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Development of microfabricated TiO_2 channel waveguides

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An optical channel waveguide is a key solution to overcome signal propagation delay. For the benefits of miniaturization, development of microfabrication process for waveguides is demanded. TiO_2 is one of the suitable candidates for the microfabricated waveguide because of the high refractive index and the transparency. In the present study, conventional microfabrication processes manufactured TiO_2 channel waveguides with 1–20 μm width on oxidized Si substrates and the propagation loss was measured. The prepared channels successfully guided light of 632.8 nm along linear and Y-branched patterns. The propagation loss for the linear waveguide was 9.7 dB/cm. [doi:10.1063/1.3615716]

An optical channel waveguide is a key component of optical interconnection among optical and optoelectronic devices, and plays a crucial role to overcome the bottleneck caused by signal propagation delay.[1,2] For the benefits of compact size, high performance, and low power consumption, development of miniaturization technology for optical channel waveguides is an urgent issue. Recently, silica and glass waveguides with diameters of submicrometer scale were developed and showed good light guiding ability.[3–5] Since the miniaturization limit of waveguides is dominated by diffraction limit $\lambda/2n$ (λ: wavelength, n: refractive index of the core),[6] waveguides with a high refractive index are highly required for further miniaturization. Titanium dioxide (TiO_2) is one of the candidates for the microfabricated waveguides because of the high refractive index and good transparency from infrared to visible region. In past two decades, microfabrication processes for TiO_2 channels have been developed by several groups. In detail, laser-beam lithography, nanoimprint, and electron-beam methods fabricated TiO_2 lines on substrates.[7–10] Furthermore, dry etching process with photolithography formed controlled microfabricated TiO_2 patterns.[11] However, there has been no report for the TiO_2 channel waveguide of which the optical property has been evaluated.

In the present study, TiO_2 channel waveguides with micrometer-size width are manufactured using conventional microfabrication processes and these optical properties are evaluated. First, the TiO_2 films used in the study are characterized by X-ray diffraction (XRD) and ellipsometry. After the fabrication of the TiO_2 channels, guiding of visible light is observed for linear and Y-branched structures. In addition, a propagation loss in linear waveguides is estimated using the cutback technique.

Figure 1 shows the scheme for fabrication of TiO_2 channel waveguides. The substrates were TiO_2 deposited Si wafers, which were purchased from Yamanaka Semiconductor (Japan). The substrates were single-side polished n-type Si(001) wafers (resistivity = 1–20 $\Omega \cdot$ cm; thickness =

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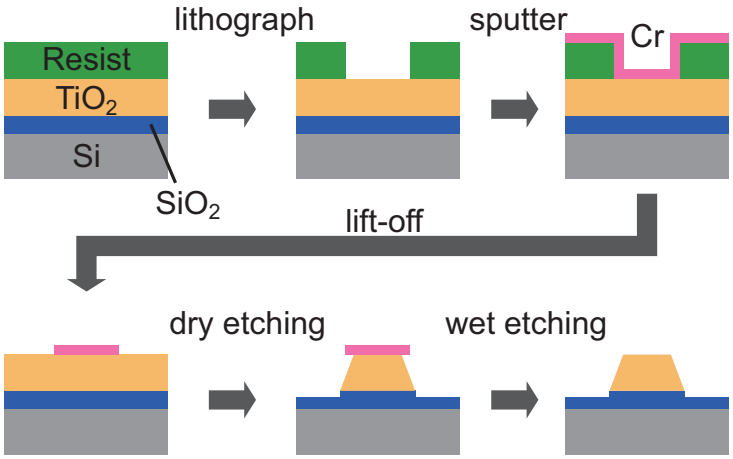

FIG. 1. Fabrication scheme for a TiO_2 channel waveguide on a thermally oxidized Si substrate.

