THIN-FILM EDGE ELECTRODE LITHOGRAPHY ENABLING LOW-COST COLLECTIVE TRANSFER OF NANOPATTERNS

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ABSTRACT

This paper reports a new lithography method using thin-film edge electrodes (TEEs) to collectively transfer nanopatterns by generating oxide on the substrate surface via an electrochemical reaction (ECR). Nanometric thick TEEs are formed on the sidewall of insulating stamping structures. ECR-based oxide patterns have the same width and shape as the TEEs because ECR is induced only between the conductor and the substrate. Oxide nanopatterns of 300 nm and 70 nm in width were collectively transferred on Si substrate in a millimeter-scale area.

INTRODUCTION

Lithography has been one of the key drivers for the semiconductor industry for the past several decades. However, the physical limits of mainstream optical lithography are coming and being replaced in time with the next-generation lithography (NGL) technologies such as extreme ultraviolet lithography (EUVL), electron beam lithography (EBL) and nanoimprint lithography (NIL) [1, 2, 3]. EBL [4] and EUVL [5] are limited mainly by the throughput and implementation costs. NIL is positioned as the most popular choice due to its inherent simplicity and low cost of operation [6, 7]. However, resolution of NIL depends on the pattern size of the mold limited by the resolution of lithography. In this study, we proposed a novel lithography method of thin-film edge electrode lithography (TEEL) as a solution.

CONCEPT AND PRINCIPLE

As shown in Fig.1, TEEL combines a thin-film edge electrode mold (TEEM) with an ECR. The TEEM consists of a base and insulating patterns with nanometric-thick TEEs and nanometric-thick insulating layer alternately formed on those of sidewall (Fig.1 a, b). The principle of TEEL is quite similar to local anodic oxidation lithography [8, 9] and nanoelectrode lithography [10]. The TEEM and the surface of target material are usually covered by a thin film of absorbed water in air. When the TEEM thus TEEs proximally approaches the target material, these absorbed layers come in contact, and a water meniscus is produced because of the capillary effect. With the application of a corresponding electric field, an electrochemical reaction is initiated in the water interface between the electrodes and the substrate through the water bridge. If the target surface is positively charged and the TEEs of TEEM are negatively charged, an ECR is induced to generate oxide patterns in the water meniscus between the TEEs and the surface of target material. Therefore, nanopatterns corresponding to the TEEs rather than the insulating patterns can be transferred because ECR takes place only between the conducting portion of the mold and the substrate (Fig.1 c).

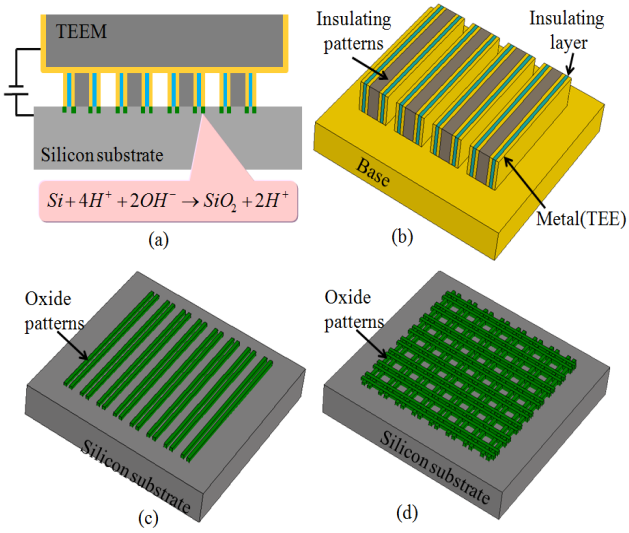


Figure 1: Schematic of the proposed thin-film edge electrode lithography (TEEL). (a) Principle of TEEL. (b) Schematic of the proposed thin-film edge mold (TEEM). (c) Schematic of the transferred oxide patterns using single TEEL. (d) Schematic of the transferred oxide patterns using multiple TEEL.

This approach allows us to select the area of target material in which ECR occurs and thus generate oxide patterns by applying the bias voltage to part of TEEs. Furthermore, several kinds of patterns more complicated than TEEs of TEEM can be transferred by conducting TEEL in different directions for multiple times (Fig. 1 d) using one TEEM.

After TEEL, an etching process can be performed to transfer the shape of the oxide patterns to the target material. When the target material for patterning cannot be oxidized, a hard mask such as a Si or a metal layer can be formed on the target surface before performing TEEL. Therefore, TEEL can be used for pattering of any materials [11].

