Interface Magnetic and Electrical Properties of CoFeB /InAs Heterostructures

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Amorphous magnetic CoFeB ultrathin films have been synthesized on the narrow band gap semiconductor InAs(100) surface, and the nature of the interface magnetic anisotropy and electrical contact has been studied. Angle dependent hysteresis loops reveal that the films have an in-plane uniaxial magnetic anisotropy with the easy axis along the InAs [0-11] crystal direction. The uniaxial magnetic anisotropy was found to be dependent on the annealing temperatures of the substrates, which indicates the significant role of the Fe, Co-As bonding at the interface related to the surface condition of the InAs(100). *I-V* measurements show an ohmic contact interface between the CoFeB films and the InAs substrates, which is not affected by the surface condition of the InAs (100).

Index Terms—**CoFeB, InAs, uniaxial magnetic anisotropy, ohmic contact.**

I. Introduction

SPINTRONIC devices, in which the spin of electrons is controlled, are expected to find applications based on hybrid semiconductor structures, for example, spin field effect transistor (Spin-FET) [1]-[3]. Many works concentrated on the epitaxial growth of single crystal ferromagnetic (FM) films on oriented semiconductor substrates, especially body-centered cubic (bcc) FM films grown on III-V semiconductor substrates by molecular beam epitaxy (MBE) [4]-[9]. There is an in-plane uniaxial magnetic anisotropy (UMA), which is unexpected from the crystal symmetry, in these heterostructures. For example, Fe/GaAs heterostructures display an in-plane UMA with the easy-axis (EA) along [110] direction regardless of the GaAs surface reconstruction [10], which is distinctively different from the cubic magnetic anisotropy of the bulk bcc structure with EA along [100] direction [4]-[9]. Several previous works attribute this UMA to an interfacial Fe-As bonding interaction [5], in which Fe prefer to bond with As or themselves rather than Ga.

While magnetocrystalline anisotropy and long range structural order may also lead to the appearance of UMA, amorphous CoFeB film that lacks magnetocrystalline anisotropy and long rang structural order has attracted extensive attention to gain insight into the origin of the UMA [11]-[13]. CoFeB thin films have been studied in many fields, including tunneling magnetoresistance [14], [15], current–induced magnetization switching, and magnetic random access memories (MRAM) [16], *etc*. Regarding high spin polarization and high resistivity, CoFeB is also a candidate as spin-injection source in Spin-FET. An in-plane UMA in CoFeB/(Al)GaAs(001) heterostructures with an EA along [110] was found [17]. The mechanism of this UMA has been proposed to be bond-orientational anisotropy (BOA) model [17]-[20]. For further application in spintronic devices, ohmic contact and low mismatch of resistivity are necessary to realize high spin injection efficiency [21]. Since InAs possesses zinc blend structure, which is the same as that of GaAs, CoFeB/InAs heterostructure shows the potential appearance of a UMA. The resistivity of InAs, as low as $\rho=1.8\times10^{-3}$ Ω·cm [22], is only 10 times higher than that of CoFeB, i.e., $\rho=1.78\times10^{-4}$ Ω·cm [23]. This means that CoFeB/InAs heterostructure has low mismatch of resistivity, about two orders of magnitude lower than that of Fe/GaAs [24], promising high spin injection efficiency.

In this letter, amorphous $Co_{40}Fe_{40}B_{20}$ thin films on InAs substrates were grown by magnetron sputtering technique. Magnetic properties were studied with a vibrating sample magnetometer (VSM), and electrical properties were studied with temperature-dependent current-voltage (*I-V*) measurements. An interfacial anisotropy in the CoFeB/InAs heterostructures with an EA along InAs [0-11] crystal direction and an ohmic contact between the CoFeB films and InAs substrates were observed.