525 μm), on which SiO_2 layers (thickness = 300 nm) were thermally grown. TiO_2 films (thickness = 600 nm) were deposited by RF magnetron sputtering for a TiO_2 target with Ar/O_2 gas (95 : 5, v/v) at 80 °C on the SiO_2 layers. Characterization of the TiO_2 films were carried out by ellipsometry and XRD method using a spectroscopic ellipsometer UVISEL NIR (Horiba Ltd., Japan) and an X-ray diffractometer X'Pert PRO MRD (PANalytical B. V., Netherland) with Cu Kα, respectively. First, the wafer was cut into 20 mm × 20 mm and 20 mm × 40 mm for Y-branched and linear waveguides, respectively. Photoresist TSMR-V50 (Tokyo Ohka Kogyo Co., Ltd, Japan) was spin-coated on the pieces of wafer. After the photoresist was exposed for the patterns with 1–20 μm width and developed, Cr films (35 nm) were deposited on the pieces by RF magnetron sputtering with Ar gas. Cr etching masks were formed by lift-off after immersion in N,N-dimethylformamide for half a day and following ultrasonication for 10 min. After the lift-off process, the pieces were cleaned by ultrasonication in ethanol and acetone for 1 min each. Reactive ion etching with CF_4 and Ar gases formed TiO_2 channel waveguides. Solution of $(NH_4)_2Ce(NO_3)_6$, $HClO_4$, and deionized water (15 : 5 : 80, w/w) removed the residual Cr masks. Finally the samples were washed by deionized water (resistivity > 18.2 M$\Omega \cdot$ cm) and were dried by N_2 stream.

Incidence of light into the waveguides was achieved using a single-mode optical fiber (mode field diameter = 4.3 μm) that was attached on a manual stage with three linear adjustable axes. The edge of the fiber was brought close to edges of the cleaved waveguides. Outgoing light from the waveguides was collected by a multi-mode optical fiber (core diameter = 50 μm) and was detected by a photodiode-type detector DET36A/M (Thorlabs, USA) backed by a current amplifier. Here, the amount of the photocurrent was linearly proportional to the light intensity. The source of incident light was a He-Ne laser (wavelength = 632.8 nm; power = 4 mW). Measurements of propagation losses were carried out using the cutback technique.[12] In order to stabilize the positional relation between the incident optical fiber and the waveguides during the measurements, the single-mode optical fiber was adhered to the edge of the waveguides by optical epoxy resin EPO-TEK 301-2 (Epoxy Technology, Inc., USA). This stabilization contributed to the depression of fluctuation of the coupling efficiency between the optical fiber and the waveguides. The propagation losses were estimated from the dependence of the transmitted light intensity on the length of the waveguides.

Figure 2(a) and 2(b) show an XRD data and a dispersion of the refractive index for a non-patterned TiO_2 film on an oxidized Si(001) substrate, respectively. The XRD pattern has no specific peak in the measured region. The lack of distinguishable diffraction lines reveals that the TiO_2 film has an amorphous phase.[13,14] The refractive index n monotonically decreases with increase of wavelength in the region; the extinction coefficient k is nearly zero at the wavelength longer than 400 nm and abruptly increases at less than 400 nm. Similar features were reported for TiO_2 films deposited by sputtering.[15–21] The refractive index at 500 nm in Fig. 2(b) is 2.49, which is in good agreement with a TiO_2 film prepared under a low pressure condition.[13] The high refractive

