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# Distribution of Refractive Indices of Si-wire Waveguides Fabricated on a 300 mm SOI Wafer Using ArF Immersion Lithography

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## 1. Introduction

Si-based photonic devices that can be fabricated by CMOS-compatible process have been studied widely. Recently, 300 mm silicon-on-insulator (SOI) wafers have been used for fabricating such Si photonic devices [1]. Using such large wafers enables us to fabricate photonic devices with high productivity and low cost providing high characteristic uniformity of individual photonic devices is attained [2]. Characteristics of Si photonic devices are strongly affected by the structure, therefore high uniformity of fabrication process is especially required [3].

In this paper, we describe characteristic distribution of Si-wire waveguide devices fabricated on a 300 mm SOI wafer using ArF immersion lithography. In order to measure optical characteristic distribution, we fabricated same shape ring resonators at different position on a wafer. Effective and group refractive indices of Si-wire waveguide were estimated from transmission spectra of fabricated ring resonators. We also describe distribution of the effective and group refractive indices on the wafer.

## 2. Distribution of line width on a wafer

In order to evaluate fabrication process uniformity, we first fabricated 100 nm width Si line patterns in SOI layer on a wafer and measured distribution of the line width using CD-SEM. Figure 1 shows the contour map of measured line width. We measured them at 84 points; the average and $3\sigma$ deviation of the measured line width are 100.6 nm and 5.3 nm, respectively. In addition, the $3\sigma$ deviation of line height can be estimated as 1.0 nm from a separate measurement of the thickness of SOI layer of the used wafer using ellipsometry. The 5.3 nm of line width distribution is small comparing former process with 200 mm SOI wafer and ArF dry lithography. In the former process, $3\sigma$ deviation of waveguide width was estimated as 7.8 nm [4].

## 3. Calculation of effective and group refractive indices

Assuming that these distribution of 100 nm width line patterns is same as that of waveguide width of 400-nm-width waveguides, we have calculated the distribution of the effective and group refractive indices of the Si-wire waveguides by using numerical simulations with finite element method (FEM). Calculated effective and group refractive indices were 2.158±0.022 and 4.415±0.009

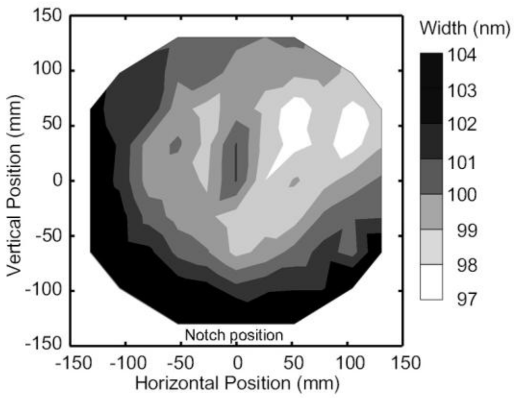


Fig.1. Contour map of the 100 nm width Si-wire patterns

for TE-like mode, and 1.663±0.011 and 3.317±0.060 for TM-like mode, respectively. The peak wavelength of ring resonator is related to the effective refractive indices $n_{eff}$ and the group refractive indices $n_g$. The wavelength shift is described as eq.(1).

$$\Delta\lambda = \lambda \frac{\Delta n_{eff}}{n_g} \tag{1}$$

Here $\Delta$ denotes deviation of variable, $\lambda$ is transmission peak wavelength. From eq.(1), the $3\sigma$ deviations of transmission peak wavelength at the wavelength of 1550 nm was measured as 7.7 nm for TE-like mode, and 5.1 nm for TM-like mode, respectively

Distribution of group refractive index also causes to change free spectral range (FSR) of ring resonator. The deviation of $FSR$ is described as eq.(2).

$$\Delta FSR = -FSR \frac{\Delta n_g}{n_g - \lambda (dn_g / d\lambda)} \tag{2}$$

In the case of ring resonator with ring radius 5 μm and coupling length 4.75 μm, $FSR$ and $\Delta FSR$ at the wavelength 1550 nm were 13.3 nm and 0.02 nm for TE-like mode, and 17.9 nm and 0.08 nm for TM-like mode, respectively.

## 4. Distribution of refractive indices by measuring ring resonators

Ring resonators were fabricated in five chips located at different place on the 300 mm SOI wafer as shown in Fig. 2 for investigating distribution of effective and group refractive indices of Si-wire waveguides. Fabricated waveguide width is 400 nm, and height is 220 nm. Five chips A, B, C, D and E are at position of 126, 129, 52, 94 and 43 mm from the center of wafer, respectively.

