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Controlled motion of domain walls in submicron amorphous wires

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Results on the control of the domain wall displacement in cylindrical $Fe_{77.5}Si_{7.5}B_{15}$ amorphous glass-coated submicron wires prepared by rapid quenching from the melt are reported. The control methods have relied on conical notches with various depths, up to a few tens of nm, made in the glass coating and in the metallic nucleus using a focused ion beam (FIB) system, and on the use of small nucleation coils at one of the sample ends in order to apply magnetic field pulses aimed to enhance the nucleation of reverse domains. The notch-based method is used for the first time in the case of cylindrical ultrathin wires. The results show that the most efficient technique of controlling the domain wall motion in this type of samples is the simultaneous use of notches and nucleation coils. Their effect depends on wire diameter, notch depth, its position on the wire length, and characteristics of the applied pulse. [http://dx.doi.org/10.1063/1.4944075]

I. INTRODUCTION

Ultrathin amorphous glass-coated wires with metallic nucleus diameters smaller than 1 μm have been recently prepared by rapid quenching from the melt.[1] Their axial magnetization process occurs through the displacement of a single 180° domain wall along the entire sample length, when the axially applied magnetic field reaches a certain threshold value, called the switching field. This type of magnetization process is referred to as bistable magnetic behavior. The motion of domain walls in such ultrathin magnetic wires is of recent interest for applications in domain wall logic devices and in miniature magnetic sensors.[2] The bistable behavior of the magnetization, along with the large velocities of the domains walls (significantly larger than 1000 m/s), are just two of the key characteristics of the submicron glass-coated ferromagnetic wires and nanowires, which recommend them for applications in spintronics (e.g., racetrack memory, magnetic domain wall logic devices, diodes and domain wall oscillators, spin-current driven domain wall motion torque) and in novel micro- and nanosensing devices. Nevertheless, such applications require an accurate and fast control over the dynamics of the magnetic domain walls, since the speed of these devices will directly depend on the velocity of the domain walls.

The fairly high values of the domain wall velocity, along with the envisaged possibility to control the nucleation of new domains and the propagation of the domain walls in these glass-coated ferromagnetic nanowires and submicron wires, have led to the idea that these materials could be a cheaper alternative to the planar nanowires prepared by means of much more complex and expensive techniques, such as electron beam lithography.[3]

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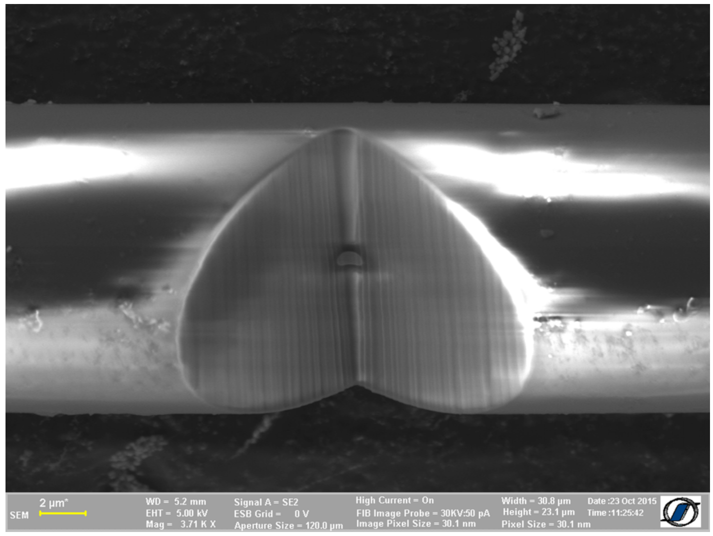

FIG. 1. Notch made by focused ion beam (FIB) in an $Fe_{77.5}Si_{7.5}B_{15}$ submicron amorphous wire with the nucleus diameter of 690 nm (top view).

The dynamics of the magnetic domain walls is heavily influenced by the presence of potential defects in the structure of the ferromagnetic wire. Structural or other types of defects, such as artificial ones made by a focused ion beam (FIB) system or by using other indentation techniques, could act as true magnetic traps or barriers for the domain wall, depending on the type and geometry of the defect. Therefore, artificial defects could play a very important role in controlling the motion and pinning of domain walls not just in planar nanowires, but also in these cylindrical nanowires and submicron wires. The domain wall pinning effect is expected to be stronger when the size of the defect is comparable with the width of the domain wall.[4] We have taken into consideration all these aspects in our study.

II. EXPERIMENTAL

Submicron amorphous glass-coated magnetic wires with the nominal composition $Fe_{77.5}Si_{7.5}B_{15}$ have been prepared by the glass-coating melt spinning method.[5] The diameters of the metallic nucleus (the actual magnetic submicron wire) have been ranging between 300 and 800 nm, whereas the glass coating thickness has been kept constant at about 5 µm.

Notches with various depths have been made in the amorphous samples using a Carl Zeiss CrossBeam NEON 40 EsB FIB system. Figure 1 shows the top view of an FIB-made notch in an amorphous submicron wire with the metallic nucleus diameter of 690 nm. The notch passes through the glass coating and reaches about 400 nm deep into the metallic nucleus, which is more than half its diameter.

