Journal of The Electrochemical Society, **158** (10) H1084-H1089 (2011)
0013-4651/2011/158(10)/H1084/6/$28.00 © The Electrochemical Society

Optimized Deep UV Curing Process for Metal-Free Dry-Etching of Critical Integrated Optical Devices

G. Sengo,[z] H. A. G. M. van Wolferen, and A. Driessen

Integrated Optical Micro Systems Group, MESA+ Research Institute; University of Twente, 7500 AE Enschede, The Netherlands

In this paper we present results of Deep UV-curing of resist followed by thermal treatment at temperatures up to 280°C. The curing process was optimized for positive resist profiles of Fujifilm with thicknesses from 0.3 to 3.0 μm. The procedure was for the first time employed to etch critical optical structures in silicon oxynitride. Furthermore, the effect of this resist treatment on the geometry and quality of the etched profiles in silicon, silicon oxide, silicon nitride, and silicon oxynitride, having dimensions as typically applied in integrated optical devices, was studied. Channel waveguides with steep and smooth sidewalls were realized, without usage of a metal hard mask which would reduce the optical performance, at high etch selectivity (up to 6) for the materials under investigation. The reliable fabrication of various integrated optical structures with critical dimensions, like sub-micron gaps between adjacent waveguide channels, was demonstrated.
 [DOI: 10.1149/1.3623584]

Manuscript submitted December 17, 2010; revised manuscript received July 14, 2011. Published August 10, 2011.

Photostabilization is a post lithographic resist treatment process, which allows hardening of the resist profile in order to maintain critical dimensions and to increase selectivity in subsequent process steps such as reactive ion etching and ion implantation. The resist structure is exposed to high intensity of Deep UV (DUV) resulting in a cross-linked outer skin of highly polymerised resist which can be hardbaked at elevated temperature far beyond the glass transition temperature (T_g) of the untreated resist. By this treatment the critical dimensions and the integrity of the resist profile are quite well maintained.

Positive photo resist is widely used masking material for the patterning of structures in IC fabrication and for the manufacturing of a wide range of micro- and nanosystems, e.g. integrated optical devices. In contrary to the electronic devices, where the patterning steps combine lateral dimensions on the nanoscale with a small step height, the main challenge in the patterning of optical devices consists in the achievement of high lateral resolution at a large step height. Typical waveguide structures for 400 to 1500 nm wavelength have a height of 100 to 1000 nm and a width of 200 to 3000 nm; while in electronic devices the relative dimensions of the layer stack are in the order of 10–50 nm for thermal SiO_2, 100–200 nm LPCVD Si_3N_4, 100–300 nm polysilicon and metal layers. In addition, the electromagnetic field in optical structures extends hundreds of nm into the surrounding layers. The roughness of the interfaces and the optical properties of these layers like index of refraction, homogeneity and absorption are critical for the performance of the devices.

In recent years, a large variety of integrated optical devices based on silicon oxynitride (SiON), silicon nitride (Si_3N_4), and silicon (Si) waveguides has been designed, realized and tested in our research group.[1–7] The majority of the integrated optical applications are based on channel waveguides with vertical side walls and a step height, which can be up to more than one micron. Moreover, some applications like gratings, photonic crystals or microring resonators[3,7] require excellent lateral resolution in order to ensure the reliable realization of sub-micron gaps between adjacent structures with large step height. Since the achievable resolution of standard lithographic processes is directly related to the thickness of the applied resist, the etch selectivity is a highly important parameter in the optical channel waveguide fabrication. Furthermore, the optical propagation loss is a crucial parameter in integrated optics. In order to realize low-loss optical channel waveguides, low sidewall roughness is a stringent requirement. In optical community the general accepted $\lambda/20$ criterion is used as rule of thumb for the roughness. For our applications, if the roughness $\leq$50 nm (i.e. $\leq \lambda/20$), the device will not suffer loss of performance.

For transferring the resist pattern into the optical waveguide layer dry etching techniques, like reactive ion etching (RIE), are exploited. Ion bombardment, inherent to dry etching processes, often causes damage to the resist profile resulting in increased sidewall roughness of the channel waveguide. Although the realization of well-defined, high quality optical channel waveguides was demonstrated by combining standard resist processing and optimized RIE etching, the range of achievable waveguide geometries become rather limited. Typical etch selectivities, achievable step height and resolution are 1:1, 1 and 1 μm, respectively. For typical SiON devices the structures have a width and height around 1×1 μm. In addition, for various applications, a gap of 0.6–0.8 μm is required. With a resist of 1 μm it is not possible to open gaps of 0.6–0.8 μm using G-line ($\lambda = 436$ nm) exposure. Therefore, one is forced to use thinner resist of around 500 nm that with conventional treatment will not withstand the dry etching process to etch 1 μm SiON.

In order to improve this performance, a more resistant masking material is required. Several strategies are known from literature: thermal treatment of resist, implementation of metal hard masks, and curing of resist followed by hardbake at elevated temperatures.

