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# Characteristics of Silver Ion-Exchanged Glass Waveguides at 633 nm and 1.5 μm

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Silver ion-exchanged glass waveguide with its large surface index difference and shallow depth is suitable to be used for the hybrid integration of semiconductor device and glass waveguide using the semiconductor film grafting technique. We report characteristics of the planar and channel glass waveguides exchanged in the diluted silver nitrate melt in the visible and infrared spectral region. Especially, we determined the fabrication parameters for single-mode channel waveguide at 1.5 μm, an important wavelength in the optical communication. Directional couplers with several different configurations were fabricated, and their 3 dB coupling length was determined as a function of wavelength and polarization.

## INTRODUCTION

Recently developed semiconductor film grafting technique,[1] which is a process to remove a thin semiconductor film from its growth substrate and re-attach to a new substrate by van der Waals forces, opened a way to integrate semiconductor device, such as detector and laser, with glass waveguide for optoelectronic components. A thin semiconductor film of high refractive index can also be grafted to a glass waveguide to modify the effective index of the waveguide for making passive integrated photonic devices. For these applications, most of the optical power of the waveguide should be near the surface in order to achieve a maximum optical coupling between the semiconductor layer and the waveguide. A silver ion-exchanged glass waveguide is a good choice among various glass waveguides, because it has a large surface index difference and a shallow waveguide depth.[2] Despite of a fair amount of papers published on the silver ion-exchanged glass waveguide, properties of the channel waveguide in the infrared region, which is important for the optical communicaton, are not well known.

In this paper, we describe the characteristics of the waveguide made of Schott B-270 glass by ion exchange in a molten mixture of silver nitrate, sodium nitrate, and potassium nitrate. Effective indices of planar waveguides made at different silver concentrations are measured at 633 nm and 1.5 μm, and analyzed to deduce the surface index difference and the diffusion coefficient. At the optimal silver concentration of 2%, channel waveguides with varying channel width are fabricated, and the fabrication parameters, such as channel width and exchange time, for a single-mode channel waveguide at 1.533 μm are determined by observing the near-field pattern. Finally, the 3 dB coupling length of the directional couplers for various combinations of the waveguide width and separation between the two waveguides are determined at 1.5 μm.

## WAVEGUIDE FABRICATION

The B-270 glass made by Schott Glass Technologies Inc. was used in this study. According to the manufacturer's data, the refractive index is 1.5211 and 1.5073 at 633 nm and 1.5 μm, respectively, and the transmission for an optical path of 10 mm including the reflection loss is 0.91 in the spectral range of 500 nm to 1.7 μm.

A molten melt containing 50 mole % $NaNO_3$, 50 mole % $KNO_3$, and $x$ mole % $AgNO_3$, $x$ being in the range of 0.5 to 5, was used for silver ion source. We chose the mixture of $NaNO_3$ and $KNO_3$ to dilute the silver nitrate, instead of more commonly used $NaNO_3$,[3] because the melting point of the mixture is much lower than that of $NaNO_3$.[4] Since the silver-sodium exchange is rather fast, lower exchange temperature is desirable to reduce the effect of any small error in the exchange time. The exchange temperature used in this study was 300℃. The potassium-sodium exchange also forms a waveguide in B-270 glass. But the surface index change of the waveguide formed in pure $KNO_3$ melt at 375℃ is 0.0065 at 633 nm, which is an order of magnitude smaller than the corresponding value of 0.076 of the waveguide formed in 2 mole % silver nitrate melt described above at 300℃. Also the diffusion coefficient of $3.0\times10^{-16}$ $m^2$/sec of the former guide is smaller than that of $4.4\times10^{-16}$ $m^2$/sec of the latter, even though the former is made at higher temperature. Hence we will neglect the contribution of potassium-sodium exchange in the following discussions.

In order to fabricate a planar waveguide, we cleaned the glass, pre-heated to the melt temperature, and immersed it in the melt for the desired time. Channel waveguide pattern was defined by an aluminum mask made by standard photolithography, 1000 Å thick aluminum evaporation and lift-off. After exchange, the aluminum mask was etched away, and the end faces of the waveguide were polished for optical coupling.

