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

Tapani Alasaarela, Antti Säynätjoki, MEMBER SPIE, Teppo Hakkarainen, and Seppo Honkanen
Helsinki University of Technology, Department of Micro and Nanosciences, Tiétolte 3, Espoo 02015, Finland
E-mail: tapani.alasaarela@tkk.fi

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 TiO₂ is demonstrated. © 2009 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.3206731]

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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 materials³ and electro-optical polymers⁴ 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 the 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 platform⁵ 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.⁶⁻⁷

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.

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.⁸ The air slot waveguide shown in Fig. 1 has a rail width in 100 nm, the slot is completely filled. For the simulations, we use a waveguide with a patterned slot width of more than 200 nm. Feature size reduction of slot structures with ALD grown amorphous TiO₂ is demonstrated.©2009 SPIE

Fig. 1 The proposed slot waveguide structure.
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.$^{3,9}$

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.

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![Fig. 2](https://journals.spiedigitallibrary.org/journals/Optical-Engineering/August-2009_Vol.48(8)/080502-2)

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

![Fig. 3](https://journals.spiedigitallibrary.org/journals/Optical-Engineering/August-2009_Vol.48(8)/080502-2)

**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.

![Fig. 4](https://journals.spiedigitallibrary.org/journals/Optical-Engineering/August-2009_Vol.48(8)/080502-2)

**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).
References


