APPLIED PHYSICS LETTERS **91**, 202507 (2007)

Using ring-shaped and magnetically coated tungsten wire as the probe of spin-polarized scanning tunneling microscopy

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(Received 20 July 2007; accepted 26 October 2006; published online 15 November 2007)

We report a method of magnetic probe fabrication using ring-shaped and iron-coated tungsten wire for spin-polarized scanning tunneling microscopy. Magneto-optic Kerr effect measurement on the probe front end shows that by controlling the saturating field direction, we can fix the probe magnetization in the specific in-plane direction. The ring is applied to the scanning tunneling microscopy and spectroscopy experiment on 6.8 ML Mn/Fe(001), and spin contrast in the in-plane direction is demonstrated. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2813614]

Spin-polarized scanning tunneling microscopy (SP-STM) has been proved to be a powerful tool for magnetic domain imaging with spatial resolution down to the nanometer scale.[1–3] According to the theory of spin-dependent tunneling, the image contrast is proportional to the projected probe magnetization along the sample magnetization direction.[4] Therefore, to control the probe magnetization direction is one crucial issue in attaining domain contrast. By coating the probe surface with different magnetic materials, SP-STM with out-of-plane or in-plane sensitivity can be readily prepared.[5] However, to identify which in-plane direction the probe magnetization points to is still difficult so far. This is because traditionally a sharp probe is preferred for STM to obtain high spatial resolution so that much effort has been taken to sharpen the probe, either by electrochemical etching, ion milling, or using single-atom tip.[6–10] All these methods result in needle-shaped probes with axial symmetry, which makes it difficult to specify the in-plane direction of the probe magnetization. To solve this problem, a method using magnetically soft material as STM probe in hollow disk shape has been proposed to bind the magnetization of the coated iron film in the disk-plane direction.[11] Two coils are wound around the probe to periodically switch the magnetization, and the lock-in amplifier is used to extract the $dI/d\mathbf{M}$ signal, as compared to another often used spectroscopy method, which extracts the dI/dV signal.[5] Although the probe prepared in such way can bind the in-plane tip magnetization, this advantage was not reportedly applied to spin-polarized scanning tunneling spectroscopy (SP-STS) experiment. Usually a flashed W tip, coated with Fe, is taken to do SP-STS experiment. Although flashing is not the only way to clean the tip surface, it is reported to be an efficient and crucial step to realize stable SP-STS experiment.[5] However, the probe of soft magnetic material cannot be flashed because of two concerns. Firstly, the alloy concentration of the soft material might change at high temperature, and secondly, the insulating coating of the coils would be destroyed at high temperature.

In light of this, we propose a method of SP-STM probe preparation by bending fine tungsten wire into a ring shape and coating it with 20 ML iron thin film. For iron film as thick as 20 ML on tungsten surface, its magnetization easy axis lies in the sample plane because of shape anisotropy.[12,13] The in-plane magnetization might be further determined by the shape anisotropy because of the asymmetric geometry of the ring probe. This shape anisotropy alone might not be strong enough to automatically align the magnetization of the as-deposited iron film along ring periphery, but a saturating field can help to align and stabilize the tip magnetization along the ring, as shown by our magneto-optic Kerr effect (MOKE) measurement below. A similar field-aligned technique was also reported in Refs. 5 and 14. In this way the orientation of probe magnetization in the sample plane can be predetermined, and the projected sample in-plane domain structure can be imaged by spectroscopy method.

