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# (Ga, Gd, As) film growth on GaAs substrate by low-energy ion-beam deposit

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**Abstract**

(Ga, Gd, As) film was fabricated by the mass-analyzed dual ion-beam epitaxy system with the energy of 1000 eV at room temperature. There was no new peak found except GaAs substrate peaks (0 0 2) and (0 0 4) by X-ray diffraction. Rocking curves were measured for symmetric (0 0 4) reflections to further yield the lattice mismatch information by employing double-crystal X-ray diffraction. The element distributions vary so much due to the ion dose difference from AES depth profiles. The sample surface morphology indicates oxidizing layer roughness is also relative to the Gd ion dose, which leads to islandlike feature appearing on the high-dose sample. One sample shows ferromagnetic behavior at room temperature.
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## 1. Introduction

In the 1960s, researchers realized that the magnetism and semiconductor properties could coexist in magnetic semiconductors and DMS although the most-well established semiconductor devices based on Si and GaAs are nonmagnetic [1]. Gallium arsenide (GaAs) has several properties, so it is superior to silicon for use in optoelectronic devices. Increasing attention has been paid to the preparation of diluted magnetic semiconductors (DMS), in recent years after the III–V-based DMS, such as (In, Mn)As and (Ga, Mn)As, has been successfully fabricated by low-temperature MBE [2–5]. The ferromagnetic transition temperature ($T_c$) has increased a little by optimal annealing study [6] in comparison with the highest reported $T_c = 110\,K$.

Rare earth ions doping of semiconductors [7–10] have spawned great interest since it is possible to combine the excellent electronic properties of

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semiconductors with the peculiar magnetic properties of rare earth ions. Gadolinium has the half-filled 4f shell that provides larger local moments ($J = 7/2$) than that of manganese ($J = 5/2$).

In this paper, (Ga, Gd, As) was fabricated by the mass-analyzed low-energy dual ion-beam epitaxy system. The samples were studied by X-ray diffraction (XRD), double-crystal X-ray diffraction (DXRD), auger electron spectrum and atomic force microscope (AFM), and alternating gradient magnetometer (AGM).

## 2. Material preparation

The samples were fabricated by the low-energy dual ion-beam epitaxy system with the mass selection function, which can purify the ions and even select isotopes to implant into the substrate. Gd ion beams were produced by Bernastype ion source. More detailed information was elaborated about this apparatus in Ref. [11]. We only used one ion-beam system to implant Gd ions into the substrate with lower energy in this experiment. The semi-insulating GaAs (1 0 0) were used as substrate which were cleaned in ethanol, acetone, and deionized water for 5 min each with ultrasonic vibration. Then they were etched in $H_2SO_4$:$H_2O_2$:$H_2O$ (6:1:1) solvent. Finally, they were rinsed in deionized water and loaded into growth chamber.

Gd ions were uniformly implanted into the substrate with high doses of $3 \times 10^{17}\,cm^{-2}$ (sample A) and $8 \times 10^{16}\,cm^{-2}$ (sample B) at room temperature, while an acceleration voltage of 1000 V is used during the growth process. The chamber pressure was kept at $10^{-6}$ Pa during the growth process.

## 3. Results and discussion

AES was carried out to analyze Gd depth profile. The composition and structure of the samples were studied by using XRD. Rocking curves were also measured for GaAs symmetric (0 0 4) reflections by DXRD. Sample surface properties were further characterized by AFM. AGM was employed to analyze magnetic properties of the samples.

### *3.1. Compositional analyses*

Auger analysis was performing on PHI-610/SAM instrument, which was used to analyze the composition on sample surface and Gd depth profile. Fig. 1 shows that there are gadolinium, carbon and oxygen on the sample surface. Carbon disappears in the samples while oxygen still exists from the AES spectra at the depth of 20 nm. However, the AES spectra of sample B are different from that of sample A at this depth because the atomic concentration of Gd is different in the two samples.

From the sample depth profiles Fig. 2 the composition distribution changes very clearly at some range below the surface. Gadolinium and oxygen have the same trends to decrease with the depth while gallium and arsenic increase with depth. The high percentage of the former two compositions on the sample surface is mainly for the deposit of gadolinium layer during the growth process, which was easily oxidized in the air after being taken out of the growth chamber. Atomic concentration of gadolinium reaches 60%. It is much higher in sample A than that in sample B on the surface. Results presented in Fig. 2 demonstrate an epilayer forms on the sample surface if large dose was selected to implant into the sample.

### *3.2. Structural analyses*

XRD was employed for analyzing the structure of the samples by using $\theta - 2\theta$ scan. There was no new peak found except the GaAs substrate main peaks (0 0 2) and (0 0 4). Rocking curves were measured for symmetric (0 0 4) reflections to yield the lattice mismatch, so GaAs(0 0 4) was analyzed with Philips X'pert-MRD by $\omega - 2\theta$ scanning at the step width of 1.08 arc s (Fig. 3). A small additional hump corresponding to the Gd-doped layer appears separated from the substrate (0 0 4) peak, indicating a lattice expansion in this region. The hump is much flatter in sample A than that in sample B, which is corresponding to the Gd ion distributions in the two samples because the Gd implant layer is thick in sample A from the AES depth profile results (Fig. 2).