## PLANAR WAVEGUIDES

Planar waveguides were made at five different silver nitrate concentrations of 0.5, 1.0, 2.0, 3.5, and 5.0 mole % to study the concentration dependence. At each concentration, about 4 waveguides were fabricated with different exchange time in the range of 0.5 to 8.5 hours.

Effective indices of the planar waveguides were measured using the usual prism coupling method for both TE and TM polarizations. The wavelengths used were 633 nm of a He-Ne laser and 1.5 μm from a color-center laser. The index profile was calculated from the measured TE effective indices using a stepwise linear Wentzel-Kramers-Brillouin (WKB) procedure.[5] A typical example is shown in Fig. 1 for the waveguides exchanged in the 2 mole% silver nitrate melt for exchange time of 1, 2, 4, and 8.5 hours at 633 nm. The surface index calculated from the WKB method is better if the number of measured indices used as input is larger. As can be seen in Fig. 1, the calculated surface index is almost same for waveguides exchanged for 4 hour (having 6 measured indices) and 8.5 hour (9 measured indices). Therefore we assumed that the surface index calculated for the waveguides supporting more than 6 modes is the real surface index.

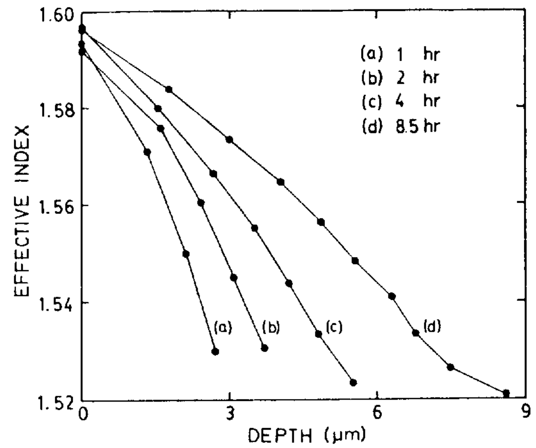

Fig. 1 Index profile of the planar waveguides exchanged in the 2 mole % silver nitrate melt for the exchange time of (a) 1, (b) 2, (c) 4, and (d) 8.5 hours.

The surface index determined as in the above is plotted in Fig. 2(a) as a function of silver nitrate concentration. As the silver concentration increases, the surface index quickly rises and saturates at 1.601 yielding an index difference of 0.080 between the waveguide surface and the substrate. An effective waveguide depth $d$ is defined as the depth where the index is in the middle of the surface and substrate indices, and an effective diffusion coefficient $D$ is obtained by fitting the data to the equation $d=(Dt)^{1/2}$. The effective diffu-

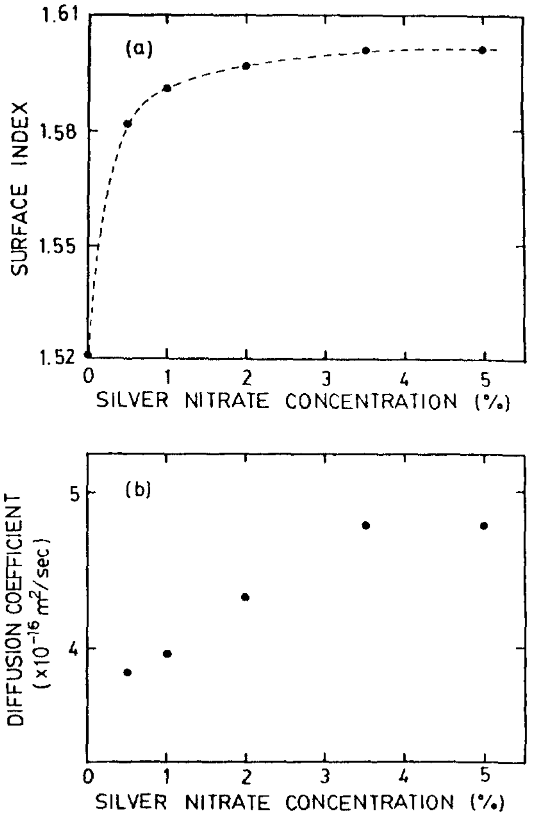

Fig. 2 Properties of the planar waveguides as a function of the silver nitrate concentration; (a) surface index at 633 nm, and (b) effective diffusion coefficient. The dotted line in (a) is an eyeguide.

