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Ferromagnetic metal/semiconductor hybrid structures for magnetoelectronics

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We report on the following new ferromagnetic metal/semiconductor heterostructure material systems: (1) Fe/InAs(100)-4×2, (2) Fe/InAs(graded)/GaAs(100), and (3) Fe/InAs/AlSb/GaSb/AlSb/InAs/GaAs resonant tunneling diodes. Single crystal Fe films have been stabilized in these structures using molecular beam epitaxy growth, as evidenced by low energy electron diffraction. The magnetic and electrical properties have been studied using *in situ* (and focused) magneto-optical Kerr effect, alternating gradient field magnetometry, and current–voltage measurements. The results show that Fe/InAs based heterostructures are very promising systems for use in future magnetoelectronic devices as they have well defined magnetic properties as well as favorable electrical properties. © *1999 American Institute of Physics.* [S0021-8979(99)79108-5]

Over the past three decades solid state electronics has developed dramatically, but with very little attention devoted to incorporating magnetic materials into integrated electronic devices. However, an exciting new field of electronics, magnetoelectronics,[1] has attracted much attention recently, which is based on the fact that electrons have spin as well as charge. Future magnetoelectronic devices, in which the spin of the electron is controlled, are expected to find applications based on hybrid semiconductor structures. This development of electronics stems essentially from the successful epitaxial growth of high quality single crystal ferromagnetic metal (FM) films on semiconductor substrates, pioneered by the work of Prinz *et al.*[1] The most extensively studied system to date is Fe/GaAs.[2–4] However, as Fe forms a rectifying contact on GaAs, the Schottky barrier (~0.8 eV for Fe/GaAs)[5] prevents efficient current injection from the FM pads into the semiconductor layer. The fabrication of ever smaller devices leads to higher current densities, which in turn need low resistance ohmic contacts to reduce thermal dissipation. Metals on narrow gap semiconductors, such as InAs which has a direct band gap as small as 0.36 eV at 300 K form low resistance ohmic contacts.[5] InAs also has a higher low-field mobility than GaAs and InP, which makes it an excellent candidate for high-speed field effect transistors. In this article, we report the epitaxial growth of three types of Fe/InAs based hybrid structures, as shown in Fig. 1, and their magnetic and electrical properties. Our most recent results on Fe/GaAs are also briefly reported for completeness.

This study was carried out in a ''multitechnique'' molecular beam epitaxy (MBE) system, which includes *in situ* magneto-optical Kerr effect (MOKE) and Brillouin light scattering (BLS) to probe the static and dynamic magnetic properties of samples, and scanning tunneling microscopy (STM), low energy electron diffraction (LEED), reflection high energy electron diffraction (RHEED), and Auger spectroscopy to provide structural, morphological, and compositional information. Experimental details are similar to those described in a previous paper.[6]

Fe/InAs(100): The crystal structure of InAs is very similar to that of GaAs, namely a zincblende structure composed of two nested face-centered-cubic cells, but the lattice mismatch of Fe and InAs ($a_0 = 6.058$ Å) of 5.4% is much larger than that of Fe/GaAs (1.3%). It is thus a challenge to grow single crystal Fe films on InAs.

The InAs(100) substrates were cleaned using a combination of oxygen plasma etching and wet etching before loading into the ultrahigh vacuum (UHV) system. Figure 2(a) is the LEED picture of the substrate after annealing at 510 °C for half an hour. The clearly reconstructed LEED pattern in

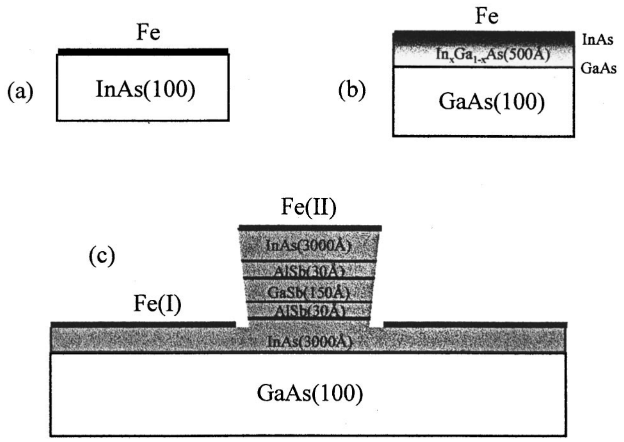

FIG. 1. Schematic diagrams of (a) Fe/InAs(100), (b) Fe/InAs (graded)/GaAs(100), and (c) Fe on patterned InAs/AlSb/GaSb double-barrier RTD.

