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Magnetic properties of Fe_3Si films with thickness from 2 to 210 monolayers (ML) epitaxially grown on GaAs (001) were studied using a superconducting quantum interference device and alternating gradient force magnetometers. Growth of these single-crystal intermetallic compound films were carried out in a multichamber molecular beam epitaxy (MBE) system. The samples were covered *in situ* with Au 50 Å thick to prevent oxidation when the samples were removed from the MBE chamber. All the films are ferromagnetic even for samples as thin as 2 ML. The easy magnetization direction of the films is parallel to the film surface. The magnetic coercivity forces (H_c) of the samples increase as the film thickness decreases to 10 ML, and then decrease when the film thickness decreases further to 2 ML.

INTRODUCTION

The integration of magnetic materials with III-V compound semiconductors may provide new devices which expand the usages of both classes of materials. Many elements and intermetallic compounds have been found to grow epitaxially on GaAs.[1-7] Among them Fe, bcc Co, and $Fe_3Al_{1-x}Si_x$ films are ferromagnetic at room temperature.[3,7]

For Fe or Co on GaAs, interaction and interdiffusion occur at some moderate temperatures of ~200 °C. In contrast, the interface between GaAs and the intermetallic compound $Fe_3Al_{1-x}Si_x$ is thermodynamically stable for temperatures up to 600 °C.[8] This compound has a BiF_3 (DO_3) structure with a lattice constant very close to that of GaAs, while bulk GaAs possesses a zinc-blende structure with a lattice constant of 5.6533 Å, as illustrated in Fig. 1.

In this paper, we focused on the magnetic properties of one member of the compound family, Fe_3Si, which has a lattice constant of 5.64 Å. The lattice mismatch between Fe_3Si (001) and GaAs (001) is only −0.23%. The stability at the interface and the small lattice mismatch allow us to prepare epitaxial ultrathin [a few monolayers (ML)] Fe_3Si films on GaAs in a multichamber molecular beam epitaxy (MBE) system.[7] We observed that Fe_3Si films down to 2 ML thick are ferromagnetic and the easy magnetization is in the film plane. The coercivities of the films increase with decreasing thickness, and then decrease when the film thickness is less than 10 ML.

EXPERIMENT

The MBE system includes two growth chambers; a solid source III-V (GaAs) chamber and a metal deposition chamber which is As free and is equipped with two electron guns and several effusion cells, capable of evaporating materials with high melting points. In this work, Fe and Si were evaporated from electron beam sources with a deposition rate of 0.5 Å/s for Fe_3Si. First, a buffer layer of GaAs 1 μm thick was grown on a GaAs (001) wafer. The sample was then transferred to the metal deposition chamber for the growth of Fe_3Si. A wide range of substrate temperatures between 250 and 500 °C were used. The growth and microstructure of Fe_3Si films were studied using *in situ* reflection high energy electron diffraction (RHEED) and transmission electron microscopy (TEM). Rutherford backscattering spectrometry (RBS) was used to calibrate the composition and the thickness of thicker Fe_3Si films. The film thickness varies from 2 to 210 ML. All of the films were coated *in situ* with a thin layer of Au 50 Å thick to prevent oxidation of ultrathin Fe_3Si films.

The magnetization was measured at room temperature (300 K) by using an alternating-gradient force magnetometer, and at 10 K by using a commercial superconducting quantum interference device magnetometer. Sizes of the

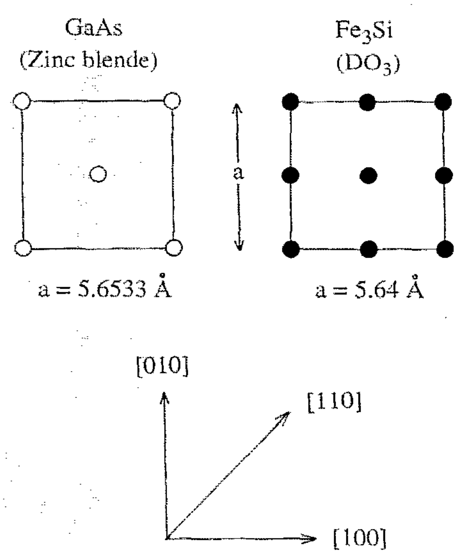

FIG. 1. (001) unreconstructed surface of GaAs and Fe_3Si with their respective lattice constants of bulk crystal structures.

