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Magnetoresistance of Planar Ferromagnetic Junction Defined by Atomic Force Microscopy

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Nanolithography by atomic force microscope local oxidation was applied to the fabrication of planar-type Ni/Ni oxide/Ni junctions from 10 nm-thick Ni films. The junction characteristics were sensitive to the lithography conditions such as the bias voltage. Successful oxidation produced junctions of nonlinear current-voltage characteristics, implying the formation of oxide barriers. Magnetoresistance (MR) at low temperatures resembled that of spin valves.

Keywords : AFM lithography, local oxidation, magnetic tunnel junction, magnetoresistance

1. Introduction

Magnetic nanostructures have attracted much research attention, and successful spintronic devices have been already demonstrated [1]. For example, the tunneling magnetoresistance (MR) observed in stacked layers of ferromagnet and insulator promises novel devices such as magnetic random access memory. With the reduction in junction size, new effects such as the current-induced magnetic switching (CIMS) behavior are expected [2]. Currently, the fabrication of CIMS devices requires sequential growth steps including insulating layers and deliberate nano-lithography steps to define a small junction area, typically 100×50 nm^2. If planar-type CIMS devices can be made from a single layer of ferromagnetic (FM) film, the switching behaviors of various materials can be tested quickly. Furthermore, it will be a lot easier to couple those devices with others, especially for microwave applications. One way of making such devices, at least for a proof-of-concept experiment, is to use atomic force microscopy (AFM). Fabrication of nanostructures by scanning probe microscope is now a well-established process [3]. Electrically induced local oxidation by AFM has been widely used to define semiconducting and metallic nanostructures reproducibly. Yet few studies have investigated magnetic nanostructures. As far as we know, Takemura and Shirakashi were the first to apply AFM local oxidation method to form FM nanostructures [4]. In the following works, they aimed to fabricate FM single electron transistors (FM-SETs) and obtained promising transport results [5]. Here, we report the fabrication of Ni/Ni oxide/Ni planar junctions as a first step toward planar CIMS devices and FM-SETs. The junction area is 500×10 nm^2, similar to that of a vertical CIMS device. Successfully oxidized junctions show nonlinear current-voltage characteristics, implying the formation of proper oxide barriers. In addition, we observed spin-valve-like MR (Ed- this acronym has already been defined above) at low temperatures. Improved control of the oxide barrier may also elucidate the ballistic MR in magnetic nanocontacts and nanoconstrictions [6].

2. Experiments

Polycrystalline, 10 nm-thick Ni films were deposited by electron beam evaporation under high vacuum. Electron beam lithography was used to pre-define, 500 nm-wide channels. A commercial AFM (n-tracer from Nanofocus Inc.) was used for local oxidation across the channel. This process was performed in a constant voltage mode at an ambient environment. The AFM was operated in a contact mode during oxidation, and in a non-contact mode during topography measurements. Two probe current-voltage characteristics and MR were measured in a closed-cycle He refrigerator with a plane-parallel magnetic field ranging up to 0.2 T. Data are taken by using a standard dc source-measure unit (Keithley 2400).

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3. Results and Discussion

Fig. 1 shows AFM images of a Ni wire before and after oxidation. The shape of Ni wire was designed to utilize the dependence of the coercive field (H_C) on the aspect ratio, called the shape anisotropy. An external magnetic field was applied along the narrow wire (500 nm-wide) direction, so the H_C of region I should be larger than that of region II. The oxide barrier was defined at the boundary between regions I and II. Humidity is one of several factors governing the oxidation process, but the change of humidity during the oxidation was not a critical factor. We maintained the humidity at 40~50%. The important factors were the bias voltage, tip scan speed, and distance between the tip and the sample expressed in terms of the force applied. Typical parameters for successful oxidation were 6.8 V, 0.18 μm/s, and 1.1 nN. In the magnified image after oxidation (Fig. 1(d)), the barrier appears to be quite thick. Indeed, the junction was opened if the bias voltage was maintained while scanning the whole channel. To fabricate junctions showing nonlinear *I-V* and switching characteristics, we decreased the bias voltage significantly when the tip approached the edge, thereby obtaining a narrow region (~100 nm) of thin oxide barrier (~10 nm high) (at the left edge in Fig. 1(d)). We assumed that the depth of oxide into the film was similar to the height above it, from the studies on AFM-oxidized Si and GaAs.

