Digital data readback for a probe storage device

Rostislav V. Lapshin[a)]
Institute of Physical Problems, Moscow, Zelenograd 103460, Russia

(Received 10 May 1999; accepted for publication 11 September 2000)

An experimentally proved method is described for data readback from an information track using separate atoms on a crystal surface as memory elements. The key idea consists of local scanning and recognition of memory elements on the carrier surface followed by attaching the device probe to them so as to keep the probe position over the track. [S0034-6748(00)02512-0]

I. INTRODUCTION

In recent years, probe storage devices[1] (PSDs) have been developed as a new and promising trend in science and engineering. Forefathers of PSDs are the scanning tunneling microscope (STM) and atomic force microscope. Possessing potentially high characteristics mostly because of their huge capacity for record density, PSDs are supposed to compete with such popular data storage as hard disk drives[2] and compact and digital video disk players.[3]

With large capacity storage, a problem encountered is that of stabilization of the read/write probe (head) over the information track.[1–4] Due to the high record density, the typical distance between adjacent bits and their own dimensions decreases substantially, the device being affect by a variety of destabilizing factors (internal and external vibrations, drifts, noises, medium defects) which dislocate the probe position thus provoking read/write errors.

The standard methods to suppress instability are toughening the tolerance for mechanical parts of the instrument and/or the embedding of feedback servo systems.[2–4] Both ways are limited by technical difficulties: the first one implies strict demands of machining and adjustment as well as of some additional elements that must be introduced into construction in order to compensate for errors and wear of the device during exploitation. In the second case, at least three highly sensitive position transducers are included in the system (two of them provide positioning in the lateral plane and one in the vertical plane) as well as three manipulators and control electronics.

The difficulties are aggravated when the storage has several operating surfaces and consequently several heads. The use of the scanning probe microscope as a high-capacity PSD seems doubtful because of its comparatively low performance. Therefore, a trend persists today towards speeding up data exchange by the creation of an integrated read/write head, which consists of either a row[5] or an array[6,7] of some tens to hundreds of probes. However, using great number of high-precision sensors and feedback loops in the microstructures suggested is rather problematic at present.

The primary aim of this work consists of demonstrating the principal possibility of probe stabilization over an atomic-sized bit track. A peculiarity of the method is that the data reading can be carried out by means of just a single sensor and a single vertical plane servo system.

II. DESCRIPTION OF THE METHOD

In general, to realize the readback method[8] suggested, the device should include a read/write probe and a positioner able to scan the carrier surface; the digital data should be arranged at the carrier so as to compose a certain system of information tracks. Thus, the PSD can be based on one of several types of scanning probe microscope depending on the medium properties and the resolution required.

The relief elements, hereafter referred to as ''memory elements,'' are interpreted as bits of digital information stored in the PSD. Relief features of both ''hill'' and ''pit'' type can serve as the memory elements. The primary concept of the readback method consists of local scanning and recognition of memory elements on the carrier surface followed by attaching the probe to them in order to keep the probe over the information track. In practice, this produces software realization of a digital lateral plane feedback loop. Since the method suggested implies recognition of the image scanned, the term relief elements should be understood in the broad sense. It can refer to physical inhomogeneities such as magnetization domains, places of localized electric charge, and so forth.

Although the recognition process used below is indifferent to the form of elements as well as to their orientation and sizes, those characteristics, in general, can participate in information coding, with the recognition algorithm being supplemented by the appropriate procedures of form, orientation, and size analysis. Note that by means of coding information by variation in form, orientation, and size of memory elements, it is possible to attain an additional increase in storage density.

In order to provide a high signal versus noise ratio, the memory elements must be of sufficient height (deep) to be distinguishable from the background with minimum errors.

Let us consider an information track (see Fig. 1) of the simplest structure in which memory elements storing the useful information bits i_n are separated by synchronization elements s_n to provide probe attachment. To be unambiguous, let us assume a round form of memory elements, al-

