Hot-wire chemical vapor deposition low-loss a-Si:H waveguides for silicon photonic devices

Swe Z. Oo,1,2,* Antulio Tarazona,2 Ali Z. Khokhar,2 Rafidah Petra,1 Yohann Franz,2 Goran Z. Mashanovich,2 Graham T. Reed,2,3 Anna C. Peacock,2 ♦ and Harold M. H. Chong1

1School of Electronics and Computer Science, University of Southampton, SO17 1BJ, UK
2Optoelectronics Research Centre, University of Southampton, SO17 1BJ, UK
3School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, Singapore
*Corresponding author: S.Oo@soton.ac.uk

Received 11 May 2018; revised 12 December 2018; accepted 18 December 2018; posted 21 December 2018 (Doc. ID 331501); published 0 MONTH 0000

We demonstrate low-loss hydrogenated amorphous silicon (a-Si:H) waveguides by hot-wire chemical vapor deposition (HWCVD). The effect of hydrogenation in a-Si at different deposition temperatures has been investigated and analyzed by Raman spectroscopy. We obtained optical quality a-Si:H waveguide deposited at 230°C that has a strong Raman peak shift at 480 cm⁻¹, peak width FWHM of 68.9 cm⁻¹, and bond angle deviation of 8.98°. Optical transmission measurement shows a low propagation loss of 0.8 dB/cm at 1550 nm wavelength, which is the first to our knowledge reported for HWCVD a-Si:H waveguide.

Published by Chinese Laser Press under the terms of the Creative Commons Attribution 4.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.
https://doi.org/10.1364/PR.99.099999

1. INTRODUCTION

Silicon photonics devices are fast evolving from discrete optical components to complete circuits that will eventually require low-loss waveguide interconnects and devices for high-density integration. The reliance of a silicon-on-insulator (SOI) platform for building up active optical devices limits the fabrication freedom in term of process temperature for the formation of a multi-layer photonics platform. Therefore, low temperature deposition of low-loss optical materials is essential for building high-density optical integrated circuits. There have been a variety of low temperature deposition techniques for optical waveguide materials. For example, the use of polymer waveguides is constrained to the uppermost optical layer because of its incompatibility with the CMOS thermal processes [1,2].

Low temperature plasma enhanced chemical vapor deposition (PECVD) materials such as silica- and nitride-based waveguides have been demonstrated. These materials can achieve low propagation losses, but their low refractive indices (∼1.5 and ∼2.1 at 1.55 µm, respectively) require mode matching to the silicon devices, adding a layer of complexity to the design and fabrication. In addition, silicon oxynitride and silicon nitride contain N-H stretching bonds from using ammonia in the deposition processes, which can cause absorption at the s- and c-band wavelength range. Although the N-H bonds can be annealed out at high temperatures close to 1000°C, such processing renders these materials unsuitable for back end of the line (BEOL) processes [3,4].

Hydrogenated amorphous silicon (a-Si:H) waveguides fabricated by the conventional deposition method (PECVD) have been investigated [5–12]. Its low refractive index difference with the crystalline SOI waveguide devices simplifies integration, especially in multilayer photonics. The waveguide losses in a-Si:H can be investigated from the perspective of its lattice network, which affects absorption in the material. In crystalline silicon (c-Si), the tetrahedral lattice structure has bond angle of 109.5° and bond length of 2.35 Å. The amorphous silicon lattice network comprises 5% and 10% deviation from crystalline in the bond angle and bond length, respectively [13]. These deviations in amorphous structure do not affect the first few neighboring atoms, which is also known as the short range order (SRO) of an a-Si network. However, the amorphous disorder can induce structural stress to the intermediate range order (IRO; that is, beyond the neighboring atoms in the network), leading to bond breakage and the occurrence of dangling bonds. This has a negative impact on the optoelectronic properties of the a-Si waveguide material, which will suffer from high absorption and degradation over time. Therefore, hydrogen passivation is crucial during or after the deposition of amorphous silicon for the development of waveguide device applications.
table 1. summary of the performance of a-si waveguides and techniques used in silicon photonics applications

