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Effect of Interlayer Exchange Coupling on the Curie Temperature in $Ga_{1-x}Mn_xAs$ Trilayer Structures

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1. Introduction

Magnetic multilayers on the base of ferromagnetic III-V semiconductors, such as $Ga_{1-x}Mn_xAs$, can be easily integrated into semiconductor circuitry and have attracted much interest because they hold promise of applications in a variety of spin-controlled devices[1]. While most of the attention, so far, has been focused on the magnetoresistance effect in these semiconductor magnetic multiplayer [2,3], very little attention has been made to the effect of the exchange magnetic coupling on the Curie temperature of the $Ga_{1-x}Mn_xAs$ ferromagnetic layers.

In this paper, we present the effect of the exchange magnetic coupling on the Curie temperature of $Ga_{1-x}Mn_xAs$ (x = 0.04) ferromagnetic layers in trilayer structures with the different thickness of nonmagnetic GaAs spacer.

2. Experimental details

The $Ga_{1-x}Mn_xAs$(Be)/GaAs/$Ga_{1-x}Mn_xAs$ trilayers were grown on semi-insulating (001) GaAs substrates in a Riber 32 MBE system. Prior to $Ga_{1-x}Mn_xAs$ deposition, a 250 nm GaAs buffer layer was grown at 600^0C. The substrate was then cooled to 270 ^{0}C for the growth of a 2 nm low temperature (LT) GaAs, followed by a 30 nm layer of $Ga_{1-x}Mn_xAs$ (x = 0.04). Then the LT-GaAs nonmagnetic spacer layer with a different thickness was grown. The top layer of these trilayer structures was a 30 nm $Ga_{1-x}Mn_xAs$ (x = 0.04) epitaxial layer additionally doped by Be. Two single epitaxial layers of $Ga_{1-x}Mn_xAs$ with and without Be doping were also grown under identical conditions to serve as the reference samples. The Mn concentration was estimated from X-ray diffraction measurements. A value of x = 0.04 was obtained for all samples in this growth series.

3. Results and discussion

Figure 1 shows the temperature dependence of the resistivity for undoped (A) and Be doped (B) of $Ga_{1-x}Mn_xAs$ (x = 0.04) single epitaxial layers and for the trilayer structures with the different thickness of GaAs spacer: (C) –5 ML, (D) –10 ML and (E) – 30 ML, respectively at zero magnetic field. The sample A without Be shows an metallic behavior, while other samples doped by Be are insulating. For sample C the insulating behavior is clearly seen in the inset of Fig.1, where the temperature dependence for this sample is shown separately. All the samples showed a maximum (a rounded cusp) near the Curie temperature T_C, shown by arrows in Fig.1. This critical behavior of resistivity in $Ga_{1-x}Mn_xAs$ was successfully described by the magnetoimpurity scattering model [4]. The resistivity cusp for sample A is very wide and its maximum cannot be defined accurately. The $Ga_{1-x}Mn_xAs$ (x = 0.04) layer doped by Be has a lower Curie temperature compared with the ferromagnetic layer without Be. This behavior is opposite to the case of $Ga_{1-x}Mn_xAs$ with a lower concentration of Mn (x = 0.03) where the additional Be doping increases the Curie temperature [4]. This occurs because the additional doping by Be of the $Ga_{1-x}Mn_xAs$ with high concentration of Mn ($x \geq 0.04$) increases the concentration of interstitial Mn and since these interstitial Mn atoms are the double donors [5] the concentration of free carriers in these materials is strongly decreased. The decreasing of the free carriers concentration causes a lowering of the Curie temperature. Since the resistivity cusp is usually observed near the Curie temperature it can be deduced from Fig.1 that the Curie temperature of the top ferromagnetic layer in our trilayer structures increases with decreasing GaAs spacer thickness. A more accurate method of determining the Curie temperature is by using the anomalous Hall effect measurements. Figure 2 shows the temperature dependence of magnetization for $Ga_{1-x}Mn_xAs$ trilayer structures obtained from the Arrot plot by assuming the skew scattering for all samples investigated. As seen from Fig. 2, the Curie temperature for the top ferromagnetic layer in trilayer structures increases with decreasing GaAs spacer thickness.

