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CHAPTER 2

Information storage using a scanning probe

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1. Introduction

Surface modification with a scanning probe microscope (SPM) is very attractive, because the dimension of the modification is ranging from sub-micron to sub-nanometer, which is much smaller than the limit of conventional photolithography [1]. Even an atomic manipulation has been achieved [2,3]. A surface modification according to a given pattern and its observation with a scanning probe can also be seen as a writing and reading procedure in an information storage device. Then the pattern produced by the surface modification is regarded as a set of data bits. The recording density estimated from the typical size of each modification becomes much higher than that of any present storage device. If the size is 10 nm, for example, the recording density can be roughly estimated to be 1 $\mathrm{Tbit/cm^2}$ (= 10^{12} $\mathrm{bit/cm^2}$). Therefore the SPM-technology is thought to make it possible to establish a high-density and huge-capacity information storage system. There have been many reports concerning information storage using an SPM [4–12].

However, the recording density is only one of the performances characterizing an information storage device. Another important performance is the transfer rate, especially the reading rate. At least it is necessary to read and write a set of data bits at a rate comparable to that of the present storage devices in order to realize a practical system.

2. Restriction in transfer rate

In the SPM, the surface image is based on some interaction between a probe and the surface of a sample when they are placed in close proximity. The surface topography is observed as the trajectory of the probe motion when the spacing between the probe and the surface is precisely controlled so as to maintain the interaction between them to be constant during scanning of the probe. The operation speed in the SPM is limited by the characteristic rate of the feedback loop, and it is generally low. The highest operation speed in the SPM is achieved in an atomic force microscope (AFM) operated in contact mode, where the tip of a probe is in contact with the surface of a sample. Then, the operation speed is limited to the mechanical resonance frequency of the cantilever for supporting the probe, which is limited to several mega-Hertz in practice.

When the data bits are formed with topographical modification of the recording medium, the reading rate of information storage with a scanning probe is restricted by the operation speed in the SPM. One of the ways to overcome this restriction is the use of a cantilever with high mechanical resonance frequency. In this case, precise fabrication of a cantilever with a small size and a small weight is necessary. Another way is the use of a recording medium in which data bits can be written without topographical modification of this recording medium. In this procedure, a scanning probe must be used for simultaneously detecting two kinds of interactions, independent of each other. The spacing between the probe and the medium is controlled based on one interaction between them, and the data bits are written and read based on the other interaction. Then the former interaction does not influence the reading rate directly, since it is not affected by the presence of the data bits. The reading rate is determined by the rate for detection of the data bits and the rate for scanning of the probe on the medium. For high-speed scanning of the probe, reducing the surface roughness of the medium and controlling the spacing between the probe and the medium with an AFM based apparatus are effective.

3. Formation of an ideal metal–insulator–metal junction

To overcome the restriction of the rate for reading and writing, another recording procedure was introduced which is not based on direct surface modification of a recording medium with a scanning probe. In this procedure, a scanning probe is used as a tool in order to form an ideal metal–insulator–metal (MIM) junction. That is, one electrode in the MIM junction is replaced by the scanning probe. For this purpose, an AFM with an electrically conducting probe is used. In practice, the conducting probe is obtained by coating a conventional cantilever for AFM with a metal film. The probe can be in contact with the sample surface using a weak force controlled by AFM so as to keep it constant, and an ideal MIM junction may be formed.

In this scheme, the electronic properties of a film used as an insulating layer can be characterized with sufficient resolution as shown in Fig. 1. If the electronic properties of the film can be modified by application of a pulse voltage to the MIM junction formed with the probe, it can be considered as another procedure to form data bits. The area with modified electronic properties can be observed using the AFM based apparatus as