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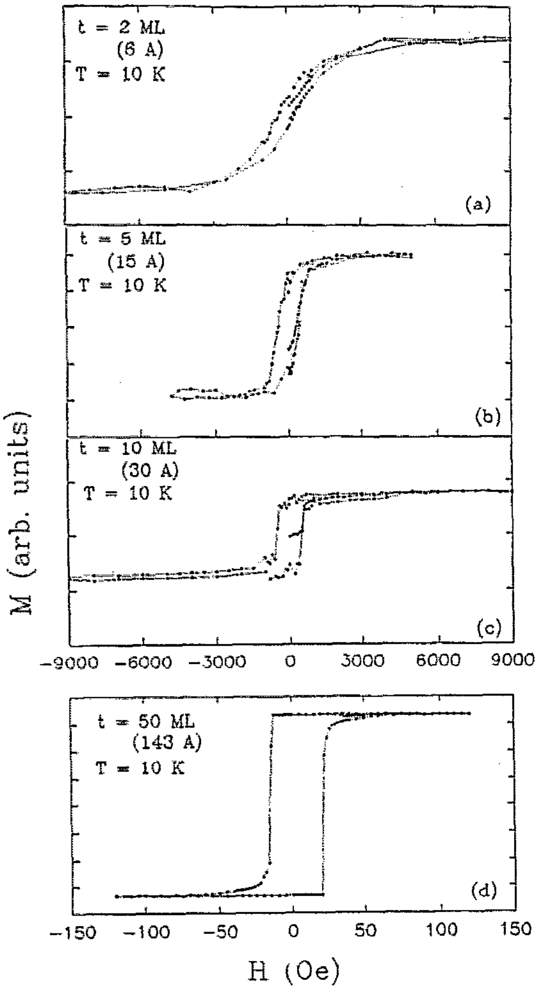

FIG. 2. Hysteresis loops of epitaxial ultrathin Fe_3Si films on GaAs (001) measured at 10 K for various film thickness; (a) 2 ML, (b) 5 ML, (c) 10 ML, and (d) 50 ML.

measured samples are ~5 mm×5 mm. The magnetic field was applied in the film plane along the [110] direction. Note that [110] of Fe_3Si is parallel with [110] of the GaAs buffer layer.[7,9] We also measured the samples with the magnetic field applied perpendicular to the film plane and in the film plane along [100].[10]

RESULTS AND DISCUSSION

Owing to a very small lattice mismatch (−0.23%), fully strained layers of Fe_3Si were grown on GaAs (001). From our previous TEM study,[9] no misfit dislocation was observed in the as-grown samples even for films as thick as 600 Å (210 ML). The cross-section images show clearly that sharp interfaces existed between Fe_3Si and GaAs. As indicated by the elongated sharp streaky RHEED patterns, an atomically smooth Fe_3Si surface was obtained even for growth of 1 ML. Moreover, Kikuchi arcs which are indicative of a well-ordered single crystal were present for films with thickness greater than 12 ML.

The magnetizations (M) versus applied fields (H) shown in Figs. 2(a)–2(d) were measured at 10 K with the

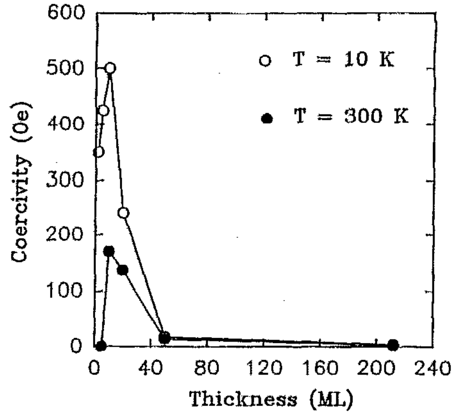

FIG. 3. Magnetic coercivity force (H_c) vs film thickness of Fe_3Si measured at 10 and 300 K.

field being parallel to the film plane and along the [110] direction. Due to the large portion of the sample being GaAs substrate which is diamagnetic, the negative slope is present in the original magnetization curve. The negative slope was corrected by assuming a linear dependence of the diamagnetic signal versus the magnetic field. From Fig. 2(a) of the sample 2 ML thick, it clearly indicates the existence of a ferromagnetic state. The magnetic moment of these measured samples is about 140 emu/g which is close to that of bulk Fe_3Si.[11] The total weight of each sample was estimated by comparing the weight before and after etching and subtracting the weight of the Au overcoating. As indicated by the behavior of initial magnetization, which is almost flat until the external magnetic field approaches the magnetic coercivity force (H_c), the domain wall pinning is very strong in these films. The samples exhibit square hysteresis loops except for the film 2 ML thick.

The H_c's of the films measured with magnetic field parallel to the film surface and along [110] direction at 10 and 300 K are shown in Fig. 3. For the thicker films, the magnetic coercive forces (H_c) are small, similar to that of bulk Fe_3Si.[11] Like most thin magnetic films, the H_c of Fe_3Si films increases with decreasing thickness and reaches a maximum for the film 10 ML thick. An H_c as high as 500 Oe at 10 K has been observed. For films with thickness less than 10 ML, however, the H_c's at 10 K, decrease slightly. The 5-ML-thick film has H_c=425 Oe, and the 2-ML-thick film has H_c=350 Oe. In contrast, the H_c's of the 5-ML-thick films at 300 K are only a few Oe. The magnetic behavior of the ultrathin Fe_3Si films with thickness less than 10 ML may be strongly affected by the Au film coated at the top.

For the measurement with the magnetic field perpendicular to the film plane, the magnetization is not saturated even under the applied field of 1.4 T. The saturation field for these films with shape anisotropy should be ~1.4 T. It indicates existence of some in-plane anisotropy. This in-plane anisotropy plus the shape anisotropy make the easy magnetization of these films parallel to the film surface.

In summary, we have studied the magnetic properties of ultrathin MBE grown Fe_3Si films. The coercivity forces of these films increase with decreasing film thickness and decrease when the film thickness is less than 10 ML. All the samples, except 2-ML-thick film, exhibit square hysteresis loops. We found that all the films are ferromagnetic even for films as thin as 2 ML.

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