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Impact of Interface States and Bulk Carrier Lifetime on Photocapacitance of Metal/Insulator/GaN Structure

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1. Introduction

Gallium nitride has recently attracted much attention as a promising material for solar-blind ultraviolet (UV) detectors due to its wide bandgap as well as thermal and chemical stability. The typical structures of photodetectors are photoconductors, Schottky diodes and metal/semiconductor/metal (MSM) structures with photocurrent measurements [1]. Metal/insulator/semiconductor (MIS) structures with capacitance measurements exhibit better thermal stability and lower noise level compared to the devices with Schottky contacts. Therefore, MIS is a good candidate for the UV sensor working at high temperature and in hazardous chemical environment, e.g., as a flame detector [2].

The electronic states, which exist at the insulator/semiconductor interface in the MIS structure, are known to be the reasons of many undesirable effects in photoelectronic devices, e.g., non-radiative interface recombination, Fermi level pinning, new defect formation and consequently the deterioration of the device performance. Thus, it is necessary to clarify the role of the interface states in MIS-based photodetector operation.

Therefore, in this work, we have calculated the dependencies of the capacitance of the metal/insulator/GaN structure versus the UV light intensity and versus the gate voltage and studied theoretically the impact of the interface states and quality of bulk GaN (in terms of carrier lifetime) on these characteristics.

2. Model and Calculation Method

Calculations have been performed for a one-dimensional model of the metal/AlO_x/GaN device with the AlO_x layer thickness of 63 nm and relative permittivity of 8 (like in [2]) and 1 mm thick n-GaN layer doped at the level of 5×10^{15} cm^{-3} (Fig. 1a). The insulator has been assumed to be ideal, i.e. there has been no leakage current in the structure.

The standard drift-diffusion model has been applied with the boundary conditions determined by the gate voltage (V_G) at the metal gate, the charge at the AlO_x/GaN interface and zero potential at the ohmic contact at the back surface of the GaN layer as well as the interface recombination. The interface state density distribution, $D_{it}(E)$, has been assumed to be U-shaped according to the disorder induced gap state (DIGS) model [3] (Fig. 1b).

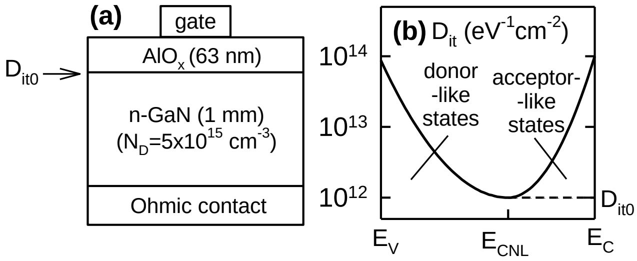

Fig. 1 (a) Model MIS structure and (b) interface state density distribution, $D_{it}(E)$, used in the calculations. E_{CNL} denotes the charge neutrality level at 1.1 eV below E_C in GaN

The model sample has been illuminated from the gate side by monochromatic light with a wavelength of 300 nm. The metal and insulator layers have been assumed to be transparent to the light which is absorbed in the GaN layer due to electron-hole pair generation. In the GaN bulk, we have taken into account band-to-band, Shockley-Read-Hall (SRH) and Auger recombination processes.

The model equations have been solved by finite element method (FEM) using COMSOL Multiphysics package. The GaN layer has been divided into about 1,000 mesh elements. The mesh has been very fine at the insulator/GaN interface and coarse in the bulk. The drift-diffusion model equations have been transformed to the form with quasi-Fermi potentials as dependent variables instead of electron and hole densities. This transformation is crucial to obtain the convergence in the solution process. During the FEM calculations, the iterative solver using the flexible generalized minimum residual method has been used. We have obtained good convergence and the relative error of about 10^{-6}.

After solving the model equations, the differential capacitance of the structure and then the photocapacitance, ΔC, i.e. the difference between the capacitance of the device under illumination and the capacitance in the dark, have been computed. The photocapacitance calculation has been performed for V_G from –0.1 to –3 V, excitation light intensity (in terms of photon flux density), Φ, from 10^{10} to 10^{20} photon cm^{-2} s^{-1}, for the minimum interface state density D_{it0} = 0, 10^{11} and 10^{12} eV^{-1} cm^{-2}, and carrier lifetime due to SRH recombination, $\tau_{SRH} = 10^{-7}$, 10^{-8} and 10^{-9} s.

