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Optical Ring-Resonator Modulator Based on 0.8 μm CMOS Technology *

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Optical ring-resonator-based modulators are fabricated on the silicon-on-insulator material through the mature commercial 0.8 μm complementary metal oxide semiconductor foundry. The device configuration is based on a single ring resonator coupled to one bus waveguide. The waveguide widths are about 1 μm. The p-i-n junctions are employed to inject currents. The experimental result shows that the ring resonators with the quality factor of above 40000 are obtained. The maximum extinction ratio of the modulators is larger than 10dB. The speed is tens of nanoseconds, and the corresponding injected current is smaller than 10 mA.

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The silicon-on-insulator (SOI) material can provide a high refractive index difference to significantly reduce the bend radius, and a platform for integrating with microelectronic devices.[1] In recent years, the optical intensity modulators with various structures based on the SOI material have been reported.[2−5] Thanks to the narrow width of the Lorentzian resonance dip in the transmission spectra, the power consumptions and the dimensions of the ring resonator (RR) modulators can be really decreased. Especially, for a comparison with Fabry–Pérot cavities, high finesse operation of the RR does not require multilayer or distributed Bragg reflectors. In this study, with a mature commercial 0.8 μm complementary metal oxide semiconductor (CMOS) foundry, ring-resonator-based modulators are fabricated. The waveguides are made in the ridge shape with the width of 1 μm.[6]

These devices are based on the single-bus-coupled ring resonator as shown in Fig. 1. The racetrack waveguide is chosen to enhance the coupling efficiency. As we know, silicon exhibits no linear electro-optic effect because of its centro-symmetric crystal structure, whereas the carrier dispersion effect is strong.[7] Therefore, we choose a p-i-n junction embedded in the ring resonator to inject electrons and holes. The change in the effective index of the ring waveguide gives rise to the modification of the resonance wavelength, which induces a strong modulation of the transmitted signal.

The evanescent coupling has been used to couple the light into and out of the cavity. Using the transfer matrix method,[8] the output optical power I_o can be expressed as a function of the input optical power I_i,

$$I_o = \frac{\gamma^2 + |t|^2 - 2\gamma|t|\cos(\phi + \Delta\phi)}{1 + \gamma^2|t|^2 - 2\gamma|t|\cos(\phi + \Delta\phi)} I_i, \qquad (1)$$

where t is the ring-bus amplitude coupling coefficient, $\gamma = \exp(-\alpha L_u/2)$ is the round-trip amplitude attenuation factor for a ring resonator with the length L_u and the linear loss coefficient α, ϕ is the round trip phase, $\Delta\phi = \Delta n_{\rm eff} k_0 L_m$ is the phase change in the ring waveguide with L_m being the modulation length, $\Delta n_{\rm eff}$ the change in the effective refractive index, and k_0 the magnitude of the propagation vector in vacuum.

According to Eq. (1), the transmitted power vanishes, when $\gamma = t$. This condition is known as critical coupling.[8] Assuming the required modification of the resonance wavelength is equal to the full wavelength width at half maximum $\Delta\lambda_{\rm FWHM}$, the corresponding phase shift can be written as $\Delta\phi \approx 2\pi\Delta\lambda_{\rm FWHM}/\Delta\lambda_{\rm FSR}$, where $\Delta\lambda_{\rm FSR}$ is the free spectral range (FSR). Given an operating wavelength λ, considering the quality factor $Q \approx \lambda/\Delta\lambda_{\rm FWHM}$ and $\Delta\lambda_{\rm FSR} = \lambda^2/(n_g L_u)$, the change in the effective index can be expressed as $\Delta n_{\rm eff} = n_g/(qQ)$, where $q = L_m/L_u$. Consequently, obtaining a large Q factor is significant for reducing $\Delta n_{\rm eff}$.

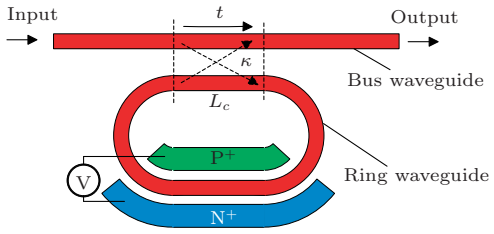


Fig. 1. Schematic of the ring-resonator modulator.

The ring resonators are fabricated on a SOI substrate with a 1-μm-thick buried oxide layer and a 1-μm-thick top silicon layer. The SOI wafers were

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bought from SOITEC Inc. The cross section of the desired waveguides is shown in Fig. 2(a). The rib waveguides have a width of 1 μm and a height of 0.42 μm, respectively. Some protection blocks are designed to surround the waveguides, as shown in Fig. 2(b). They are used to effectively prevent the long lines of photoresist from being peeled off, during the developing process. The graphs of the waveguides are formed through 1:5 stepper lithography. After dry etching the ridge waveguides, the thermal oxidation is executed to obtain a 110-nm-height SiO_2 layer as the doping mask. The n^+ and p^+ regions of the diode are implanted with phosphorus and boron to create concentrations of $10^{19}\,cm^{-3}$. A 600-nm borophosphosilicate glass (BPSG) layer is then deposited onto the wafer. Figure 2(c) shows the cross section of the fabricated waveguides. The width which becomes narrower will weaken optical field restrictions and result in an increase in bending loss. The steepness of the sidewalls can be improved through the technical adjustment of the etching process.