[a)]Electronic mail: lapshin@niifp.zgrad.ru

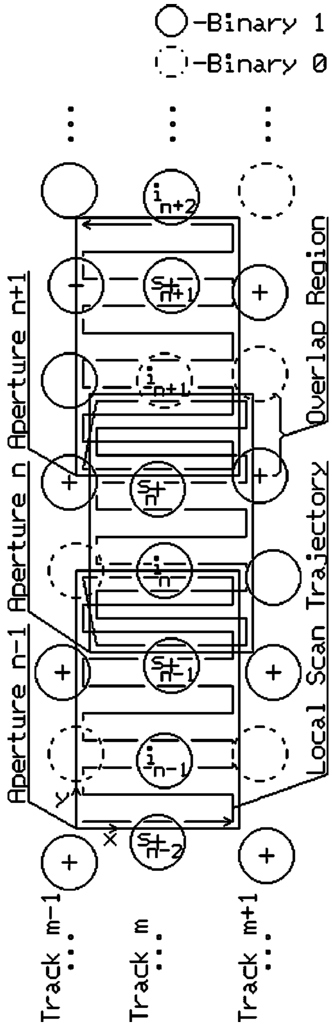

FIG. 1. PSD bit track. Information elements i_n are separated by synchronization elements s_n. The ''+'' sign marks the positions of synchroelements relative to which the rectangular aperture local positioning is carried out.

though it is not a matter of principle. The orientation of the elements is insignificant in that case; the sizes of both the information and synchronization elements are chosen to meet limitations of the microscope resolution as well as the limitations of information carrier technology.

Thus, the readback method suggested includes the following operations.

(1) Raster scan of a rectangular area (hereafter called the aperture) in the vicinity of the current synchroelement s_n.
(2) Recognition of elements within the aperture.[9]
(3) Discrimination of the elements, depending on their position in the aperture, into the information element i_{n+1} and synchronization element s_{n+1}. The element nearest to the top edge of the aperture is accepted for the next synchroelement. If nothing but the synchroelement is found, then a binary 0 is stored in that place else, a binary 1 (or vice versa).
(4) Fixing the state of the information element read. Then the above process is repeated.

The dimensions of the rectangular aperture must be chosen in such a way as to cover the next pair of elements even at the largest possible probe deviations from the track (deviations are counted from the current synchroelement position) both in the x and y directions while reading. Note that the above condition also defines the maximum number of infoelements after which comes each next synchroelement.

The use of synchroelements can be assumed effective neither with respect to achieving the ultimate readback rate nor with respect to employment of the available carrier square since both parameters decrease by half. Therefore, it is preferable to set synchroelements as rarely as possible. With stable devices, they can be completely eliminated by means of applying run-length-limited binary sequences[10] which ensure a feature (binary 1) to appear at a certain length interval (sequence of binary 0's).

Now the only memory elements interpreted as information binary 1's can serve as reference marks on the track. A number of 0's in sequence is defined by the distance between adjacent 1's. The aperture size along the manipulator's y axis is a variable value. It grows by some fixed magnitude each time until a binary 1 is revealed after recognition. Once the next portion of data has been read, the aperture returns to its initial size which corresponds to the mean distance between neighboring 1's for the code used.

The above makes up the essence of the so-called modified reading mode, which can be summarized as follows.

(1) Scan of the aperture (or increment of aperture) of the current memory element.
(2) Recognition of elements within the aperture (or within an increment of the aperture).
(3) Reveal the next memory element by its position in the aperture. This element is the farthest from the top edge of the aperture. If no next memory element is found, the aperture is incremented by a certain Δ_y and items (1) and (2) of the method are repeated. Otherwise, if next element is found, then the number of binary 0's is determined by the distance measured from the former to the bottom edge of the aperture (that distance is divisible by the distance accepted in the encoding system for a binary 0).
(4) The scope of the binary code read by a PSD is stored and the process described above is repeated.

So far only the problem of reading information has been discussed. The technique proposed can also be used for writing. The method described can be extended entirely to writing in case a preliminarily marked surface is being written, i.e., a surface where relief elements have been formed that are interpreted as synchrobits.

In case the surface is not preliminarily marked, for writing it is sufficient to create a so-called ''seed'' track on the base. In the course of writing, the probe is positioned by movement by elements of the previously written track in the way shown above; the writing itself is carried out on the current track relative to elements of the previous track.

One of the peculiarities of the readback method is the possibility of stopping, at any moment, probe movement

