Ultrahigh-density atomic force microscopy data storage with erase capability

G. Binnig, M. Despont, U. Drechsler, W. Häberle, M. Lutwyche, and P. Vettiger[a)]
IBM Research Division, Zurich Research Laboratory, CH-8803 Rüschlikon, Switzerland

H. J. Mamin
IBM Research Division, Almaden Research Center, 650 Harry Road, San Jose, California 95120

B. W. Chui and T. W. Kenny
Stanford University, Stanford, California 94305

(Received 14 December 1998; accepted for publication 4 January 1999)

We report a simple atomic force microscopy-based concept for a hard disk-like data storage technology. Thermomechanical writing by heating a Si cantilever in contact with a spinning polycarbonate disk has already been reported. Here the medium has been replaced with a thin polymer layer on a Si substrate, resulting in significant improvements in storage density. With this new medium, we achieve bit sizes of 10–50 nm, leading to data densities of 500 Gbit/in.^{2}. We also demonstrate a novel high-speed and high-resolution thermal readback method, which uses the same Si cantilevers that are used in the writing process, and the capability to erase and rewrite data features repeatedly. © *1999 American Institute of Physics.* [S0003-6951(99)00109-6]

In the beginning of research with local probes (LP), i.e., in the early years of scanning tunneling microscopy (STM), accidental local modification of surfaces was widely reported. In this respect, atomic-scale modification of surfaces was thus demonstrated long before atomic-scale imaging. The potential for storage applications was obvious, particularly because of the capability for very small bit sizes. A real practical device, however, was not yet in sight. There were no early concepts to overcome the problems of extremely low data rates, tip instability, involuntary damage of tip and sample caused by vibration, and bit erasure. Hope came with the introduction of the scanning near-field optical (SNOM)[1,2] and the atomic force microscopes (AFM),[3,4] although first impressive results were achieved with a different LP technique, called scanning capacitance microscopy.[5] Owing to the low stiffness of AFM cantilevers, the tip can be allowed to contact the surface without damage, which greatly simplifies the technique and makes it rather insensitive to vibrations. After optical deflection and piezoresistive sensing were introduced,[6,7] imaging speed became much higher with AFM than with STM. SNOM has the potential for even higher data rates as it is not limited by the mechanical response time of cantilevers, but it is not typically operated in contact mode. Parallel operation can be implemented more easily for AFM as demonstrated by research on lithographic and storage applications.[8–11] Massively parallel operation can, in principle, achieve virtually unlimited data rates. This, however, requires simple functionality and reliable operation of the individual LP devices.

One such data storage proposal of elegant simplicity is AFM thermomechanical data storage.[4,12] The resistive cantilever tip is heated by current pulses and forms indentations in a polycarbonate disk surface. In recent years, AFM thermomechanical recording has undergone extensive modifications mainly with respect to integration of sensors and heaters designed to enhance simplicity and increase data rate and storage density.[13–15] Using these heater cantilevers, thermomechanical recording at 30 Gbit/in.^{2}, and data rates of 1–10 Mbit/s for reading and 100 kbit/s for writing have been demonstrated.[13–15]

This letter describes a new hard disk-like approach with high storage density that is based on AFM thermomechanical data storage. The cantilever is equipped with an integrated tip heater. The demonstrated storage density, however, is of the order of 500 Gbit/in.^{2}. The increased density results from using a thin polymer layer on a silicon substrate as the recording medium. Erasing is also possible and is implemented blockwise rather than bit by bit. The data blocks are arranged in rectangular two-dimensional (2D) fields, and their creation requires writing by scanning the lever in the $x-y$ plane instead of writing radially with a rotating disk. An important further simplification is achieved by using the heater cantilever also as the readback sensor cantilever.

Thermomechanical writing is a combination of applying a local force to the polymer layer and softening it by local heating. Several issues are involved in this operation, including the spatial and temporal localization of the heat deposition, the melting and displacement of media to form data bits, and the wear of the tip. In previous work, the heating and cooling rates of Si cantilevers with heated tips have been studied.[14] The heat transfer from the tip to the polymer through the small contact area is very poor and is enhanced by increasing the contact area. This means the tip must be heated to a relatively high temperature (≃400 °C) to initiate the melting process. Once melting has commenced, the tip is pressed into the polymer, which increases the heat transfer to the polymer, increases the volume of melted polymer, and hence increases the bit size. Even if tip heating is stopped as soon as the melting process begins, the heat capacity of the tip and the poor thermal conduction through the polymer