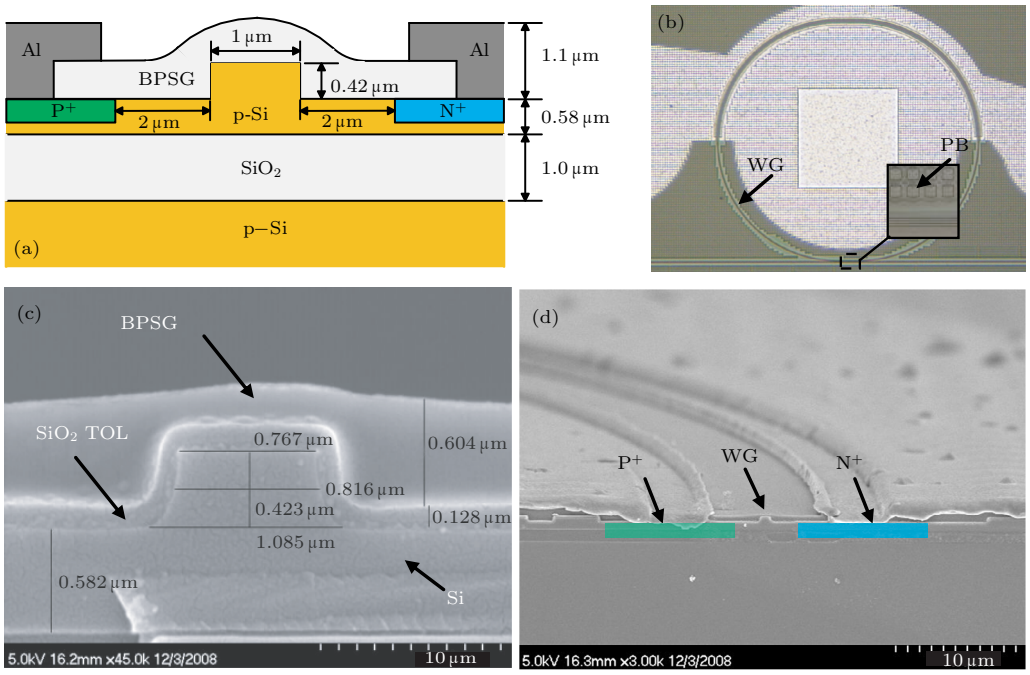


Fig. 2. (a) Desired cross-section of the waveguide, (b) top view of the modulator, (c), (d) cross section of the fabricated waveguide. WG: waveguide. TOL: thermal oxide layer. BPSG: borophosphosilicate glass. PB: protection block.

Continuous-wave light from an amplified spontaneous emission source is coupled to the waveguides through a polarization-maintaining fiber. The input and output waveguide widths are expended to 3.5 μm. We fabricated the ring resonators with different coupling lengths L_c and gaps g. The measured Q factors and extinction ratios are shown in Fig. 3, when the cavities operate in TE mode and the radiuses are the same, i.e. 300 μm. The resolution of the spectra analyzer is 0.01 nm. The Q factor of above 40,000 is obtained. As the coupling coefficient increases, the Q factor decreases.

By fitting the transmission spectra, the values of γ are estimated in the range 0.75–0.8, which mean that the losses of the ring waveguides are about 10 dB/cm. As it has been known, the Q factor is proportional to the length of the cavity. In this study, the perimeters of the RR are about 2 mm. If the ring-bus coupling ratios can be lowered to less than 80%, the Q factor above 10^4 can be obtained easily.[9] The loss can be reduced by smoothing the roughness of the waveguide sidewalls through thermal oxidation.[10]

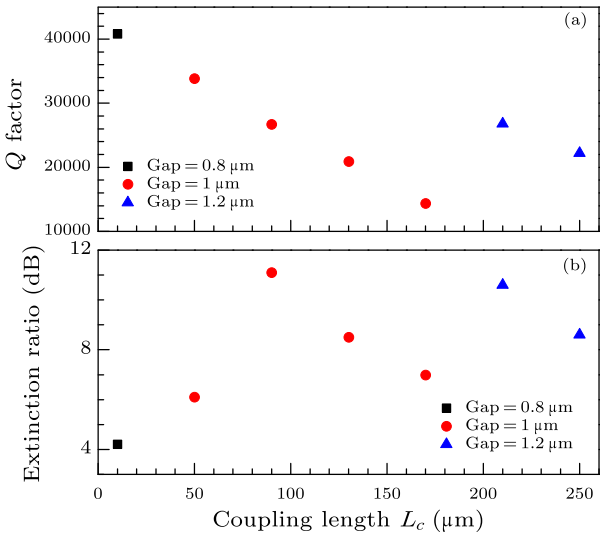


Fig. 3. (a) Q factors and (b) the extinction ratios versus the coupling lengths L_c.