<table>
<thead>
<tr>
<th>Reference</th>
<th>Material</th>
<th>Deposition Method</th>
<th>Deposited Temperature (°C)</th>
<th>Propagation Loss (dB/cm)</th>
<th>Type</th>
<th>Dimension (W x H) (nm)</th>
<th>Etched Depth (nm)</th>
<th>Upper Cladding</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1:2</td>
<td>a-Si:H</td>
<td>PECVD</td>
<td>220</td>
<td>0.7</td>
<td>Rib</td>
<td>15 x 3 μm</td>
<td>1200</td>
<td>Air</td>
<td>λ = 1310 nm, without post processing</td>
</tr>
<tr>
<td>T1:3</td>
<td>a-Si:H</td>
<td>PECVD</td>
<td>300</td>
<td>2</td>
<td>Rib</td>
<td>1100 x 1300</td>
<td>380</td>
<td>Air</td>
<td>λ = 1550 nm, without post processing</td>
</tr>
<tr>
<td>T1:4</td>
<td>a-Si</td>
<td>PECVD</td>
<td>—</td>
<td>2.7</td>
<td>Wire</td>
<td>700 x 100</td>
<td>100</td>
<td>SiO₂</td>
<td>λ = 1550 nm, 10 nm SiNx intercladding and nitrogen/argon plasma treatment</td>
</tr>
<tr>
<td>T1:5</td>
<td>a-Si:H</td>
<td>PECVD</td>
<td>300</td>
<td>3.46</td>
<td>Wire</td>
<td>480 x 220</td>
<td>220</td>
<td>SiO₂</td>
<td>λ = 1550 nm, CMP process on lower cladding</td>
</tr>
<tr>
<td>T1:6</td>
<td>a-Si:H</td>
<td>PECVD</td>
<td>300</td>
<td>1.54</td>
<td>Ridge</td>
<td>480 x 220</td>
<td>70</td>
<td>SiO₂</td>
<td>λ = 1550 nm, CMP process on lower cladding</td>
</tr>
<tr>
<td>T1:7</td>
<td>a-Si:H</td>
<td>PECVD</td>
<td>400</td>
<td>3.2</td>
<td>Wire</td>
<td>550 x 220</td>
<td>220</td>
<td>SiO₂</td>
<td>λ = 1550 nm, CMP process on lower cladding</td>
</tr>
<tr>
<td>T1:8</td>
<td>a-Si</td>
<td>PECVD</td>
<td>300</td>
<td>3.8</td>
<td>Wire</td>
<td>450 x 220</td>
<td>220</td>
<td>SiO₂</td>
<td>TEOS'</td>
</tr>
<tr>
<td>T1:9</td>
<td>a-Si:H</td>
<td>PECVD</td>
<td>250-300</td>
<td>2</td>
<td>Rib</td>
<td>2100 x 2100</td>
<td>900</td>
<td>SiO₂</td>
<td>λ = 1550 nm, without post processing</td>
</tr>
<tr>
<td>T1:10</td>
<td>a-Si:H</td>
<td>PECVD</td>
<td>250-300</td>
<td>5.3</td>
<td>Wire</td>
<td>500 x 200</td>
<td>200</td>
<td>SiO₂</td>
<td>λ = 1550 nm, without post processing</td>
</tr>
<tr>
<td>T1:11</td>
<td>a-Si:H</td>
<td>PECVD</td>
<td>250</td>
<td>0.6</td>
<td>Ridge</td>
<td>780 x 440</td>
<td>100</td>
<td>TEOS'</td>
<td>λ = 1550 nm, CMP process on deposited a-Si:H</td>
</tr>
<tr>
<td>T1:12</td>
<td>c-Si</td>
<td>—</td>
<td>—</td>
<td>3.6</td>
<td>Strip</td>
<td>445 x 220</td>
<td>220</td>
<td>Air</td>
<td>λ = 1550 nm, without post processing</td>
</tr>
<tr>
<td>T1:13</td>
<td>c-Si</td>
<td>—</td>
<td>—</td>
<td>3.4</td>
<td>Wire</td>
<td>630 x 220</td>
<td>220</td>
<td>Air</td>
<td>λ = 1550 nm, sideway smoothing by wet chemical oxidation</td>
</tr>
<tr>
<td>T1:14</td>
<td>c-Si</td>
<td>—</td>
<td>—</td>
<td>0.92</td>
<td>Wire</td>
<td>500 x 265</td>
<td>265</td>
<td>Air</td>
<td>λ = 1550 nm, without post processing</td>
</tr>
<tr>
<td>T1:15</td>
<td>a-Si:H</td>
<td>HW CVD</td>
<td>230</td>
<td>0.8</td>
<td>Wire</td>
<td>650 x 400</td>
<td>400</td>
<td>SiO₂</td>
<td>λ = 1550 nm, without post processing</td>
</tr>
</tbody>
</table>

