ADVANCED MAGNETIC MATERIALS

Edited by **Leszek Malkinski**

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Preface

Recent progress in information technology, wireless communication, biotechnology and microelectronics requires advanced technologies and new magnetic materials to meet demands of modern devices. This collection of eight chapters provides an up-to-date review of recent trends and developments in technology, characterization methods, theory and applications of modern magnetic materials with original, never published contributions from the renowned scientists in the field of magnetism. The book is addressed to a diverse group of readers which include students, engineers and researchers in the fields of physics, chemistry, bioengineering, electronics and materials science, who wish to enrich their knowledge about advanced magnetics. Depending on the discipline represented by the readers they are invited to read entire book or select chapters of particular interest. In order to help with the choice of appropriate chapters below I summarize their content:

Chapter 1. The first chapter reports on fabrication method of amorphous magnetic nanowires with the glass coating using rapid solidification of the melt. The original measurement methods and magnetic properties of the nanowires with the diameters ranging from 90 nm to 13 μm are presented. In particular, the article targets the effect of fabrication conditions and post-fabrication treatment on mobility and velocity of domain walls in the nanowires, which can be used in future racetrack memories, magnetic domain wall logic devices, domain wall diodes and oscillators, and other devices.

Chapter 2. Future microwave devices for wireless communications require extended frequency range. This chapter treats about new developments in technology and application of a new microwave material - barium hexagonal ferrite films with extremely high anisotropy, large saturation magnetization and low losses in the microwave range. The author demonstrates original results regarding prototype notch filters and phase shifters operating at millimeter range wavelengths which employ the hexagonal ferrite films.

Chapter 3. Spin electronics (or spintronics) is an emerging field of science which takes advantage of magnetic moments to build nonvolatile random access memories and other digital devices. In order to compete and eventually replace semiconductor-based electronics, the spintronic devices must use materials with nearly 100% spin polarization. The magnetite is one of the best candidates for the spintronic applications. However, its performance in existing devices is drastically reduced by the atomic structure at the surface which differs from that of the bulk. This chapter presents studies of surface reconstruction of the magnetite and describes methods for increasing spin efficiency in spintronic devices by preserving the Fe_3O_4 structure of the surface.

Chapter 4. Multiferroic composites consisting of ferromagnetic and ferroelectric materials provide a unique way of converting magnetic field into electric field. This process involves stresses at the interface between these materials and takes advantage of the piezoelectricity of the ferroelectric and the magnetostriction of the ferromagnetic phase. This chapter describes original methods of synthesis of multiferroic core-shell nanoparticles and indicates entirely new biomedical applications of such nanoparticles. Using external alternating magnetic fields it is possible to produce local electric fields near multiferroic nanoparticles which can control opening and closing of voltage-gated ion channels in mammalian cells. Ion channels are involved in generation and propagation of action potentials in nerves and their malfunction can lead to multiple diseases such as cystic fibrosis, diabetes, cardiac arrhythmias, neurological disorders or hypertension. The proposed mechanism has also potential for a new method of cancer treatment.

Chapter 5. One of challenges in the design of portable electronic devices is the optimization of on-chip inductors for the power conversion. This optimization takes into account multiple factors, such as size, a choice of fabrications method, frequency range of operation, energy losses and cost of the device. This chapter provides detailed discussion about theory, design, fabrication methods and measurements of essential parameters characterizing electroplated micro-inductors for DC-DC conversion operating with the switching frequency up to 100 MHz.

Chapter 6. The focus of this chapter is on the relation between magnetic properties and disorder in the Fe-Al system. Depending on the composition and the microstructure, different magnetic and structural orders can exist in this system including a spin-glass order. Detailed experimental studies based on magnetometry, the Mössbauer effect and X-ray diffractometry, as well as theoretical models of this system show that the atomic disorder, which can be controlled by a mechanical treatment or an annealing, leads to significant increase in the lattice parameters and the magnetization compared to those in the ordered structures. The contribution of disorder to the magnetism of these alloys depends on the Fe content of the alloy and is the largest close to the equi-atomic FeAl alloy, but in $Fe_{75}Al_{25}$ alloy it is similar to the one given by the volume change.

