Nanosilicon dot arrays with a bit pitch and a track pitch of 25 nm formed by electron-beam drawing and reactive ion etching for 1 Tbit/in.^{2} storage

Sumio Hosaka,[a] Hirotaka Sano, Masumi Shirai, and Hayato Sone
Department of Nano Material Systems, Graduate School of Engineering, Gunma University, 1-5-1 Tenjin, Kiryu 376-8515, Japan

(Received 8 September 2006; accepted 23 October 2006; published online 1 December 2006)

The formation of very fine Si dots with a bit pitch and a track pitch of less than 25 nm using electron-beam (EB) lithography on ZEP520 and calixarene EB resists and CF_4 reactive ion etching has been demonstrated. The experimental results indicate that the calixarene resist is very suitable for forming an ultrahigh-packed bit array pattern of Si dots. This result promises to open the way toward 1 Tbit/in.^{2} storage using patterned media with a dot size of <15 nm. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2400102]

Available magnetic recording density is rising at a rate of 60% per year. High-end magnetic storage media with a recording density of over 100 Gbit/in.^{2} have already been commercialized. In optical recording, the Blu-ray disk and the high-definition digital versatile disk (DVD) with a capacity of 25 Gbytes have also been developed. However, there are many technical issues to be solved for recording densities as high as 1 Tbit/in.^{2}. A breakthrough is required for future recording systems. Today, we have some technical proposals such as patterned media[1] and near field optical recording[2] which address the above issues.

Electron-beam (EB) lithography is expected to allow the formation of very fine pit or dot arrays for patterned media and next generation DVDs. Many variations of EB drawing (exposure) have been developed to allow the fabrication of semiconductor devices and optical disks.[3–5] So far, pit patterns with a minimum bit pitch (BP) and track pitch (TP) of 40 and 80 nm, respectively, have been achieved on ZEP520.[6] Furthermore, the formation of very fine dot arrays using calixarene has been reported by Fujita and co-workers.[7,8] They demonstrated the formation of 15 nm diameter dot arrays with 100 and 60 nm pitches for quantum devices and magnetic recording media. These recording media were, however, very far from the areal density of 1 Tbit/in.^{2}, because the pitches were too large. In this letter, we describe the ultrahigh-packed nanofabrication of a 1 Tbit/in.^{2} storage medium using EB exposure and reactive ino etching (RIE).

In order to achieve fine bit arrays with densities of over 1 Tbit/in.^{2}, we carried out (1) a very fine EB exposure with a fine probe and a high probe current; we also prepared (2) a thin resist layer to prevent the spread of incident electron scattering; finally, we designed (3) a highly packed pattern with a hexagonal or centered rectangular lattice structure such as cross stitch to prevent proximity effects. Item (2) refers to a thin resist layer which requires an increased acceleration voltage for precise EB drawing. We used a resist layer with thicknesses of 70 and 15 nm for ZEP520 and calixarene, respectively. The minimum thicknesses were determined so that the layer would suffer no deformation and would allow sufficient contrast in scanning electron microscopy (SEM) observation after exposure and development. Calixarene is so tough under electron irradiation that we were able to use layers as thin as 15 nm.

Our EB drawing system consists of a high-resolution SEM (JSM6500F, JEOL, Ltd.) with an in-lens-type Schottky-emission field-emission electron gun for high probe current with a fine probe, and an EB drawing controller (Tokyo Technology Co., Ltd.).[9] We used the system at a probe current of 100 pA and an acceleration voltage of 30 kV because a fine probe less than 2 nm in diameter was obtained. In the drawing, the address resolutions were 10 and 2.5 nm on the ZEP520 and calixarene resists, respectively. The development process was carried out using the commercial developers ZED-N50 (MIBK+IPA) and ZEP-RD (xylene) for 210 and 180 s using ZEP520 and calixarene, respectively.

We carried out EB exposure using ZEP520 resist for dot arrays with a BP of <100 nm and a TP of <70 nm. Figure 1 shows SEM images of the ZEP520 resist patterns drawn at an exposure dosage of around 190 $\mu C/cm^2$. After the exposure, we developed the sample by dipping it into the developer. The figure shows pit arrays with a minimum pit diameter of <20 nm at a BP of 60 nm and TPs of 50 and 40 nm, formed in the ZEP520 resist. We were unable to form higher-packed pit patterns in the ZEP520 resist than that shown in Fig. 1(b). The pit size also fluctuated at a BP of 60 nm and a TP of 40 nm [Fig. 1(c)]. The deviation became large, reaching about 18 nm with increasing exposure dosage, while it was about 11 nm in the pattern with a BP of 100 nm and a TP of 50 nm. The fluctuation gradually increased with increasing packing. This means the high-density packing patterns are not useful in optical and magnetic storage media. The results indicate that the pit array pattern at a BP of 60 nm and a TP of 40 nm has the highest density in the case of EB drawing on ZEP520 resist. The highest-density pattern corresponds to about 540 Gbytes/in.^{2} when using edge modulation recording (EMR) for optical read only memory applications.

