CMOS compatible photo-receiver based on \textit{p-i-n} integrated photonic crystal nanocavity fabricated with photolithography

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We fabricate and demonstrate a high-$Q$ PhC nanocavity with a \textit{p-i-n} junction as a photoreceiver. We achieve a measured dark current of only 12 pA at a bias voltage of -3 V. With the aid of two-photon absorption, we obtained an internal responsivity for the photodetector of 0.0133 A/W. The PhC nanocavity device was fabricated with a photolithographic fabrication process, which is CMOS compatible and constitutes an advance in silicon PhC nanocavity technologies.

\textbf{Key words:} Photonic crystal; Photoreceiver; Opto-electronics; Integrated optics

\section{1. Introduction}

Silicon photonics has recently become the leading candidate for realizing optical interconnects thanks to its ease of combination with complementary metal-oxide semiconductor (CMOS) electronic fabrication technology [1], [2]. The low operating power and capacity for the integration of silicon photonics has expanded the field of optical interconnect research. However, Si is not an efficient candidate in terms of telecom-light detection. Many researchers have used various methods in an effort to overcome this problem [3-6]. However, reducing the value of the dark current still remains a challenge. Two-photon absorption has been employed due to its low noise and ease of fabrication using a \textit{p-i-n} integrated Si waveguide [7]. Nevertheless, it requires a high optical input. A photonic crystal (PhC) nanocavity with a high $Q$ factor allows us to achieve a high photon density even at very low input power thus making it a good candidate. Furthermore, a numerical study has proved that a \textit{p-i-n} Si PhC nanocavity can achieve a high-speed highly efficient photoreceiver [8].

This report describes a PhC nanocavity as a photoreceiver that constitutes an improvement on the work reported by Tabata in 2015. We show that a PhC nanocavity photoreceiver fabricated by photolithography is comparable to those previously reported that were fabricated with an electro-beam (EB) lithography process [9].

\section{2. Device structure}

Figure 1 (a) shows a schematic illustration of our device. Input and output waveguides are coupled through barrier line defects with a width of W 1.05. A width modulated line defect for the device is formed along a W 0.98 waveguide and is sandwiched by the \textit{p} and \textit{n} regions. The length of the barrier W 0.98 is shown as $d$. The cavity was created by slightly shifting the center part of the waveguide air holes (shift = 3, 6 and 9 nm) towards the outside. There are no additional dopants in the cavity region, so it functions as the \textit{i} region in the device. The lattice constant $a$, hole radius $r$ and slab thickness $t$ of the PhC are 420, 256 and 210 nm, respectively. The size of the contact aluminum pad is about 45 $\mu$m$\times$25 $\mu$m. The distance between \textit{p} and \textit{n} ion-implanted regions is shown as $w_c = 8.9 \mu$m. The width and distance between the \textit{p} and \textit{n} regions are shown as $w_w$ and $w_i$. The parameters are $w_i = 2.9 \mu$m and $w_w = 1.68 \mu$m. The doping densities for the \textit{p} and \textit{n} regions are $2.4 \times 10^{17}$ cm$^{-3}$ and $1.4 \times 10^{17}$ cm$^{-3}$, respectively.

Figure 1 (b) shows the measured spectrum of the device. The inset shows the Lorentzian fitting of the peak. The solid black line and dotted red line represent the transmission spectrum and Lorentzian fitting, respectively.

![Fig. 1: (a) Schematic illustration of a two-dimensional width modulated line defect PhC nanocavity. (b) Transmittance spectrum of the device. The inset shows the Lorentzian fitting of the peak. The solid black line and dotted red line represent the transmission spectrum and Lorentzian fitting, respectively.](image-url)
device. It exhibits a very high loaded $Q$ of $1.9 \times 10^5$ at a peak wavelength of around 1587.59 nm. It should be noted that we obtained the high $Q$ value with a silicon PhC nanocavity device realized with a photolithographic fabrication process and clad with SiO$_2$, which makes the structure stable, robust and compatible with CMOS.

3. Photoreceiver characteristics

Next, we measured the transmission spectrum and photocurrent at the resonance wavelength. The input optical power was 10 $\mu$W. The result at different input wavelengths is shown in Fig. 2. When the light was on resonance, two-photon absorption occurred and photocarriers were generated. Although such a nonlinear detector usually has low efficiency due to the small $\chi^{(3)}$ coefficient of the material, this device exhibited a very high detection efficiency due to the strong light confinement (high $Q$).

Figure 3 shows the responsivity of the device. We increased the input power from -50 dBm to 10 dBm and measured the photocurrent. The measured internal responsivity of the photodetector was 0.0134 A/W. The external quantum efficiency (QE) of the device was 2.17% when the input power was 0.316 mW.

![Fig. 2: Transmission spectrum and photo current at resonance wavelength when input power is 10 $\mu$W.](image)

![Fig. 3: Photocurrent vs input power when the input laser is at the resonance of the cavity. The dotted green lines show the responsivities at different A/W values.](image)

We further investigated other aspects of the photodetector by measuring the dark current of the device. Figure 4 shows the dark current when the bias voltage is increased from -6 V to 0 V.

![Fig. 4: Dark current of the device when a reverse bias voltage of -7 V to 0 V is applied to the device.](image)

At a -3 V reverse bias voltage, the measured dark current was 12 pA. This value is smaller than previously reported detectors [3-7]. We achieved a small dark current because of the good crystal quality of the Si and the small dimensions of our $p$-$i$-$n$ structure.

4. Future task

In terms of photodetector application, we need to demonstrate the speed of the receiver. A cavity with a lower $Q$ should be chosen to ensure that the device can be operated at a higher optical input without exhibiting the thermo-optic effect. A low transimpedance gain should be used for this demonstration. The injected signal wavelength will be at the cavity resonance and detuned from the cavity resonance.

5. Summary

In summary, we have reported the first demonstration of a PhC nanocavity integrated with a $p$-$i$-$n$ junction and SiO$_2$ cladding as a photodetector. The device was fabricated by a photolithography fabrication process, which is CMOS compatible and this constitutes an advance in silicon PhC nanocavity technology.

References

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