Relationships between Stochastic Phenomena and Optical Contrast in Chemically Amplified Resist Process of Extreme Ultraviolet Lithography

Takahiro Kozawa, Julius Joseph Santillan,* and Toshiro Itani*

The Institute of Scientific and Industrial Research, Osaka University, 8-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan
*EUVL Infrastructure Development Center, Inc. (EIDEC), 16-1 Onogawa, Tsukuba, Ibaraki 305-8569, Japan
kozawa@sanken.osaka-u.ac.jp

The development of extreme ultraviolet (EUV) lithography has been pursued toward the 11 nm node. With the reduction in feature size, the stochastic effect becomes an essential problem in the lithography used for the high-throughput production of semiconductor devices. In this study, the relationships between stochastic phenomena [line edge roughness (LER) and stochastic defect generation] and optical contrast were investigated using a Monte Carlo simulation on the basis of the reaction mechanisms of chemically amplified EUV resists. Optical contrast did not affect the protected unit fluctuation at the boundary between lines and spaces. However, the protected unit fluctuation at the centers of lines and spaces increased with decreasing optical contrast. The stochastic defect generation is basically affected more by the optical contrast degradation than LER.

Keywords: EUV lithography, chemically amplified resist, line edge roughness, stochastic defect generation, optical contrast

1. Introduction

Extreme ultraviolet (EUV) radiation, the wavelength of which is 13.5 nm, is one of the most promising exposure sources for next-generation lithography.[1,2] The resolution of EUV lithography has already reached the sub-15 nm region.[3-6] The focus of the development of EUV lithography has shifted toward the 11 nm node. The energy of EUV photons is 14-fold higher than that of the exposure source used currently in the high-volume production lines of semiconductor devices. Because of the expensive exposure tools and the low power of exposure sources, a highly sensitive resist is required for the application of EUV lithography to the high-volume production of semiconductor devices. Also, the number of photons used for the generation of a pattern decreases with decreasing the pattern size. Therefore, the stochastic effect is a serious concern in the development of resist materials and processes for the 11 nm node.[7-10] In the lithography used for the high-volume production of semiconductor devices, a highly sensitive resist called the chemically amplified resist[11] has been used since the transition of the exposure tool from an i line of a Hg lamp to a KrF excimer laser. The chemically amplified resist is also an indispensable technology for EUV lithography. Typical stochastic events in lithography processes are the shot noise of incident photons,[10] the interaction of particles such as photons and electrons with molecules,[12] the diffusion of molecules such as acid and quencher molecules,[13] chemical reactions such as deprotection and neutralization,[14] and the dissolution of molecules in the developer.[15] Typical phenomena induced by stochastic events are the formation of the sidewall roughness of resist patterns called the line edge roughness (LER)[16,17] and the stochastic generation of defects such as pinching and bridges.[18]
Recently, we have developed a method of analyzing stochastic effects in chemically amplified resist processes. In studies using a high-performance resist called the first EIDEC standard resist (ESR1), the following relationships for the stochastic effects were revealed. In these studies, the stochastic effect was expressed using the standard deviation \( \sigma \) of the number of protected units connected to a polymer molecule after postexposure baking (PEB). (1) The relationship between LER and the stochastic effect was approximated using a cosine function:

\[
\text{LER} = 0.68\sigma_n/(\text{dm/dx}),
\]

where \( n \) and \( \text{dm/dx} \) denote the normalization by the initial number of protected units connected to a polymer molecule before PEB and the chemical gradient (the gradient of the normalized protected unit concentration), respectively. (2) The elimination of the stochastic pinching generation over a 6.1 \( \mu \)m line length required a 1.2-1.6\( \sigma \), difference between the average protected unit concentration and the dissolution point at the center of the line pattern. (3) The elimination of the stochastic bridge generation over a 6.8 \( \mu \)m line length required a 1.5-2.0\( \sigma \), difference between the average protected unit concentration and the dissolution point at the center of space.

