Fabrication of spin-coat optical waveguides for optically interconnected LSI and influence of fabrication process on lower layer MOS capacitors

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Introduction

Optical interconnection was proposed for high-speed and high-performance of LSI [1], and then the optical waveguide is necessary to be integrated on LSI without any significant damage on the lower layer devices.

Spin-coat heat-resistant polyimide resin is a suitable material for optical waveguide on LSI because it is easily fabricated at low temperature. Then the fluorinated polyimide, FPI, which was developed for long-distance optical-communication devices [2], is adopted for material of waveguide on Si chips, and the fabrication process of low-loss and miniaturized waveguide on Si substrates is studied.

It is an important interest that whether the fabrication process of FPI waveguide damages the lower layer devices. Then, the FPI waveguide is made on MOS devices, and influence of the FPI waveguide fabrication process on the MOS devices is investigated for the first time in this work.

Waveguides Fabrication

Firstly an optical waveguide is fabricated as shown in Fig. 1 (a) to investigate the propagation characteristics for the FPI waveguide on Si substrates. The core layer is made of FPI (refractive index 1.55), bottom clad layer is made of thermal oxide film (refractive index 1.46) or Spin-On-Glass, SOG (refractive index 1.38) and side and upper clad layer are made of air. The thickness of the thermal oxide film is set to 2.2 μm, SOG to 1.5 μm and FPI to 1 or 1.5 μm. After spin-coating FPI film, Al hard mask (200 nm) was deposited on FPI. By means of resist masks patterned by the electron beam lithography, Al was etched using inductively coupled plasma etcher (etching gases: $BCl_3 + Cl_2$). Then FPI film was shaped to waveguide by reactive ion etching with the O_2 plasma, and the FPI waveguide fabrication was completed by removing Al mask by wet etching.

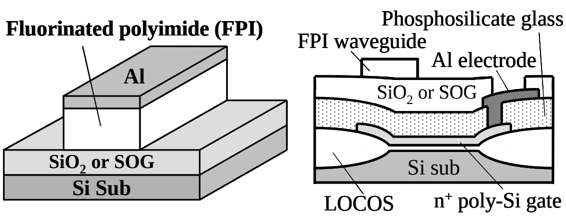

Fig. 1 Schematic structure of (a) FPI waveguide, where Al on FPI is removed after FPI etching, and (b) MOS capacitor.

Next, in order to examine the influence of the FPI waveguide fabrication process on lower devices, MOS capacitors were made and FPI waveguides were formed on it as shown in Fig.1 (b). After the SiO_2 film of 7 nm was formed on the LOCOS substrate by dry oxidation at 850°C, the poly-Si gate (area 100×100 μm^2), the phosphosilicate glass layer and the Al electrode (area 150×150 μm^2) were formed and the MOS capacitor fabrication was finished. Then FPI waveguides were fabricated after SiO_2 layer by Atmospheric Pressure CVD, APCVD or SOG layer was formed on the MOS capacitor. Finally the contact hole for the measurement was formed into the SiO_2 or SOG layer.

Result and Discussion

Figure 2 shows waveguide-width dependence of propagation loss for the fabricated FPI waveguide. The He-Ne laser (wavelength 633 nm) was used for the source of light. It is found that propagation loss becomes large when the width of core becomes small. Figure 3 (a) shows SEM image of FPI waveguide and the roughness can be seen on the side wall. As shown in Fig.3 (b), the size of the waveguide becomes smaller then the frequency to which light reflects on boundary of the core and cladding layer increases. Therefore, the propagation loss originated mainly from the boundary of the core and cladding layer and is caused by surface roughness of side wall of FPI. On the other hand, when SOG is used for clad, the propagation loss is larger than the thermal oxide film. It is thought that the propagation loss is caused by the surface roughness of SOG. Although the propagation loss of SOG is somewhat large, it is possible to use it for optical interconnection in the chip.

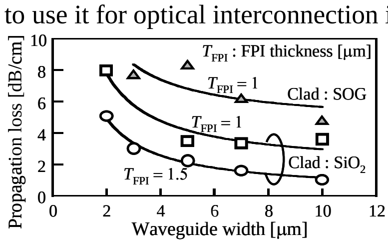

Fig. 2 Waveguide width vs. propagation loss

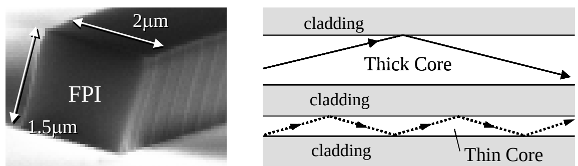

Fig. 3 (a) SEM image of FPI waveguide. (b) Light propagation in waveguide with different thickness.

