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Field emission to control tip-sample distance in magnetic probe recording

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Abstract. An integrated method using field-emission to control the tip-sample distance for non-contact magnetic probe recording is presented, adopting the exponential relation between current and electric field as feedback. I/V characteristics that correspond well to field emission theory are measured using a probe coated with a 100 nm conductive diamond layer. By using feedback to control the tip-sample distance at constant current, the distance was increased by 2.8 nm per volt applied bias. The method was tested by scanning a probe coated with 20 nm chromium over a conducting nanopatterned sample, at bias voltages of 0.5V, 5.0V and 50.0V. The measurements confirm that field emission can be applied to control the tip-sample distance, with sufficient resolution and current stability for magnetic probe recording.

1. Introduction

Since the invention of the Scanning Tunneling Microscope (STM), a storage system exploiting sharp probes for writing and reading has been a promising route towards extremely high density recording [1, 2]. Parallel writing and reading by an array of probes however has to be used to ensure a high data rate [3]. Magnetic probe recording is an interesting approach, because we can make use of magnetic materials developed in hard disk or magneto optical recording that give virtually infinite rewritability. Read-out can be achieved by magnetic sensors integrated onto the probes [4] or by measuring force as in Magnetic Force Microscopy (MFM). The MFM mode is very energy efficient [5] but can only be operated in non-contact. This means that a distance on the order of 10 nanometers is required between the probe and the medium, to minimize van-der-Waals forces and still be able to sense the small magnetic stray fields [6]. Generally, in MFM a deflection detection system and a two-pass technique is employed to scan the same line at different distances [7]. This would be difficult to implement using an array of probes. Therefore, in this paper we present an integrated method using field emission to control the tip-sample distance for the individual probes in a magnetic probe recording system.

Fowler-Nordheim theory describes the field emission process in terms of a tunneling current through a potential barrier from a metal surface into vacuum. This current is given by

$$I = \lambda A a \phi^{-1} E^2 \exp\left\{-\mu b \phi^{3/2} \big/ E\right\} \qquad (1)$$

with A the area of emission, ϕ the local work function of the emitting surface, E the applied electric field, a and b constants and λ and μ factors to correct for mathematical approximations and physical assumptions on the potential barrier shape [8]. Since the field emission current varies exponentially

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with the electric field, which in turn is proportional to the tip-sample distance, it can be used for feedback to control the tip position [9]. This field emission mode is also employed in STM, mainly for nanolithography and generally operated in ultrahigh vacuum (UHV) to maintain a stable emission current [10, 11, 12]. Current control has also been applied in MFM to keep a macroscopic magnetic tip close to a flat hard disk medium to image and even write bits [13].

In a magnetic probe recording system, probes with a cantilever as in Atomic Force Microscopy (AFM) with a magnetic coating will be used. Next to controlling the tip-sample distance, from the field emission current in principle also the cantilever resonance frequency can be obtained. Shifts in this frequency can be used to sense the magnetic stray fields from the medium. Moreover, field emission from probes enables heat-assisted writing in magnetic media [14, 15]. The field emission current detection method can therefore result in an integrated method for writing and reading data in magnetic probe recording.

2. Experimental

2.1. Instrument

For the measurements an RHK-350 STM scanner is used, see figure 1 (left). It has the possibility to mount AFM probes by using a special holder on the center piezo. Sample approach and coarse xy-movement are accomplished by inertial motion of the scanner using the three outer piezos. The sample is scanned by applying scan voltages to the three outer piezos for XY-scans with 5x5 µm range and to the center piezo for Z-positioning of the probe with 200 nm range. Sample positioning as well as data collection are done by RHK STM 1000 control electronics and RHK XPM Pro software. The instrument employed here can be operated in the field emission regime by increasing the applied bias voltage up to 500V, using a Keithley 6487 Picoammeter as a voltage source and current amplifier.

