Effective Silicon Oxide Formation on Silica-on-Silicon Platforms for Optical Hybrid Integration

Tae-Hong Kim, Hee-Kyung Sung, Ji-Won Choi, and Ki-Hyun Yoon

This paper describes an effective method for forming silicon oxide on silica-on-silicon platforms, which results in excellent characteristics for hybrid integration. Among the many processes involved in fabricating silica-on-silicon platforms with planar lightwave circuits (PLCs), the process for forming silicon oxide on an etched silicon substrate is very important for obtaining transparent silica film because it determines the compatibility at the interface between the silicon and the silica film. To investigate the effects of the formation process of the silicon oxide on the characteristics of the silica PLC platform, we compared two silicon oxide formation processes: thermal oxidation and plasma-enhanced chemical vapor deposition (PECVD). Thermal oxidation in fabricating silica platforms generates defects and a cristobalite crystal phase, which results in deterioration of the optical waveguide characteristics. On the other hand, a silica platform with the silicon oxide layer deposited by PECVD has a transparent planar optical waveguide because the crystal growth of the silica has been suppressed. We confirm that the PECVD method is an effective process for silicon oxide formation for a silica platform with excellent characteristics.

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I. INTRODUCTION

Recently, the rapid, global spread of the optical Internet and multimedia communications has accelerated the growth of optical communications networks. Optoelectronics and photonic technologies have led to remarkable progress in optical wavelength-division multiplexing (WDM) [1]-[5] and to successful demonstrations of terabit-capacity transmission. Photonic networks require various kinds of high-functioning photonic components with WDM. In addition, optical communication components and modules have rapidly changed from discrete, hybrid components [6] to planar, hybrid-integrated ones [7]-[18]. The silica-based planar lightwave circuit (PLC) for hybrid integration is a promising way to provide photonics components. Its technology makes it possible to construct high-functioning components by combining the passive function of a PLC with the active function of opto-electronic (OE) devices hybridized on silica-on-silicon PLC platforms [8]-[18].

In silica PLC platforms for hybrid integration, OE devices are flip-chip bonded on a silicon terrace as an optical bench and a heat sink of the PLC platform, and the device can be aligned by passively placing the device onto the silicon terrace. Silica PLC platforms require many fabrication processes: silicon terraces and trenches are formed by etching a silicon substrate to make silicon benches with terraces and trenches; silica film is formed by flame hydrolysis deposition (FHD); flattening the surface by polishing; and silica waveguide formation.

In making a silica platform, before the silica film can be deposited, it is necessary to form a silicon oxide layer, which must achieve excellent compatibility at the interface between the silica film and the silicon substrate [18]-[21]. In this paper, we investigate the effects of silicon oxide on silicon substrates and what processes effectively form the silicon oxide layer to create an excellent silica platform.

II. EXPERIMENTS

To examine the effects of silicon oxide in forming the silica layer by FHD, we carried out experiments on two types of silica platforms, one on a non-etched silicon substrate and one on an etched silicon substrate. First, we used silicon substrates with and without silicon oxide fabricated by thermal oxidation and PECVD processes on a non-etched, bare silicon substrate. Second, to investigate the influence of the silicon oxide layer during the formation process for the silica film on the silica platform, we used an etched silicon optical bench with silicon oxide fabricated by thermal oxidation and PECVD.

Figure 1 shows the configuration of the silica platform for the hybrid integrated optical module which we reported in [7] and used as the basic specimen for the current experiment. Figure 2 shows the detailed fabrication procedure. The silicon wafer, which was first polished on both sides, was patterned and wet-etched in a KOH solution to form the silicon bench with a terrace and a trench. Next, 1 μm thick silicon oxide layers were formed over the etched silicon bench and trench with thermal oxidation and with PECVD. Thermal oxidation was carried out at 1050 °C for 5 hours with 50% O_2 and 50% H_2O (vapor) mixtures, and silicon oxide film by PECVD was also prepared at 250 °C for 30 min using SiH_4 and N_2O gas mixtures.