The Curie temperature in magnetic material by the mean-field theory approach is related to the exchange energy per magnetic atom $E_{ex} \approx k_B T_C$. This allows us to estimate the interlayer coupling energy per atom from the variation of the Curie temperature for our trilayers structures. For sample C the interlayer exchange energy $E_{ex} \approx 1.7$ meV. This value is rather large and its magnitude is much larger than those reported for similar (GaMn)As trilayers with the GaAs spacer and with the same thickness of 30 nm for ferromagnetic layers [3]. However, it is shown that in order to obtain the correct value of the exchange coupling constant the magnetization fluctuations in the thin ferromagnetic layer should be taking into account. But it is beyond of the scope of this paper and will be presented elsewhere.

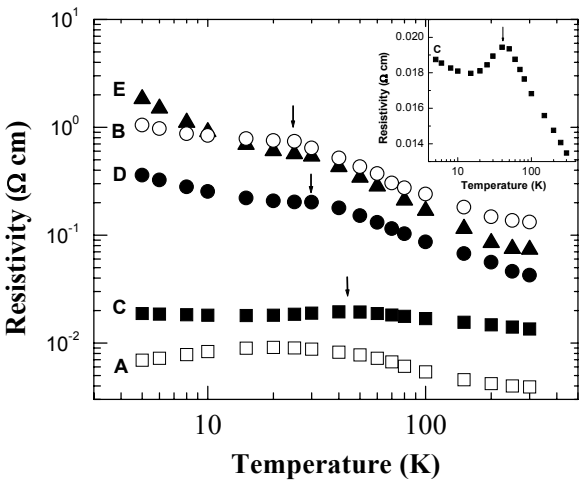

Fig.1. Temperature dependence of the resistivity for undoped (A) and Be doped (B) of $Ga_{1-x}Mn_xAs$ (x = 0.04) single epitaxial layers and for trilayer structures (C-E) with different thickness of GaAs spacer. In the inset the temperature dependence of the resistivity for sample C is separately shown.

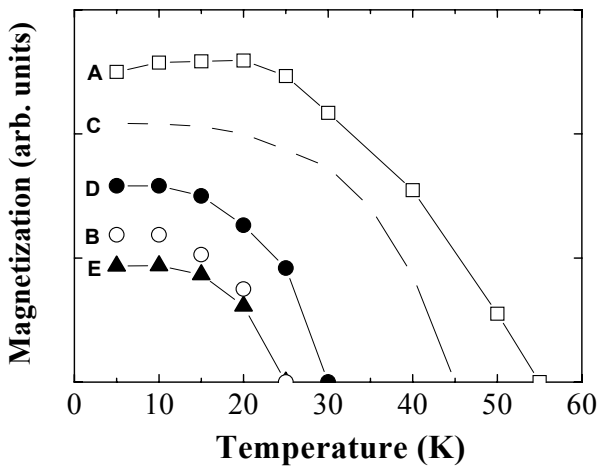

Fig.2. Temperature dependence of the magnetization determined from the Arrott plot of anomalous Hall effect measurement for $Ga_{0.96}Mn_{0.04}As$ single (A,B) layers and trilayer structures (C-E).

4. Conclusions

In conclusion, systematic measurements of the temperature dependence of the resitivity and anomalous Hall effect were carried out on $Ga_{1-x}Mn_xAs$ (Be) /GaAs/ $Ga_{1-x}Mn_xAs$ trilayer structures with the different thickness of GaAs spacer layer. It was observed that with decreasing insulating spacer thickness the Curie temperature of the ferromagnetic layer with initially low critical temperature in the decoupled state is strongly increased. This increase is due to the exchange coupling between the ferromagnetic layers mediated by the free carriers through the thin insulating spacer. The value of the exchange coupling energy calculated by using the mean-field theory gives the unrealistically large value for the investigated magnetic trilayers. In order to obtain the true value of the exchange coupling constant the magnetization fluctuations in the thin ferromagnetic layers should be taking into account.

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