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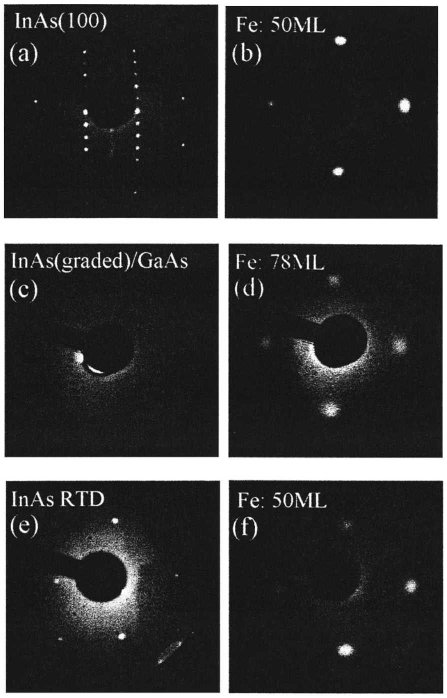

FIG. 2. LEED patterns of (a) InAs(100) substrate and (b) with 50 ML of Fe, (c) InAs(graded)/GaAs(100), and (d) with 78 ML of Fe, (e) patterned InAs/AlSb/GaSb double-barrier RTD, and (f) with 50 ML of Fe. The beam energies are 68 and 181 eV, respectively, for the substrates and for the Fe films.

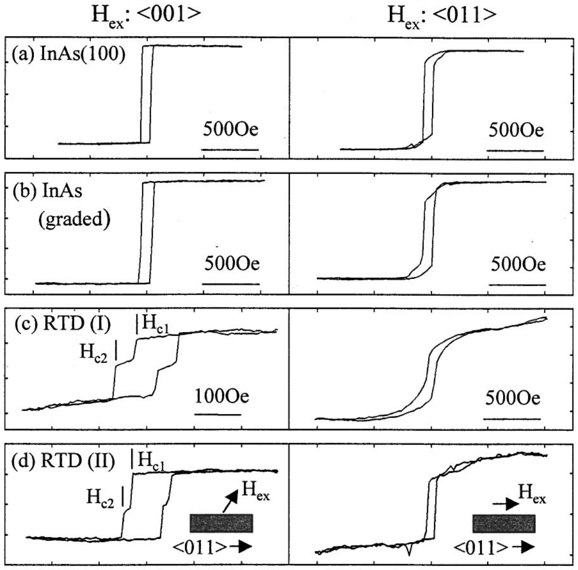

FIG. 3. MOKE hysteresis loops of (a) Fe(50 ML)/InAs(100), (b) Fe(78 ML)/InAs(graded)/GaAs(100), (c) Fe(50 ML)/RTD(I) bottom layer, and (d) Fe(50 ML)/RTD(II) top element with size 160×20 μm. All these samples were grown at 175 °C. Bottom inset: the relationship between the long axis of the element, the direction of the external magnetic field H_{ex}, and the crystal axes.

Fig. 2(a) indicates that the cleaning procedure produces a well-ordered surface. Auger measurements showed that the substrate was free of O, but contained a small amount of C. Fe films were grown at both 175 °C (Ref. 7) and room temperature. LEED spots from the Fe film appear after approximately 5 ML of deposition in both cases. The LEED spots become clearer and sharper with increasing coverage up to 25 ML and then retained a similar shape for higher coverages. A typical LEED pattern is shown in Fig. 2(b) after 50 ML of deposition at 175 °C. This demonstrates that single crystal body-centered-cubic (bcc) Fe films have been stabilized on InAs(100)-4×2 with the epitaxial relationship Fe(100)⟨001⟩‖InAs(100)⟨001⟩, i.e., the same as that for the Fe/GaAs(100) system.

