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# Single crystal Fe films grown on InAs(100) by molecular beam epitaxy

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Thin Fe films have been grown on InAs(100) by molecular beam epitaxy, and studied using *in situ* magneto-optical Kerr effect (MOKE), low energy electron diffraction (LEED), and scanning tunneling microscopy (STM). Despite the large lattice mismatch between Fe and InAs, the growth of Fe on InAs at 175 °C was found to be epitaxial with the orientation relationship Fe(100)⟨001⟩‖InAs(100)⟨001⟩, as evidenced by LEED. STM images indicate that growth proceeds via a 3D Volmer–Weber mode. The magnetic hysteresis loops measured using *in situ* MOKE show a distinct cubic anisotropy with the easy axis along ⟨001⟩, the easy axis of bulk bcc Fe, which further confirms that well ordered single crystal Fe films have been stabilized on the InAs(100) substrate. Current–voltage measurements in the temperature range of 2.5–304 K show that Fe forms an ohmic contact on InAs. We propose that Fe/InAs is a suitable heterostructure for magnetoelectronic devices as, unlike Fe/GaAs, there is no Schottky barrier to electron transport. © *1998 American Institute of Physics.* [S0003-6951(98)02029-4]

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 the exciting new field of magnetoelectronics,[1] which is based on the fact that electrons have spin as well as charge, has attracted much attention recently. Future magnetoelectronic devices, in which the spin of the electron is controlled, are expected to find applications based on hybrid semiconductor structures. In these devices spin-dependent electron transport is an essential property of the device function. A spin-polarized field effect transistor (spin FET) has already been proposed[2] based on the injection of spin-polarized electrons from a ferromagnetic source into the semiconductor.

The development of magnetoelectronics stems essentially from the successful epitaxial growth of high quality single crystal ferromagnetic metal (FM) films on oriented semiconductor substrates, where the magnetic properties can be controlled. The most extensively studied system to date is Fe/GaAs. Epitaxial growth has been achieved by several groups,[3–6] due in part to the fact that the lattice constant of bcc Fe ($a_0 = 2.866$ Å) is almost exactly half that of GaAs ($a_0 = 5.654$ Å). However, as Fe forms a rectifying contact on GaAs, the Schottky barrier (~0.8 eV for Fe/GaAs)[7] prevents efficient spin injection from the FM pads to the semiconductor substrates. The fabrication of ever smaller devices leads to higher current densities, which in turn need low resistance ohmic contacts to reduce thermal dissipation. In the case of III–V semiconductors, the nature of the metal/semiconductor contact, as well as the Schottky barrier height, depends largely on the band gap of the semiconductors, rather than the work function properties of the metal overlayers.[7] 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 contacts.[7] InAs also has a higher low-field mobility than GaAs and InP, which makes it an excellent candidate for high speed field effect transistors.[8] The crystal structure of InAs is very similar to that of GaAs, namely a zincblende structure composed of two nested face-centered-cubic cells.[9] Though 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%), bcc Fe may possibly stabilize on InAs through a lattice relaxation process. It is well known that in semiconductor growth, such as InAs on GaAs,[10] high quality epitaxy can be achieved despite the large lattice mismatch of two materials (7.1%). In this letter we demonstrate that single crystal bcc Fe can be grown epitaxially on InAs(100) and that the Fe films have well defined magnetic properties.

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. For STM measurements, the samples were transferred without breaking the vacuum to a UHV STM chamber which is attached to the main growth chamber. The MOKE hysteresis loops were collected in the longitudinal geometry using an electromagnet with a maximum field of 2 kOe, and an intensity stabilized HeNe laser.[11] Current–voltage ($I-V$) characterization was performed *ex situ* in the 304–2.5 K temperature range using a Keithley 236 source-measure unit.

The Fe films were grown on InAs(100) substrates at a rate of approximately one monolayer (ML) per minute using an *e*-beam evaporator. The substrate temperature was held at 175 °C, which was found to be the optimum growth temperature for the GaAs system.[3,5] The pressure was around 7 to $8 \times 10^{-10}$ mbar during growth. The deposition rate was monitored by a quartz microbalance which was calibrated