The applicability of straightforward thermal treatment of the resist patterns (typically around 120°C for G- and I-line resists) is usually limited, because the resist starts to reflow when its T_g is exceeded. Consequently the resist profile changes significantly and critical dimensions, like sub-micron gaps, are lost. Alternatively, in many fabrication schemes an additional metal hard mask was introduced. Although this approach often solved the selectivity problem, other loss-increasing effects, like metal contamination, and mask erosion, occur. The latter mainly causes re-deposition of small metal particles next to the channel waveguide resulting in micro-masking and the formation of spikes.[8] This is illustrated in Fig. 1, which shows a SiON waveguide where Nickel has been used as hard mask. Therefore the application of metal hard masks should be avoided in optical channel waveguide fabrication schemes. In addition, in our materials system, inorganic hard masks such as a-Si cannot be used, as the unwanted diffusion of Si-atoms into the surface layer will result in distortion of the optical field profile.

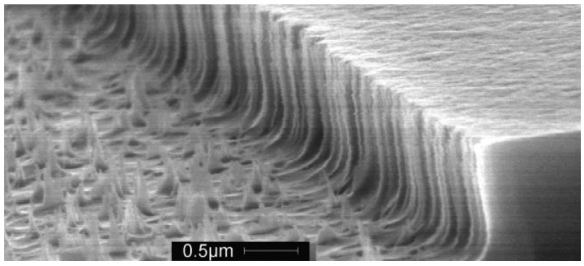

Figure 1. SEM micrograph of channel waveguide etched into a SiON layer applying an Ni hard mask and RIE.

[z] E-mail: G.Sengo@ewi.utwente.nl

Table I. Overview of parameters of applied resist layers

Code	Resist type	Dilution	Spin speed (rpm)	Resist thickness (μm)
R0-3	OIR 907/12	1:1	3200	0.3 ± 0.01
R0-5	OIR 907/12	1:2	6000	0.5 ± 0.01
R0-6	OIR 907/12	1:2	4000	0.6 ± 0.02
R0-9	OIR 907/12	—	6000	0.9 ± 0.02
R1-2	OIR 907/17	—	6000	1.2 ± 0.02
R1-5	OIR 907/17	—	4000	1.5 ± 0.02
R3-0	OIR 908/35	—	5500	3.0–0.04

A promising alternative for increasing the thermal stability and hardness of resist patterns was found by combining photostabilization of the resist with a high temperature treatment. The in this paper applied exposure process results in cross-linking of about 100 nm of the outer skin of the resist layer and allows a thermal treatment at temperatures far beyond the T_g of the untreated resist without causing deformation to the resist profile.[9] Consequently, the critical dimensions of the resist profile are maintained and the selectivity in subsequent RIE processing is increased. Several resist treatment methods have been proposed in literature: DUV hardening combined with a specific heat treatment,[9–11] plasma resist stabilization,[12] and photoresist polymerization through pulsed photomagnetic curing.[13]

The equipment for the standard DUV- curing process consists of an integrated irradiation source and a hardbaking element. The process is mostly carried out in nitrogen or oxygen atmosphere whereby the irradiation and heating is simultaneously taking place[10,14] In contrast, our process is simpler and you do not need special equipment. What one basically needs is an irradiation source with a wavelength of around 245 nm and a bake plate. The wafers are first intensely irradiated after which they are baked at temperatures of 180–280°C for 1–3 h.

In the next section we describe the experimental setup for the DUV- curing and channel waveguide etching for the selected materials. This is followed by presenting details and a discussion on the optimization of the curing process for various relevant resist thicknesses. Finally the application of the optimized resist treatment is discussed for the reliable fabrication of optical structures with dimensions down to the sub-micron scale.

Experimental

DUV-curing process optimization.—For the optimization of the DUV-curing and thermal treatment process resist layers of 3.0 μm, 1.5 μm, 1.2 μm, 0.9 μm, 0.5 μm, 0.6 μm and 0.3 μm were optimized. The applied resist type was positive G-line resist OIR 907 and 908 supplied by Fujifilm.[15] For resist layers with thicknesses below 1 μm, the resist was diluted in Ethyl 3- EthoxyPropionate (EEP) and Methyl 3- MethoxyPropionate (MMP) prior to spin coating according specifications provided by the manufacturer. An overview of the resist thickness and the relevant parameters is given in Table I.

After standard cleaning and resist spinning, the layers (R0-5, R0-6, R0-9, R1-2, R1-5, and R3-0) were exposed by an Electronic Visions EV620 Mask aligner with a 12 mW/mm^2 conventional G-line light source. For optimization of the resist treatment, laser written and E-beam masks were used. These contained a large variety of channel and gap dimensions, ranging from 0.9 to 4 μm and from 0.6 to 2 μm, respectively. The thin resist layer (R0-3), used in the fabrication of photonic crystals and gratings, was exposed by a home-made Laser Interference Lithography (LIL) system[16] operated at $\lambda = 266$ nm. The typical grating period and duty cycle were 500 nm and 2/3, respectively.

After development in OPD 4262 positive resist developer, the resist structures were irradiated at $\lambda = 245$ nm for a period varying from 5 to 40 min. Thereafter the structures were treated at temperatures of 180–280°C for 1–3 h.

