

# Compact Cavity Enhanced Si MSM Photodetector in SiN-on-SOI

(Student paper)

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## ABSTRACT

We present compact Si metal semiconductor metal (MSM) photodetector integrated SiN ring resonator in SiN-on-SOI platform. We achieved a 10X enhancement in photocurrent with SiN resonator integrated photodetector compared to integrated waveguide configuration. A maximum responsivity of 0.08 A/W is achieved with a photodetector of just 6  $\mu\text{m}$  long operated at a bias of 5 V in the 850 nm wavelength band. We present the design, fabrication and characterisation of integrated resonance photodetector. On-chip wavelength selective photodetector in 850 nm wavelength band enables next-generation scalable short-reach interconnect technology and also an opportunity for on-chip bio-sensors operating in the visible wavelength range.

**Keywords:** SiN-SOI, MSM photodetector, Ring resonator

## 1. INTRODUCTION

Silicon (Si) is an excellent photodetector in visible to near infrared wavelength (400~1100 nm) due to its relatively high responsivity. Furthermore, it is CMOS compatibility which offers excellent integration opportunity. However, the bandwidth of Si is lower than Ge or III-V photodetectors. Most of the detectors are built as bulk surface illuminated photodetectors. The responsivity of Si photodetectors could be improved by increasing the area. However, this limits the bandwidth due to enhanced depletion capacitance. Therefore, there is a trade-off between responsivity and bandwidth. Waveguide photodetectors is an alternative scheme to improve the photodetector responsivity without compromising speed. Thin Si layer in SOI substrate used in waveguide photodetector configurations overcomes the limitation of responsivity and bandwidth [1-2]. However, the maximum responsivity of Si photodetector is limited up to 0.44 A/W [3]. Recently, cavity enhanced photodetectors are explored to achieve high responsivity and large bandwidth [4-5]. By integrating with a ring resonator, wavelength selectivity can also be achieved. The wavelength selectivity offers a platform for integrated WDM photonic circuit for short reach optical interconnect operating in 850 nm wavelength band. Also, Si PDs could be used for lab-on-chip applications operating in 400-1000 nm window.

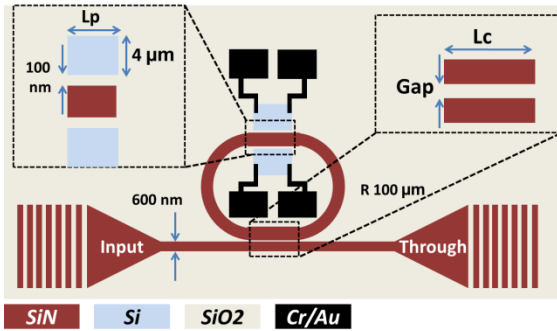


Figure 1 Schematics of the proposed structure shows the MSM photodetector integrated along the SiN ring resonator loop

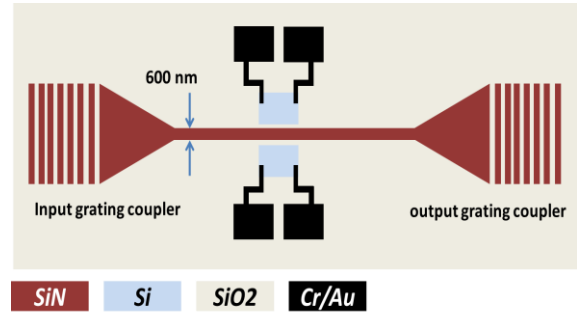


Figure 2 MSM photodetector integrated with SiN waveguide

In this paper, we propose and demonstrate a SiN ring resonator integrated Si Metal-Semiconductor-Metal (MSM) photodetector on SOI wafer. Fig. 1 shows a schematic of the proposed wavelength selective Si photodetector. A standard SOI wafer is used to fabricate the wavelength selective photodetector. SiN waveguide offers a circuit platform to realise various photonic devices while silicon is used as a photodetector. Since the top device layer in SOI wafer is crystalline, the performance of the detector is expected to be better. However, the challenge is to integrate SiN waveguides with the detector in-plane.

As a technology demonstrator, we start with an SOI wafer and use a SiN ring resonator to validate the integration process flow. Unlike vertical integration Si-on-SOI [3], in this work, we propose a compact side coupling scheme. A 220 nm thick SiN layer is used to realise a ring of 100  $\mu\text{m}$  radius with a coupling gap of 150 nm with the bus waveguide. A single mode waveguide of 600 nm is used to realise the circuit. SiN is used as the waveguide material because of its transparency in 850 nm window. The Si MSM photodetector is flanked on both sides of the SiN ring waveguide at an optimised gap of 100 nm. The Evanescent field from the ring

waveguide couples to both the MSM photodetector of the waveguide. To compare the ring enhancement photodetector on straight SiN waveguide with 600 nm width with a similar configuration shown in Fig. 2.

