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Quantitative current measurements using scanning magnetoresistance microscopy

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ABSTRACT

We have demonstrated the capability of scanning magnetoresistance microscope (SMRM) to be used for quantitative current measurements. The SMRM is a magnetic microscope that is based on an atomic force microscope (AFM) and simultaneously measures the localized surface magnetic field distribution and surface topography. The proposed SMRM employs an in-house built AFM cantilever equipped with a miniaturized magnetoresistive (MR) sensor as a magnetic field sensor. In this study, a spin-valve type MR sensor with a width of 1 μm was used to measure the magnetic field distribution induced by a current carrying wire with a width of 5 μm and a spacing of 1.6 μm at room temperature and under ambient conditions. Simultaneous imaging of the magnetic field distribution and the topography was successfully performed in the DC current ranging from 500 μA to 8 mA. The characterized SV sensor, which has a linear response to magnetic fields, offers the quantitative analysis of a magnetic field and current. The measured magnetic field strength was in good agreement with the result simulated using Biot–Savart's law.

1. Introduction

Several techniques have been developed to reveal the magnetic structure of magnetic thin films and small magnetic elements of nanometer scale [1]. Such magnetic imaging techniques are divided into two categories. One measures the magnetic fields emanating from the magnetic material and converts the field distribution into the magnetic structure. Another employs measurement techniques to directly probe the surface electron spin states. The former is also applicable for the visualization of the magnetic field distribution produced by an electric current flow. The observation of a current-induced magnetic field distribution reveals a defect such as a void [2], which is a major cause of interconnect failure in integrated circuits (ICs). Therefore, that is useful for the failure analysis of ICs. The increase in the packing density and the complexity of modern ICs has required an improvement of the spatial resolution in the observation.

The most popular technique to measure the magnetic field distribution with nanometer-scale spatial resolution is magnetic force microscopy (MFM). MFM is mainly used for magnetic domain imaging and not for current measurement. In a previous study reported by Campbell et al. [3], MFM was applied for current contrast imaging, in which the change in the magnitude of a current of approximately 1 mA (in DC mode operation) and 1 μA_{p-p} (in AC mode operation) was detected. Magnetic force measurement with a magnetic thin film coated needle sensor has revealed the magnetic field distribution associated with an AC current of 100 μA [4]. By monitoring torsional displacement of the MFM cantilever, it was demonstrated that the magnetic field associated with an AC current below 2.2 μA could be detected [5]. In general, MFM does not detect the strength of the magnetic field, so that it has been difficult to quantitatively analyze the field detected by MFM. In addition, the response frequency is limited by the mechanical resonant frequency of the force sensor; a few hundred kHz with a cantilever type force sensor, and 1 MHz with a needle type sensor.

To overcome the drawback of MFM applications, the use of a miniaturized magnetic field sensor device, such as a scanning superconducting quantum interference device (SQUID), has been investigated. Although SQUID microscopy provides quantitative measurement of a magnetic field, it requires a large sensor-sample separation of approximately 100 μm, which results in the loss of spatial resolution and field sensitivity. Application of the system to measure a current of 1 mA at 3 kHz has been demonstrated with a spatial resolution of 50 μm [6]. Another choice of magnetic field sensor is the magnetoresistive (MR) sensor. We have developed a scanning magnetoresistance microscope (SMRM) that is equipped with a micro-fabricated cantilever on which a spin-valve (SV) type MR sensor element is mounted. This SMRM system, of which the basic concept has been reported [7–9], can

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operate at room temperature under ambient conditions, and can also simultaneously acquire topographic data and magnetic information. The MR sensor has high field sensitivity for a DC field and it is also expected to be applicable for the frequency response regime up to a few GHz. In our preliminary work using an anisotropic MR sensor of NiFe, the SMRM system has been employed to measure the magnetic field produced by a current of approximately 8 mA [7]. We have improved the measurement system by introducing a SV type MR sensor [8] and applied it to the observation of magnetic domains [9].

In this paper, we report on the measurement of a current-induced magnetic field using the SMRM system with a further improved MR sensor. The improved sensor is an exchange-biased SV, which exhibits a linear response to an applied magnetic field without the requirement for an external bias field. The external bias field was used in the previous system [7]. The SV type MR sensor (SV sensor) has successfully revealed the magnetic field distribution emanating from a meander pattern of 5 μm in width with 1.6 μm spacing. The width of the sensor was 1 μm and the sensor-sample distance was 1 μm. In this experiment, the SMRM yielded quantitative information regarding the current flow in the meander pattern for the DC current ranging from 500 μA to 8 mA.