The magnetic properties were studied with *in situ* MOKE measurements. A clear magnetic signal was detected after 3–4 ML of deposition. A uniaxial magnetic anisotropy (UMA) within a narrow thickness range of about 5–12 ML was observed in samples grown at room temperature. After about 12 ML, the films grown at both temperatures clearly display a cubic anisotropy, with the magnetic easy axes along ⟨001⟩, the easy axes of bulk bcc Fe. In Fig. 3(a), representative MOKE-hysteresis loops are shown for an Fe(50 ML)/InAs(100) film along two major crystal axes. The magnetization of a Au(20 ML)/Fe(100 ML)/InAs film grown at 175 °C has been measured using alternating gradient force magnetometry (AGFM). The magnetic moment of the film is $1.7\pm0.2\times10^3$ emu/cm^3 and comparable with that of bulk Fe. It is interesting to note that the magnetization of Fe/InAs is very different from that of Fe/GaAs for the samples grown at the same temperature.[2,4] In this case the magnetization is only 1.0×10^3 emu/cm^3, reduced by 40%, for an Fe film of 96 Å (67 ML) on GaAs.[2] This indicates that Fe moments near the interface in Fe/InAs are much larger than in Fe/GaAs under the same growth condition.

The ohmic contact of the Fe/InAs interface was confirmed using current–voltage ($I-V$) measurements. Typical characteristics are as shown in Fig. 4. The $I-V$ curves are linear over the temperature range 304–2.5 K and show no indication of a Schottky barrier. The equivalent resistance is weakly dependent on temperature, varying from 5 to 2.8 Ω in the temperature range 304–2.5 K. This may be due to the increase of the mobility at low temperature.

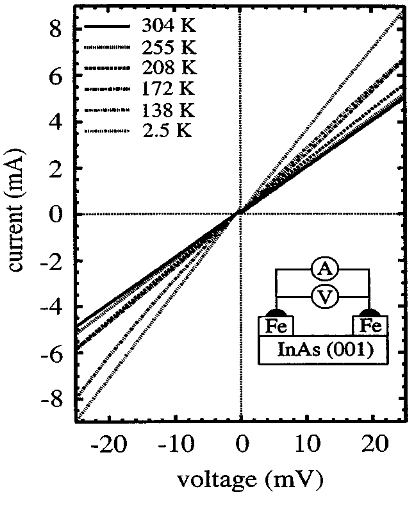

FIG. 4. $I-V$ measurements of Fe(50 ML)/InAs(100) in the temperature range of 2.5–304 K. The dimension of the Fe contacts, processed using optical lithography, is 50 μm with separation of about 250 μm.

Fe/In$_x$Ga$_{1-x}$As(500 Å)/GaAs(100): To minimize the effect of the Schottky barrier in GaAs based devices, a graded layer of n-In$_x$Ga$_{1-x}$As from GaAs to InAs over a thickness of 500 Å was grown on GaAs before FM deposition. The ferromagnetic metal should then form an ohmic contact without the need to diffuse the contacts into the active region of the devices, which would create an amorphous layer. The substrate was capped with As and then transferred to the UHV chamber for the deposition. The As capping layer was desorbed before Fe growth. No LEED pattern [Fig. 2(c)] was observed from the InAs (graded) layer, which may be due to the large roughness of the InAs graded layer. However, a clear bcc Fe LEED pattern was observed after Fe growth, as shown in Fig. 2(d). *In situ* MOKE in Fig. 3(b) showed a distinct cubic anisotropy with the easy axis along ⟨001⟩, which confirms that well-ordered single crystal Fe films have been stabilized on this InAs(graded)/GaAs substrate. $I-V$ measurement shows that there is no energy barrier across the whole structure. Detailed studies of the transport and magnetotransport properties of the devices based on this structure are under way.

