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Temperature Dependence of Magnetic State of Fe/Al Multilayered Films

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We investigated the temperature dependence of magnetization of Fe/Al multilayers fabricated by dc magnetron sputtering system. As the temperature increased from 5 K in a low magnetic field (100 G) the magnetization of the samples increased and made a broad peak at some critical temperature. Further increase of temperature decreased the magnetization as an ordinary ferromagnetic curve. Part of samples show rapid increase of magnetization at low temperature. A model developed in this study suggests that the biquadratic coupling yields such a rapidly increasing behavior of magnetization at low temperature.

I. Introduction

In 1991, the biquadratic coupling between magnetic layers in magnetic multilayered films was found in a wedge typed Fe/Cr multilayer made by molecular beam epitaxy (MBE) [1]. Also, it was found that Fe/Al multilayers with a certain Al layer thickness reveal a strong biquadratic coupling effect [2]. The biquadratic coupling effect makes the magnetic moments of neighboring magnetic layers perpendicular to each other. Two mechanisms explain this effect. One is the terraced interfacial model in which ferro- or antiferro-coupling compete each other at the boundary of the two coupling regions and compromise to yield the biquadratic coupling as an intermediate state [3]. The other is that loose spins in the non-magnetic spacer mediate the magnetic moments of neighboring magnetic layers and let their directions be perpendicular to each other [4].

In our previous work [5] we reported that Fe/Al multilayered films show a peak behavior in magnetization versus temperature (M vs. T) curve and S-like shape in magnetization versus applied magnetic field (M vs. H) curve. We suggested that the antiferromagnetic coupling between Fe layers yields such results. In this work we report that in some Fe/Al multilayers the biquadratic coupling exists in addition to the antiferromagnetic coupling. In this case it is noted that the biquadratic coupling is dominant at very low temperature.

II. Experimental

The Fe/Al multilayer films were fabricated using a computer controlled dc magnetron sputtering system with the base pressure lower than 2×10^{-8} Torr and the deposition Ar pressure at 4 mTorr. Two sputtering targets of 99.95 % pure iron and 99.999 % pure aluminum were alternately sputtered. The substrate was a polished silicon single crystal wafer of (001) surface plane. We used superconducting quantum interference device (SQUID) to measure the magnetization. The applied magnetic field was always parallel to the sample plane. Before loading the sample in the chamber the SQUID was turned off to remove any remnant magnetic field built in the superconducting rings, and the system was cooled down at zero field.

III. Results and Discussion

Fig. 1 shows the M vs. T curves measured at 100 G for Fe/Al (200 Å/ X Å) multilayers. For all these samples, the magnetization increased with increasing temperature up to the peak temperature (T_p) and decreased thereafter. In our previous work [5], we suggested that this type of magnetic behavior is indicative of antiferromagnetic (AF) coupling between Fe layers. Fig. 2 shows the plot of T_p for the samples. The T_p decreased linearly with increasing Al layer thickness, which implies weakening of AF coupling strength. The initial steep slope of magnetization at low temperature was detected in the two samples with X = 10 and X = 50. M. E. Filipkowski et al. [6] reported that this is the first order transition due to the biquadratic interlayer coupling. We calculated the M vs. T curves of our samples below T_p. The following magnetic energy equation was used to fit the M vs. T curve of Fe/Al (200 Å/50 Å) multilayer sample.

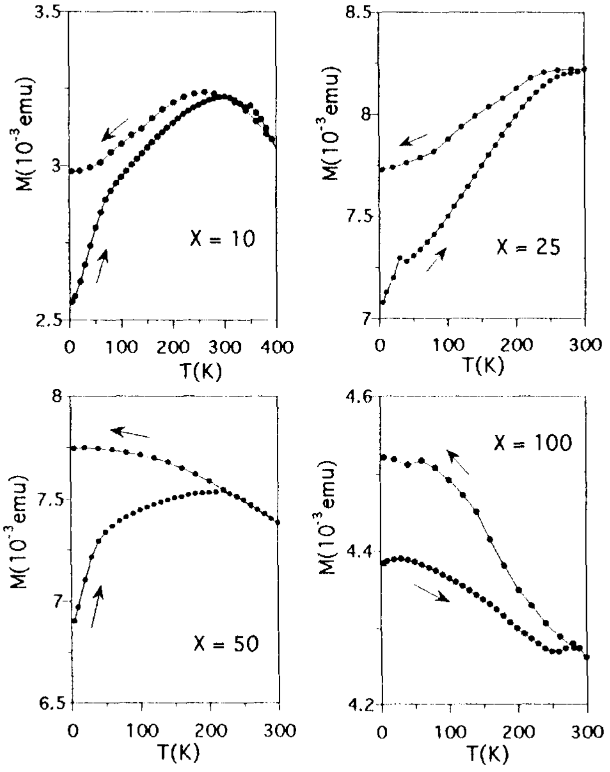

Fig. 1. Magnetization versus temperature curves of Fe/Al (200 A /X Å) multilayers measured at 100 G.

