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Nonvolatile gate effect in the PZT/AlGaN/GaN heterostructure

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Abstract

Field effect devices with ferroelectric gates can be a valuable alternative to existing ferroelectric capacitor memories combining random access, high speed, low power, non-destructive reading, and non-volatility. However, integrating the ferroelectric oxides with the semiconductor media presents a complicated issue impeding the progress in the field. AlGaN/GaN heterostructures offer a promising solution for the ferroelectric gate integration because of good chemical and thermal stability and possibility to fabricate structures with two-dimensional electron gas (2DEG) as close to the interface as 15–20 nm. In the present work we report on successful fabrication of the PZT/AlGaN/GaN heterostructure and demonstrate the possibility to modulate resistance of the 2DEG at the AlGaN/GaN interface using the ferroelectric gate. The effect of polarization reversal of 2DEG provoke a reversible non-volatile change in the resistance of 2DEG. These results suggest that ferroelectric gates integrated into GaN-based heterostructures may be potentially interesting for non-volatile memories with non-destructive reading operating in a wide temperature range.

Keywords: Interfaces; Electrical properties; Electrical conductivity; Piezoelectric properties; PZT

1. Introduction

Ferroelectric materials possess spontaneous polarization that can be switched by an external electric field. This property is employed in a number of applications including ferroelectric capacitors used for non-volatile ferroelectric random access memories (FRAM).[1] The non-destructive read operation of FeFET devices presents a significant advantage over conventional FRAM. However, difficulties with integration of the ferroelectric materials into the silicon-based systems severely limit the progress in this field. In this context, selection of the appropriate semiconductor material compatible with the high-temperature processes used for ferroelectrics is an important issue for development of devices of this kind.

AlGaN/GaN heterostructures have been intensively studied over last decade in for high-temperature and high-power electronic applications look to be promising candidates for integrated ferroelectric/semiconductor devices because of the high thermal and chemical stability. Recent reports on the successful deposition of $Pb(Zr,Ti)O_3$ (PZT)[2–5] and $BaTiO_3$[6] ferroelectric layers on GaN demonstrate the good potential of this approach. A multilayer structure comprising a layer of PZT deposited on top of the GaN/AlGaN heterostructure with 2D electron gas (2D gas) showed a hysteretic capacitance–voltage characteristic.[5] This effect was interpreted in terms of influence of the spontaneous polarization in the ferroelectric layer on the carrier concentration in 2D gas suggesting the possibility to use the system for nonvolatile memories. Only in 2006 first direct evidence of the control of the transport properties in the GaN/AlGaN hetrostructures by switching polarization in the ferroelectric gate have appeared in press.[7,8] There are several difficulties impeding the possibility of direct observation of the gate effect in the ferroelectric/semiconductor heterostructures. Most importantly the polarization retention in the ferroelectric/semiconductor sandwich is typically rather poor so that the poled state in the ferroelectric is destroyed in many cases within some hours or even faster. The reason for this is the incomplete compensation of the bound charge associated with switched polarization in the gate and the depolarization field arising due to this effect. Secondly, the 2D gas needs to be located rather close to the semiconductor/ferroelectric interface, otherwise the bound charge of ferroelectric polarization can be compensated by the charge of the opposite sign in the semiconductor without impacting the properties of 2D gas. On the other hand, direct growth of PZT on the GaN surface results in a noticeable diffusion of oxygen and other elements,[2,9] which may destroy

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the 2D gas if it is situated too close to the interface. The solutions evoked in order to avoid the interdiffusion between PZT and GaN involve either the use of the buffer layer like MgO[9] or use of relatively thick AlGaN layer in order to increase the distance between the 2D gas and the interface.[5] Unfortunately, both of these solutions could make it rather difficult to observe ferroelectric-gate-controlled change of conduction in the 2D gas.

In this work we directly demonstrate the operation of the ferroelectric gate in the PZT/AlGaN/GaN system, where the transport properties of the 2D gas are modified by re-orienting the spontaneous polarization in the gate.