Figure 4 shows the process to form the contact hole for the measurement in a clad layer. After forming a clad layer or fabricating waveguides, resist masks were formed and contact hole were formed by Chemical Dry Etching, CDE or the buffered HF, BHF. Figure 5 shows the time dependent dielectric breakdown, TDDB characteristic of MOS capacitor after depositing SiO_2 (1 μm) by APDVD on MOS capacitor and forming contact hole. It can be concluded that the damage to the gate oxide film through the contact hole formation is almost negligible.

Figure 6 shows the TDDB characteristic when SOG-coating was done with 2000 rpm (SOG thickness is about 750 nm) or 7000 rpm (SOG thickness is about 450 nm) under the humidity of 33 % or less and 68 %. The damage to the gate oxide film is observed in a case of SOG-coating with 7000 rpm, but there is no damage when the rotation speed is reduced to 2000rpm even though the humidity of 33 %. For the origin of gate oxide damage there are two possibilities. One is the stress of SOG and the other is the charge-up by the friction between sample and air. Since even for the thicker SOG (2000 rpm, humidity 68 %) the damage is smaller than the thin SOG (7000 rpm humidity 68 %), main reason of the gate damage is thought to be charge-up and the stress of SOG is almost negligible.

Further damage was found when the FPI waveguide was formed on SOG coated with 7000 rpm under the humidity of 33 % or less (Fig. 7). However, when SOG coating was done with 2000 rpm, the damage after FPI waveguide fabrication is drastically reduced.

Figure 8 shows the TDDB characteristic when FPI-coating was done on the MOS capacitor directly with 2000 rpm (FPI thickness is about 1200 nm). There is no damage when the rotation speed is reduced enough for FPI. Moreover, it can be also concluded that the stress of FPI is negligible.

These results can be understood by assuming that there is a nonlinear relation between the reliability degradation and the charge-up damage as shown in Fig. 9. The reliability degradation increases rapidly as the accumulated charge-up damage become large. It can be concluded that the reliability degradation occurs mainly when the clad layer is formed on the lower device by means of SOG-coating (white arrow in Fig. 9), and the damage during FPI waveguide fabrication (gray arrow) is not so large.

Conclusion

A microscopic optical waveguides were fabricated at low temperature and the influence on lower layer devices of the FPI waveguide fabrication process was investigated. It is found that the damage to lower layer devices is caused by the electrostatic charge during the spin-coating process on it, and this difficulty can be avoided with low rotation speed or under high humidity. These results greatly contribute to the fabrication process of the optically interconnected LSI.

Acknowledgement

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Reference

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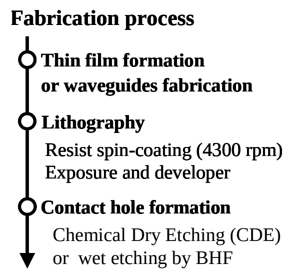


Fig. 4 Process to forming contact hole for measurement.

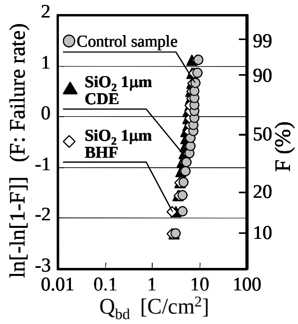


Fig. 5 TDDB characteristics of MOS capacitor after SiO_2 deposition by APCVD.

SOG-coating only

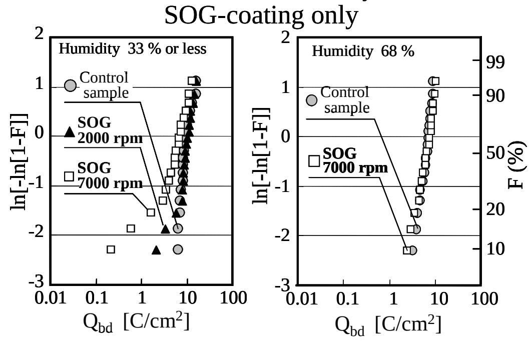


Fig. 6 Humidity and spin-speed dependence of TDDB characteristics after SOG-coating.