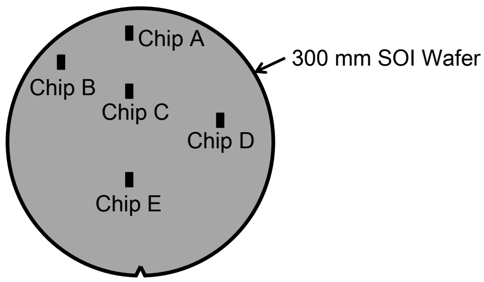


Fig.2. Location of the chips including measured ring resonator

*Effective refractive indices*

Effective refractive indices of the Si-wire waveguide were derived from measured drop peak wavelengths of ring resonator. We fabricated ring resonators with the ring radius 5 μm, the gap between ring and busline waveguide 0.2 μm and the coupling length 4.75 μm, and we measured transmission spectra of those ring resonators with wavelength range between 1540 and 1590 nm. Figure 3 shows estimated wavelength dependence of effective refractive indices. From this result, effective refractive indices at the wavelength of 1550 nm were 2.151 to 2.177 for TE-like mode, and 1.661 to 1.671 for TM-like mode. The deviations from average were less than 0.7% for TE-like mode, 0.4% for TM-like mode, respectively.

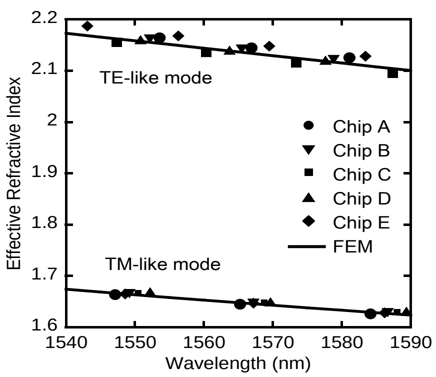


Fig.3. Wavelength dependence of effective refractive indices

*Group refractive indices*

To estimate group refractive indices, we fabricated ring resonators with the ring radius 30 μm, the gap between ring and busline waveguide was 0.3 μm, and the coupling length was 4.75 μm. The group refractive indices $n_g$ of the Si-wire waveguide can be estimated from the FSR with the following eq.(3).

$$n_g = \frac{\lambda^2}{FSR \cdot L} \qquad (3)$$

Here $L$ is circumference of ring and its designed value is about 200 μm. We measured transmission spectra of those ring resonators with wavelength range between 1540 and 1560 nm, and estimated group refractive indices by eq.(3). Figure 4 shows estimated wavelength dependence of group refractive indices. From this result, group refractive indices at the wavelength of 1550 nm were during 4.449 and 4.474 for TE-like mode, during 3.330 and 3.390 for TM-like mode. The deviations from average were less than 0.3% for TE-like mode, and 1.1% for TM-like mode, respectively..

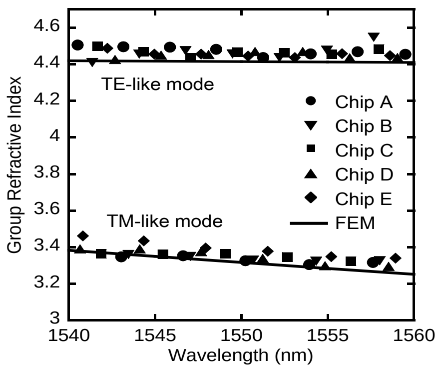


Fig.4. Wavelength dependence of group refractive indices

*Deviation of peak wavelength and free spectral range*

From estimated refractive indices and eq.(1), the deviations of transmission peak wavelength at the wavelength of 1550 nm were 4.8 nm for TE-like mode, and 2.4 nm for TM-like mode, respectively. From eq.(2), in the case of ring resonator with ring radius 5 μm and coupling length 4.75 μm, the average of FSR and the deviation of FSR at the wavelength 1550 nm were 13.2 nm and 0.04 nm for TE-like mode, and 17.5 nm and 0.07 nm for TM-like mode, respectively. These deviation values agree with those of calculated from the distribution of waveguide structures.

## 5. Conclusions

We investigated characteristic distribution of Si-wire waveguide devices fabricated on a 300 mm SOI wafer using ArF immersion lithography, and estimated distribution of fundamental devices parameters (effective and group refractive indices) on a wafer. The distribution was small enough for fabricating Si photonic devices with high productivity.


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