Fabrication details of optical structures.—The transfer of the resist pattern into an optical waveguide layer was investigated for various materials which are typically applied in integrated optics. A brief overview of the materials, their fabrication procedure and basic properties is given in Tables II and III. For more details regarding the fabrication procedure we refer to the references given in the table.

After layer deposition, the resist was structured with the above described lithographic methods exploiting the optimized DUV-curing and thermal treatment. The resist pattern was transferred into the optical layers by the following RIE/ICP systems and chemistries:

- SiO_2: Plasmatherm 790 (parallel plate), Alcatel Adixen DE (Inductive Coupled Plasma – ICP); CHF_3, O_2, C_4F_8, He, CH_4
- SiON: Plasmatherm 790 (parallel plate) CHF_3, O_2
- Si_3N_4: Elektrotech Twin System (PF 340), Plasmatherm 790 (parallel plate), CHF_3, O_2
- Si: Elektrotech Twin System (PF 340), Plasmatherm 790 (parallel plate), SF_6, CHF_3, O_2

The resist thickness and etch depth were measured with a Dektak 8 profilometer (Digital Instrument Veeco Metrology Group). Based on these measurements, the vertical resist shrinkage caused by the curing process and the etch selectivities were determined. The resist and etching profiles were inspected with a Scanning Electron Microscope (SEM) of JEOL, type JSM-5610/5610LV. From the SEM micrographs results on maintenance of critical dimensions and overall integrity of the profile were extracted.

Results and Discussion

The Mechanism behind DUV-curing.—The DUV- curing process at wavelengths between 200 and 300 nm is frequently applied in hardening of widely used near UV (436–365 nm) positive resist systems in optical microlithography. These resists are known as G-line (436 nm) and I-line (365 nm) resists and consist of novolak resin, photoactive compound (PAC) and solvent. The treatment of the resist including DUV-exposure consists of the following steps:

I) spinning of the resist
II) mask exposure
III) development of the resist
IV) DUV exposure
V) heat treatment

Table II. Overview of applied optical materials, with corresponding fabrication procedure and basic properties.

		Layer properties	
Material	Fabrication method	Refractive index (λ= 633 nm)	Film thickness (μm)
SiO_2	Thermal oxidation	1.46	3.00–8.00
SiON	PECVD (Refs. 4, 18)	1.50–1.56	0.30–1.50
Si_3N_4	LPCVD (Refs. 2, 19)	2.01	0.04–0.30
Si	⟨100⟩ wafer	3.85	500

Table III. Overview of applied DUV- curing dose, temperature and shrinkage.

Code	Resist type	Dose DUV at 245 nm (mW/cm^2)	T_{DUV} (min)	T°C	$t_{T\ (hour)}$	Verticale Shrinkage in % (Due to outgassing) @ 180°C	@ 280°C
R0-3	OIR 907/12	15	5	180	1–3		
R0-5	OIR 907/17	15	10	180	1–3	5	
R0-6	OIR 907/17	15	10	180	1–3	5	
R0-9	OIR 907/12	15	15	180	1–3	5	
R1-2	OIR 907/17	15	15	120, 180, 250, 280	1–3	5	25
R1-5	OIR 907/17	15	20	180	1–3	5	
R3-0	OIR 907/35	15	40	180, 280	1–3	7	27

Step I to III are standard and normally followed by step V, when no DUV-curing is applied, in order to increase the stability of the resist pattern below the T_g of the resist. By DUV exposure, step IV, however a thin outer layer of higher polymerization of about 100 nm (Ref. 9) is obtained. The reason for this is that the applied source had a wavelength of 245 nm which is in the high absorptive region and therefore does not allow penetration of the complete resist layer.

Once this rigid layer is performed, step V can be employed to harden the resist far beyond the T_g of the bulk without unwanted deformation of the resist structures. It is outside the scope of this application oriented study to deal with the details of steps IV and V. Instead in the following we summarize the explanations found in literature.

The novalak resins are phenol-formaldehyde obtained by acid/base catalyzed polymerization of phenol and formaldehyde. The phenol-formaldehyde was later replaced by cresol-formaldehyde resins for lithographical performance. The PAC consist of Diazonaphthaquinone (DNQ) sulfonic acid esterified with trihydroxybenzophenone.[20,21] These near UV resists are also referred to as DNQ/Novolak or Novolak–diazonaphthoquinone resists.

Two models have been suggested in describing the mechanism behind the DUV- curing process. One model suggests that PAC is responsible for crosslinking[22] and the other one suggests that the novolak resin itself exhibits crosslinking upon DUV exposure. The latter was proposed by several other authors whereby the crosslinking of novolak (in absence of PAC) was demonstrated.

Spiertz et al.[23] conducted a detailed study on the source behind crosslinking and determined the most effective wavelength region for thoroughly hardening the resist structures to be between 300 and 320 nm. These findings are in agreement with several other studies.[24–26] When using shorter wavelengths, typically around the highly absorptive region of 250 nm, the penetration depth of the resist is reduced by more than an order of magnitude.[25] As a consequence only a thin skin layer of high polymerization is formed.[9,23,27]

Spiertz at al.[23] concluded that the UV hardening of novolak resists proceeds via a direct novolak excitation followed by a crosslinking reaction. The various additives which are part of resist formulations play no essential role in the hardening mechanism.

