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Ferroelectric Field Effect Transistor Based on Modulation Doped CdTe/CdMgTe Quantum Wells

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In this work, we observed effects of changing the electron concentration and electron mobility upon the poling of the $Cd_{0.96}Zn_{0.04}Te$ ferroelectric gate deposited on the top of the CdTe-based modulation doped quantum well structure, which are confirmation of the existence of the electrostatic field originating from the ferroelectric material, which can be controlled by an external voltage. The analysis of the data obtained from the Hall effect measurements showed that the electron mobility and carrier concentration decreased by a factor of 2.5 and 1.5, respectively upon the negative poling of the gate with respect to the poled by the positive voltage. Moreover, the electrostatic field, depending on its directions, causes depletion of accumulation of electrons in the 2D channel, i.e., it is a source of the field effect.

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1. Introduction

Field effect transistors with ferroelectric gates (Fe-FET) are regarded as attractive candidates for rewritable, non-volatile memories, which combine high speed, non-destructive read-out functions, high number of operation cycles and low power consumption [1–3]. Additionally, direct writing of the polarization domains on a ferroelectric gate represents a flexible and nondestructive way of making rewritable nanostructures projected onto the conductive channel, which opens new possibilities for device downscaling [4]. The major technological issue to be resolved for successful implementation of these devices is integration of ferroelectrics into existing semiconductor technology. In this respect mixed II–VI crystals, such as $Cd_{1-x}Zn_xA$ (A = Te, Se, S) have attracted increasing attention

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of various research groups. All of these materials are known to be semiconductors and exhibit ferroelectric properties at room temperatures [5, 6].

The first observation of ferroelectricity in bulk $Cd_{1-x}Zn_xTe$ by Weil et al. [7] was based on the hysteretic behavior of electrical polarization and the temperature variation of the dielectric anomaly. Fu et al. [8] confirmed the hysteretic behavior of the electrical polarization and the electrical conductivity of this material. Recently, the ferroelectric behavior of MBE-grown thin films and bulk crystals of $Cd_{1-x}Zn_xTe$ have been also confirmed by other experimental methods [9, 10]. In these works dielectric constant hysteresis loop, peculiar optical properties and bistable resistance were observed in the $Cd_{1-x}Zn_xTe$ structures. Moreover, it was shown that an electrostatic poling of the direction of the spontaneous electric polarization in $Cd_{1-x}Zn_xTe$ thin films changes the conductivity in 2DEG electron channels in high mobility electron transistors by $Cd_{1-x}Zn_xTe$ ferroelectric gates, which is crucial for potential applications [11].

In the present paper, we demonstrate magneto-transport results of the effective control of the conductivity of 2D electrons confined in the CdTe channel by electrical pulses applied to the CdZnTe gate at the low temperatures.

2. Experimental technique

The cross-section of the investigated Fe-FET grown by molecular beam epitaxy (MBE) is presented in Fig. 1a. The two-dimensional electron channel of the device was formed by modulation doping of a 300 Å thick CdTe quantum well embedded between $Cd_{0.75}Mg_{0.25}Te$ barriers. The Fe-FET structure was formed on 4.7 μm thick $Cd_{0.75}Mg_{0.25}Te$ buffer evaporated on (100) oriented surface of a semi-insulating GaAs substrate. The thick buffer compensates the large lattice mismatch between GaAs and the CdTe-based structure and significantly improves the stability of the structure, making degradation processes much less essential

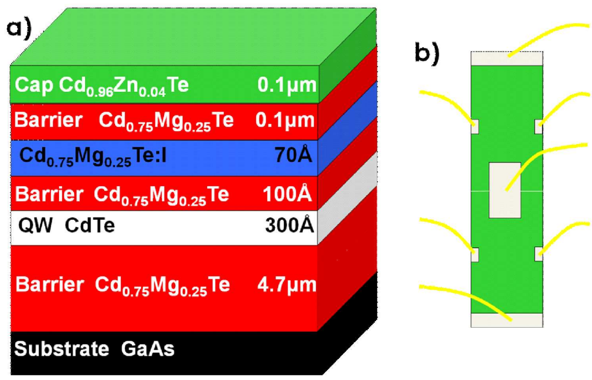

Fig. 1. The cross-section of the Fe-FET grown by MBE (a). The sketch of the Fe-FET with a six-contact Hall bar geometry and the additional contact to the ferroelectric gate (b).

than in samples with thin or without buffer layers. The substrate temperature during the growth process was kept at 350°C. The sample was grown with beam equivalent pressures in the order of 1×10^{-6} Torr. The n-type doping was achieved by doping with iodine from a ZnI_2 source. The doped $Cd_{0.75}Mg_{0.25}Te$ layer, of the thickness 70 Å was separated from the 300 Å thick CdTe quantum well by a 100 Å thick intrinsic $Cd_{0.75}Mg_{0.25}Te$ spacer. The structure is capped by a 100 nm thick $Cd_{0.96}Zn_{0.04}Te$ ferroelectric epilayer. The growth process was monitored *in situ* by reflection high energy electron diffraction (RHEED).