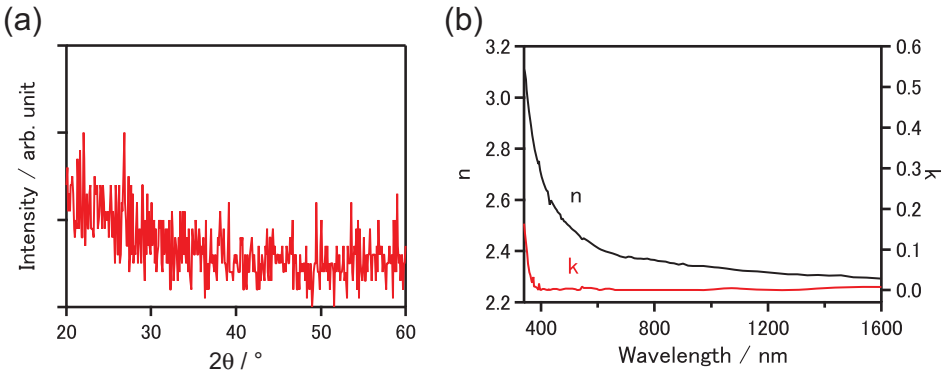

FIG. 2. (a) X-ray diffraction data and (b) refractive index for a non-patterned $TiO_2/SiO_2/Si$ sample. Symbols of n and k indicate the refractive index and the extinction coefficient, respectively. The small peak and dip structures are artifacts caused by discontinuity of phase in the ellipsometric data.

index ($n = 2.49$) means that the TiO_2 film has a high packing density, since refractive indexes are proportionally related to densities of films.[13,22]

Figure 3(a) and 3(b) show typical scanning electron microscope (SEM) images for a fabricated linear TiO_2 waveguide and its cross section, respectively. The top of the waveguide has a smooth surface. On the contrary, roughness of the sidewalls is large. The outline of the cross section becomes trapezoidal and the morphology of the TiO_2 layer shows a columnar structure. Fig. 3(c) is a top view image of a simple Y-branched waveguide, which diverges from a stem of 25 μm into two 25 μm branches. The angle of two branches is 14°. Roughness of the sidewalls on the branches is larger than that of the stem, because of the 1 μm spatial resolution of the photolithography technique in the present study. Fig. 3(d) shows propagation of red laser light through the Y-branched channel. The incident light from the single-mode optical fiber entered into the stem (left side of the figure) and propagated to the branches (right side). The light clearly divides into two moieties at the Y-junction and the excess loss is 5–6 dB compared with a linear waveguide. This result indicates that the TiO_2 channel has a good guiding ability. Fig. 3(e) shows attenuation of red light in a linear waveguide with 10 μm width. The experimental data were fitted with the following function (Lambert's law):

$$I = I_0 10^{-A(d_0-d)/10}, \tag{1}$$

where I is the intensity of transmitted light, A is the propagation loss, d_0 is the initial waveguide length, and d is the cutback length. I_0 is the initial light intensity, which is treated as a fitting parameter here. In the present study, the amount of the photocurrent is used instead of the light intensity because there is no influence on the estimation of A. The fitting result by eq. (1) gives a propagation loss $A = 9.7 \pm 0.4$ dB/cm as an average of three samples.

A propagation loss for a channel waveguide consists of three components; excess absorption of light by defect centers in material, scattering at grain boundaries, and scattering by surface roughness. The former two are caused by imperfection of the TiO_2 film and the latter originates from the device fabrication. Influence of each component on the present propagation loss (9.7 dB/cm) is discussed here. The absorption is strongly related to the crystallinity. As crystal grows, a transmittance edge of a TiO_2 film shifts to a shorter wavelength and the absorption decreases.[23] Since the present TiO_2 film has an amorphous phase, the absorption would be larger than those of properly cured TiO_2 films. The scattering at grain boundaries comes from a microstructure of films. As seen in Fig. 3(b), the cross section of the waveguide shows small columnar grains of TiO_2. The dependence of extinction coefficients on sputtering conditions elucidated that the scattering loss increased in the case of inhomogeneous and dense TiO_2 films.[13] The scattering by surface roughness depends on the conditions of the fabrication processes and the propagation mode. In the present study, typical sidewall roughness is 50–100 nm; the roughness is suppressed by improvement of the process conditions. The present TiO_2 channel of 10 μm width is a multimode waveguide, which has been

