Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp222-223

Low-Loss Polycrystalline Silicon Waveguides for High-Efficiency Optical Modulator

Tsuyoshi Horikawa[1,2], Masashi Takahashi[1,2], Junichi Fujikata[1,3], Shigeki Takahashi[1,3]
Takeshi Akagawa[1,3], Masataka Noguchi[1,3] and Noritsugu Yamamoto[1,2]
[1] Institute for Photonics-Electronics Convergence System Technology (PECST)
[2] National Institute of Advanced Industrial Science and Technology (AIST)
[3] Photonics Electronics Technology Research Association (PETRA)
West 7 SCR, 16-1, Onogawa, Tsukuba, Ibaraki 305-8569, Japan
Phone: +81-29-849-1556 Fax: +81-29-849-1533 E-mail: tsuyoshi.horikawa@aist.go.jp

1. Introduction

Silicon photonics has been drawing the much attention of integrated photonic devices for chip-to-chip interconnection [1]. Silicon optical modulator (Si-MOD) is the key device to realize the high-performance integrated devices. And the polycrystalline silicon (poly-Si) waveguide has been expected to the electro-optic performance improvement for Si-MODs with poly-Si gate [2] or poly-Si PN junction [3]. Either case, in order to improve the efficiency and the power consumption, lightly-doped poly-Si film's optical loss and electrical resistivity should be controlled at lower level simultaneously. However, systematic research on these properties of the poly-Si films has not been reported yet.

The aims of this study is twofold; first one is to establish fabrication process on the basis of the thermal solid-phase crystallization (SPC) for amorphous-Si (a-Si) film for low-loss and low-resistivity poly-Si waveguide, and the other one is to investigate the underlying physics in the optical absorption and electron scattering in poly crystalline structure. In the following section, we discuss about the poly-Si characteristic's SPC temperature dependency. In the Sec. 3, we examine the two different approaches for the waveguide property improvement. Through those studies, we successfully demonstrated low-loss and low-resistivity poly-Si waveguide which drastically outperform the high-speed and high-efficiency Si-MOD.

2. SPC temperature dependence of the optical loss and electrical resistivity in poly-Si waveguide

On SPC process, annealing temperature (T_{SPC}) influences grain growth, so we investigated the T_{SPC} affect for the waveguide properties.

The poly-Si waveguide fabrication process is described as follows, at the first, a-Si film was deposited by LPCVD with 550 ˚C SiH_4 gas source atmosphere over the SiO_2 film. The second step is crystallization of deposited a-Si film through the SPC process at T_{SPC} of 560 ˚C to 650 ˚C. In this paper, this poly-Si is denoted by SPC-SiH_4. Following step is poly-Si lightly-doping. Ion implantation with P level 10^{18} atoms/cm^{-3} and activation annealing was performed. And the channel poly-Si waveguide core pattern with 220 nm height and 440 nm width was formulated by using electron beam lithography and inductively-coupled-plasma dry etching [4]. Finally, 1-mm-thick SiO_2-overclad was deposited on the pattern. Surface roughness in poly-Si was measured by atomic force microscopy and 0.60 nm to 0.75 nm RMS values were observed for all specimens. With such small surface roughness, we consider that the optical absorption and electron propagating in poly-Si is very little.

Fig.1 (a) showed the T_{SPC} dependency to the optical transmission loss and electrical resistivity of SPC-SiH_4. The optical transmission loss showed up-trend against the T_{SPC}. The average grain size was estimated from the cross-sectional TEM, **Fig.1 (b)**, ranging from 420 nm to 500nm and it showed no obvious dependency of T_{SPC} at examined temperature range. It is interesting that regardless the grain size, the optical absorption contribute the optical loss gain while the electron scattering worsen the electrical resistivity by the $T_{SPC.}$ This contradicted result implies that the optical absorption and the electron scattering behavior at amorphous-like grain boundary area could be estimated very different manners in poly-Si waveguide.