Chapter 7. Direct characterization of the magnetic material parameters based on measurements of magnetic devices with complicated geometry is a complex problem. This chapter proposes the state-of-the-art methodology to extract materials characteristics from the measurements of electromagnetic devices. This original algorithm is robust because all uncertainties present in electromagnetic devices are taken into account in a stochastic framework. The algorithm is validated by applying it for the identification of the magnetic properties of the material in an electromagnetic device - an electromagnetic core inductor.

Chapter 8. The last chapter tackles the problem of modeling of magnetic properties. Macroscopic samples and devices consist of a large number of magnetic domains which interact and evolve during magnetization process. Therefore, modeling of magnetic hysteresis is one of the most difficult tasks in magnetism. This chapter provides a detailed description of a new model for modeling of magnetization processes in magnetic materials. It is based on a stochastic Preisach approach and uses hyperbolic analytical approximation of the Everett integral. The theory offers modeling of coercive force, remanent magnetization, hysteretic losses, Barkhausen effect, eddy current losses, exchange bias and other essential properties of the magnetic materials. It is applicable to a large variety of magnetic materials.

Research on magnetic materials is a dynamically expanding field of science and this book demonstrates some highlights rather than complete overview of this vast discipline. I hope that reading this book will spark interest of the readers and encourage them to study magnetism of advanced materials. It will also bring better understanding of challenging technologies which become a part of our life, whenever we use computers, cellphones and other modern devices.

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1

Rapidly Solidified Magnetic Nanowires and Submicron Wires

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1. Introduction

Magnetically soft amorphous glass-coated microwires are suitable for numerous sensor applications. Their typical dimensions – metallic nucleus diameter of 1 to 50 μm and glass coating thickness of 1 to 30 μm – make them promising candidates for high frequency applications, especially given their sensitive giant magneto-impedance (GMI) response in the MHz and GHz ranges (Torrejón et al, 2009). The magnetic properties of amorphous microwires are determined by composition, which gives the sign and magnitude of their magnetostriction, as well as by dimensions – metallic nucleus diameter, glass coating thickness, and their ratio – which are extremely relevant for the level of internal stresses induced during preparation. The magneto-mechanical coupling between internal stresses and magnetostriction is mainly responsible for the distribution of anisotropy axes and domain structure formation. Microwires generally display a core-shell domain structure in their metallic nucleus, with orthogonal easy axes, e.g. axial in the core and circumferential or radial in the shell, as schematically shown in Fig. 1.

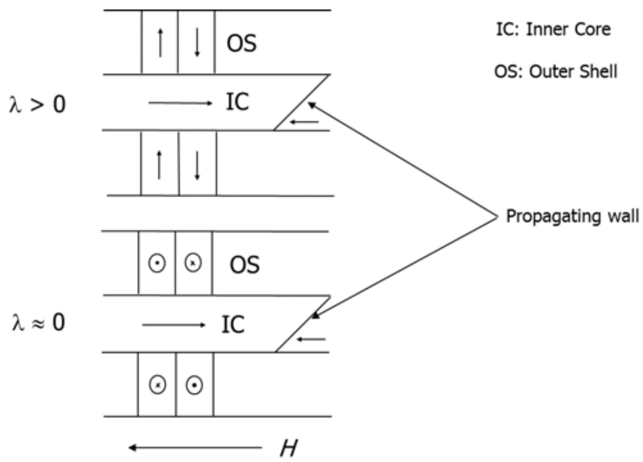

Fig. 1. Typical core-shell domain structures in amorphous glass-coated microwires with positive (λ >0) and nearly zero magnetostriction (λ ≈ 0), respectively.

An axially magnetized core, usually encountered in amorphous microwires with large and positive magnetostriction, but also in nearly zero magnetostrictive ones if their nucleus diameter is larger than 20 μm (Chiriac et al., 2007a), leads to the appearance of the large Barkhausen effect (LBE), that is a single step reversal of the magnetization in the core when the sample is subjected to a small axial magnetic field. LBE takes place through the propagation of a pre-existent 180° domain wall from one microwire end to the other, as illustrated in Fig. 1.