2. Experimental

For this experiment we used the $Al_{0.3}Ga_{0.7}N$/GaN heterostructure grown by CREE on the sapphire substrate, with a 2D gas located 20 nm below the interface. A $Pb(Zr_{0.4},Ti_{0.6})O_3$ ferroelectric film with a thickness of 130 nm was deposited by magnetron sputtering.[10] During the deposition the temperature of the substrate was kept below 600 °C in order to limit the interdiffusion between PZT and GaN. The topography image of the grown textured polycrystalline PZT film showed grain size of 50–100 nm with roughness of 10–15 nm. The X-ray diffraction pattern revealed strongly preferential 111-orientation with no presence of secondary phases, such as pyrochlore.

For the electrical measurements, Hall bar mesas with active area 50 μm × 200 μm covered by the ferroelectric layer were patterned by electron cyclotron resonance reactive ion etching[11] with the depth of pattern of 500–600 nm, which was sufficient to completely eliminate the parallel conduction. Multilayered Ti/Al/Ti/Au ohmic contacts[12] were deposited by electron beam and resistance heated evaporation without any subsequent thermal annealing. The sheet resistance, R_s, of the 2D gas was measured on the Hall bars using the standard technique with Keithley 230 current source and Keithley 6517A electrometer. The electron concentration, n_s, in the 2D gas was determined through the Hall effect measurements in the moderate magnetic field of 0.385 T and in high field of 12 T. Conduction measurements were performed in a temperature range of 12–300 K using the closed-cycle helium cryostat (Helix Technology Corporation).

To pole the PZT gate a rather high voltage of 50 V was applied to the conductive cantilever of the CP-Research scanning probe microscope (SPM). The squares of 50 μm × 50 μm were scanned consequently at the rate of 0.1 Hz in order to cover the total area of the gate (Fig. 1). Poling the ferroelectric gate by applying a negative bias to the SPM cantilever is expected to at least partially deplete the 2D gas. The capability of poling the PZT ferroelectric gate was controlled by monitoring the phase of local piezoelectric response using a standard SPM technique described elsewhere.[13] These measurements showed that poling with a negative voltage applied to the cantilever induced a preferential bottom-to-top oriented spontaneous polarization, whereas poling with the voltage of positive polarity provoked a random polarization distribution similar to that observed on an as-deposited PZT film.

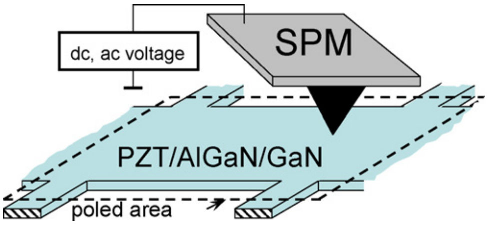

Fig. 1. Sketch of poling and measuring procedure using a Hall bar fabricated on PZT/AlGaN/GaN heterostucture.

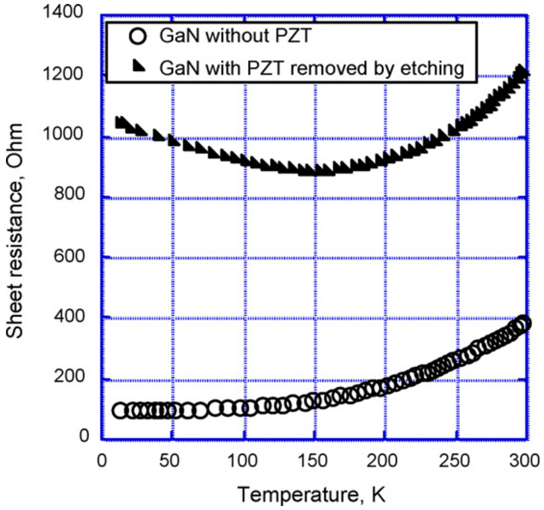

Fig. 2. Sheet resistance of the AlGaN/GaN heterostructure before and after PZT deposition.

