Evaluation of characteristic and fabrication variance of silicon photonics devices produced by CMOS

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We produced 30 chips on which silicon photonics devices were integrated at the Institute of Microelectronics (IME), and measured the resonant wavelengths and $Q$ factors of 24 chips. We compared the fabrication variance of silicon photonic devices with the results of previous research undertaken at our laboratory. In addition, we recorded a $Q$ factor of $1.6 \times 10^5$, which is the highest value yet reported as a width-modulated line defect photonic crystal nanocavity manufactured by the CMOS process.

Key words: Silicon photonics, Optical integrated circuit, CMOS process, width-modulated line defect photonic crystal nanocavity, Silicon microring resonator.

1. Introduction

In the 21st century, silicon photonics continues to develop rapidly. In recent years the environment that enables us to manufacture silicon photonic devices by the CMOS process has been well regulated. Electron beam lithography has been mainly used to produce silicon photonics devices, but for individual researchers it had been difficult to manufacture silicon photonics devices using CMOS. However, in the last few years, CMOS foundries such as the Institute of Microelectronics (IME) have emerged, thereby enabling the low-cost manufacture of large-scale systems by CMOS [1]. We designed a chip on which silicon photonics devices are integrated and fabricated 30 such chips at IME.

According to our previous research, it is necessary to reduce any fabrication variance to less than the width of the resonant spectrum of microring resonators so that an all-optical logic gate constructed with microring resonators definitely works [2].

We measured the $Q$ factors and resonant wavelengths of 24 sample microring resonators and width-modulated line defect photonic crystal nanocavities. We compared the fabrication variance of the microring resonators with the results of our previous research.

2. Construction of measurement system

Fig. 1 shows our measurement system. We constructed experimental equipment to evaluate the characteristics of silicon photonic devices. The measuring modules were fixed on piezo stages that work with a precision of 1 µm and in the range of 4 mm at maximum. The stage can move vertically and along the depth in fig. 1.

Fig. 1: Diagram of measurement system.

We installed an IR camera and a visible light camera to observe a chip from above. The visible light camera is used to roughly adjust the position of a module of interest and a waveguide on the chip. We use the IR camera to perform fine adjustments so that light is incident more exactly on the waveguide.

Dimension of the chips are 8×2 mm. A chip consists of silicon substrate, silica under cladding, silicon slab and silica over cladding. The devices we designed are fabricated in the silicon slab layer whose thickness is 210 nm. Silicon wire waveguides which is for putting light into/out devices extend from one end to another and they have spot size converters (SSCs) at each ends. They are set in columns every 50 µm and the number of them are 150. Figure 2 shows the photographs of microring resonators and width-modulated photonic crystal nanocavities. The diameter of the microrings, the width of silicon wire waveguides and the gap distance between waveguides and microrings are 10 µm, 400 µm and 200 µm, respectively.

Fig. 2: Microring resonators and width-modulated line defect photonic crystal nanocavities.

3. Measurement of transmission spectrum

We measured the transmission spectra of 25 silicon microring resonators and the same number of width-modulated line defect photonic crystal nanocavities. The input power was -15 dBm and the wavelength was swept from 1500 to 1630 nm. A preliminary experiment showed that the loss of the silicon waveguide was -7 dB/cm or less and that of the SSC was not more than -1.5 dB on one side.

Fig. 3 shows one of the transmission spectra that we measured. We used the resonant spectrum of the microring resonator shown with a red arrow to determine the $Q$ factor and the resonant wavelength. The photographs in Fig. 3 caught the moment of resonance.
Fig. 3: Transmission spectra of a microring resonator (top) and a width-modulated line defect photonic crystal nanocavity (bottom). The photographs caught the moment of resonance.

The highest $Q$ of a microring resonator was $2.0 \times 10^4$ and that of a width-modulated line defect cavity was $1.6 \times 10^5$. The highest $Q$ of a width-modulated line defect cavity was also the highest value yet reported for such a cavity fabricated by the CMOS process. The highest $Q$ of a width-modulated line defect cavity manufactured by electron beam lithography is about ten to the power of six, thus showing the difference in precision between width-modulated line defect cavities manufactured by CMOS and those manufactured by electron beam lithography.

4. Evaluation of fabrication variance

Table 1 shows the average value and standard deviation of the resonance wavelength and the $Q$ level of each resonator. Fig. 4 shows the corresponding histograms.

Table 1: Statistics of the resonant wavelengths and $Q$ factor

<table>
<thead>
<tr>
<th>Silicon microring resonator</th>
<th>Resonant wavelength (nm)</th>
<th>$Q$ factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>1550.9</td>
<td>$1.3 \times 10^4$</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>4.9</td>
<td>$0.3 \times 10^4$</td>
</tr>
<tr>
<td>Photonic crystal</td>
<td>Resonant wavelength (nm)</td>
<td>$Q$ factor</td>
</tr>
<tr>
<td>Average</td>
<td>1587.6</td>
<td>$8.1 \times 10^4$</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>7.6</td>
<td>$3.8 \times 10^4$</td>
</tr>
</tbody>
</table>

According to the above-mentioned previous study, an all-optical logic gate constructed with microring resonators will definitely perform satisfactorily if the fabrication variance of the microring resonators is less than their resonant spectrum width.

We calculated the width of the resonant spectrum from the $Q$ factor. A comparison revealed that it is necessary to reduce the fabrication variance to several percent or less.

5. Conclusion

In this study, we measured the resonant wavelengths and $Q$ factors of silicon microring resonators and width-modulated photonic crystal nanocavities fabricated by CMOS, and we compared the fabrication variance of the microring resonators with the result of our previous study. As a result, we revealed that to reduce the fabrication variance to several percent or less we must construct the all-optical logic gate with microring resonators whose performance is guaranteed. In addition, we measured $Q = 1.6 \times 10^5$, which is the highest $Q$ factor yet reported for a width-modulated photonic crystal nanocavity manufactured by CMOS.

References