II. Experiments

The samples were prepared in an ultrahigh vacuum (UHV) magnetron sputtering system. The n-type undoped InAs(100) substrates were first cleaned using acetone, ethanol, and deionized water in sequence, to remove the contaminants on the surface, and then etched with hydrochloric acid (HCl: H_2O= 1:1) for 50 seconds to remove the oxide before loaded into the UHV system. The substrates were annealed at different temperatures in the range of 530-570 °C for half an

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hour, and then cooled to room temperature before depositing the CoFeB film [1], [24]. The 3.5 nm $Co_{40}Fe_{40}B_{20}$ films with a purity of 99.99% and the 2 nm capping Ta layers were deposited on InAs (100) substrates at a rate of approximate 1.2 nm and 7.5 nm per minute, respectively, with a base pressure of 6×10^{-6} Pa and a working pressure around 0.3 Pa. During the period of depositing the films, no magnetic field was applied in the chamber and the InAs substrates were maintained at room temperature.

III. Results and Discussion

Fig. 1 shows the magnetic hysteresis loops of CoFeB films grown on InAs substrates, which were measured with VSM. The magnetic field is applied along the in-plane crystal direction [011], [001], [0-11], and [010] of the InAs(100) substrates. One can notice an obvious UMA with EA along the [0-11] direction in the samples with annealing temperature (T_a) of substrates at 570 °C, 560 °C, and 550 °C, respectively. The hard-axis (HA) in these three samples are along the [011] direction. The sample with T_a = 560 °C shows the largest saturation field of 45 Oe, about 5 Oe larger than that of the other two samples. The magnetic hysteresis loops along the EA, which display a sharp rectangular shape, are different from that of the polycrystalline and amorphous FM films deposited in an applied magnetic field. Polycrystalline and amorphous FM films deposited in an applied magnetic field typically show a UMA with EA along the direction of the applied field [12], [25]. However, there is no applied field during the film deposition in this study, and amorphous CoFeB films exhibit no magnetocrystalline anisotropy and long rang structural order. All of these indicate that the UMA of CoFeB/InAs heterostructures originates from the interface interaction between CoFeB thin film and InAs substrate [19], [24]. The sample with T_a = 560 °C shows the largest coercivity of 8 Oe, which is twice as large as that of the samples with T_a = 570 °C and 550 °C. However, the sample with T_a = 530 °C shows similar hysteresis loops along 4 major directions with an abrupt switching at 10-12 Oe followed by a gradual increase to saturation at around 40 Oe. These loops suggest no obvious UMA in the sample with T_a = 530 °C.

Angle dependent VSM measurements were performed to verify the UMA of the samples with the capability of determining the angle dependence of both the longitudinal magnetization (M_{long}) and transversal magnetization (M_{trans}), as shown in Fig. 2(a). Each data point was measured under zero magnetic field after removing an applied magnetic field along M_{long}, which was lager than the saturation field. Fig. 2(c) shows the typical angle dependence of M_{long} and M_{trans} of the sample with T_a = 560 °C. The samples with T_a = 570 °C and 550 °C exhibit similar characteristics of M_{long} and M_{trans}. We observed a period of 180° with M_{long}, as well as M_{trans} in these curves. Maximum of M_{long} and minimum of M_{trans} were observed when the magnetic field was applied along the EA, while the minimum of M_{long} and maximum of M_{trans} were observed when the magnetic field was applied along the HA. As can be seen from Fig. 2(c), the M_{trans} reduced sharply when the direction of the applied magnetic field was in the vicinity of HA. This is because the magnetization vectors have the same possibility of rotating to the parallel and anti-parallel direction of the EA after removing of the magnetic field applied along the HA, as shown in Fig. 2(b). Such results further prove the existence of in-plane UMA in these samples.