Ferromagnetic nanowires are aimed for novel spintronic applications such as racetrack memory, magnetic domain wall logic devices, domain wall diodes and oscillators, and devices based on field or spin-current torque driven domain wall motion (Allwood et al., 2005; Finocchio et al., 2010; Lee et al., 2007; Parkin et al., 2008). These applications require nanowires with characteristics that can be accurately controlled and tailored, and with large domain wall velocities, since the device speed depends on domain wall velocity. At present, spintronic applications which require magnetic nanowires are based on planar nanowires prepared by expensive lithographic methods (Moriya et al., 2010).

Recently, the large values of domain wall velocity reported in amorphous glass-coated microwires have offered new prospects for the use of these much cheaper rapidly solidified materials in spintronic applications, subject to a significant reduction in their diameter (Chiriac et al., 2009a). The amorphous nanowires are composite materials consisting of a metallic nucleus embedded in a glass coating prepared in a single stage process, the glass-coated melt spinning, at sample lengths of the order of 10^4 m (Chiriac & Óvári, 1996). In order to overcome the experimental difficulties related to the fabrication of such ultra-thin wires and to drastically reduce the typical transverse dimensions of microwires (1 to 50 μm for the metallic nucleus diameter), the apparatus used for the preparation of the rapidly solidified nanowires has been significantly modified. These efforts have led to the successful preparation and characterization of rapidly solidified submicron wires with the metallic nucleus diameter of 800 nm, reported less than 2 years ago (Chiriac et al., 2010). Figure 2 (a) shows the SEM images of a submicron amorphous wire with the nucleus diameter of 800 nm, whilst Fig. 2 (b) illustrates the optical microscopy image of the submicron amorphous wire in comparison with two typical amorphous microwires with the nucleus diameters of 4.7 and 1.8 μm, respectively. These results have opened up the opportunity to develop nanosized rapidly solidified amorphous magnetic materials for applications based on the domain wall motion.

This first success has been shortly followed by the preparation and characterization of amorphous glass-coated submicron wires with metallic nucleus diameters down to 350 nm (Chiriac et al., 2011a), in which domain wall velocity measurements have also shown very promising results (Óvári et al., 2011).

The well-known methods employed in the experimental studies have been extensively modified in order to allow one to perform complex measurements on such thin wires, especially due to the high sensitivity required to measure a single rapidly solidified ultra-thin wire (Corodeanu et al., 2011a).

Following the same path, we have been able to produce rapidly solidified amorphous nanowires through an improved technique. The diameters of the as-quenched nanowires were ranging from 90 to 180 nm (Chiriac et al., 2011b). These new materials are useful for

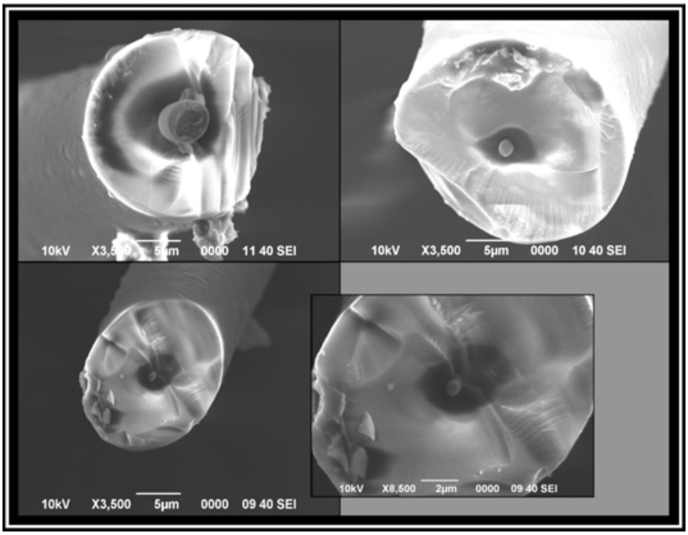

Fig. 2a. SEM images of a submicron amorphous wire with the nucleus diameter of 800 nm.

