Ferroelectric Gates with Rewritable Domain Nanopatterns for Modulation of Transport Properties in GaN/AlGaN Heterostructures

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Abstract. The concept of field-effect transistor with ferroelectric gate in combination with the advanced technique of direct domain writing is applied for modulation of transport properties of 2D electron gas located close to the interface in a GaN/AlGaN heterostructure. The ferroelectric $Pb(Zr,Ti)O_3$ film grown on top of such heterostructure was poled in a controllable way by scanning probe microscope inducing depletion or accumulation effects in the 2D gas depending on the polarity orientation. The artificially created domain arrangements can be projected onto the 2D gas provoking local depletion underneath the poled area. This ferroelectric lithography is potentially interesting for a number of applications as a flexible and nondestructive way of making rewritable patterns on low-dimensional structures with nanoscale resolution. In this work we present the first results on the ferroelectric gate patterning and its impact on the charge concentration and mobility of the 2D gas in the GaN/AlGaN heterostructure.

INTRODUCTION

Ferroelectric materials integrated into the semiconductor media have been intensively studied over the last decade for numerous electronic applications. In particular, the general property of ferroelectrics to switch the spontaneous polarization by an external electric field is exploited in non-volatile memory devices [1]. One of the implementations of the ferroelectric memory device concept is the ferroelectric field effect transistor with the gate comprising a ferroelectric layer that can be poled positively or negatively provoking charge accumulation or depletion in the transistor channel. Such devices have been successfully realized on classical Si/SiO_2 system using the $Pb(Zr,Ti)O_3$ (PZT) ferroelectric layer as a gate material [2]. The major problem of commercialization of these devices is the integration due to high processing temperatures of ferroelectric materials, which are hardly compatible with the silicon technology. Apart from the nonvolatile memories, the ferroelectric gates may be interesting for nanostructure patterning through the polarization domain engineering. The polarization domain arrangements can be created artificially by local poling of the ferroelectric layer using a Scanning Probe Microscope (SPM). Earlier the SPM-assisted direct domain writing on the PZT film was successfully used for modification of conductive properties of metallic $SrRuO_3$ layer underneath [3].

In the present work we combine the ferroelectric gate with the semiconductor structure containing 2D electron gas close to the ferroelectric/semiconductor interface. For the first time we demonstrate the effect of 2D gas depletion induced by polarization domain writing on the ferroelectric gate, which opens new possibilities for nanostructure design through domain engineering by “ferroelectric lithography”.

RESULTS AND DISCUSSION

For this experiment 400 nm thick polycrystalline PZT film was deposited on AlGaN/GaN heterostructure with a 2D electron gas located 20nm below the surface. Mesas with Hall bar geometry have been defined by electron cyclotron resonance reactive ion etching. The PZT film was poled using SPM

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technique with dc voltage of ±40V applied to the SPM conductive cantilever tip (Fig. 1).

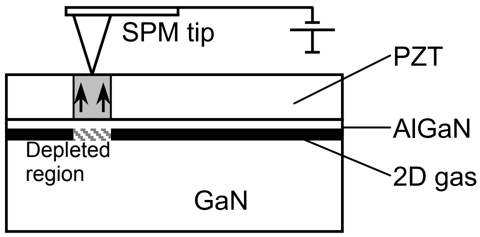

FIGURE 1. Local depletion of 2D electron gas, induced by artificially created polarization domains in PZT ferroelectric layer deposited on top of AlGaN/GaN heterostructure.

The created polarization pattern was controlled by piezoresponse force microscopy (PFM) [4] (Fig. 2).

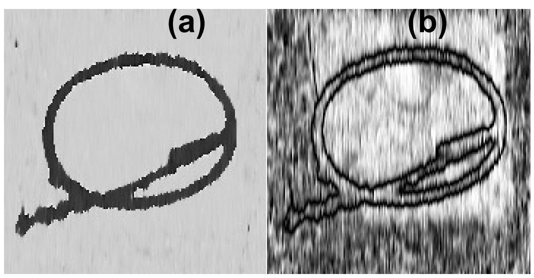

FIGURE 2. Direct writing of polarization domains on PZT film deposited on top of AlGaN/GaN heterostructure. The PFM images represent phase (a) and amplitude (b) of local piezoresponse. The scanned area is 7x7μm.

In order to evaluate the effect of the polarized ferroelectric film on the 2D gas carrier concentration the preferential polarization was induced in the area of 50x50 μm and then the concentration of electrons was measured by the Hall effect. First, measurements were done without poling in order to define the initial electron concentration. The concentration that was found to be $5x10^{12}$ cm^{-2} remained virtually unchanged within the temperature range from 77K to 298K. Then the studied area was poled with –40V (polarity corresponds to the 2D gas depletion) and the measurements were repeated. As the last step the polarity on the same area was inverted and then the third series of measurements was performed. Figure 3 shows that the electron concentration changes approximately by factor two as the sign of polarization in PZT switches. The electron mobility was virtually independent of the polarization and was measured to be 1200 $cm^2V^{-1}s^{-1}$ at 298°K and 4200 $cm^2V^{-1}s^{-1}$ at 77K. The observed temperature dependence of the depletion may be attributed to the depolarization effects and will be addressed in the upcoming papers.

To summarize, the experimental results suggest that the artificial domain pattern written on the ferroelectric gate can be projected directly onto the 2D gas. Hence, the arbitrary-shaped low-dimensional semiconductor structures can be defined with nanoscale resolution by domain engineering. The essential advantage of such "ferroelectric lithography" compared to the alternative techniques is that the created patterns are rewritable. The domain pattern can be modified or completely erased and rewritten without causing any damage to the sample, which opens new opportunities for experiments with semiconductor nanostructures as well as for device optimization. The application of the ferroelectric lithography to other systems with 2D gas with high mobility of carriers such as GaAs/AlGaAs system will be addressed in the further publications.

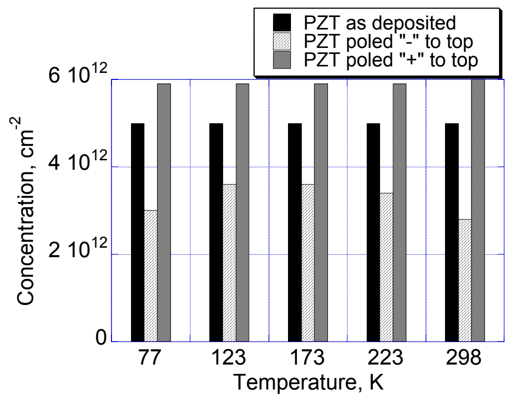

FIGURE 3. Effect of preferential top-to-bottom and bottom-to-top spontaneous polarization in the PZT film on the electron concentration in the 2D gas.

ACKNOWLEDGMENTS

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