Feature size reduction of silicon slot waveguides by partial filling using atomic layer deposition

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Abstract. We propose a novel method to realize silicon-on-insulator (SOI)–based air slot waveguides for sensing applications. The method, based on feature size reduction using conformal thin films grown by atomic layer deposition (ALD), enables a guided slot mode in a silicon slot waveguide with a patterned slot width of more than 200 nm. Feature size reduction of slot structures with ALD grown amorphous TiO_2 is demonstrated. *© 2009 Society of Photo-Optical Instrumentation Engineers.*
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Slot waveguides are high-index contrast waveguide structures where light is confined in a slot with low-index material or air.[1,2] The ability to guide light in lower index materials offers a way to make new kinds of active and passive waveguide structures on the well-established silicon platform by the integration of materials that are known from glass and polymer waveguides. Filling of slot waveguides with highly nonlinear organic materials[3] and electro-optical polymers[4] has been demonstrated, but successful filling of slots, particularly with inorganic materials, has turned out to be difficult.

Typical vertical slot waveguides for 1.55-μm wavelength have a rail width in the 200-nm and slot width in 100-nm regime. The small feature size makes the fabrication of vertical slot waveguides difficult. The 193-nm-deep UV (DUV) lithography or electron-beam lithography processes can be used, but as the feature size is not far from the minimum achievable, reproducible fabrication becomes a challenging task. The minimum feature size can be increased by reducing the index contrast with, e.g., the silicon nitride/silicon oxide platform[5] or by the complete filling of the air slot in silicon-on-insulator (SOI). However, it is the index contrast that gives rise to the slot mode, and reducing the contrast therefore weakens the slot mode character of the mode. Moreover, in sensing applications, the measured gas or liquid should interact with the air slot for maximum sensitivity. Silicon slot waveguides have already been demonstrated as gas detectors.[6]

Atomic layer deposition (ALD) was developed for making thin film electroluminescent (TFEL) displays.[7] Since then, it has been utilized in many different applications and has become a standard CMOS process in the semiconductor industry. ALD is a pulsed modification of chemical vapor deposition technology. It is based on successive, surface-controlled reactions from the gas phase. As the reactions happen only at the surface, the process is self-limiting, the growth rate is well controlled, and the grown films are extremely conformal over the surfaces.

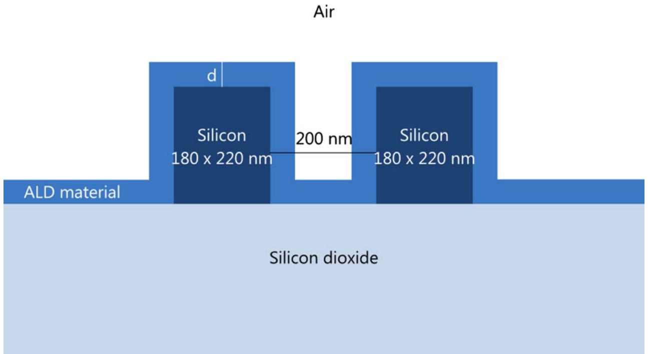

Fig. 1 The proposed slot waveguide structure.

Due to its low growth rate, ALD is usually considered feasible only for very thin films, but the low growth rate can be compensated with the easily increased batch size. Therefore, TFEL displays with more than micron thick atomic layer deposited high-quality ZnS:Mn phosphors and Al-Ti-oxide (ATO) dielectrics are in large-scale production.

We propose a novel way to realize air slot waveguides on an SOI platform using atomic layer deposited high refractive index thin films. We show that a conformal film of a high refractive index material grown onto the structure can enable the slot modes on SOI slot waveguides with a slot width of 200 nm. A good example of such film is the amorphous TiO_2 grown by low-temperature ALD.

In order to study the feasibility of the proposed method, the properties of the slot waveguide pictured in Fig. 1 are simulated by using the film mode matching (FMM) solver of the FIMMWAVE software.[8] The rail width used is 180 nm, rail height is 220 nm, and slot width is 200 nm. The thickness d of the ALD material is varied between 40 nm and 100 nm. For the simulations, we use a wavelength of 1.55 μm. As the refractive index of the ALD material, we use 2.2 (amorphous TiO_2). When d is below 40 nm, the waveguide has no guided slot mode, and above 100 nm, the slot is completely filled.

The effective indices of the quasi–transverse electric (TE) modes are shown in Fig. 2. With $d > 90$ nm, a second-order quasi-TE mode is found for the waveguide. The second-order mode is asymmetric and does not have field confinement in the air slot. The rail height can be made smaller to eliminate the second-order mode [and also the quasi–transverse magnetic (TM) mode] and to realize a slot waveguide with only a single quasi-TE slot mode.

The transverse electric field profiles for the cases with $d = 60$, 70, and 80 nm are shown in Fig. 3. The mode field profiles show that the modes in these partially filled structures are well confined in the air slot.

