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SiO_2 single layer for reduction of the standing wave effects in the interference lithography of deep photoresist structures on Si

Edson J. Carvalho[a,*], Marco A.R. Alves[a], Edmundo S. Braga[a], Lucila Cescato[b]

[a]*FEEC-Unicamp, CxP 6101, 13083-970 Campinas, SP, Brazil*
[b]*IFGW-Unicamp, CxP 6165, 13083-970 Campinas, SP, Brazil*

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Abstract

We demonstrate that the use of a single SiO_2 film, with thickness corresponding to one standing wave (SW) period allows the recording of deep photoresist structures on silicon substrates by laser interference, without use of any additional antireflecting coating. This condition corresponds just to the opposite thickness (half SW period) previously proposed for using the SiO_2 films for phase-shifting the SW pattern. Theoretical and experimental results demonstrated that for the lithography of deep structures, the contrast of the SW pattern, the minimum light intensity of the SW pattern and the photoresist adhesion are the most important parameters of the process.

Keywords: Interference lithography; Standing wave pattern; Deep photoresist structures; RIE plasma etching

1. Introduction

Holographic or interference lithography is an interesting technique for recording periodic submicrometric structures in large areas. Many of these applications require the recording on silicon wafers [1–4]. Because of the high coherence of the laser light sources, employed in the interference lithography, the use of high reflectivity substrates generate serious problems to the lithography due to the presence of an additional interference fringe, parallel to the surface, called standing waves (SW). The effect may be so strong that impedes the lithography of photoresist films thicker than half of the SW period [5–7].

The alternative for reducing the SW contrast, offered by the photoresist manufacturers, is the use of bottom antireflective coatings (BARC) [8,9]. Such coatings provide a gradual refractive index variation between the photoresist and silicon, reducing the reflection and absorbing the transmitted light. There are also many materials proposed in the literature [10–12] that coated with the right thickness work as antireflecting (AR) coatings. The use of the BARCs or ARCs, however, requires the introduction of one or more steps in the lithographic process.

Even if a photoresist film thinner than one period of the SW is used, there is a standing wave node at the interface photoresist substrate that causes an overcut profile at the bottom of the structure [6,13,14]. To modify the photoresist profile, Efremow et al. [6] proposed the use of a SiO_2 film as a phase-shift layer. By using a SiO_2 thickness equal to half period of the SW pattern, an undercut photoresist profile is obtained. However, no attention to the SW contrast was expended in this work because the employed photoresist thicknesses were smaller than one period.

In this paper, we study, theoretical and experimentally, the influence of thickness of the SiO_2 in the SW pattern in the lithography of the deep photorresist structures, recorded by laser interference.

2. Theory

When a high reflectivity substrate is coated with a thin dielectric layer, the total-reflected wave is the sum of the wave reflected at the first interface and the multiple reflections inside the dielectric film [15]. The total reflection

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*Corresponding author. Tel.: +55 19 37882455; fax: +55 19 37884145.
E-mail address: carvalho@ifi.unicamp.br (E.J. Carvalho).

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coefficient for such case is given by [15]

$$r = \frac{r_{01} + r_{12}e^{i\varphi}}{1 + r_{01}r_{12}e^{i\varphi}}. \tag{1}$$

r_{01} being the reflection coefficient at the upper interface; r_{12} being the reflection coefficient at the interface dielectric film-substrate and the phase difference φ between the multiple-reflected waves is given by:

$$\varphi = \frac{4\pi}{\lambda_0} n_1 t \cos\theta_d. \tag{2}$$

n_1 being the refractive index of the dielectric film; t its thickness and θ_d the angle of incidence (inside the dielectric film).