The CoFeB/InAs heterostructures with T_a = 570 °C, 560 °C, and 550 °C all show an in-plane UMA, whereas the sample with T_a = 530 °C exhibits no UMA. The sample with T_a = 560 °C has a higher anisotropy field than the samples with T_a = 570 °C and 550 °C. We conclude that the annealing temperature of the substrates before the deposition has significant influence on the magnetic properties of CoFeB/InAs heterostructures, not only the appearance of the UMA, but also the saturation field and coercivity. Previous works show that InAs surface is dominated by the In atoms at low annealing temperatures with surface reconstruction of (1×2) to (2×3) at 330 °C, (2×4) at 380 °C, and (4×2) at 530 °C [26]-[28]. The surface is dominated by the As atoms with no In atoms floating on top above 530 °C. At the annealing temperature of 570 °C, 560 °C, and 550 °C, since the InAs surface was dominated by As atoms, the Fe, Co-As bonding formed at the interface of CoFeB/InAs heterostructures. The Fe, Co-As bonding induced bond-orientational anisotropy resulting in the appearance of UMA in the CoFeB/InAs heterostructures with the EA along [0-11] direction [5], [17-20]. At the annealing temperature of 530 °C, lacking As atoms at the InAs surface resulted in that the Fe, Co-As bonding could not form effectively when the CoFeB film was deposited. Therefore the CoFeB/InAs heterostructure exhibits no UMA with the InAs substrate annealed at 530 °C.

The sample (T_a = 550 °C) with a UMA and the sample (T_a = 530 °C) without a UMA were used to make a comparison of different electrical properties. Samples were etched by argon ion milling with shadow masks. Then Current-Voltage (*I-V*) measurements were performed on these samples, which possessed two patterns with a 0.38 and 0.46 mm gap in the middle, respectively, as shown in Fig. 3(a). This structure can be seen as a Ta/CoFeB/InAs/CoFeB/Ta junction, the resistance of which can be analyzed as a series connection of R_{metal}, $R_{contact}$, R_{InAs}, $R_{contact}$, and R_{metal}, as shown in Fig. 3(b). Typical *I-V* curves at different temperatures of 2 K, 50 K, 100 K, 150 K, 200 K, 250 K, and 300 K are shown in Fig. 3(c) and Fig. 3(d). These curves of both samples are linear over the voltage range from -1 V to 1 V, i.e., both samples have well defined ohmic contact. The similar results are also observed in Fe/InAs, and Fe is reported 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 [1]. This should also be the origin of ohmic contact between CoFeB and InAs. The formation of ohmic contact between CoFeB and InAs does not depend on the annealing temperatures of substrates, and thus is not sensitive to the surface condition. Resistance-temperature (*R-T*) curves of these two samples are shown in Fig. 3(e) and Fig. 3(f). Resistance decreases as temperature rises from 2 K to 300 K. As R_{metal} of these two samples can be got by calculation as 2×10^{-9} Ω and 2.8×10^{-9} Ω, respectively, which is negligible compared to the total resistance, the curves mainly show the resistance of semiconductor InAs channel and the contact versus temperature. The resistance difference and change ratio versus temperature observed from Fig. 3(e) and Fig. 3(f) should come from the different width of the gap between patterns and different pattern areas of the two samples. We conclude that the CoFeB films grown by magnetron sputtering form ohmic contace with low resistance on the annealed InAs(100) semiconductor substrates.

IV. Conclusions

In summary, we grew $Co_{40}Fe_{40}B_{20}$ films on InAs (100) substrates by magnetron sputtering, and performed VSM measurements on these samples. Pronounced UMA appeared in these heterostructures with EA along [0-11] and HA along [011]. The annealing temperature of the substrates plays a significant role in the appearance of UMA, as well as the coercivity and saturation field. The origin of the uniaxial magnetic anisotropy of CoFeB/InAs heterostructures is attributed to the Fe, Co-As bonding interaction induced bond-orientational anisotropy. The CoFeB films form an ohmic contact on InAs substrates as evidenced by the temperature-dependent *I-V* measurements. The results demonstrate that CoFeB/InAs is a very promising system for application in future spintronic devices as it has both favorable magnetic and electrical properties.