Figures 2 (a) and (b) show the transfer process of conventional UV-type NIL and the proposed TEEL. The main difference between the two methods is whether resist film exists or not and whether the transfer resolution depends on the pattern size of the mold or not. Conventional NIL uses the mold to physically transfer pattern on resist film, which can cause defective patterns when releasing the mold. Compared to NIL, TEEL is able not only to reduce the number of process steps thus fabrication cost but also to avoid defect of pattern, thereby improving the accuracy because of the resistless process. The resolution of conventional NIL is dependent on the pattern size of the mold, which is limited by the resolution of the conventional lithography. On the other hand, the width of the transferred oxide pattern based on TEEL is dependent on the lateral thickness of TEEs, and the

super-narrow space of the transferred patterns is decided by the thickness of the insulating layer. Therefore, the resolution of TEEL is only dependent the lateral thickness of TEEs and the insulating layer but not on pattern size, which can be easily thinned for higher resolution.

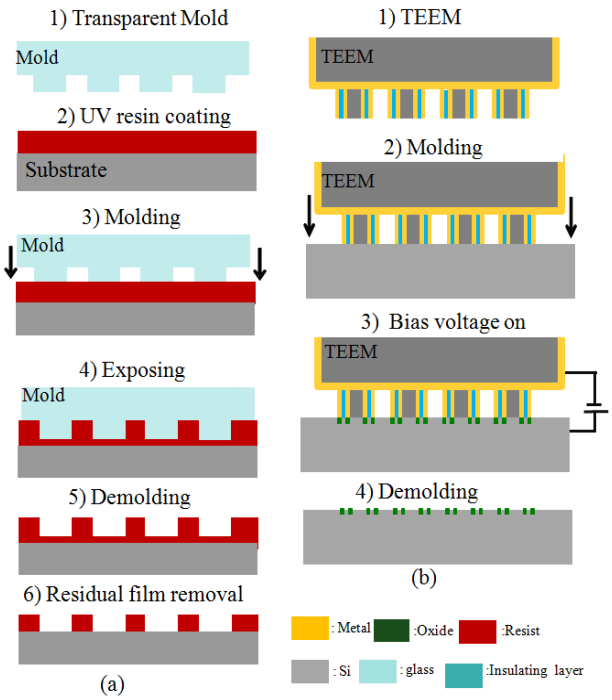


Figure 2: (a) Process chart of UV-type NIL. (b) Process chart of the proposed TEEL.

STRUCTURE OF PROTOTYPE TEEM

A prototype of TEEM shown in Fig.3 is used to verify the concept of TEEL. As shown in the figure, the prototype TEEM is composed from three parts, insulating stamping structures, nanometric-thick single-layer TEEs formed on the sidewall of the stamping structures, and a base. The TEEs are mechanically and electrically connected to the base via the insulating patterns on the base. The stamping structures made of silicon (Si) act as insulating patterns during ECR of TEEL. The TEEs enables not only to generate nano-patterns smaller than the insulating patterns on TEEM via an ECR but it also enables collective transfer and thus high throughput. In addition, gold (Au) is used as the TEEs material of TEEM for its soft contact, good electrical conductivity, and chemical stability.

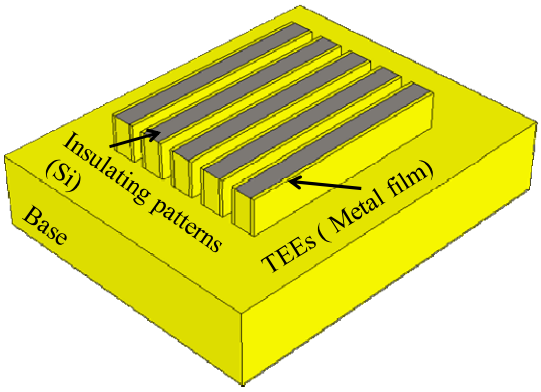


Figure 3: Schematic of prototype TEEM.

FABRICATION

The schematic of fabrication process flow is shown in Fig. 4. The fabrication process begins with a p-type (100)-oriented Si substrate with a thickness of 525 µm and an electrical resistivity of 1-10 Ω・cm. First, lithography process was conducted to form a resist pattern on Si substrate for insulating patterns of TEEM. Then, insulating patterns were shaped on the mold by DRIE (Deep Reactive Ion Etching). After that, a chromium film as an adhesion layer for gold and silicon, and a gold film for creating the TEEs were deposited through a sputtering process. At last, TEEs were shaped by lift-off process. Two kinds of TEEM with 300-nm-thick and 70-nm-thick TEEs were fabricated, which are shown in Fig. 5 and Fig.6 respectively. Both the two TEEMs had a pattern area size of 10 mm×10 mm, and the insulating patterns on the mold had a height of 4 µm and a half pitch of 5 µm, 10 µm, 15 µm and 20 µm.