2. Experimental

2.1. SMRM with SV sensor

2.1.1. Microscope system

A schematic illustration of the SMRM system is shown in Fig. 1(a). For magnetic field measurements, two current generators and a preamplifier were attached to a commercially available AFM system that uses optical deflection for the detection of cantilever displacement. Current generator I was used to apply a constant current to the MR sensor and current generator II was used to apply current to the meander-patterned wire. The micro-fabricated AFM cantilever equipped with an MR sensor at the apex shown in Figs. 1(b) and (c) (MR cantilever) was fabricated within our laboratory facilities. The MR sensor used in this study was an SV sensor, which is described in detail in the next subsection. The design dimensions of the MR cantilever are 200 μm long, 50 μm wide, and 1 μm thick. The MR cantilever was used in contact-AFM mode, so that the spring constant of the cantilever was designed to be 0.12 N/m. The apex of the MR cantilever was used as an AFM probe to obtain topographic images of the sample surfaces. Au/Ti electrodes were patterned so as to make contact with the SV sensor with a spacing of 1.4 μm. The sensor output (MR signal) was measured using a four-point method and was amplified using a preamplifier with a gain of 100. The SV sensor was designed to have a linear response to the magnetic field component parallel to the long direction of the MR cantilever. The SMRM operates in contact AFM mode and simultaneously records a topographic signal and an MR signal. Since the MR cantilever was tilted at 13° with respect to the sample surface and the SV sensor was 4.4 μm apart from the apex, the sensor scanned 1 μm above the sample surface. Although the upper boundary for the spatial resolution of the SMRM is limited by the dimensions of the SV sensor, which were $1 \times 5\,\mu m^2$ in this study, the SMRM images obtained provided a field distribution with a spatial resolution of at least 1 μm. In addition, the SMRM has a controlling mechanism to maintain a constant distance between the sensor and the sample surface, so that the sensor can measure the field strength at a fixed height. The information regarding the distance makes it possible to quantitatively analyze the measured fields and to determine the strength of the current producing the magnetic fields. Schrag et al. [10] have previously reported on current imaging using SMRM with a commercial MR head. They demonstrated the current density imaging of a 3 μm conductor, which carries a 3 mA modulation current at 80 kHz, with a 0.1 μm SiO_2 overlayer. Moreover, the report provided current density images of the conductor undergoing electromigration. In the system used by Schrag et al., the MR head physically contacted the sample surface. This confines the system to the measurement of samples that have a flat surface and an insulating layer, so as not to crash the head and scratch the sample. In the proposed SMRM system of this study, the distance between the AFM probe part and the sample surface can be controlled by AFM operation with the MR cantilever. The distance between the sensor and sample surface can also be controlled. This means that the proposed system is not confined by the limitations requiring a flat sample surface or the necessity for thick passivation layers.

2.1.2. SV sensor

In this study, we used an exchange-biased SV sensor [11]. The multilayer for the SV sensor was fabricated using magnetron sputtering apparatus for a layered structure of Ta (5.0 nm)/IrMn (10.0 nm)/NiFe (5.0 nm)/Cu (3.0 nm)/NiFe (5.0 nm)/Ta (5.0 nm). The SV multilayer consists of two ferromagnetic layers separated by a thin nonmagnetic layer. The magnetization of one ferromagnetic layer is pinned in a certain direction by exchange coupling with the neighboring antiferromagnetic layer (IrMn), while the magnetization of the other ferromagnetic layer is free to rotate in

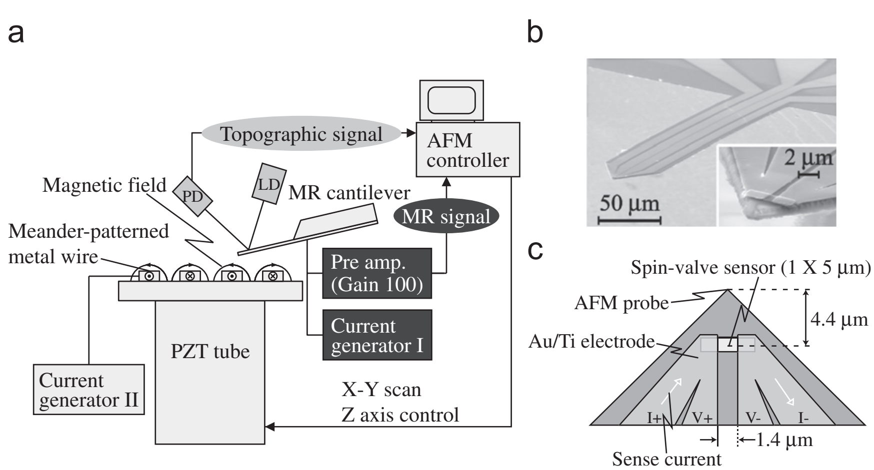

Fig. 1. Measurement system and cantilever for scanning magnetoresistance microscope (SMRM): (a) Schematic diagram of the SMRM system. (b) Scanning electron microscope image of a fabricated MR cantilever. The inset is an enlarged image of the apex. (c) Schematic diagram of the apex of the fabricated MR cantilever.