THICK-FILM LITHOGRAPHY USING LASER WRITE

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ABSTRACT
Mask-making process using laser direct-write has been broadly applied in the microelectronics and the PC board industries. In this paper, we report the thick-film lithography of laser write mainly for the x-ray mask in the LIGA application. Several schemes of multiple writing are successfully demonstrated in terms of the sidewall straightness and free from intensity fluctuation of laser light. Present study applied the positive resist of AZ P4620 prepared with a thickness of 30 μm, anti-reflection coating of AZ BARLi II on the substrate, and intensity filler to achieve smooth and straight sidewalls.

INTRODUCTION
One of the major issues of fabricating the x-ray mask for the deep and ultra-deep x-ray lithography (DXL and UDXL) is to generate the gold absorber with a thickness ranging from 20 μm to 30 μm [1,2]. The shape and the precision of the absorber wall are important for the product precession. Two major tools fabricating the x-ray mask are x-rays or UV light. The contact printing of the UV lithography is known to perform an intrinsic low and even pattern-dependent precession, which are induced by two aspects. Firstly, lithography error [3,4] generated by the unstable proximity gap, especially for the conformal mask applying slightly curved polymer sheet as the substrate [1]. Secondly, unstable sidewalls produced by the size-dependent development of the thick photoresist-trench. The projection writing of laser provides precision and resolution in the order of the diffraction limit. But, it suffers strong absorption during the thick-film writing as the AZ P4000 resist is applied in this report. Figure 1 illustrates the schematic drawing of the laser write. The defocus can be adjusted above the photoresist so that a less curved sidewall can be obtained by the attenuation of dose rate in photoresist. This work proposes a process of multiple-writings for the projection lithography using the near UV laser and demonstrates the smooth and straight sidewall.

INSTRUMENTATIONS
The workhorse was the low-cost laser-writer DWL 66 made by the German company Heidelberg Instrument. Figure 2 illustrates the optical setup of the DWL 66. This optic system exhibits very stable writing with the depth of focus (DOF) as 28 μm and the lens of 20-mm focal length. In the present study, we chose the 50-mW He-Cd laser as the g-line source with a wavelength of 442 nm. A resolution of better than 50 nm can be achieved using a 40-nm addressed grid. In the case of the 30-μm thick resist, the write lens with a focal length of 20 mm is applied. The spot size and the depth of focus (DOF) of this 20mm-lens are 3.5 μm and 28 μm, respectively. The edge roughness generated by this 20-mm lens is stated in the manual as 150 nm. An air gauge performs the auto-focusing mechanism to control the gap between the write lens and the resist surface with an accuracy of 100 nm. The range of defocus is ±70 μm. An acousto-optic modulator (AOM) and two 30% intensity filters control the power settings of the laser spot.

In this paper, we applied the thick photoresist of AZ P4620. With a single spin process of the resist coating, a thickness of 30 μm is achieved by RC-8 (Karl Suss). The refractive index of resist are 1.693 + i0.015 and 1.674 + i0.010 at the laser wavelength for the unbleached and the bleached cases, respectively [5]. The high extinction coefficients of both cases are tolerable for the 10-μm process but they are very critical for the 30-μm process. Photoresists of better transparency such as AZ 9200 has been successfully applied for the 100-μm case [5]. The test substrate is the bare silicon wafer which has the refractive index of 4.75 + i0.16 at the wavelength of 442 nm [6].

INTERFERENCE
The laser light has a long coherent length that is useful in many applications. However, it induced the surface roughness and the periodic grooves on the sidewall (Fig. 3). This standing wave generated a sinusoidal distribution of the exposure dose in the photoresist with a characteristic length around 100 nm [7]. The SEM micrograph showed periodic lines paralleled to the silicon substrate and extended from the substrate interface into resist of several microns. The choice of a multi-wavelength light source or a more transparent photoresist may imply the less significance of the interference effect, but the interference effect becomes very serious for the laser writing on a thick and heavily absorptive resist. This interference would slow down the development such that a thin resist layer was very difficult

