Ferromagnetism in Mn/X/Si (X = B, BN, B4C, SiC) trilayers

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Abstract

The ferromagnetism in Mn(6 nm)/X(0.5 nm)/Si(6 nm) (X = B, BN, B4C, SiC) trilayers was investigated. The as-deposited trilayers did not exhibit ferromagnetism, but the trilayers annealed around 700 K did exhibit ferromagnetism at 77 K. The annealed Mn/B4C/Si trilayer has a Curie temperature above 300 K. The Mn/B/Si, Mn/BN/Si and Mn/SiC/Si trilayers have Curie temperatures around 260 K.

1. Introduction

Some Mn-based alloys and compounds exhibit ferromagnetism although they do not contain ferromagnetic elements. Mn/Al [1], Mn/C/Si [2,3] and Mn/SiO2/Si [4] multilayers exhibit ferromagnetism at room temperature. Ferromagnetic Mn/C/Si multilayers also show semiconductive properties and ferromagnetic semiconductors are being applied to new devices such as magnetic transistors. The ferromagnetism in the above multilayers is believed to occur at the interfaces of the Mn layers. However, the origin of the ferromagnetism is uncertain. From the results of the Mn/C/Si and the Mn/SiO2/Si multilayers, it appears that carbon and oxygen are necessary to cause ferromagnetism in Mn/X/Si multilayers. However, the elements that cause ferromagnetism with the Mn and the Si layers are unclear.

In this study, the magnetism in the Mn/X/Si trilayers, which X was either B, BN, B4C or SiC, were investigated in order to clarify elements that cause ferromagnetism with the Mn and the Si layers. Elements X were near carbon in the periodic table since Mn/C/Si trilayers exhibited a high saturation magnetization [2,3]. In the previous studies [3,4], annealing caused ferromagnetism in Mn/C/Si and the Mn/SiO2/Si trilayers. Thus, the effects of the annealing on the magnetization of the Mn/X/Si trilayers were also investigated. Moreover, the saturation magnetization was examined as a function of the measurement temperature.

2. Experimental procedures

The Mn/X/Si (X = B, BN, B4C, SiC) trilayers were deposited on Si(100) substrates using an ion beam sputtering apparatus. The Mn layers and Si layers were 6 nm thick, while the X intermediate layers (X = B, BN, B4C, SiC) was 0.5 nm thick. The acceleration voltage of the ion gun was 600 V with the ion current of 60 mA. The Ar pressure during deposition was 0.02 Pa. The Mn and the Si layers had identical deposition rates of 0.1 nm/s and that for the intermediate layers was approximately 0.01 nm/s. The samples were annealed in a vacuum of 1.3 × 10^-4 Pa for 1 h at various temperatures between 523 and 783 K.

The magnetization curves of the trilayers were measured at 77 and 300 K using a vibrating sample magnetometer (VSM). In order to clarify the Curie temperature of the trilayers, a superconducting quantum interference device (SQUID) magnetometer measured the saturation
magnetization at the applied field of 10 kOe as a function of the measurement temperature between 10 and 300 K.

3. Results and discussion

Fig. 1 shows the magnetization curves measured at room temperature of the Mn/X/Si (X = B, BN, B$_4$C, SiC) trilayers annealed at 693 K. The trilayers do not exhibit ferromagnetism at room temperature.

When the measurement temperature is decreased to 77 K, the trilayers all show ferromagnetism as shown in Fig. 2. The Mn/B/Si trilayer exhibits the highest saturation magnetization. The saturation magnetization decreases as the intermediate layer material changes from BN, SiC to B$_4$C.

In order to understand the effects of annealing on the saturation magnetization, the trilayers were annealed at various temperatures. As shown in Fig. 3, the trilayers annealed below 700 K do not exhibit ferromagnetism at room temperature. When the annealing temperature is increased to 703 K, only the Mn/B$_4$C/Si trilayer exhibits ferromagnetism at room temperature, which disappears once the annealing temperature is higher than 750 K.

When the measurement temperature is decreased to 77 K, the Mn/B/Si, the Mn/BN/Si and the Mn/SiC/Si trilayers exhibit ferromagnetism after the annealing above 600–660 K, as shown in Fig. 4. Although the measurement temperature is 77 K, the Mn/B$_4$C/Si trilayer requires an annealing temperature above 700 K in order to exhibit ferromagnetism. The reason that the Mn/B$_4$C/Si trilayer requires a higher annealing temperature to cause the ferromagnetism is unclear.

