Materials Research Bulletin 72 (2015) 50–59

Contents lists available at ScienceDirect

Materials Research Bulletin

journal homepage: www.elsevier.com/locate/matresbu

Spin-anticrossing effects in Co–SiO_2–Fe and ZnO–SiO_2–CuO three-nanolayer devices

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ARTICLE INFO

Article history:
Received 28 December 2014
Received in revised form 24 June 2015
Accepted 28 June 2015
Available online 23 July 2015

Keywords:
A. Layered compounds
A. Metals
B. Laser deposition
B. Sputtering
C. Electron spin resonance
C. Electron microscopy
D. Spin-density waves
D. Electronic structure

ABSTRACT

Presently we report measurements of the spin-anticrossing spectra in the Co–SiO_2–Fe and ZnO–SiO_2–CuO three-nanolayer sandwich structures. The spin-anticrossing spectra in these systems are quite specific, differing from those observed earlier in other similar structures built of different materials. The theoretical model developed earlier is extended and used to interpret the available experimental results. A detailed *ab initio* analysis of the magnetic-field dependence of the output magnetic moment is also performed. The model predicts a spin-anticrossing spectrum comprising a series of peaks, with the spectral structure determined by several factors, discussed in the paper.

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1. Introduction

Various resonance phenomena are induced in a range of materials by continuous external microwave or radiofrequency electromagnetic fields in the presence of tunable magnetic fields and detected by either the steady-state resonance techniques or by pulsed microwave or radiofrequency fields in the presence of constant magnetic fields [1]. All of these resonance effects are strongly dependent on the relaxation properties of the spin states. The spin–lattice relaxation mechanisms have been studied earlier in detail for metals and metal particles of different size [2–9]. Spin–lattice relaxation in metals may be caused by (i) interaction of spin polarized states with electromagnetic fields induced by fluctuations of the electric charge density, (ii) phonon density, (iii) spin–orbit (SO) interactions and (iv) higher-order interactions involving nuclear spin. The spin–spin relaxation processes also affect the spin state dynamics. Therefore, it is very important to develop new methods of theoretical and experimental studies of spin state dynamics in solids. The analysis of spin-polarized state dynamics using novel experimental and theoretical approaches is an important fundamental problem. The spin-anticrossing (SA) effects created in multi-nanolayer systems may be considered as resulting from the spin-polarized state filtration and have potential applications in quantum spin-polarized state filters (QSPSF). Such a device, described earlier and based upon metal–dielectric–iron and metal–dielectric–semiconductor structures [10–12] allows transferring spin-polarized states between nanolayers of different nature and chemical composition, measuring the values of the *g*-factor difference between the device nanolayers and estimating the respective relaxation parameters of the spin-polarized states. Recently, we analyzed several theoretic approaches to the formation of the spin-polarized states in ferromagnetics, conductors and semiconductors, proposing a phenomenological model for the spin-polarized state transfer. This modeling approach assumes transfer of spin-polarized states between different nanolayers [10–12]. Experimental measurements of the SA-resonance spectra in four-layer sandwich structures were also carried out [10]. The presently discussed Co–SiO_2–Fe (Co/Fe) and ZnO–SiO_2–CuO (ZnO/CuO) structures produce distinct spectra, differing from those obtained earlier for other nanolayer sandwich structures [10–12]. These spectra are analyzed and interpreted using the earlier and presently developed theoretical models.

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http://dx.doi.org/10.1016/j.materresbull.2015.06.050
0025-5408/Published by Elsevier Ltd.

2. Experimental

2.1. Device description

The experimental setup used in the current studies has already been described in detail earlier [10–12]. It was built around the home-made nanosandwich structure. This setup used a ferrite needle (1) (Murata), with the needle tip 50 mm in diameter made of a stainless-steel capillary filled with ferrite powder suspended in glycerol, and the body 1 mm in diameter. The saturation field and the frequency band for the ferrite are 11–13 kG and $\nu_{H,O}=(1\text{–}1.5)\times10^8$ Hz, respectively. The transmission of the ferrite at frequencies $\nu_H > \boldsymbol{\nu}_{H,0}$ is described by

$$\vartheta(\nu_H) = \vartheta(\nu_{H,0})e^{-\frac{\nu_H-\nu_{H,0}}{\nu_{H,0}}} \tag{1}$$

A spiral coil of copper wire (0.3 mm wire diameter, 10 turns) was wound on the needle body. The needle tip touched the surface of a Si substrate at the (1 0 0) plane. The opposite surface of the Si substrate, equally (1 0 0), was covered by a sandwich structure, prepared as described separately. A second ferrite item (Murata), with the input surface 10 mm in diameter and the body 1 mm in diameter, contacted the output metal surface by way of a magnetic contact provided by ferrite powder suspended in glycerol (1:1 w/w) (Murata, 25 mm average particle diameter). Copper wire, 0.3 mm in diameter, was wound on the body of the item (10 turns). Note that the same high-frequency ferrite material was used everywhere, rated for up to 100 MHz applications. The entire assembly with the nanosandwich sample was placed into a liquid nitrogen bath (T = 77 K), to reduce noise.

