A Model for Mark Size Dependence on Field Emission Voltage in Heat-Assisted Magnetic Probe Recording on CoNi/Pt Multilayers

Li Zhang, James A. Bain, Jian-Gang Zhu, Leon Abelmann, and Takahiro Onoue

***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 with a duration of 500 ns were applied to a CoNi/Pt multilayered film. 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 when the pulse voltage is above a threshold voltage. The threshold voltage depends on the material work function of the tip, with W having a threshold voltage about 1 V lower than Pt. The emission area of our tip-sample system derived from an analytic expression for field emission current is approximately equal to the mark size, and is largely independent of pulse voltage. This emission area is large compared to lateral heat diffusion in the film. Thus higher applied voltages lead to higher peak temperatures in the model of the write process, but the mark diameter remains relatively unchanged.**

***Index Terms*—Field emission, high-density recording, prolate spheroidal coordinates, scanning tunneling microscope.**

I. 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 magnetooptical (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 (STM), 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 have performed similar experiments on an alternate medium and now have a model of the writing process based on the Fowler-Nordheim theory [8] that quantitatively explains the writing threshold voltage and the mark size insensitivity to applied voltage.

II. Experiments

The recording medium in these experiments is a CoNi/Pt multilayered film. It consists of 20 repeats of 0.55 nm-$Co_{50}Ni_{50}$ and 0.87 nm-Pt bilayers, yielding a total film thickness of about 28 nm. The multilayers are sputtered on a bare silicon substrate, with a 23 nm thick Pt seedlayer. The Argon pressure in the sputter chamber is 1.6×10^{-2} mbar and the back pressure is less than 5×10^{-8} mbar. The same techniques as reported previously [7] were used to measure the perpendicular anisotropy, K_u, the saturation magnetization, M_S, and the coercivity, H_C, of the film at room temperature. We obtained $K_u = 2.5 \times 10^5$ J/m^3, $M_S = 3.4 \times 10^5$ A/m, and $H_C = 1.1 \times 10^5$ A/m. The exchange constant of the film, A, is estimated to be 1.0×10^{-11} J/m. The Curie temperature of the film is about 250 °C, as measured by a VSM at elevated temperature.

A Digital Instruments Dimension 3000 scanning probe microscope (SPM), was used for writing and imaging. AFM (atomic force microscopy) mode was applied to scan the topographic features of the film, and MFM (magnetic force microscopy) mode was used to image the magnetic domain structures. STM was used for thermal writing. During STM scanning, the tip-sample junction is held at a bias voltage of 100 mV and set point current of 2 nA, from which the tip-sample spacing is estimated to be 0.7 nm during scanning [9]. 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 ($\mathrm{BW} = 15$ kHz) from reacting to the increased current and withdrawing the tip [7]. The equivalent circuit of the system is shown in Fig. 1, where the writing voltages were applied at node A. Tip voltages were measured at node B to support the estimates of the current using F-N theory discussed below.

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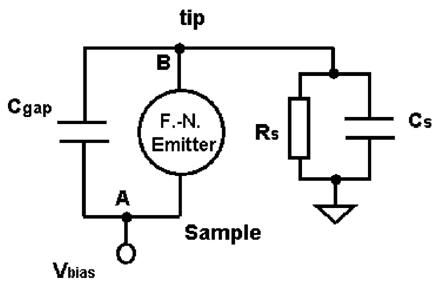

Fig. 1. Equivalent circuit of the STM system in writing. In this circuit, given $C_s = 5$ pF, $R_s = 1$ M-Ohm, and $C_{gap} = 0.1$ pF, estimated from [10].

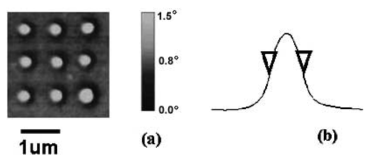

Fig. 2. MFM image of marks. (a) MFM image of marks made by 6 V pulses and (b) mark size is measured by the FWHM of the MFM signal.

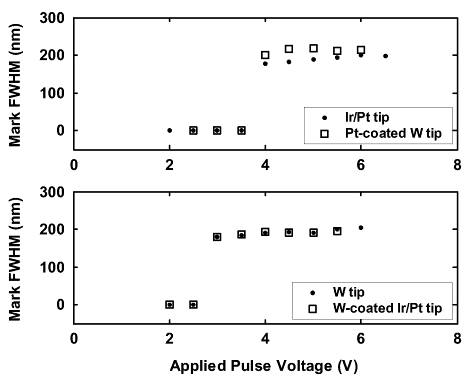

Fig. 3. Average mark size as a function of the applied pulse voltage, written by Ir/Pt tip, Pt-coated W tip, W tip, and W-coated Ir/Pt tip, respectively.

In order to examine the effect of the work function of the STM tips (5.6 eV for Ir/Pt tip and 4.7 eV for W tip), four types of tips were used: commercial Ir/Pt tips (mechanically cut) with and without a 10-nm W coating, and commercial W tips (chemically etched) with and without a 10-nm Pt coating.

No externally applied field was used in these experiments, although it will clearly be necessary in any recording system implementation of this method. Demagnetizing fields from the surrounding region of the material switch the magnetization of the heated area.

