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Ferromagnetic/III-V Semiconductor Heterostructures and Magneto-Electronic Devices

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***Abstract* —The interface magnetic and electronic properties of two Fe/III-V semiconductor systems, namely Fe/GaAs and Fe/InAs, grown at room temperature have been studied. A "magnetic interface", which is essential for the fabrication of magneto-electronic (ME) devices, was realized in both Fe/GaAs and Fe/InAs systems with suitable substrate processing and growth conditions. Furthermore, Fe/InAs was shown to have favorable interface electronic properties as Fe forms a low resistance ohmic contact on InAs. Two prototypes of ME device based on Fe/InAs are also discussed.**

***Index Terms*: ultrathin films interface magnetism, Fe/GaAs, Fe/InAs, magnetoelectronics**

I. INTRODUCTION

Based on the fact that electrons have spin as well as charge, an exciting new field of electronics, magnetoelectronics (ME) has attracted much attention recently [1, 2]. Future magneto-electronic devices, in which the spin of the electron is controlled, are expected to find applications based on hybrid ferromagnetic metal (FM)/semiconductor structures. Such spin-sensitive devices require well defined and magnetic interface layers. However, the "magnetic dead layers" at the interface as previously reported on Fe/GaAs[3, 4], would be detrimental to the spin-dependent transport. The fabrication of ever-smaller devices leads to higher current densities, which in turn need low resistance contacts at the interface to reduce thermal dissipation. Thus the interface magnetic and electronic properties of the ferromagnetic/semiconductor heterostructures are key issues for current research.

The most extensively studied system to date is Fe/GaAs [3-6]. As Fe forms a rectifying contact on GaAs [7], the Schottky barrier prevents efficient electron-injection from the FM pads to the semiconductor substrates. Our preliminary studies [8] of Fe/InAs have shown that bcc Fe can be stabilized on InAs, which has a narrow gap of about 0.36eV at 300K, as shown in Fig.1, and forms low resistance contacts. In this paper we report the *interface* magnetic and electronic properties of both Fe/GaAs and Fe/InAs systems. We further proposed two prototype spin-selective devices based on Fe/InAs hybrid structures.

II. MBE GROWTH

This study was carried out in a "multi-technique" molecular

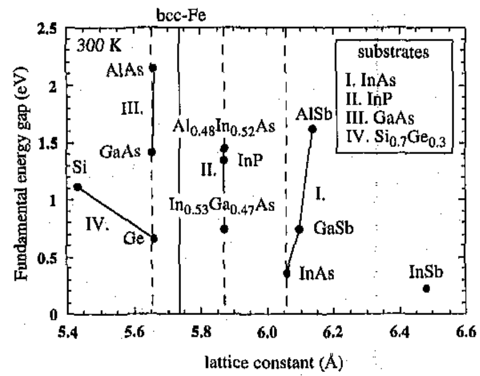

Fig. 1 The fundamental energy gap against lattice constant for several III-V compounds and Si - Ge. The lattice constant (x2) is shown for bcc Fe.

beam epitaxy (MBE) system [8]. Fe films were grown at a rate of one monolayer (ML) per minute using an e-beam evaporator and at room temperature in this study rather than elevated temperatures to reduce the intermixing at the interface [4]. The GaAs substrates used were As capped GaAs(100) prepared in another UHV chamber. A buffer layer (~0.5 μm) of homoepitaxial GaAs was grown on the commercial wafer to provide the smoothest possible GaAs surface. The InAs(100) substrates used were commercial wafers. Before loading into the UHV system, the substrates were cleaned using a combination of oxygen plasma etching and wet etching (HCl : H_2O = 1 : 4). The GaAs and InAs substrates were annealed at 550°C for one hour and 510°C for half an hour, respectively, before Fe deposition. LEED and RHEED measurements showed that the surface of the GaAs(100) is Ga-rich 4×6 reconstruction, and that of InAs(100) is In-rich 4x2 reconstruction. The epitaxial growth of the films was monitored with both LEED and RHEED. Clear diffraction patterns from the Fe overlayers were observed after about 3-5ML of deposition. The epitaxial relationships as shown by LEED and RHEED patterns are Fe(001)<100>||GaAs(001)<100> and Fe(100)<001>||InAs(100)<001>. Detailed studies of the growth morphology and lattice relaxation will be presented elsewhere.