Assuming that the upper interface is formed by photoresist–SiO_2, the bottom interface is SiO_2–Si and the incident light ($\lambda_0 = 457.9$ nm) is linearly polarized in TE direction we can calculate the total reflectance ($R = |r|^2$) by using Eq. (1). For each incident angle, the reflectance is a periodic function of the SiO_2 film thickness. For an incident angle inside the photoresist of $\theta_r = 7.88^\circ$ (corresponding to a fringe period $\Lambda = 1\,\mu m$), a refractive index of the unexposed photoresist $n_r = 1.67$, a refractive index of silicon oxide $n_1 = 1.465$ and a refractive index of the silicon substrate $N_2 = 4.599 + i0.13051$, the first maximum of the reflectance occurs for a SiO_2 film thickness of 79 nm while the first minimum corresponds to the SiO_2 thickness of 158 nm.

In Fig. 1 the reflectance is plotted as a function of the incident angle (θ_r), for the SiO_2 film thickness equal to 158 and 79 nm. In the same figure it is shown for comparison the reflectance for the single photoresist–Si interface. As it can be seen, from this figure, for the θ_r range, corresponding to fringe pattern periods $\infty \leqslant \Lambda \leqslant 0.36\,\mu m$), the reflectance for the SiO_2 thickness of 158 nm is approximately constant and equal to the reflectance for the single photoresist–Si interface. This occurs because the refractive index of the SiO_2 is lower than that of the photoresist. A reduction of the reflectance is only possible if an AR dielectric film with refractive index higher than the photoresist is used [15].

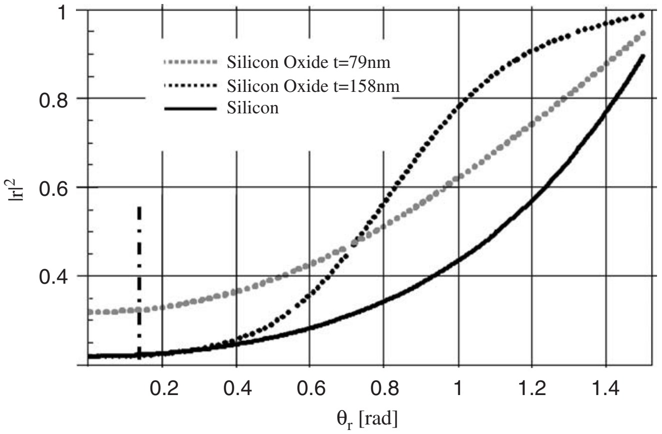


Fig. 1. Graphic of the reflectance $|r|^2$ as a function of incident angle inside the photoresist for three different substrates: (a) bare Si; (b) Si coated with a SiO_2 film thickness of 79 nm; and (c) Si coated with a SiO_2 film thickness of 158 nm.

In the interference lithography, two laser beams reach the sample forming symmetric angles in relation to its normal (direction y in Fig. 2a). The interference light pattern inside the photoresist film is a superimposition of multiples waves in the two directions of incident beams and their respective reflections. The resulting irradiance inside the photoresist film is given by [5]:

$$I = (1 + |r|^2 + 2|r|\cos(k_y y)) \times [(I_1 + I_2)(1 + m)\cos(k_x x)], \tag{3}$$

I_1 and I_2 being the irradiances of the interfering beams inside the photoresist, r is the total reflection coefficient at