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to remove. Figure 4 illustrates the standing waves calculated using Fresnel formula near the substrate in bleached and unbleached cases [8]. The writing intensity was quite low at the boundary of the silicon substrate due to the attenuation by the 30 μm photoresist. The destructive interference provided additional effect to lower the laser intensity as shown in Fig. 4. The developing rate became critical at the positions of the destructive interference, since the increase of the developing time was not a linear function of the exposure dose. To verify this calculation, we applied the anti-reflective coating of AZ BARLi II on the substrate. Since BARLi II is designed for the i-line (365 nm) application, it is impossible to cancel the reflection completely at the laser wavelength using only single layer. Double coating was required for the better reflection cancellation. Two samples were prepared to demonstrate the effect of anti-reflective coating, i. e. bare substrates without coating and substrates with the anti-reflective coating of the 0.43-μm BARLi II. Figure 5 illustrates the impact of anti-reflective coating on the developing time, especially for the low-power setting. Note here that all of the power settings were accomplished with the AOM only and no intensity filter has been involved. Multiple writings were applied as the power setting higher than 100%.

We believed that the vertical line on the resist wall as illustrated in Fig. 3 was due to the intensity fluctuation. The measured edge roughness of the 30-μm resist is worse than the reported value of 150 nm in the manual. It was observed that this fluctuation increased as the resist thickness increases. As shown in Fig. 6, the resist was not developed completely on purpose so that the intensity fluctuation can be observed easily. The trenches were written twice with a speed of 200 mm/s. The second write had a delay time about seconds to the first write. The displacement between two lines was 3.2 μm. We have found that the fluctuations are closely correlated between two lines. It was not time-correlated fluctuation since the time interval between writings was arbitrary. The phenomenon implied that the fluctuation was position dependent. The source of the position-dependent fluctuation considered at the first guest was the reflection at the resist surface. This can be verified also by the Fresnel calculations of the reflectance using the three-layer configuration of the air/photoresist/substrate. Although the reflection between substrate and photoresist is strong, it does not contribute to the overall reflection due to the attenuation of the thick resist. According to this same argument, the thickness variation of the photoresist has no contribution to the fluctuation of the reflectance. If this argument is wrong, we expect to observe stronger fluctuation for thinner resist. Therefore, this three-layer system of the 30-μm resist can be treated as only one reflection interface that is the resist surface. One of the remaining possibilities of the reflectance fluctuation is the surface quality of the photoresist. However, the reflection on the interface between air and photoresist is only 5%. The surface roughness with an rms-value about 1 nm was measured by the surface-profile meter and

illustrated in Fig. 7. It is impossible to believe that this tiny roughness is the source of the fluctuation. Furthermore, the fluctuation lines with characteristic distance of microns observed in Fig. 6 are almost orthogonal aligned to the writing direction. The random orientation of the surface roughness could not explain this fluctuation alignment. Some of the other possibilities had been considered such as surface tilt and vibration of lens and x-y stage, however, they were not able to generate this characteristic feature-size of fluctuations.

Although the cause of the intensity fluctuation was not identified, we tried to prove that the reflection on the resist surface induced the fluctuation. Experiments were designed to cancel the reflections. As we applied the antireflective coating on top of the resist, the fluctuation was reduced as comparing Figs. 6(a) and 6(b). The remaining fluctuations of Fig. 6(b) might be caused by the residual reflection. The antireflective coating eliminated about 80% of the original reflected intensity. The residual reflection should be 20% to generate the rest of the exposure fluctuations. The second experiment was then simply described as follows. The mirror was tilted such that the reflected light could not go back to the AOM before the laser (illustrated in Fig. 8). The fluctuation was further reduced (as shown in the enlarged SEM micrograph of Fig. 6(c)). Simple calculation indicated that the setup shown in Fig. 8 blocked much more reflection than the antireflective coating with some residual fluctuations still. The three pictures of Fig. 6 were prepared in the same batch of the same lithography conditions.

The third experiment included the insertion of intensity filters into the light path between the lens and the laser to reduce the reflected light. We wrote the resist three times using one third laser power at the same place to obtain the same exposure dose. Figures 9(a) and 9(b) demonstrate the effect of multiple writing with the intensity filter. These figures show that the intensity filter does reduce the fluctuations. The crucial part of this arrangement was only to replace the AOM as an intensity filter with a real attenuation filter. Figures 10(a) and 10(b) demonstrate the same effect on the 10-μm resist using multiple writing plus intensity filter. In this case, the residual fluctuation was hardly observed as the resist was fully developed.