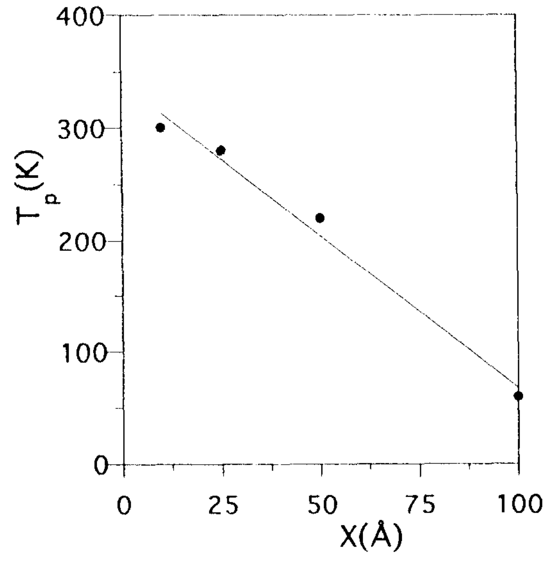

Fig. 2. Peak temperature T_p of Fe/Al (200 Å /X Å) multilayers as a function of Al layer thickness.

$$E = -(\vec{H}_{k1}\cdot\vec{M}_1 + \vec{H}_{k2}\cdot\vec{M}_2) - \lambda\,\vec{M}_1\cdot\vec{M}_2 - Q\frac{(\vec{M}_1\cdot\vec{M}_2)^2}{M_1 M_2} + \vec{H}\cdot(\vec{M}_1+\vec{M}_2)$$

where the first term is the interaction energies between anisotropy field ($\vec{H}_k$) and magnetization vector ($\vec{M}$) of neighboring magnetic layers and the fourth term is zeeman interaction energies between an applied field ($\vec{H}$) and the magnetization vectors. The second term is the AF coupling energy and the third term is the biquadratic coupling energy. The applied field H is a fixed value and the coefficients of each coupling term are functions of temperature. By the theoretical work of J. R. Cullen and K. B. Hathway the AF coupling was found to be linearly decreased with increasing temperature [7]. To obtain the AF coupling coefficient with such a linear dependence, it was assumed that the AF coupling vanishes at T_p, so that AF state changes to the FM. By using such a fact, the coefficient was assumed as:

$$\lambda = \lambda_0 \frac{(T-T_p)}{T_p}\ .$$

The biquadratic coupling was found to be decreased exponentially with increasing temperature by M. E. Filipkowski et al. [6]. The coupling coefficient was described as:

$$Q = Q_0\,(\frac{T_0}{T})\exp(-\frac{T}{T_0})$$

where the Q_0 is a positive constant and T_0 is the second order transition temperature such as T_p in the M vs. T curve.

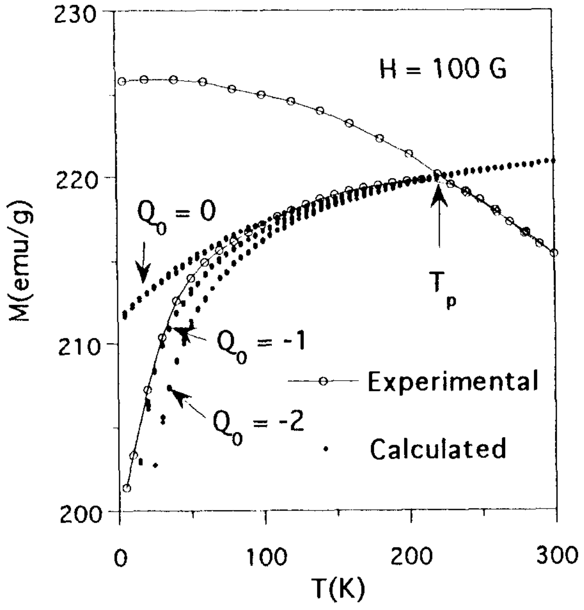

Fig. 3. Calculated and measured magnetization versus temperature curves of Fe/Al (200 Å /50 Å) sample.