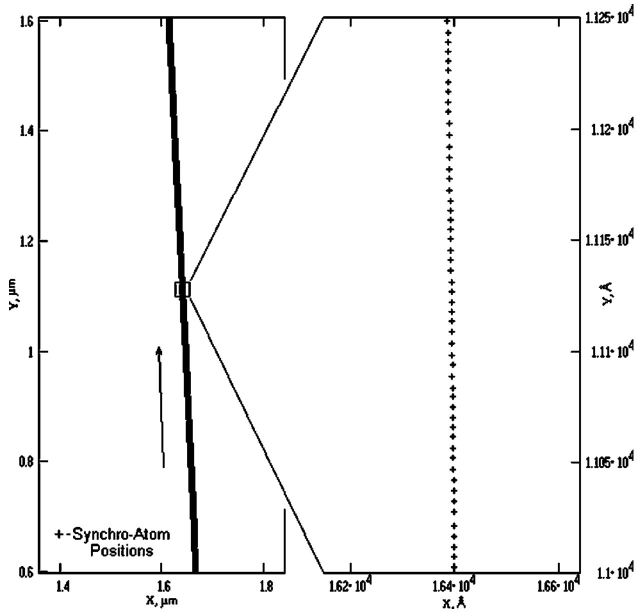

FIG. 2. Displacement of the STM probe along a crystallographic direction by a chain of 2048 carbon atoms serving as the bit track synchroelements. The atoms located between synchroatoms are informational (not shown), in this case they are all binary 1's. The path length distance is ≊1 μm. The readback rate is 33 infoatoms/s. The number of probe attachment failures is 0. The arrow points to the direction of probe movement.

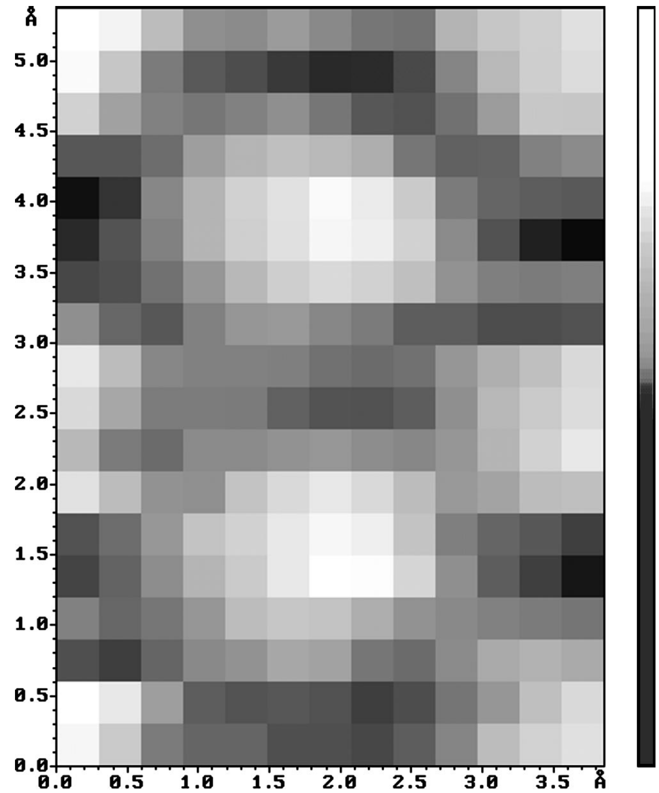

FIG. 3. A 13×18 aperture. The image is smoothed. The carbon atom at the top of the aperture acts as a synchroelement and the atom at the bottom acts as an infoelement. Constant Z mode, $U_{tun}=50$ mV, $I_{tun}=993$ pA. The number of samples per point is 1. The scan velocity is 294 nm/s.

along the bit track by attaching to the current memory element and to keep in that state for an arbitrarily long time.

III. EXPERIMENTAL RESULTS

The tracking method given was successfully realized and tested on ultimate STM-resolvable surface structure elements, i.e., atoms. In particular, movement was executed by carbon atoms on the surface of highly oriented pyrolytic graphite (0001) along a crystallographic direction at a distance not much longer than 1 μm (see Fig. 2). The movement simulated readback from the information track. The read rate made 33 infoatoms per second.

The experiments were executed on microscope Solver P4 (NT-MDT Co.) operating in air. A mechanically cut NiCr wire was used as the tip. The microscope resolution was 0.296 Å along the x axis and 0.298 Å along the y axis. A typical view of a (13×18) pixels^2 aperture is shown in Fig. 3. As the controller, a 100 MHz $i486DX4$ IBM-compatible computer was used, yielding a mean recognition rate of 455 apertures per second (the number of iterations while searching for horizontal cutting plane[9] equaled to 2–3).

Before tracking had begun the specimen was oriented so that one of the crystallographic directions on the surface lay parallel to the Y manipulator (residual misalignment made some 3°). The value of the neighboring aperture overlap was two pixels. The mean drift velocity in the lateral plane at the measurements was about 0.3 Å/s. The instability of the aperture position across and along the track was ±0.2 and ±0.3 Å, respectively, per local scan. The root mean square noise value in the vertical plane was ±16 pA.

On the whole, the results obtained prove the possibility of stability following an information track of minimum width and quite reliable reading data from carriers, with separate atoms serving as the memory elements.