Figure 3 gives a brief overview of the fabrication process steps. The device is fabricated on an SOI substrate with 220 nm thick Si and 2  $\mu\text{m}$  thick buried oxide. First, Si layer is patterned with electron-beam lithography and dry etch process to define the Si photodetector region. A thin 50 nm PECVD linear SiO<sub>2</sub> is deposited followed by 220 nm thick LPCVD SiN deposition on the patterned SOI. The SiN is patterned in with electron-beam lithography, and dry etch process to realise waveguide, grating coupler and ring resonator structures. Finally, metal contact pads are fabricated by with electron-beam lithography and lift-off process. Chrome/Gold metal stack is used as the metal pads to form Schottky junction on Si. Fig. 4 shows the optical image of the fabricated device.

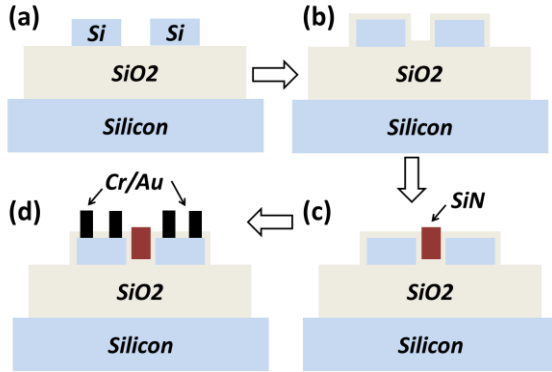


Figure 3 (a) 220 nm Si patterned in Ebeam litho and dry etch, (b) 50 nm PECVD SiO<sub>2</sub> deposited, (c) 220 nm LPCVD SiN deposited and patterned in Ebeam litho and dry etch to define waveguide, ring, and grating coupler, (d) Lift off to define metal contacts on Si

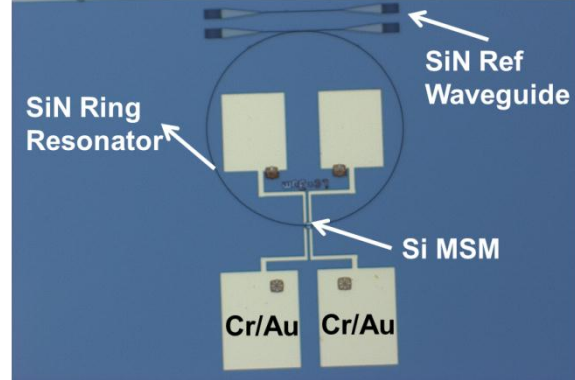


Figure 4 Optical image of the fabricated device

## 2. Characterisation

The spectral characteristics of the fabricated device is measured using an LED source (850-900 nm) and an optical spectrum analyser. Light is coupled in and out through grating coupler. Fig. 5 shows the normalised transmission response of SiN ring with and without Si photodetector. The transmission is normalised with a straight reference waveguide with an identical grating coupler. We observe an insertion loss of about 5 dB, which we attribute to non-optimal coupling taper between the grating and single-mode waveguide. The insertion loss could be improved with an optimised low-loss taper. The spectral response of the ring resonator shows reduced extinction and improved quality factor due to absorption in the Si MSM detector. We observed an extinction change from 14 dB to 6 dB, and quality factor enhances from 3800 to 4400 (Fig. 6 and Fig. 7).

Fig. 8 shows the IV characteristics of the MSM photodetector coupled to SiN ring and SiN waveguide. The optoelectronic characteristics of the device were measured using a narrowband laser around 870 nm. We measure a dark current as low as 10 nA at 5 V reverse bias. MSM photodetector integrated with SiN waveguide with 6  $\mu\text{m}$  length gives the photocurrent of 68 nA at 5 V bias. For an MSM photodetector integrated SiN ring resonator, we measure a maximum photocurrent of 800 nA which is more than 10 times higher than the waveguide integrated MSM of same interaction length of 6  $\mu\text{m}$ . Ring coupled MSM detectors having sufficient photocurrent even at very low bias voltages shows the promise for highly sensitive, and low power photodetector.

