Characterization of heat-assisted magnetic probe recording on CoNi/Pt multilayers

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Abstract

A method of heat-assisted magnetic recording (HAMR) potentially suitable for probe-based storage systems is characterized. In this work, field emission current from a scanning tunneling microscope (STM) tip is used as the heating source. Pulse voltages of 2–7 V were applied to a CoNi/Pt multilayered film fabricated on either bare silicon or oxidized silicon substrates. Different types of Ir/Pt and W STM tips were used in the experiment. The results show that thermally recorded magnetic marks are formed with a nearly uniform mark size of 170 nm on the film fabricated on bare silicon substrate when the pulse voltage is above a threshold voltage. The mark size becomes 260 nm when they are written on the identical film fabricated on an oxidized silicon substrate. The threshold voltage depends on the material work function of the tip, with W having a threshold voltage about 1 V lower than Pt. A synthesized model, which contains the calculation of the emission current, the simulation of heat transfer during heating, and the study of magnetic domain formation, was introduced to explain experimental results. The simulation agrees well with the experiments.

Keywords: High-density perpendicular recording; Heat-assisted magnetic recording (HAMR); Scanning tunneling microscope; Probe recording

1. Introduction

The super-paramagnetic effect which induces the thermal relaxation of recorded information [1] is the fundamental obstacle to increasing magnetic recording density. To achieve thermal stability of recorded information, increases in the coercivity and anisotropy of the recording medium are needed. This makes traditional recording more difficult because conventional heads cannot generate sufficient field to switch the magnetization of the bits in thermally stable media. To overcome this obstacle, heat-assisted magnetic recording (HAMR), has been proposed [2]. HAMR draws on concepts from traditional magneto-optical (MO) recording for the writing process, but is not restricted to optical read-back.

In addition to optical heating methods suggested by extensions of MO recording, another possible approach to HAMR is the use of field emission current from a sharp metallic tip for heating. This has the possibility of very high spatial resolution as scanning tunneling microscopes (STMs), which have similar architectures, show atomic resolution in surface observation [3–5]. Nakamura et al. [6] demonstrated this writing method with an STM several years ago, and saw a mark size that increased with increasing tip voltage. We have also demonstrated the process previously [7], but saw very little dependence of mark size on tip voltage above a certain writing threshold. In this work, we performed similar experiments on an alternate medium and built a synthesized model of the writing process that quantitatively explains the writing threshold voltage and the mark size insensitivity to applied voltages.

2. Experiments

2.1. Medium and experimental setup

The recording medium in our work is a CoNi/Pt multilayered film. It consists of 20 repeats of 0.55 nm-Co\textsubscript{50}Ni\textsubscript{50}
and 0.87 nm-Pt bilayers, yielding a total film thickness of about 28 nm. The multilayers are sputtered on two kinds of substrates simultaneously: a bare silicon substrate and an oxidized silicon substrate. The thickness of the oxidation layer is about 400 nm. There is a 23-nm-thick Pt seed layer between the film and the substrate. The Argon pressure in the sputter chamber is $1.6 \times 10^{-2} \text{mbar}$ and the back-pressure is less than $5 \times 10^{-8} \text{mbar}$. We measure its anisotropy in perpendicular orientation $K_u = 2.5 \times 10^5 \text{J/m}^3$, saturation magnetization $M_S = 3.4 \times 10^5 \text{A/m}$, coercivity $H_C = 1.1 \times 10^5 \text{A/m}$ (or 1.4 kOe) and nucleation field $H_n = 4.3 \times 10^5 \text{A/m}$ at room temperature in a vibrating sample magnetometer (VSM). The M–H loop of this medium is shown in Fig. 1. From the figure we find that the “appearing” nucleation field $H'_n$ is very close to the coercivity $H_C$. However, the actual nucleation field should be the sum of $H'_n$ and the demagnetizing field $H_D$ generated by the medium itself, which is equivalent to the saturation magnetization $M_S$. The Curie temperature of the film is about 250°C. The temperature-dependent property of magnetic parameters (like $H_C$, $M_S$, $K_u$, and $H_n$) is also measured by VSM at elevated temperatures. All of them show a linear dependency to the temperature from room to Curie point.

A Digital Instruments Dimension 3000 scanning probe microscope (SPM) was used for writing and imaging. Atomic force microscopy (AFM) mode was applied to scan the topographic features of the film, and magnetic force microscopy (MFM) mode was used to image the magnetic domain structures. STM was used for thermal writing. In this work, two types of STM tips are used: one Ir/Pt alloy, and the other W. During STM scanning, the tip-sample junction is held at a bias voltage of 100 mV and a set point current of 2 nA, from which the tip-sample spacing is estimated to be 0.7 nm during scanning [8]. The film is heated locally by applying pulses of 2–7 V in amplitude and 500 ns in duration, with a rise time of 100 ns to the sample. Short pulses prevent the position feedback system (BW = 15 kHz) from reacting to the increased current and withdrawing the tip [7].

