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Control of Ferromagnetism in a (Ga,Mn)As – Based Multiferroic System via a Ferroelectric Gate

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Abstract. We report the implementation of a ferroelectric gate field effect transistor (FeFET) with a ferromagnetic (Ga,Mn)As conducting channel. The Curie temperature T_C in the channel is modulated by non-volatile poling of the gate. The ferroelectric state, and thus also the altered ferromagnetic behavior, persists for periods of more than a week. T_C control is demonstrated by resistance, magnetotransport and hysteresis measurements.

Keywords: Magneto-transport properties, Multiferroics, Dilute magnetic semiconductor, (Ga,Mn)As, FeFET, Films.
PACS: 85.30.Tv Field effect devices, 71.55.Eq III-V Semiconductors, 75.50.Pp Magnetic semiconductors, 85.50.Gk Non-volatile ferroelectric memories

INTRODUCTION

Multiferroic systems with coupled ferroelectric and ferromagnetic responses attract a lot of interest in view of their potential applications in memories and spintronic logic elements. A ferroelectric-ferromagnetic bilayer presents potential benefits of non-volatile electrical switching, low operation voltage and the possibility to modulate the properties at the nanoscale via polarization domain engineering. Earlier, non-volatile electric-field control of ferromagnetism, using a ferroelectric gate, has been reported in oxide ferromagnetic layers that do not lend themselves to integration with semiconductors[1, 2].

Here we report a ferroelectric gate device demonstrating non-volatile electric-field-controlled switching of ferromagnetism in a dilute magnetic semiconductor (Ga,Mn)As channel and show that polarization reversal of the gate by a single voltage pulse of 35V results in a persistent modulation of the Curie temperature as large as 5%.

SAMPLE AND DEVICE FABRICATION

A 7nm (Ga,Mn)As film (6% doped) was grown by low-temperature (250°C) molecular beam epitaxy onto a 330nm high-temperature GaAs buffer layer on a semi-insulating GaAs (001) substrate. Uniaxial anisotropy, with the easy magnetization axis parallel to the [1-10] axis, was confirmed by superconducting quantum interference device magnetometry, as reported earlier for similar films[3].

A Hall bar mesa is formed by wet etching. Then a 200nm thick co-polymer film [P(VDF-TrFE): polyvinylidene fluoride with trifluoroethylene] is spun-on. Finally, the Au(100nm) gate electrode is defined by a lift-off process.

Control of Ferromagnetism

The control of ferromagnetism using the ferroelectric gate demonstrated here relies on the mediation of the Mn-Mn exchange interaction by the strongly spin-orbit coupled valence band holes. The Curie temperature T_C can thus be a significant function of the hole density, offering the potential for altering the ferromagnetic response by electric-field control. The ferroelectric P(VDF-TrFE) films on a 7nm (Ga,Mn)As layer show a stable reversal of spontaneous polarization, characterized by a sharp polarization hysteresis loop with remnant polarization close to 6 μC/cm^2.

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RESULTS

Ferroelectric control of the hole density in the channel can be seen in Fig. 1, which compares the normalized resistivities of the channel before and after poling the gate. The position of the peak is determined for accumulation as well as for depletion. Its value changes from 91K in accumulation to 85K in depletion. Since it is linked to the Curie temperature T_C, this demonstrates that the polarization state of the gate significantly modulates T_C.

Additionally, magnetotransport and extraordinary Hall effect resistivity measurements are performed. A standard Arrott plot analysis infers a Tc shift associated with ferroelectric polarization switching of 3.8K (4.7%) and thus confirms the alternation of the magnetic properties.

The measured T_C shifts are in good agreement with the predicted sublinear hole-concentration dependence[4] as also discussed also elsewhere[5].

Another important characteristic related to ferromagnetism is hysteretic behavior. In the following experiment, the external magnetic field B is applied along the Hall bar channel (which corresponds to the easy magnetic axis). The transverse resistance R_{xy} versus B is plotted. A significant change in R_{xy} is observed when the magnetization rotates through 180°.

Throughout the whole temperature range up to 60K, an alternation of the magnetic behavior can be observed between accumulation and depletion state. Figure 2 shows curves obtained at 60K. The hysteretic behaviour is clearly seen in accumulation, whereas it is hardly resolved in depletion. The change in R_{xy} after magnetization rotation can be ascribed to a small misalignment (0.1°) of the Hall bar plane to the easy magnetic plane.

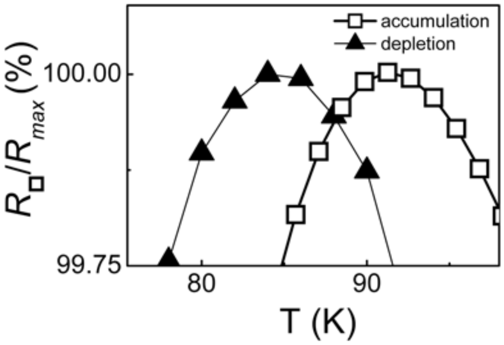

FIGURE 1. Normalized resistance versus temperature around the maximum in accumulation and depletion state.

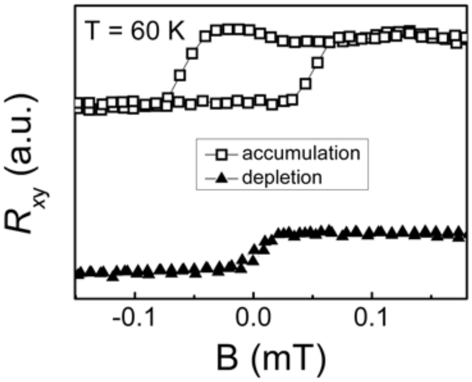

FIGURE 2. The difference in the magnetic behavior is clearly observed in the hysteresis loops of transverse resistance at 60K.

Overall this work establishes a number of advances towards the implementation of a ferroelectric FET hybrid-multiferroic device. A widely-recognized incompatibility between ferroelectrics and III-V semiconductors has been resolved by integration of a polymer ferroelectric in a FeFET configuration. Poling and retention in the polymer ferroelectric gate and persistent control of the semiconductor channel carrier density have all been successfully demonstrated. A polymer-gate integrated into a dilute magnetic semiconductor (Ga,Mn)As FET structure has led to the electric-field-mediated control of ferromagnetism in the semiconductor channel.

Recent studies on backgated (Ga,Mn)As structures with built-in low-voltage normal gates are compatible with this FeFET structure. This can provide an insight into key topics like fundamental condensed-matter studies in fields (such as collective phenomena in systems with strong spin–orbit coupling).

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