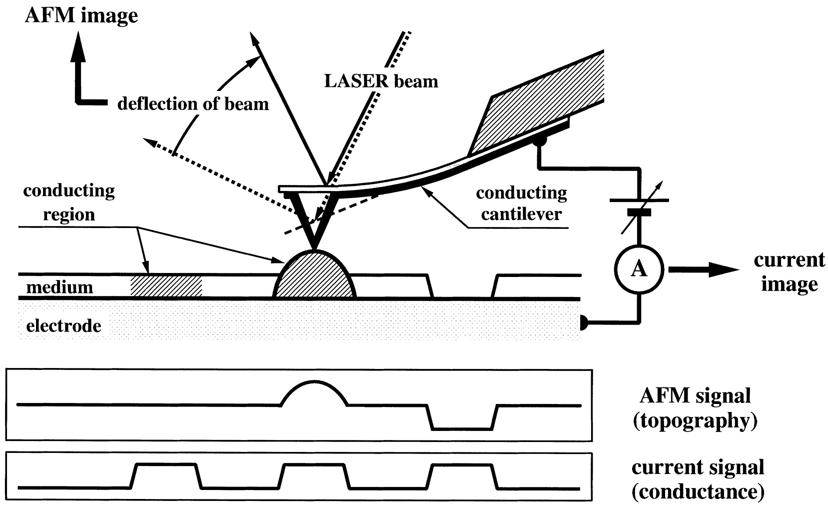

Fig. 1: Schematic drawing of an AFM based apparatus with an electrically conducting probe. Surface topography and electronic properties of a recording medium are simultaneously characterized using this apparatus.

shown in Fig. 1. If the size of the modified area is small enough, it can be regarded as a bit in high-density information storage. One expects to realize high-speed reading and writing if the modification is not associated with a change in surface morphology. One also expects to establish a system capable of rewriting if the modification is reversible.

One of the actual recording media to realize the above mentioned new recording procedure is a polyimide Langmuir–Blodgett (LB) film. Sakai et al. reported a switching and memory phenomenon in a MIM junction with LB film as insulating layer [13]. It shows a reversible transition between high and low conductance states by application of pulse voltages. Each state has a corresponding threshold, and the state is maintained for application of voltage below the threshold, even 0 V. That is, this MIM junction shows a non-volatile memory effect. This phenomenon shows a clear material dependence, and does not depend on junction area [14]. Conventional polyimide is one of the typical materials showing this phenomenon.

Formation of an MIM junction using a scanning probe and a polyimide LB film has been already achieved [15]. The polyimide LB film was deposited on Au(111) surface, and its thickness was 2.4 nm. Furthermore, formation of an ideal MIM junction using an AFM based apparatus has also been achieved [16,17]. The transition from low conductance state to high conductance state has been induced by application of pulse voltage to the polyimide LB film through the scanning probe. The area where the transition in conductance occurred has been observed as the conducting spot in the current image obtained using the conducting AFM probe. On the other hand, no change has been observed in the AFM image obtained simultaneously and independently. So, when a polyimide LB film is used as a recording medium in information storage with a scanning probe, a set of data bits composed of conducting spots can be formed without change in surface morphology. The reading rate depends on the rate in current detection

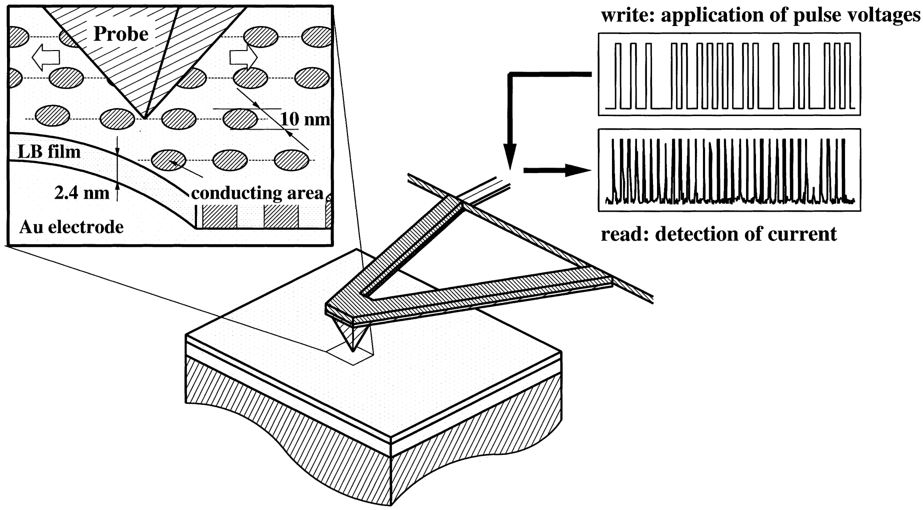

Fig. 2: Schematic drawing of an information storage system using an AFM based apparatus and a polyimide LB film. A local conducting area as a recording bit is not accompanied by a morphological change.