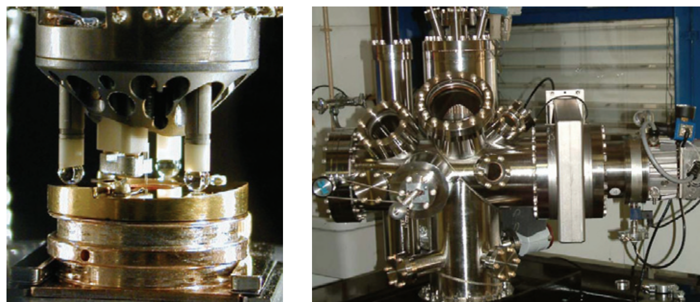

Figure 1: STM (left) and UHV system (right) for field emission measurements

To improve the stability of the field emission current, the STM is operated in UHV and isolated from vibrations. The UHV system (figure 1, right) has been designed for a base pressure of $1 \cdot 10^{-10}$ mbar. Vibration isolation has been realized by means of a damping table and viton stage. The system has the possibility for in-situ storage, exchange and thermal conditioning of probes and samples.

2.2. Field emission probes

In the experiments presented in this paper, AFM probes have been used with two different coatings to improve the field emission properties. The first probe (Nanosensors CDT-NCHR) is coated with ~100 nm of polycrystalline diamond, highly doped with boron to lower the resistivity. From the scanning electron microscope (SEM) image in figure 2 (left), a tip radius of 300 nm can be estimated. The probe has a force constant of 42 N/m, length of 125 µm and resonance frequency of 320 kHz. Figure 2 (right) shows a second probe (Nanosensors PPP-NCLR), which is coated in-house by sputtering 20 nm chromium. This probe has a tip radius of ~20 nm, force constant of 48 N/m, length of 225 µm and resonance frequency of 190 kHz. Both probes have a high force constant to limit the cantilever deflection due to electrostatic forces to less than 1 nanometer for the applied bias voltages.

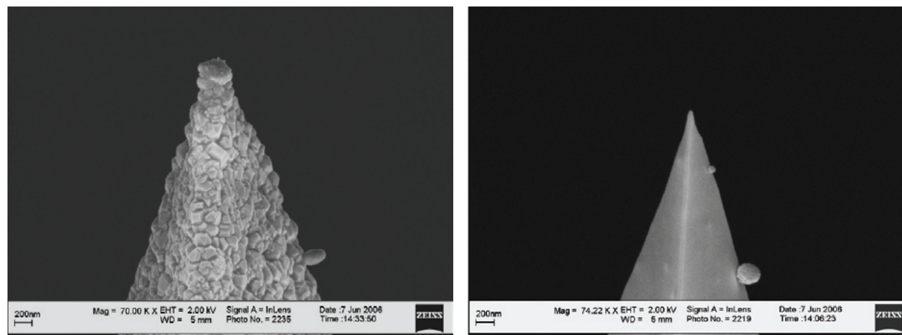

Figure 2: AFM probe tips with 100 nm conductive diamond coating (left) and 20 nm chromium coating (right)

2.3. Samples patterned using laser interference lithography

To test and characterize the method of using field emission to control the tip-sample distance, a special sample with a well-defined topography was prepared. Figure 3 shows a SEM image of this sample. The sample consists of a 500 nm thick low pressure chemical vapor deposited (LPCVD) silicon nitride layer on a p-type <100> silicon wafer. To create a high density dot pattern we employed standard photolithographic resist (OiR 907/12), that was thinned and spin-coated resulting in a thickness of 200 nm. A laser interference lithography (LIL) setup available at our laboratory was used to create a sub-micrometer resist pattern. The nitride was patterned through the resist mask by a standard CHF_3/O_2 plasma in a parallel plate etcher, resulting in dots with 365 nm periodicity, 190 nm diameter and 35 nm height. Resist removal took place in oxygen plasma. A coating of 5 nm chromium and 15 nm platinum was sputtered on the patterned silicon-nitride layer to make the sample conductive. This same LIL method is used to pattern magnetic materials over large areas, to be able to achieve higher densities in magnetic recording [16].

