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INVESTIGATION OF TRAPS IN AlGaN/GaN HETEROSTRUCTURES BY ULTRASONIC VIBRATIONS

A method of dynamic deformations has been proposed as a useful informative tool in the characterization of transportation properties of a two-dimensional electron gas (2DEG) in AlGaN/GaN heterostructures. It is found that the exposing of a sample to ultrasonic vibrations results in the persistent acousto-conductivity (PAC) which was observed up to room temperatures. The PAC behaves itself like persistent photoconductivity (PPC), and the carrier density in the 2DEG channel is primarily contributed by the transfer of electrons excited from traps (like DX centers) as a result of their reconstruction under the ultrasonic loading.

Keywords: electronic transport, heterostructure, 2DEG, gallium nitride, ultrasound.

1. Introduction

The properties of a two-dimensional electron gas (2DEG) at the AlGaN/GaN interface are currently intensively studied because of the great potential of GaN-based devices for electronic [high-electron-mobility transistors (HEMTs)] [1] as well as optoelectronic [lasers and light emitting diodes (LEDs)] applications [2]. AlGaN/GaN-based HEMTs are promising for high-voltage, high-frequency and high-power applications [3, 4]. The impressive intrinsic material parameters favor their operation under extreme conditions. It has been shown that, as a result of the interfacial charge induced by the piezoelectric and pyroelectric effects in this material system, the concentration of electrons in 2DEG can be controlled by the thickness and Al content of the AlGaN layer grown on the (0001) GaN surface, without the need for the modulation doping [5].

In spite of these advantages, the GaN HEMT technology still faces various reliability issues. One such major reliability issue detrimental to the device operation is the electron trapping phenomenon [6]. The trapping of electrons in these devices leads to the current dispersion or current collapse, when the devices are operating at high voltages [7]. These traps are found on the surface of the HEMT structure or distributed within AlGaN barrier or GaN buffer regions [8]. Though a significant progress has been achieved in the growth and fabrication technology, the occurrence of traps in GaN HEMTs still persists. Various reports suggest that traps could also be created, when the devices operate at high temperatures and high voltages over a long period of time. Moreover, the high-temperature conductivity in AlGaN/GaN heterostructures can involve a contribution from different conductivity channels, and the particular attention has to be given to the proper determination of the electron mobility and concentration in the 2DEG region in order to eliminate the possible influence of a parallel conduction. Indeed, in most papers, no temperature dependence of the 2DEG sheet density is observed below 100 K, which is consistent with the conduction dominated by the 2DEG, while the apparent increase of the electron concentration at higher temperatures suggests the involvement of an additional 3D conductivity channel in the 100–300 K interval or the manifestation of trapping/retrapping processes [9].

For realizing a reliable AlGaN/GaN HEMT technology, it is necessary to have a systematic understanding of trapping effects in GaN HEMTs. Here, we will present the results of controllable changes in the mobility and carrier concentration under ultrasonic treatment. In addition, the role of electrically active traps in the electron transport is discussed.

2. Experiment

The structure under study was grown by the metalorganic chemical vapor deposition (MOCVD). An

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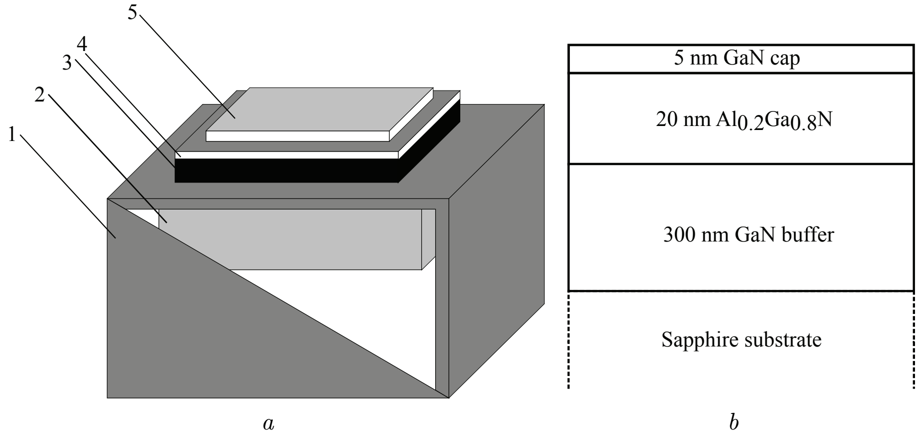