In this study, the relationships between stochastic phenomena (LER and stochastic defect generation) and optical contrast were investigated using a Monte Carlo simulation on the basis of the reaction mechanisms of chemically amplified EUV resists. The chemical reactions induced upon the formation of line-and-space patterns with an 11 nm half-pitch were simulated. The effects of optical contrast on the protected unit fluctuation at the centers of lines and spaces and at the boundary between lines and spaces were determined.

### 2. Simulation Model and Method

In the simulation, an aerial image of incident EUV photons, \( I(x, y, z) \) (perpendicular to line pattern, \( y \); parallel to line pattern, \( z \); depth direction), was approximated using a cosine function:

\[
I(x, y, z) = \frac{A}{2} \left[ 1 + \cos C \left( \frac{\alpha x}{p_{1/2}} \right) \right]
\]

Here, \( A \), \( C \), and \( p_{1/2} \) represent the exposure dose, the contrast of the optical image, and the half-pitch of the line-and-space pattern, respectively. Poly(4-hydroxy styrene) was assumed as a backbone polymer for chemically amplified resists. Exposure dose was changed from 5 to 70 mJ cm\(^{-2}\). \( p_{1/2} \) was 11 nm. The exposed area was 2\( p_{1/2} \times 1000 \) nm\(^2\). EUV photons were randomly injected into the target area in accordance with the photon intensity expressed by Eq. (1). The injected photons were randomly absorbed by the resist films in accordance with Lambert’s law. The electron trajectories after EUV absorption and the reaction of electrons with acid generators were calculated in accordance with the reported procedure. The acid generator concentrations were 10 and 20 wt% in a triphenylsulfonium-triflate (TPS-Tf) equivalent. The corresponding quantum efficiencies of acid generation were 2.0 and 2.5, respectively. The decrease in proton yield caused by the protection of the proton source (hydroxyl group) was taken into account in the calculation of quantum efficiency.

The preneutralization of acids before PEB was assumed because an annealing-type resist was generally used in EUV lithography. The proton migration range at room temperature was set to 2.4 nm. Using the acid distribution after the preneutralization as the initial condition, the catalytic chain reaction during PEB was calculated by a Monte Carlo method. An acid molecule was assumed to diffuse in the resist matrix with a paired form of a proton and a counteranion at an elevated temperature. The motion of the acid and quencher molecules at each time step \( \Delta t \) is given by \( \sqrt{6D \Delta t} \), where \( D \) represents the diffusion constant of the acid or quencher molecule. The direction of motion was determined using uniform random variables. The
periodic boundary condition was applied in the horizontal direction. The reflective boundary condition was applied in the vertical direction. During PEB processes, when the acid molecule reached a quencher molecule within the effective reaction radius for neutralization, the acid molecule was regarded to be lost through neutralization. When the acid molecule reached a protected unit of the polymer within the effective reaction radius for deprotection, \( R_{\text{eff}} \), the acid molecule was regarded to induce the deprotection of the polymer. The effective reaction radii for deprotection were 0.1 and 0.2 nm. The parameters used in the simulation are summarized in Table I.[27-30] Other details of the reaction mechanisms have been reported elsewhere.[20,21]