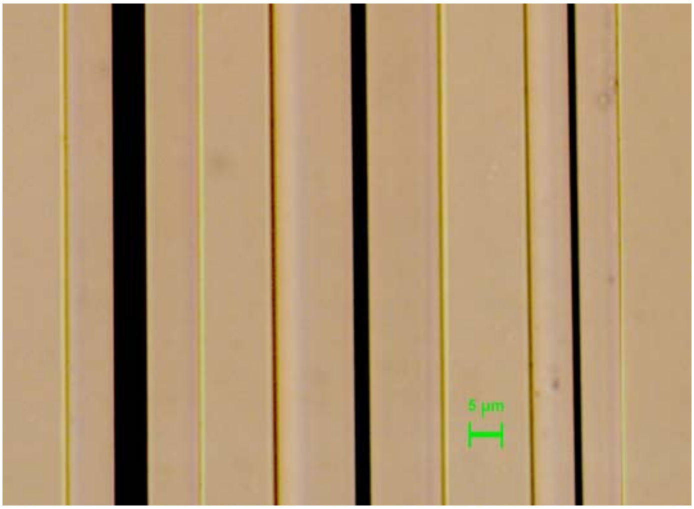

Fig. 2b. Optical microscopy images of the submicron amorphous wire in comparison with two typical amorphous microwires with the nucleus diameters of 4.7 and 1.8 μm, respectively.

applications in both domain wall logic type devices and in novel, miniature sensors. The accurate control of the domain wall motion could be performed without irreversible modifications of the wire geometry, as recently pointed out (Vázquez et al., 2012). Nevertheless, there are several issues to be addressed before these new materials can reach their full practical potential: their integration in electronic circuits, the use of lithographic methods to prepare the miniature coils required to inject and trap domain walls, the clarification of the role of glass coating and whether or not it should be kept, removed or just partially removed – and in which stages of the device development, issues related to the manipulation of wires with such small diameters, etc.

Figure 3 shows two SEM micrographs of a glass-coated $Fe_{77.5}Si_{7.5}B_{15}$ amorphous magnetic nanowire with the metallic nucleus diameter of 90 nm and the glass coating of 5.5 μm, taken at different magnifications.

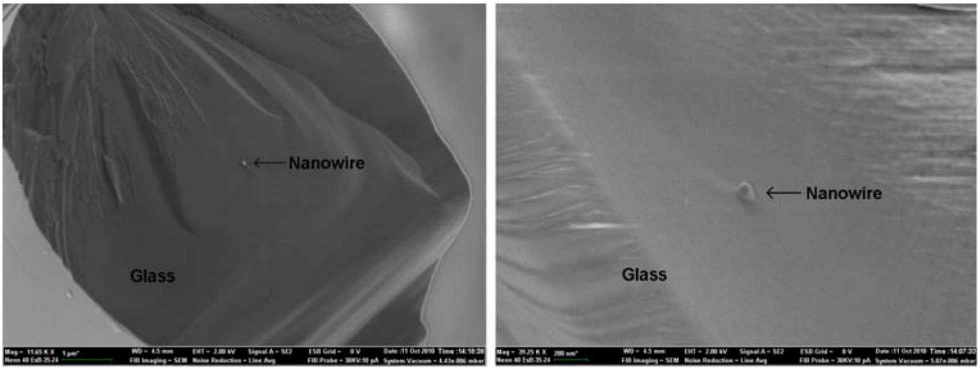

Fig. 3. SEM micrographs at two different magnifications of a rapidly solidified amorphous nanowire with positive magnetostriction having the metallic nucleus diameter of 90 nm and a glass coating thickness of 5.5 μm.

A new method for measuring the domain wall velocity in a single, ultrathin ferromagnetic amorphous wire with the diameter down to 100 nm has been developed in order to measure such novel nanowires (Corodeanu et al., 2011b). The method has been developed in order to increase the sensitivity in studying the domain wall propagation in bistable magnetic wires in a wide range of field amplitudes, with much larger values of the applied field as compared to those employed when studying the wall propagation in typical amorphous microwires. The newly developed method is especially important now, when large effort is devoted to the development of domain wall logic devices based on ultrathin magnetic wires and nanowires.