Fig. 1. Experiment setup (*a*) and sample layout (*b*). Shield case (*1*), piezoelectric converter (*2*), acoustic medium (metal plate) (*3*), mica foil substrate (*4*), sample (*5*)

unintentionally doped sapphire wafer was used as a substrate for the growth of the HEMT heterostructure consisting of a GaN buffer layer (300 nm), $Al_{0.2}Ga_{0.8}N$ barrier layer (20 nm), and GaN cap layer (5 nm). The structure was investigated with the high-resolution X-ray diffraction (HRXRD) using a PANalytical X'Pert Pro MRD XL diffractometer equipped with the $CuK_{\alpha 1}$ radiation ($\lambda = 0.154056$ nm), four-bounce (220) Ge monochromator, and three-fold (220) Ge analyzer.

In order to characterize the layers, we applied the Hall effect under the van der Pauw configuration was performed using indium contacts annealed at 450 °C placed at the four corners of a square (6×6 mm^2). The experiments have been conducted in a magnetic field of 0.47 T and in the temperature interval of 80 to 315 K.

In the study, we used the dynamic deformations method in which ultrasonic vibrations with a tunable frequency and adjustable amplitude were applied to the structure wafer. Ultrasonic vibrations are generated in the wafer using an external $LiNbO_3$ piezoelectric transducer. The vibrations propagate into the wafer from the transducer and form quasistanding acoustic waves at the resonance frequency. A longitudinal acoustic wave propagates along the piezoactive [0001] direction. The specific power introduced into the sample equals $P_{us} \sim 10^4$ W/m^2 at a voltage of 15 V applied to a transducer that corresponds to a deformation in the acoustic wave $\epsilon_{us} = (2P_{us}/\rho v^3)^{1/2} \sim \sim 10^{-6}$ and strain of $\tau_{us} = (2\rho v P_{us})^{1/2} \sim 10^6$ N/m^2, where ρ and v are the density and sound velocity, respectively. A thermoelectric cooler was used to stabilize the temperature under applied voltage. The scheme of the packaged AlGaN/GaN HEMT mounted on an acoustic unit is shown in Fig. 1, *a*. The scheme of a sample is shown in Fig. 1, *b*.

3. Results and Discussion

The temperature dependences of the carrier density and mobility for our sample with and without the exposure to ultrasound are shown in Figs. 2 and 3. To prevent the influence of the ambient illumination, all data are collected in the dark. First, let us look at the data obtained without ultrasound. The mobility decreases with increasing the temperature in a high temperature range and is nearly constant at low temperatures. This behavior is typical of 2DEG. At the same time, the sheet carrier concentration measured at low temperatures is higher than that calculated for a specific AlGaN/GaN interface [5]. A deviation of the measured sheet carrier concentration due to the Hall effect from the calculated values can be caused by the free carrier concentration in the GaN buffer layer, as well as the existence of traps in the barrier [10, 11]. The latter is confirmed by increasing the carrier concentration in the high temperature range. Possible positions of the traps are shown on the schematic diagram of the conduction band profile for the sample under study presented in Fig. 4. For simulating the band structure and energy levels, we used the nextnano software [12].

To verify the hypothesis of the effect of a charged trap density in the AlGaN barrier layer and GaN

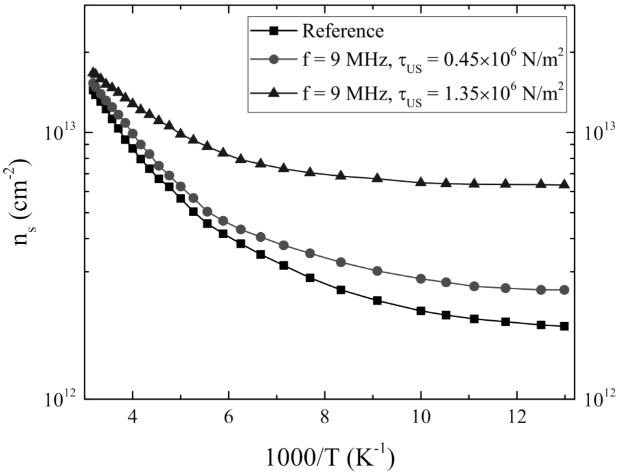

Fig. 2. Sheet carrier density versus 1000/T measured with the van der Pauw method