STRAIGHT SIDEWALL
Although uniform dose along the penetration path is essential to obtain a straight wall, it is impossible to obtain that uniformity due mainly to the light absorption of resist. For regular operation, we utilize the defocus effect of projected light to manipulate a constant dose on the wall against the attenuation and Figure 1 demonstrates this principle schematically by defocus the laser light above the resist surface. This defocus method worked well for 10-μm resist (Fig. 10). Poor result was obtained (Fig. 11) even as the extreme conditions of overly long developing time (20 minutes) and high power setting (100%) were set. No significant improvement was observed if the developing time is longer. The sidewall waist was always developed faster than the corner, which led to

worse straightness. These extreme conditions were overthrown, as the resist was written three time using the doses 27% + 27% + 27% and a delay time around 5 minutes between each writings. Since the development at the corner was faster so the time was reduced to 10 minutes. Figure 12(a) and 12(b) illustrate the stable results of the multiple-writing process with and without defocus, respectively. The defocus effect was not obvious as expected due to the strong attenuation of AZ P4000 resist.

To examine the effect of the multiple exposures, the same experiment was performed using a contact aligner. The AZ P4620 resist of 30-μm was exposed under the following conditions: one-shot exposure on one sample but two shots on the other sample with a delay time of 2 minutes. Both processes experience the same dose but the outcomes were different. Two-shot exposures exhibited a faster development at the corner and wider trenches. From these observations, it was realized that something diffused cross the lithography sidewall during the multiple writes. During the exposures, the photochemical process destructs the dissolution inhibitor and generates nitrogen gas and hydrophilic indene acid that enhances the dissolution rate in physical and chemical mechanisms, respectively [9]. Upon photolysis to generate indene acid, moisture present in the resin is absorbed in the Wolff rearrangement. The relaxation time of the Wolff rearrangement is much longer than the exposure time of laser scanning, i. e. the rearrangement process is still ongoing after laser spot leaves. As we proceeded second exposure, partial resist has been bleached by the first exposure that provided a slight change (1%) of the refractive index but significant change on the extinguish coefficient (30%). Supposed that the crucial element diffused cross the wall, the area near sidewall became more sensitive and more transparent for the third exposure. Experiences showed that the resist sensitivity was the function of the moisture content [10]. Also, it was speculated that the moisture diffusion speeded the development on the corners. Explanation in details requires further study.

CONCLUSION

This newly developed laser technology is a low-cost approach of LIGA process. The simplicity of laser write shortens the fabrication duration of x-ray mask with the high flexibility. Photoresists of the AZ P4000 series are not the best choice of the thick-film application due mainly to its high absorption. Many problems due to the strong attenuation in the resist have been observed near the substrate as the film-thickness approaches 30 μm. Proposed scheme of the multiple writing plus several adjustments solved the above-mention issues and successfully obtained the smooth and straight sidewalls.

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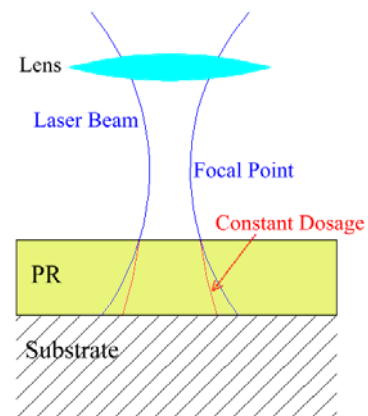10. Private communications with Heidelberg Instruments.

