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Actual information storage with a recording density of 4 Tbit/in.^{2} in a ferroelectric recording medium

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A new method to achieve real information recording with a density above 1 Tbit/in.^{2} in ferroelectric data storage systems is proposed. In this system, data bits were written in the form of the polarization direction, and the data were read by scanning nonlinear dielectric microscopy technique. The domain-switching characteristics of the virgin and inversely prepolarized media were compared, and the conditions of the pulse voltage for writing were optimized. As a result, actual data containing 64×64 bits were recorded at an areal density of 4 Tbit/in.^{2}. The bit error rate was evaluated to be 1.2×10^{-2}. © *2010 American Institute of Physics*. [doi:10.1063/1.3463470]

With current advances in information processing technology, the importance of high-density data storage devices continues to increase. As an alternative to magnet storage, recording system with polymer layer media using thermomechanical effect and ferroelectric data storage system are being developed.[1,2] Ferroelectrics can hold bit information in the form of the polarization direction of individual domains.[3–8] Moreover, the domain walls in typical ferroelectric materials is as thin as a few lattice parameters,[9,10] suitable for high-density data storage media. Up to now, recording with a density of around 10 Tbit/in.^{2} in very small areas in a medium has been achieved by forming several dots, and the smallest single nanodomain dot with a size of 2.8 nm diameter was successfully formed.[11] However, recording of real information data with a density of over 1 Tbit/in.^{2} has not yet been achieved. This is because real information is complex and nonuniform and so is difficult to write successfully. In this letter, we describe an approach to high-density data storage with a density above 1 Tbit/in.^{2} in a ferroelectric material.

Scanning nonlinear dielectric microscopy (SNDM) is the first successful purely electrical method for observing ferroelectric polarization distributions with subnanometer resolution.[12–14] We used SNDM as the information storage and playback apparatus. Writing information is carried out by applying relatively large voltage pulses to the ferroelectric recording medium, and thereby the polarization direction is locally switched. The pulse generator is connected to the bottom electrode of the medium; thus, positive domains (which appear on the probe side surface of the medium) are written by positive voltage pulses, while negative domains are written by negative pulses. The dark and bright dots shown in the images in this report represent negative and positive domains, or "1" and "0" data bits, respectively. The read and write (R/W) head was required to be controlled with high location precision and high stability for high-density recording, and therefore, we developed SNDM with low location drift, which was evaluated to be 0.2 nm/min.

Single crystal congruent $LiTaO_3$ (CLT) was selected as the recording medium. We fabricated an ultrathin, uniform CLT medium by mechanically polishing a single crystal followed by dry etching.[15] The thickness of the medium was approximately 30 nm and the area was 6×6 mm^2, all of which is available for data storage. The surface of the CLT recording medium was oriented in the negative domain.

First, we demonstrated that rewritable storage could be realized using our CLT thin ferroelectric medium. An SNDM image of a 6×6 inverted domain dot array with a dot diameter of 15 nm formed on a CLT by applying 8.0-V, 100-ns voltage pulses is shown in Fig. 1(a). This corresponded to 1.4 Tbit/in.^{2}. We selected six dots along the diagonal line of the dot array. These dots were sequentially erased by applying −10.0-V, 200-ns voltage pulses as shown in Fig. 1(b). An "erase" pulse longer than the "write" pulse was used to ensure erasure of the dots even in the case when the tip position slightly missed the center of the dot to be erased. Of course, the duration of the erase pulse intrinsically needed is the same as that of the "write" pulse, as long as sufficiently precise tip positioning is possible. This is the first demonstration of ferroelectric rewritable storage in the Tbit/in.^{2} class. In addition, it became clear that our system has sufficient location precision for high-density recording. Next, a monochrome image consisting of 64×64 bits data was prepared as a master pattern of actual information data. The master is shown in Fig. 2(a) and an SNDM image observed after writing is shown in Fig. 2(b). In order to form a fine domain structure (indicated by bright contrast) on the initially nega-

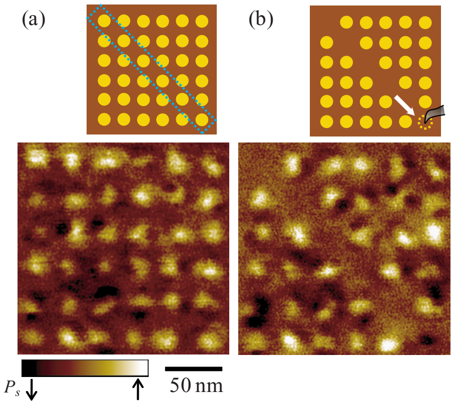

FIG. 1. (Color online) Nanodomain manipulation. Image of a dot array with a diameter of 15 nm (a) before and (b) after the erase.