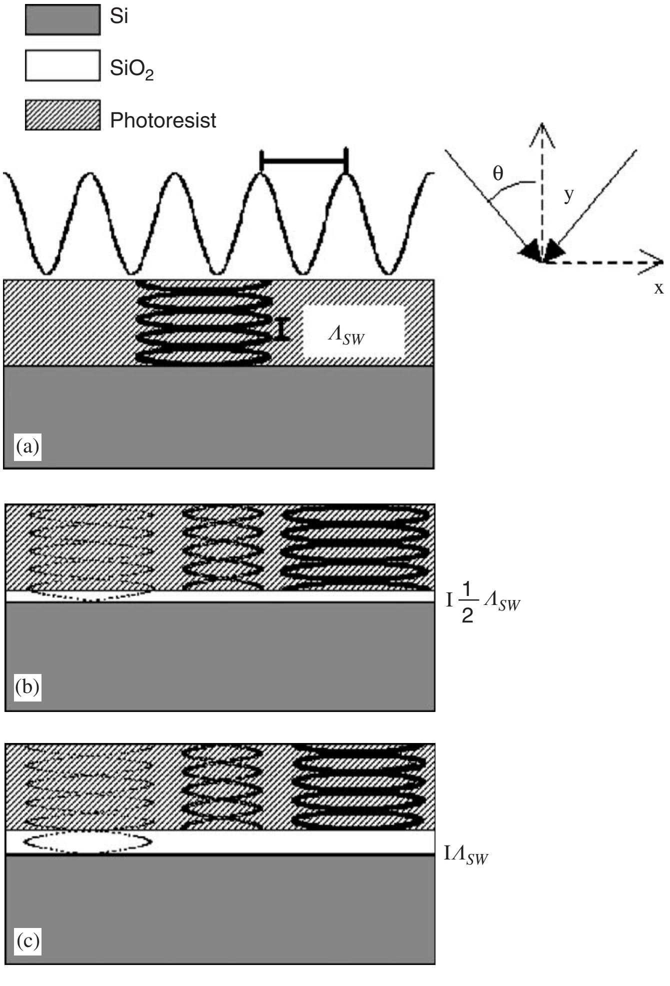


Fig. 2. Scheme of the standing wave patterns generated, inside the photoresist, by the waves reflected: (a) at the Si substrate; (b), at a SiO_2 film with 79 nm thickness; and (c) at a SiO_2 film with 158 nm thickness. The left pattern corresponds to the standing wave assuming only the reflection at the interface SiO_2–Si. The central pattern is generated by the reflection at the photoresist–SiO_2 interface and the right pattern corresponds to the actual standing wave pattern, resulting by the sum of all reflected waves in the photoresist. Note that the pattern generated by the photoresist–SiO_2 interface is in phase with the pattern generated by the reflection at the SiO_2–Si for the SiO_2 film thickness of 79 nm and in counter phase for the thickness of 158 nm.

the interface photoresist–substrate, and the fringe contrast m is defined as

$$m=\frac{2\sqrt{I_1I_2}}{I_1+I_2}. \tag{4}$$

The first term in Eq. (3) corresponds to the SW pattern that is parallel to the surface (direction x in Fig. 2a) and has a period Λ_S, while the second term corresponds to the principal fringe pattern, perpendicular to the surface (direction y in Fig. 2a) and whose period is Λ. Both periods are obtained from Eq. (3) by

$$k_x=\frac{2\pi}{\Lambda}=\frac{4\pi}{\lambda_0}n_r\,\sin(\theta_r)=\frac{4\pi}{\lambda_0}\sin(\theta), \tag{5}$$

$$k_y=\frac{2\pi}{\Lambda_{SW}}=\frac{4\pi}{\lambda_0}n_r\,\cos(\theta_r), \tag{6}$$

with n_r being the photoresist refractive index, λ_0 the laser wavelength in vacuum and θ and θ_r the half angle formed between the incident beams in air and inside the photoresist film, respectively.

The angle $\theta_r=7.88^\circ$ (corresponding to a fringe period $\Lambda=1\,\mu m$), marked in the graphic of Fig. 1 as a dotted vertical line, corresponds to a *SW period* $\Lambda_{SW}=158\,nm$ (inside the SiO_2). Note that the minimum of the total reflectance occurs just for this thickness of the SiO_2 film while the maximum of the reflectance occurs just for the thickness proposed by Efremow [6] of half SW period (79 nm).

The variation of the Reflectance, due to the different SiO_2 film thickness, changes the contrast of the *SW* pattern and the minimum light intensity at the nodal planes. Considering only the first term in Eq. (3) we can define the contrast of the SW as

$$C_{SW}=\frac{2|r|}{1+|r|^2}. \tag{7}$$

The minimum light intensity at the nodal plane corresponding to the two SiO_2 film thicknesses (79 and 158 nm) is, respectively (from Eq. (3)):

$$I_{min}=0.185[(I_1+I_2)(1+m)\cos(k_xx)] \tag{8}$$

and

$$I_{min}=0.28[(I_1+I_2)(1+m)\cos(k_xx)]. \tag{9}$$

Table 1 resume the values for the SW contrast (Eq. (7)) and the values of the SW minimum light intensity, for the two SiO_2 thicknesses. Note that, although there is a small variation in the contrast of about 12%, the SW minimum light intensity changes of about 45%.

