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On intermittent-contact mode sensing using electrostatically-actuated micro-cantilevers with integrated thermal sensors

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***Abstract*— Ultrahigh data storage densities on the order of 1 Tb/in^2 or higher can be achieved by using scanning-probe microscopy techniques to write, read back and erase data on very thin polymer films. The written information is usually read back in contact mode because it is simple to implement and analyze. However, the physical contact between the probe-tip and the media leads to wear of the tip due to abrasive and adhesive forces. Tip wear has adverse effects on the read and write performance at ultrahigh data storage densities. In this paper, an intermittent-contact mode read operation is presented that has been developed to improve the durability of probe-based devices by significantly reducing tip wear. The electrostatic pull-in force between the cantilever and the silicon substrate underneath the polymer medium is used as the actuating force for intermittent-contact operation. The cantilever response is highly nonlinear because of the large adhesion between the tip and the soft polymer medium, which forces the cantilever to remain in contact with the medium for significant fraction of its periodic orbit. For fast and noninvasive reading a feedback controller is designed to ensure reliable small-amplitude operation. Significant improvements in both of the read-lifetime and the rate of signal amplitude-loss were achieved using the intermittent-contact read method compared with the contact read method because of substantial reduction in tip wear rate.**

I. INTRODUCTION

Techniques akin to scanning probe microscopy (SPM) can be used to modify and interrogate materials down to the atomic scale [1]. The nanometer-sharp probes used in these techniques are suitable for the development of ultrahigh-density storage devices [2], [3], [4], [5], [6]. Probe-based storage technologies can be regarded as the natural candidates for extending the physical limits that magnetic storage is approaching i.e. the superparamagnetic effect. On the other hand, data rates of 1 Gb/s or more are achieved by magnetic recording, whereas the mechanical resonant frequencies of cantilevers limit the data rates of a single cantilever to a few Mb/s for SPM-based data storage. The solution for substantially increasing the data rates in such devices is to employ a large number of cantilevers operating in parallel, with each cantilever performing write/read/erase operations over a dedicated part of the storage medium.

The MEMS-based scanning probe data-storage device described in detail in [4], [5], [6], combines ultrahigh density, small form factor, and high data rates. A two dimensional array of atomic force microscope (AFM) cantilevers is used to store information in the presence and absence of indentations written on a nanometer-thick polymer film (see Fig. 1). Each cantilever can perform write/read/erase operations over an individual storage field having area on the order of 100×100

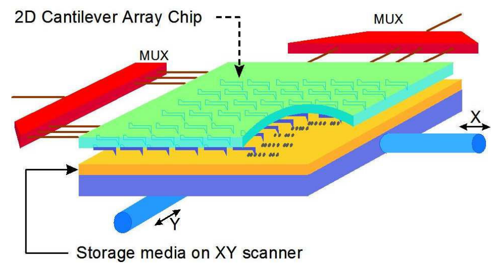

Fig. 1. Schematic of a MEMS based ultrahigh density data storage system.

μm^2. The polymer medium is spin-coated on a MEMS-based X/Y microscanner, which has integrated electromagnetic actuators and thermoelectric position sensors.

Although such probe-based devices are attractive because of the high density and high data rate prospects, an important challenge is their reliability and durability. Sharp tips are required for high-quality writing and reading of information at ultrahigh-densities. It is perceived that tip wear has adverse effects on the performance of probe-based devices. In this paper, tip wear during continuous reading is studied for an intermittent contact read method. To reduce tip wear and increase the data rate during reading, a small-amplitude operation is employed. To enable reliable small-amplitude intermittent contact operation, a feedback scheme is incorporated to prevent adhesion and non-contact, and to compensate for drifts in the system.

The remainder of the paper is arranged as follows. First, in section II, a single-lever data storage setup that is used to write and read information on thin polymer films is described. In section III, cantilever and tip-medium interaction models as well as the feedback scheme are described. Finally, in section IV, experimental results obtained with the single-lever setup are presented.

