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Abstract

Ultrahigh storage densities of up to 1 Tbit/in.^{2} can be achieved by local-probe techniques to write, read back, and erase data in very thin polymer films. The thermomechanical scanning-probe-based data-storage concept called Millipede combines ultrahigh density, terabit capacity, small form factor, and high data rate. After illustrating the principles of operation of the Millipede, we introduce a channel model for the analysis of the read back process, and compare analytical results with experimental data.

1. Introduction

Techniques that use nanometer-sharp tips for imaging and investigating the structure of materials down to the atomic scale, such as the atomic force microscope (AFM) and the scanning tunneling microscope (STM) [1–3], are suitable for the development of ultrahigh-density storage devices [4–9]. As the simple tip is a very reliable tool for the ultimate local confinement of interaction, tip-based storage technologies appear as natural candidates for extending the physical limits that are being approached by conventional magnetic storage. Areal densities achievable by today's magnetic recording technologies are limited to about 100 to 150 Gbit/in.^{2} by the well-known superparamagnetic limit. Several proposals have been formulated to overcome this limit, for example the adoption of patterned magnetic media, for which, however, the biggest challenge remains the patterning of the magnetic disk in a cost-effective manner. On the other hand, data rates well above 800 Mbit/s are achieved by magnetic recording, whereas the mechanical resonant frequencies of the AFM cantilevers limit the data rates of a single cantilever to a few Mbit/s for AFM data storage. The feedback speed and low tunneling currents limit STM-based storage approaches to even lower data rates. The solution for substantially increasing the data rates achieved by tip-based storage devices is to employ arrays of cantilevers operating in parallel, with each cantilever performing read/write/erase operations over an individual storage field [7–9].

In this paper, we consider the "Millipede" concept, as described in [7–9], for the realization of highly parallel scanning-probe data storage, characterized by areal densities up to 0.5 to 1 Tbit/in.^{2}, far beyond the expected superparamagnetic limit, and parallel operation of very large two-dimensional (32×32) AFM cantilever arrays with integrated tips and write/read functionality. After illustrating the principle of the Millipede, we introduce an equivalent model for the characterization of the read-back signal from a thermomechanical sensor, and compare analytical results with experimental data.

2. Principles of operation of the Millipede

The Millipede device shown in Fig. 1 is a highly parallel scanning-probe data-storage system, where information is stored as sequences of "indentations" and "no indentations" written on nanometer-thick polymer films using an array of AFM cantilevers. Each cantilever performs write/read operations over an individual storage field with size on the order of 100×100 μm^2 [7–9]. Thermomechanical writing is achieved by applying a local force by the cantilever/tip to the polymer layer, and simultaneously softening the polymer layer by local heating. Initially, the heat transfer from the tip to the polymer through the small contact area is very poor, but

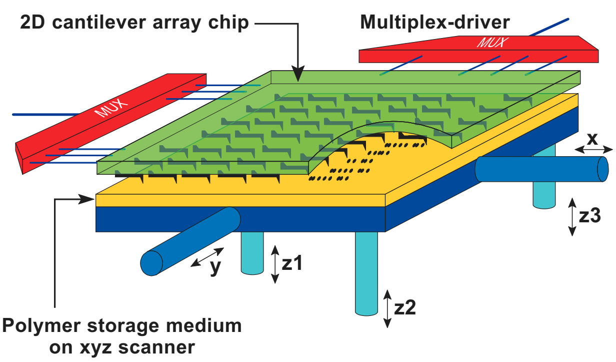

Figure 1. Illustration of the Millipede concept. From [7].

improves as the contact area increases. This means that the tip must be heated to a relatively high temperature of about 400ºC to initiate the softening. Once softening has initiated, the tip is pressed into the polymer, and hence increases the bit size. Figure 2a shows data bits of 40 nm in diameter that have been written using a 1-μm thick, 70-μm long, two-legged Si cantilever, whose legs are made highly conducting by high-ion implantation, whereas the heater region remains low-doped. Figure 2b shows that 40-nm bits can be written very close to each other without merging, implying a potential storage areal density on the order of 400 Gbit/in.^{2}. For example, a (32×32) cantilever array with 1024 storage fields, each having an area of 100×100 μm^2, has a capacity of about 6 Gbit on a chip area on the order of 3×3 mm^2. More recently single-cantilever areal densities up to 1 Tbit/in.^{2} have been demonstrated, although currently at a somewhat degraded write/read quality, as illustrated in Fig. 2c.

