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Magnetic excitations in ferromagnetic semiconductors

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ABSTRACT

Magnetic excitations in a series of GaMnAs ferromagnetic semiconductor films were studied by ferromagnetic resonance (FMR). Using the FMR approach, multi-mode spin wave resonance spectra have been observed, whose analysis provides information on magnetic anisotropy (including surface anisotropy), distribution of magnetization precession within the GaMnAs film, dynamic surface spin pinning (derived from surface anisotropy), and the value of exchange stiffness constant *D*. These studies illustrate a combination of magnetism and semiconductor physics that is unique to magnetic semiconductors.

1. Introduction

Ferromagnetic (FM) semiconductors such as GaMnAs continue to hold the interest of the scientific community, both for their fundamental scientific interest and for their compatibility with modern semiconductor technology that may lead to novel non-volatile spintronic applications [1,2]. Since the speed of manipulating spin alignment is expected to be crucial in all these applications, it is essential to investigate the time dependence of spin processes (spin dynamics) and their relationship to itinerant charge carriers in solids on which spintronic devices will be based. Recently extensive studies of magnetic excitations in FM semiconductors were carried out by Brillouin light scattering (BLS) [3], ferromagnetic resonance (FMR) [4–8], and time-resolved magneto-optical Kerr effect [9–14]. However, our understanding of the fundamental magnetic excitations in these materials—which are intimately related to the exchange interaction between Mn ions and holes—is still far from complete [4,15].

In this work, we have concentrated on the study of multiple spin wave resonance (SWR) modes observed in FMR experiments carried out at microwave frequencies. Using comprehensive models of spin dynamics and dynamic surface spin pinning, we were able to obtain accurate values of the exchange, bulk, and surface anisotropy constants which ultimately determine the behavior of spin excitations in ferromagnetic films [6,13]. These results and their analysis may lead to the identification of principles governing hole-mediated spin-dynamic effects in III-Mn-V ferromagnetic semiconductors generally. In particular, the understanding of these principles may hold the key to extraordinarily fast manipulation of spins based on the combination of semiconductor physics and magnetism that is unique to these materials.

2. Sample fabrication

A series of GaMnAs films were grown in a Riber 32 R&D molecular beam epitaxy (MBE) machine on semi-insulating GaAs (0 0 1) substrates. A 100-nm-thick GaAs buffer was first grown at a substrate temperature 600 °C to achieve an atomically flat surface. The substrates were then cooled to 250 °C for growth of a 2-nm-low-temperature (LT) GaAs buffer, followed by deposition of 100–200-nm $Ga_{1-x}Mn_xAs$ layers with various Mn concentrations x (from 0.02 to 0.08). Pieces cleaved from each specimen were subsequently annealed in N_2 gas for 1 h at 280 °C in order to examine the effects of such heat treatment on spin dynamics.

3. Experimental setup

In this study, we measured the angular dependence of FMR spectrum for each specimen (both as-grown and annealed) with the dc applied magnetic **H** in two geometries, described below. The measurements were carried out at 9.46 GHz using a Bruker electron paramagnetic resonance (EPR) spectrometer, in which **H**

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was in the horizontal plane, while the microwave magnetic field was acting vertically on the sample. The sample was placed in a suprasil tube inserted in a liquid helium continuous flow cryostat, which could achieve temperatures down to 4.0 K. The GaMnAs layers were cleaved into two square pieces with edges along the [1 1 0] and [1 $\bar{1}$ 0] directions. Each piece was then placed in one of two geometries, referred to as "in-plane" and "out-of-plane". The out-of-plane geometry is when the sample plane and its [1 1 0] edge are vertical, which allows measurement with **H** oriented at any angle between **H**∥[0 0 1] (normal orientation) and **H**∥[1 $\bar{1}$ 0] (in plane orientation). The in-plane geometry is when the sample plane is horizontal, allowing us to map the FMR spectrum when **H** is confined to the layer plane.

4. Results and discussion

Along with FMR investigations, spin wave resonance spectra have also been observed in various samples [5,16,17]. In particular, the SWR spectra observed on our samples (with thicknesses in the range from 100 to 200 nm) exhibited certain universal features, illustrated by the data in Figs. 1 and 2 taken at $T = 4.0$ K on a 120-nm-thick $Ga_{0.92}Mn_{0.08}As$ film for several magnetic field orientations. As shown in Fig. 1, the spectrum clearly evolves as **H** is rotated from the perpendicular out-of-plane orientation (**H**∥[0 0 1], $\theta_H = 0°$) to the in-plane orientation (**H**∥[1 $\bar{1}$ 0], $\theta_H = 90°$). For

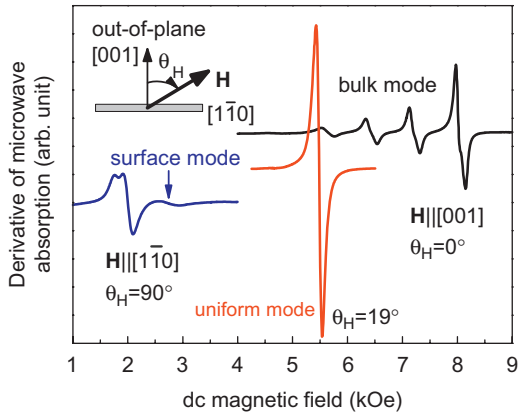

Fig. 1. (Color online) SWR spectra observed in the out-of-plane configuration (see inset) for a 120 nm $Ga_{0.92}Mn_{0.08}As$ specimen at $T = 4$ K, at three orientations θ_H for **H** between [1 $\bar{1}$ 0] and [0 0 1] directions. The arrow indicates the surface spin wave mode.