II. SINGLE-LEVER DATA-STORAGE SETUP

The single-lever data-storage setup (see Fig. 2) is built to serve as the development platform for the MEMS-based data-storage system described in [4], [5], [6]. A custom-designed cantilever holder is manufactured to use the cantilevers identical to those employed in the MEMS data storage device, with all their functionalities. Using the positioning screws in the holder, the cantilever can be moved in the vertical direction, and its pitch and yaw can be adjusted. Commercial x/y/z scanners and controllers from Physik Instrumente (PI) are used in this setup. The scanners are always operated in closed loop with good reference tracking. The polymer medium is spin-coated on top of a silicon substrate and

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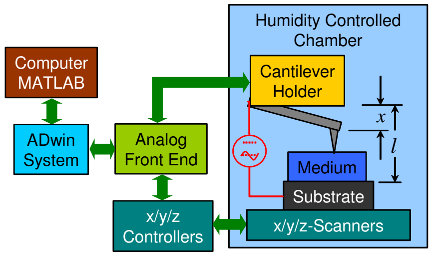

Fig. 2. Schematic of a single-lever data storage setup that serves as the development platform for a MEMS-based ultrahigh-density data-storage system.

clipped on top of the scanner. The scanner and the holder are placed inside an acoustic isolation chamber, which also has humidity and temperature control.

The operation of the single lever setup is fully automated and controlled from a matlab based software on a computer. The cantilever and the scanners/controllers are interfaced with the computer through a real-time digital system (ADwin) and an analog printed circuit board called the analog front end, AFE (see Fig. 2). AFE processes the signals during read and write operations. Various programming and system input data are generated in the computer and transferred to ADwin. Upon receiving command, ADwin then generates the corresponding input and timing signals and applies them to the cantilever and scanner-controllers through AFE. The scanner position and cantilever read-back signals are processed in AFE and collected in ADwin and then transferred to the computer. Likewise, the temperature and humidity inside "humidity controlled chamber" are also monitored and controlled from the software.

The write and read operations in the single-lever storage setup are identical to those in the MEMS-based device. In this paper, the read operation is considered. The read operation is performed through a thermoelectric read-back sensor on the cantilever. The sensor is a micro-heater with temperature-dependent resistance. During reading the micro-heater is typically operated at about 200°C. The principle of thermal sensing is based on the fact that the thermal conductance of the air gap between the heater platform and the polymer layer changes according to the distance between them [7]. When the tip moves into an indentation, the distance between cantilever and polymer film shrinks and the heat transport through the air gap becomes more efficient. As a result the temperature of the heater decreases, which results in a reduction of its resistance and associated increase of a current when a constant voltage is applied across it. Therefore, during the read process, the current through the read-back sensor reaches different values depending on whether the tip moves into an indentation (bit '1') or over a region without an indentation (bit '0').

III. Modelling

In intermittent-contact mode operation of a scanning probe microscopy based device, the effect tip-medium interaction force on the micro-cantilever response can be analyzed by considering models for the micro-cantilever and the interaction force. Modelling can help in understanding the reliability of operation and developing methodologies to extract surface properties of the medium.

The cantilever dynamics can be described by a second order model,

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = f_{es}\left(t, x(t)\right) + \phi\left(x(t)\right), \quad (1)$$

where m, c and k are the effective mass, damping coefficient and the spring constant of the cantilever, respectively and $x(t)$, $f_{es}(t, x(t))$ and $\phi(x(t))$ are the cantilever deflection, the applied actuation force and the tip-medium interaction force, respectively.

In the data-storage setup the cantilever and the silicon substrate, which is coated with polymer on top of it, act like two charged plates facing each other when a potential difference is applied across them; as a result an electrostatic force is generated between them which pulls the free-end of the cantilever towards the substrate. The base of the cantilever is fixed and the overall bending of the cantilever is small compared to the separation between the cantilever and the substrate. Therefore, it can be assumed that the cantilever and the substrate act like charged parallel plates.