3. Results and discussion

Figure 1 shows the representative calculation results. The latent image of the line-and-space pattern calculated with an optical contrast of 1.0 is shown in Fig. 1(a). Quencher concentration, PEB time, and dissolution point were optimized to maximize the chemical gradient at the intended boundary \( (x=\pm p_{1/2}/2) \). The initial number of protected units connected to a polymer molecule before PEB was 10 on average. By changing the initial standard deviation of the number of protected units connected to a polymer molecule \( \sigma \) from 0 to 3.0, the standard deviation after PEB (final standard deviation) was calculated as shown in Fig. 1(a). The fluctuation in the number of protected units near the intended boundary leads to the fluctuation of the crossing point between the latent image and the dashed line marked by \( N_{\text{DP}} \) (dissolution point) and results in LER.[26] The relationships among LER, the chemical gradient, and the stochastic effect have been discussed in detail.[31-34] The fluctuation in the number of protected units near the center of the line pattern leads to the generation of pinching.[18] It has been reported that the elimination of pinching is important for the development of chemically amplified resists with sub-15 nm resolution.[4] Also, the fluctuation in the number of protected units near the center of space leads to the generation of bridges.[18] The dependence of the protected unit fluctuation at \( x=\pm p_{1/2} \) and 0 on half-pitch has been investigated. It has been reported that the probability for the stochastic defect generation rapidly increases with the reduction in half-pitch.[35] In this study, such dependence on optical contrast is discussed from the viewpoints of LER, pinching, and bridges. As shown in Fig. 1(a), the final standard deviation depended on the \( x \) position and initial standard deviation. The difference between the average numbers of protected units connected to a polymer molecule \( x=\pm p_{1/2} \), 0, and \( \pm p_{1/2}/2 \) in \( \sigma \) unit, \( (N_L-N_{\text{DP}})/\sigma_L \), was calculated to be 2.20, 1.70, and 1.11 for \( \sigma=0, 1.5, \) and 3.0, respectively. \( \sigma_L \) is the standard deviation of the number of protected units connected to a polymer molecule before PEB.

The profiles of the standard deviations of the number of protected units connected to a polymer molecule are also shown. The acid generator concentration was 20 wt%. The effective reaction radius for deprotection was 0.2 nm. The exposure dose was 30 mJ cm\(^{-2}\). The quencher concentration, PEB time, and dissolution point were optimized to maximize the chemical gradient at the intended boundary. \( N_L \), \( N_S \), and \( N_{\text{DP}} \) represent the average numbers of protected units connected to a polymer molecule at \( x=\pm p_{1/2}, 0, \) and \( \pm p_{1/2}/2 \), respectively. \( \sigma_L \) is the standard deviation of the number of protected units connected to a polymer molecule before PEB.
be 1.43, 1.48, and 1.68 nm for $\sigma_i=0$, 1.5, and 3.0, respectively. The required LER is 0.64 nm for the 11 nm node. Also, the difference between the average numbers of protected units at $x=0$ and $\pm p_{1/2}/2$ in $\sigma_i$ unit, $(N_{DP}-N_{S})/\sigma_S$, was calculated to be 1.37, 1.33, and 1.31 for $\sigma_i=0$, 1.5, and 3.0, respectively. $\sigma_S$ is the standard deviation of the number of protected units connected to a polymer molecule at $x=0$. For ESR1, $(N_{DP}-N_{S})/\sigma_S$ should be more than 1.5-2.0 for the elimination of bridges over a 6.8 $\mu$m line length.[18] By decreasing optical contrast from 1.0 to 0.6, a similar calculation was carried out as shown in Fig. 1(b). Quencher concentration, PEB time, and dissolution point were optimized for an optical contrast of 0.6. By decreasing optical contrast, not only the latent image quality but also the profile of the final standard deviation changed. $(N_{L}-N_{DP})/\sigma_L$ decreased to 0.96, 0.88, and 0.70 for $\sigma_i=0$, 1.5, and 3.0, respectively. The chemical gradient decreased to 0.092 nm$^{-1}$. The final standard deviations at $\pm p_{1/2}/2$ were 2.80, 2.89, and 3.17, respectively. LER was calculated to be 2.07, 2.14, and 2.34 nm for $\sigma_i=0$, 1.5, and 3.0, respectively. $(N_{DP}-N_{S})/\sigma_S$ was calculated to be 0.81, 0.79, and 0.75 for $\sigma_i=0$, 1.5, and 3.0, respectively. Thus, the stochastic effects significantly depended on optical contrast. Details are discussed in the following sections.