Sison et al.[28] reported that the crosslinking mechanism in photoresists involve the interaction between the DNQ and the novolak resin, or, interaction of the novolak resin by itself.

While the conclusions might sound solid that the various additives play no essential role in hardening mechanism, one should be aware however that although DNQ/Novolac resists are the principal pattern transfer materials of the semiconductor industry for many years - the first DNQ/Novolac system was introduced in a positive tone printing plate around 1950 (Ref. 29) - there was never a clear understanding of the way these resists work until a decade ago.[21]

Based on the aforementioned investigations, one tends to give the preference to the second model as the source of crosslinking to withstand hardbake at elevated temperatures far beyond the Tg of the resist, namely: Novolak resin.

Regarding the most effective wavelength region (300–320 nm) to thoroughly harden the resist, one should be aware that there might be a slight shift in the region from resist to resist sort because the amount of cresol (novolak), used in different resist formulations, affects light absorption.[30]

In addition to the DNQ/Novolak resist system, DUV curing is also applied to the high resolution DUV resist (248 nm) used for 180 nm applications as well, to enable elevated hardbake temperatures. Like DNQ/Novolak these DUV resists consist of three components, however with a different chemistry. The main components are a polymer matrix with photo acid generator (PAG) and photosensitizer.[20,31,32] These photo resists are called chemically amplified (CA) resists because upon photochemical reaction, the acid concentration increases. The amplification of acid during the postexposure bake (PEB) causes chemical transformations in the resist which makes the exposed regions of the resist soluble in basic developers. In contrast to DNQ/Novolak resist, the main component in CA resists is photo-inactive, exhibiting no strong absorption of the light. This makes it possible to design high transmittance acid labile polymers in deep UV regions.

Because the chemistry of DUV- resists is different compared to DNQ/Novolak, also the reaction products during DUV-curing are different. Therefore an empirical approach is used to optimize the DUV-curing of DUV-resists,[11] however as noted by R. Mohondro[14] it is not 'copy-exact' compared to DNQ/Novolak resists and the process engineer needs to take the time to optimize the DUV-curing, for there are various DUV-resists available with slightly different formulations.[29]

Optimization of the curing and heating process.—The success of the photostabilization process strongly depends on the optimization of the two decisive processing steps, namely the irradiation and heating.[14] If the irradiation is not performed well, the internal stress due to heating or softening of the material above T_g might cause the deformation of the resist profile. On the other hand if the heating process is not carried out properly, the core of the resist profile will not have enough time to outgas and to harden resulting in deformation of the structure.

The optimization of the Fujiflim OIR 907 and 908 positive photo resist procedure is based on the DUV hardening of the outer skin and subsequent baking. The aim of this work was to develop a reliable, fast and repeatable method to produce high quality critical optical sub-micron structures with standard available lithographical equipment and without usage of metal masks. Detailed fundamental resist investigations were beyond the scope of this study. We applied flood exposure ($\lambda = 245$ nm and intensity 15 mW/cm^2) and baked the structures at 180°C for 1–3 h.

Despite the high absorption at 245 nm, we succeeded to hardebake structures of 0.3–3.0 μm G-line resist at 180°C for 1–3 h and produced high quality critical optical structures. After dry etching, the hardened resist could be removed by a combination of oxygen plasma and 100% HNO_3. Typical times to remove the resist were, depending on the thickness, 10–30 min O_2- plasma and 30 min HNO_3. In the following we first will discuss the optimization of 1.2 μm resist that will serve as example to the optimization of other thicknesses.

Structured, 1.2 μm- thick positive resist is commonly applied in integrated optics, because due to the good trade-off between resolution limitations and achievable etch depths the fabrication of a large range of devices is enabled. Therefore the DUV- curing and thermal treatment process were first optimized for 1.2 μm-thick resist patterns (R1-2). The cross-section of a typical structure as obtained in this resist after standard lithography is depicted in Fig. 2a. Channels with horizontal dimensions down to 1 μm and gaps of 1 μm can be reliably realized. The side-wall angle is about 82°, what means that the ratio of the bottom width of the structure over the top width is about 1.1. For the optimization of the curing process the following parameters have been varied: DUV exposure time t_{DUV}, hardbake temperature T and hardbake time t_T. The impact of this parameter variation on the properties of the resist structure is summarized in Tabel III.

Figure 2b shows the result of hardbaking without DUV- curing. As can be seen, the profile has severely changed because of flowing of the resist when exceeding the T_g, with the result of loss of the critical dimensions. Figure 2c shows the importance of DUV irradiation. The irradiation is too short to form a strong crosslinked outer-skin to withstand elevated temperatures above Tg, resulting in the reflow of the profile. Figure 2d is the result of 5 min DUV-curing followed by hardbake at 120°C for 30 min. The critical dimensions as well as integrity of the structure are well-maintained. However, at higher temperature and longer baking time, the irradiation for 5 min is not sufficient to form the outer skin of 100 nm to withstand high temperatures. Experiments with Irradiation for 10 min showed that though it withstood the hardbake, however it is still not long enough to maintain the critical dimensions at elevated temperatures and longer baking time.