Let ℓ denote the effective separation between the cantilever and the substrate when the electrostatic potential difference between them is zero. Let $x(t)$ denote the effective change in separation between the cantilever and the substrate when the cantilever bends because of voltage $V(t)$ applied to the substrate. The instantaneous electrostatic pull-in force $f_{es}(t)$ is given by

$$f_{es}(x(t)) = \frac{\epsilon_0 A}{2(\ell - x(t))^2} V^2(t), \quad (2)$$

where ϵ_0 and A are the electric permittivity of air and the effective area between the cantilever and the substrate, respectively. Note that the electrostatic pull-in force is always attractive and a nonlinear function of the voltage V and the separation $(\ell - x(t))$.

The dynamics of the cantilever in (1) take the following form when electrostatic actuation is applied:

$$m\ddot{x} + c\dot{x} + kx = \frac{\epsilon_0 A}{2(\ell - x)^2} V^2 + \phi(x). \quad (3)$$

where the dependence of $x(t)$ on time has been dropped for notational convenience.

Note that the mechanical restoring force of the cantilever increases linearly with x, whereas the electrostatic pull-in force increases more rapidly as a nonlinear function of x. The cantilever-tip snaps into contact with the medium beyond a certain position $x_{snap-in}$, where the equivalent electrostatic spring constant $k_{es} = \epsilon_0 A V_0^2/(\ell - x)^3$ exceeds the cantilever mechanical spring constant k [8], given by

$$x_{snap-in} = \frac{\ell}{3}. \quad (4)$$

Note that if $x(t) < x_{snap-in}$ then the cantilever approaches the medium smoothly. In intermittent-contact operation described in the following section the cantilever is operated smoothly and (4) is avoided at all times.

1) Intermittent-contact operation: An intermittent-contact operation is developed to prevent prolonged tip-medium contact while scanning which results in tip wear and associated decrease of the lifetime of probe-based devices. In this mode of operation a small voltage signal $V(t)$ is chosen for electrostatic forcing, so as to achieve small tip-medium interaction force. The snap-in condition is avoided at all times during intermittent-contact operation by fixing the initial tip-medium separation sufficiently small so that the tip touches the medium before (4) is satisfied. The cantilever is permanently bent towards the medium and a very small tip-medium separation is maintained by applying an offset voltage V_0. At the same time, the tip intermittently probes the polymer surface through the additional application of a small periodic voltage $V_{ac}(t)$. The net applied voltage is given by

$$V(t) = V_0 + V_{ac}(t). \tag{5}$$

Note that $V(t)$ does not change sign because $V_0 > |V_{ac}(t)|, \forall t$. Small oscillations are desirable to achieve a high data rate because it takes less time for the cantilever to come in and out of contact with the polymer surface. Let us write the cantilever deflection as,

$$x(t) = x_0 + \tilde{x}(t), \tag{6}$$

where x_0 and $\tilde{x}(t)$ denote the mean deflection and the periodic oscillation of the cantilever. The free dynamics of the cantilever can be obtained from (3) by removing the tip-medium force $\phi(x(t))$. Substituting (6) in (3) and ignoring terms of second and higher orders, the free cantilever dynamics can be approximated by a time-varying linear differential equation (because $V(t)$ does not change sign with time t) given by

$$\begin{aligned} & m\ddot{\tilde{x}}(t) + c\dot{\tilde{x}}(t) + \left(k - \frac{\epsilon_0 A V^2(t)}{(\ell - x_0)^3}\right)\tilde{x}(t) \\ = \quad & -kx_0 + \frac{\epsilon_0 A}{2(\ell - x_0)^2} V^2(t). \end{aligned} \tag{7}$$