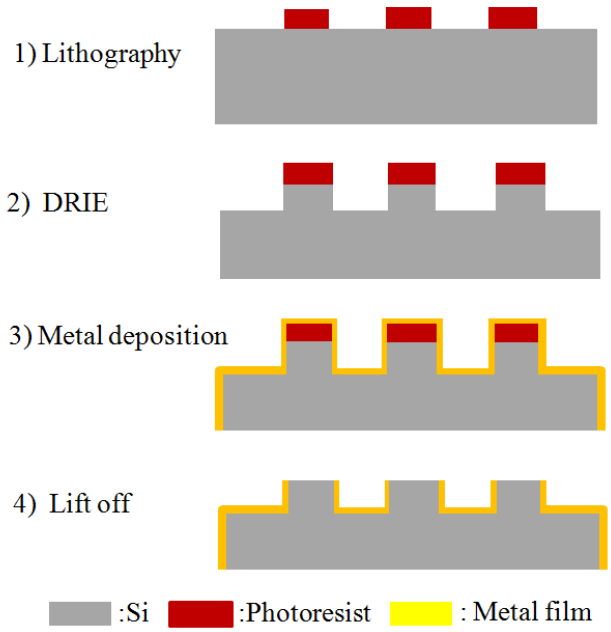


Figure 4: Fabrication Process flow.

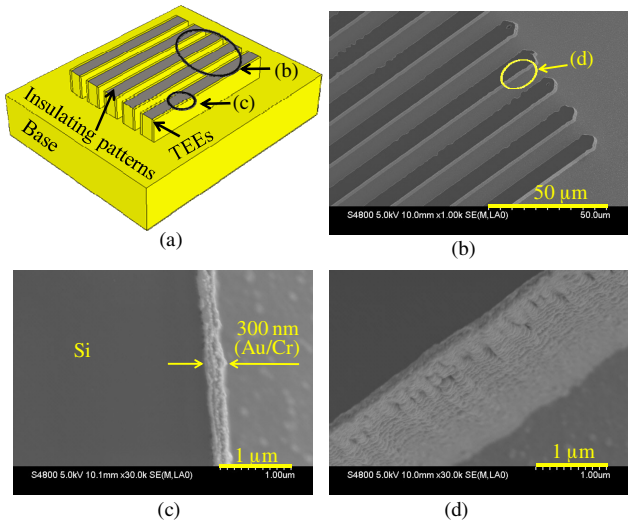


Figure 5: (a) Schematic of the prototype TEEM. (b) SEM image of the fabricated TEEM with 300-nm-thick TEEs. (c) Tow view of the fabricated TEE. (d) Close-up SEM image of the developed TEE.

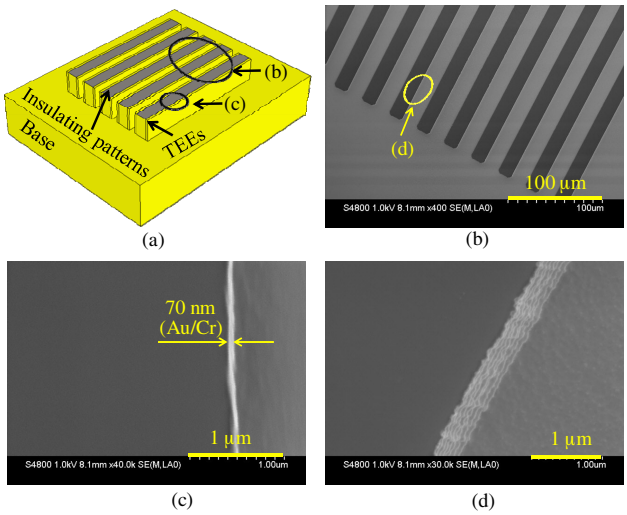


Figure 6: (a) Schematic of the prototype TEEM. (b) SEM image of the fabricated TEEM with 70-nm-thick TEEs. (c) Tow view of the fabricated TEE. (d) Close-up SEM image of the developed TEE.