The scheme shown in Fig. 2 illustrates the effect of the contrast and of the phase shift in the SW pattern inside the photoresist film. Fig. 2a shows SW pattern for the bare silicon substrate, that presents a node at the interface photoresist–Si because $n_r<N_2$. Figs. 2b and c show the scheme of the SW for the SiO_2 thicknesses of 79 and 158 nm, respectively. In these cases the resulting SW pattern (Eq. (3)) may be decomposed in a pattern formed by the waves reflected at the photoresist–SiO_2 interface and a pattern due the waves reflected at the SiO_2–Si interface. Note that the pattern formed by waves reflected at the photoresist–SiO_2 interface always present a anti-node at this interface, because $n_r>n_1$, while the phase shift of the pattern formed by the reflection at SiO_2–Si interface depends on the SiO_2 thickness. For the thickness $t=79\,nm$ (Fig. 2b), although the SW pattern has an anti-node at the interface (as proposed by Efremow et al. [6] to obtain an undercut photoresist profile), the patterns are in phase, increasing the contrast of the resulting SW pattern. For the SiO_2 thickness $t=158\,nm$ (Fig. 2c), the patterns are counter phased decreasing the contrast of the resulting SW pattern, but with a node at the interface (resulting in an overcut photoresist profile).

Table 1
Theoretical values for the contrast of the SW pattern and minimum light intensity of the SW for the SiO_2 film with thickness of 79 and 158 nm

	SiO_2 thickness	
	$t=79\,nm\ (\Lambda_{SW}/2)$	$t=158\,nm\ (\Lambda_{SW})$
C_{SW}	0.86	0.77
SW minimum light intensity	0.185	0.28

3. Experiment

In order to verify experimentally the effect of the SiO_2 film thickness on the SW in the interference lithography, similar exposures and development were performed using the photoresist Hoechst AZ 1518, diluted 1:1 in AZ thinner. The photoresist was spin coated on bare Si substrates and on SiO_2 films thicknesses of 72 and 157.4 nm, thermally grown in Si substrates.

The samples were, pre-baked at 70 °C for 20 min and then exposed to a fringe-locked holographic interference pattern [16], using the line $\lambda=457.9\,nm$ of an Ar laser. The interference pattern period was $\Lambda=1\,\mu m$, resulting in a semi-angle between the interfering beams in air of $\theta=13.24^\circ$ (in air) or $\theta_r=7.88^\circ$, inside the photoresist film.

For these experimental conditions and assuming a refractive index of the photoresist $n_r=1.67$, the period of the SW inside the photoresist film will be (from Eq. (4)) $\Lambda_{SW}=0.143\,\mu m$ and inside the SiO_2 ($n_1=1.465$) will be $\Lambda_{SW}=0.158\,\mu m$. The exposure dose was about 400 mJ/cm^2, and the development was done using MIF 312 diluted 1:1 in deionized water during 45 s.

For the recording of two-dimensional photoresist structures, a double holographic exposure was employed. In this case, after the first exposure of light energy dose of 380 mJ/cm^2, the sample was rotated 90° and exposed again to the same light energy.

