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Magnetic scanning gate microscopy of a domain wall nanosensor using microparticle probe

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ABSTRACT

We apply the magnetic scanning gate microscopy (SGM) technique to study the interaction between a magnetic bead (MB) and a domain wall (DW) trapped in an L-shaped magnetic nanostructure. Magnetic SGM is performed using a custom-made probe, comprising a hard magnetic NdFeB bead of diameter 1.6 μm attached to a standard silicon tip. The MB–DW interaction is detected by measuring changes in the electrical resistance of the device as a function of the tip position. By scanning at different heights, we create a 3D map of the MB–DW interaction and extract the sensing volume for different widths of the nanostructure's arms. It is shown that for 50 nm wide devices the sensing volume is a cone of 880 nm in diameter by 1.4 μm in height, and reduces down to 800 nm in height for 100 nm devices with almost no change in its diameter.

1. Introduction

Magnetic force microscopy (MFM) is a well-established scanning probe microscopy (SPM) technique for imaging magnetic domains within the nanoscale range. Due to its high resolution, down to 10 nm [1,2], MFM allowed the study of domain walls (DWs) inside nanostructures in great detail [3,4]. While in general the tip's stray magnetic field is only weakly coupled to the sample in order to minimize mutual magnetic influence, sometimes it is useful to introduce a stronger interaction between the tip and the sample. For instance, MFM has been used in the past to nucleate domain walls (DWs) along magnetic nanowires [5], or more recently, by attaching a single magnetic bead to an AFM tip, it was used to study the interaction between the bead and a hard micromagnet array [6].

DW-based technology has initially emerged for MRAM applications [7] as well as a way to manipulate [8–11] and detect magnetic beads (MB) [12–15]. Geometrically constrained DWs inside magnetic nanostructures produce a stray magnetic field and can interact with nearby magnetic objects. This interaction can be detected by either MFM or by measuring the change in the device resistance due to the anisotropic magnetoresistance effect (AMR) [16].

Scanning gate microscopy (SGM) is commonly used for electrical studies of semiconductors where the tip acts as a local gate through capacitive coupling to the sample. Magnetic SGM combines MFM and AMR measurements and allows imaging the device's electrical conductance as a function of the position of the scanning magnetic probe. In magnetic SGM, the stray magnetic field from the tip modifies the transport properties of the sample due to the AMR effect. The strength of the interaction can be modified by changing the distance between the sample and probe, making magnetic SGM a well-suited technique to study magnetoresistive devices, e.g. DW-based devices.

Here, we present magnetic SGM as a method to study the interaction between a DW and a MB. The DW is trapped in a Permalloy L-shaped nanosensor [12,15], while the MB is attached to a non-magnetic scanning probe. The L-shaped nanostructure has been chosen, as a DW can easily be placed or removed from its corner by applying an external magnetic field, and in the past they were used as nanosensors for MB detection [12,15]. In the present work, an AFM system is used to place the MB in different positions

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with respect to the DW, while measurements of the AMR signal allow detection of the effect generated by the MB's stray field on the device resistance. The presence of the DW can be detected either by AMR measurements or by MFM imaging.

2. Methods

The magnetic L-shaped nanostructures [15–17] with widths of $W = 50$, 75 and 100 nm were fabricated from a polycrystalline Py/Pt (25/2 nm) film using e-beam lithography and ion etching. The basic design includes two arms of 4 μm in length with a 1-μm disk at the end of each arm (Fig. 1a). Electrical leads were fabricated by sputtering deposition of Ta ($\sim$6 nm) and Au ($\sim$150 nm).

The L-shaped Py nanodevices possess 4 well-defined remanent magnetization states, depending on magnetization along the 2 arms and the previous field history [16,17]. These states are tail-to-tail DW, head-to-head DW, and two states with no DW. In the configuration shown in Fig. 1, where both arms of the device are at about 45° with respect to the x-axis, it is possible to switch from one DW state to the other simply by applying a magnetic field along the x-axis. These simple magnetic states, in combination with the AMR effect, allow monitoring the magnetic state of the device by measuring the resistance across the corner. Since magnetization along the arms is parallel to the electrical current, the presence of a DW creates a region with magnetization perpendicular to the current, reducing the resistance of the device and allowing to differentiate between the presence and absence of a DW. The typical change in resistance for a DW placed at the corner of these devices is about 0.2%.