TEEL

As shown in Fig. 2 (b), the transfer process of TEEL consists of 4 steps: 1) set the TEEM and Si substrate on the pressing unit; 2) applied a force to ensure the contact between the TEEM and substrate; 3) applied a bias voltage between the TEEM and the substrate to induce electrochemical reaction for generating oxide pattern corresponding to TEEs; 4) released the TEEM from the substrate by unloading the force. The setup for performing TEEL shown in Fig.7 was composed of a pressing unit and an electrical unit. The pressing unit enabled application of force ranging from 0 to 500 N, while the electrical unit could apply a constant bias voltage from 0 to 40 V in increments of time from 10µs to 1s. A p-type (100) oriented Si substrate with an electrical resistivity of 5-10 Ω・cm was used for target material of TEEL.

At first, the TEEM shown in Fig.5 with 300-nm-thick TEEs was used for pattern transfer. TEEL was conducted with 150 N contacting force and pulsed bias voltage of 20 V applied between the TEEM and the substrate in air with a humidity of 58% and a temperature of 23.7 °C. To prevent the target surface from Joule heating, the bias voltage with a pulse duration of 1 s and a period of 1 s was applied. TEEL was carried out twice and the total time of bias application was 4 s and 4 min. The transferred oxide patterns with a total time of bias application of 4s and 4 min were shown in Fig. 8 (a)-(b) and Fig.8(c)-(d) respectively. From Fig.8, it can be seen that oxide patterns with a line width of about 300 nm were collectively transferred on the Si substrate in an area of hundreds of micrometer. The total area size in which pattern transfer was conformed was in a millimeter scale. Furthermore, the transferred oxide pattern shown in Fig. 8(c) became more uniform than that in Fig. 8 (a). These results indicated that ECR would proceed sufficiently as the time of bias application increases, resulting in uniform transfer by absorbing the contact variation between the substrate and the TEEs of TEEM.

Moreover, both the oxide patterns shown in Fig.8 (a) and (c) were thought to be transferred by the TEEs formed on the insulating patterns with a half pith of 15 µm on TEEM. However, the transferred pattern shown in Fig. 8(a) has a half pitch of about 30 µm, while the transferred pattern shown in Fig. 8(c) has a half pitch of about 15 µm. If the TEEs of the fabricated prototype of TEEM have the same height and the TEEM are exactly parallel to the Si substrate, only the oxide lines of 15 µm interval could have been transferred. However, the shape of the prototype TEEM especially the TEEs was not perfect and the parallelism between the TEEM and the substrate was not controlled during TEEL, which might have resulted in a partial contact of the TEEs with the substrate. Therefore, only one side of the TEEs formed on the sidewall of insulating patterns came in contact with the substrate to generate oxide patterns. When the total time of bias application became large enough, ECR could proceed sufficiently to generate patterns even when there was a small gap between the TEEs and the substrate. It will explain why the oxide patterns with a 15 µm interval corresponding to the interval of the insulating patterns were transferred when increasing the time of bias application from 4 s to 4 min.