III. INTERFACE MAGNETISM

The evolution of the ferromagnetic phase has been studied in detail using *in-situ* magneto-optic Kerr effect (MOKE) measurements. The MOKE hysteresis loops were collected in the longitudinal geometry using an electromagnet with a

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maximum field of 2kOe, and intensity stabilized HeNe laser. The thickness dependencies of the MOKE intensity of Fe/GaAs and Fe/InAs are shown in Fig. 2(a) and (b) respectively. The magnetic phase proceeds via three phases as shown by a schematic diagram in Fig.3: a non-magnetic phase (I), a short-range-ordered superpara-magnetic phase (II) [9], and a ferromagnetic phase (III). The empty and filled circles in Fig 2 are the results before and after the onset of the long-range ferromagnetic phase respectively. The critical thicknesses are rather close in both systems, suggesting the similarity of the evolution of ferromagnetic phase in the Fe/III-V semiconductor heterostructures. Nonmagnetic phase I (GaAs: 0-3.5ML, and InAs: 0-2.5ML). STM measurements [10] show that the films grown at room temperature are not continuous in this initial stage due to 3D-growth mode of both systems. The lack of magnetic signal is due to the smaller initial cluster size, which prevents the development of magnetic ordering, or the ordering above room temperature.

Superparamagnetic phase II (GaAs: 3.5-4.8ML, and InAs: 2.5-3.8ML). As more Fe is deposited, the islands grow and coalesce to form bigger clusters. The exchange interaction within these clusters becomes stronger and leads to internal ferromagnetic ordering, so giving rise to the well-known superparamagnetic phase [11]. The MOKE intensity increases rapidly in these narrow thickness ranges. Ferromagnetic phase III (GaAs: >4.8ML, and InAs: >3.8ML). With further increase in the coverage, the islands coalesce and long range ferromagnetic ordering develops. The hysteresis loops after the onset of the ferromagnetic phase show that the films have a well-defined magnetic coercivity and remanence ratio, indicating the behaviour of a continuous film. After the critical thicknesses of about 4.8ML and 3.8ML for Fe/GaAs and Fe/InAs respectively, the MOKE signal is approximately *linearly* proportional to the thickness as shown by the filled circles. Extrapolation of these data suggests that there are *no magnetically dead layers*, and that the entire Fe film is ferromagnetic in both systems after the onset of ferromagnetism. We thus demonstrated that a "magnetic interface" can be achieved in both Fe/GaAs and Fe/InAs systems. The MOKE signals above about 12-14ML show a slightly reduced slope in Fe/GaAs and increased slope in Fe/InAs. This behaviour may be due to structural changes at higher coverages [10].

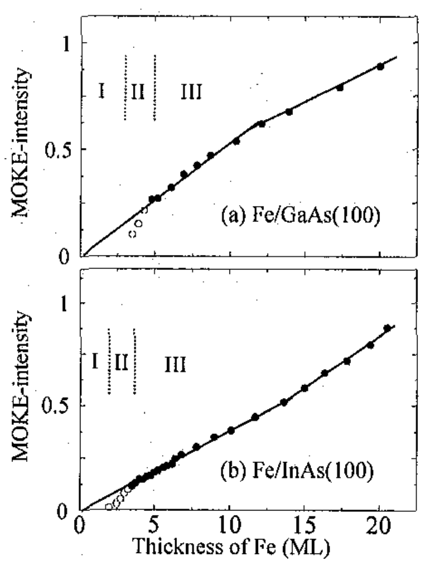

Fig.2 Thickness dependencies of the *In-situ* MOKE intensity of (a) Fe/GaAs(100)-4x6 and (b) Fe/InAs(100) –4x2 grown at room temperature.

VI. INTERFACE ELECTRONIC PROPERTIES

It is well known that metals form a rectifying contact on GaAs and the Schottky barrier is about 0.8eV independent approximately on the work function of the metals [7]. Metals are 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, which was performed *ex-situ* in the 304 - 2.5 K temperature range using a Keithley 236 source-measure unit. The Fe contacts, with dimensions of approximately 50μm, were processed using optical lithography and a combination of CHF_3 based reactive ion etching and selective wet etching. The substrate is n-type InAs with ~ 2.5 x 10^{18} cm^{-3} sulfur doping. Typical I-V characteristics are shown in Fig. 4. They are linear over the temperature range 304 to 2.5K and show ohmic contact at the Fe/InAs interface. The equivalent resistance is weakly dependent on temperature, varying from 5 to 2.8 Ω in the temperature range 304 to 2.5K. This may be due to the increase of the mobility at low temperature.