The under-clad silica layer on the silicon substrate and bench with silicon oxide were formed by FHD and planarized by mechanical polishing. The core layer was also deposited by FHD. The patterns of the PLC core were formed by reactive ion etching (RIE) of the core layer. The structure of the planar optical waveguide in the silica PLC platform had a 6 μm thick square waveguide core buried in thick under- and over-clad layers. The over-clad silica layer with a thickness of about 20 μm was also formed by FHD. For planarization of the over-clad surface, the over-clad layer was also RIE-etched until the silicon patterns were exposed.

The surface morphology of the silica film and platform was observed by an optical microscope. The cross-sectional morphology of the planar silica optical waveguide in the silica platform was investigated by using a microscope with visible light transmission through the silica waveguide. Far field images of the planar silica waveguide were observed by alignment of the optical fiber connected with a 1550 nm laser. The propagation loss of the 38 mm long planar optical waveguide was measured with an optical power meter at 1550 nm.

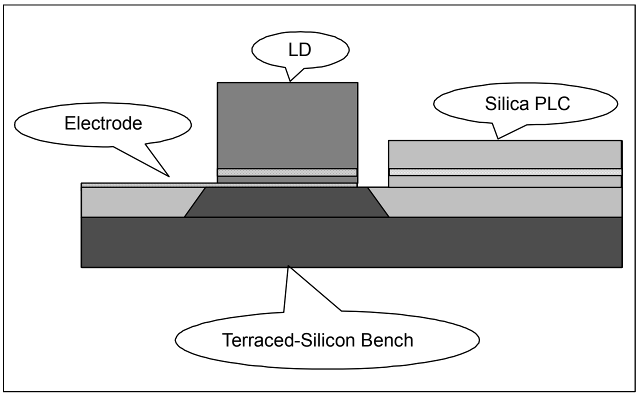


Fig. 1. Configurations of a silica-on-silicon platform.

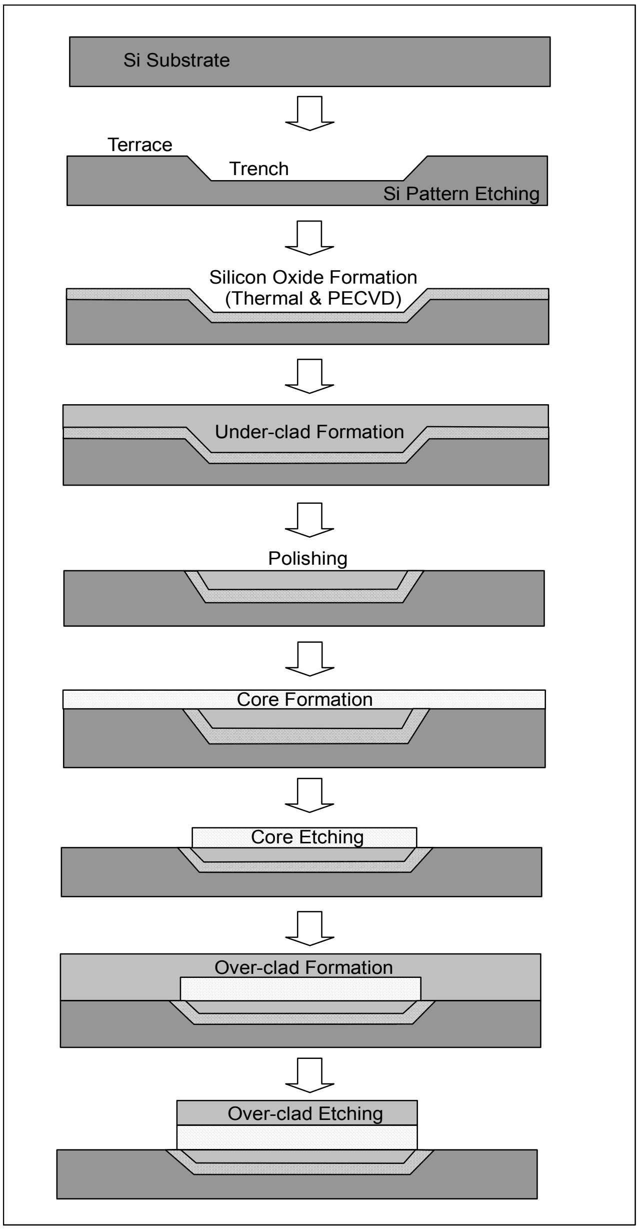


Fig. 2. Fabrication procedures for a silica-on-silicon platform.