In our previous studies,[31-35] we have discussed the latent image quality including the protected unit fluctuation mainly assuming an acid generator concentration of 10 wt% in a TPS-Tf equivalent and an effective reaction radius of 0.1 nm for deprotection. The corresponding quantum efficiency was 2.0. Effective reaction radius was assumed on the basis of the analysis results of the resists called the SSR series.[36-40] The dependence of chemical gradient on optical contrast was calculated assuming the same parameters as in our previous studies, as shown in Fig. 2(a). Chemical gradient deteriorated with decreasing optical contrast. When the optical contrast was 1.0, the corresponding LER was 2.13 nm at an exposure dose of 30 mJ cm$^{-2}$ with the assumption of $\sigma_i=0$. LER was increased to 3.07 nm by decreasing optical contrast to 0.6. This value is markedly different from the required value. Acid generator concentration and effective reaction radius were increased to 20 wt% in TPS-Tf equivalent and 0.2 nm, respectively, to decrease LER to a realistic value. The effective reaction radius of 0.2 nm itself is not unrealistic, because the effective reaction radius for ESR1 has recently been reported to be 0.16 nm.[19] The calculation result is shown in Fig. 2(b). Chemical gradient was roughly increased twofold. Namely, LER was roughly reduced by half. The quantum efficiency corresponding to 20 wt% TPS-Tf was 2.5. By increasing acid generator concentration and effective reaction radius, the dependence of chemical gradient on optical contrast became weaker. In this study, the relationship between stochastic effects and optical contrast is discussed assuming an acid generator concentration of 20 wt% and an effective reaction radius of 0.2 nm.

Figure 3 shows the dependence of optimum acid diffusion length on optical contrast. The acid diffusion length optimized in terms of the chemical gradient did not depend on optical contrast. Also, it was confirmed that optimum acid diffusion length was independent of acid generator concentration, namely, the quantum efficiency of acid generation. However, optimum acid diffusion length depended on the effective reaction radius for deprotection. The optimum acid diffusion lengths for 11 nm line-and-space patterns calculated at an acid generator concentration of 10 wt% and an effective

![Figure 2](image-url)

*Fig. 2. Dependence of chemical gradient on optical contrast.* (a) and (b) were calculated with the parameter sets $(R_{eff}, C_{AG}) = (0.1, 10)$ and $(0.2, 20)$, respectively. The numerical values on the right sides of the graphs denote the optical contrast.
reaction radius of 0.1 nm were 8.8, 8.2, and 8.0 nm at 10, 20, and 30 mJ cm\(^{-2}\) exposure doses, respectively. The optimum acid diffusion lengths calculated at an acid generator concentration of 20 wt% and an effective reaction radius of 0.2 nm were 7.6, 7.1, and 7.0 nm at 10, 20, and 30 mJ cm\(^{-2}\) exposure doses, respectively. It has been reported that the optimum acid diffusion lengths in 16 nm line-and-space patterns are 10.6, 10.1, and 9.9 nm at 10, 20, and 30 mJ cm\(^{-2}\) exposure doses, respectively.[13,41] In the 11 nm node, acid diffusion length should be reduced roughly by 20 %, compared with that in the 16 nm node if the same effective reaction radius is assumed.

By changing exposure dose, the average numbers of protected units at \(x=\pm p^{1/2}_1\), 0, and \(\pm p^{1/2}_2\) were calculated. Quencher concentration and PEB time were optimized to maximize the chemical gradient for each exposure dose. Figure 4 shows the dependences of \(N_L\), \(N_{DP}\), and \(N_S\) on optical contrast. With a decrease in optical contrast, \(N_L\) decreased and \(N_S\) increased. \(N_{DP}\) did not significantly depend on optical contrast. The difference between \(N_L\) and \(N_{DP}\) and that between \(N_{DP}\) and \(N_S\) were decreased by decreasing optical contrast.