After FPI waveguide fabrication

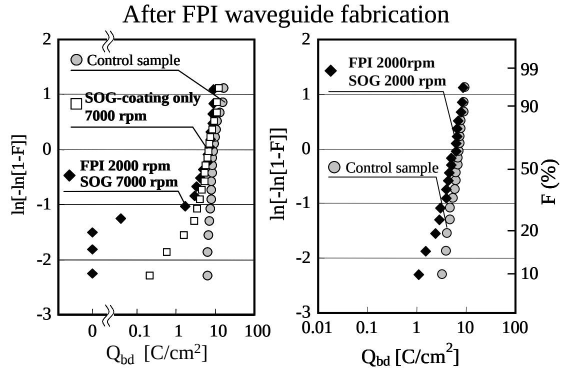
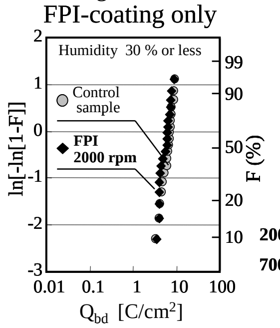


Fig. 7 Spin-speed dependence of TDDB characteristics after FPI-waveguide fabrication.

FPI-coating only



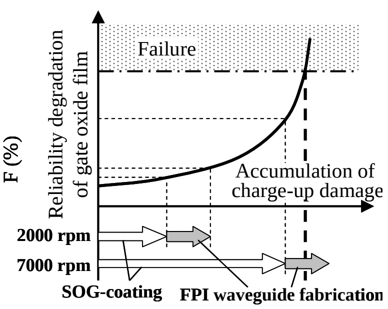


Fig. 8 TDDB characteristics after FPI-waveguide fabrication.

Fig. 9 Interpretation of reliability degradation for multi-processing.

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Introduction

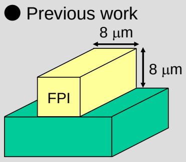
Integration of optical interconnections on Si-LSI

- Monolithic integration of waveguides
- Without any significant damage to the lower layer devices.

●Material of optical waveguides on LSI

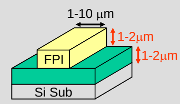
Fluorinated Polyimide, FPI
- Heat resistant up to 360 °C
- High transparency
- Easy fabrication by spin-coating

● Previous work



For long-distance optical-communication devices

● This work



For integration on Si-LSI

● Purpose of this work

1. Fabrication of waveguide on Si substrate at low temperature
2. Influence of FPI waveguide fabrication process on lower layer devices

Fabrication process of FPI waveguide

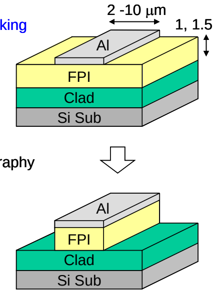
Lower clad layer formation
- Spin-on-glass, SOG 400 ℃ baking
  or thermal SiO_2 film etc.

Core (FPI) formation
- Spin-coating and 360℃ baking

Al hard mask formation
- Al deposition
- Resist patterning with EB lithography
- **Al dry etching**

FPI dry etching
- O_2 Reactive Ion Etching

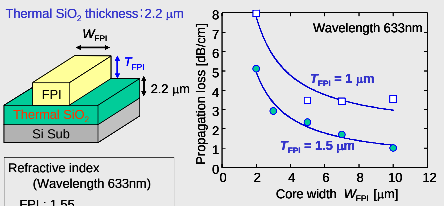
Hard mask removal



Propagation loss of miniaturized FPI waveguides on Si substrate

● Clad : Thermal SiO_2

Thermal SiO_2 thickness : 2.2 µm

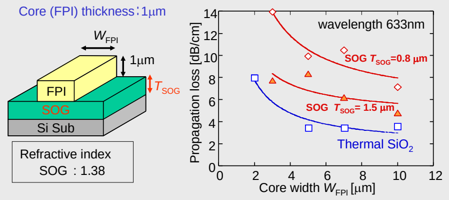


Refractive index
(Wavelength 633nm)
FPI : 1.55
Thermal SiO_2 : 1.46

The propagation loss increases when the core size become small.

