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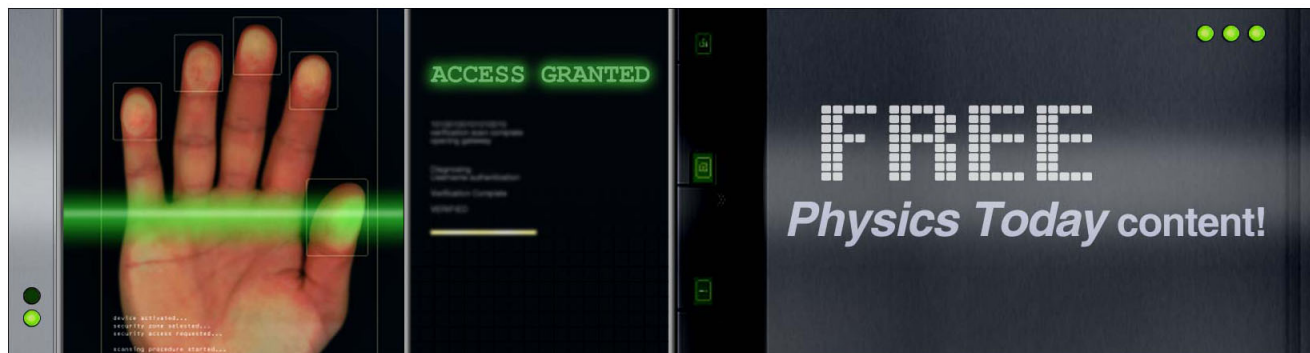
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Transparent amorphous silicon channel waveguides with silicon nitride intercladding layer

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We have experimentally demonstrated single mode amorphous silicon channel waveguides with low optical transmission loss of 2.7 ± 0.4 dB/cm for TE mode in the 1550 nm range. This result was achieved by using hydrogen passivation of *a*-Si dangling bonds and a thin, low loss silicon nitride intercladding layer prepared by plasma enhanced chemical vapor deposition between the waveguide core and the oxide cladding layer. The silicon nitride intercladding layer reduces waveguide sidewall roughness scattering and preserves the hydrogen passivation. © 2009 American Institute of Physics. [DOI: 10.1063/1.3117363]

Amorphous silicon (*a*-Si) is attractive as an alternative optical waveguide material to single crystalline silicon for its high refractive index and capability of low cost deposition on SiO₂. Hydrogen passivation improves *a*-Si's transparency by reducing dangling bond absorption in *a*-Si. However, in order to integrate *a*-Si optical waveguides at interconnection level, hydrogen passivation is often lost due to hydrogen evolution at 450 °C. A thin silicon nitride intercladding layer deposited using plasma enhanced chemical vapor deposition (PECVD) method is designed to preserve the H passivation, thus improving optical transparency in *a*-Si waveguide core.¹ An additional complication is that PECVD silicon nitride introduces extra optical loss due to N–H bond resonance absorption. As a result, the overall *a*-Si channel waveguide transmission loss coefficient α consists of the *a*-Si bulk absorption loss coefficient α_{a-Si} , sidewall roughness scattering loss coefficient $\alpha_{sidewall}$, and bulk absorption loss coefficient of the cladding layers, e.g., the silicon nitride $\alpha_{nitride}$, as expressed as

$$\alpha = \Gamma_{a-Si} \alpha_{a-Si} + \alpha_{sidewall} + \Gamma_{nitride} \alpha_{nitride} + (1 - \Gamma_{a-Si} - \Gamma_{nitride}) \alpha_{oxide},$$

where Γ_{a-Si} , $\Gamma_{nitride}$, and $(1 - \Gamma_{a-Si} - \Gamma_{nitride})$ are the confinement factors in *a*-Si waveguide core, in silicon nitride intercladding layer, and in oxide cladding, respectively; α_{oxide} is the bulk absorption loss coefficient of the oxide cladding which is negligible. Minimizing α_{a-Si} , $\alpha_{sidewall}$, and $\alpha_{nitride}$ is the key to improving the total transparency of the *a*-Si waveguide.

In this paper, we demonstrate low optical transmission loss of 2.7 ± 0.4 dB/cm for TE mode in single mode, *a*-Si channel waveguide devices with 10 nm low loss silicon nitride intercladding layer at 1560 nm, comparable to single crystalline silicon counterparts. Figures 1(a) and 1(b) shows the waveguide configuration and index profile with the incorporation of a PECVD silicon nitride intercladding layer between the *a*-Si waveguide core and the PECVD SiO₂ ($n=1.46$) cladding. This thin nitride layer (e.g., n

$=1.90$ – 2.09) reduces *a*-Si sidewall refractive index contrast, reducing the sidewall roughness scattering loss coefficient $\alpha_{sidewall}$.² It also works as a hydrogen diffusion barrier to preserve hydrogen passivation.