The minimum DUV-curing time for resist R1-2 to maintain the critical dimension and the integrity of the profile was found to be 15 min as shown in Fig. 2e where the resist profile was baked at 180°C for 3 h.

After achieving the optimum DUV-curing time, the resist can be further baked at higher temperatures. Structures baked at 250°C for 2 h maintained the critical dimensions as well as the overall integrity. The quality of the structures started however to degrade at temperatures above 280°C.

Figure 2f is the result of hardbake at 280°C for 2 h. Although the quality of the profile is still maintained well, however the so-called "foot" is clearly being formed. It appears that the bottom of the profile is slightly broader than the top which is of course partly inherent to the lithographic process, as can be seen in Fig. 2a. The occurrence of the "foot" is also clearly observed by I. Pollentier et al.[17]

To avoid the forming of the "foot", it is necessary to apply the hardbake below 280°C. For our applications, the resist structures are hardbaked at 180°C.

Besides the commonly applied layers of 1.2-μm thickness, resist patterns based on films with a different thickness are particularly interesting for various, specific applications. Optical components like directional couplers, arrayed waveguide gratings, ring resonators or race track sections require a well-defined gap between adjacent channel waveguides in order to guarantee correct overlap and coupling conditions. When applying a waveguide technology based on high-index materials, e.g. Si_3N_4, or arrayed waveguide gratings in SiON, required gap dimensions are at the sub-micron level.[5,7] For these applications improved resolution in the lithography is crucial. Therefore, thinner resist (R0-5, R0-6), was investigated. For fabrication of gratings and photonic crystals with LIL resist R0-3 was used. Resist with significantly larger thickness (R3-0, R1-5) is mainly interesting for applications with low resolution demands requiring a deep etch step in oxide and silicon like multimode devices or preparation of end facets.

The optimization of the DUV-curing and thermal treatment of the resist layers with different thickness was carried out similar to the optimization of the 1.2-μm resist. The results are summarized in Fig. 3.

As discussed in Sec. 3.1, the DNQ/Novolac resists have high absorption in the 245 nm region. The thicker the resist, the higher the absorption[24,25] obviously, and therefore longer exposure time is required. For 3 μm resist it was found that a minimum exposure time of 40 min is needed to create a crosslinked skin which withstands temperatures of 180°C for 1–3 h. This kind of resist thicknesses are used for etching deep profiles in SiON, SiO_2 and Si where other masks cannot be used. Following the same procedure, the

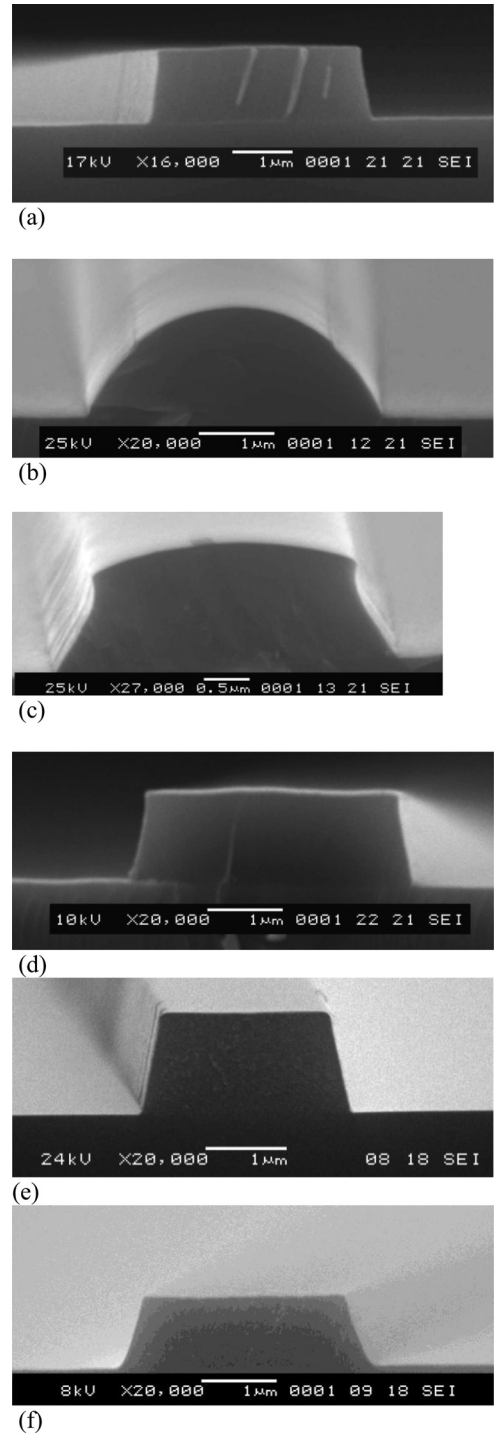

Figure 2. SEM micrographs with cross-sectional view of resist profiles - (a) after development step of standard lithography procedure, (b) harbake at 120°C for 30 min without DUV-curing, (c) DUV-curing for 1:30 min and hardbake at 120°C for 30 min, (d) DUV- curing for 5 min followed by hardbake at 120°C for 30 min, (e) DUV-curing for 15 min followed by hardbake at 180°C for 3 h, (f) DUV-curing for 15 min followed by hardbake at 280°C for 2 h.