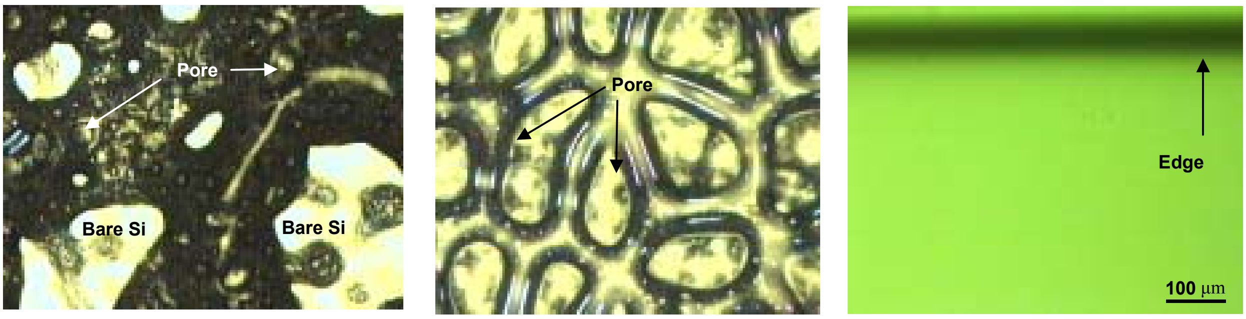
III. RESULTS AND DISCUSSIONS

To confirm the influences on surface morphology of silica film with non-etched silicon substrates, we used silicon substrates both with and without silicon oxide as starting materials. Figure 3 shows the surface morphologies of the silica film on the silicon substrates. In Figs. 3(a) and (b), the silica film, that was formed by FHD respectively on a bare silicon substrate and a silicon substrate with a 0.4 μm thick silicon oxide layer shows many large pores, while the silica film with a 1 μm thick silicon oxide layer thermally oxidized shows a clean surface and transparent film without any pores.

Figure 4 shows the surface morphologies of the silica film on silicon substrates with silicon oxide layers formed by PECVD with various thicknesses. The silica film on a silicon substrate with a 0.4 μm silicon oxide layer (Fig. 4(a)) shows many large pores; with a 0.6 μm silicon oxide layer (Fig. 4(b)), it reveals fine pores; and with a 1 μm silicon oxide layer, it has a defect-free surface. The PECVD result is very close to the 1 μm thick silicon oxide layer thermally oxidized. As the thickness of the silicon oxide layer increased, the defects in the silica film formed by FHD decreased, and finally disappeared.

The silicon oxide apparently played a role in creating good compatibility at the interface of the silica film and silicon substrate. Therefore, we conclude that a silicon substrate with a silicon oxide layer with a thickness of 1.0 μm or above must be used as a starting material to realize single planar optical devices, such as planar optical splitters, combiners, and WDM channel devices, on non-etched silicon substrates.

Our results suggest that the type of process for forming the silicon oxide layer is crucial to achieving good compatibility between the silicon bench and silica under-clad. The silicon oxide layer was necessary to achieve a transparent under-clad for the silica platform. To determine which process for forming the silicon oxide layer achieves the best compatibility between the silicon bench and the silica under-clad, we tested two processes for forming the silicon oxide layer before forming the under-clad of silica glass film by FHD: thermal oxidation and PECVD.



(a) without silicon oxide: bare silicon (b) 0.4 μm silicon oxide (c) 1.0 μm silicon oxide

Fig. 3. Surface morphologies of silica film on silicon substrates with the silicon oxide layer formed by thermal oxidation: (a) without silicon oxide: bare silicon, (b) 0.4 μm silicon oxide, and (c) 1.0 μm silicon oxide.