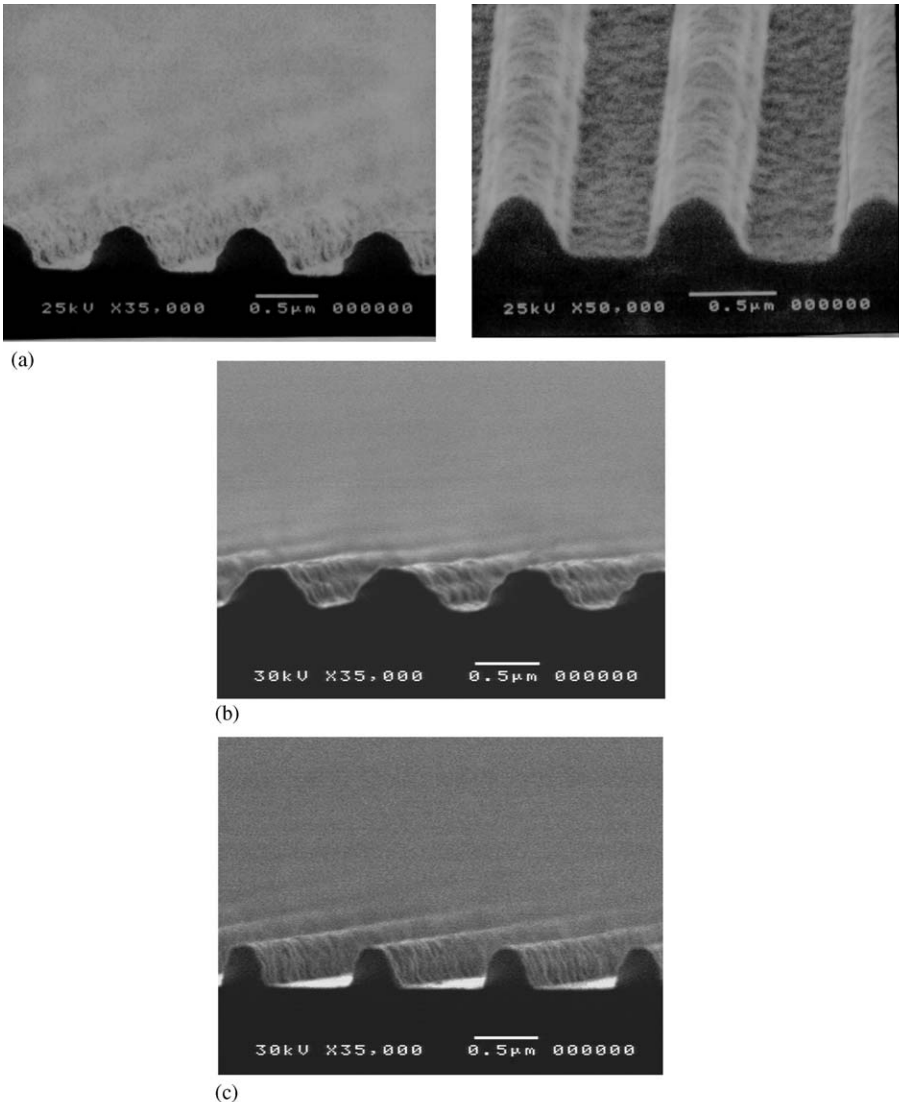
The cross-section of the recorded photoresist structures was analyzed by scanning electron microscopy (SEM).

4. Results and discussion

Fig. 3 shows the SEM photographs of the structures recorded in photoresist films with 300 nm of thickness, at the same conditions, on a bare silicon substrate (Fig. 3a), on a SiO_2 film with a thickness of 72 nm (Fig. 3b) and with 157.4 nm (Fig. 3c). These thicknesses of SiO_2 correspond to approximately to the maximum and minimum contrast of SW pattern, calculated in Section 2 (Fig. 2). Although the variation in the contrast (12%) and in the light intensity minimum (45%) seems to be small, both effects together are responsible for the remarkable difference in the lithography between the photoresist structures shown in Figs. 3b and c. In particular, the minimum light intensity determines the capability of the developer to cross the SW nodal planes [17]. This effect is particularly amplified due to the non-linear behavior of the photoresist development ratio as a function of the exposure dose [17].