sion coefficient is plotted in Fig. 2(b) as a function of silver nitrate concentration. It is $0.044\times10^{-14}\ \mathrm{m^2/sec}$ at 2 mole %, and reduced by 20% at 0.5 mole %.

At 1.5 μm, only 3 or 4 modes are observed and the WKB analysis would be less accurate. The estimated surface index shows a concentration dependence similar to that in Fig. 2(a) with a saturated index difference of 0.08, which is about equal to that at 633 nm.

The TM effective index is same as TE effective index within experimental error ($\sim 3\times10^{-4}$) for the tightly confined modes, i.e., lower-order modes of the waveguides exchanged for longer time, but becomes significantly smaller for the shallower modes. For example, the TM index at 1.5 μm of the waveguide exchanged in the 2 mole % melt for 20 minutes is 1.5127 as compared with 1.5159 of the TE index. This dependence on mode confirms that the birefringence is due to the waveguide geometry, not due to the material property of the substrate.

## CHANNEL WAVEGUIDES

For the channel waveguide fabrication, we chose 2 mole % silver nitrate melt where the surface index begins to saturate; at lower concentration the reduction of the surface index is significant, while at higher concentration there would be a chance of silver reduction leading to a higher propagation loss[13] without any significant increase in the surface index. In order to determine channel width and exchange time for a single-mode waveguide at 1.5 μm, we fabricated channel waveguides with width varing from 3 to 15 μm by a step of 0.5 μm on the same glass slide for exchange time from 15 to 30 minutes. The channel width in this paper refers to that of the mask, and the actual waveguide width may be larger due to the diffusion under the mask during the exchange.

A light of wavelength 1.533 μm from a semiconductor laser was coupled into the waveguide through a fiber, and the output pattern captured by a camera was displayed on a vedeo screen. For a fixed exchange time,

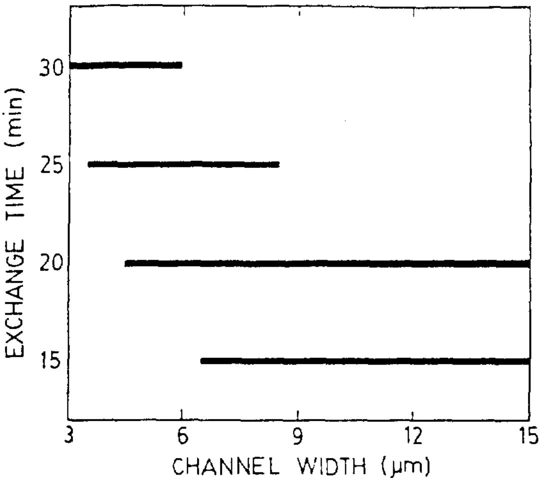

Fig. 3 Width of the channel waveguide that supports TE single-mode propagation at 1.533 μm for four different exchange time of 15, 20, 25, and 30 minutes.

the channel width for a single mode was determind by examining this output near-field pattern. The error in determining the boundary of the single-mode range is about 0.5 μm. The results are summarized in Fig. 3, where the channel width that supports a single-mode TE propagation is plotted for exchange time of 15, 20, 25, and 30 minutes. The results for TM polarization shift to wider channel width by 0.5 to 1.0 μm, which is consistent with the fact that the TM effective index is smaller than TE. For the channel width of 6 to 7 μm, which is the diameter of a typical single-mode fiber, exchange time of about 20 minutes yields a single-mode guide for both polarizations.