(a) 0.4 μm silicon oxide (b) 0.6 μm silicon oxide (c) 1.0 μm silicon oxide

Fig. 4. Surface morphologies of silica film on silicon substrates with the silicon oxide layer formed by PECVD: (a) 0.4 μm silicon oxide, (b) 0.6 μm silicon oxide, and (c) 1.0 μm silicon oxide.

Figure 5 shows the surface morphologies of terraced silicon benches with silicon oxide layers. Figure 5(a) shows the silicon bench formed with thermal oxidation treatment. The terraced region that was protected by photoresist during the silicon substrate etching was very clean but the trench etched by the KOH solution showed a defective surface morphology. These defects were generated after the thermal oxidation of the silicon substrate. The thermal oxidation of the silicon caused oxygen elements to diffuse into the silicon at high temperatures. Some residual defects on the surface of the silicon trench could have been generated during the wet etching process [22]-[28] and then the defects reacted with the oxygen directly during the thermal oxidation at a high temperature of 1050 °C.

On the other hand, Fig. 5(b) shows the terraced silicon bench with a silicon oxide layer prepared by PECVD. There were no surface defects on the silicon bench. In the silicon oxide process by PECVD, the residual defects induced during wet etching were covered by the silicon oxide layer due to the reaction at the low temperature of the PECVD. This process produced a decrease of inhomogeneous nucleation because of the low reaction temperature and growing factors that resulted in few defects on the silicon during the FHD process to form the silica under-clad layer. These defective reactants generated during the silicon oxide formation process served as the preferred nucleation site during silica clad formation prepared by the FHD process at a temperature of 1300 °C.

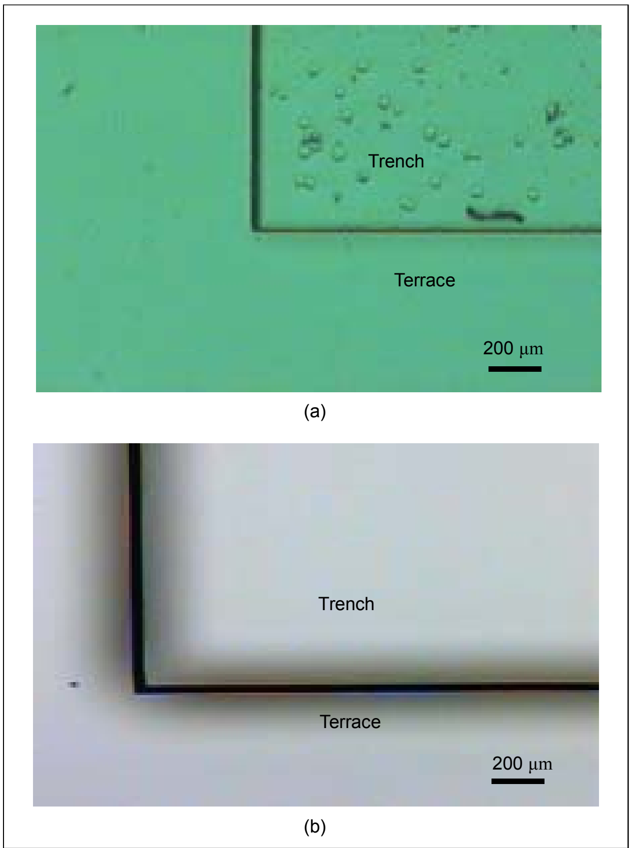


Fig. 5. Optical micrographs of a silicon optical bench with a terrace and trench: (a) thermal oxidation, (b) PECVD.

Figure 6 shows optical micrographs of the optical waveguides in the trench in a silica platform with silicon oxide grown by thermal oxidation. There are many crystallites between the optical waveguides (Fig. 6(a)); the optical waveguides are seriously distorted and there are also large defects which are about 20 μm (Fig. 6(b)).

Figure 7 shows an optical micrograph of optical waveguides in the trench on a silica platform with silicon oxide deposited by PECVD. As the figure shows, the optical waveguides by the PECVD method are formed clearly without any defects and there is no formation of crystallites in the trench.