Note that the effective spring constant of the cantilever changes as a function of $V(t)$. In intermittent-contact operation, the periodic component of $V(t)$, i.e. V_{ac}, has a small peak-to-peak range compared with the offset voltage V_0. The effective spring constant of the cantilever given by (7) can therefore be approximated by an average value. Accordingly, the free cantilever dynamics in (7) can be approximately described by a time-invariant linear differential equation:

$$\begin{aligned} & m\ddot{\tilde{x}}(t) + c\dot{\tilde{x}}(t) + \left(k - \frac{\epsilon_0 A V_0^2}{(\ell - x_0)^3}\right)\tilde{x}(t) \\ = \quad & -kx_0 + \frac{\epsilon_0 A}{2(\ell - x_0)^2} V^2(t). \end{aligned} \tag{8}$$

The state-space representation of the linear time-invariant model of the free cantilever dynamics is given by

$$\begin{aligned} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} &= \overbrace{\begin{bmatrix} 0 & 1 \\ -\left(\omega_0^2 - \frac{K_{esf} V_0^2}{(\ell - x_0)^3}\right) & -\frac{\omega_0}{Q} \end{bmatrix}}^{A} \overbrace{\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}}^{x} \\ & - \overbrace{\begin{bmatrix} 0 \\ 1 \end{bmatrix}}^{B} \left(\omega_0^2 x_0 - \frac{K_{esf}}{2(\ell - x_0)^2} V^2(t)\right), \end{aligned} \tag{9}$$

where $x = [\tilde{x}; \dot{\tilde{x}}]$ and $K_{esf} = \frac{\epsilon_0 A}{m}$. Note that $\frac{k}{m} = \omega_0^2$ and $\frac{c}{m} = \frac{\omega_0}{Q}$, where ω_0 and Q are the natural resonant frequency and the quality factor of the cantilever, respectively.

2) Tip-medium interaction model: During the intermittent-contact read operation, the imaging (bit-detection) data is collected by sampling the read-back (deflection) signal, with a fixed delay once in every period of the cantilever oscillation. The touch-down time of the tip on the medium and the subsequent contact time depend on the tip-medium separation and the surface profile of the medium. To ensure reliable image data collection so that the read-back signal is sampled when the tip is in contact with the medium, the cantilever is forced to have contact for a significant fraction of its oscillation period. Apart from typical Van der Waals forces the polymer medium exerts a significant adhesive force on the cantilever. When the tip is in contact with the polymer surface, the attractive Van der Waals force is very small and the cantilever response is dominated by the strong Van der Waals repulsive force and the adhesive force. Such a cantilever-medium interaction force ϕ can be approximated by a piecewise linear model [9].

During intermittent-contact read operation, when the applied voltage $V(t)$ is reduced, the electrostatic pull-in force reduces and the cantilever attempts to pull back using its mechanical restoring force. The net restoring force is the difference between the mechanical restoring force and the electrostatic pull-in force, which is a function of $x(t)$ and $V(t)$ (see (2)). The cantilever remains in contact with the polymer for as long as the adhesive force is greater than the net restoring force. When the net restoring force exceeds the adhesive force, the cantilever comes out of contact with the polymer surface. The adhesive force suddenly vanishes and as a result the cantilever suddenly snaps off the surface. This effect of the tip-medium interaction on the cantilever is as if an impulsive force acts on it that results in an instantaneous state jump. Likewise, when the cantilever comes in contact with the polymer the effect on the cantilever is as if an instantaneous reset in state occurs, which remains unchanged until the cantilever snaps off the surface. In state-space form, the snap-off tip-medium interaction model can be modelled as

$$\phi_n(t) = \overbrace{\begin{bmatrix} \triangle x_{1,n}^{out} \\ \triangle x_{2,n}^{out} \end{bmatrix}}^{\triangle x_n^{out}} \delta(t, nT + T_n^{out}), \tag{10}$$

where

$$\delta(t_1, t_2) = \begin{cases} 0 & \text{if } t_1 \neq t_2 \\ 1 & \text{if } t_1 = t_2 \end{cases},$$

$\phi_n(t)$, $\triangle x_n^{out}$ and T_n^{out} are the tip-medium interaction force, the state jump and the time delay during the n-th T-periodic oscillation cycle when the cantilever snaps off the medium, respectively. $\triangle x_n^{out}$ and T_n^{out} depend on the tip-medium separation and the nature of contact between them. For simplicity, these parameters can be precalculated and fixed as constants in intermittent contact operation.