III. Results

Similar to our previous work [7], the written marks are magnetic in nature and the writing is reversible. The mark size is determined as the full-width half maximum of the MFM signal, shown in Fig. 2.

The dependence of mark size on the applied voltage and tip work function for Ir/Pt, W, Pt-coated W tip and W-coated Ir/Pt tip is shown in Fig. 3. The threshold voltage for writing is 4 V for both the Ir/Pt tip and the Pt-coated W tip, and 3 V for both the W-tip and the W-coated Ir/Pt tip. The average mark diameter is about 170 nm, almost uniform above the threshold.

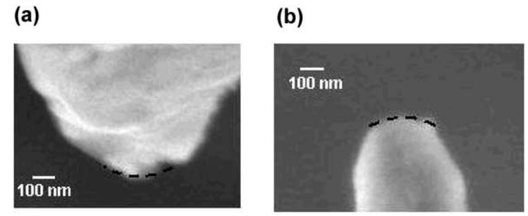

Fig. 4. SEM images for both tips. (a) Ir/Pt tip and (b) W tip.

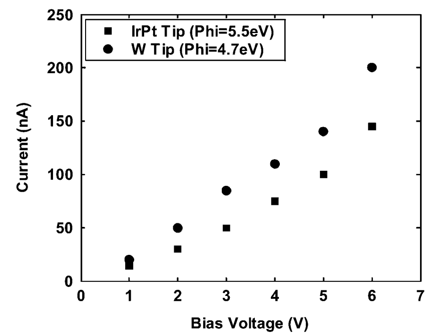

Fig. 5. Estimated *I-V* curve for both types of tips.

A discussion of the field emission behavior is given below to explain these observations. In order to inform these discussions, scanning electron micrographs of both tips were taken and are shown in Fig. 4.

IV. Discussion

From J. Simmons' theory [9], tunneling happens between a tip and surface when the bias voltage is below the work function of the tip. When the bias voltage exceeds the work function, field emission replaces the tunneling. The classical theory of field emission is based on the one-dimensional, planar Fowler-Nordheim equation [8]. An analytical extension of this theory to nonplanar, tip-anode geometries was explored by Zuber *et al.* [11]. Due to the shape of the tip, a prolate-spheroidal coordinate system is introduced [12].

This model requires knowledge of the tip radius over the range of emission, which we estimate to be around 1000 nm for the tips shown in Fig. 4. It also requires the tip medium spacing (0.7 nm), and the work function of the tip material (given above). The output of the model is the emission area that contains 99.9% of the current and the total emitted current. It should be noted that some approximations were made due to the tip being very sharp and far from the medium [12], which have been avoided in our application of the model.

Applying this model to our experiment with the known voltage drop across the Fowler-Nordheim emitter in Fig. 1 yields a beam diameter of 160 nm, and beam current as a function of voltage as given in Fig. 5. Note that the total currents are roughly linear with applied voltage, as predicted by the model, even though the current density goes as the square of the electric field in the F-N expression.

Mark size is determined by the thermal profile at the end of the heating cycle [7]. We have used FEMLAB to estimate the heated zone diameter, which will be the subject of a separate publication. As a simple approximation, we assume the mark

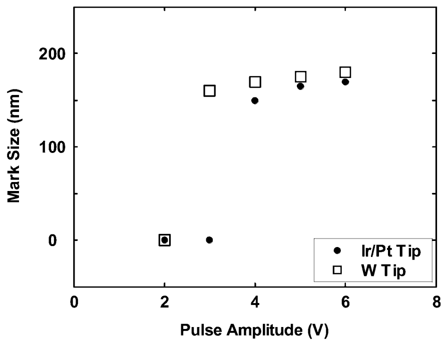

Fig. 6. Mark size extrapolated from the thermal profiles in the simulation by FEMLAB, for both tips in different voltages.

diameter is the same as the location of the thermal contour that is equal to 250 °C (the medium's Curie temperature). The model assumes the input power is the product of the current in Fig. 5 and the known applied voltage, and that the power is delivered uniformly over a circle with the same diameter as the beam. Fig. 6 shows a plot of the mark size estimated in this way from the FEMLAB simulations as a function of applied voltage for both tips. Note that this figure reproduces the threshold behavior and the weak dependence of mark diameter on applied voltage, as well as the difference between W and Pt tips.

Examination of the model in detail reveals the reason for both of these trends. Due to the multilayer structure of the film, its thermal conductivity is greatly reduced. On the other hand, both the Pt underlayer and the silicon substrate have high thermal conductivity. High thermal conductivity silicon behaves as an excellent heat sink. As a result, most of heat is conducted through the substrate, instead of in the lateral direction in the film. Therefore, the heated region is almost the same as the mark size, since there is very little heat spreading. The threshold voltage is explained as insufficient heating in low voltages, where the Curie temperature is not reached.

V. Conclusion

We have demonstrated a thermo-magnetic writing process using an STM on perpendicular CoNi/Pt multilayered medium. For the applied pulse voltage of 3–6 V, the written magnetic mark has almost uniform size of 170 nm. This size is close to the emission diameter (160 nm) of our tip-sample system derived from a prolate-spheroidal coordinate system. We propose to reduce the mark size to the minimum domain size supported by the medium by using a sharper tip in the writing process.

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