The influence of the artificial defects made with the FIB system on the nucleation of new domains and propagation of the domain walls along the samples has been investigated by using a set-up based on a NANOMOKE-2 facility for the study of magneto-optical Kerr effect (MOKE). In this way, the propagation of a magnetic domain wall in a certain region of the sample can be monitored through the Kerr transitions corresponding to the magnetization reversal. The laser beam is directed and focused on a particular area of interest using lenses. By successively monitoring two different regions – one located before the artificial defect and another one located after the defect, in the direction of the domain wall displacement – one can study the changes induced in the dynamics of the domain wall by such artificial defects.

We enforced the nucleation of a new magnetic domain with reverse magnetization at the left end of the 6 mm long sample, as illustrated in Figure 2. To make sure that the domain wall propagates in the desired direction, i.e. towards the artificial defect, the nucleation pulse is synchronized

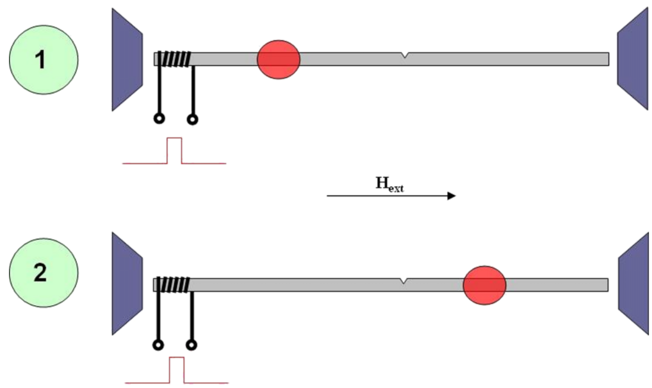

FIG. 2. Schematic of the method for monitoring the nucleation of reverse domains and the propagation of the associated domain walls in 6 mm long submicron amorphous wires by successive measurements in two adjacent areas of an artificial defect (notch). H_{ext} is the excitation field generated with a quadrupole electromagnet.

with the positive alternation of the excitation magnetic field H_{ext}. In order to generate the nucleation field in a certain region (e.g., in the leftmost part of the sample), we used in the performed experiments small nucleation coils positioned at the desired locations, such as the left end of the sample in the case represented in Figure 2. The nucleation field is the value of the axially applied magnetic field for which the first deviations from the uniformly magnetized state begin to appear, leading to the nucleation and formation of a new magnetic domain with reverse orientation of the magnetization.

For the ac magnetization of the sample, we employed a quadrupole electromagnet powered by a bipolar voltage source. The 6 mm long samples are placed between the poles of the electromagnet, which are located at a distance of 20 mm from each other, in order to ensure a uniform excitation field H_{ext}. The operating frequency of the ac excitation magnetic field was 2 Hz, which means that the domain wall is passing through the monitored region four times per second. The nucleation coils were fed to a pulse generator which allows adjusting both the frequency of repetition of the pulses and their duration. Pulses through the nucleation coil are synchronized with the excitation magnetic field, having the same frequency and the possibility of adjusting the position of the pulse with respect to the amplitude of the excitation signal. The duration of a nucleation pulse was 50 µs and its amplitude was 80 Oe. A first condition to be met for the purpose of these experiments is that the position of the nucleation pulse has to correspond to the values of the amplitude for an excitation field lower than the coercivity of the sample so that the domain wall will be pushed towards the sample end in the desired direction, through the artificial defect (see Figure 2).

During the propagation of the domain wall, the excitation field can be considered to be homogeneous along the sample length, since the domain wall velocity is very high in comparison with the increment time of the excitation field.

The Kerr signal corresponding to the Kerr transitions was plotted versus the excitation applied magnetic field for the two adjacent areas of the artificial defect (before and after the defect).

III. RESULTS AND DISCUSSION

Figures 3 and 4 show the combined effects of the nucleation pulse and of the magnetic trap represented by the defect (notch made using the FIB system) on the MOKE hysteresis loops measured before and after the notch, on $Fe_{77.5}Si_{7.5}B_{15}$ submicron wires with different diameters (690 nm and 530 nm, respectively).

Figure 3 shows that, without the nucleation pulse, the hysteresis loop is symmetrical, the rather large coercivity of nearly 30 Oe being the same in the case of this sample with and without the notch (loop without notch is not shown for this reason), which indicates that it originates mainly in the nucleation at the wire end, and that the pinning field at the notch site is somewhat smaller. When a nucleation pulse is applied, the loop becomes asymmetrical, and the overall coercivity decreases,