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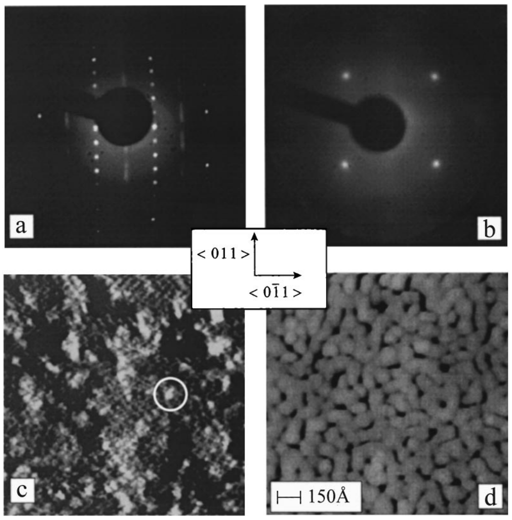

FIG. 1. LEED patterns of (a) InAs(100)-4×2 substrate, 68 eV, (b) Fe(50 ML)/InAs(100), 136 eV and STM images of (c) InAs(100) substrate, bias voltage 1.7 V and tunnelling current 2.0 nA, and (d) Fe(50 ML)/InAs(100), bias voltage 0.35 V and tunnelling current 2.6 nA. The scanned area for both images is $1500\times1500$ Å$^2$. The circle in (c) indicates a small cluster on the surface.

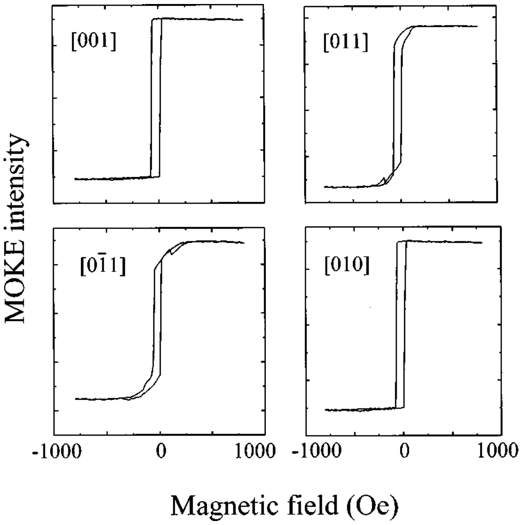

FIG. 2. *In situ* MOKE hysteresis loops of Fe(50 ML)/InAs(100) for the magnetic field applied along four major crystal axes.

using RHEED oscillations of Fe on a Ag(100) single crystal. The InAs(100) substrates were cleaned using a combination of oxygen plasma etching and wet etching ($HCl:H_2O = 1:4$) before loading into the UHV system and annealing in the chamber at 510 °C for half an hour before growth.

The LEED picture of the substrate after annealing is shown in Fig. 1(a). The fourth-order spots along the $\langle 011\rangle$ direction are very sharp and there is some streaking of the twofold spots in this direction, showing a In-terminated 4×2 reconstruction of the surface.[12] The clearly reconstructed LEED pattern in Fig. 1(a) indicates that the InAs substrate surface has a high degree of crystallographic order with a long coherence length. Auger measurements show that the substrate is free of O, but has a tiny C peak, after the annealing. The LEED patterns were monitored as Fe was deposited. No Fe LEED pattern was observed for the first 4 ML, which shows that the growth is not layer-by-layer. After approximately 5 ML of deposition, faint LEED spots from the Fe film appear. The LEED spots become clearer and sharper with increasing coverage up to 25 ML and then retain a similar shape for higher coverages. A typical LEED pattern is shown in Fig. 1(b) after 50 ML of deposition, which demonstrates that single crystal bcc Fe films have been stabilized on InAs(100)-4×2. The epitaxial relationship is $\mathrm{Fe}(100)\langle 001\rangle \| \mathrm{InAs}(100)\langle 001\rangle$, i.e., the same as that for the Fe/GaAs system.[3,6,13]

Large area STM images ($1500\times1500$ Å$^2$) of the substrate and a 50 ML film are shown in Figs. 1(c) and 1(d), respectively. The average width of flat terraces of the substrate as suggested by Fig. 1(c) is around 350 Å. The roughness of the substrate is about 3 Å, corresponding to an atomic layer step. There are some structures of ~9 Å height and ~60 Å in average diameter on the surface [one of these is indicated by the circle in Fig. 1(c)], which may be In clusters formed due to the high annealing temperature[12] required to remove contamination from the surface. The surface of the film as shown in Fig. 1(d) has an island structure with average size of about $100\times250$ Å$^2$, which is very different from that of the substrate. The surface roughness of the film is about 15 Å. The lack of an Fe LEED pattern for the first few monolayers and the island structure of the film surface show that the growth of Fe on InAs(100)-4×2 proceeds via the three dimensional Volmer–Weber growth mode. Transmission electron microscopy (TEM) measurements are being carried out to study the interface structure and gain further insight into the epitaxial growth mechanism in this system.