'TEOS', tetraethyl orthosilicate.

'COMP, chemical mechanical polishing/planarization.'
possible to obtain different film thickness. The a-Si:H thickness
is 400 nm deposited at 0.01 mBar with a silane and hydrogen
gas mix ratio of 2.4:1. The 400 nm thickness is chosen so that
the Raman laser (wavelength) penetration depth can fully inter-
rogate the deposited a-Si:H film without interference from the
background silicon dioxide layer. After the a-Si:H deposition,
the film was covered with 5 nm thick PECVD SiO$_2$ at 350°C as
a passivation layer to prevent atmospheric degradation. We pre-
tpared two batches of a-Si:H waveguides. The first batch was
fabricated using standard photolithography and anisotropic in-
ductively coupled plasma (ICP) etching to produce 2 μm wide,
fully etched wire waveguides, which were used as control sam-
pies to study the role of hydrogen in the structural ordering and
to correlate this to the optical propagation loss. The second
batch was fabricated using direct write lithography and aniso-
tropic ICP etching to produce fully etched wire waveguides
with widths of 250, 350, 550, 650, and 850 nm. For each
width in batch two, waveguides with different lengths ranging
from 3 to 10 mm were produced with grating couplers. Finally,
the a-Si:H waveguides were clad with a 1 μm thick PECVD
SiO$_2$ layer.

3. MEASUREMENT SYSTEMS

There are other measurement and characterization techniques
such as electron spin resonance (ESR) and the constant photo-
current method (CPM) to evaluate the defects of amorphous
silicon [12,31]. These are the viable methods to evaluate
absorption in a-Si. In this work, however, we used Raman spec-
troscopy to evaluate the atomic structure to understand the
crystallinity and density of the material. A Renishaw Invia
Raman spectrometer with 532 nm Nd:YAG excitation laser
was used. The laser has a penetration depth of 100 nm for
a-Si:H material. A scanning electron microscope (SEM) and
atomic force microscope (AFM) were used to examine the cross
section and surface roughness of the waveguide. Based on
the analysis of the Raman spectra, the best Gaussian fit of
a-Si:H network material with optimal $T_{\text{sub}}$ was determined.
Preliminary transmission measurements were then conducted
on the a-Si:H waveguides deposited at various $T_{\text{sub}}$, with di-
 dimensions of 2 μm width × 400 nm height, using the Fabry–
Perot [32] method to correlate with the Raman results. The
light was coupled into the device by the end-fire coupling ap-
proach with ×40 magnification objective lens at the input and
output of the waveguide. The output light is fed to an InGaAs
photodetector. Using the optimized material, wire waveguides
with a range of widths were fabricated to evaluate its optical
propagation losses. The propagation losses were measured
using the cut-back method with the fiber grating couplers with
a total insertion loss of 3 dB, and the optical transmission was
normalized to the grating couplers. Agilent 8163B, an inte-
grated tunable laser source, and a photodetector system were
used to couple light in and out of the waveguides by gratings
and TE polarized optical fibers.