The addition of external magnetic field is very important in HAMR work [2]. However, it is not the focused point that is examined in this paper. When written marks were isolated with a distance greater than five times the mark diameter, the demagnetizing field from its neighborhood will be enough to switch the magnetization during heating. In this case, the external field is not necessary. We will explain it in detail in this paper. The study of the effects of an external magnetic field on thermo-magnetic writing will be published elsewhere.

2.2. Basic results: writing marks on medium (silicon substrate) by Ir/Pt tip

Some sample marks are shown in Fig. 2. Those marks were written by Ir/Pt tip, and on the film fabricated on bare silicon substrate. The mark size is determined as the full-width half-maximum (FWHM) of the MFM signal. Similar to our previous work [7], those written marks are magnetic in nature and the writing is reversible.

An important task in my work is to examine the dependence of mark size on bias voltage and other parameters. In this section, marks were written by an Ir/Pt tip on the film fabricated on a bare silicon substrate. Fig. 3 shows the plots of average mark size and the rate of successful writing as a function of pulse voltage. In the figure, the upper plot shows the average mark diameter as a function of applied pulse voltage. In this plot, the average value of mark size is based on the average of observed marks. Failed writing was not counted. In order to capture these statistics, another plot was displayed below the former one in Fig. 3, to show the rate of successful writing by a single voltage. We observe a threshold voltage of writing at 4 V. Below 4 V, no marks were observed; above 4 V, mark size increases slightly with increasing bias voltage. The average mark size is about 170 nm.
2.3. Writing marks by different tips

In order to study the effect of STM tip work function on the writing, different tips were used to write marks on the same medium as above. In addition to Ir/Pt tip, we used W tip to write marks and the results were shown in Fig. 4. From the figure, we found that the mark size above threshold voltage is similar to the marks written by Ir/Pt tip, but the threshold voltage drops to 3–3.25 V. It is well known that a major difference of Ir/Pt alloy and W is their work function, 5.5 eV for Pt or Ir and 4.6 eV for W. To further demonstrate the effect of tip work function on writing, we did the following contrast experiments. An Ir/Pt tip was coated by a 5-nm-thick layer of W, and a W tip was coated by a 5-nm-thick layer of Pt. Those STM tips were imaged in SEM and their radii are about 1000 nm.
after writing. So the 5-nm layer does not change the shape of those tips. Those two special tips were applied to write marks and the results were displayed in Figs. 5 and 6, respectively. We found that the threshold voltage for the W-coated Ir/Pt tip is about 3 V and the threshold voltage for the Pt-coated W tip is about 4 V. Thus, the threshold voltage is dependent on the materials of the STM tip.

2.4. Writing marks on medium (oxidized silicon substrate) by Ir/Pt tip

In this section, the effect of another parameter, the substrate of the medium, on writing was examined. In HAMR project, the heat transfer is a key issue in thermomagnetic writing. As we know, silicon is a good thermal...
conductor while its oxidization is a poor conductor. In order to examine this effect, an identical film was fabricated on an oxidized silicon substrate, as stated before. An Ir/Pt tip was used to write marks on this film and the results were shown in Fig. 7. We found that larger mark size was achieved for the same voltage. In average it is about 260 nm. The threshold voltage is about 3.5 V, slightly lower than the writing on the medium with silicon substrate.

3. Models and discussion

In this section, a synthesized model is discussed in detail. It includes the model of emission current, model of heat transfer, and model of magnetic domain dynamics in the film. The purpose of the model of emission current is to figure out the emission current and its region. Because the pulse voltage is known, we will be able to figure out the electrical power by obtaining the amount of the writing current. The emission region gives out the size of heating spot during writing. Based on the geometry of the STM tip from its SEM image and the bias voltages applied between the tip and sample, an analytical extension of Fowler–Nordheim theory [9] in field emission was explored in a prolate-spheroidal coordinate system [10,11]. Both the emission radius and the emission current were calculated [12]. Data achieved from this model is sent to the model of heat transfer. Due to the structure of the medium and \( z \)-axial symmetry of the heating source, a model of two-dimensional heat transfer with a transient heat source in a multilayered structure [13] is introduced. In our simulation, the multilayered film is simplified as a single uniform layer with a much reduced thermal conductivity [14]. In addition to the film layer, the Pt seed layer and the substrate (either bare silicon or oxidized silicon) are considered as separate units in the simulation of the thermal profile. The source of the transient heat is from the emission current. The electrical power, which is equal to the product of the emission current and the bias voltage, is converted to the thermal power. Here we assume that most of the electrical power is absorbed by the metallic film because the current flows from the STM tip to the sample in a very short time. The emission radius gives out the size of the heating spot on the top of the film layer. Numerical simulation was
executed in FEMLAB, a software tool on finite element in Matlab [15]. Via this way we obtained the thermal profile in the film right after the heating halts.