3. Effects of high-temperature anneal and source gas in a-Si deposition

In this section, we report the two of waveguides properties improvement results. First one is that the effect of additional high-temperature annealing (HTA) at 1100 ˚C in order to make the grain growth and boundary volume reduction [5,6]. In second approach, we examined poly-Si fabricated by SPC for Si_2H_6 base a-Si [SPC-Si_2H_6].

On **Fig. 2** and **Fig. 3**, the T_{SPC} dependency for the transmission and the resistivity was plotted with SPC-SiH_4, HTA-SiH_4 and SPC-Si_2H_6 respectively. The optical loss was drastically improved to 1.0 dB/mm by applying HTA (Fig.2), although the loss in SPC-Si_2H_6 keeps the same level with the SPC-SiH_4. As for the electrical resistivity, HTA-SiH_4 and SPC-Si_2H_6 resulted lower than SPC-SiH_4 (Fig.3). In particular, the SPC-Si_2H_6 resistivity 0.03 Ω-cm was obtained which is very similar to the single crystal Si value (0.02 Ω-cm).

Fig. 4 shows the Raman spectra for lightly-doped films of SPC-SiH_4, HTA-SiH_4 and SPC-Si_2H_6 observing the peak at 522 cm^{-1}. Enlarging the lower-energy side tail of the main peak, it is found that the HTA and the Si_2H_6 showed less shoulder height than the SPC-SiH_4, which could comprehend as the decrease of amorphous phase (~483 cm^{-1}) and microcrystalline phase (~500 cm^{-1}). Further research should be needed to understand the fabrication process affect for the film properties by the result of HTA-SiH_4 and SPC-Si_2H_6 in different manner. In summary, we observed the photon and electron contradicted behavior at grain boundary though it realized the low loss a-Si waveguide. And also we deeply examined the LPCVD chemistry and successfully determined the SPC process to control the Poly-Si Crystallinity that successfully demonstrated the low-loss and low-resistivity poly-Si waveguide.

4. Conclusions

We have demonstrated low loss 1.0 dB/mm poly-Si waveguides fabricated by the SPC a-Si films. Electrical resistivity of 0.03 Ω-cm was obtained for lightly-doped poly-Si with P doping level 1 x 10^{18} cm^{-3}. The relationship between physical properties and waveguide characteristics was discussed as for the photon and electron behavior at the grain boundary. The fabrication process was successfully developed in this study and promising result to realize the high performance Si-MODs.

Acknowledgements

This research is granted by JSPS through the FIRST Program, initiated by CSTP, and was conducted at TIA-SCR.

References

[1] I. A. Young et al., IEEE Com. Mag. 184 (2010)
[2] J. Fujikata et al., Optical Fiber Conf. 2010, OMI3.
[3] K. Preston et al., Opt. Express 17, 5118 (2009)
[4] N. Hirayama et al., 2011 JSAP, 24a-KB-10.
[5] Q. Fang et al., Opt. Express 16, 6425 (2008)
[6] L. Liao et al., J. Electron Mater. 29, 1380 (2000)

