empty and also acceptor-like states that are neutral when empty and negative when occupied. Acceptor-like levels are energetically situated in the upper part and donor-like traps in the lower part of the semiconductor energy gap. The traps were simulated both with continuous energy distribution because interface states are commonly assumed to be distributed across the whole energy gap as well as a sharp energy level. The energy distance from the conduction band minimum (CBM) for acceptor levels and from the valence band maximum (VBM) in the case of donor type levels was assumed to be 0.5 eV. Using different deep level energies gave no significant influence on the resulting *C-V* characteristics. Sometimes it is assumed in literature that the interface states are distributed in a special and limited part of the gap.

The AlGaN/GaN structure consisted of 25 nm thick AlGaN barrier layer and 75 nm thick GaN buffer layer. Doping concentration of AlGaN barrier layer was assumed to be $1\text{x}10^{18}$ cm^{-3} and for GaN buffer layer we considered two doping concentrations assumed, $1\text{x}10^{17}$ cm^{-3}, and $1\text{x}10^{16}$ cm^{-3}, the sheet concentration of positive piezoelectric charge at the AlGaN/GaN interface responsible for the 2DEG formation was set to $8\text{x}10^{12}$ cm^{-2}. Schottky barrier height at the metal/AlGaN interface was chosen to be 1.3 V.

Finally we arrived at the charge concentration and the electric potential throughout the whole volume of the structure. If we assume that the mobile charge is able to follow immediately the change of the applied external potential we can calculate the capacitance of the structure as a differential capacitance where dQ is the change of the charge in the structure for two close external voltages differing in dV and it is practically differential capacitance of the structure.

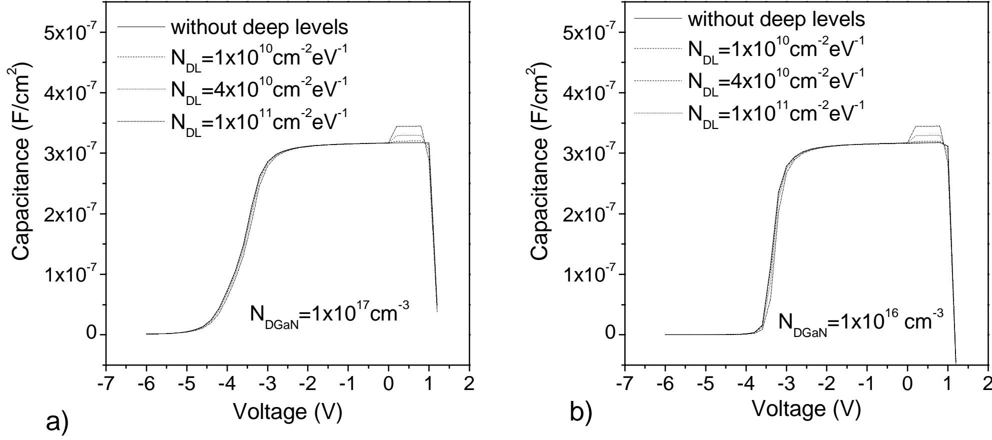

Fig. 1. *C-V characteristic of AlGaN/GaN structure with different concentration of interface traps a) with* $N_{DGaN} = 1x10^{17}\ cm^{-3}$ *and b)* $N_{DGaN} = 1x10^{16}\ cm^{-3}$.

$$C = \frac{dQ}{dV}, \tag{3}$$

The way of capacitance simulation assumes that all mobile charges follow the external signal. The result of our simulation is then so called low frequency capacitance of the structure.

3. Results and discussion

We first assumed in our simulation that there is a continuous distribution of interface states between AlGaN and GaN layers. We used constant distribution of interface states in energy. In order to describe how the doping concentration of GaN layer is related to the deep traps influence on the *C-V* characteristics, we simulated *C-V* curves for two different GaN doping concentrations - 1x10^{17} cm^{-3} and 1x10^{16} cm^{-3}. *C-V* curves for these two doping concentrations of GaN layers and different concentrations of deep levels are in Fig. 1. The difference between the curves is in steepness of the capacitance decrease when GaN starts to be depleted [9]. For lower GaN doping concentration the capacitance decreases more quickly with voltage because of larger thickness of GaN depleted for the same voltage change. Also shift of *C-V* curves towards higher forward voltages is observed and especially for larger traps concentration. Going to forward voltages the electrons emitted from interface states between AlGaN and GaN contribute to the capacitance and the capacitance increases and has a small plateau because the traps are distributed throughout the whole GaN energy gap.