The non-volatile gate effect was studied on the PZT/AlGaN/GaN heterostructure using the following procedure. First, the Hall bar with PZT as-deposited was measured in the entire temperature range in order to determine R_s and n_s and calculate the electron mobility μ. Then the entire gate was poled with the negative bias applied to the tip and the same measurements were repeated. In the next step, the gate was poled in the opposite direction and the transport properties were measured again. Finally, PZT was removed by chemical etching and the same measurement was repeated. Additionally, for comparison purposes R_s and n_s were measured on the virgin AlGaN/GaN sample without any PZT deposited on it.

3. Results and discussion

The virgin AlGaN/GaN sample without PZT deposited on it showed a behavior typical for this kind of 2D gas structure where R_s monotonically decreases with temperature (Fig. 2). In order to examine a possible impact of the PZT deposition on 2D gas properties these results were compared with the sample where PZT was deposited and subsequently removed by chemical etching. Fig. 2 shows that for the sample with removed PZT R_s is larger by factor 3–5 compared to the virgin AlGaN/GaN sample. This degradation of 2D gas is presumably provoked by the interdiffusion of the elements from PZT and AlGaN causing the defect formation at the AlGaN/GaN interface region. Nevertheless, the 2D gas was not completely destroyed and remained

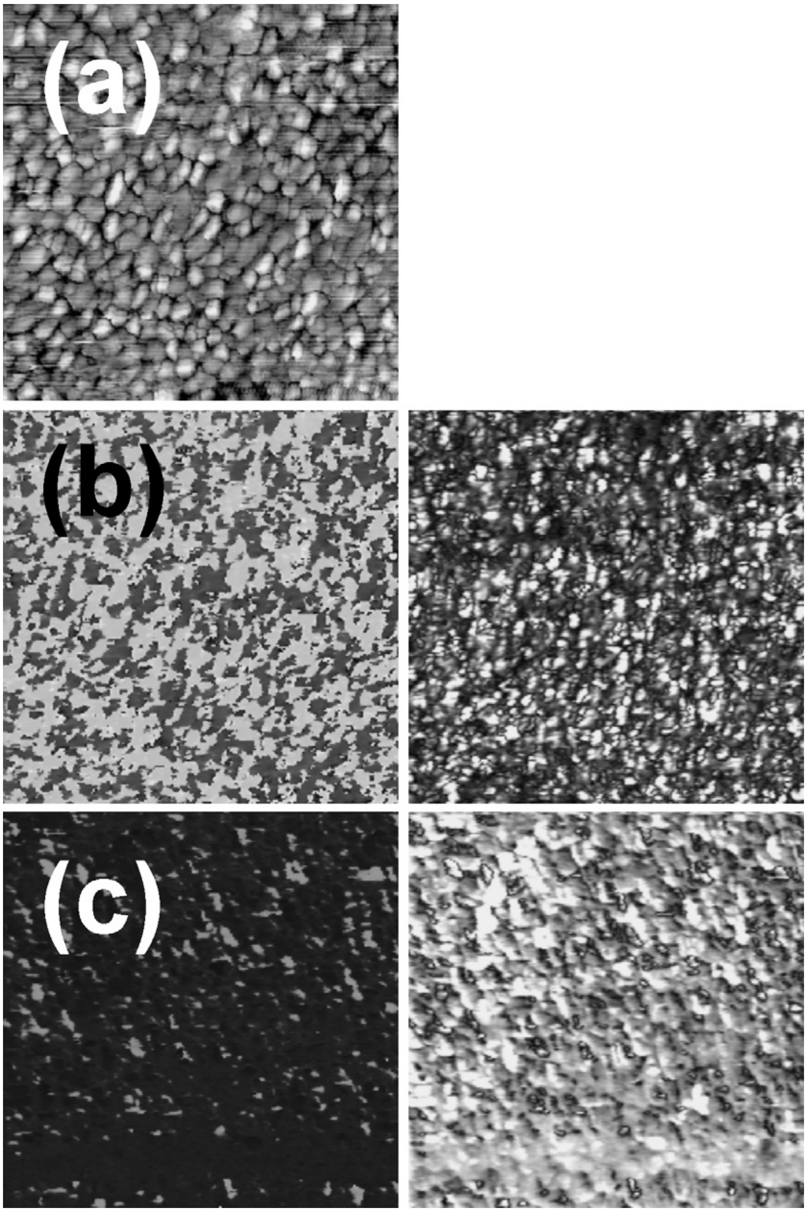

Fig. 3. 2 μm × 2 μm scans representing PZT topography (a), phase ((b) and (c), left) and amplitude ((b) and (c), right) of local piezoelectric response; (b) shows the piezoelectric activity of the PZT film before poling and (c) after poling with −50 V.