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Fig. 1. Normalized magnetic hysteresis loops of Ta(2nm)/CoFeB(3.5nm)/InAs heterostructures with T_a = 570 °C (first arrow), T_a = 560 °C (second arrow), T_a = 550 °C (third arrow), and T_a = 530 °C (forth arrow). The loops were measured with magnetic field along the four major axes [011] (first column), [001] (second column), [0-11] (third column) and [010] (forth column) at room temperature. UMA with an EA along [0-11] have been observed in the samples with T_a = 570 °C, 560 °C, and 550 °C, respectively, while no UMA can be found in the sample with T_a = 530 °C.

Fig. 2. (Color online) (a) Schematic diagram of the measurements. M_{long} and M_{trans} were measured after removing the magnetic field, which was first applied to saturate the samples. (b) Schematic magnetic domains after the applied field was removed. (c) Angle dependent remanent magnetization/ saturation magnetization (*Mr/Ms*) of the CoFeB/InAs heterostructure with substrate annealed at 560 °C.

Fig. 3. (Color online) (a) Schematic diagram of the patterned samples used to perform the electrical measurements. (b) Equivalent circuit of the measurements, R_{metal} represents the resistance of Ta and CoFeB pads, $R_{contact}$ represents the contact resistance between CoFeB and InAs, and R_{InAs} represents the resistance of InAs channel. *I-V* curves of (c) sample with T_a = 550 °C, and (d) sample with T_a = 530 °C in the temperature range of 2-300 K. *R-T* curves of (e) sample with T_a = 550 °C, and (f) sample with T_a = 530 °C.

