# Exchange bias of a ferromagnetic semiconductor by a ferromagnetic metal

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We demonstrate an exchange bias in (Ga,Mn)As induced by antiferromagnetic coupling to a thin overlayer of Fe. Bias fields of up to 240 Oe are observed. Using element-specific x-ray magnetic circular dichroism measurements, we distinguish a strongly exchange coupled (Ga,Mn)As interface layer in addition to the biassed bulk of the (Ga,Mn)As film. The interface layer remains polarized at room temperature.

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Ferromagnetic (FM) semiconductors offer the prospect of combining high-density storage and gate-controlled logic in a single material. The realization of spin-valve devices from FM semiconductors requires the controlled switching of magnetization in adjacent layers between antiferromagnetic (AFM) and FM configurations. This has motivated several theoretical investigations of interlayer coupling in all-semiconductor devices[1], and AFM coupling has recently been demonstrated in (Ga,Mn)As multilayers separated by $p$-type non-magnetic spacers[2]. However, the Curie temperature $T_C$ of (Ga,Mn)As is currently limited to 185 K in single layers[3], and is typically much lower for layers embedded within a heterostructure[2], which is an obstacle to the practical implementation of semiconductor spintronics.

The development of FM metal/FM semiconductor heterostructures has the potential to bring together the benefits of metal and semiconductor based spintronics, offering access to new functionalities and physical phenomena. Recent studies of MnAs/(Ga,Mn)As and NiFe/(Ga,Mn)As bilayer films have shown FM interlayer coupling and independent magnetization behavior, respectively[4,5]. Of particular interest is the Fe/(Ga,Mn)As system, since the growth of epitaxial Fe/GaAs(001) films is well-established[6]. Remarkably, a recent x-ray magnetic circular dichroism (XMCD) study has shown that Fe may induce a proximity polarization in the near-surface region of (Ga,Mn)As, antiparallel to the Fe moment and persisting even above room temperature[7]. Devices incorporating Fe/(Ga,Mn)As therefore offer the prospect of obtaining non-volatile room temperature spin-polarization in a semiconductor.

Until now, no information has been revealed about the coupling of Fe to (Ga,Mn)As layers away from the near-surface region. At the surface, the (Ga,Mn)As layer may be highly non-stoichiometric and Mn-rich, due to its non-equilibrium nature[8,9]. Previously, Fe/(Ga,Mn)As layers were produced by a process including exposure to air followed by sputtering and annealing prior to Fe deposition, which may further disrupt the interface order. The origin of the interface magnetism then had to be inferred by comparison to a series of reference samples[7]. Demonstration of coupling between the bulk of the layers, *i.e.*, an exchange bias effect, would provide direct evidence of the interface magnetic order. Moreover, such coupling would offer new means of manipulating the FM semiconductor spin state and utilizing the proximity polarization effect in a spintronic device.

Here, we demonstrate an antiferromagnetic coupling and exchange bias in Fe/(Ga,Mn)As bilayer films, by combining element-specific XMCD measurements and bulk-sensitive superconducting quantum interference device (SQUID) magnetometry. As with previous studies of FM metal/FM semiconductor bilayers[4,5] (and in contrast to AFM coupled FM metal/FM metal exchange bias structures[10,11]) the layers are in direct contact without a non-magnetic spacer in between. We distinguish interface and bulk (Ga,Mn)As layers that are respectively strongly and weakly antiferromagnetically coupled to the Fe overlayer. In agreement with Ref.[7], the interface layer remains polarized at room temperature.

The Fe and (Ga,Mn)As layers of the present study were both grown by molecular beam epitaxy in the same ultra-high vacuum system, in order to ensure a clean interface between them. The (Ga,Mn)As layer of thickness 10 to 50 nm was deposited on a GaAs(001) substrate at a temperature of 260°C, using previously established methods[3,8]. A low Mn concentration of $x \approx 0.03$ was chosen in order to avoid the formation of compensating Mn interstitials. The substrate temperature was then reduced to $\sim$0°C, before depositing a 2 nm Fe layer, plus a 2 nm Al capping layer. In-situ reflection high energy electron diffraction and ex-situ x-ray reflectivity and diffraction measurements confirmed that the layers are single-crystalline with sub-nm interface roughness. SQUID magnetometry measurements were performed using a Quantum Design Magnetic Property Measurement System. Mn and Fe $L_{2,3}$ x-ray absorption and XMCD