## DIRECTIONAL COUPLERS

Directional couplers were made by ion exchange in the 2 mole% silver nitrate melt for 20 minutes. Four different combinations of (waveguide width)/(separation between the waveguides)/(waveguide width) were used; 6/3/6, 7/3/7, 6/4/6 and 7/4/7 in the unit of μm. For each configuration, 20 couplers were made with the length of the coupling region varying from 0.25 mm to 5.0 mm by a step of 0.25 mm. The transition region between the coupling region and the separated region was at an angle of 0.5 degree.

The coupling ratio was measured by launching light to one of the pair waveguides and detecting the output power from each of the two waveguides. The light source was a color-center laser with a tuning range of 1.45 to 1.55 μm. A plot of output power ratio versus coupling length gave a good sinusoidal curve, and the 3 dB coupling length was read from the curve.

Table 1 summarizes the 3 dB coupling length for the four different configurations at three different wavelengths for both TE and TM polarizations. As expected, the coupling length is longer for the couplers with larger waveguide width and larger separation between the waveguides, in which case the light power is more tightly confined in the waveguides. Also it is longer at shorter wavelength and for TE polarization for the same reason. It is interesting to note that the ratio of the coupling lengths for TE and TM is about two, depending on the configuration and the wavelength. This property may be utilized in the polarization splitter.

Table 1 TE/TM 3 dB coupling length (in mm) of the directional couplers for four different configurations (in μm) at three different wavelengths ($\lambda$ in μm).

| Configuration | $\lambda = 1.45$ | $\lambda = 1.50$ | $\lambda = 1.55$ |
|---|---|---|---|
| 6/3/6 | ··· | 1.4/0.7 | ··· |
| 7/3/7 | ··· | 1.8/1.1 | ··· |
| 6/4/6 | 3.7/2.0 | 2.9/1.4 | 2.1/0.9 |
| 7/4/7 | 4.1/2.9 | 3.5/2.1 | 2.9/1.5 |

## SUMMARY

We studied the properties of the waveguide made of Schott B-270 glass exchanged in the silver nitrate melt diluted with sodium nitrate and potassium nitrate. The surface index difference and the diffusion coefficient for the planar waveguide were obtained at 633 nm and 1.5 μm as a function of silver nitrate concentration. With the optoelectronic applications for the optical communication in mind, the fabrication parameters for the single-mode channel waveguide at 1.5 μm were determined; silver nitrate concentration of 2 mole %, exchange temperature of 300℃, exchange time of 20 minutes, and channel width of 6 to 7 μm. Directional couplers were made using these parameters, and 3 dB coupling length was determined for different configurations, wavelengths, and polarizations.

The properties of the channel waveguide may be sensitive to the details in the fabrication process. For example, if the conductivity of the aluminum mask is higher, it reduces the exchange rate,[6] leading to a longer exchange time for the same waveguide. Indeed, we observed that, if we use a different evaporator to deposit the aluminum mask, the properties of the waveguide change slightly. Therefore, for those who want to reproduce the results in this work, the parameters in this paper should be regarded only as a guide.

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# 은 이온 교환법으로 만든 유리 도파로의 633 nm와 1.5 μm에서의 특성 연구

유 건 호
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.(1992년 6월 30일 받음)

은 이온 교환법으로 만든 유리 도파로는 표면 굴절율 차가 크고 도파로 깊이가 얕기 때문에, 반도체 박막 이식법을 이용한 반도체 소자와 유리 도파로의 혼성 집적에 사용되기에 적합하다. 이 논문은 묽게 한 잘산화은 용액에서 이온 교환으로 만들어진 평면 및 채널 유리 도파로의 가시광선 및 적외선 파장 영역에서의 특성을 보고한다. 특히, 광통신에 중요한 파장인 1.5 μm에서의 단일 모우드 채널 도파로의 제작 조건을 결정하였다. 또한 여러가지 다른 구성 형태의 방향성 결합기가 제작되어, 파장과 편광 방향에 따른 3 dB 결합 길이가 결정되었다.