suitable for the transport experiments. The resistance decreased with temperature down to 120 K as expected. At lower temperature this trend is inversed because of a slight decrease of the electron concentration.

To explore the possibility of switching the polarization in the ferroelectric gate we collected the amplitude and phase maps of local piezoelectric response (Fig. 3). The results show that the non-poled PZT film has a random polarization domain pattern, whereas the negative voltage applied to the SPM tip induces preferential bottom-to-top orientation of the spontaneous polarization, which is expected to deplete at least partially the 2D gas. This measurement was performed about 1 h after termination of the poling treatment. The white spots in phase image indicate the areas where the polarization is back-switched to the opposite direction due to the depolarization effects. Poling of the PZT ferroelectric gate with a bias of positive polarity resulted in a random domain pattern similar to that observed for the as-deposited PZT.

The major result of this work is the reversible change of conduction of 2D gas by switching the gate polarization. Poling the gate with negative voltage resulted in a decrease in R_s by a factor 2.5–3 (Fig. 4). After erasing this poled state by applying a positive voltage the initial conduction was restored. Combined Hall effect and conductivity measurements show that not only n_s but also the mobility μ decreases as a result of the gate poling. The decrease in mobility can be explained either by the change of shape of the potential barrier confining the 2D gas and/or by the strongly nonuniform domain pattern in the poled gate. This non-homogeneity of the spontaneous polarization may result in a non-uniform depletion profile, which reduces the electron