The exposure dose dependence of the standard deviation of the number of protected units connected to a polymer molecule at \(x=\pm p^{1/2}_1\) after PEB was calculated. Figure 5 shows the effect of optical contrast on the final standard deviation at \(x=\pm p^{1/2}_1\). The dependence calculated with an optical contrast of 1.0 is shown in Fig. 5(a). When the initial standard deviation was 3.0, the final standard deviation did not markedly depend on exposure dose. With the decrease in the initial standard deviation, the exposure dose dependence increased. The final standard deviation significantly decreased with the increase in exposure dose when the initial standard deviation was close to 0. When optical contrast was decreased, a similar trend was observed as shown in Figs. 5(b) and (c). For \(\sigma_t=3.0\), the final standard deviation did not depend on optical contrast. However, the final standard deviation was increased by decreasing optical contrast at \(\sigma_t<3.0\). Also, the exposure dose dependence was markedly abrogated by decreasing optical contrast. Consequently, the final standard deviation significantly differed in the high-exposure-dose
region for a different optical contrast when the initial standard deviation was close to 0. These results indicate that the protected unit fluctuation can be suppressed by decreasing the initial standard deviation and increasing exposure dose. However, this effect is abrogated when the optical image is degraded by optimizing the process conditions in terms of the chemical gradient.

Next, the exposure dose dependence of the final standard deviation at $x=\pm p_{1/2}$ was calculated. Figure 6 shows the effect of optical contrast on the final standard deviation at $x=\pm p_{1/2}$. The final standard deviation did not depend on optical contrast. The dependence of final standard deviation on the initial standard deviation became lower than that at $x=\pm p_{1/2}$.

Finally, the exposure dose dependence of the final standard deviation at $x=0$ was calculated. Figure 7 shows the effect of optical contrast on the final standard deviation at $x=0$. Unlike the case for the acid generator concentration of 10 wt% and the effective reaction radius of 0.1 nm,[35] the final standard deviation did not significantly depend on the initial standard deviation at $x=0$. At an exposure...
dose of 5 mJ cm\(^{-2}\), the final standard deviation was slightly increased by decreasing optical contrast. At an optical contrast of 1.0, the final standard deviation was decreased by increasing exposure dose. However, the dependence of the final standard deviation on exposure dose was decreased by decreasing optical contrast. Therefore, the suppression of the protected unit fluctuation by increasing exposure dose cannot be expected when optical contrast is reduced.

From the results shown in Figs. 4 and 5, the exposure dose dependence of \((N_L-N_{DP})/\sigma_L\) at \(x=\pm p_{1/2}\). The optical contrasts were (a) 1.0, (b) 0.8, and (c) 0.6. The acid generator concentration was 20 wt%. The effective reaction radius for deprotection was 0.2 nm. \(\sigma_i\) was changed from 0 to 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0. The dashed lines \((1.4\sigma)\) represent the difference between the average number of protected units and the dissolution point at which severe pinching of resist lines started to be observed for ESR1 (6.1 \(\mu m\) length) and are shown for reference.

\(x=\pm p_{1/2}\) was calculated. Figure 8 shows the effect of optical contrast on \((N_L-N_{DP})/\sigma_L\). The difference required for the elimination of line breaks and severe pinching within a 6.1 \(\mu m\) line length in the case of ESR1 is shown for reference in Fig. 8.[18] A larger difference is considered to be required for the long-range elimination of line breaks and pinching. When the initial standard deviation was close to 3, \((N_L-N_{DP})/\sigma_L\) decreased with decreasing
optical contrast owing to the decrease in $N_L-N_{DP}$. However, $(N_L-N_{DP})/\sigma_L$ decreased with decreasing optical contrast owing to not only the decrease in $N_L-N_{DP}$ but also the increase in $\sigma_L$ when the initial standard deviation was close to 0. In the 11 nm node, the decrease in the initial standard deviation is probably required for the suppression of pinching.[35] The increase of the protected unit fluctuation at $x=\pm p_{1/2}$ caused by the optical contrast degradation is a significant problem.