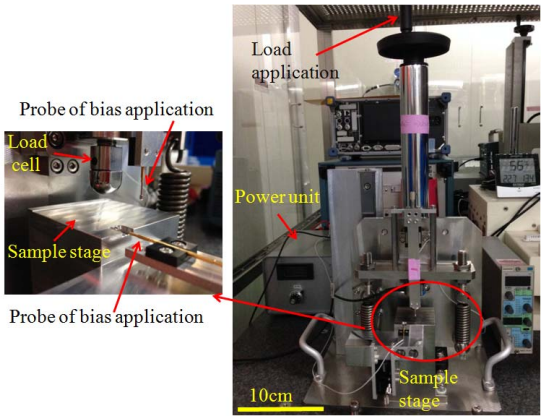


Figure 7: Picture of the setup for performing TEEL

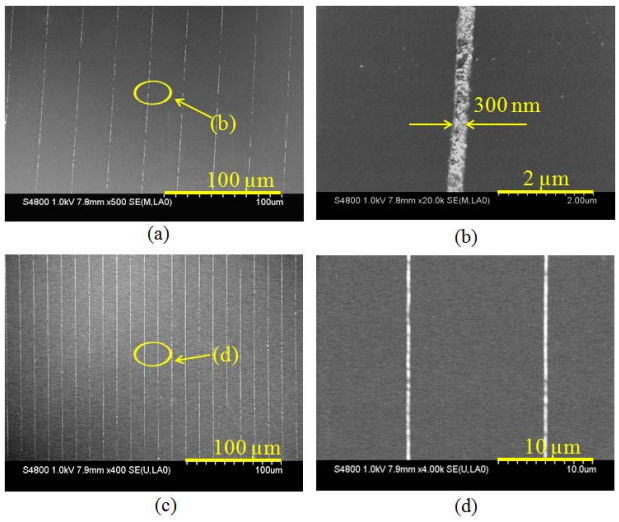
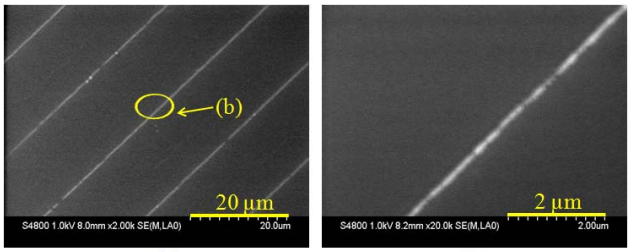


Figure 8: (a) SEM image of the transferred oxide patterns when applying the bias voltage of 20 V for 4s. (b)Close-up SEM image of the transferred oxide patterns in (a). (c) SEM image of the transferred oxide patterns when applying the bias voltage for 4min. (d) Close-up SEM image of the transferred oxide patterns in (c).

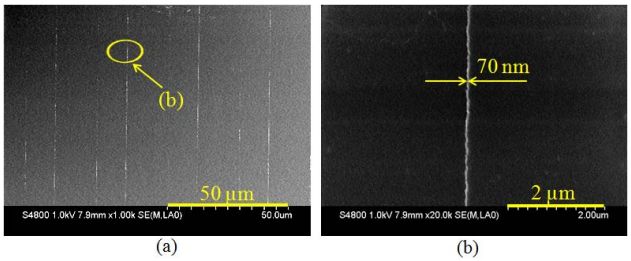
In order to transfer the oxide pattern to Si substrate, dry etching using a SAMCO RIE-10 NR system was performed with transferred oxide pattern served as the mask shown in Fig.8(c). RIE was conducted under the conditions as follows: an etching gas of SF_6 at a flow rate of 50 sccm, a pressure of 5 Pa, a power of 50 W and an etching time of 10 s. Oxide patterns after 10 s etching are shown in Fig.9. From Fig.9, it can be seen that oxide patterns still remained and that Si was successfully etched. The etched oxide pattern was measured by AFM (Atomic Force Microscope) and the etching thickness was found to be about 40 nm. Furthermore, the width of the oxide pattern was reduced from 300 nm to 200 nm after a 10 s RIE etching, which was thought to have been caused by the thickness difference in the center and the edge of the transferred oxide patterns. These results indicated that Si patterns with a finer line width could be achieved by transferred oxide patterns generated by TEEL.

Next, TEEL was performed using the fabricated TEEM with 70-nm-thick TEEs shown in Fig.6. Conditions of TEEL were the same as described above, and the total time of bias application was 4 min. The transferred oxide patterns shown in Fig.10 had a line width of about 70 nm and an interval of 15 µm, which were consistent with the width of the TEEs and half pitch of the insulating patterns. These results indicated that the line width of the transferred oxide pattern was reduced correspondingly by reducing the thickness of TEEs.



(a) (b)

Figure 9: (a) SEM image of the transferred oxide pattern shown in Fig.8(c) after 10 s RIE etching. (d) Close-up SEM image of the transferred oxide pattern after 10 s RIE etching.



(a) (b)

Figure 10: (a) SEM image of the transferred oxide patterns by TEEM with 70-nm-thick TEEs. (b) Close-up SEM image of the transferred oxide patterns.

CONCLUSION

A novel lithography method of TEEL using TEEs to collectively transfer nanopatterns by generating oxide on the substrate surface via an ECR was proposed as a candidate of NGL for realizing high resolution and high through put while maintaining low implementation cost. A prototype of TEEM with a nanometric thick single-layer TEEs formed on the sidewall of the micro-scale insulating patterns was used to verify the concept of TEEL. Two kind of TEEMs with 300-nm-thick and 70-nm-thick TEEs were fabricated using microelectromechanical systems techniques. Oxide nanopatterns with a line with of 300 nm and 70 nm were collectively transferred on Si substrate based on ECR, and the concept of TEEL was found to be effective.

We aimed to develop TEEL to realize transfer resolution of sub-20-nm in high throughput and low cost so that this technique would be available for industrial use. We are currently reducing the thickness of TEEs for high resolution and improving the TEEM and the transfer equipment for uniform transfer of patterns in large scale.

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