IV. DISCUSSION

The readback method, being a digital one by nature, permits one to increase the probability of correct read/write (noise immunity) by using additional digital image processing (repeated reading with averaging, various types of smoothing, procedures for increasing the contrast, and for detecting the edge of a feature, etc.), as well as to improve the quality of control by introducing digital correcting filters.

With atoms used as memory elements, the method developed can be most effectively realized on crystal surfaces where there exists an intrinsic highly ordered system of information tracks. Small atom clusters, various kinds of molecule chains, sequences of pores, and similar elements that are self-assembled in ordered surface structures can also be read out by the method proposed.

The main drawback of the method described is its low read/write rate, which is accounted for by the necessity of making local scans and recognitions. In order to increase the read/write rate, first a specialized microscope capable of scanning at least 45 times faster should be built.[11] This microscope must possess good temporal stability at atom imaging, which is achievable in vacuum only. Note that as the speed increases, the microscope gets less sensitive to thermodrift and vibrations which are the main disturbing factors, thereafter the aperture sizes could be reduced.

Second, a specialized controller based on a 500 MHz processor must be developed. As a controller is used, the aperture scanning along with correction of its position on the track might be carried out with no processor involved, so an infoatom is being recognized at the same time as a synchroatom is being scanned. As a result, a delay connected with aperture recognition decreases by half which is equivalent to a two times increase in the recognition rate. By means of extrapolation, the cutting plane position and the mean local trend of the surface for the current aperture can also be determined while the aperture is being scanned.

Since the task of recognition within an aperture is easily multithreaded, it is desirable that the controller be multiengined. In the case of a multiprobe PSD, the computations might be organized in time-sharing mode when the same processor supports several probes. Estimates show that, after having made the above improvements, atomic PSD's readback rate can be brought to 1 kbit/s which is quite acceptable for the given class of devices.

The method can find use at the initial stage of PSD development for natural modeling and identification of the readback/write process, for investigation of writing mechanisms, for finding out dispersion of sizes and positions of memory elements on the track, for analysis of track defects, for determination of lateral orientation, local trends, and mutual track placement, and so forth.

The essential advantage of the method is its simplicity, since no precision lateral position sensors with their electronics are required for its realization, nor are a complicated cantilever, schemes for signal decoupling, nor a scheme for reading information signal from memory element. The absence of additional mechanical and electrical components improves device characteristics such as its reliability.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation of Fundamental Research (Project Nos. 96-02-17870 and 99-02-17259) and by the Fund for Physics of Solid Nanostructures (Project No. 96-2012). The author is grateful to O. E. Lyapin, V. N. Ryabokon, and V. V. Efremov for discussions and for checking the manuscript, to A. V. Emelyanov and A. P. Alehin for organization and encouragement of the work, and to S. A. Saunin for consultations and the microscope control program source he provided.

[1] H. J. Mamin, B. D. Terris, L. S. Fan, S. Hoen, R. C. Barrett, and D. Rugar, IBM J. Res. Dev. **39**, 681 (1995); S. Hosaka, IEEE Trans. Magn. **32**, 1873 (1996).
[2] E. Grochowski and R. F. Hoyt, IEEE Trans. Magn. **32**, 1850 (1996).
[3] G. Bouwhuis, J. Braat, A. Huijser, J. Pasman, G. van Rosmalen, and K. Schouhamer Immink, *Principles of Optical Disc Systems* (Hilger, Bristol, 1985).
[4] B. W. Chui, H. J. Mamin, B. D. Terris, D. Rugar, and T. W. Kenny, IEEE Proceedings of the Eleventh Annual International Workshop on Micro Electro Mechanical Systems, 1998, p. 12.
[5] S. C. Minne, Ph. Flueckiger, H. T. Soh, and C. F. Quate, J. Vac. Sci. Technol. B **13**, 1380 (1995).
[6] S. A. Miller, K. L. Turner, and N. C. MacDonald, Rev. Sci. Instrum. **68**, 4155 (1997).
[7] M. Lutwyche, C. Andreoli, G. Binnig, J. Brugger, U. Drechsler, W. Haeberle, H. Rohrer, H. Rothuizen, and P. Vettiger, in Ref. 4, p. 8.
[8] R. V. Lapshin, Russian Patent No. 98,119,766 (filed 1998).
[9] R. V. Lapshin, Rev. Sci. Instrum. **69**, 3268 (1998).
[10] G. F. M. Beenker and K. A. Schouhamer Immink, IEEE Trans. Inf. Theory **29**, 751 (1983); D. T. Tang and L. R. Bahl, Inf. Control. **17**, 436 (1970).
[11] R. V. Lapshin and O. V. Obyedkov, Rev. Sci. Instrum. **64**, 2883 (1993).