To read the written information, the heater cantilever is given the additional function of a thermal readback sensor by exploiting its temperature-dependent resistance. In general, the resistance increases nonlinearly with heating power/temperature from room temperature to a peak value of 500–700ºC. The peak temperature is determined by the doping concentration of the heater platform, which ranges from 1×10^{17} to 2×10^{18} cm^{-3}. Above the peak temperature, the resistance drops as the number of intrinsic carriers increases because of thermal excitation. For sensing, the resistor is operated at about 350ºC, a temperature that is not high enough to soften the polymer as in the case of writing. The principle of thermal sensing is based on the fact that the thermal conductance between heater platform and storage substrate changes according to the distance between them.

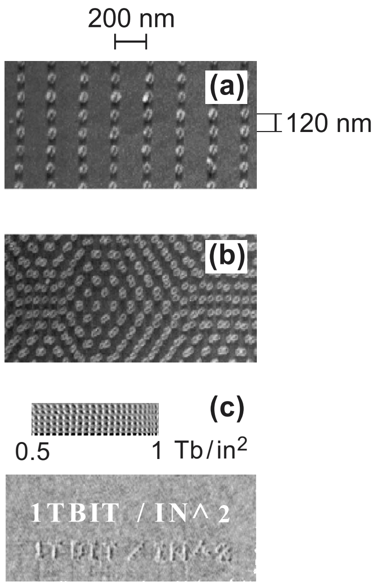

Figure 2. Series of 40-nm data bits formed in a uniform array with (a) 120-nm and (b) variable pitch, resulting in bit areal densities of up to 400 Gb/in.^{2}. (c) Ultra-high-density bit writing with areal densities approaching 1 Tb/in.^{2}. From [9].

The medium between the heater platform and the storage substrate, in our case air, transports heat from the cantilever to the sample. When the distance between cantilever and sample is reduced as the tip moves into a bit indentation, the heat transport through the air becomes more efficient. As a result, the evolution of the heater temperature in response to a pulse applied to the cantilever is different and, in particular, the maximum value achieved by the temperature is smaller than in the case in which no bit indentation is present. As the value of the variable resistance depends on the temperature of the cantilever, the maximum value achieved by the resistance will be smaller as the cantilever moves over an indentation. Therefore, during the read process, the cantilever resistance reaches different values whether it moves over an "indentation" (bit "1") or a "no indentation" (bit "0"). The thermomechanical cantilever sensor, which transforms temperature into an electrical signal that carries information, is electrically equivalent, to a first degree of approximation, to a variable resistance. A detection circuit must therefore sense a voltage that depends on the value of the cantilever resistance to make a decision whether a "1" or a "0" is being written. The relative variation of thermal resistance is on the order of 10^{-5}/nm. Hence a written bit "1" typically produces a relative change of the cantilever thermal resistance $\Delta R^{\Theta}/R^{\Theta}$ of about 10^{-4} to 5×10^{-4}. Note that the relative change of the cantilever electrical resistance is on the same order of magnitude. As a consequence, one of the most critical issues in detecting the presence or absence of an "indentation" is the high resolution required to extract the signal that contains the information about the bit being "1" or "0". The signal carrying the information can be viewed as a small signal superimposed to a very large offset signal.

Write/read operations depend on a mechanical parallel x/y scanning of either the entire cantilever array chip or the storage medium. The tip-medium contact is maintained and controlled globally, i.e., not on an individual cantilever basis, by using a feedback control for the entire chip, which greatly simplifies the system. Early results demonstrating the concept of the entire chip approach/leveling [10] indicate that overall chip tip-apex height control to within 500 nm is feasible. The stringent requirement for tip-apex uniformity over the entire chip is determined by the uniform force required to reduce tip and medium wear due to large force variations resulting from large tip-height nonuniformities [11]. As the Millipede tracks the entire array without individual lateral cantilever positioning, thermal expansion of the array chip has to be small or well controlled. For a 3×3 mm^2 silicon array area and 10-nm tip-position accuracy, the chip temperature has to be controlled to about 1ºC. This is ensured by four temperature sensors in the corner of the array and heater elements on each side of the array. Thermal-expansion considerations are a strong argument for a two-dimensional array arrangement instead of one-dimensional, which would make a chip 32 times longer for a (32×32) array of cantilevers.