As-deposited PECVD silicon nitride contains nitrogen-hydrogen (N–H) bonds whose resonance absorption is centered at 1510 nm.^{1,3,4} Development of processes that can minimize N–H concentration in PECVD silicon nitride is the key to achieving low loss optical transmission in *a*-Si waveguides in the 1550 nm region. Such process must be compliant with low loss, hydrogenated *a*-Si process thermal budget of less than 450 °C to prevent high optical loss due to crystallization of *a*-Si (>650 °C) and H out-diffusion (450–650 °C).⁵ We used an *in situ* nitrogen/argon (N₂/Ar) plasma treatment process to reduce H in the as-deposited nitride film at 300 °C. Experimental details for H reduction

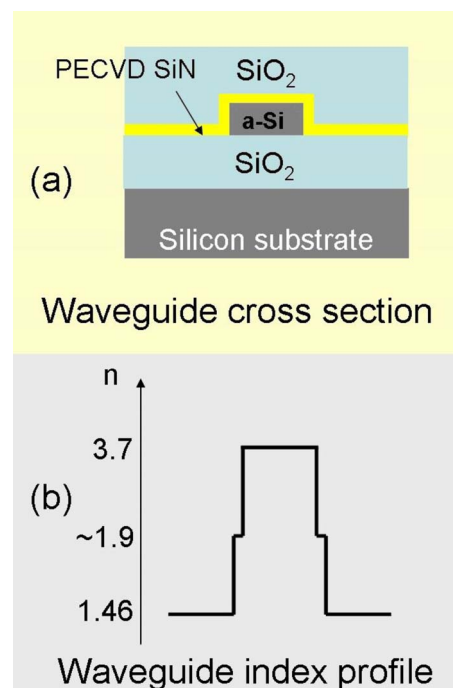


FIG. 1. (Color online) (a) Schematic of the waveguide cross section and (b) waveguide index profile.

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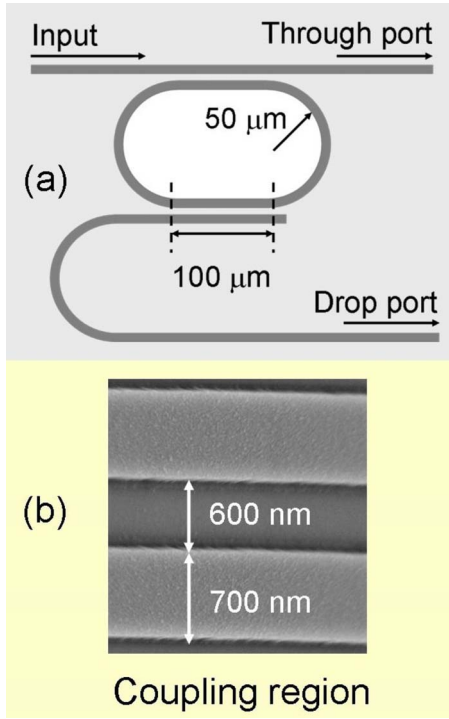


FIG. 2. (Color online) (a) Schematic of the racetrack resonator and (b) a SEM image of the coupling region.

in PECVD silicon nitride using plasma treatment can be found elsewhere.⁶ In our optimal process, 80% NH bonds is removed from the as-deposited thin film. The resulting refractive index is 1.90.

The nitride plasma treatment can be seamlessly integrated with the waveguide fabrication process flow. On 1 μm thermal SiO_2 under cladding layer the device cross section is 700 nm(width) \times 100 nm(height) waveguide core fabricated by direct reactive ion etch of *a*-Si. To study the effect of the different silicon nitride intercladding layers, the wafer was broken into quarter-size pieces and the following samples were obtained:

- (1) Sample 1: Control, with no nitride intercladding layer.
- (2) Sample 2: Deposited with 10 nm as-deposited nitride intercladding layer ($n=2.10$).
- (3) Sample 3: Deposited with 10 nm plasma-treated nitride intercladding layer ($n=1.90$).

In the final step, all samples were cladded with 1 μm PECVD SiO_2 as the top cladding layers. Waveguides transmission losses can be derived accurately from the resonance spectrum of a first order resonator.⁷ The racetrack resonator design helps enhance the optical coupling for large coupling gaps of 600 nm. The coupling distance is 100 μm . The bend radius is 50 μm at which radiation loss due to bending is negligible. The resulting round trip loss of the resonator is solely the waveguide transmission loss. Figure 2 shows the schematics of the device configuration and a scanning electron microscopy (SEM) image of the coupling region. We obtain the resonator spectrum for TE mode only because with a 1 μm thick under cladding layer the TM mode is intentionally lost due to substrate leakage.