The Curie temperature of the trilayers was investigated by measuring the saturation magnetization as a function of measurement temperature. The Mn/B/Si, the Mn/BN/Si and the Mn/SiC/Si trilayers were annealed at 693 K, while the Mn/B$_4$C/Si trilayer was annealed at 703 K since the Mn/B$_4$C/Si trilayer required an annealing temperature above 700 K to cause ferromagnetism. As shown in Fig. 5, the saturation magnetizations at 10 K of the Mn/X/Si trilayers are 0.12, 0.11, 0.07 and 0.06 memu for the X = B, BN, B$_4$C and SiC, respectively. If all the Mn atoms cause the magnetic moments for the ferromagnetism in the trilayers, the saturation magnetizations correspond to the magnetic moments of about 0.5 $\mu_B$/Mn-atom for the Mn/B/Si and the Mn/BN/Si trilayers, and about 0.3 $\mu_B$/Mn-atom for the Mn/SiC/Si and the Mn/B$_4$C/Si trilayers. The real magnetic moments are higher than the above values because only the Mn atoms near the interfaces to the Si layers contribute to the value of the magnetic moment. However, the number of the Mn atoms contributing to the magnetic moments is ambiguous since the number of the Mn atoms that are diffused by annealing is unclear and the diffused Mn atoms contribute to ferromagnetism, which will be discussed later. The figure also shows that the saturation magnetization decreases as the intermediate layer material changes from BN, SiC to B$_4$C.
magnetization of all the trilayers decreases as the temperature increases. The Curie temperatures of the Mn/B/Si, the Mn/BN/Si and the Mn/SiC/Si trilayers are around 260 K. For the Mn/B_4C/Si trilayer, the slope of the changes in the saturation magnetization varies around 120 K and the saturation magnetization does not become zero at 300 K. Therefore, it is proposed that there are two types of ferromagnetic substances with different Curie temperatures in the Mn/B_4C/Si trilayer. One of the ferromagnetic substances has a Curie temperature near 120 K and the other ferromagnetic substance has one above 300 K.

The above results indicate that the boron and the carbon are required to cause ferromagnetism. However, it is unclear whether the nitrogen is necessary for ferromagnetism. Moreover, since annealing is required to cause ferromagnetism and annealing changes the film structures, it is hypothesized that structural changes, which occur while annealing, are essential to cause ferromagnetism.

Two possible reasons for the ferromagnetism are considered. (1) The intermediate layers including the boron or the carbon help diffuse the Mn atoms into the Si layers and the Mn atoms cause the carriers. The Ruderman-Kittel-Kasuya-Yoshida (RKKY) interaction or the double exchange interaction caused by the carriers, which are noted as the origins of ferromagnetism in the diluted magnetic semiconductors [5–7], aligns the magnetic moments of the Mn atoms. (2) Annealing produces unknown ferromagnetic compounds near the Mn layers. In the Mn–Si systems, Mn_3Si and Mn_5Si_3 are antiferromagnetic materials [8,9]. Only the MnSi is ferromagnetic, whose Curie temperature and magnetic moment are around 40 K and 0.4 μB/Mn-atom, respectively [10,11]. The Curie temperature of the MnSi is much lower than those of the Mn/X/Si trilayers in this study. Therefore, it is plausible that the Mn/X/Si trilayers include other ferromagnetic compounds that have high Curie temperatures. It is also reported that the carbon-doping changes the Mn_3Si_3 compound from antiferromagnetic to ferromagnetic and the Curie temperature of the Mn_3Si_3C_0.75 compound is 350 K [9]. Therefore, it is likely that the Mn/SiC/Si and the Mn/B_4C/Si trilayers in this study include the Mn_3Si_3C_0.75 compounds. On the other hand, ferromagnetic compounds for the Mn/B/Si and the Mn/BN/Si trilayers are unknown and novel. However, we did not confirm the ferromagnetic compounds because the X-ray diffraction peaks from the compounds for the Mn/B/Si and the Mn/BN/Si trilayers in the X-ray diffraction experiment were not observed due to the amount of the ferromagnetic compounds or the crystallinity of the compounds were small.

4. Summary

The as-deposited Mn/X/Si (X = B, BN, B_4C, SiC) trilayers do not exhibit ferromagnetism. The trilayers annealed near 700 K exhibit ferromagnetism at 77 K. The Mn/B_4C/Si trilayers annealed around 700 K also exhibit ferromagnetism at room temperature. The Mn/B/Si, the Mn/BN/Si and the Mn/SiC/Si trilayers have the Curie temperatures around 260 K, while the Mn/B_4C/Si trilayer has a Curie temperature above 300 K.

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