Figure 1: Schematic drawing of the laser write. The attenuation in photoresist move the contour of the constant dose to less curved line as the defocus process is applied.
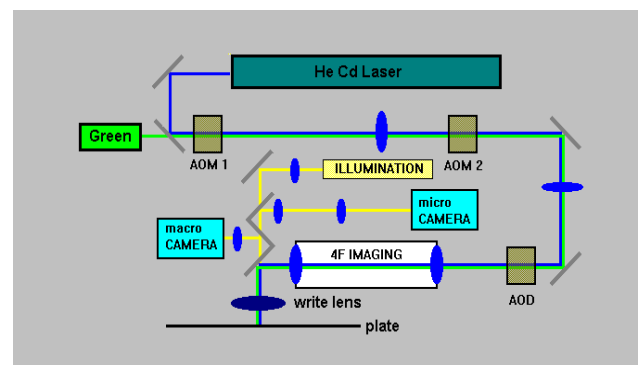

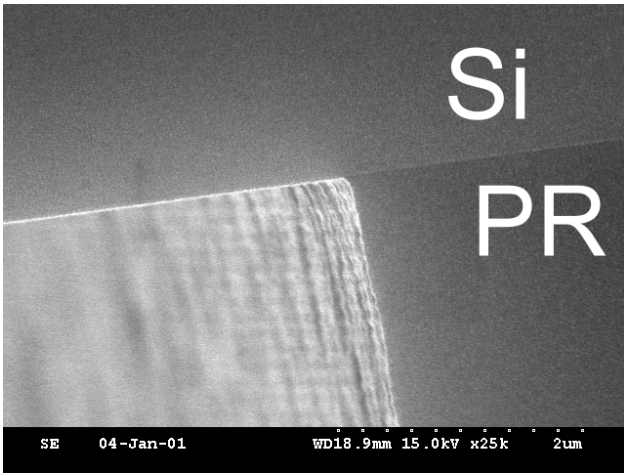Figure 2: Optics of the DWL 66 (Courtesy of Heidelberg Instrument).

Figure 3: SEM micrograph of the photoresist (PR) near the silicon (Si) substrate. Periodic grooves paralleled to the substrate on the resist are induced by the standing wave. The vertical line is induced by the intensity fluctuation.
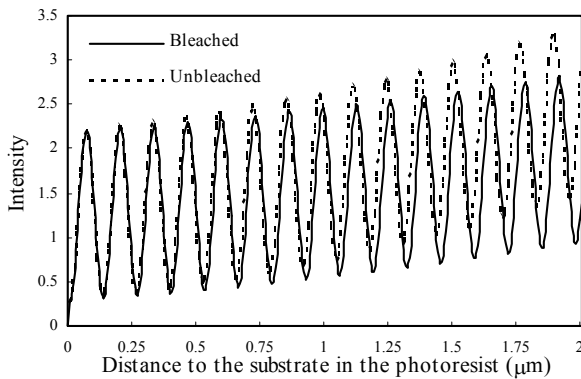

Figure 4: The exposure intensity of the standing waves in the photoresist near the bare silicon substrate. The intensity with an arbitrary scale has been normalized by the average intensity at the boundary.
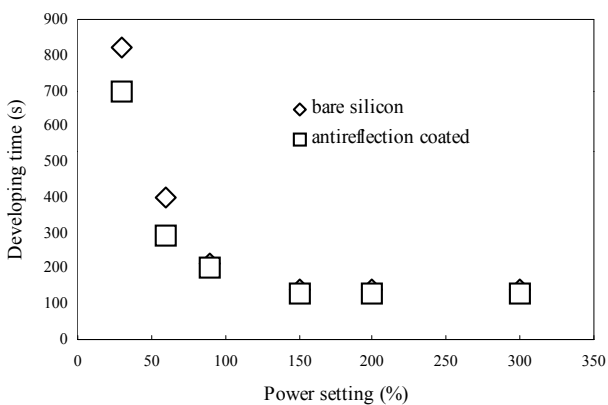