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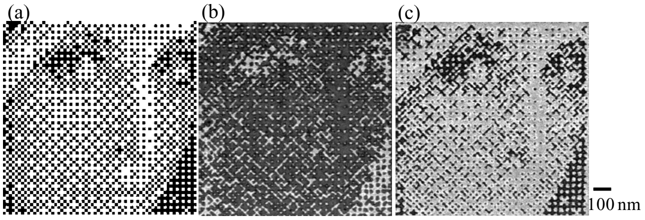

FIG. 2. Actual information data written in a CLT medium. (a) Master image, (b) SNDM image observed after writing on a virgin surface, and (c) SNDM image observed after writing on a prepolarized surface. The bit spacing was 18 nm (surface recording density: 2.0 Tbit/in.^{2}).

tive polarized surface (indicated by dark contrast) of the medium at a bit spacing of 18.0 nm, which is equivalent to a recording density of 2.0 Tbit/in.^{2}, +6.5 V, and 20 ns voltage pulses were selected as the optimum condition of the applied pulse voltage. In Fig. 2(c), at first, a dc bias was applied by preliminary scanning in order to reverse the polarization direction of the whole area from its initial state. As a result, the surface was positively polarized. Then −15.5 V and 5 ns voltages pulses were applied, which were optimum to form negative dots on the reversed polarization surface. The bit error rate (BER) was evaluated to be 1.1×10^{-2} (b) and 3.1×10^{-3} (c), respectively.[15] These results reveal that nanodomain patterns can be written more correctly on the medium that is prepolarized to the positively reversed domain compared to the medium of the negatively polarized state. Thus, in order to record real information data at a high density, we conducted a prepolarizing process before writing data bits in subsequent experiments.

Next, several pattern designs were written to obtain and demonstrate basic data writing. Pattern A is the isolated negative dot surrounded by a positive domain, on the other hand pattern C is the isolated positive dot. Pattern B is a close-packed arrangement composed of positive and negative domains. An SNDM image observed after writing at a bit spacing of 12.8 nm is shown in Fig. 3. The written pattern is composed of negative domains obtained by applying negative pulses with a duration time of 5 ns. The amplitude of the voltage pulses was changed in the range of 15 to 17 V. In pattern B, the optimum value of the pulse amplitude is estimated to be −16 V in order to form a dot with a size of 12.8 nm. Using −15-V, 5-ns pulses, dot patterns do not appear. Also, errors increased due to excessive expansion when −17-V, 5-ns pulses were applied. The dot density in pattern A was lower than that in pattern B, and a higher amplitude voltage of −17 V was required to switch polarization compared to pattern B. In pattern C, dots were written more densely compared to pattern B and the amplitude to switch polarization was lower compared to patterns A and B. The optimum value of the pulse amplitude was estimated to be 15 to 16 V to form dots with a size of 12.8 nm. From writing several dot array patterns, it has been found that the optimum pulse voltage to keep the dot size constant depends on the proximal domain direction and conditions. We conclude that if a higher amplitude voltage is applied, the incidence of miswritten dots would have decreased in areas of low dot density. However, at the same time, errors would have increased in areas of high dot density because the dots would have become too large. This observation suggests that if probe tip was not tiny compared to dot, dots in areas of high dot density have a tendency to expand because the field for domain wall lateral expansion can be much lower than the field to reverse polarization.[16] In other words, the area in the vicinity of earlier formed domain dots feels effects of the previously applied electric field forming the former domain dots. As a result, it seems that, in above mentioned areas of high dot density, an effective coercive field to expand the domain walls decreases and the walls more easily move and expand in comparison with the areas of low dot density. In order to reduce the incidence of miswritten dots, a new method has been formulated, which uses a variable applied voltage at each dot. In new attempt, a higher amplitude voltage was used in areas of low dot density, and a lower amplitude voltage in high-density areas, in order to produce correct size dots over the entire area when we recorded actual information data that included various patterns.[17] We thus recorded actual data with a bit spacing of 12.8 nm (areal recording density is 4 Tbit/in.^{2}) using the variable pulse method. The applied voltage was categorized into following three types according to how many “1” bits existed surrounding the written dot: voltage (pulse 1) where less than two positive dots out of the surrounding eight bits exist, voltages (pulse 2) where two to three “1” (positive dot) out of the surrounding dots, and voltage (pulse 3) where over three “1” bits exist. We set “pulse 1,” “pulse 2,” and “pulse 3” to −14.7 V and 5 ns pulses; −11.9 V and 5 ns pulses; and −11.4 V and 5 ns pulses, respectively. One of the reasons that the pulse parameter was not in agreement with the parameter of the test writing is tip abrasion caused during writing and reading. The SNDM image and close-ups observed after writing with the variable pulse method are shown in Fig. 4. Most dots were patterned with suitable size in both high and low dot density areas. The BER was evaluated to be 1.2×10^{-2}. Analysis of the error data showed that the incidence of “1” bits miswritten as “0” bits was about 3.5 times larger than that of “0” bits miswritten as “1” bits and most bits out of the miswritten “0” bits errors arose when three or more bits out of the surrounding bits were “1.” This observation suggests that excessive expansion of the surround dots caused the error of “0” bits miswritten as “1” bits because the threshold field for domain wall motion can be much lower than the field to reverse polarization.[16] In addition, the incidence of miswritten bits may be reduced by increasing

