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Magneto-optical and magnetic properties in a Co/Pd multilayered thin film

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ABSTRACT

The paper describes investigation of ferromagnetism at low temperatures. We explored the magneto-optical properties, influenced by photon–magnon interactions, of a ferromagnetic Co/Pd multilayered thin film below and above the magnon Bose–Einstein Condensation (BEC) temperature. Analyses of SQUID and MOKE low temperature experimental results reveal a noticeable phase transition in both magnetic and magneto-optical properties of the material at the BEC temperature.

1. Introduction

In a magnetically ordered material, the collective precessional motion of spins causes the excitation of waves in the material. These waves are denoted as spin waves and their particle representation exhibit energy quanta called magnons [1,2]. Initial experimental evidence for the existence of spin waves came from measurements of the temperature dependence of the saturation magnetization of ferromagnets where the results obeyed the Bloch $T^{3/2}$ law [3].

Magnons are bosons and they obey Bose–Einstein statistical distribution. In previous thermal magnetic studies [4], we found that the confined magnons in some metallic ferromagnetic materials exhibited a Bose–Einstein condensation (BEC) at cryogenic temperatures (below 50 K). BEC of magnons has also been observed by microwave parametric pumping of magnons in an yttrium iron garnet (YIG) thin film [5]. The Bose–Einstein condensation entails the occupation of a single quantum state by a large fraction of bosons below a critical temperature [6–11].

Here we report an experimental investigation of magneto-optical and magnetic properties of a Co/Pd multilayered thin film of nanometer thickness. Previous studies [12,13] have shown that periodic structures of multilayered ultra-thin films exhibit a large magneto-optical and perpendicular magnetic anisotropy, hence, the Co/Pd was a good candidate for the study. Our findings reveal an interesting behavior of the temperature dependence of the confined magnons in the sample. A description of the experiments and results are discussed in the next sections in this paper.

2. Experiments

2.1. Magnetization

The Co/Pd test sample was grown by molecular beam epitaxy on silicon dioxide substrate using electron beam evaporation and designed to exhibit large perpendicular magnetic anisotropy. For enhancement in the Kerr rotation and Kerr loop squareness ratio (ratio of Kerr rotation at remanent to saturation), we constrained the thickness of the ferromagnetic Co/Pd multilayers to less than 50 nm as described in [13]. The patterning of the films where formed during the growth process. The sample composition is as follows: Fe(1.5 nm)/Pd(10 nm)/[Co(0.3 nm)/Pd(1 nm)] × 15/Pd (10 nm)/SiO_2(22 nm)/Si(100) substrate. The ferromagnetic film is less than 20 nm. The annealing temperature of the sample was 250 °C for 60 min. The Fe cap layer aids to give a significant the Kerr signal response to the sample [14].

Magnetization measurement of the test sample was made using a SQUID magnetometer (Quantum Design, MPMS XL 5.0 T). The sample chamber of the SQUID magnetometer was cooled to a low temperature of 5 K and stabilized with the aid of liquid

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Helium bath and a temperature sensor. The Co/Pd sample was placed on the sample holder unit of the magnetometer and the magnetometer automatically evacuates all air bubbles on the sample surface before inserting the sample into the sample chamber inside the magnetometer. Starting at 5 K, a magnetic field of 0.5 T was applied inside the sample chamber of the magnetometer and superconducting coils in the magnetometer measures the magnetic moments and averages the values after a user-specified settling time duration of approximately two minutes and stores the recorded value. This value is a measurement of the sample saturation magnetization at the applied field and temperature. The applied field was then removed (apply zero field) and the coil measured the magnetic moments and averages the values after a user-specified settling time duration of two minutes and stores the recorded value. This measurement is the sample's remanent magnetization. The above process is repeated for various temperatures ranging from 5 K to 300 K.

2.2. *Magneto-optical*

Polar Kerr rotation θ_K was examined at 632.8 nm with an automated cryogen-free low-temperature PEM-based MOKE system. Details of the experimental setup and procedures are described in [15]. The detected reflected laser signal from the PEM-based MOKE simultaneously contains signal components that are directly proportional both Kerr rotation angle and Kerr ellipticity. The signals in the detector that correspond to the fundamental frequency, 1*f* (proportional to ε_K) or 2*f* (proportional to θ_K) of the PEM modulation frequency were measured while sweeping the magnetic field (4 kOe to −4 kOe) from positive to negative saturation and back again to produce a hysteresis loop of θ_K or ε_K versus applied magnetic field. The hysteresis loops at different sample temperatures (9 K to room temperature) were measured and recorded for data processing.