Figure 8 shows XRD patterns of a silica platform from the silicon oxide fabrication process. Figures 8(a) and (b) show XRD patterns from silica platforms using silicon oxide formed respectively by thermal oxidation and PECVD treatments. In Fig. 8(a), the peak of the cristobalite crystal structure exhibits an angle of 21.7 degrees, indicating that

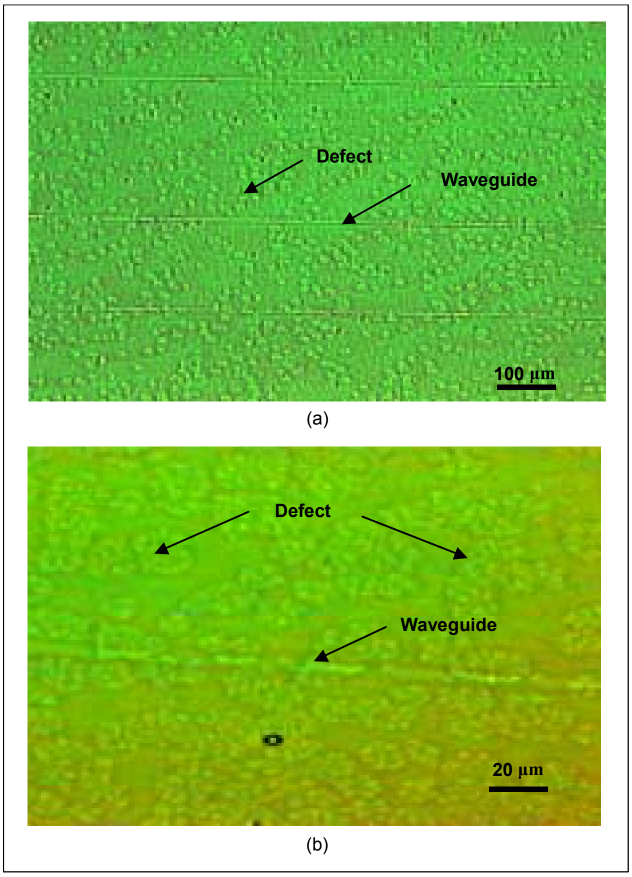


Fig. 6. Optical micrographs of optical waveguides in the trench on a silica glass platform with silicon oxide formed by thermal oxidation: (a) low magnification, (b) high magnification.

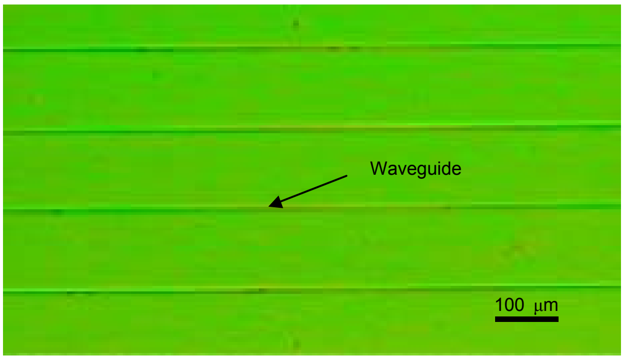


Fig. 7. Optical micrographs of optical waveguides in the trench on a silica glass platform with silicon oxide formed by PECVD.