[a)]Electronic mail: pv@zurich.ibm.com

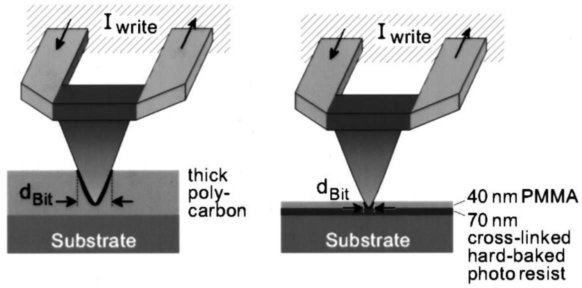

FIG. 1. (a) Previous storage medium consisting of a bulk polycarbonate layer. (b) For smaller bit sizes, a new storage medium consisting of a thin writable PMMA layer on top of a Si substrate with a crosslinked film of photoresist in between is used.

lead to the formation of large bits. Moreover, the poor thermal conduction of the polymer causes the heated region to remain hot even after the tip has cooled, enabling further displacement of media and an increase of bit size.

This can be improved if the thermal conductivity of the substrate can be increased, and if the depth of tip penetration can be limited. We have explored the use of very thin polymer layers deposited on Si substrates to improve these characteristics,[16] as illustrated in Fig. 1. The harder Si substrate prevents the tip from penetrating farther than the film thickness allows, and it enables more rapid transport of heat away from the heated region, as Si is a much better heat conductor than the polymer. We have spun a 40 nm film of polymethylmethacrylate (PMMA) onto Si substrates and achieved bit sizes ranging between 10 and 50 nm. We noticed, however, increased tip wear, probably caused by the contact between tip and Si substrate during writing. Therefore we introduced a 70 nm layer of crosslinked photoresist between the Si substrate and the PMMA film to act as a softer penetration stop to avoid tip wear. PMMA was chosen because it has a sufficiently low glass transition temperature (150 °C) for thermal writing and can be spun on as thin, flat, uniform films. Si was chosen as the substrate for its low cost, availability, thermal stability, and high thermal conductivity. The photoresist was used because of its low surface roughness, its softness, and its thermal stability.

Using this layered storage medium, data pits 40 nm in diameter have been successfully written as shown in Fig. 2. The writing was performed using a 1-μm-thick, 70-μm-long, two-legged Si cantilever. The resistive heater region at the tip is formed by heavy-ion implantation of the cantilever legs with the lightly doped tip region masked off. Electrical pulses 2 μs in duration were applied to the cantilever with a period of 50 μs. This is relatively slow compared to previous work. The main difference is that a scanner instead of a rotating disk was used as driving mechanism. The scanner was part of an AFM and not yet optimized for high-speed storage applications. In future work, we will reduce the coupling between scanning and the z motion of the lever, and perform measurements at highest writing speed possible with this medium. The tip velocity in these measurements was 2400 μm/s. Uniform arrays of data marks can be written, Fig. 2(a). Figure 2(b) shows that marks can be written very close to each other without merging, implying a potential bit areal density of 400 Gbit/in.^{2}.

Imaging and reading are done using a new method.[17]

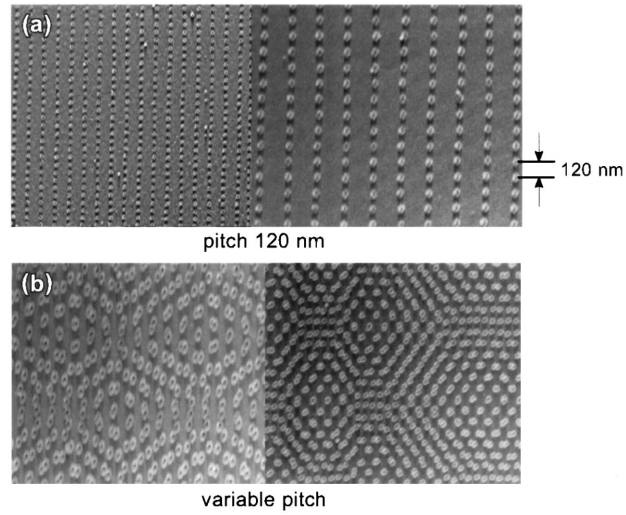

FIG. 2. (a) Series of 40 nm data pits formed in a uniform array, demonstrating reliable thermal writing. (b) Different arrangement of data pits, with some pits written virtually next to each other with no merging. This results in bit areal densities of ≃400 Gbit/in.^{2}. All images obtained by the thermal readback technique.

