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Low-Loss Amorphous Silicon Multilayer Waveguides Vertically Stacked on Silicon-on-Insulator Substrate

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Low-loss amorphous-silicon (a-Si) waveguides comprising three vertically stacked layers prepared on silicon-on-insulator substrates are demonstrated. We have fabricated multilayer a-Si waveguides and investigated their loss characteristics; this is the first such investigation to our knowledge. All the process temperatures were regulated below 400 °C for the complementary metal oxide semiconductor (CMOS) backend processes for the optical components on an LSI. Recently, the ultrafast nonlinear characteristics of a-Si waveguides have attracted additional attention. 7) However, in order to integrate the optical components on an LSI through backend processes, all the fabrication processes for the optical components should be regulated to below 400 °C in order to avoid damages to the complementary metal–oxide–semiconductor (CMOS) layer. Amorphous silicon (a-Si) is the most promising material for optical circuits since it can be deposited under low-temperature conditions by plasma-enhanced chemical-vapor-deposition (PECVD). 6) In addition, multilayer stacking can be realized by depositing a-Si and SiO₂ alternately, and high-density three-dimensional optical circuits can thereby be realized on the LSI. Recently, the ultrafast nonlinear characteristics of a-Si waveguides have attracted additional attention. 7)

Fig. 1. (Color online) (a) Schematic diagrams of c-Si (first layer) and a-Si waveguides (second and third layers) and (b) cross-sectional and (c) top SEM images of the third layer of the a-Si waveguide formed by PP-RIE.

in Fig. 1(a), and the cross-sectional scanning electron microscope (SEM) image of the third layer waveguide is shown in Fig. 1(b). The fabrication process is described below.

The waveguides were patterned by electron beam lithography (EBL) with a double-layered positive resist Zeon ZEP520A and with a C₀₂-containing microcomposite in order to enhance the etching selectivity between the resist and Si-films. 12) The waveguide pattern was formed by dry etching wherein two types of dry etching systems — parallel-plate reactive-ion-etching (PP-RIE) and inductively-coupled-plasma (ICP) RIE — were used. For the second layer fabrication, c-Si layer was removed and 1-μm-thick SiO₂ was deposited by PECVD from tetraethyl orthosilicate (TEOS) [TEOS flow rate: 14 sccm, O₂ flow rate: 300 sccm, gas pressure: 120 Pa, power: 250 W, deposition temperature: 300 °C]. Subsequently, a-Si was deposited by PECVD on the SiO₂ layer as the second layer. The third layer was also fabricated by repeating the previous processes. The SEM image from the top of the third layer waveguide is shown in Fig. 1(c). The sidewall roughness values (3σ’ values; σ’ is the standard deviation) of the waveguides after PP-RIE and ICP-RIE were measured by

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the function of the SEM (Hitachi S-5000) to be 3.3 and 2.4 nm, respectively; further, the sidewall angles of each waveguide were 81° and 85°, respectively.

It is well known that a-Si tends to have high optical absorptions under certain conditions. We measured the extinction coefficient and refractive index of the deposited a-Si by using the ordinary ellipsometry method. The deposition conditions were as follows. SiH₄ flow rate: 100 sccm, Ar flow rate: 100 sccm, power: 100 W, and deposition temperature: 300 °C. Figure 2 shows the wavelength dependence of the refractive index and extinction coefficient for the a-Si film. From the results, the real part of the refractive index was 3.48, and the material absorption in our deposition film at 1.55-μm wavelength can be expected to be negligible.

The surface roughness of each layer before and after the deposition of the a-Si layer was measured by using an atomic force microscope (AFM); these roughness values are listed in Table I as root-mean-square (RMS) values. σᵣₑₜₐₚ refers to the surface roughness before a-Si deposition for each layer (in other words, the roughness of the top of the SiO₂ film). For the first layer (c-Si), the value was measured after etching the c-Si film. σᵣₑₜₐₚ refers to the roughness values after the a-Si deposition. The table lists the RMS roughness for the a-Si films under the deposition pressures of 30 and 130 Pa during PECVD. The top surface roughness of a-Si film is inferior to that of c-Si film when the deposition pressure was 130 Pa.

The top surface roughness as well as the corresponding AFM image as a function of the deposition pressure is shown in Fig. 3. As the deposition pressure decreased, the surface roughness reduced from 1.06 nm (130 Pa) to 0.30 nm (30 Pa), and this can be attributed to increases in the migration length at lower deposition pressures. When the deposition pressure was 30 Pa, the surface roughness was 40–50% higher after the deposition of the a-Si layer and approximately twice and thrice that of the c-Si layer after the depositions of the second and third a-Si layers, respectively.