4. MATERIAL CHARACTERIZATION

Raman spectroscopy has been used for atomic structural
characterization of a-Si:H [33,34]. The Raman spectrum of
standard a-Si:H has four Raman active phonon modes, namely,
a transverse acoustic (TA) peak at 135 cm$^{-1}$, a longitudinal
acoustic (LA) peak at 330 cm$^{-1}$, a longitudinal optical (LO)
peak at 450 cm$^{-1}$, and a transverse optical (TO) peak at
480 cm$^{-1}$, which can be used to determine the structural qual-
ity of a-Si:H [35]. Due to the symmetry in the face centered
cubic (fcc) lattice, c-Si has a narrow sharp Raman peak from the
TO phonon mode $\omega_{\text{TO}}$, positioned at 520 cm$^{-1}$, with a full
width at half-maximum (FWHM) $\Gamma_{\text{TO}}$ of about 3.5 cm$^{-1}$
[35]. In amorphous silicon, the small change in the structural
distortion of the SRO network induces substantial modification
to the phonon density of states. Thus, there is no translation
symmetry, and $\omega_{\text{TO}}$ has a broad Raman peak positioned near
480 cm$^{-1}$, with $\Gamma_{\text{TO}} \sim 60$ cm$^{-1}$ [36,37]. Structural distortion
also induces a change in bond length and bond angle $\Delta \theta_b$.
In the Raman spectrum of the amorphous silicon network, the
TO phonon (vibration) mode is attributed to SRO, while the
TA, LA, and LO phonon vibration modes are from the
structural distortion in the IRO network [34]. Moreover,
the area intensity ratio of $I_{\text{TA}}/I_{\text{TO}}$, $\omega_{\text{TO}}$, and $\Gamma_{\text{TO}}$ are sensitive
to the change in bond angle of the a-Si network and $I_{\text{TA}}/I_{\text{TO}}$
also indicates structural disorder in IRO.

Figure 1 shows the Raman shift results from the effect of the
deposited temperatures and the structural behavior of the
a-Si:H, Figure 1(a) presents Raman spectrum of a-Si:H material
deposited at 230°C, in which all vibration modes are defined.
Figure 1(b) provides the Raman shift of $\omega_{\text{TO}}$ as a function of
$T_{\text{sub}}$, where the dotted line is a guideline for the center of
the Raman line 480 cm$^{-1}$. The plot shows that $\omega_{\text{TO}}$ does not
depend on the $T_{\text{sub}}$ from 190°C to 320°C as compared to
PECVD [34]. The results indicate two regimes for the
HWCDV, namely, the diffusion control regime and kinetic
control regime indicated in Fig. 2(a), where hydrogenation
influences the a-Si:H quality during deposition. It has been
shown that the concentration of hydrogen increases with a de-
crease of $T_{\text{sub}}$ in HWCDV [38]. In our experiment, the change
of $T_{\text{sub}}$ was achieved by changing the diameter of the tungsten
filaments. This could induce the additional change in hydrogen
concentration, even though the flow rate of the precursors and
filament temperature were maintained. It appears there is an
interplay of the two mechanisms due to hydrogen and $T_{\text{sub}}$
during the deposition process. The a-Si:H material deposited
at 210°C, 230°C, and 250°C shows a low structural disorder
of the amorphous network with $\omega_{\text{TO}}$ appearing around
480 cm$^{-1}$, which indicates high-quality a-Si:H deposited in
this temperature range. It also suggests that hydrogen passiva-
tion into the dangling bonds stabilize the SRO of a-Si. For
a-Si:H material deposited at 190°C and 320°C, there is an up-
shift in $\omega_{\text{TO}}$ to 490 cm$^{-1}$ and 493 cm$^{-1}$, respectively, as shown
in Fig. 1(b). This is due to the mixture of micro- and nano-scale
voids in the amorphous silicon network [33,39,40]. As shown
in the inset of Fig. 1(b), the deconvolution of the amorphous
peak into two Gaussian functions are related to the amorphous
and intermediate voids.

