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Loss Measurement of Multiple Layer a-Si Waveguides toward 3D Si-Optical Circuits

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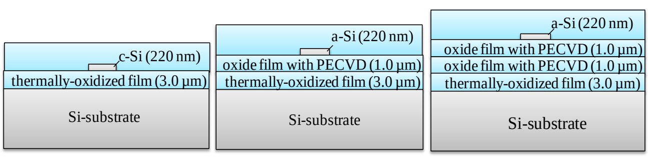
1. Introduction

A Silicon-based optoelectronic circuit technology is attractive as a solution for the current limitation of Si-LSIs such as global-wire signal delay and heat generation. Advantageous use of the silicon for the optical circuits can offer the monolithic integration of optical and electric functions on a single chip [1,2]. The high refractive index contrast between a silicon core and a SiO_2 cladding allows the reduction of the waveguide size to sub-micrometer range, which is similar or less size of the global wire. To integrate optical circuits on conventional CMOS electrical circuits in their backend process, all films must be deposited at the temperatures lower than 400 ^{o}C to avoid damage on the CMOS based electronic function layer. The a-Si film can be deposited in low temperature condition using plasma enhanced chemical vapor deposition (PECVD) [3], and it is suitable for multilayer integration which can provide higher density. Many researchers focused on the low loss a-Si waveguide [4,5]. However, no report about the characteristics of more than three stacked layers of Si waveguides has been published.

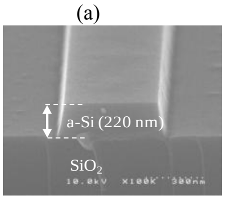
In this paper, we report the fabrication of multi layered a-Si wire waveguides up to 3 layers and those characteristics for the first time.

2. Fabrication method and characteristic

The fabricated Si waveguide structure is shown in Fig. 1(a). The core consists of 220-nm-thick crystalline silicon (c-Si) or a-Si layer with 450-nm width.



(a)



(b)

Fig. 1 (a) Schematic view of c-Si waveguide and multilayer a-Si waveguide and (b) SEM view of 2nd layer a-Si waveguide after RIE etching.

The waveguides were patterned by EBL exposure with double layered EB resists containing micro-composite C_{60} [6] and etched by conventional parallel plate reactive ion etching (RIE) process. Figure 1 (b) shows a SEM view of the a-Si wire waveguide after the RIE etching. The c-Si waveguides were covered by 1.0-µm-thick silicon dioxide (SiO_2) which deposited by PECVD (gas pressure: 120 Pa, bias power: 250 W, TEOS: 7 sccm, temperature: 300 ^{o}C). The following processes were used for a-Si multilayer integration. For the 2nd layer a-Si film, after cleaning a c-Si on SOI wafer with a typical RCA solution and RIE Si dry etching, a 1-µm-thick SiO_2 film was deposited by PECVD. Silane (SiH_4) and argon gases were used for the deposition of a-Si under the temperature of 300 ^{o}C.

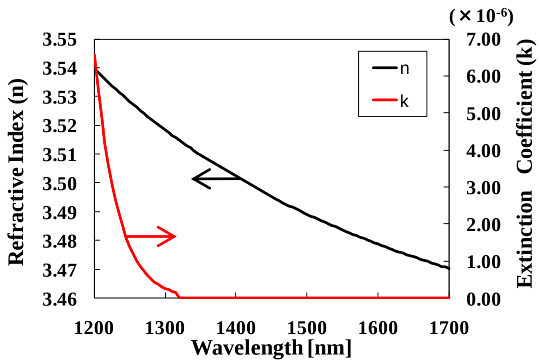


Fig. 2 The wavelength dependence of the refractive index and extinction coefficient for an a-Si film.

Figure 2 shows the real and imaginary parts of the refractive index of our a-Si film measured by ordinary ellipsometry method. Very small material absorption can be expected at 1.55 µm-band. Propagation loss of each waveguide was measured by coupling transverse-electric (TE) polarized light of 1.55 µm wavelength.

Table 1
α is propagation loss of each Si waveguide.