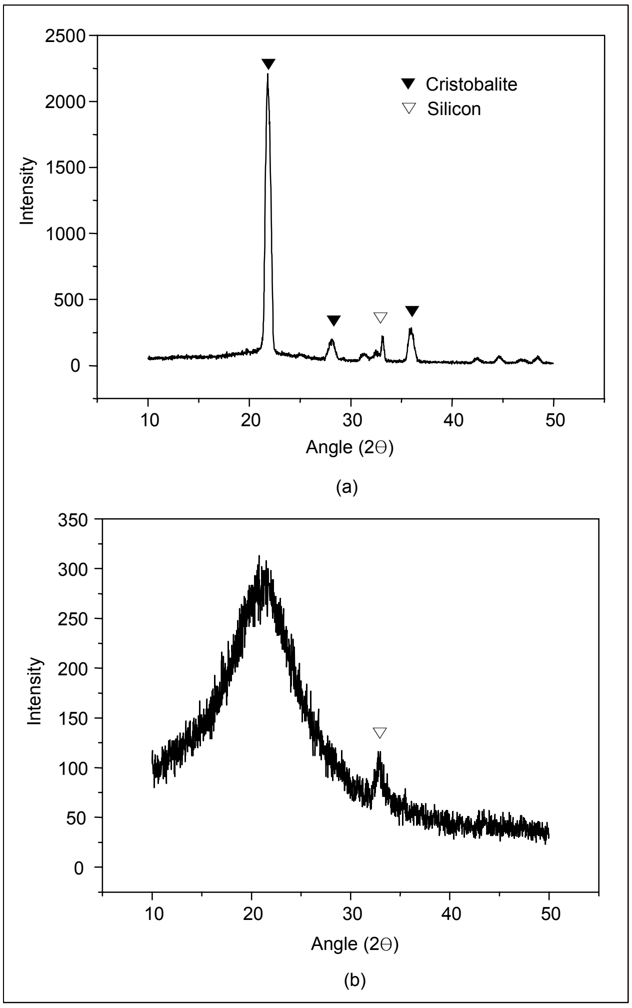


Fig. 8. XRD patterns of silica glass platforms with silicon oxide: (a) thermal oxidation, (b) PECVD.

defects shown in Fig. 6 were due to the cristobalite crystal. In Fig. 8(b), the overall XRD peaks with the PECVD process show an amorphous structure without the peaks of a cristobalite crystal structure.

Figure 9 shows the cross-sectional morphologies of the optical waveguides on a silica platform. In Fig. 9(a), the morphology of the optical waveguide in the silica platform using silicon oxide formed by thermal oxidation was deformed. The transmitted visible light intensity was weak due to distortion of the waveguide by the cristobalite crystal growth. The cross-sectional morphology of the planar optical waveguide in the silica platform using silicon oxide formed by the PECVD method (Fig. 9(b)) showed that a defect- and deformation-free optical waveguide could be obtained. This result indicates that eliminating cristobalite crystals with a low processing temperature is necessary for forming high quality planar optical waveguides in silica platforms.

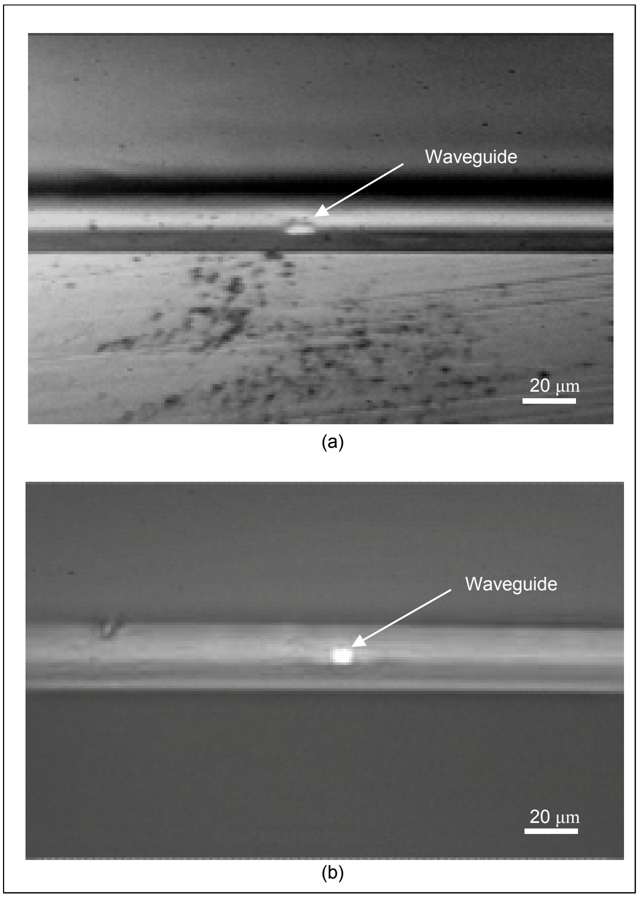


Fig. 9. Cross-sectional morphologies of optical waveguides on silica platforms with silicon oxide: (a) thermal oxidation, (b) PECVD.