The SPM system (Aura, NT-MDT with home-built transport measurement stage) allows the application of an in-plane magnetic field during scanning (field along the x-axis in the range $\pm$80 mT), as well as electrical connections to the sample using an external lock-in amplifier for resistance measurements with AC bias current. Fig. 1 shows the schematics of the electrical circuit used in the experiments. In Fig. 1a V_{AC} is the applied voltage, turned into current bias mode by the resistor R, which is set to a value much larger than the resistance of the nanostructure (i.e. 36 kΩ at the resistor, compared to typically 100 Ω at the nanostructure with $\pm$1% of maximum variation between saturation and remanence). The voltage V in Fig. 1a is measured by the lock-in and converted into resistance for the final SGM image. The frequency of the AC current is 21 kHz and its amplitude is 100 μA. The data acquisition time per point was chosen to be 3 times larger than the time constant of the lock-in.

The scanning probes for SGM (Fig. 1b and c) were custom-made by removing the apex of a commercial silicon AFM tip and placing a MB on the flattened tip using a FIB machine equipped with micromanipulators. The fixing method was similar to the one developed to attach small magnets on MEMS [18]. The tip's spring constant (56.29 N/m) and its resonant frequency (351.5 kHz) were measured using the standard thermal tune calibration technique. The large spring constant is used to reduce the deflection of the tip due to the extra mass and magnetic moment added. The MBs used in this work are commercial hard magnetic NdFeB microspheres with diameter of $\sim$1.6 μm and moment, $m \sim 2\text{–}10 \times 10^{-10}$ emu [19]. Prior to the experiment, the microspheres were magnetized by applying a magnetic field of $\sim$2 T perpendicular to the cantilever. The coercivity of the NdFeB microspheres [19] is $\sim$ 500 mT, which is more than ten times the magnetic field value applied during SGM measurements. A commercial magnetic probe was selected to take the MFM images (MESP by Bruker, with resonant frequency of $\sim$ 75 kHz, spring constant of $\sim$2–5 N/m, coated with CoCr, magnetized along the vertical direction).

Both MFM and SGM experiments were done first by imaging the complete topography of the sample in tapping mode, and then performing a sequence of MFM and SGM scans at specified tip–sample distances, using the recorded topography as a reference. This scanning mode was used in order to reduce the tip–sample interaction during the topography scan. To study the different types of MB–DW interactions (i.e. tail-to-tail, head-to-head DW, or no DW), the magnetization state of the device was changed in between MFM or SGM scans by ramping the magnetic field along the x-axis.

3. Results

3.1. Comparison between different magnetization states

Fig. 2 shows MFM (left column, obtained with a commercial magnetic probe) and corresponding SGM (right column), images of the corner of a device with $W = 75$ nm. SGM images have been obtained using the customized tips with the attached MB. Both sets of images were taken as described above, by first imaging the

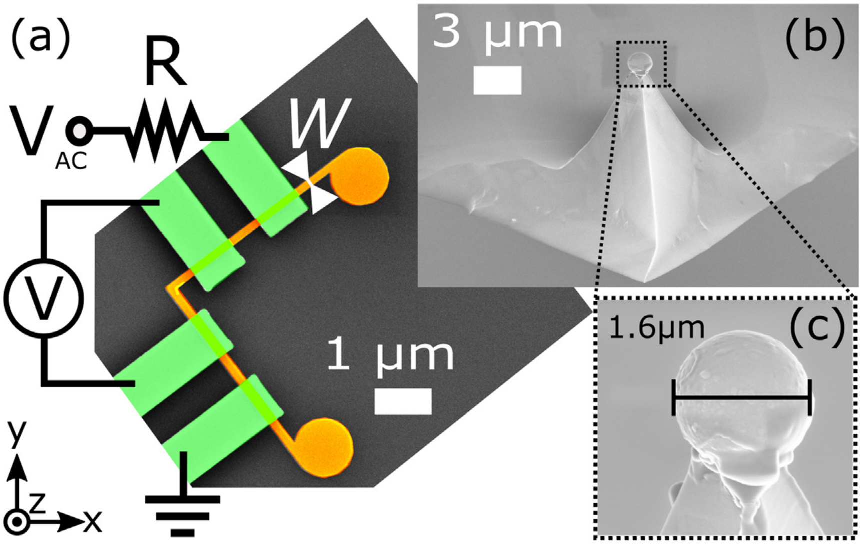

Fig. 1. (a) False color SEM image of a DW nanostructure (orange) with Au contacts (green) and schematics of the electrical circuit. (b) and (c) SEM images of a modified tip with an NdFeB microsphere attached. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)