V. SPIN-POLARIZED FET

Datta and Das[12] have suggested the construction of a spin-polarized field effect transistor (FET), which applied the spin-injection concept to a semiconductor. Such devices have not yet been demonstrated as far as we know. This may be due to the difficulty in achieving a low resistance contact between the FM pad and the two dimensional electron gas(2DEG). To minimize the effect of the Schottky barrier in GaAs based devices, a graded layer of n-$In_xGa_{1-x}As$ from GaAs to InAs with a thickness of 50nm has been grown on GaAs before FM deposition. A spin FET device is being developed for which schematic diagrams are shown in Figs. 5

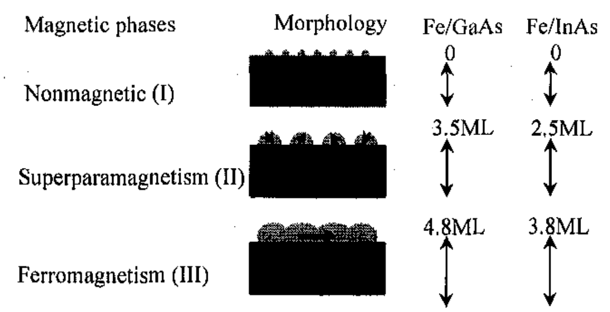

Fig. 3 A picture of the correlation between the coverage, morphology and magnetic phases of Fe films on GaAs(100) and InAs(100) substrate grown at the room temperature.

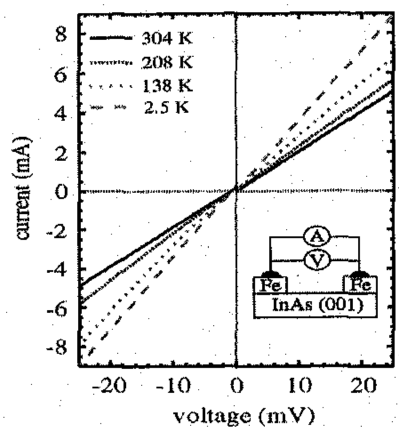

Fig.4 I-V measurements of Fe(50ML)/InAs(100) in the temperature range of 2.5 to 304K.

(a) and (b). The spin-polarized carriers are injected and collected by single crystal Fe elements, for which the electrons are expected to have a long coherence length. With an InAs graded buffer layer, there is no energy barrier for the electron to tunnel through FM-2DEG-FM channel making InAs a favorable choice of materials. The device can operate in two modes: a) Control by external electric field - a gate voltage is applied to the 2DEG to alter the spin precession, as proposed by Prinz et al[1]. b) Control by an external magnetic field – switching of each Fe pad could be controlled separately by applying an external magnetic field if the two Fe pads have different shapes. Single crystal Fe films have been grown on this graded InAs buffer layer and *in-situ* MOKE showed that the films have well defined magnetic properties [13]. We are optimizing the fabrication condition in order to realize smallest possible separation of two Fe pads.

IV. Spin-Polarized RTD

InAs/AlSb/GaSb resonant tunneling diodes (RTD) are of great interest in the fabrication of high-speed analog devices as well as multi-valued logic circuits [14]. If magnetic materials could be incorporated with this semiconductor heterostructure, a novel device, namely a spin-RTD might be developed, in which both the energy and spin of the electrons are controlled for device operation. Fig. 5 (c) shows schematically the device structure with a patterned element. A double-barrier RTD of this type was grown by MBE on GaAs (100). The elements of width 20μm and length varying from 20 to160μm were patterned using selective wet etching. We have shown that Fe grows epitaxially on both top and bottom InAs layers. By varying the shape of the elements, different switching fields for the top and the bottom layers, as required for device operation have been realized [13]. Details about the MBE growth of the RTD, and the fabrication and characterization of the devices will be published elsewhere.

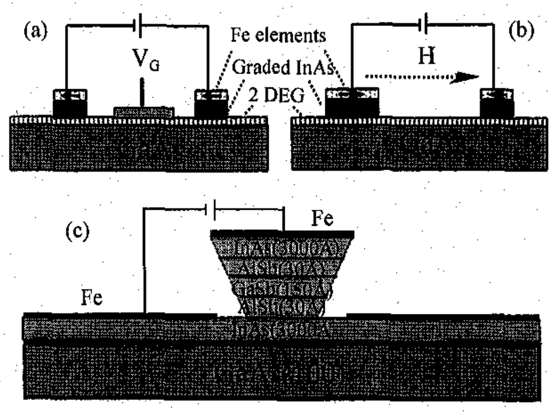

Fig.5 Schematic diagrams of (a) spin-polarized-FET controlled by external electric field, and (b) Controlled by the external magnetic field, and (c) a spin-polarized RTD of Fe on patterned InAs/AlSb/GaSb double barrier-RTD.

IIV. Summary

We have studied the epitaxial growth, magnetic and electronic properties of both Fe/GaAs and Fe/InAs systems. The interface magnetic and electronic properties of these two systems have been studied and compared in details. We have demonstrated that with suitable substrate preparations and growth conditions both Fe/GaAs (100) and Fe/InAs films do not exhibit a magnetically "dead" layer at the interface and Fe forms low resistance ohmic contact on InAs. Two prototype spin-selective devices, namely spin-polarized FET and spin-polarized RTD, were proposed.

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