To demonstrate the filling of slots with ALD, we did experiments with test slot structures of different widths using standard silicon wafers. The result of a filling experiment with 100 nm of amorphous TiO_2 grown at a low tem-

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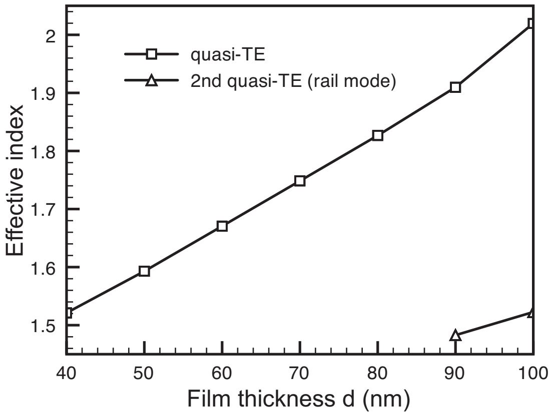

Fig. 2 The effective indices for the simulated slot waveguide structures as a function of the ALD film thickness *d*.

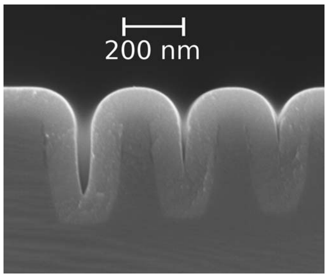

Fig. 4 Scanning electron micrograph (SEM) of slots fabricated to a (100) silicon wafer and an ALD coated with 100 nm of amorphous TiO_2 using $TiCl_4$ and water in 120 °C. The leftmost slot structure resembles the one simulated in Fig. 3(c).

perature is shown in Fig. 4. The structures have nonstraight sidewalls and rounded corners, which are due to the natural features of the etching processes and the ALD growth. The deposition was done using Beneq TFS-500 ALD reactor using $TiCl_4$ and water as precursors. The process used for TiO_2 is well known and produces good quality films. A relatively low growth temperature of 120 °C was chosen to get amorphous films, which are expected to yield minimal scattering losses in waveguides.

To confirm the good waveguiding properties of the ALD-grown amorphous TiO_2 films, we deposited approximately 460-nm-thick films on glass substrates using similar processing parameters as in slot filling experiments. The properties of these slab waveguides were measured using the well-known prism coupling technique with a Metricon 2010/M Prism Coupler having the loss measurement feature as an option. As expected, at 1.55-μm wavelength, the slabs guided one TE-mode with a measured effective index of 2.03, which gives a refractive index of about 2.25 for the films. The propagation losses were estimated by scanning a multimode optical fiber along the light propagation direction and measuring the scattered light. The measured propagation losses are <1 dB/cm, which is close to the measurement accuracy of the technique. The loss of 1 dB/cm should not be significant in slot waveguides, where losses of 10 dB/cm or 15 dB/cm have been measured.[3,9]

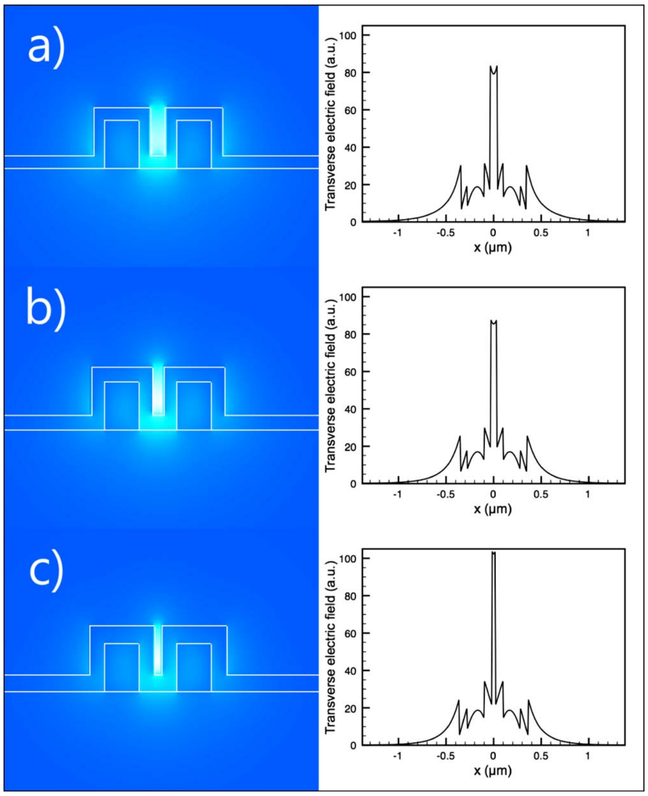

Fig. 3 The quasi-TE mode field profiles and their cross sections at the middle of the slot for the slot waveguides with ALD film thickness of (a) d=60 nm, (b) d=70 nm, and (c) d=80 nm.

The ALD technology opens many new possibilities for realizing new kinds of slot waveguide structures. The digital atomic layer accurate control of thickness on all surfaces enables the design of easily realizable sandwich structures on vertical as well as horizontal surfaces. Also, a wide range of materials can be deposited for different purposes.[10]

In this letter, we have discussed the possibility of realizing slot waveguides with wide silicon slots and ALD-grown amorphous TiO_2 thin films. The simulations show that a silicon slot waveguide covered with a high refractive index material has good electric field confinement in the remaining air slot. The initial processing and ALD growth trials show that a conformal film of amorphous TiO_2 can be easily grown into slot structures. ALD also has a natural surface smoothing feature, which should reduce the waveguide scattering losses.

Acknowledgments

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