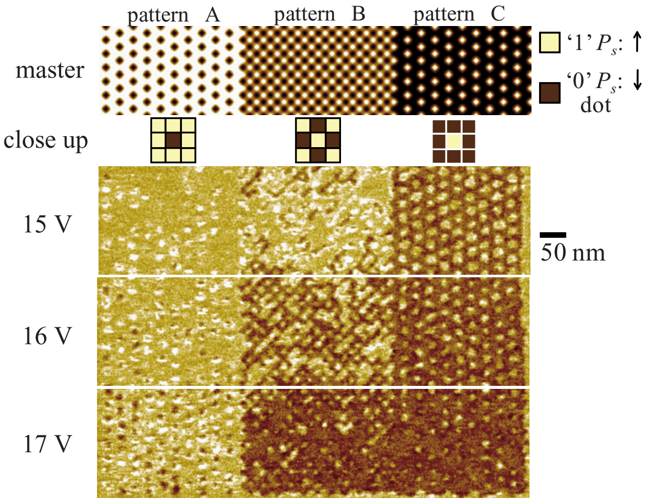

FIG. 3. (Color online) Nanodomain structures written by changing the pulse amplitude in the range of 15–17 V with a bit spacing of 12.8 nm.

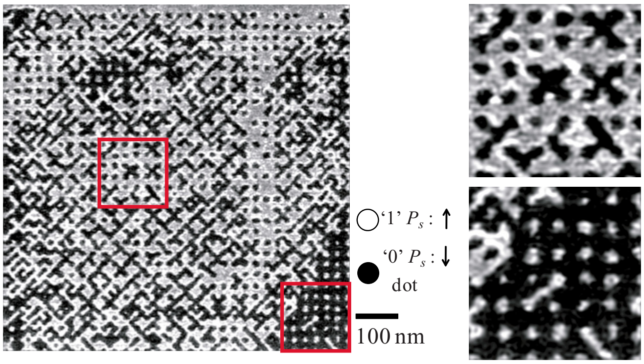

FIG. 4. (Color online) Actual data recorded at a bit spacing of 12.8 nm (areal density: 4 Tbit/in.^{2}) and close-ups of high and low density dot areas.

the categorization number of the applied voltage and setting more appropriate pulse conditions.

In the present study, several experiments were conducted on nanodomain formation in CLT single crystals to record data bits densely. A series of data recordings with a density of 2 Tbit/in.^{2} revealed that the polarization reversed state of the medium prior to writing was superior to the virgin state in terms of forming nanopatterns correctly. Finally, we successfully achieved the recording of actual information data with a density of 4 Tbit/in.^{2} by changing the pulse amplitude according to the bit arrangement.

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