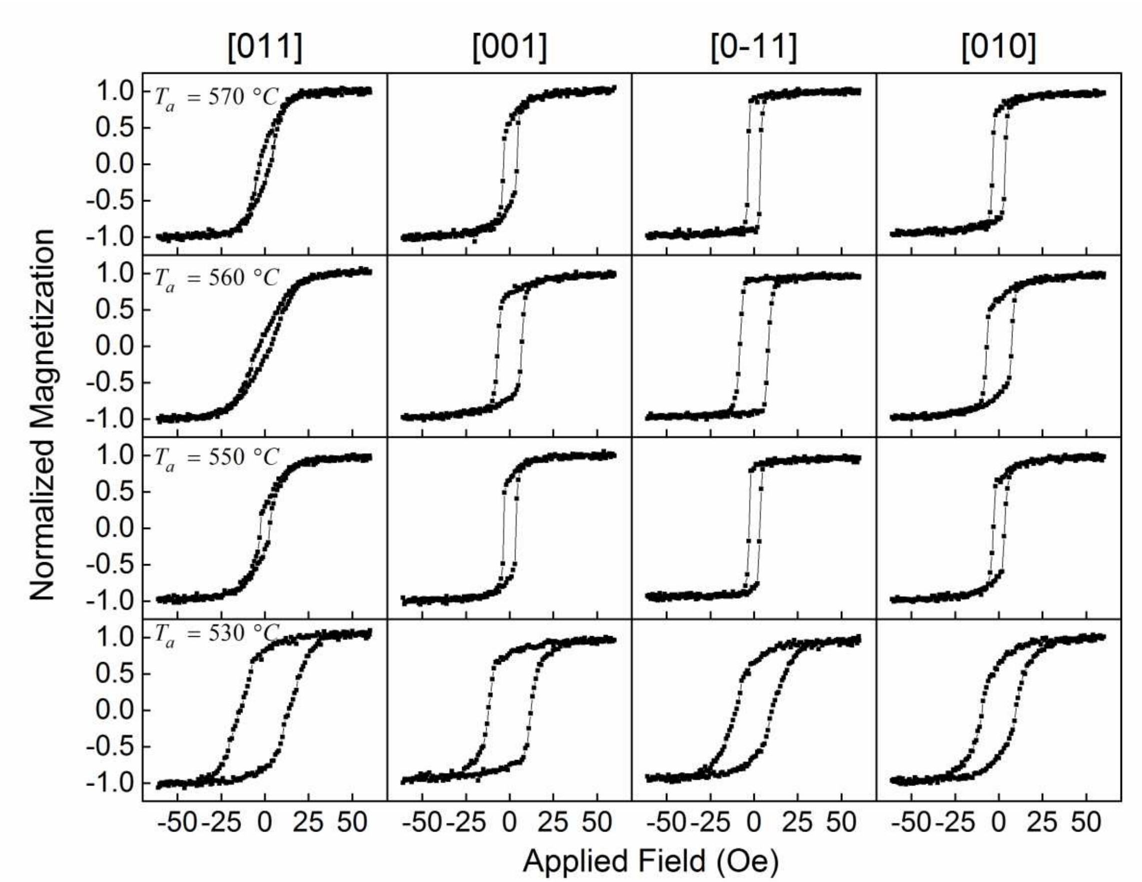

Fig. 1 Zhenyao Wu *et al.*

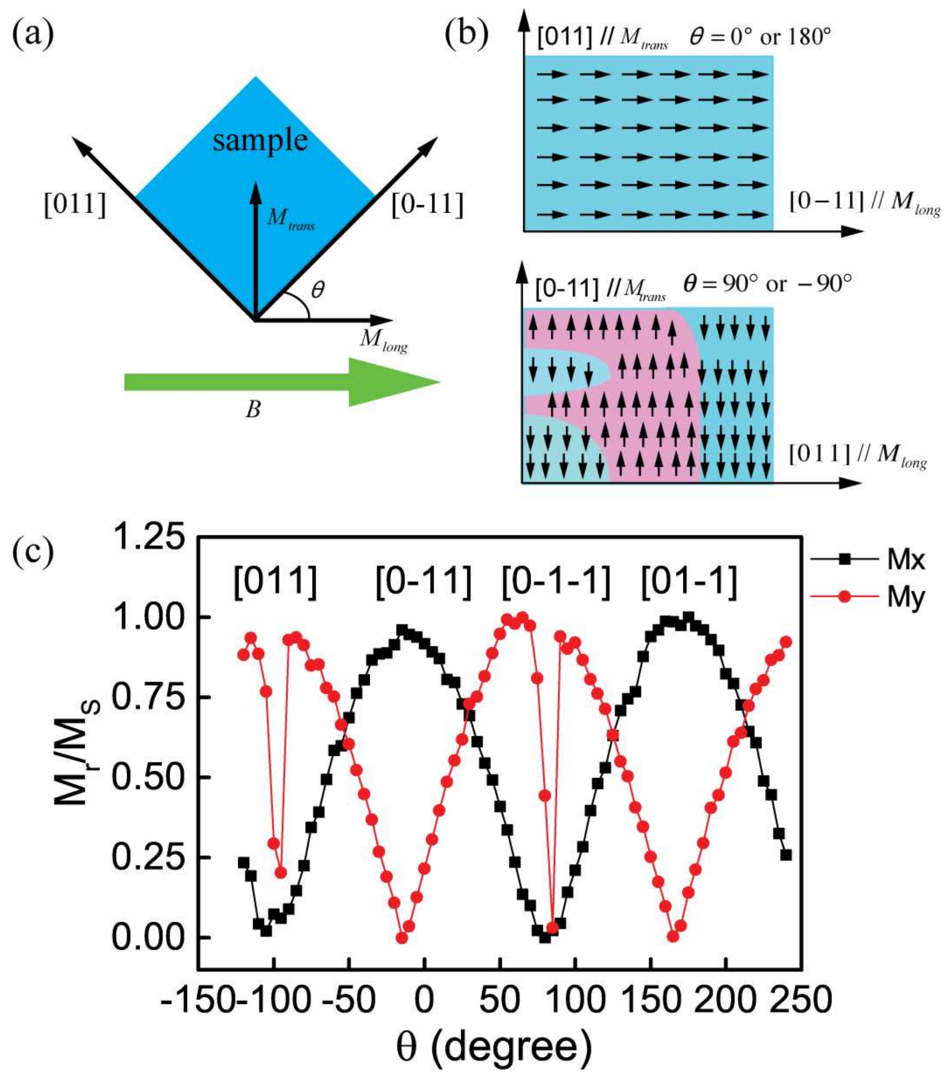