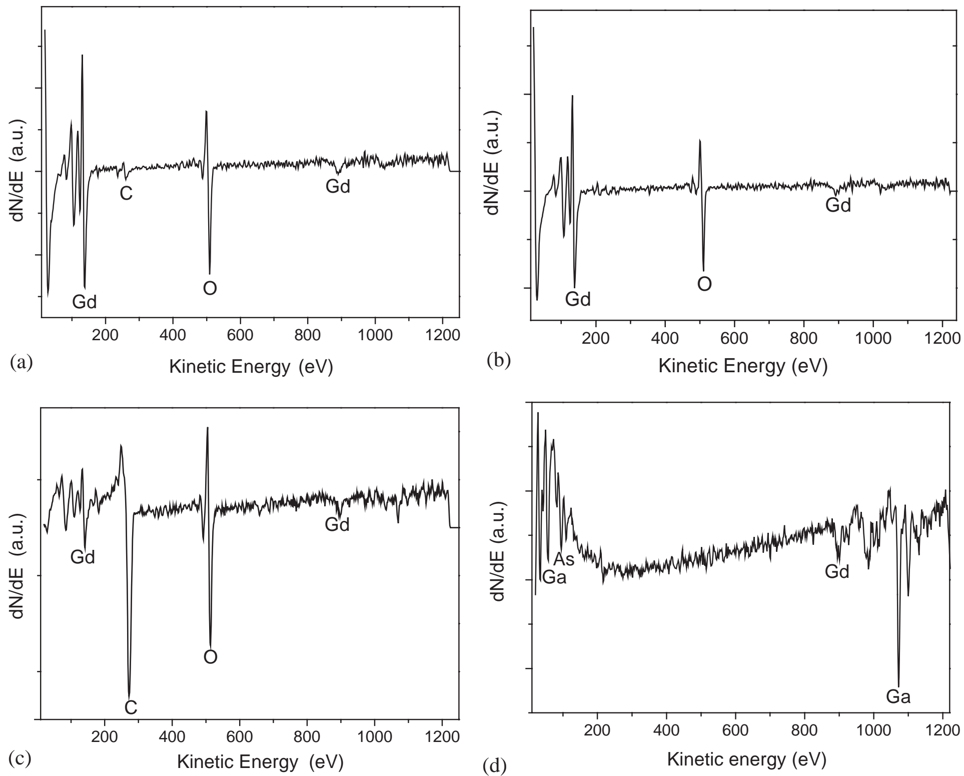


Fig. 1. Auger electron spectroscopy: (a) AES on the sample A surface; (b) AES at the 20 nm depth of sample A; (c) AES on the sample B surface; and (d) AES at the 20 nm depth of sample B.

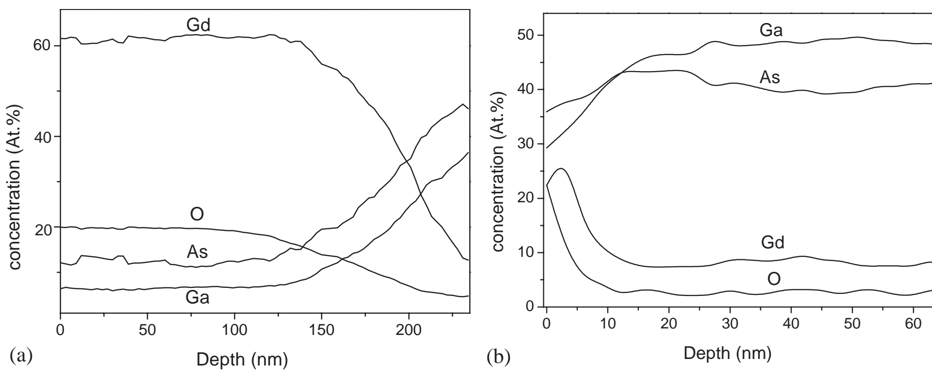


Fig. 2. Auger electron spectroscopy depth profiles of samples A and B.