Note that the SiO_2 thickness in Fig. 3b corresponds to the presence of an anti-node of the SW pattern at the interface photoresist–SiO_2 (as proposed by Efremow et al. [6] to phase-shift the SW pattern) while that of Fig. 3c corresponds to the presence of a node at the interface photoresist–SiO_2 (as illustrated in Fig. 2). These results clearly demonstrate that, for the recording of deep photoresist structures, the use of a SiO_2 film thickness equal to half period of the SW is not appropriate. By the other hand, as the deep photoresist structures present multiple SW periods, the phase shift of the SW does not change the profile. The unique effect of this phase shift would be a small change in the dimensions of the base of the recorded structures.

It can be observed also that the photoresist structure recorded on the SiO_2 film thickness of 157.4 nm (Fig. 3c) presents a much better definition in the opened channels than that recorded on bare silicon (Fig. 3a). The



(a)
(b)
(c)

Fig. 3. Recorded profiles in an AZ 1518 photoresist films, spin coated with 3000 r.p.m. (resulting in a thickness of about 0.3 μm): (a) on a Si substrate; (b) on a SiO_2 film of 78 nm thermally grown on a Si substrate; and (c) on a SiO_2 film of thickness 157.4 nm.

photoresist structure on the bare Si substrate presents a larger width and an enlargement of the microscopy (Fig. 3a) shows the presence of a roughness on the bottom, indicating the presence of residual photoresist. The better definition in the opened channels in the photoresist structures on SiO_2 film thickness of 157.4 nm is quite repetitive and cannot be explained by the theoretical results of Section 2. This fact indicates that the adhesion of photoresist on different substrates plays a fundamental hole in the photoresist lithography [18–21]. Nagata and Kawai [18] demonstrate that the adhesion of the photoresist, when immersed in developer, is much better on Si than on SiO_2 films. This fact explains the much better quality of the lithography on SiO_2 films (Fig. 3c) in comparison to that on Si (Fig. 3a). The poor photoresist adhesion on SiO_2 is responsible for the complete removal of the thin unexposed photoresist layer at the interface photoresist–SiO_2 (bottom of the structures).

To demonstrate the feasibility of the interference lithography on Si substrates using SiO_2 film thickness of one SW period, we recorded both one (Fig. 4a) and two-dimensional (Fig. 4b) deeper photoresist structures (700 nm). Note that the ripple caused by the SW pattern is better defined in the two-dimensional structure because it was exposed to the interference pattern twice. Besides the ripple, the lithography of two-dimensional structures on SiO_2 films with the thickness equal to one period of SW pattern is always successful while it does not work for the bare Si substrates and different SiO_2 film thicknesses.

Fig. 4c shows a low-magnification microscopy of the array of photoresist structures that exhibits clear bottom surface around the structures. The view of the array show also the uniformity of the structures that remains unchanged in all recorded area of about 1pol^2. Figs. 4d and e show the structures lithographed in the SiO_2 layer, by RIE with CF_4 (for 20 min with a RF power of 50 W), using the