The responsivity of the MSM photodetector is estimated from the optical power coupled in the reference waveguide. Fig. 9 plots the responsivity with bias voltage for waveguide coupled and ring coupled MSM photodetector. Ring coupled MSM photodetector gives the responsivity around 0.08 A/W at 5 V compare to 0.005 A/W of waveguide integrated MSM photodetector. Fig. 10 shows the photocurrent obtained from MSM with a different coupling length of ring and bus waveguide to improve the coupling efficiency. As the coupling length increases between bus and ring ( $L_c$ ), the responsivity also increases due to higher power coupling. The length of the photodetector ( $L_p$ ) is kept constant while varying the power coupling. The responsivity could be further improved by increasing the photodetector length. To obtain the power enhancement inside the ring resonator, we estimated the transmission coefficient and loss coefficient of the ring resonator [6]. Based on the extinction coefficient of 6dB, FSR of 0.5 nm and FWHM of 200 pm of the MSM photodetector integrated ring resonators, we estimate a power enhancement factor of 11 inside the ring resonator at resonating wavelengths.

The estimation agrees well with the measured photocurrent enhancement of a factor of 10 compared to a waveguide integrated photodetector. MSM photodetector integrated to ring resonator also shows the similar enhancement in the photocurrent as mentioned before.

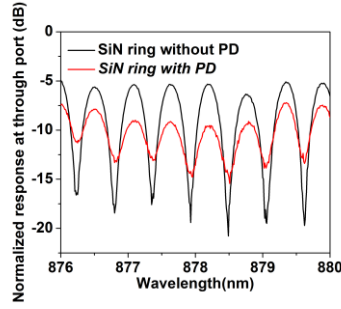


Figure 5 SiN ring response at the through port

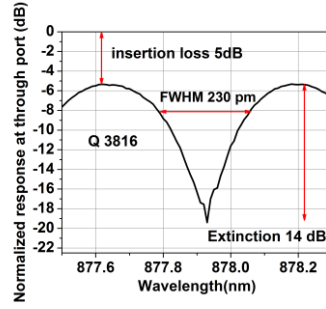


Figure 6 Resonance of a ring without MSM integrated.

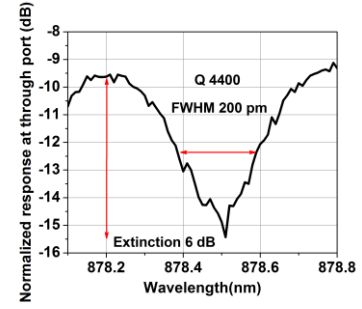


Figure 7 Resonance for ring with MSM integrated

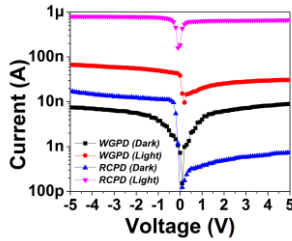


Figure 8 IV characteristics of the MSM PD integrated to SiN ring (RCPD) and SiN waveguide (WGPD)

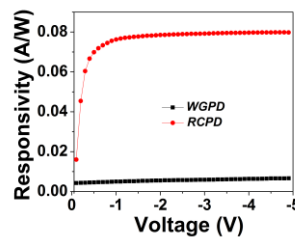


Figure 9 Responsivity Vs Bias voltage of the MSM PD integrated to SiN ring (RCPD) and SiN waveguide (WGPD)

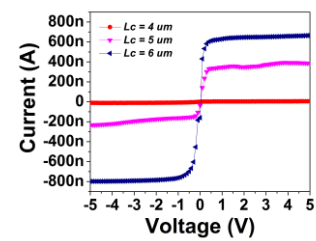


Figure 10 Ring coupled MSM photodetector IV Vs Coupling length between bus and ring ( $L_c$ )

### 3. CONCLUSIONS

In conclusion, we have demonstrated SiN resonator integrated silicon MSM photodetector on SOI wafer platform. By using a resonant cavity, we show 10X enhancement in photocurrent compared to a simple waveguide integrated photodetector. We achieved a responsivity of 0.08 A/W at 5 V bias around 870 nm wavelength with a Si MSM detector which is just 6  $\mu$ m long. The demonstration shows a promising path towards realising an integrated Si photonic with SiN photonic circuit. The proposed combination of SiN and Si could potentially address short reach WDM requirement and sensing application as well. Furthermore, to validate the quality of photodetector, high-speed response of photodetector would confirm the suitability for data-com application.

### ACKNOWLEDGEMENTS

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