### 3.3. Surface morphology

Atomic force microscopy is a noninvasive technique to deliver three-dimensional realistic impressions of the measured sample surface. It is an easy and fast method to show the change in the amplitude of the surface roughness. The surface morphology of the (Ga, Gd, As) film was imaged by AFM (Fig. 4). The AFM image of sample A shows islandlike feature while there is no such kind

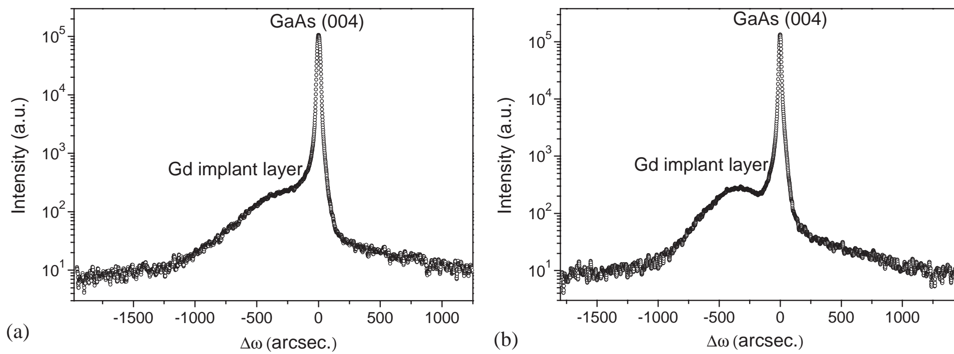


Fig. 3. Experimental GaAs (0 0 4) X-ray rocking curves for samples A and B.

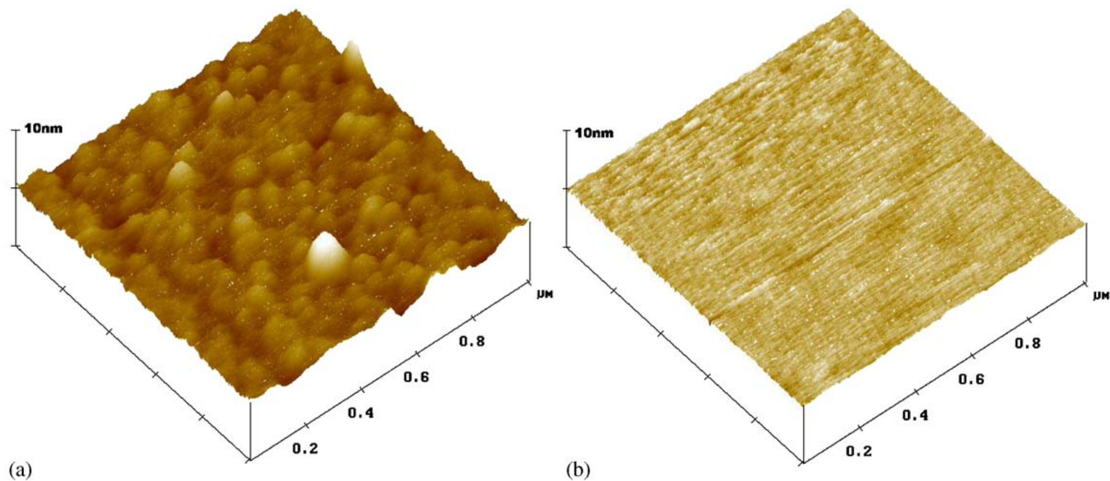


Fig. 4. AFM morphology of surface of samples A and B.

of characteristic on the surface of sample B. The AFM results indicate that the profiles of the surface coverage changed with the Gd implantation dose because the thickness of the deposit Gd film on surface was in proportion to it.

### 3.4. Magnetic property

We use a Model 2900 MicroMag$^{TM}$ AGM to perform the magnetization measurements at room temperature (Fig. 5). Only sample A reveals room-temperature ferromagnetic behavior from the magnetization measurements by AGM though there was an oxidizing gadolinium epilayer on the two samples surface. The Curie temperature of

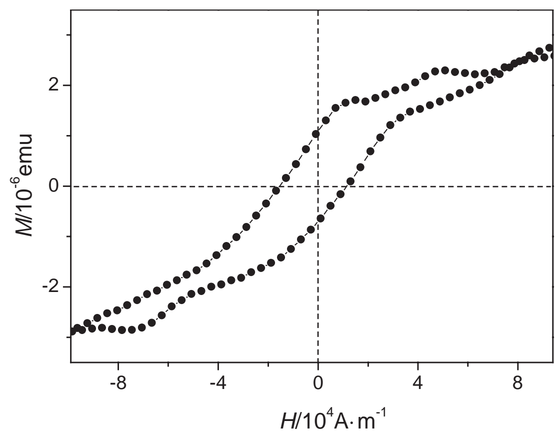


Fig. 5. Magnetization data of sample A by AGM at room temperature.

Gadolinium is 293 K so we cannot make sure if the ferromagnetism is related to (Ga, Gd, As) film before making further investigation on it.

## 4. Conclusion

(Ga, Gd, As) films were fabricated by the mass-analyzed dual ion-beam system with doses of $3\times10^{17}$ and $8\times10^{16}\,cm^{-2}$. Rocking curves were measured for symmetric (0 0 4) reflections to yield the lattice mismatch after there was no new peak found by XRD. Gadolinium deposited on surface and formed oxidizing layer, whose thickness was in proportion to the implantation dose from AES depth profiles and AFM results. Ferromagnetic behavior shows in sample A though further investigation is still needed.

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