Fig. 2 Zhenyao Wu *et al.*

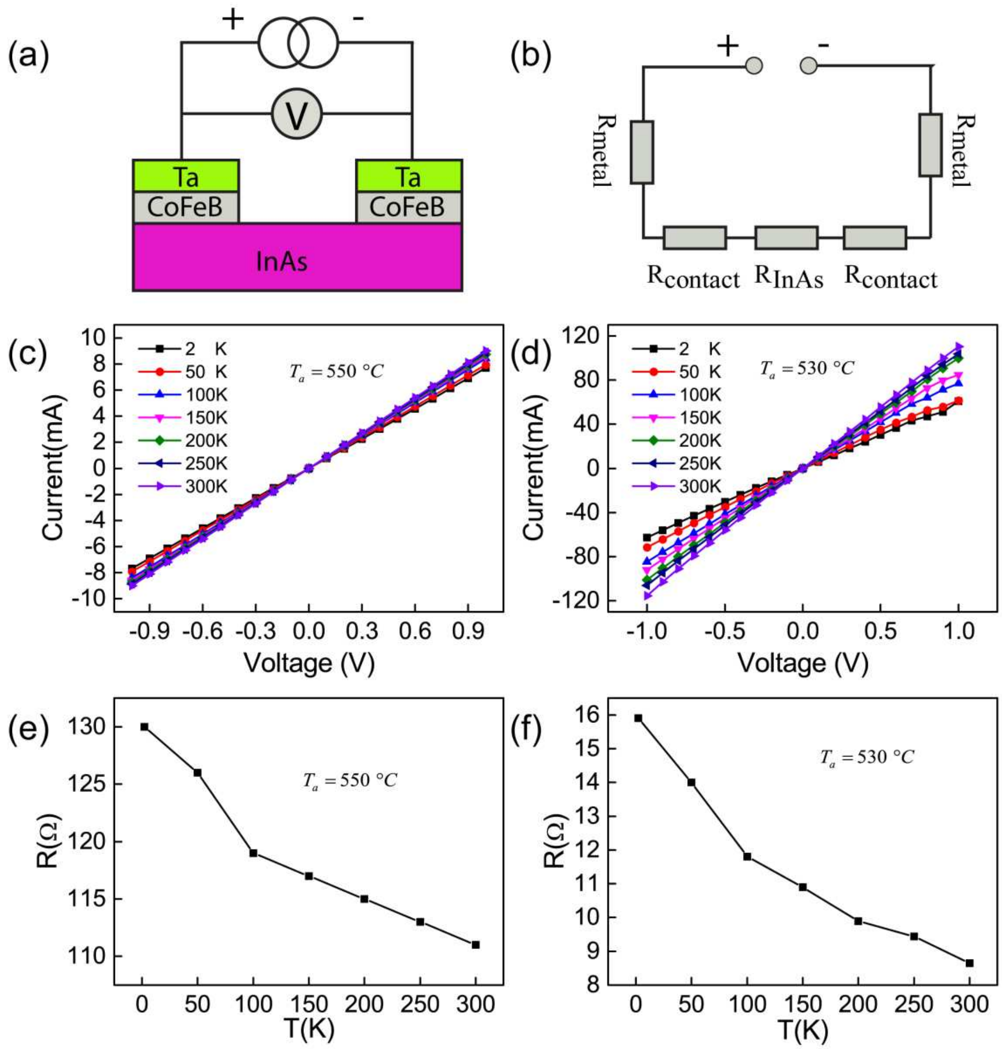

Fig. 3 Zhenyao Wu *et al.*