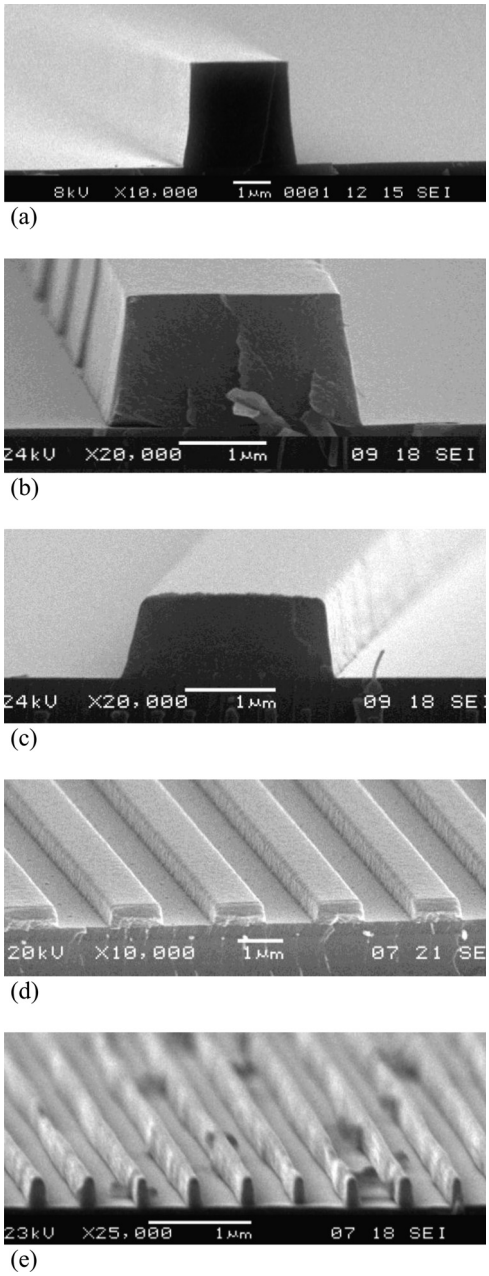

Figure 3. SEM micrographs with cross-sectional view of resist profiles after optimized DUV-curing and thermal treatment for (a) Resist R3-0, DUV- curing for 40 min followed by hardbake at 180°C for 2 h, (b) Resist R1-5, DUV-curing for 25 min, followed by hardbake at 180°C for 3 h, 3 (c) Resist R0-9, DUV-curing for 15 min, followed by hardbake at 180°C for 3 h, 3 (d) Resist R0-5, DUV-curing for 10 min, followed by hardbake at 180°C for 3 h, 3 (e) Resist R0-3, DUV-curing for 5 min, followed by hardbake at 180°C for 2 h.

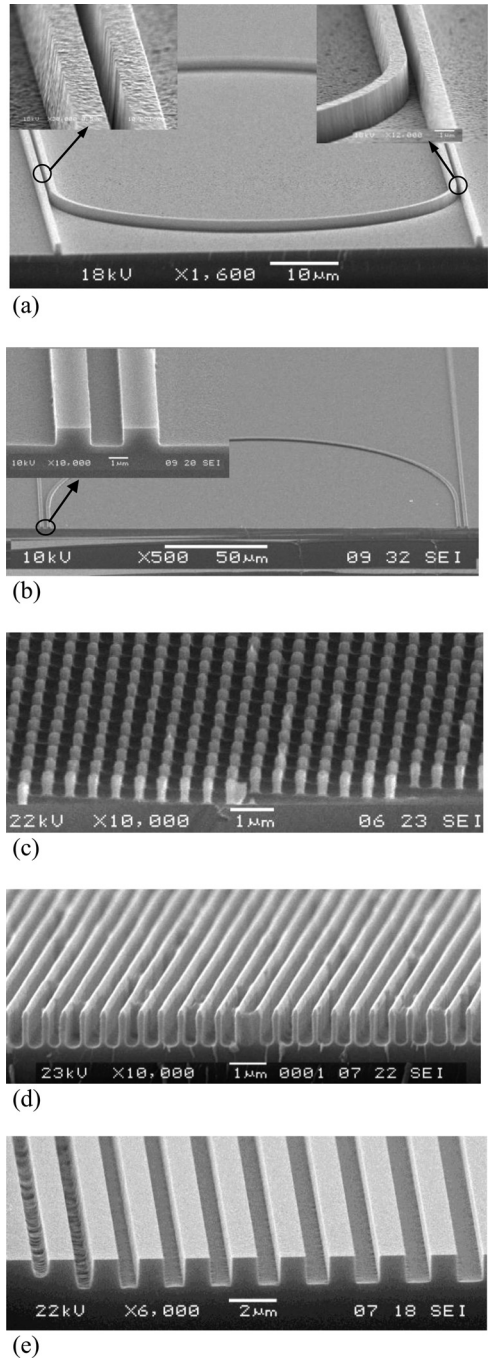

Figure 4. SEM micrographs with cross-sectional view of optical waveguides and teststructures after striping of resist, a) Example of a microring resonator with a gap of 600 nm between the waveguide and the ring. The height is 1.7 μm etched in SiON layer of 2.5 μm deposited on 8 μm thermal oxide wafer using resist R0-5, b) Example of microresonator with a height of 0.9 μm etched in silicon . The gap is around 1.6 μm, c) Example of photonic pillars of 750 nm height etched in silicon using resist R0-3 obtained by LIL, d) Example of gratings of 750 nm etched in silicon using resist R0-3 obtained by LIL, e) Example of a SiON test structure of 1.1 μm using resist R0-6.