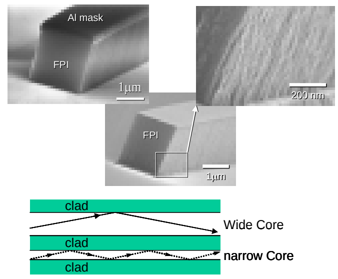
● Clad : SOG

Core (FPI) thickness : 1µm



Refractive index
SOG : 1.38

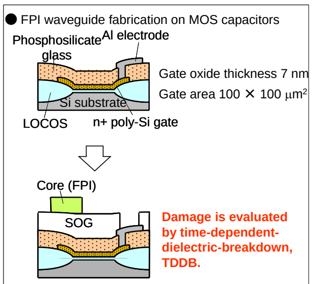
- When SOG is used for clad layer, the propagation loss is larger than the thermal oxide film used. ⇨ **Surface roughness of SOG**
- The propagation loss becomes large when the clad becomes thin. ⇨ **Leak of light to Si substrate**



Surface roughness of side wall
⇩
Propagation loss

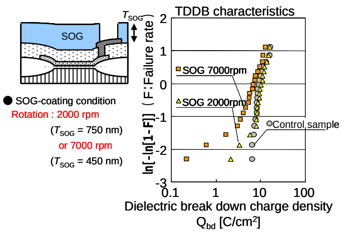
Influence of FPI waveguide fabrication process on lower layer MOS capacitor

●Investigation of damage to lower layer MOS capacitors



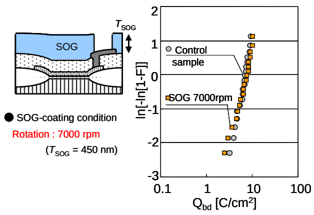
Damage is evaluated by time-dependent-dielectric-breakdown, TDDB.

●Case of SOG-coating only
(Humidity : less than 35 %)



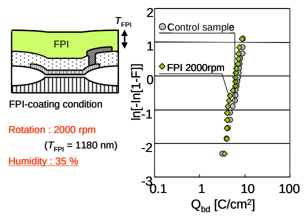
The higher the rotational speed during spin-coating is, the larger the degradation is.

●Case of SOG-coating only
(Humidity : 68 %)



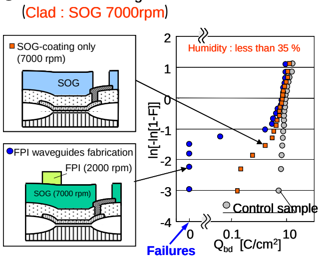
Damage under high humidity is almost negligible even if the rotation speed is 7000rpm. ⇨ **Charge-up by the friction**

●Case of FPI spin-coating



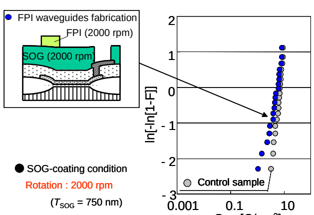
Damage can be suppressed by reducing the rotational speed at spin-coating of FPI.

●Case of FPI waveguides fabrication
(Clad : SOG 7000rpm)



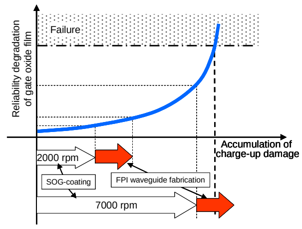
Further damage is found when the FPI waveguide is formed on SOG-coated with 7000 rpm under the humidity of less than 35 %.

●Case of FPI waveguides fabrication
(Clad : SOG 2000rpm)



The damage by FPI waveguide fabrication is drastically reduced when the rotation speed at SOG-coating is 2000 rpm.

● Interpretation of 2000 rpm and 7000 rpm SOG coating data



When the charge-up damage exceeds a certain threshold value, the reliability degradation rapidly increases .

Conclusion

- Miniaturized waveguides fabrication on Si substrate at low temperature
- Influence of FPI waveguide fabrication process on lower layer MOS capacitor
  - The damage is caused mainly by the electrostatic charging during spin-coating process. This difficulty can be avoided with low rotation speed or under high humidity.
  - When the charge-up damage exceeds a certain threshold value, the reliability degradation rapidly increases.

Acknowledgement
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