Figure 3 highlights the resonance spectra and their Lorentzian fits of the devices from Samples 1–3, respectively. The resonance wavelength (λ_R), extinction ratios (r_e),

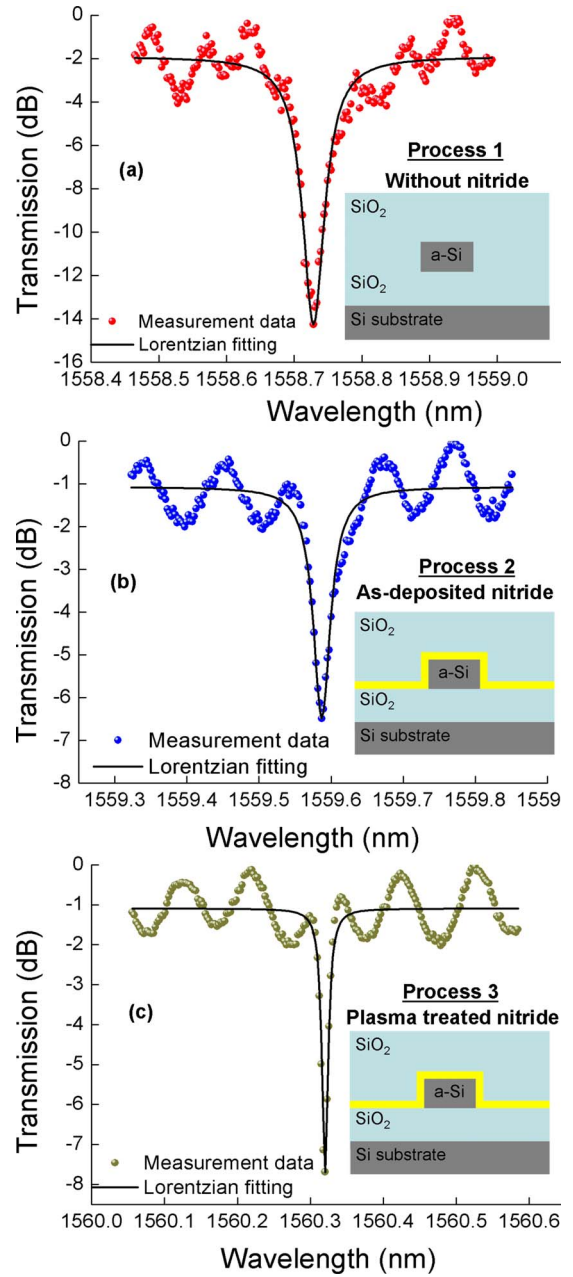


FIG. 3. (Color online) [(a)–(c)] Resonance spectra over the same 0.6 nm range for process 1–3, respectively. The black lines are the corresponding Lorentzian fits. The large periodic ripples are the Fabry–Pérot resonances from the waveguide input and output facets.

and quality factors (Q) are obtained from their Lorentzian fits, summarized in Table I. Incorporation of a 10 nm as-deposited nitride intercladding layer around the *a*-Si channel waveguide core reduced the waveguide transmission loss coefficient from 12.0 ± 1.8 dB/cm to 6.5 ± 0.9 dB/cm. These

TABLE I. Summary of the resonance wavelength λ_R , extinction ratio r_e , quality factor Q , and transmission loss coefficients α for samples with processes 1–3, respectively.

Sample ID	λ_R (nm)	r_e (dB)	Q	α (dB/cm)
1	1558.146	12.3	22 500	12.0 ± 1.8
2	1559.587	5.4	60 400	6.5 ± 0.9
3	1560.319	6.9	141 800	2.7 ± 0.4

results are in good agreement with previous reports in Ref. 1 where the loss values are derived from straight waveguides using the “cut-back” method. The plasma-treated nitride film further reduced the *a*-Si waveguide core transmission loss to 2.7 ± 0.4 dB/cm. The 3.8 dB/cm loss reduction results from removal of 80% of NH bonds from the as-deposited PECVD nitride film.

In conclusion, we have demonstrated a minimal transmission loss of 2.7 ± 0.4 dB/cm for TE mode at 1560 nm in single mode, *a*-Si channel waveguides, comparable to single crystalline silicon channel waveguides. Our approach consists of using a well-passivated *a*-Si waveguide core and a low loss PECVD silicon nitride intercladding layer. We discovered that removal of 80% of NH bonds in nitride film results in 3.8 dB/cm transmission loss coefficient reduction in *a*-Si channel waveguides. This nitride layer also preserves

H passivation and potentially allows *a*-Si waveguide to maintain its low loss property at temperatures higher than 400 °C.

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