The extent of oxidation was checked by transport measurements. As shown in Fig. 2(a), the resistances of the fully-oxidized and less-oxidized wires differed by an order of magnitude. A junction resistance of about several tens of kΩ at room temperature was a good sign of oxidation for the geometry that was considered in this study. The current-voltage characteristic at low temperature ex-

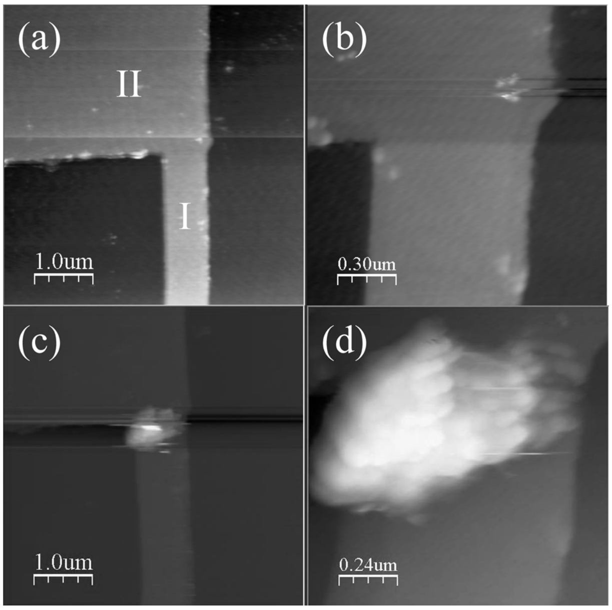

Fig. 1. Images of a Ni wire (bright area) before (a, b) and after (c, d) oxidation.

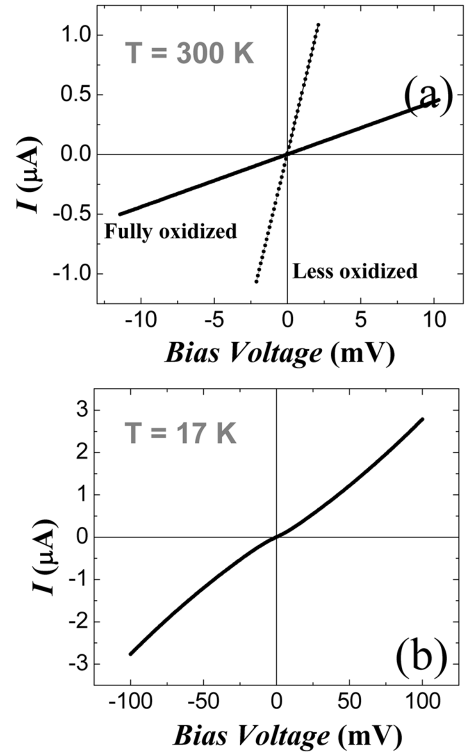

Fig. 2. *I-V* characteristics at room temperature (a) and at 17 K dized Ni wire are included in (a).

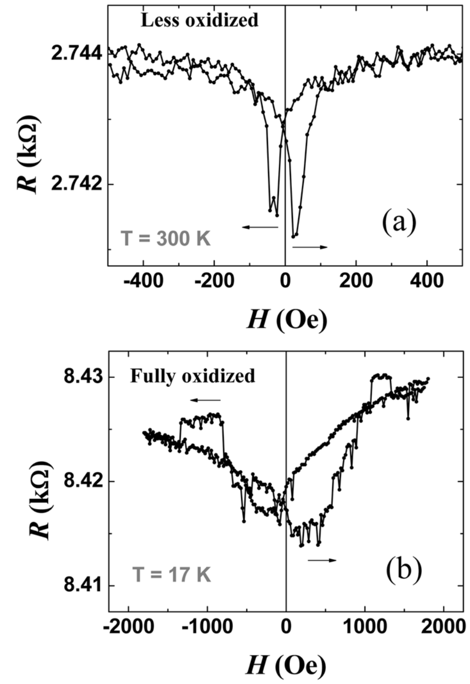

Fig. 3. Typical anisotropic magnetoresistance (MR) of an as-prepared Ni wire (a), and spin-valve-like MR of an oxidized wire B (b). Note the different switching fields.

hibited nonlinear behaviour, which were attributed to tunneling through the Ni oxide barrier. However, the possible presence of nanochannels at the bottom or edges of the Ni film could not be fully excluded.

The major result of this study was the spin-valve-like MR shown in Fig. 3(b). While typical anisotropic MR was observed in as-grown or less-oxidized wires with H_C around 50 Oe (Fig. 3(a)), the junction MR showed a broad transition at around H=800 Oe, indicative of the coercive field of region II, and a rather sharp transition at H=1400 Oe, the coercive field of region I. A much larger MR has been reported in a previous study using a similar geometry [7], but the resistance was more than two orders of magnitude smaller than ours (in the high bias limit inferred from the data). It was therefore difficult to interpret the MR of Ref. [7] because of tunneling. Despite the small and unsymmetrical MR of the present study, significant improvement is expected with better control of the AFM local oxidation.

4. Conclusion

Planar-type Ni/Ni oxide/Ni junctions were successfully formed by local oxidation technique. The combination of electron beam lithography and AFM lithography yielded a small junction area (500×10 nm^2). Nonlinear current-voltage characteristics implied the formation of proper oxide barriers. Spin-valve-like MR was observed in magnetic nanostructures made by AFM local oxidation. Further studies toward planar CIMS devices and FM-SETs are presently being conducted.

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