The propagation losses of a-Si waveguides fabricated by PP-RIE [CF₄ gas flow: 10 sccm, pressure: 0.3 Pa, bias power: 20 W, waveguide width: 450 nm, sidewall roughness: 3.3 nm (3σ value), sidewall angle: 81°] were measured by coupling transverse-electric (TE) polarized light from a tunable laser emitting at around 1.55-μm wavelength. The light was coupled to the waveguides through tip lensed single-mode fibers, and the propagation losses were calculated by using the cutback method. For the deposition pressure of 130 Pa, the propagation losses of the first c-Si layer, the second, and the third a-Si layers were 6.0, 10.2, and 12.0 dB/cm, respectively. The propagation loss of the second layer a-Si waveguide with the deposition pressure of 30 Pa was 7.0 dB/cm, i.e., only 1 dB/cm higher than that of the first layer c-Si waveguide.

Previous experiments had focused on the surface roughness of multilayer waveguides. In our study, we changed the etching machine from PP-RIE to ICP-RIE in order to cut down the sidewall roughness. Low process pressures can be applied by using ICP-RIE that assists the directionality of the ion flux in the chamber, and moreover, these characteristics lead to better vertical shapes during etching process. We fabricated multilayer a-Si waveguides up to the third layer with ICP-RIE [CF₄ gas flow: 10 sccm, pressure: 0.03 Pa, ICP power: 5 W, bias power: 150 W]. The deposition pressure of 30 Pa was used for a-Si; here we had no noticeable changes in the surface roughness between PP-RIE and ICP-RIE. Further, the waveguide width was changed to 500 nm. We assumed that the propagation loss reduces with wider widths even though the effect is negligible. The sidewall angle improved from 81 to 85° when the ICP-RIE etching process was used, and the sidewall roughness (3σ value) was estimated to be 2.4 nm. The propagation losses of the first layer c-Si waveguide and the second and third layer a-Si waveguides were measured to be 1.6, 3.8, and 3.7 dB/cm, respectively.

To determine the reasons for the propagation loss degradation with multilayer waveguides, we plotted the measured propagation losses against the sum of the RMS values of the top and bottom surface roughness values (σₑₜₐₚ² + σₑₜₐₚ庳²)½ (Fig. 4). The solid line in the figure shows the calculated results of the scattering loss after considering

![Fig. 2.](image-url) (Color online) Wavelength dependence of the refractive index and extinction coefficient for a-Si film.

![Table I.](image-url) Surface roughness of each layer (RMS).

<table>
<thead>
<tr>
<th>Measured point</th>
<th>First (c-Si) 130 Pa</th>
<th>Second 30 Pa</th>
<th>Third 130 Pa</th>
<th>Third 30 Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td>σₑₜₐₚ Top (nm)</td>
<td>0.17</td>
<td>1.06</td>
<td>0.30</td>
<td>1.03</td>
</tr>
<tr>
<td>σₑₜₐₚ Bottom (nm)</td>
<td>0.18</td>
<td>0.24</td>
<td>0.24</td>
<td>0.37</td>
</tr>
</tbody>
</table>

![Fig. 3.](image-url) (Color online) Surface roughness of a-Si film as a function of deposition pressure in the form of AFM images, (a) 30, (b) 50, (c) 90, and (d) 130 Pa.
the surface roughness and sidewall roughness for the PP-RIE-etched waveguides.\textsuperscript{14-16} The scattering loss at the sidewall was assumed to be 5.6 dB/cm. The measured propagation losses agreed well with the calculated ones, and this indicates that the primary cause of the propagation loss difference between the c-Si and a-Si waveguides is the scattering loss from the surface and not the material absorption of a-Si. Therefore, reducing the surface roughness as well as side wall roughness is very important for fabricating low-loss a-Si waveguides.

The relationship between the scattering loss and surface roughness is also calculated as a dashed line in Fig. 4 for the ICP-RIE etched waveguides; the scattering loss at the sidewall was estimated to be 1.2 dB/cm. The propagation loss drastically reduced in these samples as a result of the improvements in the sidewall roughness. All the propagation losses of each waveguide are summarized in Table II.

In summary, we have fabricated multilayer a-Si waveguides and investigated their loss characteristics for the first time to our knowledge. Further, we have confirmed the deterioration of the surface roughness for multilayer waveguides. The surface roughness and sidewall roughness dependence of the propagation loss have been described and the effects of the roughness values have been estimated separately. When the deposition pressure of a-Si was decreased from 130 to 30 Pa, the scattering from the surface roughness decreased, leading to improvements in the propagation loss. The scattering loss from the sidewall roughness also decreased when the etching method was changed from PP-RIE to ICP-RIE. The propagation losses of the first layer c-Si waveguide and second and third layer a-Si waveguides were obtained as 1.6, 3.8, and 3.7 dB/cm, respectively.

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Table II. The propagation loss of each layer waveguide.

<table>
<thead>
<tr>
<th>Etching method</th>
<th>First (c-Si)</th>
<th>Second (c-Si)</th>
<th>Third (c-Si)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP-RIE (dB/cm)</td>
<td>6.0</td>
<td>10.2</td>
<td>7.0</td>
</tr>
<tr>
<td>ICP-RIE (dB/cm)</td>
<td>1.6</td>
<td>-</td>
<td>3.8</td>
</tr>
</tbody>
</table>