For a fixed applied field (H = 100 G), the M vs. T curve of the Fe/Al (200 Å/50 Å) sample was calculated using the two expressions for the coefficients described above. The fitting to the experimental curve was focused in the region below T_p.

The fitting parameters were varied to find the best fitting result. Fig. 3 shows the fitting result on the Fe/Al (200 Å/50 Å) sample. When no biquadratic coupling is involved, namely $Q = 0$, the initial slope of the magnetization is not steep. As the biquadratic coupling becomes effective ($Q < 0$), the initial slope becomes steep, yielding excellent fitting at $Q = -1$.

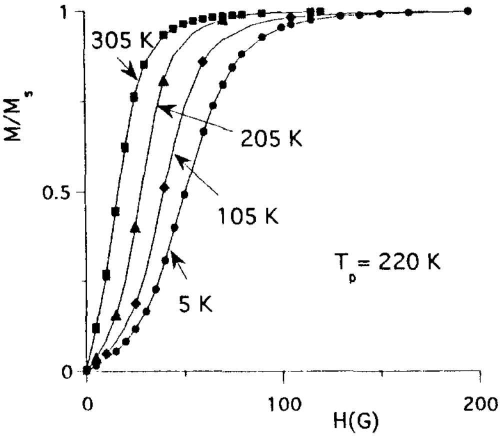

Fig. 4. Magnetization versus magnetic field curves calculated at different temperatures. Parameters λ_0 and Q_0 are 0.04 and −0.2 respectively.

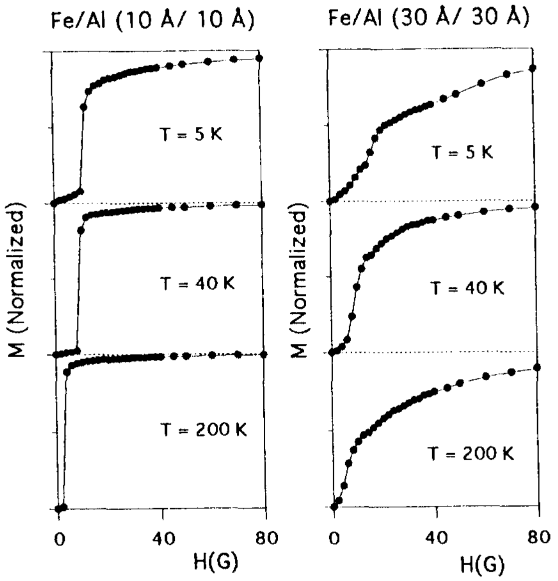

Fig. 5. Magnetization versus magnetic field curves of Fe/Al (10 Å /10 Å) and Fe/Al (30 Å/ 30 Å) multilayers measured at different temperatures.

The M vs. H curves at different temperatures were calculated using the coefficients above. Fig. 4 shows the calculated magnetization curves at four different temperatures, which are 5, 105, 205, and 305 K respectively. The peak temperature T_p used in the calculation was 220 K. It is noted that the curve shape below T_p is S-like but above T_p is ferromagnetic. This results is consistent with the fact that the magnetic state below T_p is AF and above T_p is FM as suggested in our previous work. This can be compared with the measured magnetization curves of Fe/Al (10 Å/10 Å) and Fe/Al (30 Å/30 Å) samples in Fig. 5. The measured curves showed a systematic evolution into the ferromagnetic type with increasing temperature. The calculated curve also evolves systematically to ferromagnetic type with increasing temperature and the saturation field decreases as temperature increases. These results imply that the interlayer coupling energy decreases with increasing temperature.

Ⅳ. Conclusion

In the M vs. T measurements of Fe/Al (200 Å/X Å) multilayers, it was found that as the Al layer thickness increases, the peak temperature decreases linearly, indicating weakening of the AF interlayer coupling strength.

In two samples (Fe/Al (200 Å/50 Å) and Fe/Al (200 Å/10 Å)) the biquadratic coupling effect was observed by the first order transition of the magnetization. The calculated M vs. T curve showed that the biquadratic coupling term creates the steep slope of magnetization at low temperature. As a result, as temperature increases from 5 K the magnetic state of the two samples varies to AF coupling state from biquadratic coupling state and further increase of temperature yields a transition to FM state. Two other samples (Fe/Al (200 Å/25 Å) and Fe/Al (200 Å/100 Å)) did not show the biquadratic coupling effect but AF coupling at low temperature below T_p. Also, the measured and calculated M vs. H curves of Fe/Al multilayers evolve into FM state from AF state with increasing temperature. The peak temperature T_p represents the magnetic transition temperature that divides the two states.

Acknowledgements

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