and the rate in probe scanning, as far as the probe traces the sample surface in contact. If the sample surface is very flat, the reading rate can be expected to be much higher than and not restricted by the mechanical resonance frequency of the cantilever. The size of the conducting spot is about 10 nm in diameter. The recording density can be estimated to be 1 Tbit/cm^2 from this spot size when the conducting spots are considered to be data bits.

Fig. 2 shows a schematic drawing of the information storage system using the AFM based apparatus and the polyimide LB film as the recording medium. The probe is scanned on the recording medium in contact. In the recording procedure, the array of pulse voltages according to a set of binary data is applied to the medium through the probe during scanning, and high-conductance regions are formed in the medium. After recording, current flow through the medium is detected with the probe during scanning and the obtained scan profile of current is converted to the set of binary data. In such a configuration, a pattern of encoded binary data consisting of more than a thousand conducting spots could be formed in a 2×2 μm^2 area. And then reading the information back could be accomplished by converting the line scan profiles of the current image to bit patterns [18].

4. Size of data bits

The size of the conducting spots was about 10–20 nm in diameter, independent of various kinds of probes. The probes are coated with metal thin films, typically Pt film. Fig. 3(a) shows a scanning electron microscope (SEM) image of a tip of a probe coated with Pt. The Pt film has grain structures, which are several 10 nm in diameter. The tip

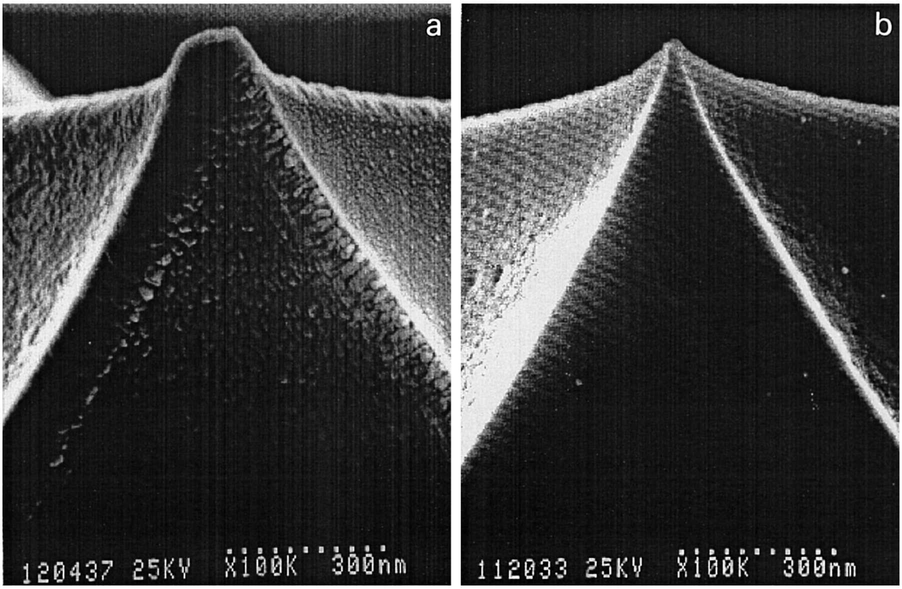

Fig. 3: Scanning electron microscope images of a tip of a probe coated with Pt (a) and a tip of a probe fabricated by the replicating method (b). Reproduced from Ref. [19] with permission (© 1997 IEEE).