In Fig. 3, the linear model of the electrostatically actuated cantilever (9) combined with state jump model for tip-medium interaction (10) is compared with nonlinear model

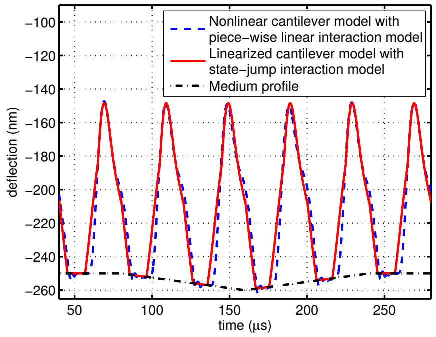

Fig. 3. The resonant frequency and quality factor of the cantilever are $f_0 = 80$ kHz and $Q = 3.2$, respectively.

of the electrostatically actuated cantilever (3) combined with piece-wise linear model for the tip-medium interaction [9]. The resonant frequency and quality factor of the simulated cantilever are $f_0 = 80$ kHz and $Q = 3.2$, respectively. The topography of the medium represents a 10 nm deep triangular data-bit shape. The cantilever and piece-wise linear tip-medium interaction model parameters are chosen such that the intermittent-contact operation resembles a cantilever from a MEMS-based storage device acting on a polymer medium. The operating frequency is chosen, lower than the resonant frequency of the cantilever, as $f = 25$ kHz ($T = 40\mu s$). The bandwidth of the integrated thermal sensors in the current design is smaller than the resonant frequency of the cantilever [10]. It is observed in simulations that at lower operating frequencies, the farthest position of the tip from the medium remains unchanged largely independent of the profile of the medium. Note that the cantilever behaves as a linear system with a sinusoidal input and an additional impulsive input from the medium at the time instant when it snaps off it. The responses to these inputs add up with different time delays for different topography profiles of the medium, in such a way that at each time the cantilever reaches the same farthest point from the medium. This enables a feedback scheme required for reliable operation which is explained in the following section.

3) Feedback: Voltage offset control: Note that the thermal read-back signal $V_R(t)$ is a measure of the separation between the cantilever (reading micro-heater) and the polymer surface. The peak in the read-back signal $V_{out}(t)$ is a measure of the maximum separation between the read heater and the medium when the tip is out of contact with the medium during intermittent-contact read operation. Likewise, the trough in the read-back signal $V_{in}(t)$ is a measure of the separation between the read heater and the medium when the tip is in contact with the medium. When the tip 'falls' into an indentation, the separation between the read heater and the polymer surface is reduced by the depth of the indentation and consequently the reduction in the value of $V_{in}(t)$ is a measure of the depth of an indentation. In the intermittent-contact read operation, $V_{out}(t)$ is used as the feedback signal to maintain a set point separation between the cantilever and the polymer surface, whereas $V_{in}(t)$ is used as the bit detection signal. Simulations show that $V_{in}(t)$ and $V_{out}(t)$ are independent of each other when the intermittent-contact operating frequency is smaller than the resonant frequency of the cantilever (see Fig. 3). Thus, the feedback scheme can be implemented without affecting the bit detection signal.