Figure 5: The development times to remove the 30-μm resist vs. the power setting of laser writer. The silicon substrates were prepared with bare silicon substrate and with antireflective coating.
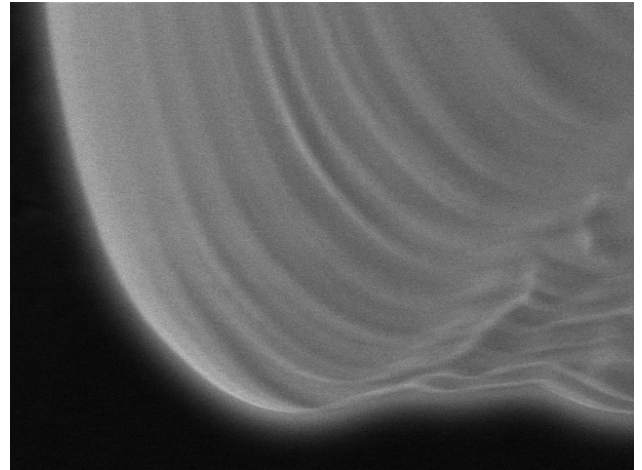
Figure 6(c): SEM image of the intensity fluctuation on a developed photoresist with the experimental setup of Fig. 8 and without the antireflective coating atop the resist.
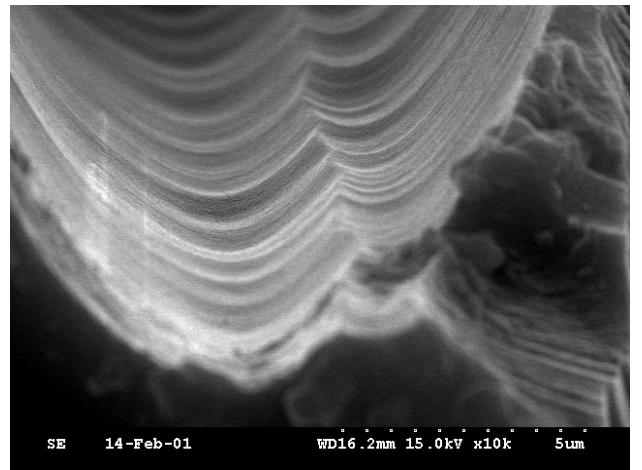
Figure 6(a): SEM image of the intensity fluctuation on a developed photoresist without the antireflective coating atop the resist.
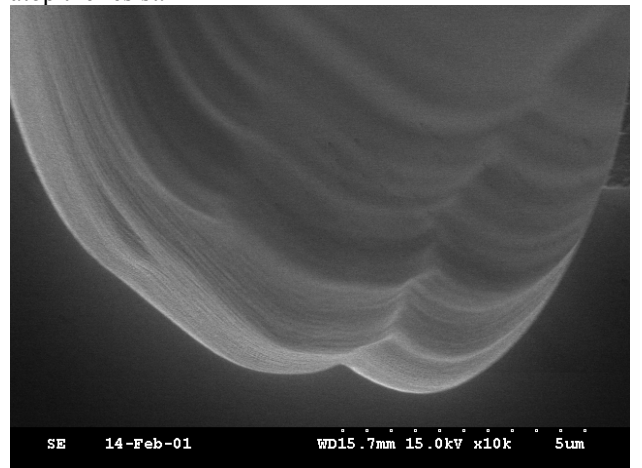
Figure 6(b): SEM image of the intensity fluctuation on a developed photoresist with the antireflective coating atop the resist.
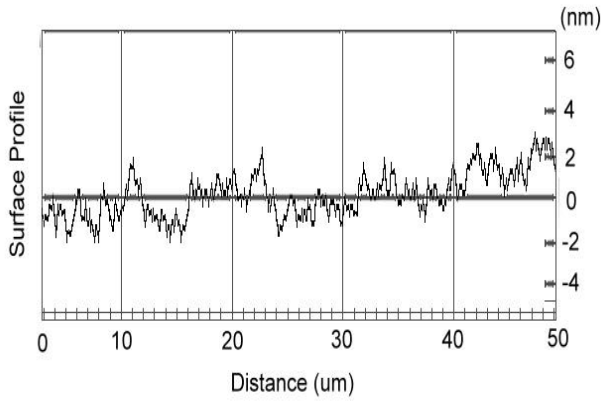
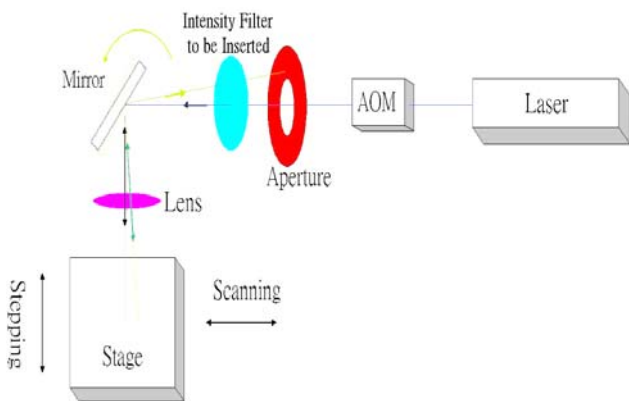Figure 7: The surface profile of the photoresist measured using the surface profiler (Veeco).

