

Fabrication and Characterization of MnAs/GaAs Heterostructures for Studies of One-Dimensional Spin Transport

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Introduction:

MnAs is an attractive material for use in studies of ferromagnet/semiconductor heterostructures. Its room-temperature ferromagnetic properties and its ease of growth by molecular beam epitaxy (MBE) on arsenide semiconductors have motivated its use as a source of spin-polarized electrons in experiments in the field of spintronics [1]. In this work we present results on the fabrication and characterization of MnAs/GaAs nanowires. Freestanding nanowires with diameters down to 75 nm were fabricated and magnetic force microscopy (MFM) studies of nanowires with diameters down to 100 nm were conducted. Future experiments utilizing these nanostructures will provide information on the influence of geometrical confinement on the transport of spin-polarized electrons. Recent experiments on electron spin dynamics in InGaAs lateral channels have demonstrated one-dimensional electron spin dynamics in channels an order of magnitude greater than the electron mean free path [2]. The structures fabricated in this work could be used to do electrical spin transport experiments to further understand the effects of reduced dimensionality on spin-polarized transport in semiconductors.

Procedure:

The nanowires were processed from a thin film grown by MBE. The film consisted of a 25 nm thick layer of MnAs on top of 1.5 μm of n-GaAs ($n = 5.25 \times 10^{17} \text{ cm}^{-3}$) grown on a semi-insulating GaAs substrate. Superconducting QUantum Interference Device (SQUID) measurements showed the MnAs layer to have a coercivity of approximately 200 Oe at 300 K.

The thin film samples were processed into freestanding nanowires using a two-step process. In the first step a pattern is defined on the sample surface via e-beam lithography. Using the negative maN-2403 e-beam resist as an etch mask, the pattern was transferred to the thin film via reactive ion etch (RIE), creating arrays of nanowires with diameters from 75 nm to 500 nm. The RIE was conducted using a Cl_2 and Ar gas mixture with gas

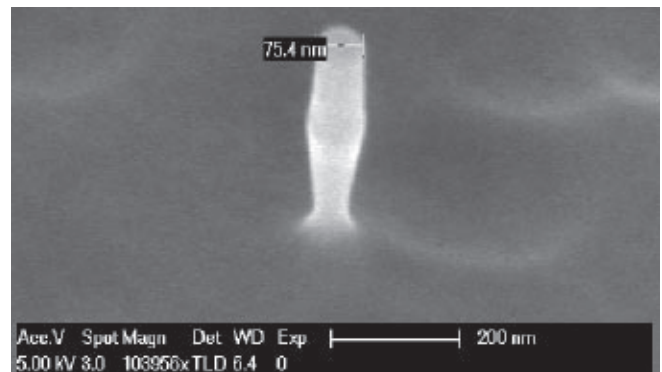


Figure 1: SEM image of a 75 nm diameter nanowire at 45°.

flow rates of 1 and 20 sccm, respectively, while the RF power was 50 W and the chamber pressure was 10 mT.

The magnetic properties of the MnAs nanowire caps were investigated with an Asylum MFP-3D atomic force microscope (AFM) using a magnetic cantilever tip. The AFM was used to take MFM images to characterize the ferromagnetic ground states of the MnAs caps. MFM images in an applied magnetic field were also taken with an Asylum research variable field module (VFM).

Results:

Freestanding nanowires with diameters down to 75 nm were successfully fabricated. Figure 1 shows a scanning electron microscope (SEM) image of a 75 nm diameter nanowire with a height of approximately 350 nm. The nanowire fabrication process was robust; typically 100% of the dots patterned during e-beam lithography were successfully etched into nanowires. Undercutting of the GaAs layer limited the nanowire heights—the greatest height to diameter aspect ratio achieved was approximately 6 to 1 using a Cl_2 -based RIE recipe.