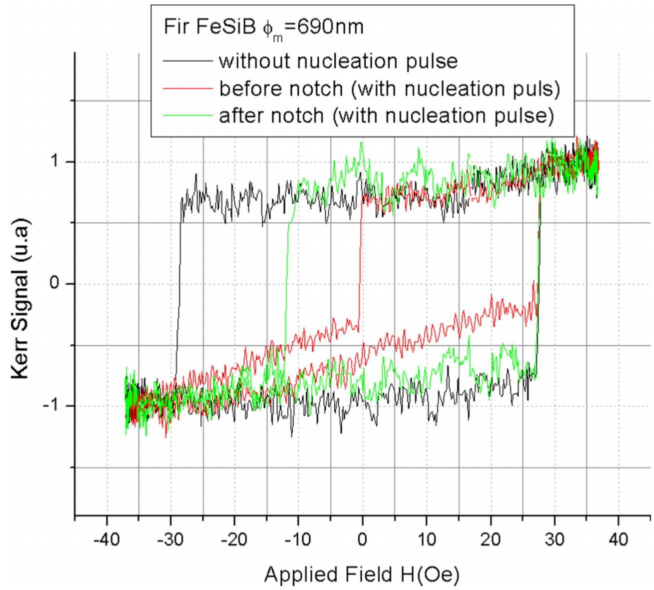

FIG. 3. MOKE hysteresis for two adjacent zones of the defect in two separate cases: with and without nucleation pulse (notch depth in the metallic core is about 400 nm) in the case of the $Fe_{77.5}Si_{7.5}B_{15}$ sample with the metallic nucleus diameter of 690 nm.

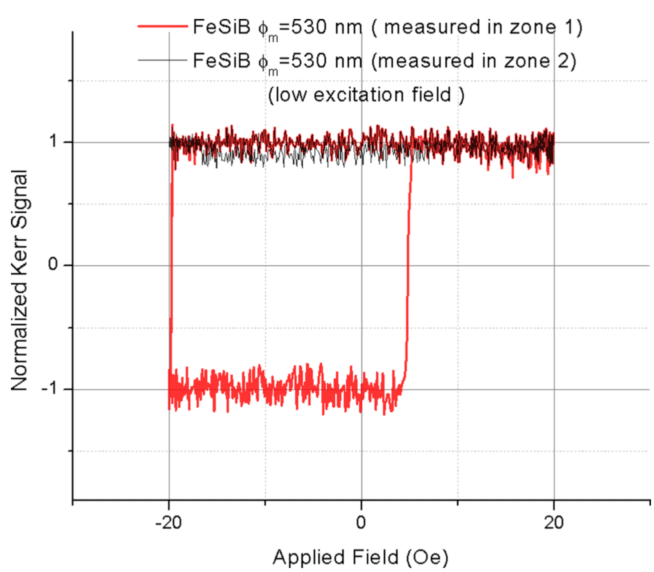

FIG. 4. Kerr transition vs. applied field for low amplitude of the excitation field in the case of an $Fe_{77.5}Si_{7.5}B_{15}$ amorphous submicron wire with the metallic nucleus diameter of 530 nm. The notch depth is 300 nm in this case.

being larger after the notch, due to the additional energy required to push the domain wall through the defect. The loops are affected by the remanence of the quadrupole, and they have been aligned by adjusting the dc bias field in order to clearly show the differences among the three illustrated cases.

One can have different values for the domain wall pinning field, depending on the depth of the notches. Figure 4 shows the low-field MOKE hysteresis loop for a sample with the nucleus diameter of 530 nm. If the applied field is low, then it is not enough to push the wall through the energy barrier caused by the defect, and, therefore, the propagation of the wall is restricted to the region located to the left of the notch.

Thus, a magnetic field with an amplitude comparable or even higher than the coercivity of the sample with the defect is required in order to push the domain wall out of the magnetic trap and to continue the magnetization reversal within the entire volume of the sample. For samples with no defects and no nucleation pulses applied, the hysteresis curves are square and perfectly centered with respect to the applied excitation magnetic field, i.e. magnetization switching occurs in both directions for the same value of the applied field. For amplitudes of the magnetic field smaller than the coercivity, no hysteresis is detected, since magnetization reversal does not occur anymore (see Figure 4). When applying a nucleation pulse, an asymmetric hysteresis loop is obtained, due to the generation of a domain wall that will propagate along the sample, reversing the magnetization in the entire sample. In the case of the samples with notches, during the propagation of the domain wall, at the location of the defect, there is a reduction in the surface of the wall that yields a change in the spin structure. This change in the spin structure of the domain wall is responsible for the effect of the domain wall pinning. Hence, larger values of the applied field are required in order to overcome the pinning field, in some cases comparable to or even larger than the coercivity, and to push the domain wall through the notch.

IV. CONCLUSION

We have demonstrated the possibility to generate and pin a domain wall in well defined regions of our samples. The measurements have shown that the simultaneous use of nucleation pulses method and artificial defects (notches made by FIB), can yield a good and efficient control of the domain wall movement in ferromagnetic amorphous submicron wires. Magneto-optical Kerr effect (MOKE) surface hysteresis loop measurements have been performed in order to study the influence of the FIB-made notches and of the nucleation coils on coercivity and on the overall characteristics of the domain wall propagation. Their effect depends on the diameter of the amorphous wire, on the depth of the notch, as well as on the characteristics of the applied nucleation pulse.

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