In the Arrhenius plot of Fig. 2(a), at $T_{\text{sub}}$ 320°C of the
diffusion control regime, hydrogen concentration in a-Si:H is ex-
pected to be less for the passivation of dangling bonds than the
one deposited at $T_{\text{sub}}$ 190°C, which has reduced densified layer
with micro/nano-scale voids and increased average bond length of Si-Si atoms. These a-Si:H films with voids will have an inhomogeneous strain, which translates to a broadening of the $\omega_{\text{TO}}$ peak, as reported by Hishikawa et al. [34], showing a shift in $\omega_{\text{TO}}$ due to the change in the stretching force of Si-Si bonds in SRO. For the presence of the Si-H and Si-H$_2$ stretching modes, we managed to obtain broad Raman shift spectra between 1600 cm$^{-1}$ and 2300 cm$^{-1}$ (not shown) for the 190°C, 230°C, and 320°C samples. When these spectra were fitted with the Voigt function, we obtained low to medium stretching modes of 2091 cm$^{-1}$, 2048 cm$^{-1}$, and 1818 cm$^{-1}$ for the respective deposition temperatures of 190°C, 230°C, and 320°C. The Raman shift of the 230°C and 320°C samples are the closest to the Si-H bond at 2000 cm$^{-1}$, which indicates hydrogenation of the a-Si lattice network. Our measurement agrees with Johnson et al. [41], Matsumura [42], and Smets et al. [43] that their a-Si:H also has a broad Raman peak, showing evidence of Si-H and Si-H$_2$ bonds and also suggesting nano-crystalline and voids in the amorphous silicon network [44]. However, for further verification of Si-H and Si-H$_2$ bonds in a-Si network, FTIR could provide more information of the hydrogen content in the material.

The peak position of TO also indicates the effect of stress in the film, where tensile stress downsifts $\omega_{\text{TO}}$ and compressive stress upshifts $\omega_{\text{TO}}$. Ratnayake et al. [45] suggest that there is a linear relationship with regard to the deposition temperature. The film deposited at 210°C shows evidence of tensile stress with a downshift to 476 cm$^{-1}$, while the film deposited at 320°C indicates compressive stress with an upshift to 493 cm$^{-1}$. The Raman spectral information for a-Si:H networks deposited at different $T_{\text{sub}}$, at different deposition rates, and with different surface roughnesses is tabulated in Table 2.

The FWHM width of the TO peak ($\Gamma_{\text{TO}}$) is proportional to the structural angular distortion, which means the larger $\Gamma_{\text{TO}}$, the more structural distortion in the bond angle distribution [36]. Figure 1(c) shows the dependence of structural deformation on the substrate temperature $T_{\text{sub}}$. The material deposited at 210°C has a FWHM $\Gamma_{\text{TO}}$ of 67 ± 1 cm$^{-1}$ compared to the pure amorphous Si, which has a $\Gamma_{\text{TO}}$ of 60 cm$^{-1}$. Han et al. [33] reported that device-quality a-Si:H has a $\omega_{\text{TO}}$ centered at 480 cm$^{-1}$ with FWHM $\Gamma_{\text{TO}}$ of 70 cm$^{-1}$, which closely matches our experimental $\omega_{\text{TO}}$ result at 480.5 cm$^{-1}$ with $\Gamma_{\text{TO}}$ at 68.9 cm$^{-1}$ for the a:Si-H material deposited at 230°C.
Based on Beeman’s linear relationship [36] \( \Gamma = 15 + 6\Delta \theta \), between \( \Gamma_{\text{TO}} \) and bond angle deviation \( \Delta \theta \), the a-Si:H material deposited at 230°C has a bond angle deviation of 8.98°, with respect to the crystalline Si bond angle. Our bond angle deviation result is within the range reported by Beeman et al. and Han et al. on a fully formed amorphous silicon network [33,36]. The FWHM \( \Gamma_{\text{TO}} \) becomes wider when \( T_{\text{sub}} \) is at 190°C and 320°C (shown in Table 2), which implies changes in inter-atomic lattice spacing due to either compressive or tensile strain and thus larger bond angle fluctuations. The exact bond angle fluctuation requires future X-ray diffraction measurements and correlates to \( \omega_{\text{TO}} \) and \( \Gamma_{\text{TO}} \) with a \( T_{\text{sub}} \) that requires more temperature points. For now, our goal is to achieve low temperature deposition of a-Si:H for silicon photonics applications.