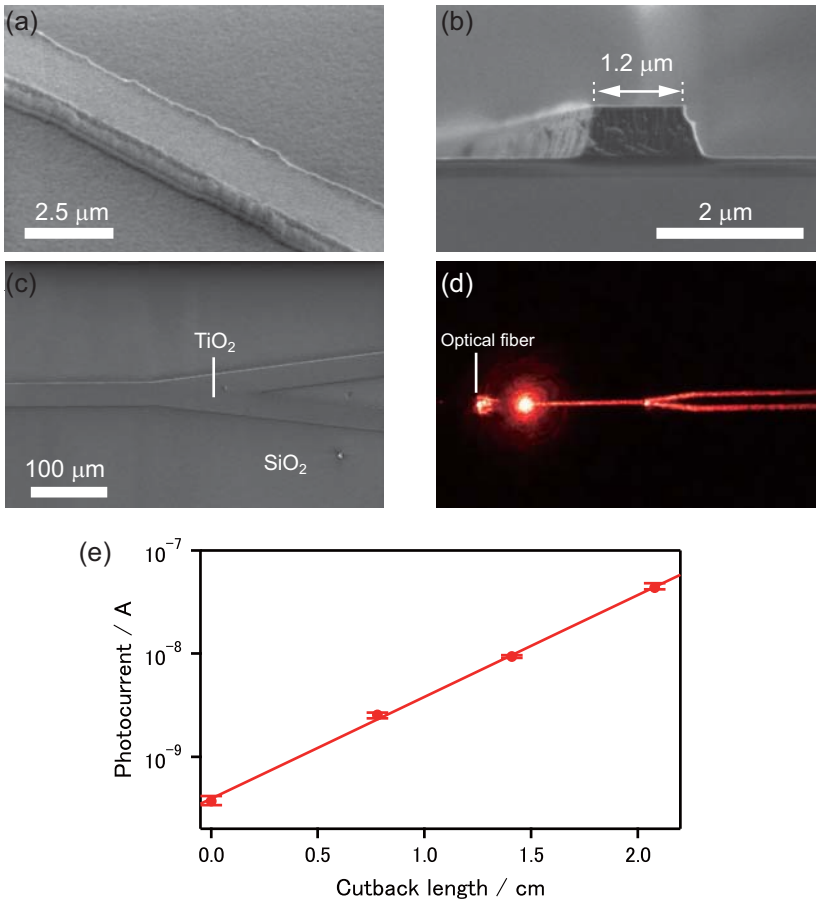

FIG. 3. Scanning electron microscope (SEM) images of (a) bird's eye view and (b) cross sectional view of a linear waveguide. Top view images of SEM and photography for a Y-branched waveguide are shown in (c) and (d), respectively. Typical variation of outgoing light in intensity is shown in (e) as a function of cut length. The result of eq. (1) in the text is shown by the solid line.

estimated from a numerical calculation for a TiO_2 core with a cross section of 600 nm × 600 nm using FIMMWAVE software (Photon Design Ltd., UK). The incident light couples with multiple modes in both horizontal and vertical directions during propagation. Since the coupled higher-order modes have strong distributions in intensity at the interface between a core and a cladding, the higher-order modes are sensitive to surface roughness and rapidly attenuate. However, considering the loss by surface roughness for an Si channel waveguide,[24] contribution of the surface scattering is not ignorable but small for the waveguide of 10 μm width. Therefore, the present loss would be mainly due to the imperfection of the TiO_2 film. TiO_2 channel waveguides with a high transparency would be obtainable by consideration of following points: crystallinity, surface roughness, film density, film microstructure, and propagation modes. Propagation loss for a TiO_2 channel waveguide would decrease to those of the planar waveguides (2 dB/cm), in which the prepared TiO_2 films are homogeneous, sparse, and thin.[25,26]

In summary, TiO_2 channel waveguides with micrometer-size width were fabricated using microfabrication process and their optical characteristics were observed. The channels successfully guided light of 632.8 nm along linear and Y-branched patterns. The estimated propagation loss revealed that the TiO_2 channel waveguides had less transparency than those of past planar waveguides. The authors gave the strategy for the fabrication of highly transparent TiO_2 channel waveguides. The present study contributes to development of miniaturization technology for optical interconnection.

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