The maximum extinction ratio is above 11 dB. It

has been noted that the small spectral resolution of the spectral analyzer limits the measurable maximum of the extinction ratios. The spectral resolution is about 1/30 of $\Delta\lambda_{\rm FSR}$. Using Parseval's relation and Eq. (1), the measurable maximum of the extinction ratios is about 17 dB when $\gamma = 0.7$. As γ increases, $\Delta\lambda_{\rm FWHM}$ decreases, so that the measurable maximum drops. In addition, the ripples in the transmission spectra also affect the measurement data. The ripples appear to be due to the Fabry–Pérot effect caused by the reflections of the two facets. The ripple magnitude can be reduced by end face coating.

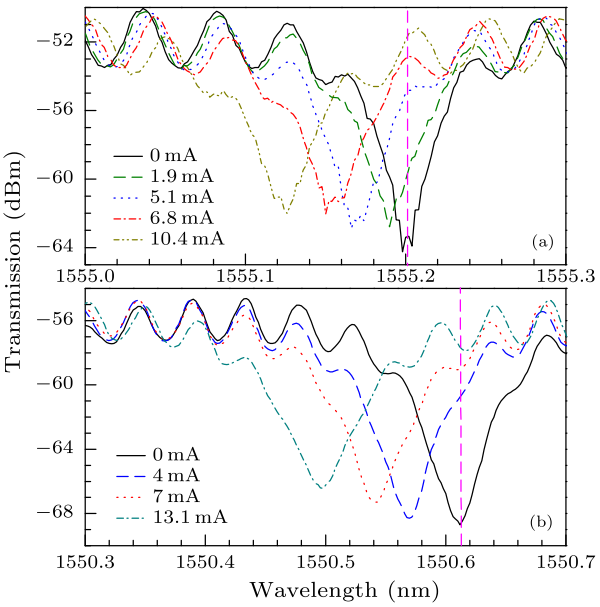


Fig. 4. Transmission spectra, when (a) $R = 30\,\mu$m, $L_m = 1033\,\mu$m, $L_c = 90\,\mu$m, $g = 1.0\,\mu$m, $Q = 26700$; (b) $R = 150\,\mu$m, $L_m = 821\,\mu$m, $L_c = 350\,\mu$m, $g = 1.4\,\mu$m, $Q = 16000$.

To modulate the signal, forward voltages are applied on the p-i-n junctions embedded in the ring resonators with the radiuses of 300 μm and 150 μm. As the injected currents increase, the blue shifts of the resonance wavelengths have been observed, as shown in Fig. 4. The required currents are smaller than 10 mA for the modulation. Considering $\Delta\phi = 2\pi\Delta\lambda/\Delta\lambda_{\rm FSR} = \Delta n_{\rm eff} k_0 L_m$ where $\Delta\lambda$ is the modification of resonance wavelength, $\Delta n_{\rm eff}$ can be deduced from $\Delta\lambda$, versus the injected currents as shown in Fig. 5. A change of -10^{-3} in the effective refractive index can be obtained, when the injected current density is about 8.2 kA/cm^2. Thanks to the ring resonators, the required injected current density can be smaller than 2 kA/cm^2 for the modulation. To enhance the efficiency, the overlap between optical mode and depletion region has to be increased. The speeds of the modulators depend on the free carrier lifetime. The measurement data show that the speed would be dozens of nanoseconds. For higher modulation speeds, the p-i-n junction spacing and the widths of the waveguides should be decreased to reduce the carrier lifetime and the transit time.

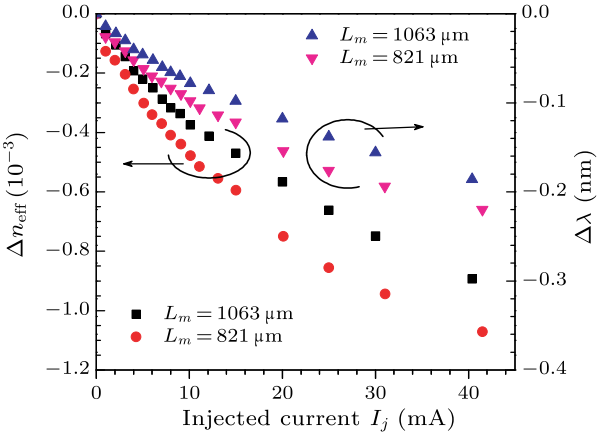


Fig. 5. Modifications of the resonance wavelengths and the corresponding changes in the effective index versus the injected currents.

In summary, through the commercial 0.8 μm CMOS foundry, the ring-resonator-based modulators are fabricated, without any special fabrication processes. The Q factor of above 40000 is obtained. It can be enhanced by reducing the loss or increasing the perimeter of the ring resonator. The modulation is based on the free-carrier dispersion effect. The electrons and holes are injected through the p-i-n junctions. The currents are smaller than 10 mA, and the extinction ratios are more than 10 dB.

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