The TA phonon mode at the Raman peak position of \( \sim 135 \text{ cm}^{-1} \) is attributed to the bond bending mode in the IRO of the amorphous network, while the TO phonon at \( 480 \text{ cm}^{-1} \) is attributed to the bond stretching mode in the SRO of the amorphous network [38]. By taking the Raman area intensity ratio of \( I_{\text{(TA)}} \) peak to \( I_{\text{(TO)}} \) peak, we can study the role of hydrogen on the TA bending modes (IRO) and TO stretching modes (SRO). Figure 1(d) presents information related to the role of hydrogen on IRO or SRO. In the hydrogen-dominated diffusion control regime, bond bending decreases \( ([I_{\text{TA}}/I_{\text{TO}}}] \) as the hydrogen concentration increases, which indicates that the effect of hydrogen on the structural disorder is more prominent in IRO than SRO. This observation matches the experimental results of Gupta et al. [38]. In the temperature \( (T_{\text{sub}}) \)-governed kinetic control regime, bond stretching increases with decreasing \( T_{\text{sub}} \), indicating that thermally induced structural distortion is more obvious in the SRO. These results show a balance between hydrogen diffusion and thermal deposition required to achieve device-quality a-Si:H. The experiments also show the optimized temperature of 230°C, which meets the above requirement.

The cross-section SEM images of the a-Si:H films are shown in Fig. 2(b), where the red box highlights the core thickness of 400 nm surrounded by silicon dioxide. Inset: the field intensity profile of the propagation mode (at \( \lambda = 1.55 \mu\text{m} \)) obtained from the 2 μm width waveguide.

### Table 2. Raman Spectral Information of a-Si:H Network for Different Substrate Temperatures

<table>
<thead>
<tr>
<th>( T_{\text{sub}} ) (°C)</th>
<th>( \omega_{\text{TO}} ) (cm(^{-1}))</th>
<th>( \Gamma_{\text{TO}} ) (cm(^{-1}))</th>
<th>( \Delta \theta ) (°)</th>
<th>( I_{\text{(TA)}}/I_{\text{(TO)}} )</th>
<th>Deposition Rate (nm/s)</th>
<th>Surface Roughness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>190</td>
<td>490</td>
<td>79.85</td>
<td>10.81</td>
<td>2.08</td>
<td>0.46</td>
<td>1.32</td>
</tr>
<tr>
<td>210</td>
<td>476.36</td>
<td>66.5</td>
<td>8.58</td>
<td>1.36</td>
<td>0.57</td>
<td>1.1</td>
</tr>
<tr>
<td>230</td>
<td>480.5</td>
<td>68.9</td>
<td>8.98</td>
<td>0.73</td>
<td>0.55</td>
<td>1</td>
</tr>
<tr>
<td>250</td>
<td>480</td>
<td>68.25</td>
<td>8.88</td>
<td>1.12</td>
<td>0.55</td>
<td>0.84</td>
</tr>
<tr>
<td>320</td>
<td>492.6</td>
<td>90.78</td>
<td>12.63</td>
<td>1.84</td>
<td>0.52</td>
<td>3.58</td>
</tr>
</tbody>
</table>