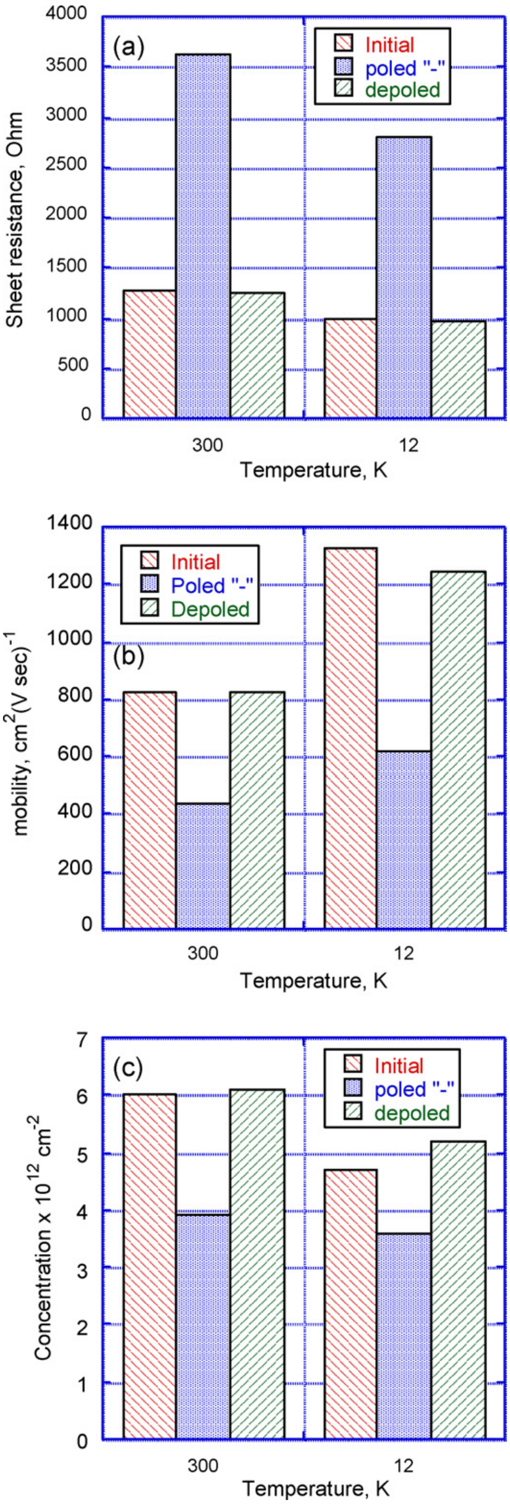

Fig. 4. Sheet resistance (a), mobility (b) and concentration (c) of electrons in 2D gas in the PZT/AlGaN/GaN structure, for as-deposited PZT, PZT poled with −50 V applied to SPM cantilever and PZT depoled by applying +50 V.

mobility. After erasing the poled state both n_s and μ are nearly completely restored (Fig. 4).

The effect of depletion observed in this experiment is much weaker that one may expect according to the charge associated with the spontaneous polarization. Indeed, the carrier density of 10^{13} cm^{-2} in the 2D gas corresponds to a charge density of 1.6 μC/cm^2, whereas the remnant polarization in PZT is normally about 20 μC/cm^2. However, the situation where the remnant polarization is completely screened by the charge of opposite sign located at a distance of 20 nm from the interface is unrealistic, because in that case the depolarization electric field is prohibitively so high that it would depole the PZT completely.[14] In reality, the more realistic scenario is that more than 90% of the polarization is compensated in a much thinner layer close to the PZT/AlGaN interface and the remaining charge is distributed within a relatively wide region including the AlGaN/GaN junction with 2D gas. It may be possible to reach a stronger depletion effect by optimizing the PZT deposition process in a way to reduce the inter-diffusion that enhances formation of charged defects. Additionally, a ferroelectric layer with a higher quality interface may provide a more uniform polarization pattern with better retention, which could also contribute to a stronger depletion effect.

Poling the gate with the positive voltage of +50 V was not successful and the resulting polarization distribution was random similar to the as-deposited PZT. The conduction of 2D gas remained virtually the same as for the PZT before poling (Fig. 2b). Removal of the PZT by chemical etching provoked a small change in the conduction properties of 2D gas (Fig. 2a).

4. Conclusion

To summarize, the ferroelectric gate operation in the PZT/AlGaN/GaN system has been directly demonstrated. A poled PZT gate was shown to induce a partial depletion effect in 2D gas reducing its conductivity by factor 2.5–3. This effect was erased by depoling the PZT gate. On the other hand, some important issues still have to be resolved before the PZT/AlGaN/GaN system becomes suitable for the ferroelectric FETs. In particular, the PZT deposition process needs to be optimized in order to reduce the interdiffusion that provokes degradation of 2D gas and probably deteriorates PZT retention. With improved quality of PZT and optimized poling procedure one may expect stronger depletion effect than that obtained in the present work. Apart from ferroelectric FETs the PZT/AlGaN/GaN system may be of interest for making nanopatterns in 2D gas by ferroelectric domain engineering. Earlier local domain writing was proposed for projection of the artificial domain patterns onto the metallic $SrRuO_3$ layer.[15] In a similar way, direct domain writing on the gate may by used to induce completely erasable and rewritable nanofeatures in the two-dimensional electron gas.

Acknowledgements

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