We tried to form higher-packed patterns using calixarene with a thickness of about 15 nm. Figure 2 shows SEM images of ultrahigh-packed dot array resist patterns. The exposure dosage was 34–40 mC/cm^2. In the experiment, we successfully formed a 30 nm pitch pattern [Fig. 2(a)], and it was almost possible to form a 25 nm pitch pattern although we required very fine adjustment of EB focus [Fig. 2(c)]. The

[a]FAX: +81-277-30-1707; electronic mail: hosaka@el.gunma-u.ac.jp

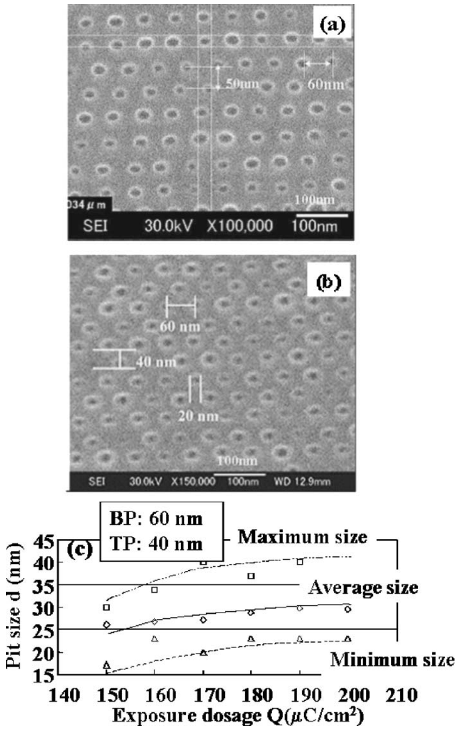

FIG. 1. SEM images of an ultrahigh-packed pit resist pattern on ZEP520 (190 mC/cm^2, 30 kV). (a) BP of 60 nm and TP of 50 nm. (b) BP of 60 nm and TP of 40 nm. (c) Variation of the ZEP520 pit size with exposure dosage in the ultrahigh-packed pit arrays.

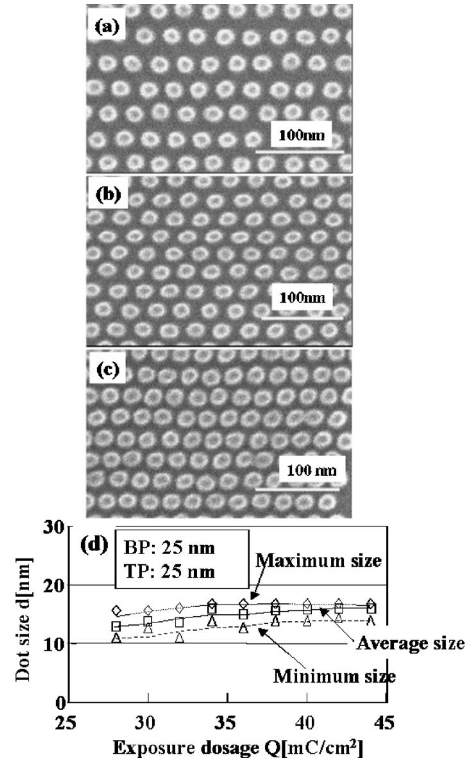

FIG. 2. SEM images of a calixarene resist dot pattern. EB exposure with (a) a BP of 30 nm and a TP of 30 nm at a dosage of 34 mC/cm^2. Exposure with (b) a BP of 30 nm and a TP of 25 nm at 36 mC/cm^2. Exposure with (c) a BP of 25 nm and a TP of 25 nm at 40 mC/cm^2. (d) Variation of the calixarene dot size with exposure dosage.

25 nm pitch pattern corresponds to an ultrahigh recording density of about 2.04 Tbits/in.^{2} in optical ROM using EMR. When applied to magnetic patterned media, this corresponds to about 1 Tbit/in.^{2}. Figures 2(a)–2(c) indicate that even the probe current changed in the EB exposure process, whereas the dot size hardly changed when using calixarene. Figure 2(d) shows a variation in the dot size against the exposure dosage for a BP and a TP of 25 nm. The deviation is as small as about 3 nm. The fluctuation was almost constant for the dosage range of 28–44 mC/cm^2. The proximity effect is so small that we can apply EB drawing to the nanofabrication of ultrahigh-packed dot patterns. The calixarene resist is very suitable to EB drawing for nanofabrication. Since the obtained dot size was 11–13 nm in diameter, it is possible to fabricate ultrahigh-packed dot arrays with a BP and a TP of <25 nm.

