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# Temperature dependence of interlayer coupling and magnetization in amorphous-FeNiB/Ru multilayers

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## Abstract

For amorphous-FeNiB (2.0 nm)/Ru multilayers, an oscillatory interlayer coupling is observed with the variation of the Ru spacer thickness. At 0.8 nm thick Ru layer, near the first antiferromagnetic coupling maximum, the energy of the effective interlayer coupling at low temperature $T$ is found to change as a linear function of $T^{3/2}$. At the same time, the spontaneous magnetization of the samples at low temperature scales as a linear function of $T$. Therefore, the temperature dependence of the energy of the effective coupling might be controlled by thermal spin waves in the ferromagnetic layers.

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The oscillatory interlayer coupling between ferromagnetic (FM) transition metal layers through nonmagnetic (NM) spacers has been studied extensively over the last decade because of its important applications in magneto-electronic devices and its intriguing physics [1,2]. The interlayer coupling is found to decrease monotonically with increasing temperature [3–6]. The experimental results can be analyzed by two major theoretical models [7–10]. Some experiments show that the (bilinear) interlayer coupling at finite temperatures is controlled by the electron distribution near the Fermi surface [4,7,8]. However, experiments in Ni/Cu/Co and Ni/Cu/Ni trilayers

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and Fe/V multilayers show that at low temperatures the bilinear coupling is a linear function of $T^{3/2}$ [6]. The $T^{3/2}$ dependence coincides with the second model, in which the temperature dependence is assumed to originate from the magnetic excitation (thermal spin waves) [9,11]. Therefore, more experiments are required to clarify the mechanism of the temperature dependence of the bilinear coupling.

In this community, in order to suppress the effect of temperature variation of the magnetization, most measurements were made at temperatures far below the Curie temperature $T_C$ of these FM materials (Fe, Co, Ni, and their alloys). Since the decrement of the normalized magnetization $M(T)/M(0)$ is very small in the measured temperature range, the effect of the NM spacer on the temperature variation of the interlayer coupling can be addressed well. Alternatively, in order to reveal the effect of magnetization on temperature dependence of interlayer coupling, it will be helpful to use FM materials with low $T_C$.

For magnetic multilayers with antiferromagnetic (AFM) interlayer coupling, the magnetization reversal process depends not only on the interlayer coupling but also on the anisotropy of the FM layers. In general, it is not enough to calculate the interlayer coupling energy from hysteresis loops. When the FM anisotropy energy is much smaller than the AFM coupling energy, however, the hysteresis loop is slanted and magnetization reversal process can be described by magnetization coherent rotation model. As it is well known, pinholes usually exist in sputtered magnetic multilayers. As a result, the strength of the bilinear coupling is reduced and the biquadratic coupling is induced [12]. Therefore, biquadratic coupling should be considered in calculations of hysteresis loops. The remanent ratio is equal to zero if the bilinear coupling is stronger than the biquadratic coupling and $J_1 < 4J_2 < 0$. In this way, for $H < H_S$ (saturation field), one can have the following relationship [13]:

$$H = \frac{4}{tM_S}\left[(4J_2 - J_1)\frac{M_H}{M_S} - 8J_2\left(\frac{M_H}{M_S}\right)^3\right], \qquad (1)$$

where $M_H$ and $M_S$ are the magnetization component along the external field and the saturation magnetization of the constituent FM layers, respectively. $t$ is the FM layer thickness, and $J_1$ and $J_2$ are the energies of the bilinear and biquadratic couplings, respectively. At $H = 0$ we can have the following equation:

$$J_{\text{eff}} = \frac{M_S^2 t}{4\alpha}, \qquad (2)$$

where $\alpha = \partial M_H/\partial H$ is the slope of the magnetization curve at $H = 0$, which can be calculated from the measured magnetization curve near the zero field, and the effective interlayer coupling energy $J_{\text{eff}} = 4J_2 - J_1$. An approximation that the saturation magnetization is replaced by spontaneous magnetization for fields near zero field can be made. Note that $M_S$ refers to spontaneous magnetization below. In this paper, we study the temperature dependence of the interlayer coupling and the magnetization in amorphous-FeNiB/Ru multilayers. Note that the transition metal Ru can induce strong AFM interlayer coupling [2]. With amorphous FM materials, low $T_C$ can be obtained by compositional modification [14]. In this way, the interlayer coupling can be studied in a wide range of normalized temperature $T/T_C$. More importantly, the amorphous FM materials normally have very small intrinsic anisotropy and the AFM coupling can, therefore, be accurately determined from the slanted hysteresis loops. The FM and AFM couplings between amorphous FM layers are found to change alternatively with the Ru layer thickness. At the first AFM coupling maximum, the effective interlayer coupling energy decreases with decreasing temperature as linear functions of the $T^{3/2}$. A correlation between the interlayer coupling and the spontaneous magnetization as a function of temperature is found.

A large specimen (0.5 cm × 5 cm) of [Ru (0–3.0 nm)/$Fe_4Ni_{76}B_{20}$(= FeNiB)(2.0 nm)$]_{40}$ multilayer was deposited onto Si(1 0 0) substrates by DC magnetron sputtering with a base pressure of $10^{-8}$ Torr. The FM and NM layers were made from FeNiB and Ru targets, respectively. Their deposition rates are 0.1 and 0.2 nm/s with the Ar pressure of 5 m Torr during deposition. A 10.0 nm thick Ru buffer layer was deposited to make a