3. Results and discussions

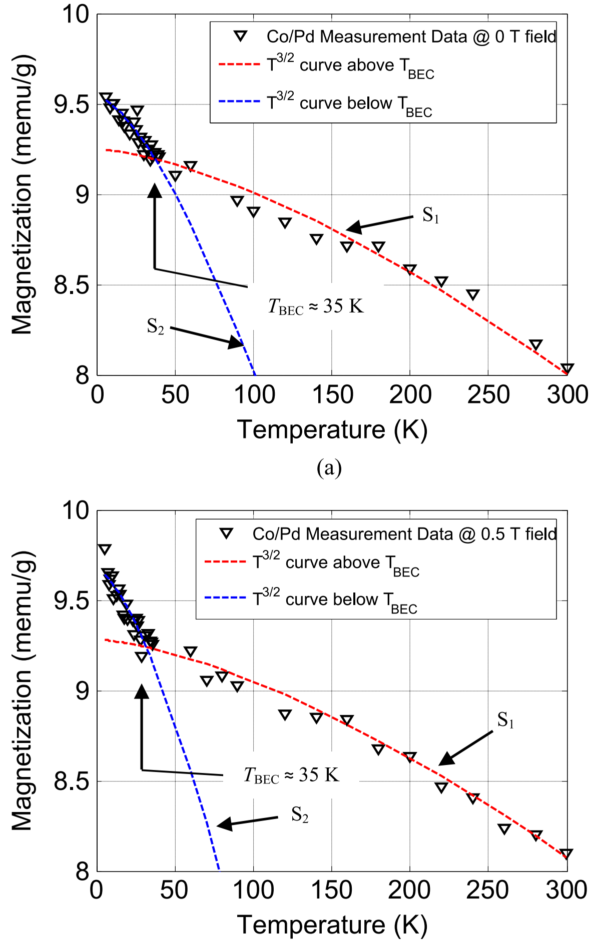
The results of the SQUID magnetization experiments are depicted in Fig. 1(a) and (b). The plots show the temperature variation of the remanent and saturation magnetization curves (substrate diamagnetic component included) for the sample. We observed an upturn in the slope within the vicinity of 35 ± 3 K. The data points in each plot is fitted with two $T^{3/2}$ curves, each having a different slope and intersect at the upturn point that is attributed to the magnon BEC temperature. The function of the curves used to fit the remanent and saturation magnetization temperature responses are listed in (Eqs. (1) and 2) respectively. The expressions (in units of emu/g) are

$$M_S(T)\big|_{H=0} = \begin{cases} 95.34 \times 10^{-4} - \left(1.52 \times 10^{-6}\right)T^{3/2}, & T < T_{BEC} \\ 92.48 \times 10^{-4} - \left(0.24 \times 10^{-6}\right)T^{3/2}, & T > T_{BEC} \end{cases}, \tag{1}$$

and

$$M_S(T)\big|_{H=0.5T} = \begin{cases} 96.7 \times 10^{-4} - \left(2.40 \times 10^{-6}\right)T^{3/2}, & T < T_{BEC} \\ 92.8 \times 10^{-4} - \left(0.23 \times 10^{-6}\right)T^{3/2}, & T > T_{BEC} \end{cases}, \tag{2}$$

where *T* is in units of Kelvin. In each equation, the slope of the fitting curve below and above the T_{BEC} temperature is denoted as S_2 and S_1 respectively. For the remanent magnetization response, $S_2 = 1.52 \times 10^{-6}$ and $S_1 = 0.24 \times 10^{-6}$ while for the saturation magnetization response, $S_2 = 2.40 \times 10^{-6}$ and $S_1 = 0.23 \times 10^{-6}$. An extension to the Bloch $T^{3/2}$ law model discussed in [16] illustrates how the chemical potential of magnons influence the magnetization temperature response. The model is derived in [16] to be given as



(a)

(b)

Fig. 1. SQUID measurement of Co/Pd thin film temperature response for (a) normalized remanent magnetization (b) normalized saturation magnetization.

$$M_S(T) = \begin{cases} M_S(0) - \dfrac{2.612 M_S(0)}{8\pi^{3/2} s_0}\left(\dfrac{k_B T}{2J_0 s_0}\right)^{3/2} & , T < T_{BEC} \\ M_S(0) - \dfrac{M_S(0)}{8\pi^{3/2} s_0}\left(\dfrac{k_B T}{2J_0 s_0}\right)^{3/2} \displaystyle\sum_{n=1}^{\infty}\left(\dfrac{e^{n\zeta/k_B T}}{n^{3/2}}\right) & , T > T_{BEC} \end{cases}, \tag{3}$$

where T_{BEC} is the BEC threshold temperature, k_B is the Boltzmann's constant, J_0 is the exchange energy, ζ is the chemical potential, and s_0 is the magnitude of spin projection vector. $M_S(0)$ is the magnetization at $T=0$ (maximum magnetization). The summation of the exponential term is dependent on the chemical potential of magnons in a magnetic material. At temperatures below the T_{BEC}, the magnetization, arising from the magnons, exhibits the traditional Bloch's $T^{3/2}$ law due to a zero chemical potential (summation term equals 2.612), while at temperatures above the T_{BEC}, the magnons still exhibit the Bloch's $T^{3/2}$ law but with the inclusion of the temperature variation of the chemical potential of the magnons.

The comparison of Eq. (2) with the model in Eq. (3) shows the influence of a non-zero chemical potential term in the magnetization response above the T_{BEC} temperature. Also, the exchange energy extracted from expressions in (Eqs. (1) and 2) were found to be approximately 3.54×10^{-22} J and 2.63×10^{-22} J respectively. This finding was anticipated because the exchange energy is at a