exposure time for 1.5, 0.9, 0.5, and 0.3 μm was determined to be 25, 15, 10 and 5 min respectively.

This simple resist hardbake method has been employed to produce high quality optical structures, as could be verified by careful optical characterization. The measurements on a extremely sensitive interferometric device (an arrayed waveguide grating AWG for the wavelength range of 740–960 nm) are in excellent agreement with simulations.[5] Without hardbake the critical dimension loss would have been around 100 nm, while employing the hardbake procedure no loss could be observed. The performance of devices also strongly depends on the uniformity and refractive index of the PECVD layers. It appears that obtaining a good uniformity in structural dimensions and refractive index over 4- inch wafer is a quite challenging task.

Etch selectivity.—Experiments have been carried out with resist baked at 180 and 280°C to investigate the etch selectivity. There was no noticeable difference measured between resist baked at these

two temperatures. Therefore, for the further experiments, the resist profiles had an optimized hardbake with a final temperature step at 180°C.

For PECVD SiON layers of 1.0–2.5 μm deposited on silicon, a selectivity of 6 was obtained. For layers of 1.5–2.5 μm SiON deposited on 8 μm thermal oxide a selectivity of 5 was obtained. For silicon a selectivity of 4–5 is obtained for etching controlled structures of 200 nm up to 1000 nm in the PF 340 Reactive Ion Etching twin system. For hardbaked resist no sidewall loss of etched structures was observed. As regards roughness of structures, it depends highly on mask quality (E-beam or laser written) and the height of etched structure. The deeper the etched structure, the more pronounced the roughness.

For oxide, a selectivity of 4 was obtained in the Plasmatherm 790 and a selectivity of 6 was obtained in the Alcatel Adixen DE Inductive Coupled Plasma etching machine.

Examples of optical structures etched with DUV-cured and hardbaked resist at 180°C.—Initial experiments have been carried out with PECVD SiON layers ranging from 1.0 to 2.5 μm, because from the lithographic point of view, SiON is the most difficult material in achieving high resolution and high etching steps. If the photostabilization process could be optimized for SiON, other materials like SiO_2, Si_3N_4 and Si would form no problem. Under specific conditions it is possible for conventional contact mask lithography with a source wavelength of 436 nm, to open gaps of 600 nm, for example between a waveguide and a laterally coupled microring resonator.

Employing the optimized resist treatment process, a variety of critical optical structures in SiON, SiO_2, Si and Si_3N_4 have been realized. In Fig. 4 some examples, as a matter of demonstration, of these critical optical structures are presented.

Figure 4a is a typical example of a microring resonator used for telecom applications obtained by SiON- technology using resist R0-5. Microring resonators with a gap of around 1 μm and a thickness 2.5 μm, etched in SiON, using resist R0-9, were successfully realized. Figure 4b is an example of microring resonator etched in Silicon.

Figures 4c and 4d are examples of respectively photonic pillars and gratings of 750 nm height etched in silicon using resist R0-3. In Fig. 4d, the resist has not been removed after etching. There is still around 150 nm resist left. The defect in the cross-section is not caused by polymers, but by cleaving.

In Fig. 4e a SiON test waveguide structures of 1100 nm height is obtained by using resist R0-6. The sidewall angle is 89° and the minimum gap size is 700 nm. The first and second gap from left are not completely open. This has to do with layer thickness, lithography and reactive ion etching.

Conclusion

In this work we applied for the first time the skin hardening procedure to optimize DUV- curing of Fujifilm OIR 907 and OIR 908 positive G-line photo resist at 245 nm source wavelength. Despite high absorbance in the region of 245 nm, we successfully hardbaked structures of 0.3–3.0 μm G-line resist at 180°C for 1–3 h and produced high quality critical optical sub-micron structures with standard available lithographical equipment. The structures could be further baked up to 280°C.

The DUV-curing of the resist is proven to be strong, repeatable and robust to withstand the subsequent process steps with minimum loss of critical dimension. The method is safe, clean, reliable, easy to apply and can be used for the production of a wide range of critical optical devices in silicon, thermal silicon oxide, nitride and silicon oxynitride. In this way, the use of metal masks, causing severe problems in optical applications, can be avoided.

The resist structure is exposed to high intensity of DUV radiation resulting in a cross-linked outer skin with a higher degree of polymerization which can be hardbaked at elevated temperature far beyond the original T_g of the resist. In this way the critical dimensions and the integrity of the resist profile is quite well maintained. The higher the hardbake temperature, the higher the losses of the critical dimensions and the more pronounced the forming of the "foot" at the bottom of the profile. Therefore, to avoid 'footing' of the resist, the structures were standard baked at 180°C for 1–3 h.