In the MEMS-based data-storage device the thin film polymer used as medium is spin-coated on top of a silicon substrate. It is desired to have a very flat and homogeneous surface. However, on the single-lever setup, where the medium is exposed to the environment, we observed that the polymer surface is not homogenous with respect to adhesion and may suffer from contamination of various forms, such as dust particles [1]. It is possible during intermittent-contact operation that the tip adheres to the surface because of an unexpected large adhesive force which exceeds the restoring force in the entire period of oscillation of the cantilever. Nonuniform peak-to-peak oscillation of the cantilever was also observed while scanning over large areas. Small undulations on the polymer surface, a tilt in the scanner with respect to the cantilever-holder, or a small cross-coupling between the x/y/z scanners might cause such an effect.

The feedback scheme is implemented in order to increase the reliability of intermittent-contact operation. The actuation signal for the feedback is the offset voltage V_0 applied to the substrate. The control signal is V_{out} corresponding to the farthest position of the cantilever from the medium. Similar to the way (8) was derived it can be shown from (3) and (5) that the nominal transfer function from the offset voltage V_0 to the offset cantilever position x_0 is given by

$$G_{\text{nom}}(s) = \frac{K_{esf}/\left(2(\ell - x_0)^2\right)}{\left(s^2 + \frac{\omega_0}{Q}s + \omega_0^2 - \frac{K_{esf}V_0^2}{(\ell - x_0)^3}\right)}. \tag{11}$$

Then the nominal closed-loop transfer function $T_{nom}(s)$ of the feedback scheme which controls a small peak-to-peak cantilever oscillation is given by

$$T_{nom}(s) = \frac{G_{nom}(s)}{1 + G_{nom}(s)K(s)}, \tag{12}$$

where $K(s)$ is the transfer function of the controller. Note that in the experiments a PI controller was used.

In Fig. 4 (upper panel) the read-back signal is shown. Specifically, a time window during which the tip could not come out of contact with the polymer medium in intermittent-contact operation is shown. In Fig. 4 (bottom panel) the read-back signal is shown when the offset voltage control is incorporated into the intermittent-contact scheme. It can be immediately observed that the read back signal and thus the trajectory of the tip motion, is periodic and homogeneous.

IV. Experimental Results

Intermittent-contact read experiments for tip-wear assessment have been carried out on a single-lever setup (as described in section II). Small peak-to-peak cantilever oscillation and feedback for improved reliability are employed. Relative humidity less than 5% and steady ambient temperature are maintained during the entire experiment.

[1]These medium inhomogeneities and contamination are not encountered in the MEMS device, where the medium is enclosed in a tight assembly, and direct contact with the environment is avoided.

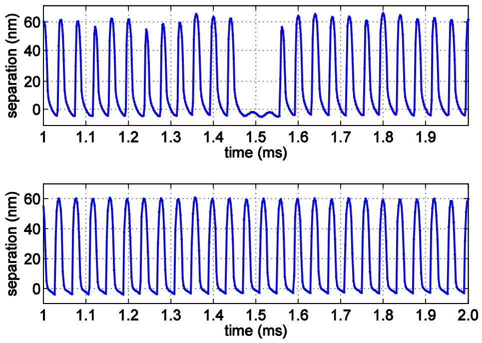

Fig. 4. Read-back signals from an intermittent-contact experiment (bottom) with and (top) without feedback. Without the feedback loop, the cantilever adheres to the polymer surface spontaneously.

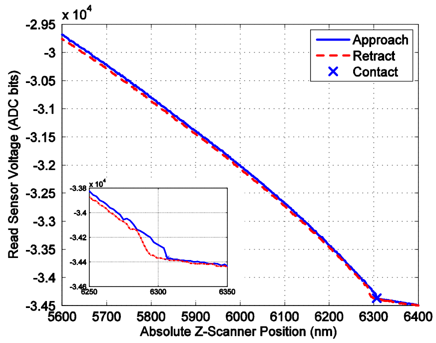

Fig. 5. A force/distance curve obtained by moving the z-scanner. The read-back signal is a nonlinear function of the tip-medium separation, which can be approximated by a second-order polynomial.