of the probe is also composed of some Pt grains. The size of conducting spots may be determined by the size of the grains. This seems to be a reason why the size of a conducting spot does not depend on the probes. To form a smaller conducting spot, a curvature in the tip of the probe has to be formed less than that in a grain of the coated metal. Yagi et al. fabricated a probe with a quite sharp tip by replicating a Si mold with pyramidal etch pits [19]. Fig. 3(b) shows an SEM image of a tip of a probe fabricated by the replicating method. Its curvature is estimated to be around 15 nm in radius. Fig. 4 shows a current image (a) and an AFM image (b) observed simultaneously using the replica probe [19]. Conducting spots observed in the current image were induced using the same probe. The sizes of the conducting spots are 10 nm or less. In addition, a monoatomic step structure in the Au(111) surface can be seen in the AFM image, which shows an increase in resolution of the AFM due to the decrease in the curvature in the tip of the probe. This shows that conducting spots with small sizes of 10 nm or less can be formed stably using the replica probe, and also shows that no degradation of the tip occurs during forming the conducting spots by application of pulse voltages.

5. Rate of reading and writing

It has been reported that a conducting spot could be formed by application of a voltage pulse with 2 μs width, and the bit could be read within about 10 μs [18].

The main problem in high-speed writing is attributed to the stray capacitance around the MIM junction with the scanning probe. Actually, the writing with a 2 μs pulse was

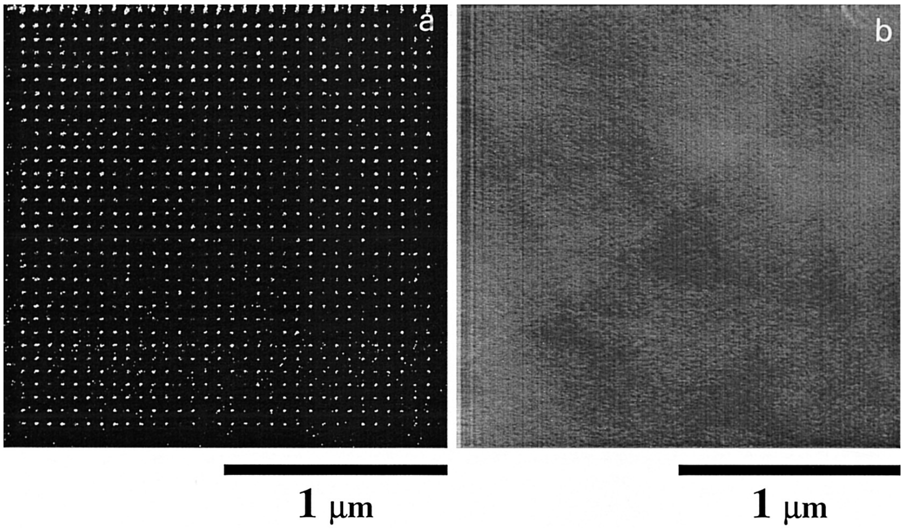

Fig. 4: Current image (a) and AFM image (b) observed simultaneously using the replica probe. Conducting spots in the current image were induced by applying 13 V, 0.2 μs, rectangular voltage pulses using the same probe. Reproduced from Ref. [19] with permission (© 1997 IEEE).

achieved by a reduction of the stray capacitance. Furthermore, the transient response of the current observed during the spot formation by applying a 2 μs voltage pulse indicated that further reduction of the stray capacitance would make it possible to form a conducting spot with a voltage pulse shorter than 1 μs. The increase of the current by the contribution of the transition to the high-conductance state was fast enough.

Actually, it is possible to form the conducting spot with a pulse voltage shorter than a 2 μs pulse. The conducting spots observed in Fig. 4(a) are formed by application of 0.2 μs voltage pulses [19]. The formation of conducting spots could be carried out by the application of pulse voltages of 25 ns in width under further optimization in stray capacitance, though such a result is not shown here. This indicates that a reading rate of about 40 Mbps may be achieved.

For reading at a fast rate, high-speed scanning of the probe and high-speed detection of the current are necessary. To detect a low current at high scanning rate, a current amplifier is designed which has a small input capacitance and little gain for low frequencies. Using the current amplifier, it was demonstrated that the edge of the conducting spot could be detected within about 10 μs during scanning at a rate of 8 μm/s. This indicated that achieving a reading rate of about 100 kbps could be expected if the probe could be scanned with sufficient speed, typically 2 mm/s for an array of 10 nm spots [18].