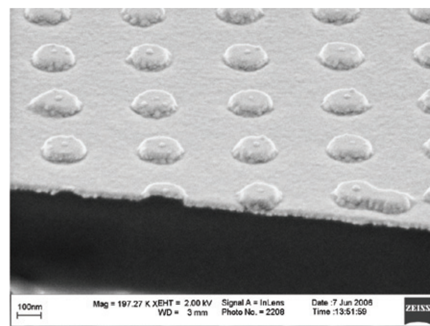

Figure 3: Sample patterned using LIL resulting in dots with 365 nm periodicity, 190 nm diameter and 35 nm height, after application of a Cr(5)Pt(15) coating

3. Results and discussion

3.1. Gap dependence

The probe coated with conductive diamond was brought into contact with a metal-coated (5 nm Cr, 15 nm Pt) silicon sample by monitoring the current from the cantilever. Next the STM scanner was retracted to increase the tip-sample distance to 40 nm and the position feedback was disabled. A positive bias sweep was applied to the sample to extract current from the tip. This measurement was repeated for increasing tip-sample distances from 40 nm to 400 nm. The gap dependence of the I/V characteristics is shown in the left graph of figure 4. From the measurements it can be obtained that for increasing distances higher voltages are needed to extract the same field emission current, from about 15V for 40 nm to a maximum of 120V for 400 nm.

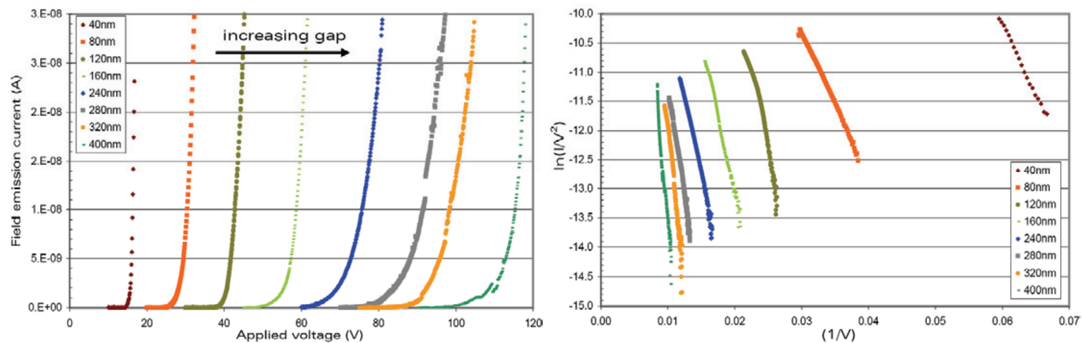

Figure 4: Gap dependence of I/V characteristics (left) and the corresponding Fowler-Nordheim plots (right) measured for gaps up to 400 nm between diamond coated probe and metal surface

By plotting the I/V curves on a semi-logarithmic scale as is done in the right graph of figure 4, we can fit our data to the Fowler-Nordheim equation in logarithmic form:

$$\ln\left(I/E^2\right)=\ln\left(\lambda A a\phi^{-1}\right)-\mu b\phi^{3/2}/E \qquad (2)$$

The linear behavior of the Fowler-Nordheim plots shows that the I/V curves are in good agreement with field emission theory. The field emission parameters that have been used to fit our data are the emission area and the field enhancement factor, that relates the electric field for a given applied bias voltage to the tip-sample geometry. These parameters are in reasonable agreement with the expected values for a tip radius of 300 nm.