\( \omega_{\text{TO}} \) and \( \Gamma_{\text{TO}} \) obtained from the 2 \( \mu\text{m} \) width waveguide deposited at different \( T_{\text{sub}} \) temperatures. Figure 2(a) shows the deposition rate and the propagation loss of the a-Si:H waveguide for the different temperatures. The mass transport control (also known as diffusion control) deposition regime is observed at temperatures above 210°C, which is characterized by small changes of the deposition rate with temperature. The surface-limited or kinetic control regime occurs below 200°C, where the deposition rate is dependent on temperature changes. The small drop in the deposition rate at 320°C could also suggest that gas reactions are more prominent above this temperature, but temperatures above this point were not investigated as they are outside the temperature range of interest. The average deposition rate of a-Si:H material is 0.55 nm/s for the temperature range 210°C–320°C, while the deposition rate drop to 0.45 nm/s at \( T_{\text{sub}} \) of 190°C. It is noteworthy that the trend in the Raman shift matches the
trend in the propagation loss measurements, where the loss of a-Si:H deposited at 190°C and 320°C is higher compared to those of a-Si:H at 210°C, 230°C, and 250°C. The waveguide deposited at 230°C gives the lowest loss of 1 dB/cm. The inset in Fig. 2(b) shows the optical intensity profile from the end facet of the waveguide. We note that the AFM root mean square (rms) surface roughness of the a-Si:H film deposited at 190°C and 320°C is 1.32 nm and 3.58 nm, respectively, while the a-Si:H deposited at 210°C, 230°C, and 250°C has a rms roughness of about 1 nm (see Table 2).

From the Raman characterization, the a-Si:H film deposited at $T_{\text{sub}}$ of 230°C is a promising candidate for low-loss silicon photonics platforms. Therefore, a 400 nm thick a-Si:H film was deposited at 230°C, wire waveguides with different widths were fabricated as mentioned in Section 2, with their propagation losses assessed by the cut-back method, and coupling with optical fibers was performed via grating couplers. The ellipsometer measurement showed refractive index $n = 3.695$, $\kappa = 3.167 \times 10^{-6}$, and estimated band gap energy $E_g = 1.624$ eV was measured for the bulk material at 1550 nm using the Cody–Lorentz model [46].

The measured propagation losses at a wavelength of 1550 nm for different widths are shown in Fig. 3(a). The cross-section image of a waveguide with a width of 350 nm is shown in the inset of Fig. 3(b). Waveguides with widths ranging from 350 to 850 nm were measured under TE polarization, while the narrow 250 nm wide waveguide was measured under TM polarization only. The propagation loss [decibels per centimeter (dB/cm)] as a function of waveguide width is plotted in Fig. 3(b). The propagation loss was decreased with increasing width. The lowest propagation loss is 0.8 dB/cm for the 650 nm wide waveguide, while the 350 nm wide waveguide has a loss of 27 dB/cm. The higher loss is due to the weaker optical confinement and mode interaction with the surrounding sidewall roughness and air voids as seen in the inset of Fig. 3(b). For an 850 nm wide waveguide, the loss was increased to 3 dB/cm, which could be attributed to the fabrication error. Since the optical confinement is well within the 650 nm wide waveguide, and as the rms surface roughness is low, we focused our analysis on how much material absorption contributes to the loss after the hydrogenation and deposition at 230°C. The extinction coefficient $\kappa$ can be calculated using the measured loss as the absorption coefficient $\alpha$, where $\alpha = (4\pi\kappa)/\lambda$. Using the excitation wavelength at 1550 nm, the extinction coefficient $\kappa$ is $1.85 \times 10^{-6}$.