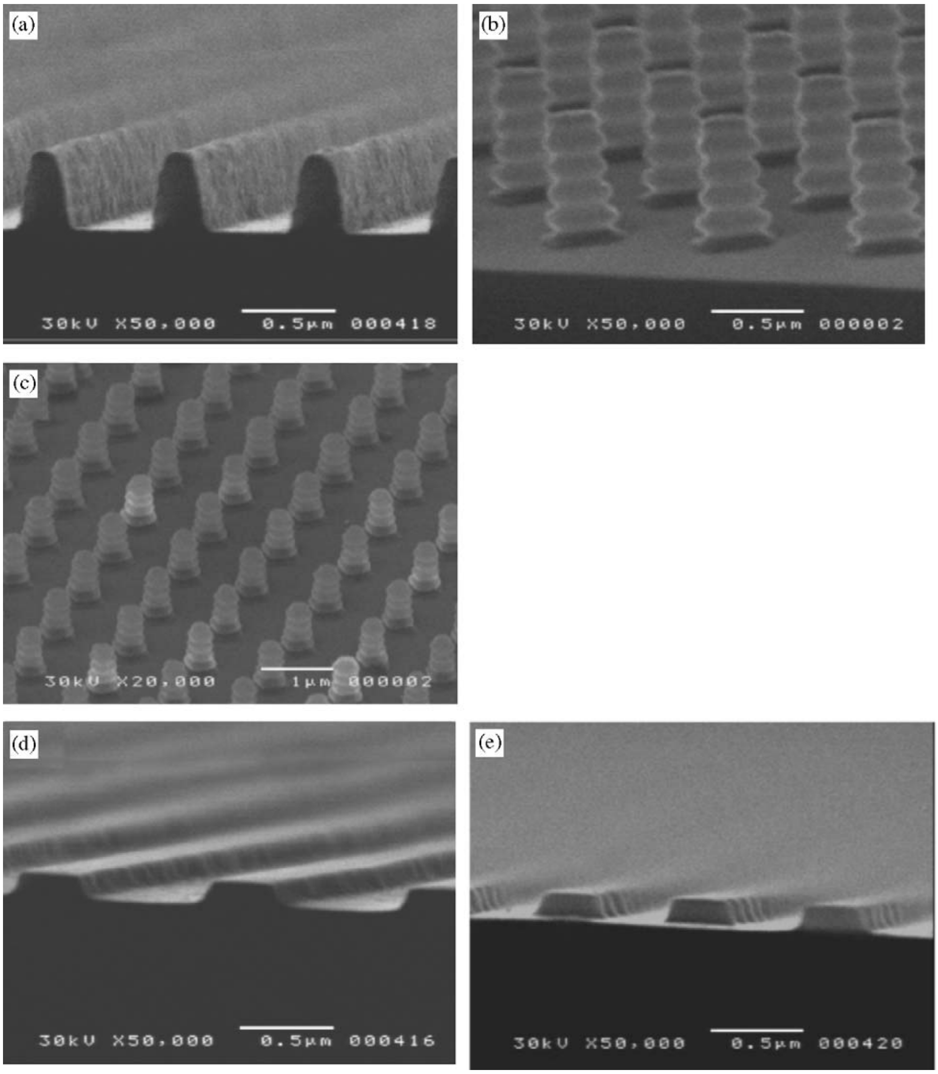


Fig. 4. One- and two-dimensional structures recorded in AZ 1518 photoresist on SiO_2 films with 157.4 nm, grown on silicon substrates and corresponding patterns transferred to the SiO_2 by RIE with CF_4. (a) One-dimensional photoresist structure; (b) two-dimensional photoresist structure; (c) low magnification view of the two-dimensional photoresist structures; (d) one-dimensional SiO_2 structures; and (e) two-dimensional SiO_2 structures.

photoresist structures of Figs. 4a and b as masks, respectively.

5. Conclusion

We reported the use of a single SiO_2 thermally grown layer with a thickness equal to one period of the SW pattern to improve the interference lithography of deep photoresist structures on silicon substrates.

We demonstrated that for the recording of deep photoresist structures, the phase shift of the SW pattern is not important, but the contrast of the SW pattern allied with the light intensity minimum are responsible for a remarkable difference in the lithography on Si substrates with different SiO_2 thickness. In particular, the minimum light intensity determines the capability of the developer to cross the SW nodal planes.

Due to the small variations of the total reflectance with the incident angle for the thickness of SiO_2 equal to one period of the SW pattern, this same SiO_2 film thickness can be used to record a wide range of fringe periods.

Although the contrast of the SW pattern, as well as the minimum light intensity are the same for bare silicon wafers and for SiO_2 films with thickness equal to one period of SW, the different adhesion of the photoresist on the SiO_2 and on Si explains the remarkable difference in the quality of the lithography for both cases.

The use of a single SiO_2 layer with a right thickness instead of BARs or ARs simplifies the entire process and is fully compatible with the VLSI technologies because: the SiO_2 can be thermally grown on silicon substrate; the SiO_2 can be patterned using the photoresist as mask; and the SiO_2 pattern is a good mask for etching the Si.

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