The magnetic properties were studied with *in situ* MOKE measurements. A clear magnetic signal was detected after 4 ML of deposition. The amplitude and the remnant ratio of the MOKE loops increase with increasing coverage. Above about 15 ML of Fe, square loops were observed when the field is applied along the $\langle 001\rangle$ directions, similar to those in Fig. 2, which shows MOKE-hysteresis loops for an Fe(50 ML)/InAs(100) film along the four major crystal axes. The films clearly display a cubic anisotropy, with the magnetic easy axes along $\langle 001\rangle$, the easy axes of bulk bcc Fe. It is noteworthy that the uniaxial anisotropy, which was found in the Fe/GaAs system,[3,13] was not observed in the Fe/InAs(100)-4×2 structure in the thickness range of 15–50 ML. The coercivity $H_c$ of the 50 ML film is $28\pm1$ Oe, which is very similar to that of Fe/GaAs; e.g., $H_c=25$ Oe and $H_c\sim30$ Oe were reported by Florczak and Dahlberg,[4] and Gester *et al.*,[13] respectively. For the loops with the field applied along the $\langle 011\rangle$ directions, the curves indicate an abrupt switching at 28 Oe followed by a gradual increase to saturation at approximately $380\pm50$ Oe. If a coherent rotation process is assumed for the magnetization along the $\langle 011\rangle$ hard axis, the cubic anisotropy $H_k=2K_1/M$ of the films is about 380 Oe. This value is slightly smaller than that of the bulk bcc Fe, $H_k\sim550$ Oe, and comparable with the cubic anisotropy of a Fe(73 Å, ~50 ML)/GaAs(100) film, $H_k\sim400$ Oe.[13] Magnetic properties are well known to depend sensitively on film structure. The distinctly anisotropic hysteresis loops in Fig. 2 and the comparable coercivity and cubic anisotropy to that of Fe/GaAs system suggest that high quality bcc Fe films with well defined magnetic properties

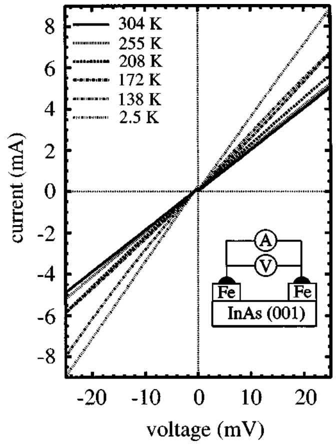

FIG. 3. $I-V$ measurements of Fe(50 ML)/InAs(100) in the temperature range 2.5–304 K. The dimension of the Fe contacts, processed using optical lithography, is 50 $\mu$m with separation of about 250 $\mu$m.

can be stabilised on the InAs(100)-$4\times2$ substrate.

Fe is expected to form an ohmic contact to InAs due to the pinning of the Fermi energy in the conduction band at the InAs surface, which results in a charge accumulation layer at the surface. In order to verify this, the samples were characterized by current–voltage ($I-V$) measurements. Before removal from the chamber, the samples were capped with 30 Å of Au to prevent oxidization. The Fe contacts with dimensions of approximately 50 $\mu$m were processed using optical lithography and a combination of $CHF_3$ based reactive ion etching and selective wet etching.[14] The substrate is *n*-type InAs with $\sim 2.5\times 10^{18}$ cm$^{-3}$ sulphur doping. Typical $I-V$ characteristics are shown in Fig. 3. They 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 is due to the increase of the mobility at low temperature. We conclude that MBE grown Fe films form low-resistance ohmic contacts on InAs(100) substrates that have been cleaned by a combination of plasma and wet etching, followed by annealing in UHV prior to the deposition.

In summary, single crystal Fe films have been successfully grown on InAs(100) substrates using molecular beam epitaxy. The orientation of the growth is determined by LEED to be the same as that for the Fe/GaAs system, namely Fe$(100)\langle 001\rangle \| $InAs$(100)\langle 001\rangle$, and STM images show that growth proceeds via a 3D Volmer–Weber mode. MOKE measurements show that the films have a well defined cubic anisotropy and negligible uniaxial anisotropy. The Fe films form a low resistance ohmic contact to InAs as evidenced by the temperature dependent $I-V$ measurements. The results demonstrate that Fe/InAs is a very promising system for use in future magnetoelectronic devices as it has both favorable magnetic and electrical properties.

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