The heater cantilever used originally only for writing was given the additional function of a thermal readback sensor by exploiting its temperature-dependent resistance. The resistance increases roughly linearly with temperature by a factor of 3 from room temperature to 500 °C. Above 500 °C the resistance drops as the number of intrinsic carriers increases due to thermal excitation. For sensing, the resistor is operated at ≃350 °C. The principle of thermal sensing is based on the fact that the thermal conductance between the resistor and the storage substrate changes according to the spacing between the two. The medium between lever and storage substrate—in our case air—transports heat from one side to the other. When the spacing between heater and sample is reduced as the tip moves into a pit, the heat transport through air will be more efficient, and the heater's temperature and hence its resistance will decrease. Thus, changes in temperature of the continuously heated resistor are monitored while the cantilever is scanned over data pits, providing a means of detecting the pits. Figure 3 illustrates this concept.

This effect is most efficient for a heater–sample spacing of about 1 μm. For much wider spacings, the heat sink through air can be ignored compared to that through the legs of the lever. For a much narrower spacing, the mean free path of the molecules in the air becomes comparable to the gap width, and the heat conductance becomes independent of spacing.

The sensitivity of the heat sensor is difficult to compare with that of piezoresistive strain sensors. The former, for example, is completely independent of the spring constant of

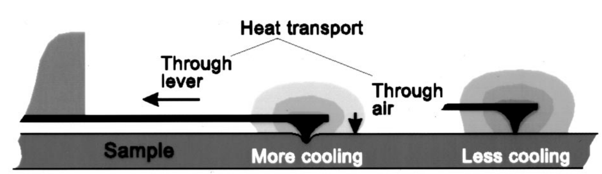

FIG. 3. Principle of AFM thermal sensing. The tip of the heater cantilever is continuously heated by a direct current power supply.

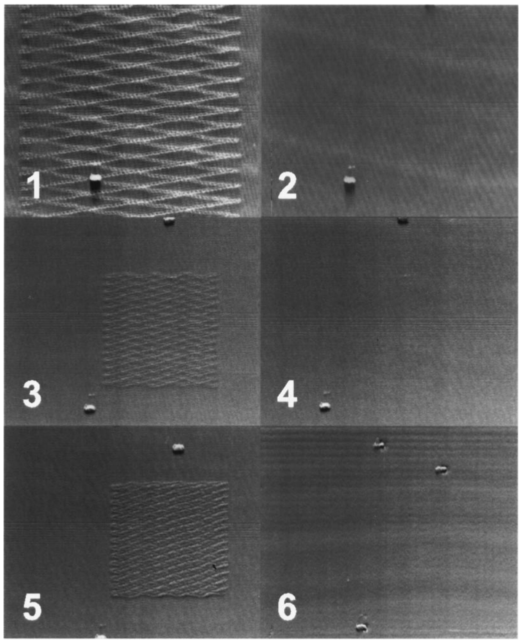

FIG. 4. AFM image of thin PMMA layer demonstrating three erasing/rewriting cycles.

the lever, unlike the piezoresistive method, and also depends on the kind of substrate to be investigated. Thermally unstable substrates are less suitable as they require a lower heater temperature. In our measurements on PMMA, $\Delta R/R$ values of 10^{-6}–10^{-5}/nm have been found, resulting in an excellent signal-to-noise ratio when the tip is scanned over a 40-nm-deep data pit. This is demonstrated by the images in Fig. 2 obtained by this thermal readback technique. The bandwidth of the thermal sensor depends on the geometrical design of the lever. In a simple model, the time constant for cooling the resistor is given by its heat capacitance and the thermal conductivity between resistor and the heat sink of lever and substrate. Scaling the length and thickness of the lever while leaving the width of the lever and heater area constant scales the thermal time constant but leaves the tunnel conductance and spring constant of the lever the same. Extremely short levers with thicknesses on the nanometer scale are desirable to achieve response times shorter than 1 μs. We measured response times of about 10 μs for our levers.

Erasing is done simply by thermal reflow of a rectangular storage field as a whole. Whereas for bit sizes of $\simeq$1 μm or more, erasing is difficult or not possible at all, bits of 100 nm or smaller can be erased very easily by heating the media of one storage field to $\simeq$150 °C for a few seconds. We observed no alteration of the PMMA film after repeated writing and erasing as shown in Fig. 4. With this approach, storage fields of a few hundred microns can be erased en bloc.

