Electro-optic modulator based on p-i-n integrated photonic crystal nanocavity fabricated with photolithography

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We report the first demonstration of an electro-optic modulator based on a photonic crystal (PhC) nanocavity with a p-i-n junction. Our device is fabricated with a photolithographic process, which is used in the complementary metal-oxide semiconductor (CMOS) process and can mass-produce devices. Moreover, the SiO\textsubscript{2} cladding of our device can also be realized in the CMOS process. We show that our device has a high-Q photonic crystal nanocavity ($Q = 1.4 \times 10^5$) and that we can change its refractive index by injecting carriers into the structure. Finally, we demonstrate GHz modulation based on the carrier plasma dispersion effect and the electro-optic property of this device showing a –3 dB cut-off frequency of nearly 1 GHz.

**Key words:** Silicon photonics, photonic crystal, optical modulator, width-modulated line defect photonic crystal nanocavity, carrier-plasma effect and all-optical switching.

1. Introduction

Silicon photonics has expanded the optical interconnect research field thanks to its low operating power, capacity for integration and the proficiency with which it can be combined with other existing silicon photonics devices. Silicon photonics is also the leading candidate for realizing optical interconnects due to its ease of combination with complementary metal-oxide semiconductor (CMOS) electronic fabrication technology [1], [2]. Therefore, an optical modulator that can be integrated in a CMOS chip has been intensively investigated [3]. A PhC nanocavity, which has a high quality factor ($Q$) and a small mode volume ($V$), has attracted many researchers [4]. A recent study showed that a photolithographically fabricated PhC nanocavity is compatible with CMOS [5].

This report summarizes our 2015 research in which we demonstrated an electro-optic modulator based on a p-i-n integrated photonic crystal nanocavity fabricated with a photolithographic process. We show that our results are similar to those previously reported for a photonic crystal nanocavity silicon modulator fabricated with an electron beam (EB) lithography process [6].

2. Device structure

Figure 1 shows a schematic illustration of our device. Input and output waveguides are coupled through barrier line defects whose width is W1.05. A cavity can be created by slightly shifting the center part of the waveguide air holes outwards. Shifting the air holes will increase the width of the waveguide at the center and that will lead to mode gap confinement and light will be confined. Figure 1 also shows the lattice constant $a$, hole radius $r$ and slab thickness $t$. The size of the contact Al pad is 45 $\mu$m x 25 $\mu$m. The parameters are $w_{i}=2.9$ $\mu$m, $w_{e}=1.68$ $\mu$m, $w_{c}=8.9$ $\mu$m and the doping density of the $p$ and $n$ regions are $9.5 \times 10^{10}$cm$^{-3}$, $5.7 \times 10^{10}$cm$^{-3}$, respectively.

3. Spectrum characteristics

3.1 CW operation

Figure 2 shows the transmittance spectrum of the PhC nanocavity. A high $Q$ of $1.4 \times 10^5$ is achieved at a wavelength of 1587.27 nm. The photon lifetime corresponds to 0.12 ns. The high $Q$ is achieved by fabricating the PhC nanocavity with a photolithographic process.
results are shown in Figure 3. Figure 3(b) shows that the transmittance spectrum shifts to a shorter wavelength. By applying a forward bias voltage to the electrodes, carriers are injected into the structure and change the refractive index. As the voltage is increased, more carriers are injected into the structure. Therefore, the transmittance spectrum shifts to a shorter wavelength, which indicates that the modulation through the carriers is more dominant than caused by heat. However, Figure 3(c) shows that when more than 2.0 V is applied, the transmittance spectrum begins to shift to a longer wavelength region. This is due to the predominance of the thermo-optic effect in the device. At this stage, the thermo-optic effects dominate the carrier plasma dispersion.

There is no transmittance shift when less than 0 V (reverse bias voltage) is applied to the electrodes. This is because almost no current flows (Figure 3(a)) at a reverse bias voltage. The transmittance shows clear resonant shifts when 1.2 V is applied, which corresponds to a current flow of about 2.76 µA. We calculated the capacitance of this device using $C = \frac{\epsilon_s S d}{w_l}$ where $S = t \times w_w$, $d = w_i$ and $\epsilon_s$ is the dielectric constant of silicon. The capacitance is $5.88 \times 10^{-18}$, which is very small because this device is small.

### 3.2 Radio-frequency operation

To measure the time average transmittance spectrum, we applied a rectangular pulse frequency signal generated by a pulse pattern generator to the electrodes. Note, we simultaneously performed the operation in the CW mode. A $\pm v$ voltage is applied to inject and extract carriers from the structure.

Figure 4 shows the results. The transmittance spectrum shows a clear shift to a longer wavelength. This is due to the longer injection of the carriers and makes them diffuse away from the $p-i-n$ area. Therefore, the carrier extraction is inefficient at the electrodes, and carrier recombination around the cavity leads to a temperature increase. As a result, the transmittance spectrum shifts to a longer wavelength. A clear split peak can be seen when the voltage increases. This shows a to-and-fro cavity motion in the structure caused by applying $\pm v$ to the electrodes.

Next, we demonstrate an electro-optic modulation. We observed an on-to-off and off-to-on modulation by tuning the wavelength to match the peaks of the transmittance spectrum, and the speed of the modulation range is 100 MHz to 1.0 GHz. Figure 5 shows the results.

The obtained results show that a GHz optical modulation is successfully demonstrated with a photolithographic PhC nanocavity integrated $p-i-n$ junction.

Finally, we calculated the extinction ratio by measuring the modulation depth of each frequency. We obtained an electro-optic property for this device of almost 0.5 GHz.
We strongly believe that we shall obtain a higher frequency bandwidth if we optimize the insulator width. As discussed above, the extremely small capacitance should allow even faster operation. This can be achieved if, for example we utilize the width of the $i$ region and the depletion technique [7], [8].

5. Conclusion

We obtained a high $Q$ with a photolithographically fabricated PhC nanocavity. We demonstrated a GHz modulation operation based on the carrier plasma dispersion effect and achieved a high-speed modulation in silicon. The operating power consumption can be reduced thanks to the large optical modulation. We believe that an even faster modulation operation could be obtained in the future by optimizing our device.

References