We simulated also the capacitance properties of the structures with traps with sharp energy level. For the donor and also the acceptor levels we assumed the energy distance from the VBM (donor type trap) and CBM (acceptor type trap) edge 0.5 eV. The *C-V* characteristic of the structure with the donor-type trap level is in Fig. 2a. No shift of *C-V* curves has been observed for the structures with different traps density. The reason is that the donor traps are populated in reverse bias and they are electrically neutral in this charge state. The only difference comparing to the structure without interface traps is the capacitance decrease at lower forward voltages for large traps densities.

For the case of acceptor level with activation energy 0.5 eV present in the structure the results are shown in Fig. 2b. We see different influence on *C-V* curves than for the case of the donor type traps. There is a voltage shift to the right of

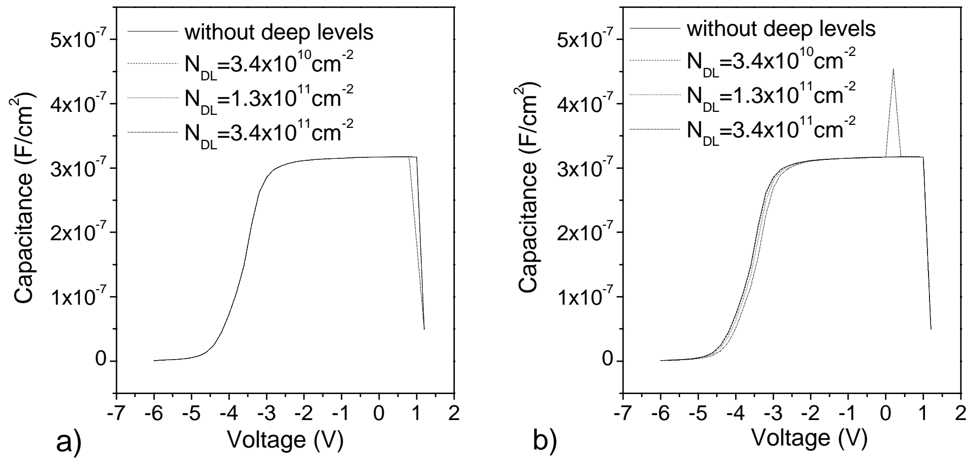

Fig. 2. *C-V characteristic of AlGaN/GaN structure with different concentration of interface donor-like trap a) and acceptor-like trap b) with activation energies 0.5 eV.*

the *C-V* curves for the structures with interface traps. The similar shift has been observed for the structures with donor and acceptor like traps (Fig. 1) and the reason for this shift is again negative charge in populated acceptor traps in reverse bias voltage region. When the energy level is closer to the CBM the capacitance peak shifts to more negative voltages and the peak is higher for the same traps concentration (not shown).

In conclusion we found out that for low frequency measurement the presence of interface states between AlGaN and GaN may be detected by the *C-V* method. The traps at the AlGaN/GaN interface cause the capacitance peaks and voltage shift of the curves towards positive voltages. The higher the density of states the more pronounced the effect is.

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References

[1] A. Brannick, N. A. Zakhleniuk, B. K. Ridley, L. F. Eastman, J. R. Shealy, and W. J. Schaff, *Microelectron. J.* **40,** 410 (2009).
[2] Y. S. Park, M. Lee, K. Jeon, I. T. Yoon, Y. Shon, H. Im, C. J. Park, H. Y. Cho, and M.-S. Han, *Appl. Phys. Lett.* **97** 112110 (2010).
[3] Y. Nakano, Y. Irokawa, and M. Takeguchi, *Appl. Phys. Express* **1** 091101 (2008).
[4] L. Semra, A. Telia, and A. Soltani, *Surf. Interface Anal.* **42** 799 (2010).
[5] L. E. Byrum,, G. Ariyawansa, R. C. Jayasinghe, N. Dietz, A. G. U. Perera, S. G. Matsik, T. Ferguson, A. Bezinger, and H. C. Liu, *J. Appl. Phys.* **105** 023709 (2009).
[6] Z.-Q. Fang, B. Claffin, D. C. Look, D. S. Green, and R. Ventury, *J. Appl. Phys.* **108** (2010) 063706.
[7] I. D. Mayergoyz, *J. Appl. Phys.* 59 195 (1986).
[8] E. Korman and I. D. Mayergoyz, *J. Appl. Phys.* **68** 1324 (1990).
[9] J. Osvald, *J. Appl. Phys.* **106** 013708 (2009).