Fe/InAs/AlSb/GaSb/AlSb/InAs/GaAs RTD: InAs/AlSb/GaSb resonant tunneling diodes (RTDs) are of great interests in the fabrication of high-speed analog devices as well as multivalued logic circuits.[8,9] If magnetic materials could be incorporated with this semiconductor heterostructure, a novel device, namely spin-RTD might be developed, in which both the energy and spin of the electrons are controlled for device operation. Here we report the preliminary results on one of the key steps to realize such a spin-RTD device: MBE regrowth of independent ferromagnetic metals contacted to both top and bottom InAs layers on a patterned RTD substrate. Figure 1(c) shows schematically the diagram of the device structure with a patterned element. This double-barrier RTD was grown by MBE on GaAs(100) in another UHV system. The elements of width 20 μm and length varying from 20 to 160 μm were patterned using selective wet etching. The MBE growth of the RTD, and the fabrication and characterization of the devices will be published elsewhere.[9]

The LEED pictures of the substrate and after Fe deposition are shown in Figs. 2(e) and 2(f), respectively. The substrate shows a 1×1 pattern, but no reconstruction was observed. The LEED picture after Fe deposition shows that single crystal bcc films have been stabilized on this substrate. However, we would like to note that the LEED pattern here was generated mainly from the bottom Fe layer, as the diameter of the electron beam is about 500 μm. Upon scanning the beam across the sample surface the LEED pattern remained relatively unchanged. This suggests that Fe grows epitaxially on both top and bottom InAs layers, as further indicated by the anisotropic focused MOKE loops shown in Figs. 3(c) and 3(d).

The magnetic properties of the samples were probed using *ex situ* focused MOKE after capping with 20 ML of Au. The MOKE loops from the bottom Fe/InAs (I) and a $160\times20\,\mu$m element (II) were shown in Figs. 3(c) and 3(d), respectively. The loops from both top and bottom Fe layers show a ''two-jump'' behavior when the field is applied along the ⟨001⟩ direction, the easy axis for bcc Fe. Such two jump loops were observed in continuous Fe/GaAs films, which was attributed to a mixture of the cubic anisotropy of bcc Fe and an interface uniaxial anisotropy.[3] In this sample with patterned elements, this two-jump behavior may be due to a combination of cubic anisotropy and shape anisotropy. The critical fields, $H_{c1}=18\pm2$ Oe and $H_{c2}=65\pm2$ Oe, of the bottom layer are significantly different from that of the top layer, in which $H_{c1}=29\pm2$ Oe and $H_{c2}=49\pm2$ Oe. This indicates that the anisotropy strengths differ between the bottom and top layers due to the differing local dipole field strengths associated with the detailed shape. A consequence of the difference between the critical fields for the top and the bottom layers is that different magnetization configurations can be realized, using appropriate external fields, as required for device operation. The MBE regrowth of magnetically independent FM contacts on patterned semiconductor devices, as demonstrated here, may open a way for the study of vertical spin-dependent electron tunneling and the fabrication of three-dimensional devices.

Fe/GaAs(100): We have recently optimized the growth conditions in Fe/GaAs in order to achieve a large moment at interface. A buffer layer (~0.5 μm) of homoepitaxial GaAs was grown on the commercial wafer to provide the smoothest possible GaAs surface. The substrate was annealed to 550 °C for 1 h to obtain a clean and well-ordered Ga-rich 4×6 surface. The samples were grown at room temperature. A combination of the *in situ* MOKE and *ex situ* AGFM measurements shows that the *entire* Fe film is ferromagnetic with a bulk-like moment after the onset of the ferromagnetism at about 5 ML.[6]

In summary, single crystal Fe has been successfully grown on InAs(100), InAs(graded)/GaAs(100), and patterned InAs/AlSb/GaSb double-barrier RTD. We propose that Fe/InAs based ferromagnetic metal/semiconductor hybrid structures are important for the study of spin electronics and the realization of future devices.

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