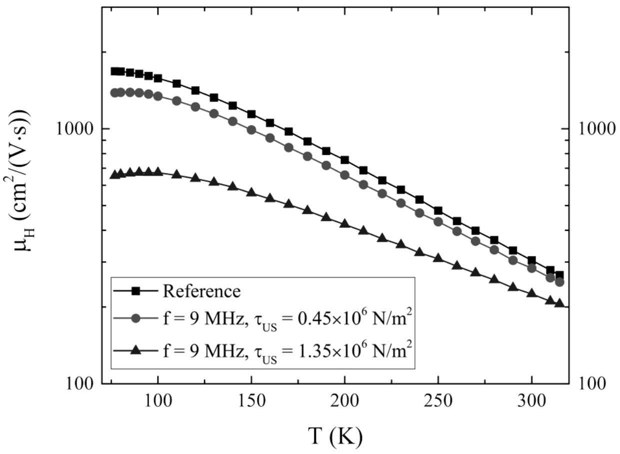

Fig. 3. Hall mobility versus temperature measured with the van der Pauw method

channel layer on the carrier concentration in the 2DEG channel, the method of dynamic deformations was used. The exposure of the sample to ultrasonic vibrations leads to increasing the carrier concentration at low temperatures and decreasing the slope at high temperatures. The increase in the carrier density is accompanied by a decrease in the mobility. The observed changes in the carrier concentration and mobility are intensified with enhancing the power introduced into the sample. Changes in the mobility can be explained as follows. As the 2DEG density increases, the charge distribution centroid moves toward the interface. This, of course, would result in an increase in the interface roughness scattering. Another scattering mechanism that should decrease the mobility in our sample is the alloy disorder scattering. Indeed, since the carrier concentration is too high, the wave function penetrates into the AlGaN barrier, and the scattering due to an alloy disorder should be taken into account. Both scattering mechanisms will result in a decrease of the mobility. In general, our results agree with the previously reported study of the 2DEG mobility as a function of the 2DEG density [13, 14].

Nevertheless, the question is still open: what is the cause for the high 2DEG density in our sample? To elucidate this point, we investigated the tran-

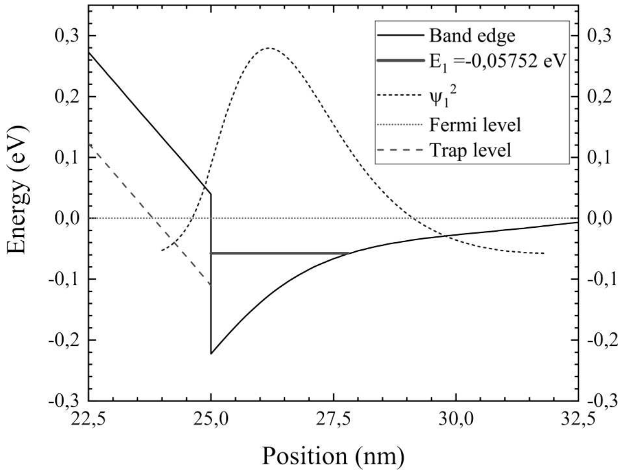

Fig. 4. Schematic band structure of the sample

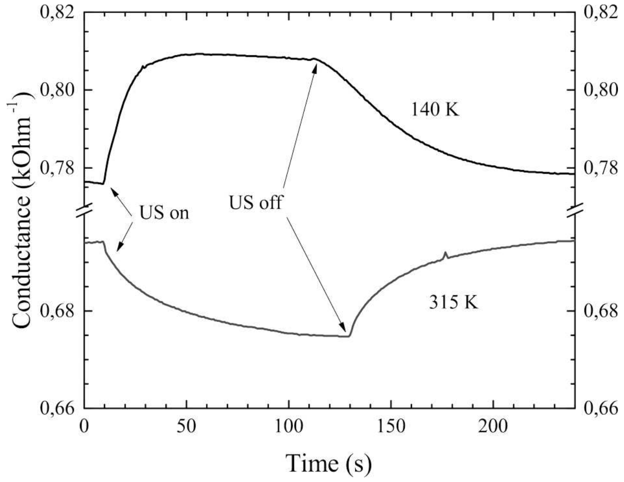

Fig. 5. Time-dependence of the conductance after the application of ultrasound at 140 and 315 K. The applied strain is 1.35×10^6 N/m^2