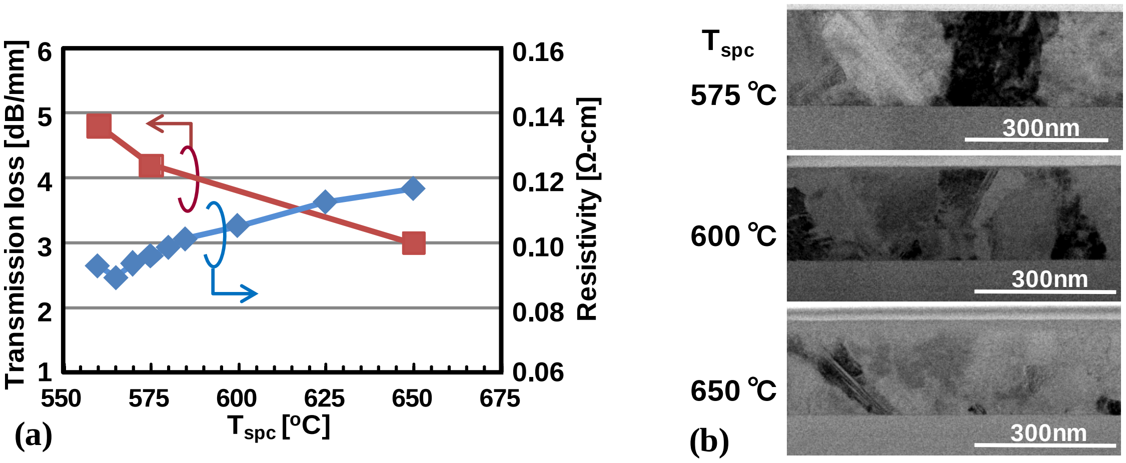

Fig. 1 The T_{spc} dependency for (a) the optical transmission loss, electrical resistivity and (b) cross-sectional TEM.

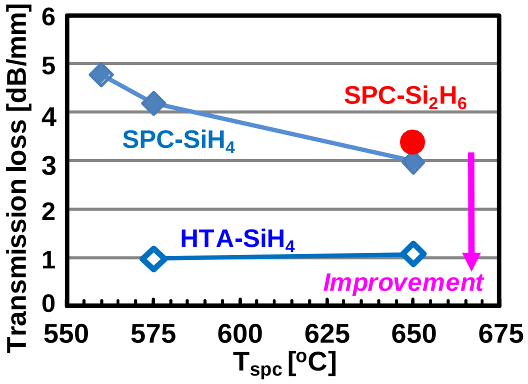

Fig. 2 The T_{spc} dependency of transmission for SPC-SiH_4, HTA-SiH_4 and SPC-Si_2H_6.

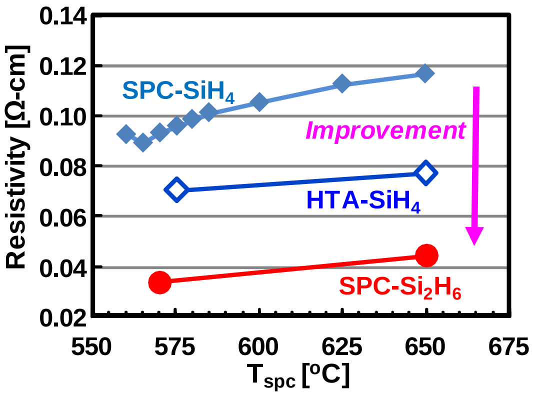

Fig. 3 The T_{spc} dependency of resistivity for SPC-SiH_4, HTA-SiH_4 and SPC-Si_2H_6.

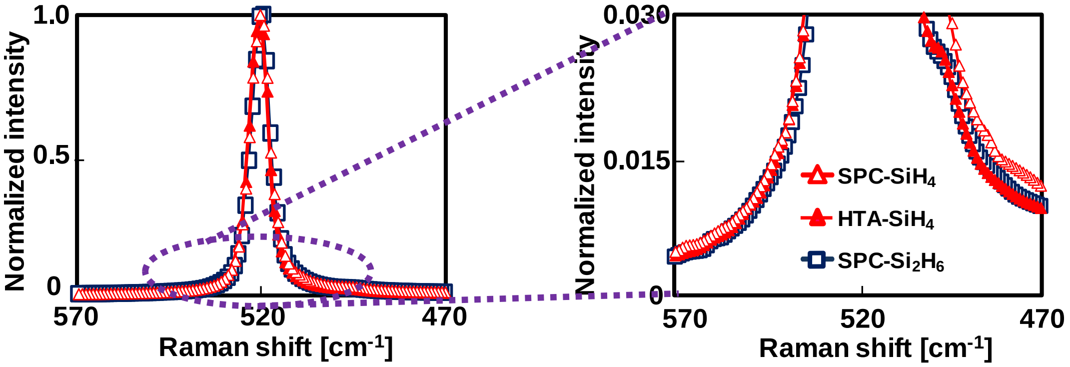

Fig. 4 Raman spectra of P-doped poly-Si for SPC-SiH_4, HTA-SiH_4 and SPC-Si_2H_6.