Figure 10 shows far field image patterns of planar optical waveguides in silica platforms with silicon oxide treatment by thermal oxidation and PECVD. In Fig. 10(a), the propagation mode of the optical waveguide in the silica platform with silicon oxide formed by thermal oxidation was dim and indistinct because the planar optical waveguide was deformed by the defects shown in Fig. 6. On the other hand, when an incidence light of 1550 nm was connected to the planar optical waveguide in the silica platform with silicon oxide deposited by PECVD, a round, bright propagation mode was observed (Fig. 10 (b)). The propagation loss of the optical waveguide with a length of 38 mm in the silica platform with silicon oxide formed by thermal oxidation was 13.5 dB at a 1550 nm wavelength. The propagation loss of the planar optical waveguide in the silica platform with silicon oxide deposited by PECVD showed 0.41 dB. This means that the optical signal of a planar optical waveguide on a silica platform with silicon oxide deposited by PECVD is transmitted well and has good optical characteristics.

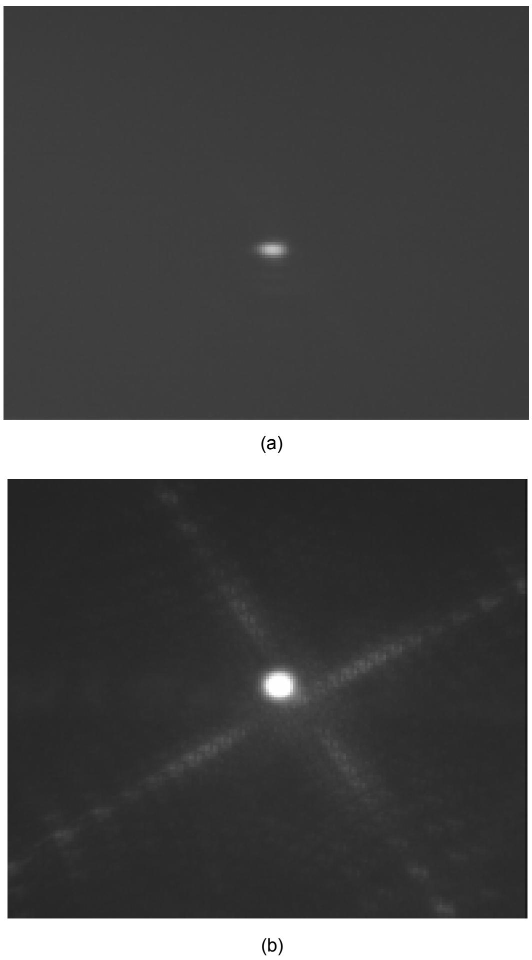


Fig. 10. Far field image patterns of planar optical waveguides on silica platforms with silicon oxide: (a) thermal oxidation, (b) PECVD.

IV. CONCLUSIONS

We reached the following conclusions from our experimental investigation.

First, silica film deposited by FHD on silicon without a silicon oxide layer has many large bubbles. If however, the silica film deposited by FHD on silicon has a 1 μm silicon oxide layer thermally oxidized, it has a clean surface without bubbles and is transparent.

Second, a silica platform formed by thermal oxidation exhibits defects in the trench region of the etched silicon and generates deformed optical waveguides due to cristobalite crystal formation. In addition, the propagation mode of this waveguide was vague and dim.

Third, the optical waveguides with a silicon oxide layer formed by PECVD were formed clearly with no formation of crystallites in the trench. Their shapes and near-field images were clear and bright. We confirmed that the PECVD method for formation of silicon oxide could suppress crystal growth in the process of silica platform formation by FHD.

Fourth, we therefore concluded that the PECVD method of forming silicon oxide can be used to fabricate transparent planar optical waveguides on silica platforms for hybrid integrated optical modules. We demonstrated that the formation of the silicon oxide layer by PECVD rather than thermal oxidation prevents the crystallization of silica and that the silica-on-silicon platform thus formed has good optical characteristics.

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