sient behavior of the conductivity induced by ultrasonic vibrations. We observed that the conductivity in the 2DEG channel at the AlGaN/GaN interface is extremely sensitive to ultrasound. As shown in Fig. 5, the acousto-induced changes in the conductivity persist for a long time after the removal of ultrasound. Changes in the conductivity depend on two parameters ($\Delta\sigma = \Delta n \Delta\mu$). When ultrasound is switched on, the concentration of free carriers increases ($\Delta n > 0$), while the mobility decreases ($\Delta\mu < 0$). At different temperatures, the dominating parameter will determine changes in conductivity: increasing ($T = 140$ K) or decreasing ($T = 315$ K). Thus,the persistent acousto-conductivity (PAC) behaves itself like the persistent photoconductivity (PPC), and the carrier density in the 2DEG channel is primarily contributed by the transfer of electrons excited from traps (like DX centers) as a result of their reconstruction under the ultrasonic loading. The latter is confirmed by the X-ray diffraction measurements of lattice strains presented in Fig. 6. In Fig. 6, the relative changes in the strain due to the ultrasound loading are shown. The lattice parameter c was obtained from high-resolution XRD spectra of the (0004) GaN reflection.

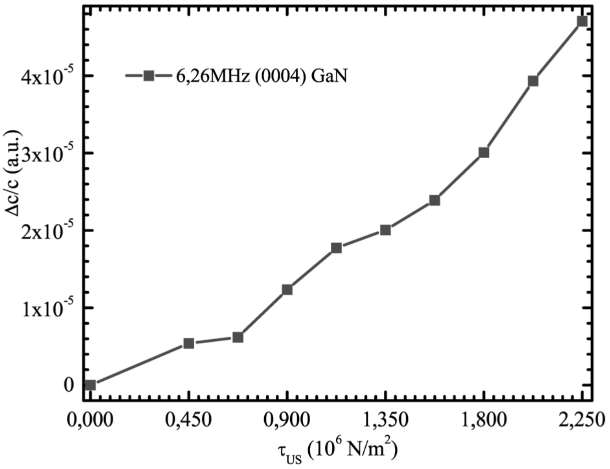

Fig. 6. Dependence of the strain in the GaN layer on the voltage on a $LiNbO_3$ piezoelectric transducer

The lattice parameter increases with the voltage on a transducer. It should be noted that a change in a strain would also lead to a change in the piezoelectric polarization and, therefore, in the 2DEG density. But, in our case, this item is not significant and can be omitted. According to Chadi–Chang model [15], the DX-center is a center with a negative correlation energy. The reaction representing the emptying of a DX-center in this model can be written as $d^+ + DX^- \rightarrow 2d^+ + 2e^-$, where d^+ are positively charged donors, DX^- is a negatively charged DX-center, and e^- are electrons promoted from the DX-center to the conduction band. When the DX centers are emptied, the lattice strain caused by local bonding changes may occur [16, 17] that we observe in the experiment. The result is in agreement with the 0.16 eV energy band of the electrically active traps in the AlGaN barrier identified in the analysis of PAC transients at various temperatures. The physical origin of these traps is still being investigated, but, most probably, it could be caused by defects related to oxygen [18, 19] or alloy fluctuations [20]. It should be emphasized that the transfer energy of elastic vibrations to the high-frequency modes of point defects can occurs with the assistance of dislocations only. The dislocation density estimated for our structure is 10^{10} cm^{-2} that one close to an equivalent volume trap density of 10^{16}–10^{17} cm^{-3}. This fact provides the efficiency of the method of dynamic deformations for the investigation of defects.

4. Conclusions

In summary, we have investigated the effect of ultrasound vibrations on the transport characteristics of the AlGaN/GaN heterostructure. We have found that exposing the sample to ultrasonic vibrations resulted in the acousto-conductivity that was persistent up to room temperatures. We have demonstrated that the observed PAC transient characteristics are correlated with the PPC effect caused by deep level impurities. We believe that the method of dynamic deformations should be a useful informative tool in the characterization of transport properties of the two-dimensional electron gas in AlGaN/GaN heterostructures.

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ДОСЛІДЖЕННЯ ПАСТОК В ГЕТЕРОСТРУКТУРАХ AlGaN/GaN УЛЬТРАЗВУКОВИМИ КОЛИВАННЯМИ

Метод динамічних деформацій пропонується як корисний та інформативний інструмент для опису властивостей транспорту двовимірного електронного газу (2DEG) в гетероструктурах AlGaN/GaN. Виявлено, що прикладання ультразвукових коливань до зразка приводить до стійкої звукопровідності (СЗП), яка зберігається аж до кімнатної температури. Поведінка СЗП подібна до стійкої фотопровідності, і основним внеском у густину носіїв заряду в каналі 2DEG є перехід збуджених електронів із пасток (подібно до DX центрів), що є результатом їх перебудови під впливом ультразвукового навантаження.

Ключові слова: електронний транспорт, гетероструктура, двовимірний електронний газ (2DEG), нітрид галію, ультразвук.