3.2. Field emission to control tip-sample distance

For control of the tip-sample we use feedback to the position of the probe to keep the current constant. In figure 5 the result is shown for the diamond coated probe. When the bias voltage is increased from 0.1 V to 10.0 V, the probe is retracted from the sample to keep the current setpoint of 0.3 nA The relative probe height was determined from the voltage signal to the Z piezo. The probe is raised with 2.8 nm for every volt increase in the sample bias. This linear dependence is in agreement with field emission theory. The fluctuations observed in the measurement are caused by instabilities in the field emission current and are small enough to control the tip-sample distance with a resolution of 1-2 nm.

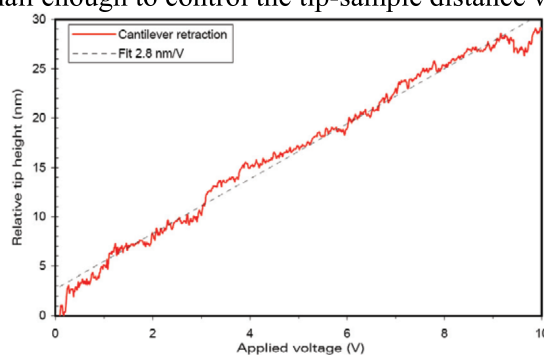

Figure 5: Relative height of diamond coated probe as function of applied bias voltage during feedback operation (constant current 0.3 nA)

3.3. Scanning using field emission probes

The patterned sample is scanned applying field emission to control the tip-sample distance, using the AFM probe coated with 20 nm of chromium. Figure 6 shows 1x1 μm scans using 0.5V, 5.0V and 50.0V bias voltage respectively at 0.3 nA current setpoint. For the left image, a maximum scan rate of 250 nm/s was used. At higher speeds unwanted tip-sample contacts occurred because of the height of

the dots. In the middle image, the probe is operated in the field emission regime at increased distance using a bias voltage of 5.0V. A decrease of resolution can be observed and a slightly higher scan rate of 333 nm/s was used. By increasing the bias voltage to 50.0V a further loss of resolution can be seen, caused by the increase in tip-sample distance. This larger distance allows for much higher scan rates up to 4 µm/s. Although the noise level increases due to instabilities of the field emission current, the signal is still sufficient to be able to track the dots. The current stability may be improved by changing the probe coatings, improving the vacuum conditions and thermal conditioning of probes and sample.

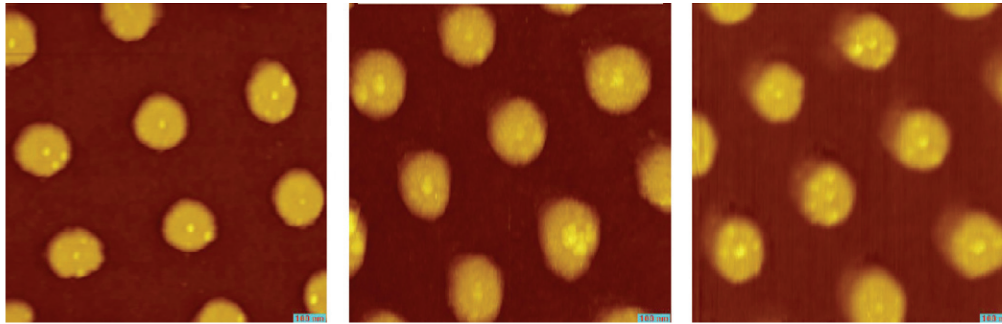

Figure 6: Patterned sample scanned using Cr coated probe at 0.5V (left), 5.0V (middle) and 50.0V (right) respectively

4. Conclusions

Stable field emission could be shown from coated AFM probes at increasing distances. The field emission current can be used to control the tip-sample distance and to image a conducting patterned surface without external deflection detection system. An increase in the tip-sample distance by increasing the bias voltage results in a decrease in resolution, and an increase in the maximum possible scan-rate. The measurements confirm that the field emission method can be applied to control the tip-sample distance, with sufficient resolution and current stability for magnetic probe recording.

5. Acknowledgements

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