Ferroelectric control of ferromagnetism in diluted magnetic semiconductors

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Integration of ferroelectric gates on magnetic semiconductor structures is a challenging problem because of a number of issues including processing incompatibility between these two groups of materials. High interest in such hybrid multiferroic structures is relating to their potential application in new memories and spintronic logic elements. In the present work we demonstrate a structure in which the magnetic response is modulated by the electric field of the poled ferroelectric gate. Such ferroelectric-ferromagnetic bilayer presents potential benefits of nonvolatile electrical switching, low operation voltage and a possibility to modulate the properties in nanoscale via the 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]. Device-oriented exploration of such systems requires an implementation combining a thin film ferroelectric gate and a commonly-exploited semiconductor suitable for integration in semiconductor devices. Here we report the first ferroelectric gate device demonstrating non-volatile electric-field-controlled switching of ferromagnetism in a ferroelectric-dilute magnetic semiconductor (DMS) Ga(Mn)As. Specifically, we show that polarization reversal of the gate by a single voltage pulse results in a persistent modulation of the Curie temperature as large as 5%. Such electric-field-driven control of ferromagnetism relies on the mediation of the Mn-Mn exchange interaction by the strongly spin-orbit coupled valence band holes which control both the strength of the magnetic interactions and the magnetocrystalline anisotropies[3]. The Curie temperature T_C can thus be a significant function of the hole density p, offering the potential for altering the ferromagnetic response by electric-field control. In a conventional FET system first reported by Ohno et al. [4] control of ferromagnetism requires the application of a large gate voltage and is not persistent. In contrast a ferroelectric gate offers the potential for the large non-volatile carrier-density control needed in these heavily doped materials, by modest voltages (potentially can be less than 5 V in ultra-thin ferroelectric films). Ferroelectric gates can offer sub-nanosecond response times, and possibility of direct domain writing for reversible modulation of the magnetic properties in sub-micron scale.

The issue of processing incompatibility between oxide ferroelectrics requiring the temperatures above 400 °C and Ga(Mn)As was overcome by choosing instead of traditional ferroelectrics a ferroelectric co-polymer polyvinylidene fluoride with trifluoroethylene P(VDF-TrFE). The ferroelectric P(VDF-TrFE) films on (Ga,Mn)As showed a stable reversal of spontaneous polarization characterized by a sharp polarization hysteresis loop with remnant polarization close to 6 $\mu C/cm^2$. This relatively small charge density dictates using thinnest Ga(Mn)As layers, in our case the thickness was 7 nm.

Control of ferromagnetism via the polarization reversal in ferroelectric gate has been monitored using magnetotransport and extraordinary Hall effect resistivity measurements. The Arrott plot analysis [5] allowed for inferring T_C shift associated with the ferroelectric polarization switching. Two studied samples with slightly different structure showed the T_C shift of 3.8K (4.7%) and 1.9K (2.2%), respectively. These magnitudes are found to be in good agreement with the established understanding of hole-mediated exchange in (Ga,Mn)As. Another manifestation of altering magnetic state in the DMS cannel due to the spontaneous polarization was a change in the hysteretic behavior of magnetization.

To summarize, a number of important steps toward implementation of a ferroelectric FET multiferroic device hase been presented in this work, including quantitative description based on theoretically-predicted and experimentally-determined behaviour of the magnetic properties of (Ga,Mn)As. A widely-recognised incompatibility between ferroelectrics and III-V semiconductors has been solved by integration of a polymer ferroelectric in an FeFET configuration. Poling and retention in the polymer ferroelectric gate and control of the semiconductor channel carrier density to low temperatures have all been demonstrated successfully. A polymer-gate integration in a dilute magnetic semiconductor (Ga,Mn)As FeFET has led to an electric-field-mediated control of ferromagnetism in the semiconductor channel that has been thoroughly investigated by magneto-transport measurements. The effects are in agreement with the established understanding of hole-mediated exchange in (Ga,Mn)As.

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