From the results shown in Figs. 4 and 7, the exposure dose dependence of $(N_{DP}-N_S)/\sigma_S$ at $x=0$ was calculated. Figure 9 shows the effect of optical contrast on $(N_{DP}-N_S)/\sigma_S$. The difference required for the elimination of bridges within a 6.8 $\mu$m line length in the case of ESR1 is shown for reference in Fig. 9.[18] Similarly to the pinching, a higher difference is considered necessary for the long-range elimination. $(N_{DP}-N_S)/\sigma_S$ decreased with decreasing optical contrast. This was caused by the decrease in $N_{DP}-N_S$ and the increase in $\sigma_S$.

4. Conclusions

The relationships between stochastic phenomena (LER and stochastic defect generation) and optical contrast were investigated using a Monte Carlo simulation on the basis of the reaction mechanisms of chemically amplified EUV resists. Optical contrast did not affect the protected unit fluctuation at the boundary between lines and spaces. When the optical image was degraded, LER increased because of the decrease in chemical gradient. However, the protected unit fluctuation at the centers of lines and spaces increased with a decrease in optical contrast. Also, the difference between the average number of protected units at the center of lines or spaces ($N_L$ or $N_S$) and the dissolution point ($N_{DP}$) decreased with decreasing optical contrast. The stochastic defect generation was basically affected more by the optical contrast degradation than LER.

Acknowledgement

This work was partially supported by the New Energy and Industrial Technology Development Organization (NEDO).

References

1. S. Wurm, Jpn. J. Appl. Phys., 46 (2007) 6105.
2. T. Itani, J. Photopolym. Sci. Technol., 24 (2011) 111.
3. K. Maruyama, H. Nakagawa, S. Sharma, Y. Hishiro, M. Shimizu, and T. Kimura, Proc.

---

Fig. 9. Exposure dose dependence of $(N_{DP}-N_S)/\sigma_S$ at $x=0$. The optical contrasts were (a) 1.0, (b) 0.8, and (c) 0.6. The acid generator concentration was 20 wt%. The effective reaction radius for deprotection was 0.2 nm. $\sigma_i$ was changed from 0 to 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0. The dashed lines (1.75 $\sigma_i$) represent the difference between the average number of protected units and the dissolution point at which bridges disappeared for ESR1 (6.8 $\mu$m length) and are shown for reference.

---

SPIE, 8325 (2012) 83250A.

4. H. Tsubaki, S. Tarutani, N. Inoue, H. Takizawa, and T. Goto, Proc. SPIE, 8679 (2013) 867905.

5. Y. Ekinci, M. Vockenhuber, M. Hojeij, L. Wang, and N. Mojarad, Proc. SPIE, 8679 (2013) 867910.

6. R. Peeters, S. Lok, E. Alphen, N. Harned, P. Kuerz, M. Lowisch, H. Meijer, D. Ockwell, E. Setten, G. Schiffelers, J.-W. Horst, J.
Stoeldraijer, R. Kazinczi, R. Droste, H. Meiling, and R. Kool, Proc. SPIE, 8679 (2013) 86791F.

7. M. D. Smith, J. Biafore, and C. Fang, Proc. SPIE, 8682 (2013) 868203.

8. G. Gallatin, P. Naulleau, and R. Brainard, Proc. SPIE, 8322 (2012) 83221C.

9. W. Gao, A. Philippou, U. Klostermann, J. Siebert, V. Philipsen, E. Hendrickx, T. Vandeweyer, and G. Lorusso, Proc. SPIE, 8322 (2012) 83221D.

10. C. A. Mack, Proc. SPIE, 8325 (2012) 83251K.

11. H. Ito, Microlithography/Molecular Imprinting (Springer, Heidelberg, 2005) Advances in Polymer Science Series, Vol. 172, p. 37.