The Fe-FET structures were characterized by a DC magneto-transport measurement at various temperatures (1.4–300 K) in magnetic fields up to 9 T. The Hall measurements were performed using six-contact Hall bar geometry. Ohmic contacts were made by soldering indium, which was placed on the top of the samples and subsequently annealed at 200°C for a few seconds. Besides the six contacts, an additional contact was formed by a silver paste on the ferroelectric $Cd_{0.96}Zn_{0.04}Te$ cap layer, as shown in Fig. 1b. This ferroelectric gate was poled by applying positive or negative DC voltage of about 50 V between the gate contact and the 2D channel contacts. The Hall and conductivity measurements were performed using the DC technique as a function of magnetic field at various temperatures.

3. Results and discussion

As the first stage of the transport characterization of the Fe-FET structures, we checked the electrical resistance of a reference sample — a 5 μm thick $Cd_{0.96}Zn_{0.04}Te$ layer grown directly on a semi-insulating GaAs substrate. The resistance of the reference layer is very high at low temperatures (immeasurable below the liquid nitrogen temperature) and all attempts to switch the conductivity states of ferroelectric layer were unsuccessful. This result clearly indicates that the modulation-doped quantum well is the only conducting channel in the investigated structure. Moreover, it points out that electric field, which appears in the ferroelectric layer is a single parameter, which can be modified, when the electric poling is applied to the structure.

In the presence of a perpendicular magnetic field, the energy levels of two-dimensional electrons split as a result of Landau and spin quantization into discrete Landau levels separated by the cyclotron and spin energies. Scattering broadens the Landau levels and gives rise to the 2D magneto-transport described by the Ando–Uemura theory [12]. Figure 2a presents the Hall effect results obtained on the Fe-FET sample at 1.4 K. The sample was measured twice: after poling of the ferroelectric gate by a negative and positive voltage with respect to the 2D electron channel. For both poling directions, we observed the typical features of the integer quantum Hall effect (IQHE), i.e., quantized Hall plateaus at integral values of the Landau level filling factor, ν (Fig. 2a). However, the slope of the Hall signal changes upon the direction of the poling indicating that the concentration of the 2D electrons in the conducting channel has been changed. The effect is clearly visible when one compares the magnetic field positions of the IQHE plateaus with the same filling factor. For instance, for $\nu = 3$ the plateau appears at about 8 T for the positive gate poling and shifts to about 6 T for the negative gate poling. The shift confirms the change of the carrier concentration. In addition, for the negative gate poling the IQHE plateaus become narrower which can be a sign of the lower carrier mobility than in the case of the positive gate poling. The carrier concentrations determined from the slope of the Hall effect signal are equal to $n = 4.11 \times 10^{11}$ cm^{-2} and $n = 5.94 \times 10^{11}$ cm^{-2} for the negative and positive gate poling, respectively.