Parallel operations of large two-dimensional arrays is achieved by a row/column time-multiplexed addressing scheme similar to that implemented in DRAMs. In the case of Millipede, the multiplexing scheme is used to address the array column by column with full parallel write/read operation within one column [9]. In particular, readback-signal samples are obtained by applying a read pulse to the cantilevers in a column of the array, low-pass filtering the cantilever response signals, and finally sampling the filter output signals. This process is repeated sequentially until all columns of the array are addressed, and then restarted from the first column. The time between two pulses corresponds to the time it takes for a cantilever to move from one bit position to the next. For a (32×32) cantilever array, a distance between the centers of two consecutive indentations (pitch) of 40 nm, a constant velocity of the *x*/*y* scanner of 250 μm/s, and pulses of duration of 5 μs that are periodically applied to each cantilever at a rate of 6.25 kHz, a data rate of 6.4 Mbit/s is achieved using the multiplexing scheme described above. A full parallel operation would increase the data rate to 204.8 Mbit/s.

3. The read-channel model

In this section, we consider the readback channel for a single cantilever, scanning a storage field where bits are written as indentations or no indentations, which will also be referred to as "logical marks", in the storage medium. The model of the read channel, which we consider for the analysis of the detection system, is illustrated in Fig. 3. As discussed in Section 2, a cantilever is modeled as a variable resistance that depends on the temperature at the cantilever tip.

To evaluate the evolution of the temperature of a heated cantilever during the read process, we resort to a simple RC-equivalent thermal circuit, as illustrated in Fig. 4, where $R^{\Theta}(1+\eta_x)$ and C^{Θ} denote the thermal resistance and capacitance, respectively. The parameter $\eta_x = \Delta R_x^{\Theta}/R^{\Theta}$ indicates the relative variation of thermal resistance resulting from the small change in the air gap width between the cantilever and the storage medium, as compared to the case of a flat surface without indentations. Subscript *x* indicates the *x*-distance in the direction of scanning from the initial point. Therefore, the parameter η_x will assume the largest absolute value when the tip of the cantilever is located at the center of an indentation. The heating power that is dissipated in the cantilever heater region is expressed as

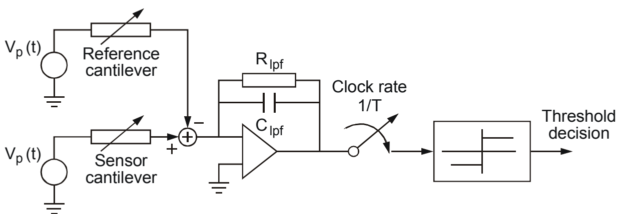

Figure 3. Block diagram of the detection circuit.

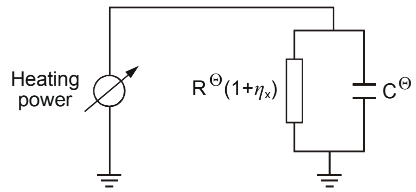

Figure 4. RC-equivalent thermal model of the heat transfer process.

$$P^e(t,\Theta(t,x)) = \frac{V_C^2(t)}{R^e(\Theta(t,x))}, \tag{1}$$

where $V_C(t)$ is the voltage across the cantilever, $\Theta(t,x)$ is the cantilever temperature, and $R^e(\Theta(t,x))$ is the temperature-dependent cantilever resistance.

As the heat-transfer process depends on the value of the thermal resistance and on the read-pulse waveform, $\Theta(t,x)$ depends on time *t* and distance *x*. However, as the time it takes for the cantilever to move from the center of a logical mark to the next is much larger than the duration of a read pulse, we assume that $\Theta(t,x)$ does not vary significantly as a function of *x* during the period a read pulse is applied, and that it decays to the ambient temperature Θ_0 before the next pulse is applied. Therefore the evolution of the cantilever temperature in response to a pulse applied at time $t_0 = x_0/v$, at a certain distance x_0 from the initial point of scanning and for a certain constant velocity *v* of the scanner, obeys a differential equation that is expressed as

$$\begin{aligned}\Theta'(t,x_0) + \frac{1}{R^{\Theta}(1+\eta_{x_0})C^{\Theta}}(\Theta(t,x_0)-\Theta_0) \\ = \frac{1}{C^{\Theta}}\frac{V_C^2(t)}{R^e(\Theta(t,x_0))}.\end{aligned} \tag{2}$$