Figure 8: The setup of the experiment to inhibit the reflected light goes back to the AOM and the laser source.
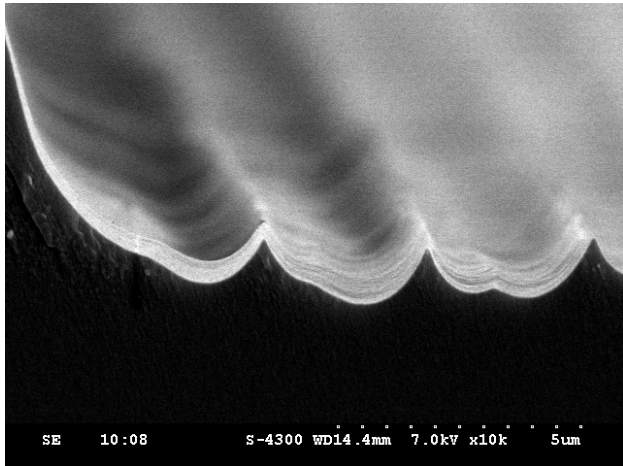

Figure 9(a): Single write with one 30% intensity filter and 100% power setting.
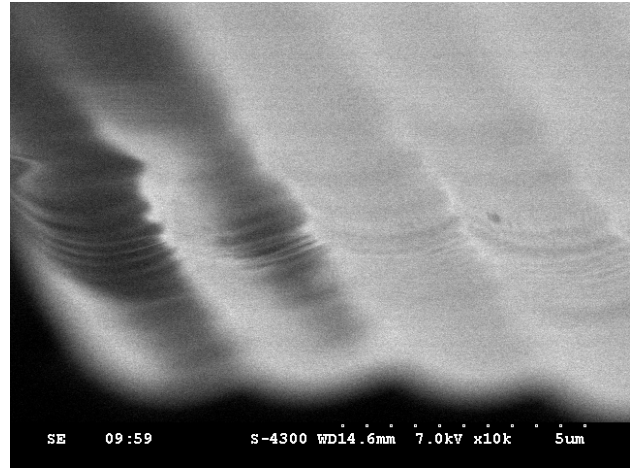

Figure 9(b): Triple writes with two 30% intensity filters and 100% power setting.
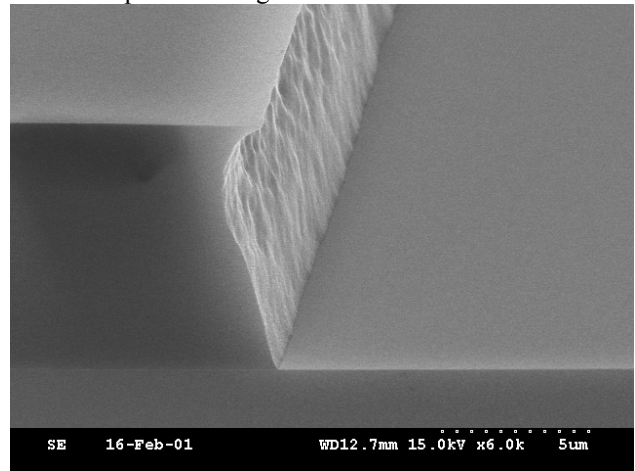