To prepare such a ring probe, a tungsten wire with diameter of 125 μm is bent to a ring shape with radius of curvature of about 1 mm and spot welded onto the probe carrier such that the periphery is parallel to the sample, as shown in Fig. 1. Loaded into an ultrahigh vacuum chamber, the ring is electron bombarded to get rid of the surface oxide layer and contaminate, an important step to performing SP-STS measurement. After that, 20 ML Fe is head-on deposited on it at room temperature using electron bombardment evaporator with calibrated deposition rate.[15]

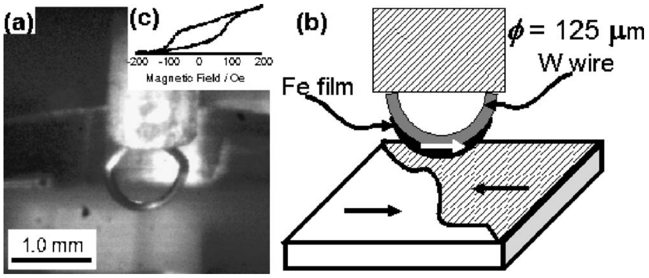

FIG. 1. (a) Photography of the ring probe made of 125-μm-wide tungsten wire, (b) schematics of the parallel magnetizations of the sample and iron film coated on the ring tip, and (c) Kerr hysteresis loop for the field applied parallel to the ring plane.

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To verify the magnetic property of such probe, it is capped with several monolayers of Cu and the MOKE measurement at ambient conditions is performed. With the laser beam focused on the most front end of the ring, the hysteresis loop for field applied parallel to the ring plane is measured and shown in Fig. 1(c). One can clearly observe a square hysteresis loop with coercivity around 80 Oe. This indicates that the probe magnetization with the help of shape anisotropy can be easily stabilized along the ring periphery after applying saturating field. As a result, it can serve as a spin-sensitive probe for mapping out the in-plane domain structure of the sample.

We choose Mn/Fe(001) as the test system because Mn exhibits layer-wise antiferromagnetism when the thickness is larger than 3 ML,[16–18] and its spin direction is determined by the ferromagnetic iron whisker substrate, whose dimension is 2 mm wide and 10 mm long, preferring the magnetization parallel to the long axis. The whole experiment is conducted in an ultrahigh vacuum chamber whose base pressure is 2×10^{-10} mbar and equipped with various thin film deposition and characterization tools.[19] The Fe(001) substrate is cleaned by cycles of sputtering and annealing until a clear low energy electron diffraction pattern could be observed. After that, the routine process is to sputter the substrate for 1 h at room temperature and then at 1000 K for another half hour, followed by cooling to 400 K and depositing Mn film on it at the same temperature with the deposition rate around 1.5 ML/min. After the deposition, the sample is transferred to the STM chamber, inside which the STM and STS experiments are performed at room temperature with the field-aligned magnetic ring probe prepared by the method mentioned above. In the spectroscopy mode, 101 data points of tunneling current from a bias voltage of $-0.5 - +0.5$ V are taken at each pixel with feedback loop open, and numerically differentiated to get the conductance spectra.

The STM constant current image of 6.8 ML Mn/Fe(001) is shown in Fig. 2(a), whose scanning parameters are a sample bias voltage of +0.1 V and feedback current of 0.1 nA. Mn grows in a layer-by-layer way so that we can observe the sixth and seventh layers on the surface. The interlayer distance is measured to be 0.19±0.03 nm from the line profile shown in Fig. 2(c). The current map of the same area at +0.5 V is also shown in Fig. 2(b). Contrast between the sixth and seventh layers can be observed in the current map, which is further justified by the line profiles of topography and current map at the same place in Fig. 2(c). The seventh layer has current of about 5% higher than the sixth layer. Since there is no chemical difference between these two Mn layers, the contrast can only be attributed to the spin difference. The spin-dependent densities of states result in the different $I(V)$ curves of the parallel and antiparallel configurations.

The averaged *I-V* spectra of the sixth and seventh layers are shown in Fig. 3. It is observed that the seventh layer has slightly higher current all the way from 0 to +0.5 V than the sixth layer. To express the difference clearer, the numerically differentiated spectra are shown in the same figure. We note that the conductance of positive bias voltage is higher than that of negative bias, which reflects the difference between the unoccupied and occupied densities of states of the sample. Furthermore, the conductance increases almost linearly with bias voltage from 0 to +0.4 V, and then rises with steep slope. This trend could be decomposed into an exponential background plus a surface state peak, as pointed out by Bischoff *et al.* in Ref. 20. These spin polarized surface states can enhance the contrast in the current map.