12. T. Kozawa, S. Tagawa, H. B. Cao, H. Deng, and M. J. Leeson, J. Vac. Sci. Technol. B, 25 (2007) 2481.

13. T. Kozawa, Jpn. J. Appl. Phys., 52 (2013) 016501.

14. T. Kozawa, Jpn. J. Appl. Phys., 51 (2012) 116503.

15. J. J. Santillan, K. Yamada, and T. Itani, Appl. Phys. Express, 7 (2014) 016501.

16. G. M. Gallatin, Proc. SPIE, 5754 (2005) 38.

17. T. Kozawa, S. Tagawa, J. J. Santillan, M. Toriumi, and T. Itani, J. Vac. Sci. Technol. B, 25 (2007) 2295.

18. T. Kozawa, J. J. Santillan, and T. Itani, Jpn. J. Appl. Phys., 52 (2013) 076502.

19. T. Kozawa, J. J. Santillan, and T. Itani, Appl. Phys. Express, 6 (2013) 026502.

20. T. Kozawa and S. Tagawa, Jpn. J. Appl. Phys., 49 (2010) 036501.

21. T. Itani and T. Kozawa, Jpn. J. Appl. Phys., 52 (2013) 010002.

22. T. Kozawa and S. Tagawa, Jpn. J. Appl. Phys., 50 (2011) 076505.

23. H. Yamamoto, T. Kozawa, A. Nakano, K. Okamoto, S. Tagawa, T. Ando, M. Sato, and H. Koman, Jpn. J. Appl. Phys., 44 (2005) 5836.

24. K. Natsuda, T. Kozawa, K. Okamoto, and S. Tagawa, Jpn. J. Appl. Phys., 45 (2006) L1256.

25. K. Natsuda, T. Kozawa, K. Okamoto, and S. Tagawa, Jpn. J. Appl. Phys., 46 (2007) 7285.

26. T. Kozawa, Jpn. J. Appl. Phys., 51 (2012) 086504.

27. R. Hirose, T. Kozawa, S. Tagawa, T. Kai, and T. Shimokawa, Jpn. J. Appl. Phys., 46 (2007) L979.

28. T. Fukuyama, T. Kozawa, S. Tagawa, R. Takasu, H. Yukawa, M. Sato, J. Onodera, I. Hiroswa, T. Koganaw, and K. Horie, Appl. Phys. Express, 1 (2008) 065004.

29. T. Kozawa and S. Tagawa, Jpn. J. Appl. Phys., 50 (2011) 030209.

30. H. Yamamoto, T. Kozawa, A. Nakano, K. Okamoto, Y. Yamamoto, T. Ando, M. Sato, H. Koman, and S. Tagawa, Jpn. J. Appl. Phys., 43 (2004) L848.

31. T. Kozawa, Jpn. J. Appl. Phys., 51 (2012) 116503.

32. T. Kozawa, Jpn. J. Appl. Phys., 51 (2012) 126501.

33. T. Kozawa, J. J. Santillan, and T. Itani, Jpn. J. Appl. Phys., 53 (2014) 036503.

34. T. Kozawa, J. Photopolym. Sci. Technol., 26 (2013) 643.

35. T. Kozawa, J. J. Santillan, and T. Itani, to be published in Jpn. J. Appl. Phys., 53 (2014).

36. T. Kozawa, H. Oizumi, T. Itani, and S. Tagawa, Appl. Phys. Express, 3 (2010) 036501.

37. T. Kozawa, H. Oizumi, T. Itani, and S. Tagawa, Jpn. J. Appl. Phys., 49 (2010) 066504.

38. T. Kozawa, H. Oizumi, T. Itani, and S. Tagawa, Jpn. J. Appl. Phys., 49 (2010) 116505.

39. T. Kozawa, H. Oizumi, T. Itani, and S. Tagawa, Jpn. J. Appl. Phys., 50 (2011) 076503.

40. T. Kozawa, H. Oizumi, T. Itani, and S. Tagawa, Jpn. J. Appl. Phys., 50 (2011) 126501.

41. T. Kozawa and T. Hirayama, Jpn. J. Appl. Phys., 53 (2014) 016503.