Magnetic characterization of the nanowire caps done by MFM showed ferromagnetic behavior in MnAs caps with diameters down to 100 nm (the 75 nm nanowires were not measured because this array was not located during imaging). Figure 2 shows three nanowires of diameter 500 nm and height 350 nm. The image shows the MnAs

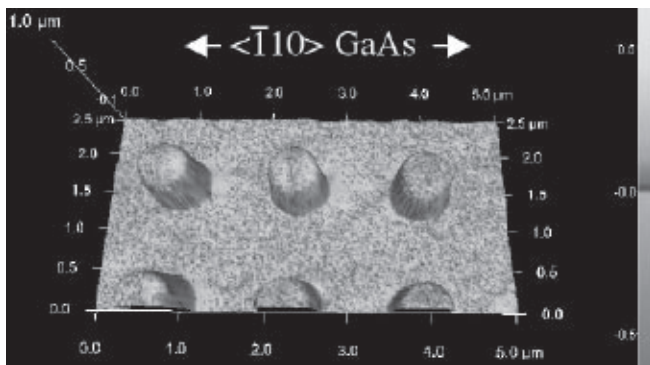


Figure 2: MFM image of 500 nm diameter nanowires overlaid on the AFM image (topography). The MFM image shows two single-domain MnAs discs (left, center) and one two-domain MnAs disc (right).

caps to be ferromagnetic. MFM scans also showed MnAs caps of diameter 500 nm to be either single-domain or multi-domain, and showed MnAs caps of diameters less than 500 nm to be only single-domain. Figure 3 shows an MFM scan of four 100 nm diameter nanowires. The MFM scan was done at a height of 275 nm above the sample surface to avoid contact with the nanowires. The large scan height results in poor resolution of the domain structure of the 100 nm MnAs caps. In order to obtain a better image of the MnAs caps, the nanowires were placed in a magnetic field along the MnAs easy axis large enough to reverse the magnetization of the MFM tip but not large enough to reverse the magnetization of the MnAs caps. Figure 3 shows that the fringe fields around the MnAs caps invert after the magnetization of the MFM tip is flipped. This response suggests that the MnAs caps are ferromagnetic with a coercive field larger than the applied field.

Future work will focus on using the MnAs/GaAs nanowires for studies of one-dimensional spin transport. Initial spin transport measurements could be done electrically at room temperature using a conductive atomic force microscope (CAFM) and a VFM. The CAFM measurements could be followed by low-temperature electrical measurements to provide a more complete understanding of spin transport in these

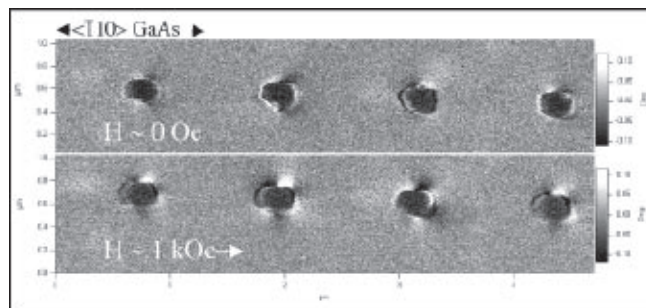


Figure 3: MFM images of 100 nm diameter nanowires imaged before (top) and after (bottom) MFM tip magnetization reversal. After switching the MFM tip magnetization the MFM image inverts, clearly demonstrating ferromagnetic behavior in the MnAs caps.

nanowires. Such low-temperature measurements would require nanowires processed so that the MnAs caps are contacted with a metal electrode. Processing these nanowires entails conformally coating the nanowires with a dielectric, planarizing between the nanowires using a spin-on dielectric like polyimide, and then etching to free the MnAs caps for metal evaporation. The purpose of the conformal dielectric coating is to structurally enhance the nanowires, as it was determined that the freestanding nanowires break at spin speeds greater than 3 krpm.

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References:

- [1] Wolf et al. Science 294, 1488 (2001).
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