When comparing the minimum calixarene dot size (13 nm) on the calixarene resist with the minimum ZEP520 pit size (20 nm) on the ZEP520 resist, we have to consider that the difference may be caused by differences in molecular size and structure of the two types of resist. The molecular size of calixarene is <1 nm in diameter, and the molecular size of ZEP520 is a few nanometers when its shape is sphere. However, ZEP520 sometimes has a chainlike molecular structure with a length of >1 μm. This indicates that EB drawing using calixarene is more suitable to the fabrication of ultrahigh-packed data storage patterns than EB drawing using ZEP520.

Using the dot array patterns of calixarene, we studied the possibility of forming ultrahigh-packed Si dot arrays by RIE with CF_4 gas in a microwave. The microwave power was 200 W, the operation pressure about 10^{-3} Torr, and the bias −60 V. The etching time was 1–2 min. After RIE and O_2 ashing, we obtained SEM images of the Si dot arrays on the Si wafer, as shown in Figs. 3(c) and 3(d). The ashing was done in the same RIE machine at a pressure of about 10^{-3} Torr, a power of 200 W, and a bias of −120 V. Figures 3(a) and 3(b) correspond to the calixarene resist patterns in Figs. 3(c) and 3(d) of the etched Si dot arrays, respectively. The figures show that RIE performed isotropic etching. We also measured the rates of etching on the Si substrate and the calixarene resist from the figures. The rates of etching on silicon vertically (in depth) and laterally were estimated to be about 10 and 2 nm/min, respectively. The rate of etching on calixarene was 6–8 nm/min vertically. From the SEM images, it is clear that the etching rate for low dot density was faster than that for high dot density. The cross section of the

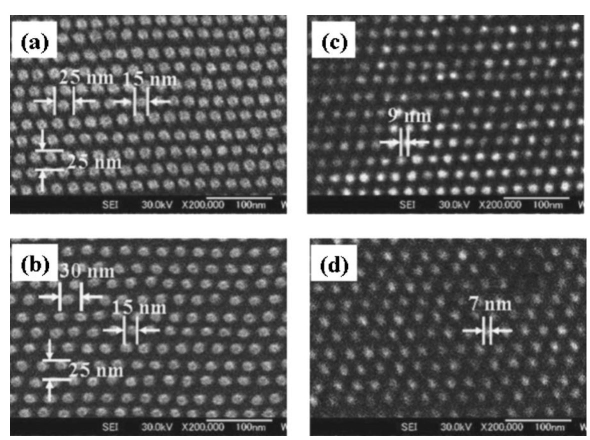

FIG. 3. SEM images of [(a) and (b)] calixarene resist dot arrays and [(c) and (d)] RI-etched Si dot arrays. [(a) and (c)] A BP of 25 nm and a TP of 25 nm. [(b) and (d)] A BP of 30 nm and a TP of 25 nm.

dots was unclear but we will study the dots in detail in the future. The present technique is expected to allow the fabrication of ultrahigh-density dot arrays with a dot diameter of around 10 nm and a dot height of about 20 nm.

The authors would like to thank K. Itoh, S. Watanabe, and M. Noguchi of the Department of Electronic Engineering, Gunma University, for their technical support with regard to the EB drawing. This research was performed as part of the Kiryu Ohta City Area project supported by the Ministry of Education, Culture, Sports, Science and Technology of Japan.

[1]J. Lohau, A. Moser, C. T. Rettner, M. E. Best, and B. D. Terris, IEEE Mag. **37**, 1652 (2001).

[2]S. Hosaka, T. Shintani, M. Miyamoto, A. Kikukawa, A. Hirotsune, M. Terao, M. Yoshida, K. Fujita, and S. Kammer, J. Appl. Phys. **79**, 8082 (1996).

[3]S. Hosaka, M. Ichihashi, H. Hayakawa, S. Hishi, and M. Migitaka, Jpn. J. Appl. Phys., Part 1 **21**, 543 (1982).

[4]S. Ogata, M. Tada, and M. Yoneda, Appl. Opt. **33**, 2032 (1994).

[5]Y. Kojima, H. Kitahara, M. Katsumura, and Y. Wada, Jpn. J. Appl. Phys., Part 1 **37**, 2137 (1998).

[6]S. Hosaka, T. Suzuki, M. Yamaoka, K. Katoh, F. Isshiki, M. Miyamoto, Y. Miyauchi, A. Arimoto, and T. Nishida, Microelectron. Eng. **61-62**, 309 (2002).

[7]J. Fujita, Y. Ohnishi, S. Manako, Y. Ochiai, E. Nomura, T. Sakamoto, and S. Matsui, Jpn. J. Appl. Phys., Part 1 **36**, 7769 (1997).

[8]M. Ishida, J. Fujita, T. Ogurai, Y. Ochai, E. Ohshima, and J. Momoda, Jpn. J. Appl. Phys., Part 1 **42**, 3913 (2003).

[9]S. Hosaka, H. Sano, K. Itoh, and H. Sone, Microelectron. Eng. **83**, 792 (2006).