Monolithic Integration of Si-Dot Light Emitting Diodes, Si Photodiodes, and Spin-Coated Optical Waveguides on Si LSI

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1. Introduction

In order to overcome problems of signal propagation delay and power dissipation in metal interconnection in LSIs, the optical interconnection has been proposed [1]. A monolithic integration of optical components such as light sources, waveguides, and photodetectors, at low temperatures is required to avoid the damage to the underlying Si devices. A fluorinated polyimide (FPI) is one of the suitable materials for the optical waveguide because it can be formed at low temperature less than 400°C which is an acceptable temperature over the metal interconnection [2].

In this study, monolithic integration techniques of Sidot light emitting diodes (SDLEDs) [3], p-i-n photodiodes (PDs), FPI waveguides, and grating couplers on the same Si substrate have been developed as shown in Figs. 1 and 2. The light propagation characteristics from the SDLED through the waveguide with grating coupler, and the light detection by the p-i-n PDs have been investigated.

2. Device fabrication

SDLEDs are fabricated on p-type Si substrate (1 k Ω -cm) having local oxidation of Si (LOCOS) isolation as shown in Fig. 1. By alternately carrying out low-pressure chemical vapor deposition (LPCVD, using SiH₄+N₂, 560°C) and thermal oxidation, the four-layer stacked Si-dots/SiO₂ structure is formed. Poly-Si film (80 nm thick) is deposited by LPCVD (645°C) and doped with phosphorous in POCl₃+O₂ at 850°C.

A structure of the fabricated p-i-n PD is shown in Fig. 2. To form p^+ and n^+ diffusion regions, boron and phosphorus ions are implanted with an ion dose of 5×10^{15} cm⁻² at 50 keV. After forming diffusion regions, non-doped silicate glass (NSG) and phosphosilicate glass (PSG) layers are deposited by atmospheric pressure chemical vapor deposition and then Al electrode is formed.

Spin-on-glass (SOG) of 1.4 μ m in thickness is formed on PSG layer and baked at 400°C. Grating couplers are designed for vertical coupling (grating period $\Lambda = 411$ nm for He-Ne laser, and $\Lambda = 622$ nm for SDLED, wavelength = 950 nm) and formed on SOG layer by reactive ion etching (RIE: using CF₄+H₂). FPI film of 1.5 μ m in thickess is spin-coated on SOG, and baked at 360°C. Al metal mask for FPI etching is formed by dry etching (etching gases: BCl₃+Cl₂), and then the FPI waveguide is patterned by RIE with O₂ plasma. The waveguide corners on top of PDs are covered with Al and TiN in order to increase the incident light to PDs.

3. Results and Discussion

Figure 3 shows the fabricated device to evaluate the performance of grating coupler. FPI waveguide is 20 μ m in width and 4 mm in length. The light through FPI waveguide and two grating couplers is observed by CCD camera as shown in Fig. 3(c).

To examine the light propagation in the waveguide, He-Ne laser (wavelength: 633 nm) is incident vertically into the points A to J in Fig. 4 (a). The waveguide is $20 \,\mu m$ in width, and 4 or 6 mm in length. The grating couplers exist only at the points A and F, while there is no grating at the other points. Figure 4 (b) shows the photocurrent of PDs, which is observed even though the light is incident to the places with no grating coupler. The reason is thought as follows: the incident light on field oxide region generates free carriers in Si substrate, and they diffuse to the PDs. This phenomenon may cause crosstalk, but this can be avoided when silicon-on-insulating substrate is used. When the light is incident on the point A (or F), the photocurrent is larger than the case of point B or C (G or H). Therefore, the light from A or F is guided by the waveguide. Figure 5 shows the relation between incidence points of light, r (distance from the photodiode) and the photocurrent. Dotted curve is obtained by solving the diffusion equation for the photogenerated carriers in Si substrate. From the solid straight line connecting points A and F, the light propagation loss is calculated to be ~ 9.9 dB/cm. When r = 0, photocurrent extrapolated from the straight line is about 0.19 nA. On the other hand, the measured current when the light is incident to point E or J (adjacent to PDs) were about 26 nA. The ratio $0.19/26 = 7 \times 10^{-3}$ may indicate the coupling efficiency for two grating couplers, which leads to coupling efficiency of 8.5% per each grating coupler. This value is roughly consistent with the designed value (~ 10 %).

Figure 6 shows a spectrum of emitted light from SDLED. There is a peak around 1.2 μ m, and the spectrum is relatively broad due to the size scattering of Si-dots. The wavelength can be shortened by shrinking the dot size to the wavelength sensitive to the Si p-i-n PDs. Figure 7 shows the photograph and the CCD image of the fabricated SDLED and FPI waveguide. The waveguide is 10 or 20 μ m in width, and 1 mm in length. The light from the output grating coupler is very weak because the light power from SDLED is not sufficiently strong. Therefore, the communication between SDLED and PD on the same substrate did not succeed.

4. Conclusion

The fabrication technologies for monolithic integration of SDLEDs, p-i-n PDs, optical waveguides, and grating couplers have been developed. Photocurrent by the propagation light through waveguides and grating couplers is confirmed. Light emission by SDLED has been confirmed, but the output light intensity through waveguides and grating couplers are not sufficiently strong yet. It is necessary to improve the light emission efficiency of the SDLED as well as the coupling efficiency of the light coupler with the waveguide.



Fig. 1. Schematics of (a) FPI waveguide and SDLED, (b) four layer stacked Si-dot/SiO₂, and (c) AFM image of Si dots.



Fig. 2. Schematics of (a) FPI waveguide, grating coupler and p-i-n PD, (b) structure of p-i-n PD, and (c) FPI waveguide on p-i-n PD.



Fig. 3. (a) Schematic and (b) photograph of a device to evaluate performance of the grating coupler. When the light is incident normal to the left Al mirror, the propagation light is observed at the right mirror (c).

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Fig. 4. (a) Incidence position of He-Ne laser light and (b) response of p-i-n PDs. Bias voltage applied to the PDs is 7 V.



Fig. 5. Distance between incident point of light and photodiode vs. photocurrent. Propagation loss of FPI waveguides is ~ 9.9 dB/cm.

Fig. 6. Light intensity of the fabricated SDLED vs. wavelength.



Fig.7. (a) Photograph of fabricated SDLED and FPI waveguide and (b) observed CCD image.