Based on the measurement of the temperature-dependent properties of magnetic parameters of the film, we use a simplified model to describe this property. Fig. 8 shows the linear dependence of all the magnetic parameters as a function of temperature from room temperature to the Curie point of the film. Although the simplification does not 100% fit the real properties of the medium, it works very well in this model. We incorporate the thermal profile in the film into the distribution of the magnetization as a function of temperature and position. Due to the z-axial symmetry of the recording bits, we only need to consider the radial-dependent magnetization distribution. Maxwell’s equations [16] were applied to calculate the magnetic field generated by the medium itself with a non-uniform magnetization distribution, which is just the demagnetizing field of the medium. Numerical method is used in calculation because of the numerical simulation of the thermal profile in the previous step. Here let me briefly describe the calculation of the magnetic field from a cylinder in a non-uniform magnetization distribution. The magnetic field from a uniformly magnetized cylinder can be expressed analytically as a function of the radial position and z-position in cylindrical coordinates, $\vec{H}(r, z)$ [16].

In this model, we assume that only the z-component of the field, $H_z(r, z)$, plays a role in the switching of the magnetization because it is parallel to the magnetization of the perpendicular medium. Now the magnetization of the cylinder is not uniform during heating. We approximate in the following way: divide the cylinder to many concentric cylindrical rings, and calculate the magnetic field from each ring. This method is shown in Fig. 9: a cross section of the cylinder is sketched with a ring having an inner radius $r$ and an outer radius $r + dr$. With a very small $dr$ (typically 1 nm in our simulation), we can assume that the magnetization of the ring is uniform $M(r)$. Then the magnetic field generated by the ring can be calculated by $\overrightarrow{H(\text{ring})} = \overrightarrow{H(M(r + dr))} - \overrightarrow{H(M(r))}$, the difference of two magnetic plates with uniform magnetization. By this way, the total field from the film can be the sum of the field from each ring.

Before further discussion, let us study a specific example, the simulation of evolution of thermal profile and magnetization in the case of writing by a Pt tip and 5 V on the medium fabricated on a bare silicon substrate. Fig. 10 shows the plots of the temperature profile and the magnetic field as a function of radial position, with heating the center at the origin. With heating, the temperature of...
the medium at the center of the heating spot increases; both its magnetization and nucleation field decrease accordingly; at the same time, the temperature of surrounding location does not increase distinctly. Therefore, the demagnetizing field at the center of the heating spot can exceed the nucleation field. According to the M–H loop of the medium (Fig. 1), its magnetization begins to switch when the field reaches a nucleation field, $H_n$. Therefore, the demagnetizing field will be sufficient to switch the magnetization of the center upon a certain high temperature. Once this event has been identified in the simulation, a reversed domain in the center is formed and thus a mark is written. The domain wall bounding the mark is allowed to grow under the influence of the local field (mainly demagnetizing field here) until it reaches a stable point. When a reversed domain in the heating center forms after the film cools down to room temperature, mark size can be extrapolated by the range of this reversed domain.

Now let us display the results of the calculated mark size by applying different voltages, STM tips, substrates of the film in simulation. Fig. 11 shows the simulation results of the mark size vs. pulse voltage by different STM tips and medium substrates. They agree well with experimental results in Fig. 3–7. Simulation predicts a threshold voltage about 0.5 V higher than is observed, likely due to the fact that the model does not capture subtle effects in the shape of the thermal profile or the exact dependence of the magnetic parameters on temperature.

4. Conclusion

We have demonstrated a thermo-magnetic writing process using an STM on perpendicular CoNi/Pt multilayered medium. For the applied pulse voltage of 3–7 V, the written magnetic mark has almost uniform size of 170 nm on the medium with the silicon substrate but 260 nm on the medium with the oxidized silicon substrate. The threshold voltage of writing is closely related to the work function of the STM tips. A synthesized model describes the writing process and the simulation results agree well with experiments. From this model, we are able to predict the tip and medium configurations and applied powers that should permit marks appropriate for recording at 1 Tbit/in² and beyond.

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References