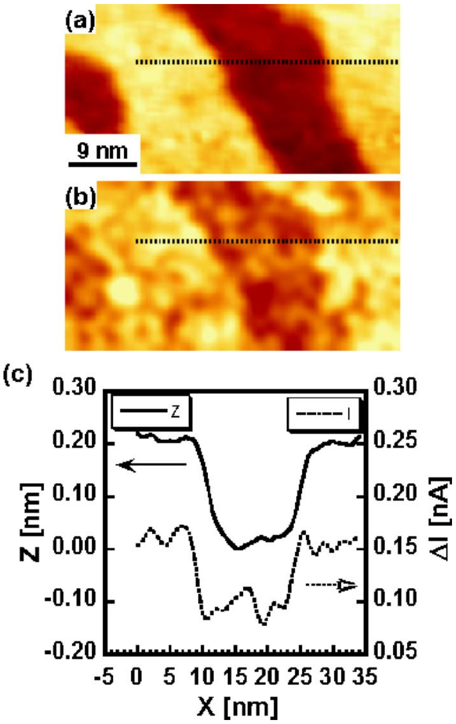

FIG. 2. (Color online) (a) STM constant current image of 6.8 ML Mn/Fe(001) with feedback parameters of $V=+0.1$ V, $I=0.1$ nA, and (b) its current map at +0.5 V. Line profiles along the black dashed lines in (a) and (b) are shown in (c).

Blunt it may be, the spatial resolution of the ring probe made by this simple method is not a problem in this system. Actually, since it is the very end of the probe atom that contributes overwhelmingly most of the tunneling current, even a blunt tip can give spatial resolution down to the nanometer scale if the sample is flat enough,[21] which is exactly the case for Mn thin films on iron whisker. The atomic step edge is resolved to be within 2 nm in Fig. 2(c).

According to the theory of spin-dependent tunneling, the differential conductance at **r** and bias voltage V can be expressed as $dI/dV(\mathbf{r},V)=C(1+P_t P_s \cos\theta)$, where θ is the angle between P_t and P_s, C is spin averaged differential conductance at $(\mathbf{r},V)$, and P_t, and P_s are the polarizations of the probe and sample, respectively.[22] By applying the saturating field, we can adjust the direction of probe magnetization parallel to the sample and maximize the spin contrast. The cur-

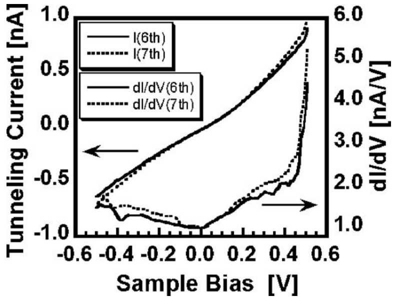

FIG. 3. *I-V* spectra, averaged over the sixth and seventh layers, respectively, with their numerically differentiated conductance spectra shown in the lower part. The seventh layer has larger current than the sixth layer over the whole voltage range.

rent asymmetry of 5% measured from Fig. 2(c) is comparable to the previous result in Ref. 23.

In conclusion, the success of obtaining spin contrast demonstrates the capability of tungsten ring probe made by bending the fine tungsten wire with a diameter of 125 μm. Such probe is easy to prepare. After the magnetization of the probe is saturated by field, it can give a well defined in-plane magnetization direction of the coated ferromagnetic thin film, and thus can be applied to image the magnetic domain structure with spin sensitivity in a specific in-plane direction down to nanometer scale.

This work was partially supported by the National Science Council of Taiwan and ITRI.

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