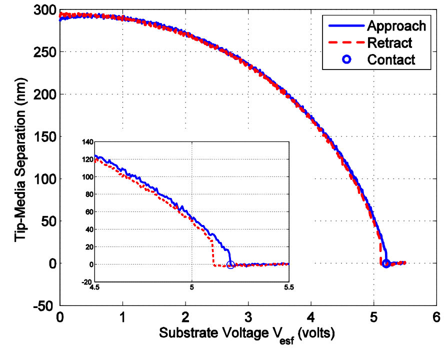

Fig. 6. A force/distance curve obtained by applying electrostatic force on the cantilever.

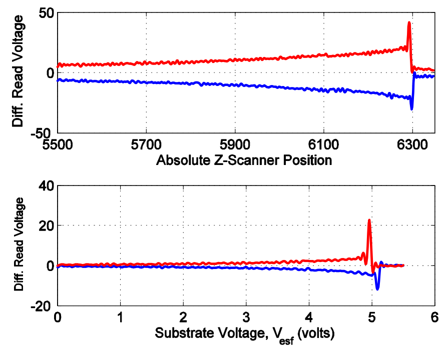

Fig. 7. During force/distance curve experiments using (top) z-scanner and (bottom) electrostatic force, peaks in the numerical derivative of the read back signal appear when the tip-medium contact and out of contact points occur.

In the single-lever setup, the tip-medium separation is varied by moving the z-scanner in closed-loop by using a PI controller, and force/distance curves are obtained. The frequency of operation of the scanner is kept low for good reference tracking. The separation between the cantilever and the medium is sensed through the read back signal V_R (see Fig. 5). The z-scanner approaches the cantilever until tip-medium contact occurs and then it retracts to a desired position. The cantilever snaps off the polymer surface during retraction. The tip-medium contact point during approach and the snap-off point during retract can be accurately detected from the numerical derivative of V_R (see Fig. 7 (top)). The tip-medium contact and snap-off point correspond to different positions of the z-scanner. The difference between these positions provides an estimate of the adhesion force between tip and medium. Note that the z-scanner position is known from the reference voltage given to its controller provided the approach and retract are performed sufficiently slow, i.e. within the closed-loop bandwidth of the controller and the scanner. The z-scanner position signal is otherwise also available from the capacitive position sensor. Note also that electrostatic forcing is not applied to the cantilever in this step of the experiment.

After tip-medium contact has been detected during approach, the z-scanner is withdrawn slowly to a desired tip-medium separation x_{sep}. The z-scanner is then maintained at that position by the PI controller. Then an electrostatic force/distance curve is obtained (see Fig. 6). Substrate voltage V is slowly increased until tip-medium contact is detected using the numerical derivative of the read-back voltage V_R (see Fig. 7 (bottom)) and then slowly reduced to zero. The electrostatic voltages required to bring the tip in and out of contact differ during the approach and the retract process. The difference in these voltages is a measure of the tip-medium adhesion force. Note that this measure is also a function of the initial tip-medium separation x_{sep}.

Tip wear is expected to be low in intermittent-contact read operation because of the smaller normal force and shorter time scale of normal and adhesive (abrasive) forces compared with those in contact read operation. Intermittent contact tip

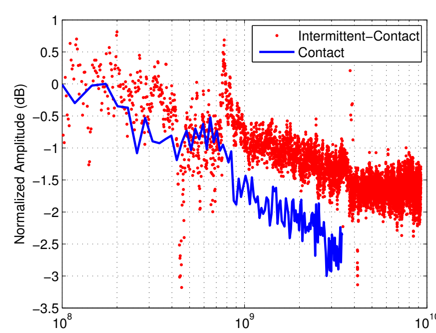

Fig. 8. Normalized average signal amplitude (dB scale) during an intermittent-contact and contact read experiment.