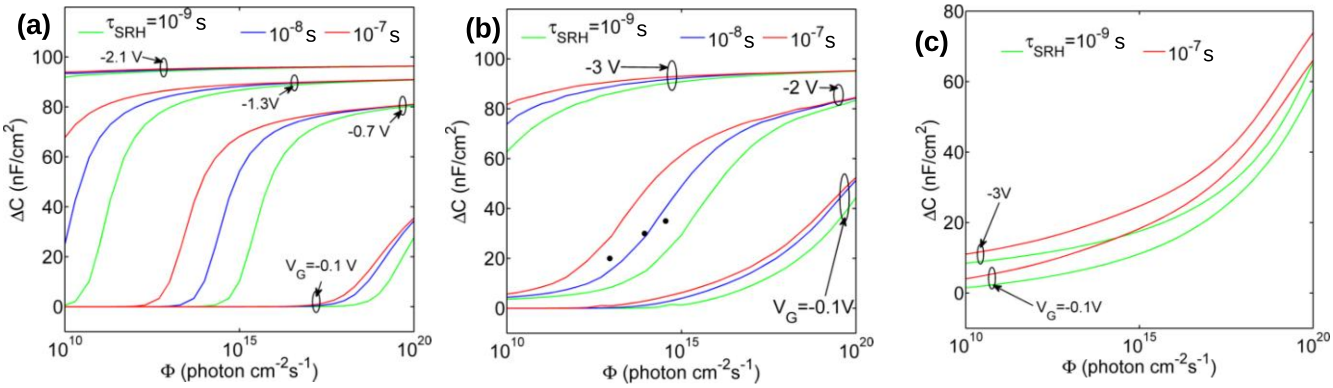

Fig. 2 The calculated dependencies of photocapacitance, ΔC, versus excitation light intensity, Φ, for some values of gate bias, V_G, and carrier lifetime, τ_{SRH}, in the MIS structures (a) without interface states ($D_{it} = 0$), (b) with $D_{it0} = 10^{11}$ and (c) with $D_{it0} = 10^{12}$ eV^{-1}cm^{-2}. The assumed $D_{it}(E)$ distribution was like in Fig. 1b. The experimental data after [2] are shown as black dots in Fig. 2b.

3. Calculation Results and Discussion

The Ideal MIS Structure

Figure 2a presents the $\Delta C(\Phi)$ characteristics for some values of V_G and of τ_{SRH} calculated for the MIS structure without states at AlO_x/GaN interface. The shape of $\Delta C(\Phi)$ is S-like: ΔC is close to zero at low values of Φ, then it increases for moderate Φ and saturates for high Φ. The boundary between the first and the second region can be adjusted by V_G but the slope of $\Delta C(\Phi)$ in the second region seems to be independent of V_G and of τ_{SRH}. On the other hand, for the fixed values of V_G and Φ the ΔC signal is higher for longer τ_{SRH}, especially when $V_G \approx -0.7$ V and $\Phi \approx 10^{14}$ photon cm^{-2} s^{-1}. These features are interesting from the viewpoint of photodetector applications. $\Delta C(\Phi)$ dependence is not linear, even in a narrow range of Φ. Therefore, the MIS-based photodetector should be carefully calibrated if the precise quantitative measurements are necessary.

The Influence of Interface States

The $\Delta C(\Phi)$ characteristics for several values of V_G and τ_{SRH} computed in the structure with a slightly disordered ($D_{it0} = 10^{11}$) and highly disordered ($D_{it0} = 10^{12}$ eV^{-1} cm^{-2}) interface are shown in Figs. 2b and 2c, respectively. The general shape of the curves is retained but the interface states decrease the slope of $\Delta C(\Phi)$ curves in their second region and reduce the ΔC values for the same Φ and V_G as compared to those ones in the ideal MIS structure (Fig. 2a). Another problem is a smaller sensitivity of $\Delta C(\Phi)$ curves to V_G value. One can notice that the region occupied by $\Delta C(\Phi)$ curves for V_G from –0.1 to –2 V is much smaller in Figs. 2b and 2c than in Fig. 2a. Both effects are undesirable from the viewpoint of photodetector application.

The reasons of these problems are the screening of the gate field by the charge in the interface states and the interface recombination of electron-hole pairs. The former phenomenon decreases the control of electron-hole separation in the interface region, the latter directly reduces carrier concentration and thus photocapacitance.

Furthermore, if the interface states exist, the increase in ΔC signal due to τ_{SRH} extension is much smaller than in the case of the ideal MIS structure. Therefore, the passivation of the insulator/GaN interface is more important than improvement of bulk GaN quality in terms of τ_{SRH}.

4. Comparison with Experimental Data

In Fig, 2b, the calculation results have been compared qualitatively with the measurements of a fabricated metal/AlO_x/GaN device [2] with the same AlO_x thickness and n-GaN doping level as in the model structure. The experimentally observed dependence of ΔC versus V_G and Φ is consistent with our theoretical predictions and ΔC experimental values are in the same order of magnitude as theoretical ones.

5. Conclusions

The illuminated metal/AlO_x/GaN structure was studied by numerical solving of drift-diffusion model equations using FEM taking into account the electronic states at the insulator/GaN interface and SRH recombination in the bulk GaN. It was shown that the dependencies of the photocapacitance versus excitation light intensity exhibit S-like shape and can be adjusted by the gate voltage. The interface states decrease the slope of $\Delta C(\Phi)$ curves and ΔC values as well as reduce the possibility of the characteristics adjustment by V_G. The impact of bulk carrier lifetime is not so critical. Thus, the interface passivation is crucial for the optimization of the MIS-based UV photodetector performance.

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