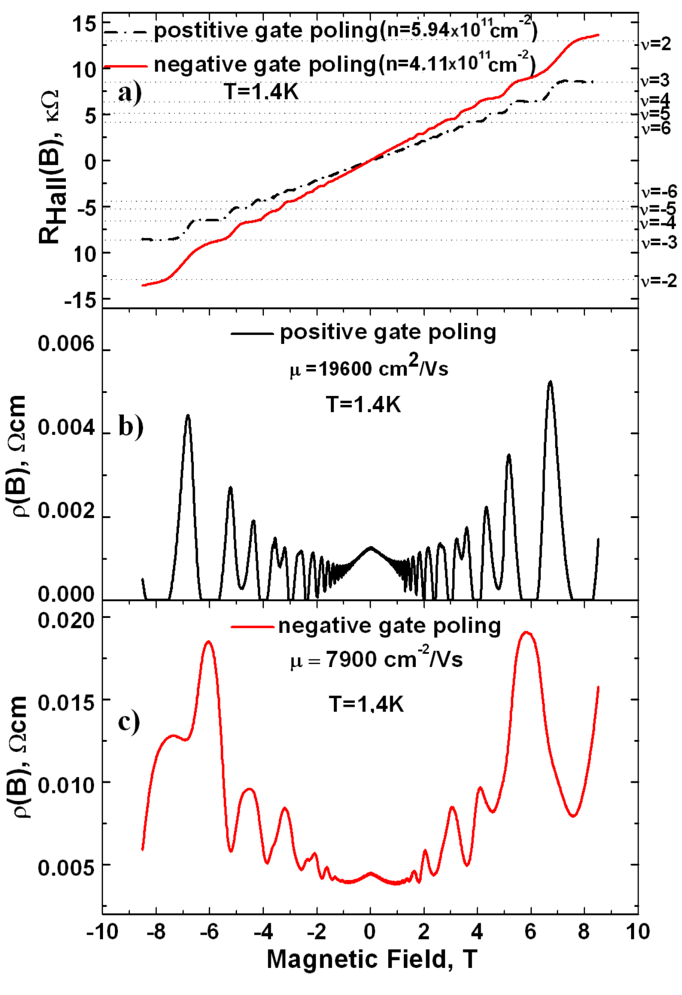

Fig. 2. Hall resistance ρ_{xy} (a) and longitudinal resistivity ρ_{xx} (b, c) of Fe-FET after applying a positive or negative electric pulses DC voltage between the ferroelectric gate and the 2D channel.

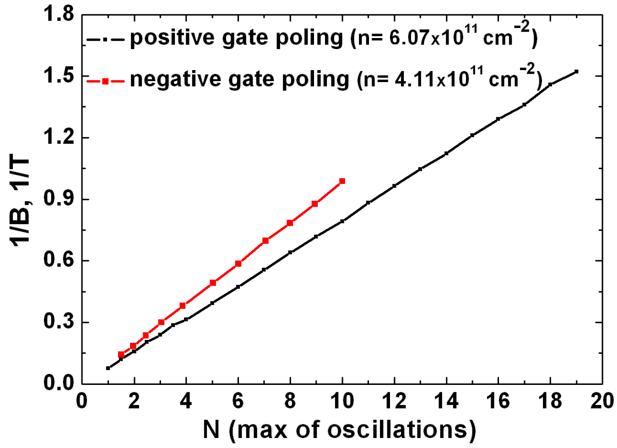

Fig. 3. Analysis of Shubnikov–de Haas oscillations for two polarization states.

The influence of the gate poling on the electron concentration and mobility in the 2D channel is confirmed by the longitudinal resistance measurements shown in Fig. 2b and c. The minima and maxima of the Shubnikov–de Haas (SdH) oscillations visible in the parallel resistance, ρ_{xx}, are clearly shifted for the two polarization states. In addition, for the negative gate poling the oscillations are less resolved which is a sign of the lower mobility. The standard analysis of the magnetic field positions of the SdH oscillations, shown in Fig. 3, yields the electron concentrations of 4.11×10^{11} cm^{-2} and 6.07×10^{11} cm^{-2} for the negative and positive gate poling, respectively. These values have a very good agreement with the magnitudes, obtained from the Hall effect measurements.

Because of the existence of built-in potentials originating from the ferroelectric gate the determination of the absolute values of the electron mobility in the investigated Fe-FET structure is rather difficult. The electrostatic potential gives rise to the parallel signal which makes the measurement of the resistance uncertain. However, in a reference structure, grown in the same MBE run but not covered by the $Cd_{0.96}Zn_{0.04}Te$ ferroelectric gate, the mobility of the 2D electrons in the CdTe channel was found to be in the order of 130 000 cm^2/(V s). Although the determination of the absolute values of electron mobility is not possible, we can compare the change of the mobility upon the poling. The analysis of the amplitude of the SdH oscillations in the Fe-FET structure shows that the electron mobility decreases by a factor of 2.5 upon the negative poling of the gate with respect to the mobility of the electrons poled by the positive voltage.

4. Conclusions

The observed effects of changing the electron concentration and electron mobility upon the poling of the $Cd_{0.96}Zn_{0.04}Te$ ferroelectric gate deposited on the top of the CdTe-based modulation doped quantum well structure confirms the existence of the electrostatic field originating from the ferroelectric material which can be controlled by an external voltage. The electrostatic field, depending on its directions, causes depletion of accumulation of electrons in the 2D channel, i.e., it is a source of the field effect.

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