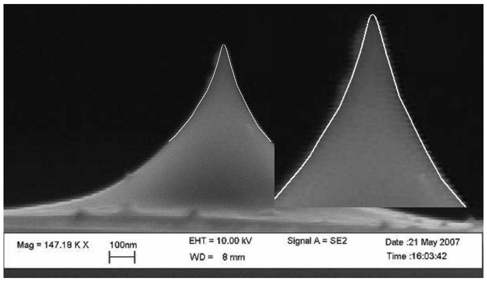

Fig. 9. Scanning electron microscopy image of a tip after tip wear experiment and the tip shape in white line before the experiment

wear experiments were carried out on several cantilevers with each experiment lasting several weeks. In the experiment described here, intermittent-contact reading was employed on a part of the storage medium where data was recorded at 1 $\mathrm{Tb/in}^2$ density using the same cantilever-tip as for reading. First, an initial tip-medium separation of 300 nm was set and maintained by the z-scanner/controller. By using the electrostatic force/distance curve the voltages required to pull the cantilever into tip-medium contact and then out of contact were found to be 5.02 and 4.93 V, respectively. For the intermittent contact read operation a sinusoidal voltage signal with offset $V_0 = 4.925$ V, amplitude $A_t = 295$ mV (i.e. $V_{max}(t) = 5.22$ V and $V_{min} = 4.63$ V) and frequency $f_t = 25$ kHz was applied to the substrate. Correspondingly, The feedback parameters for offset voltage control were chosen as proportional gain $K_p = -5 \times 10^{-2}$ and integral gain $K_i = -1 \times 10^{-6}$.

The normalized average read-back amplitude corresponding to the indentations over the entire written data pattern is plotted in Fig. 8 throughout the duration of the continuous reading experiment, for the contact and intermittent-contact read modes. At the end of the experiment, a total of 0.93×10^{10} symbols had been read which is equivalent to a tip travel distance of approximately 140 m. The number of total read symbols was chosen to be compatible with standard endurance performance specifications of semiconductor-based memories. Note that after an initial transient period, the indentation amplitude signal, which is a measure of the quality of the detected signal, degraded very slowly with time for the intermittent-contact read mode. On the other hand, the associated contact read mode exhibited a steeper amplitude loss throughout the experiment, and eventually failed before the desired number of read events was reached. The estimated amplitude loss rate in intermittent-contact reading was 0.014 dB/decade, which is a substantial improvement compared with what is typically observed in contact reading (1.8 dB/decade in this experiment).

The scanning electron microscopy (SEM) images of the tip before and after the intermittent-contact experiment are overlaid and shown in Fig. 9. The tip-shape remained almost unchanged after the experiment. In intermittent-contact reading the tip retains its sharpness for high density data storage which was verified by writing and reading back, with good quality, a data pattern at 1 $\mathrm{Tb/in}^2$ density with the used tip at the end of after the tip-wear experiment.

V. Conclusion

Ultrahigh data-storage densities on the order of 1 $\mathrm{Tb/in}^2$ or more can be achieved using scanning probe microscopy based data-storage. The maintenance of tip sharpness is essential for continuous reading and writing of information at ultrahigh densities. Contact-mode read operation leads to significant tip wear. An intermittent-contact mode operation is presented in this paper that significantly reduces the wear rate of the tip. Small peak-to-peak oscillations of the cantilever were employed to reduce tip wear and achieve high data rate. A feedback scheme was essential for reliable operation of the intermittent-contact operation in a single cantilever setup. The cantilever dynamics during intermittent-contact operation have been described by a linear model together with a state-jump model for the effect of the tip-medium interaction force on the cantilever. It was observed in the experiments that the tip-sharpness was maintained after reading approximately 10^{10} symbols, i.e. equivalent to 140 m of tip travel, and that it was sufficient to read and write information at 1 $\mathrm{Tb/in}^2$ with good quality. Moreover, the rate of reduction of the read signal amplitude was improved significantly compared with contact-mode operation.

VI. Acknowledgements

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