Acknowledgment

This work is partly funded by the several projects among other the Dutch National Broadband Photonics Access project, Flexible Multiwavelength Optical Local Access Network Supporting Broadband Services, Laser Interference Lithography and Freeband BBphotonics project, agencies STW, Senter and IOP.

1. K. Wörhoff, C. G. H. Roeloffzen, R. M. de Ridder, A. Driessen, and P. V. Lambeck, *J. Lightwave Technol.*, **25**, 1276 (2007).
2. P. V. Lambeck, G. J. Veldhuis, R. G. Heideman, and K. Wörhoff, *Quin. Anal.*, **18**, 10 (1999).
3. W. C. L. Hopman, H. J. W. M. Hoekstra, R. Dekker, L. Zhuang, and R. M. de Ridder, *Opt. Express*, **15**, 1851 (2007).
4. K. Wörhoff, L. T. H. Hilderink, A. Driessen, and P. V. Lambeck, *J. Electrochem. Soc.*, **149**, F85 (2002).
5. N. Ismail, F. Sun, G. Sengo, K. Wörhoff, A. Driessen, R. M. de Ridder, and M. Pollnau, *Opt. Express*, **19**, 8781 (2011).
6. B. I. Akca, N. Ismail, G. Sengo, F. Sun, J. Kalkman, A. Driessen, M. Pollnau, K. Wörhoff, and R. M. de Ridder, *IEEE J. Sel. Top. Quantum Electron.*, Submitted.
7. D. J. W. Klunder, F. S. Tan, and T. V. van der, H. F. Bulthuis, G. Sengo, B. Docter, H. J. W. M. Hoekstra, and A. Driessen, *J. Lightwave Technol.*, **21**. 1099 (2003).
8. C. Roeloffzen, Ph.D. Thesis, University Twente, Netherlands (2002).
9. R. Allen, M. Foster, and Y. Yen, *J. Electrochem. Soc.*, **129**, 1379 (1982).
10. R. Mohondro, J. Eisele, D. Whisteside, T. Romig, and M. Bishop, *Future Fab Int.*, **1**, 235 (1997).
11. G. Jordhamo and W. Moreau, *Proc. SPIE*, **2724**, 588 (1996).
12. W. H. L. Ma, *Proc. SPIE*, **333**, 19 (1982).
13. P. A. Ruggerio, *Solid State Technol.* **27**, 165 (1984).
14. R. Mohondro, *Solid State Technol.*, **46**, 69 (2003).
15. http://www.fujifilm-ffem.com, last accessed June 2011.
16. F. J. van Soest, H. A. G. M. van Wolferen, H. J. W. M. Hoekstra, *Jpn. J. Appl. Phys. Part 1*, **44**, 6568 (2005).
17. Pollentier, P. Jaenen, C. Baerts, and K. Ronse, *Future Fab Int.*, **12**, 161 (2002).
18. M. G. Hussein, K. Wörhoff, G. Sengo, and A. Driessen, *Thin Solid Films*, **515**, 3779 (2007).
19. K. Wörhoff, P. V. Lambeck, H. Albers, O. F. J. Noordman, N. F. van Hulst, and Th. J. A. Popma, *Proc. SPIE*, **3099**, 257 (1996).
20. R. Debmalya, P. K. Basu, S. V. Eswaran, *Photoresists Microlithogr. Reson.* **7**, 44 (2002).
21. A. Reiser, Z. Yan, Y.-K. Han, and M. S. Kim. *J. Vac. Sci. Technol. B*, **18**, 1288 (2000).
22. H. Hiraoka and J. Pacansky, *J. Vac. Sci. Technol.*, **19**, 1132 (1981).
23. E. J. Spiertz, F. A. Vollenbroek, R. D. Verhaar, and J. G. Dil, *Proc. Microcircuit Eng.*, **85**, 527 (1985).
24. K. J. Orvek and M. L. Dennis, *Proc. SPIE*, **771**, 281 (1987).
25. J. C. Matthews and J. I. Willmott, Jr., *Proc. SPIE*, **470**, 194 (1984).
26. E. B. Vàzsonyi, S. Holly, and Z. Vèrtesy, *Microelectron. Eng.*, **5**, 341 (1986).
27. D. W. Johnson, *Proc. SPIE*, **469**, 72 (1984).
28. E. Sison, M. D. Rahman, D. Durham, and J. Hermanowski, *Proc. SPIE*, **2438**, 378 (1995).
29. S.-Y. Moon and J.-M. Kim, *J. Photochem. Photobiol.*, **8**, 157 (2007).
30. E. Gipstein, A. C. Ouano, and T. Tompkins, *J. Electrochem. Soc.*, **129**, 201 (1982).
31. E. Reichmanis and L. F. Thompson, *Microelectron. Eng.*, **14**, 215 (1991).
32. P. B Sahoo, R. Vyas, M. Wadhwa, and S. Verma, *Bull. Mater. Sci.*, **25**, 553 (2002).