With reference to the block diagram of the read channel illustrated in Fig. 3, the source generates the read pulse $V_P(t) = V_C(t)$ that is applied to the cantilever variable resistance. Furthermore, the active low-pass RC detector filter, where R_{lpf} and C_{lpf} denote the resistance and capacitance of the low-pass filter, respectively, is realized using an ideal operational amplifier that exhibits infinite input impedance, zero output impedance, and infinite frequency-independent gain. The readback signal $V_o(t,x_0)$, which is obtained at the low-pass filter output in response to the applied voltage $V_P(t) = A\,\text{rect}((t-t_0)/\tau))$, where

$$\text{rect}\left(\frac{t}{\tau}\right) = \begin{cases} 1 & \text{if } 0 \le t \le \tau \\ 0 & \text{otherwise} \end{cases}, \tag{3}$$

and *A* denotes the pulse amplitude, obeys the differential equation

$$V_o'(t,x_0) = \frac{1}{R_{\text{lpf}}C_{\text{lpf}}}\left(-V_o(t,x_0) + \frac{R_{\text{lpf}}}{R^e(\Theta(t,x_0))}V_P(t)\right). \tag{4}$$

As the voltage at the output of the low-pass filter depends on the variable resistance value $R^e(\Theta(t,x_0))$, the readback signal is determined by solving jointly the differential equations (2) and (4), with initial conditions $\Theta(t_0,x_0)=\Theta_0$ and $V_o(t_0,x_0)=0$. As an example, a comparison between experimental and synthetic readback signals is given in Figs. 5 and 6 for a time constant of the low-pass filter $\tau_{\text{lpf}}=1.18\,\mu$s, and two values of the duration of the applied rectangular pulse.

Assuming that ideal control of the scanner is performed, such that the time of application of a read pulse corresponds either to the cantilever being located at the center of an indentation for detecting a bit "1", or away from an indentation for detecting a bit "0", two possible responses are obtained at the output of the low-pass filter as solutions of (2) and (4), which we denote by $V_o(t,x_0\,|\,\alpha_{x_0}=1)$ and $V_o(t,x_0\,|\,\alpha_{x_0}=0)$, respectively. By sampling the readback signal at the instant $t_s=t_0+\tau$, simple threshold detection may in principle be applied to detect a written bit, where the value of the threshold is given by

$$V_{\text{Th}}=½[V_o(t_s,x_0\,|\,\alpha_{x_0}=1)+V_o(t_s,x_0\,|\,\alpha_{x_0}=0)]\,. \qquad (5)$$

As mentioned in Section 2, one of the most critical issues in detecting the presence or absence of an indentation is the high resolution required to extract the small signal $V_o(t_s,x_0\,|\,\alpha_{x_0}=1)-V_o(t_s,x_0\,|\,\alpha_{x_0}=0)$ which contains the information about the bit being "1" or "0", superimposed to the offset signal $V_o(t,x_0\,|\,\alpha_{x_0}=0)$. As illustrated in Fig. 3, a solution to this problem consists in subtracting from the readback signal a reference signal that is obtained by applying at time $t=t_0$ the read pulse $V_P(t)$ to a cantilever scanning a storage field where no indentation is written. The readback signal is thus given by

$$\widetilde{V}_o(t,x_0)=V_o(t,x_0)-V_{o,\text{ref}}(t,x_0\,|\,\alpha_{x_0}=0). \qquad (6)$$

In this case, the threshold is set at

$$\widetilde{V}_{\text{Th}}=½[V_o(t_s,x_0\,|\,\alpha_{x_0}=1)-V_o(t_s,x_0\,|\,\alpha_{x_0}=0)]\,. \qquad (7)$$

The implementation of the detection scheme analyzed here is presented in [12].

We consider now read pulses that are periodically applied at the instants $t_n=nT$, where the rate $1/T$ is sufficiently low, i.e. $T\gg\tau$, such that the cantilever temperature and the output voltage achieve the above initial conditions at the instants t_n. We assume that ideal timing recovery is performed, i.e. the period T is equal to the time it takes for the cantilever to move from the center of a logical mark to the next, and that at the instants t_n the cantilever is located at the center of logical marks. Setting $x_0=0$, the readback signal samples that are obtained in response to N pulses applied to the cantilever for detecting a sequence of N binary symbols are expressed as

$$s(t_{s,i})=\sum_{n=0}^{N-1}\widetilde{V}_o(t_{s,i},x_n),\quad t_{s,i}=iT+\tau,\quad i=0,\ldots N-1, \qquad (8)$$

where $\widetilde{V}_o(t,x_n)$ is given by (6) for pulses applied at time t_n and at distance $x_n=nTv$ from the initial point of scanning. Note that the functions $V_o(t,x_n)$ and $V_{o,\text{ref}}(t,x_n\,|\,\alpha_{x_n}=0)$ in (6) are given by the solution of the differential equations (2) and (4) for $\eta_x=\Delta R^{\Theta}_{x_n}/R^{\Theta}$ and $\eta_x=0$, respectively.