The home-built current generator was controlled *via* an I/O data acquisition board (PCI-6034E DAQ, National Instruments), which was programmed in the LABVIEW environment that ran on a Dell PC. The generator fed pulsed currents of up to 10 A into the input coil. The pulse shape was programmed to reproduce the linear function:

$$I_2(t) = \begin{cases} 0, & 0 \le t < t_0 \\ I_0 \times (t-t_0), & t_0 \le t < t_0+\tau \\ 0, & t_0+\tau \le t \end{cases} \tag{2}$$

where I_0, t_0 and τ (pulse amplitude, start time and duration) were chosen to obtain the required magnetic field sweep rate. The output coil was connected to a digital oscilloscope (LeCroy; WaveSurfer 432), which collected and averaged the output signal. The I/O DAQ board generated an analog signal that controlled the current generator, and a rectangular TTL pulse 100 ns in duration that triggered the oscilloscope with its rising edge, 100 ns before the start of the analog control signal sweep.

2.2. Multilayer sandwich structure preparation

A detailed description of the device preparation procedure and multilayer sample characterization has been presented earlier [10]. Charge sputtering, vacuum evaporation and laser vapor deposition were used to deposit the metal, oxide and SiO_2 layers, respectively. The nanolayer deposition procedure has been described earlier [10–14]. The layer thickness was controlled by transmission electron microscopy (TEM) on cross-cut samples, prepared using heavy-ion milling. The nanolayer devices were used in the present series of experiments, with the measurements mostly conducted at LN_2 temperature (77 K), unless expressly specified otherwise. The spin-anticrossing resonance spectra and their amplitude dependence on the magnetic field sweep rates were recorded using the same data acquisition system as earlier [10], briefly described above.

3. Results and discussion

We studied the exchange-resonance spectra for a series of nanolayer sandwich devices, with Co/Fe and ZnO/CuO structures. These Co/Fe and ZnO/CuO devices used the Co (h_{Co} = 7.6; 8.1; 8.7;

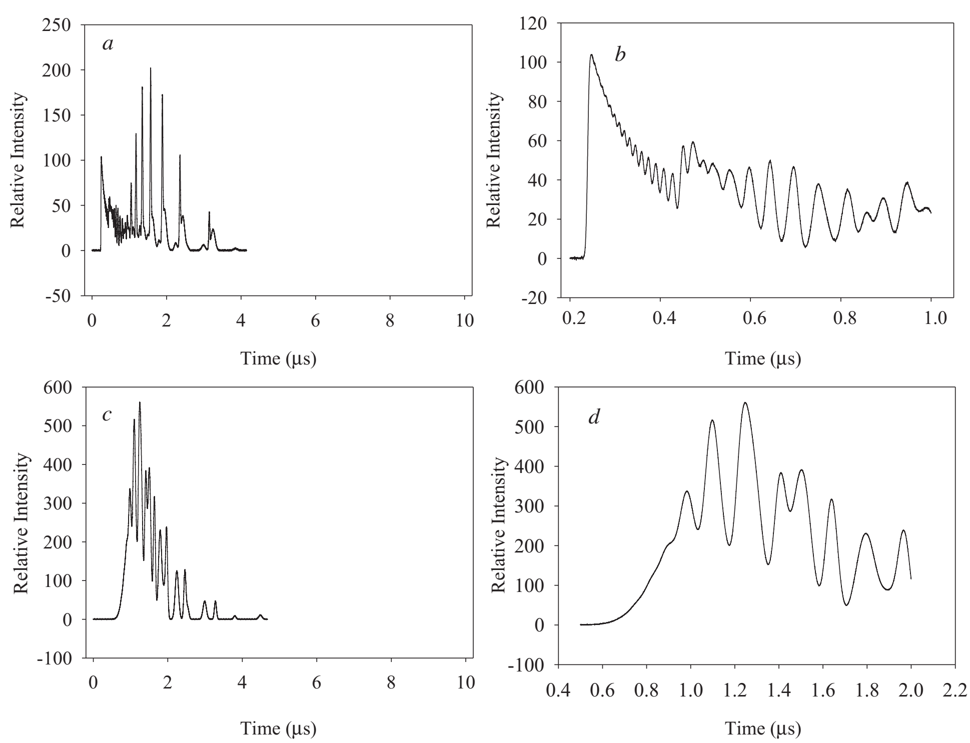

Fig. 1. The experimental spin-anticrossing resonance spectra (a,b) Co (7.6 nm)–SiO_2 (7.9 nm)–Fe (7.9 nm) sandwich structure; (c,d) ZnO (7.4 nm)–SiO_2 (7.6 nm)–CuO (7.7 nm) sandwich structure, all recorded at 77 K (LN_2).