High-speed scanning at a rate of 2 mm/s has been actually performed without damage to the medium. In this procedure, the probe was scanned so that the trajectory of its tip drew a circle. Although the scanning rate of 2 mm/s is much higher compared with that in a conventional AFM observation, the surface roughness of the polyimide LB film deposited on Au(111) is so small that high-speed scanning of the probe on it

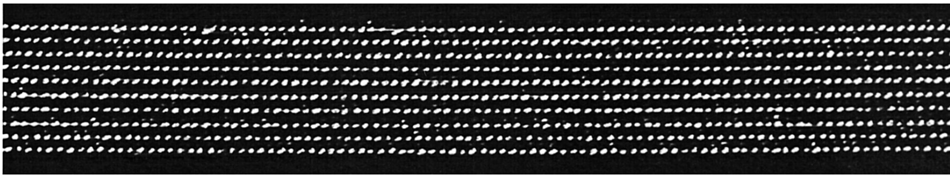

Fig. 5: Current image of a part of the recorded 1 Mbits. The area is about $3.5 \times 0.7\ \mu\text{m}^2$. (Reproduced from Ref. [20] with permission.)

seems to be possible. When both the detection rate of 10 μs per bit and the scanning rate of 2 mm/s are achieved simultaneously, a reading rate will be achieved of 100 kbps. It should be noticed that the severe requirements on mechanical resonance frequency of the cantilever are not necessary.

6. Error rate

Stable formation of about one thousand data bits without the degradation of the tip of the probe has already been achieved in an area of $2 \times 2\ \mu\text{m}^2$ as shown in Fig. 4(a). For practical use, stable writing of a larger number of data bits must be confirmed, and error rate estimation is required. Yano et al. demonstrated 1 Mbit recording in an area of $40 \times 80\ \mu\text{m}^2$ without tip degradation [20]. Fig. 5 shows a current image of a part of the recorded 1 Mbits. The area is about $3.5 \times 0.7\ \mu\text{m}^2$. An image similar to Fig. 5 can be acquired at any area where the voltage pulses were applied. In 1 Mbit recording, a transient response in current was monitored for each pulse application. A transition to the high-conductance state was confirmed when the current exceeded a predetermined value within a predetermined period of voltage application. That is, the case that the current exceeding this value was not observed within the period was regarded as a failure in the formation of the bit. Thus, the error rate was estimated to be 1.7×10^{-4} for 1 Mbit recording [20].

7. Conclusion

The concept of an information storage system was demonstrated based on the formation of ideal MIM junctions using an AFM with a conducting probe. In practice, polyimide LB film is used as an insulating layer in an MIM junction, and a local conducting region in the polyimide LB film induced by applying a pulse voltage through the probe is considered to a recording bit. The reduction of bit size, the possibilities of fast rate reading and writing, and further stable bit writing were also shown. In this system, the surface topography of the medium is maintained even after writing data bits, which makes possible to read and write data bits at fast rates without severe requirements for the mechanical resonance frequency of a cantilever. Then an extremely flat surface of the recording medium is required over a wide range. It is essential to fabricate a sufficiently flat and large medium. LB film seems to be a suitable recording medium, since the thickness of the film can be precisely controlled on a molecular scale. So, it is important to fabricate a flat and large substrate.

Today, the recording density in some present storage devices reaches several tens gigabit per square inch. And it is growing at a rate of 60% every year. If today's growing rate has to be kept, it is predicted that the recording density will be equal to the atomic density of the solid surface within twenty years. Molecular memory will also be realistic. Then, the storage devices will have to read and write the data bits with atomic resolution at a rate further exceeding that of present storages. The scanning probe method has enough potential concerning the resolution. However, the higher the recording density, the lower the reading rate becomes actually. The use of multiple probes and the parallel operation of them is an effective way to achieve a faster read and write rate[21–24]. However, essential breakthroughs on the problem of the reading rate also seems to be necessary.

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