To evaluate the origin of the losses, we performed numerical analysis using a commercial software called MODE Solutions by Lumerical that uses a finite-difference eigenmode (FDE) solver approach to calculate the loss. We modeled all fabricated widths of the wire waveguides in the following order: (a) with absorption but without roughness and (b) with an absorption coefficient, sidewall/surface roughness, and air voids, which are the artifacts from fabrication. Simulations for different waveguide widths were executed using the $n$ and $\kappa$ values from the ellipsometer. First, the extinction coefficient was added into the material to simulate the propagation loss of the waveguide due to the material absorption at 1550 nm wavelength. The extracted extinction coefficient is $1.845 \times 10^{-6}$, which closely matched to our analytical estimate of $1.85 \times 10^{-6}$. Under the assumption of high optical confinement, the simulated loss of 0.73 dB/cm is comparable to the experimental loss of 0.8 dB/cm for the 650 nm wide waveguide. Further simulation with only the extinction coefficient on other waveguide widths shows no significant changes to the propagation loss. AFM measurement of surface roughness is shown in Fig. 4(a). From the cross-sectional view of the waveguide [inset of Fig. 3(b)], air voids are present between the SiO$_2$ cladding and the a-Si:H waveguide. All these roughness factors were taken into account in the simulation condition (b). The sidewall of waveguide has the anisotropic roughness (7 nm correlation length) to resemble the etching result, while the AFM measured top and bottom surface roughness is 3.58 nm (worst case). The same sidewall roughness was applied to the air void, where the width of the air void is 50 nm at an angle of 30° to emulate the fabricated features shown in Fig. 3(b). All waveguides support the fundamental TE mode, except from the waveguide that has 250 nm...
425 6. CONCLUSION

From the Raman results, in addition to a-Si:H Raman shift of 480 cm$^{-1}$, it is critical to achieve a FWHM of less than 70 cm$^{-1}$ and a bond angle deviation of $6.6^\circ < \Delta \theta_c \leq 10^\circ$. This is to ensure the optical quality of a-Si:H material for waveguide device applications. We have achieved those conditions at a deposition temperature of 230°C and shown that the absorption loss is lower than the scattering loss. We demonstrated, for the first time to our knowledge, a very low optical loss of 0.8 dB/cm at 1550 nm wavelength using the HWCD method. This low-loss waveguide offers a potential interconnection solution for high-density silicon photonics integration.

426

4 Funding. Engineering and Physical Sciences Research Council (EPSRC) (EP/L00044X/1, EP/N013247/1, EP/ L02112G/1).

427 Acknowledgment. The authors would thank Southampton Nano Fabrication Centre, University of Southampton. Reed is a Royal Society Wolfson Merit Award holder. He is grateful to both the Royal Society and the Wolfson Foundation. The authors acknowledge Dr. Antoine F. J. Runge for his help in the optical measurement using the Fabry–Perot method. All authors also thank Dr. David Thomson for letting us use his grating coupler transmission measurement setup.

428

References


Queries

1. AU: Per journal style, abbreviations are not allowed in the title. Please check the edit to the manuscript title.

2. AU: References must be cited in order in the text. We have renumbered the references to achieve this. Please carefully check the citations in text.

3. AU: Please define "FTIR" in this sentence: "However, for further verification of Si-H and Si-Hn bonds in a-Si network, FTIR could provide more information of the hydrogen content in the material."

4. AU: The funding information for this article has been generated using the information you provided to OSA at the time of article submission. Please check it carefully. If any information needs to be corrected or added, please provide the full name of the funding organization/institution as provided in the CrossRef Open Funder Registry (https://search.crossref.org/funding).

ORCID Identifiers

The following ORCID identifiers were supplied for the authors of this article. Please review carefully. If changes are required, or if you are adding IDs for authors that do not have them in this proof, please submit them with your corrections for the article. Authors who do not have iDs on the proof may add them by logging into their OSA account. To do this, click on the “Update Account” link on your Prism homepage or log-in directly to http://account.osa.org, then click the button “Create or Connect your ORCID iD” in the ORCID section of the Participation tab. If the ORCID window does not appear, then change your browser settings to enable pop-ups. Please indicate in your corrections if you or any coauthors have done this. Each individual author is responsible for adding or correcting his or her iD using the steps outlined above.

- Swe Z. Oo  https://orcid.org/0000-0001-7146-6009
- Yohann Franz  https://orcid.org/0000-0001-7721-7740
- Anna C. Peacock  https://orcid.org/0000-0002-1940-7172