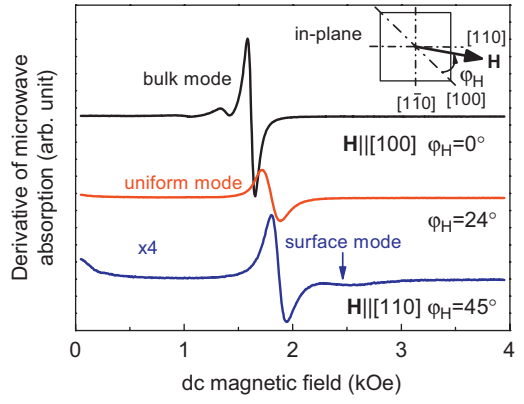

Fig. 2. (Color online) SWR spectra observed in the in-plane configuration (see inset) for a 120 nm $Ga_{0.92}Mn_{0.08}As$ specimen at $T = 4$ K, at three field orientations φ_H for **H** between n [1 0 0] and [1 1 0]. The arrow indicates the surface spin wave mode.

H∥[0 0 1] a resonance spectrum consists of 4 well-resolved Portis-type [18] SWR lines occurring at equal magnetic field separations. As one rotates **H** away from the perpendicular orientation, the SWR modes successively disappear, and eventually—at some critical angle θ_c (19° in Fig. 1)—the multi-mode SWR spectrum vanishes except for a single narrow resonance line. This line corresponds to the uniform FMR mode. For angle $\theta_H > \theta_c$, the multi-mode nature of the SWR spectrum reemerges, generally containing two or three broad resonances. One of these resonances (on the high-field side) is identified as an exchange-dominated non-propagating surface mode [19], also known as a surface spin excitation mode observed in the case of unpinned surface spins [20].

In the in-plane configuration (see Fig. 2) the angular dependence of the SWR spectrum shows a four-fold symmetry, with a slight two-fold distortion [21]. At $\varphi_H = 0°$ (**H**∥[1 0 0], i.e., along the easy axis) the spectrum consists of at least three SWR lines (which can be seen with greater magnification), which are found to obey the Kittel quadratic relations [22]. As **H** is rotated away from the easy axis, the multi-mode character of the spectrum gradually disappears, transforming into a single resonance line at φ_c (in Fig. 2 $\varphi_c = 24°$). As **H** continues to approach the hard axis (the in-plane [1 1 0] direction, $\varphi_H = 45°$ in Fig. 2), the spectrum transforms to one consisting of multiple absorption lines, including one corresponding to a surface mode.

The SWR spectra and their angular dependence shown in Figs. 1 and 2 can be qualitatively understood using the Rado–Weertman boundary conditions [23] and Puszkarski's surface inhomogeneity model [19]. Here, the spin pinning condition at each film surface can be described by the surface energy density F_S. One can then show that when $F_S > 0$, the spins are *pinned* at the surface, and a series of bulk SWR modes with real wave vectors $k_\perp$ is observed. For **H**∥[0 0 1] the dispersion of these waves is modified to obey a linear law, corresponding to the so-called Portis model [18].

As **H** tilts away from the [0 0 1] direction, F_S decreases, causing the surface spin pinning to fade away. At the critical-angle orientation corresponding to $F_S = 0$ (e.g., for $\theta_H = \theta_c = 19°$ in Fig. 1) only one resonance peak remains, corresponding to the uniform mode with $k_\perp = 0$. Finally, when **H** continues to approach the [1 1 0] or [1 $\bar{1}$ 0] directions, a weak higher-field mode appears several hundred Oersteds above the strongest mode (see Figs. 1 and 2). This mode is identified as a non-propagating surface mode (i.e., $k_\perp$ is imaginary for that mode), consistent with the case $F_S < 0$, and representing the condition when surface spins are *unpinned* [12]. Further analyses suggest that the magnetic anisotropy fields (both uniaxial term $H_{2\perp}$ and cubic term $H_{4\parallel}$) must differ by some amount in the bulk and surface regions [7,24]. The fact that magnetic anisotropy is different in the surface region (i.e., that there exists a surface anisotropy field) is the essential mechanism determining surface spin pinning, and thus also the character of SWRs observed in GaMnAs films [7].

For completeness, spin wave profiles (i.e., spin precession intensities along the growth direction z) of symmetric spin-wave modes corresponding to indices $n = 1$ and 3 are shown in Fig. 3 for four field orientations [7,12]. Comparing with the Kittel-type SW profile observed for **H**∥[1 0 0], the SW configuration for **H**∥[0 0 1] is distorted and concentrated in the center of the film. In contrast to both these cases, for **H**∥[1 1 0] the SW with $n = 1$ is localized at the surfaces of the film, thus forming a surface mode. At the critical angle θ_c the surface energy density $F_S = 0$, and only the uniform mode is observed (represented by the straight horizontal line, $k_\perp = 0$, for $n = 1$ in Fig. 3). The intensities of the higher modes are zero in this case.

To investigate the dependence of SWRs on the Mn concentration, we have chosen three specimens grown at similar conditions,