	α (dB/cm)	σ_{top} (nm)	σ_{bottom} (nm)
1st layer c-Si	6.0	0.17	0.18
2nd layer a-Si (130 Pa)	10.2	1.06	0.24
3rd layer a-Si (130 Pa)	12.0	1.03	0.37
2nd layer a-Si (30 Pa)	7.0	0.30	0.24

Measured losses of the c-Si waveguide and a-Si waveguides are summarized in Table 1. In addition, Table 1 shows the surface roughness at the top and bottom of the Si waveguides taken from an AFM. The propagation loss of the 1st layer c-Si waveguide, the 2nd and the 3rd layer a-Si, which were deposited at 130 Pa of gas pressure, waveguides were 6.0 dB/cm, 10.2 dB/cm and 12.0 dB/cm, respectively. The sidewall roughness, $\sigma_{sidewall}$, of a-Si wire waveguides showed approximately the same value ($\sigma_{sidewall}$: 1.1 nm) of the c-Si waveguide. The calculated scattering loss due to the $\sigma_{sidewall}$ of the Si waveguides are 5.6 dB/cm [7], which is agree with the measured loss of the c-Si waveguide in Table.1.

From the ellipsometry analysis in Fig. 2, we believed the main cause of the additional loss for a-Si came from the surface roughness. To improve the surface roughness of a-Si layers, we changed the deposition gas pressure to control surface roughness. Various deposited a-Si surface roughness as a function of deposition pressure was measured using atomic force microscope (AFM) as shown in Fig.3.

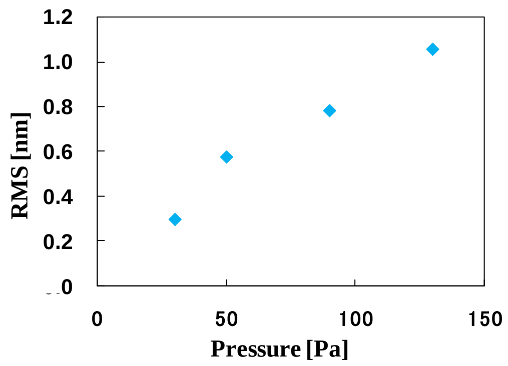


Fig. 3 RMS values of a-Si film surfaces depend on the deposition pressure.

The root-mean-square (RMS) values of 2nd layer a-Si for 130 Pa and 30 Pa were 1.06 nm and 0.30 nm, respectively. By reducing the deposition pressure we can get longer migration length and it leads to the improvement of surface roughness value.

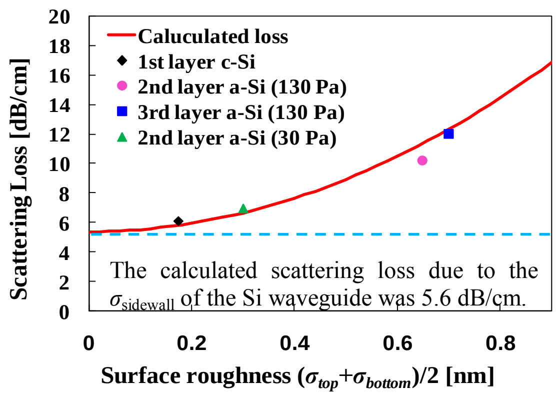


Fig. 5 Measured loss (diamonds), calculated loss (solid line) due to the surface roughness of the Si wire waveguides.

After reducing the a-Si deposition pressure, the propagation loss of the a-Si waveguide was improved as 10.2 dB to 7.0 dB. Measured propagation losses are plotted against the average RMS of top and bottom surface roughness (σ_{top}, σ_{bottom}) as shown in Fig. 5, where the solid line indicates the calculated result [8] and agree well with measured results (diamonds). Measured data of a-Si and c-Si are plotted on the same line which confirms that the difference in propagation loss of each waveguide is attributed to the scattering loss due to the surface roughness at the top and bottom of the Si waveguides, not by the material absorption of a-Si waveguides even for multiple layer stacks.

3. Conclusions

In conclusion, we investigated the propagation loss of the multilayered a-Si waveguides and their characteristics for the first time. The propagation loss of the 1st layer c-Si waveguide, the 2nd and the 3rd layer a-Si waveguides were 6.0 dB/cm, 10.2 dB/cm, and 12.0 dB/cm, respectively.

The propagation loss was improved by reducing the deposition pressure of a-Si from 130 Pa to 30 Pa. It leads to the reduction of surface roughness. The surface roughness of a-Si layer was reduced 1.06 nm to 0.30 nm, and the propagation loss was improved as 10.2 dB/cm to 7.0 dB/cm, which is 1 dB/cm additional loss compared with the loss of c-Si waveguide. These values indicate that the propagation loss of a-Si waveguide is greatly influenced by the scattering loss due to the surface roughness not by the material absorption loss of a-Si waveguide.

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