Besides the spintronic applications, the investigation of rapidly solidified amorphous submicron wires and nanowires is aimed towards the understanding of the changes in the magnetic domain structure, which makes the bistable behavior possible, and in the switching field, at submicron level and at nanoscale.

2. Experimental techniques for the characterization of rapidly solidified amorphous nanowires and submicron wires. Domain wall velocity measurements

2.1 Magnetic characterization

Given the ultra-small diameters of rapidly solidified submicron wires and nanowires (metallic nucleus diameters between several tens of nanometers and hundreds of nanometers), the use of the classical characterization techniques employed for typical microwires with diameters between 1 and 50 μm (Butta et al., 2009; Kulik et al., 1993) in order to measure their basic magnetic properties, e.g. to determine their magnetic hysteresis loops, is not viable due to the low sensitivity and signal-to-noise ratio (SNR). Therefore, in order to investigate the magnetic properties of a single ultrathin magnetic wire, a reliable measuring system has been developed (Corodeanu et al., 2011a). The new procedure has been employed to measure a single ultrathin magnetic wire, i.e. a submicron wire or a nanowire, using a digital integration technique. The new experimental set-up has been developed in order to increase the sensitivity and to extract from the noisy signal a reliable low frequency hysteresis loop for a single submicron wire or nanowire.

The main components of the measuring system used in the experiments are: the magnetizing solenoid, the system of pick-up coils, a low-noise preamplifier, a function generator, and a data acquisition board. A schematic of the system is shown in Fig. 4.

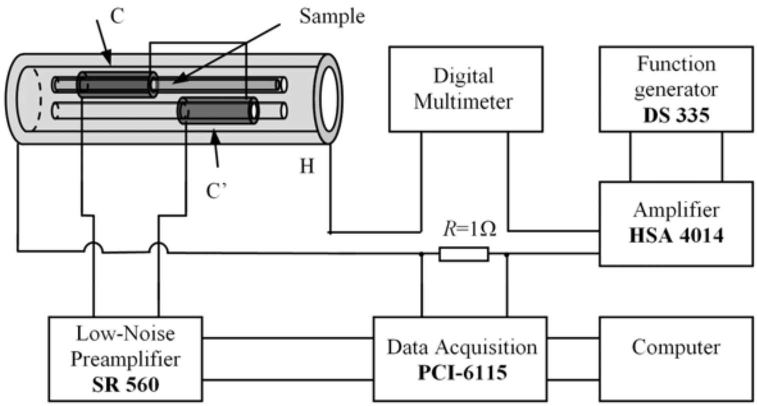

Fig. 4. Schematic of the experimental system employed for the magnetic characterization of rapidly solidified amorphous nanowires and submicron wires.

The magnetizing solenoid is powered by a Stanford Research DS 335 function generator through a high power bipolar amplifier HSA 4014, being capable of generating magnetic fields up to 30,000 A/m. Two pick-up coils connected in series-opposition are used in order to avoid any induced voltage in the absence of the sample. Each pick-up coil is 1 cm long and has 1,570 turns, wound with enameled 0.07 mm copper wire on a ceramic tube with an outer diameter of 1.8 mm and an inner diameter of 1 mm. A 1 Ω resistor (R) is used to provide a voltage proportional to the applied magnetic field. The voltage induced in the pick-up coil is amplified up to 50,000 times using a Stanford Research SR560 low-noise preamplifier in order to obtain a measurable value of the induced voltage and a high SNR. The voltage drop on the resistor R and the amplified induced voltage from the pick-up coil system are digitized using a National Instruments PCI-6115 four channels simultaneous data acquisition board. The acquisition of the signals was done using a sampling frequency between 800 kHz and 10 MHz (with 5,000 to 62,500 points/loop at 160 Hz). The acquired signals have been processed using LabVIEW based software.

Two methods have been employed to measure the hysteresis loops. For the first one, it was necessary to make an average over a large number of acquired signals, while for the second one only two recordings of the signal were required (with and without the sample), followed by digital processing to trace the hysteresis loop.