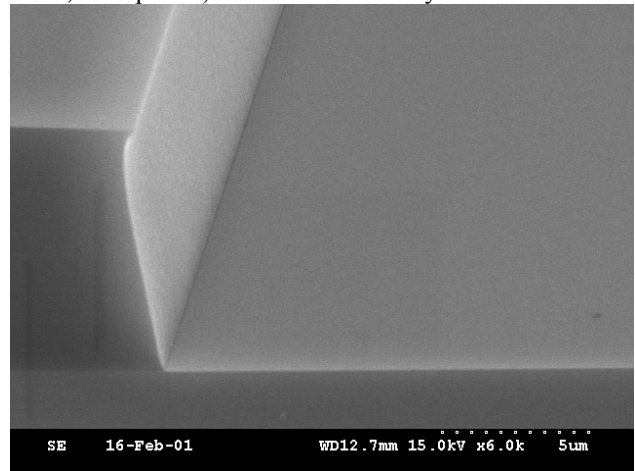Figure 10(a): SEM micrograph of single write (10-µm resist, 40% power) without the intensity filter.

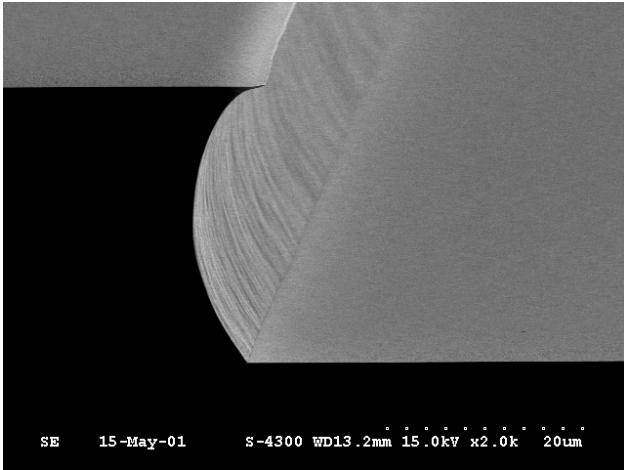Figure 10(b): SEM micrograph of double write (10-µm resist, 21%+21% power) with a 30% intensity filter.

Figure 11: SEM micrograph of 30-µm resist made by following conditions: single write, 100% power, 20-minutes development.
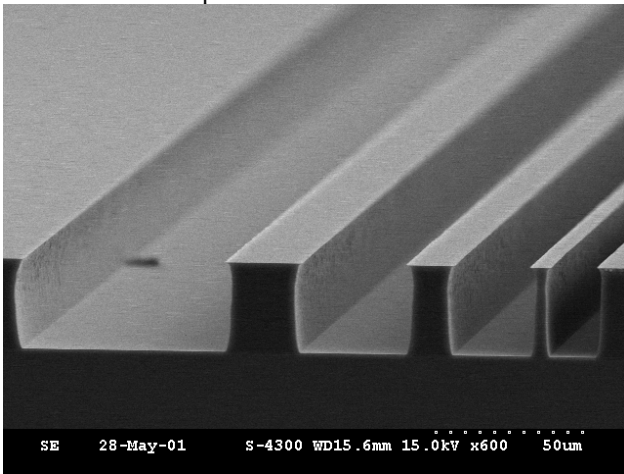

Figure 12(a): SEM micrograph of 30-µm resist trenches of 60-µm, 30-µm, 20-µm and 10-µm width without defocus in writing process.

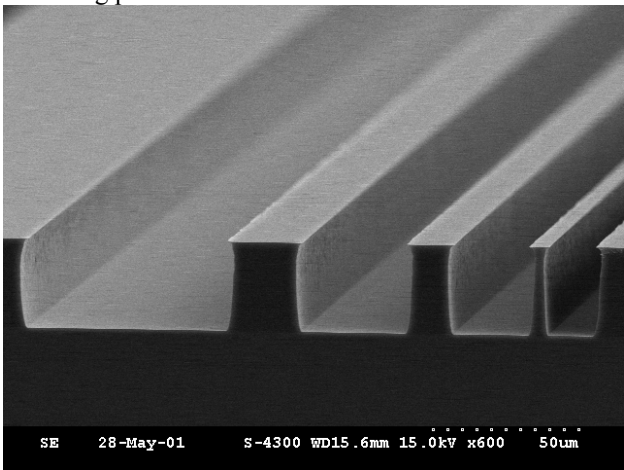Figure 12(b): SEM micrograph of 30-µm resist trenches of 60-µm, 30-µm, 20-µm and 10-µm width with 30-µm defocus in writing process.