We have demonstrated several features of an improved thermomechanical AFM data storage technology. Media consisting of thin polymer layers on a Si substrate enable formation of very small data features because of the limited tip penetration and improved thermal transport. A new method for readback based on sensing of thermal transport has been presented, and repeated erasing and rewriting of data have been demonstrated. All of these elements are consistent with the use of 2D arrays of heater cantilevers scanned over fields of a stationary substrate, which could become the basis of an advanced microelectromechanical system-based data storage technology.

The authors are pleased to acknowledge J. Brugger, U. Dürig, P. Guéret, H. Rothuizen, H. Rohrer, D. Rugar, P. F. Seidler, and B. Terris for their technical contributions, stimulating discussions, and encouraging support. Financial support by DARPA (Contract No. DABT63-95-C-0019), IBM Fellowship, and NSF Career Programs is highly appreciated.

[1] D. W. Pohl, W. Denk, and M. Lanz, Appl. Phys. Lett. **44**, 651 (1984).
[2] E. Betzig, J. K. Trautman, T. D. Harris, J. S. Weiner, and R. L. Kostelak, Science **251**, 1486 (1991).
[3] G. Binnig, Ch. Gerber, and C. F. Quate, Phys. Rev. Lett. **59**, 1942 (1987).
[4] H. J. Mamin, B. D. Terris, L. S. Fan, S. Hoen, R. C. Barrett, and D. Rugar, IBM J. Res. Dev. **39**, 681 (1995).
[5] R. C. Barrett and C. F. Quate, J. Appl. Phys. **70**, 2725 (1991).
[6] G. Mayer and N. M. Amer, Appl. Phys. Lett. **53**, 1044 (1988).
[7] M. Tortonse, H. Yamada, R. C. Barrett, and C. F. Quate, in *The Proceedings of Transducers '91* (IEEE, Pennington, NJ, 1991), p. 448.
[8] S. C. Minne, G. Yaralioglu, S. R. Manalis, J. D. Adams, A. Atalar, and C. F. Quate, Appl. Phys. Lett. **72**, 2340 (1998); K. Wilder, B. Singh, D. F. Kyser, and C. F. Quate, J. Vac. Sci. Technol. B (in press).
[9] IBM, U.S. Patent No. 5,843,477 (10 November 1998).
[10] M. Lutwyche, C. Andreoli, G. Binnig, J. Brugger, U. Drechsler, W. Häberle, H. Rohrer, H. Rothuizen, P. Vettiger, G. Yaralioglu, and C. Quate, Sens. Actuators A (in press).
[11] M. Despont, J. Brugger, U. Drechsler, U. Dürig, W. Häberle, M. Lutwyche, H. Rothuizen, R. Stutz, R. Widmer, H. Rohrer, G. Binnig, and P. Vettiger, *IEEE International Micro Electro Mechanical Systems Technical Digest 1999–Orlando, FL, 17–21 January 1999* (IEEE, Piscataway, NJ, 1999), p. 564; P. Vettiger, J. Brugger, M. Despont, U. Drechsler, U. Dürig, W. Häberle, M. Lutwyche, H. Rothuizen, R. Stutz, R. Widmer, and G. Binnig, J. Microelectron Eng. (unpublished).
[12] H. J. Mamin and D. Rugar, Appl. Phys. Lett. **61**, 1003 (1992).
[13] B. W. Chui, H. J. Mamin, B. D. Terris, T. D. Stowe, D. Rugar, and T. W. Kenny, Appl. Phys. Lett. **69**, 2767 (1996).
[14] B. W. Chui, T. D. Stowe, Y. S. Ju, K. E. Goodson, T. W. Kenny, H. J. Mamin, B. D. Terris, R. P. Ried, and D. Rugar, J. Microelectromech. Syst. **7**, 69 (1998).
[15] R. P. Ried, H. J. Mamin, B. D. Terris, L. S. Fan, and D. Rugar, J. Microelectromech. Syst. **6**, 294 (1997).
[16] IBM PCT application with int'l application No. PCT/IB97/00894, ''Method of forming ultrasmall structures and apparatus therefor'' (filed July 17, 1997).
[17] IBM PCT application with int'l application No. PCT/IB97/00895, ''Investigation and/or manipulation device'' (filed 17 July 1997).