The readback signal (6) at the output of the low-pass filter is observed in the presence of additive noise. Therefore, the readback signal for detection of the i-th binary symbol is given by

$$r(t_{s,i})=s(t_{s,i})+w(t_{s,i}), \qquad (8)$$

where $w(t)$ denotes the noise signal. The components of the noise signal that must be taken into account are thermal noise (Johnson's noise) from the sensor and the reference cantilever resistances, which during the read process achieve a temperature of about Θ_1 = 350ºC, and from the low-pass filter resistance, as well as noise from equivalent noise sources in the operational amplifier.

To determine system performance, we evaluate the signal-to-noise ratio at the detection point, expressed as

$$\text{SNR}=10\log_{10}\left(\frac{\widetilde{V}^2_{\text{Th}}}{\sigma^2_w}\right), \qquad (10)$$

where the variance of the noise is approximated as

$$\sigma^2_w=\int_{-\infty}^{+\infty}\frac{[4k\Theta_1R^e(\Theta_1)+W_{\text{OA}}(f)](R_{\text{lpf}}/R^e(\Theta_1))^2+2k\Theta_0R_{\text{lpf}}}{\left|1+j2\pi f\tau_{\text{lpf}}\right|}df, \qquad (11)$$

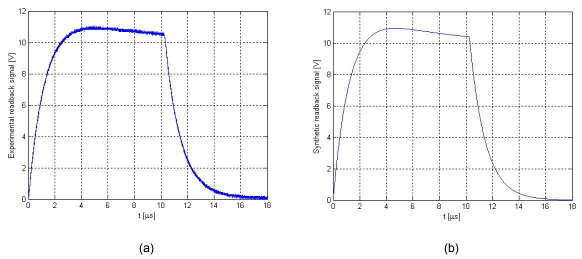

Figure 5. (a) Experimental and (b) synthetic readback signals for $\tau=10.25\,\mu$s.

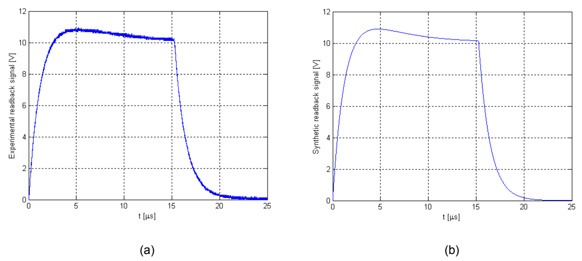

Figure 6. (a) Experimental and (b) synthetic readback signals for $\tau=15.25\,\mu$s.

where $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant and $W_{OA}(f)$ denotes the equivalent input voltage noise power spectral density of the operational amplifier. For typical values of the system parameters, an SNR in the range 14 to 20 dB is obtained.

Assuming that the indentations have a regular shape, which may be derived by the visco-elastic model of bit writing described in [9], or approximated by simple functions of the raised-cosine type, a synthetic model for the simulation of the readback signal to evaluate detection and servo/timing recovery algorithms is obtained by applying oversampling pulses to the cantilever at the rate K/T, provided the condition $T/K >> \tau$ is satisfied. A comparison between the read-back signal obtained along a data track and that obtained by the synthetic model is shown in Fig. 7.

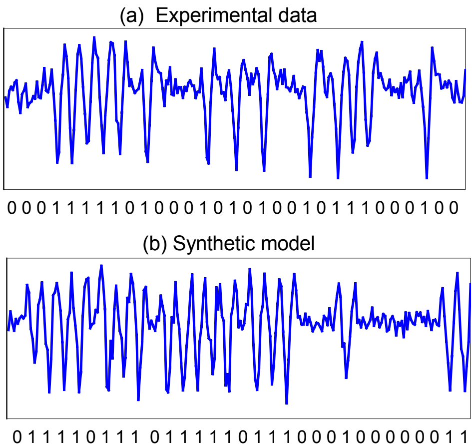

Figure 7. Comparison between (a) the readback signal obtained experimentally along a data track and (b) the readback signal obtained by the synthetic model.

4. Conclusion

The Millipede has the potential to achieve ultra high storage areal densities, on the order of 1 Tbit/in.^{2}. The high areal storage density, small form factor, and low power consumption make Millipede very attractive as a candidate future storage technology for mobile applications, offering several gigabytes capacity at data rates of several megabytes per second. The read-channel model introduced in this paper provides the methodology for analyzing the system performance and assessing various aspects of the detection and servo/timing algorithms that are key to achieving the system reliability required by the applications envisaged.

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