A colloidal-quantum-dot solution for photodetection beyond 1.6 µm in silicon photonics

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Photodetection beyond the wavelength of 1.6µm remains a challenge in silicon photonics due to the absence of suitable epitaxial materials. In this study, we have successfully integrated lead sulfide (PbS) colloidal quantum dot photodiodes (QDPDs) onto silicon waveguides using standard process techniques. The integrated photodiodes exhibit a remarkable responsivity of 1.3 A/W (with an external quantum efficiency of 74.8%) at a wavelength of 2.1µm, a low dark current of only 106 nA and a bandwidth of 1.1 MHz under a -3 V bias. To demonstrate the scalability of our integration approach, we have developed a compact 8-channel spectrometer incorporating an array of QDPDs. This achievement marks a significant step toward realizing a cost-effective photodetector solution for silicon photonics, particularly tailored for a wide range of sensing applications around the 2 µm wavelength range.

Introduction

Silicon photonics is an attractive technology for many applications, ranging from data communication to sensing. However, its current applications are largely confined to the wavelength range below 1.6 µm, primarily due to the constraints of monolithically integrated Ge detectors. Yet, there are a wide range of applications, such as environmental monitoring, medical diagnostics, and industrial sensing, that show superior performance at longer wavelengths[1]. One commonly used technique for integration of longer wavelength detectors onto silicon waveguides is based on wafer or die bonding of III-V materials, such as InP [2] and GaSb based compounds [3]. However, this integration requires large-area planarized surfaces and uses costly III-V epitaxy and bonding technology. Monolithic grown of GeSn alloy on Si is an alternative solution, but it currently yields photodiodes with high dark current [4].
Colloidal quantum dots (QDs) offer a promising route for integration into silicon photonics beyond the telecom range, with their advantages of flexible wavelength tunability, cost-effective synthesis and processing. Pb, Ag or Hg based QD have recently demonstrated their wavelength response capabilities in the short-wave infrared and mid-wave infrared [5]. In this work, we demonstrate the integration of PbS QD-based photodiodes (QDPDs) on silicon waveguides with standard processing techniques. These waveguide-coupled QDPDs (WG-QDPDs), with a wavelength response extending beyond 2.1 µm, exhibit low dark current, high responsivity, and decent speed. Moreover, we demonstrate a compact spectrometer operating at approximately 2.1 µm, achieved through the integration of a QDPD array with an eight-channel planar concave grating.

PbS Quantum Dot Photodiodes

Before integrating QDPDs on waveguides, we carried out optimization of the material stack on the bottom-illuminated QDPDs (BI-QDPDs) that were fabricated on glass-ITO substrates. The material stack used for the QDPD is shown in Figure 1a, comprising an ITO bottom electrode, a 30 nm sol-gel ZnO film functioning as an electron transport and hole blocking layer, a multilayer QD stack and a Au top electrode. For the QD stack, we used QDs with exciton absorption centered around 2.1 µm, as illustrated in Figure 1b, for absorption and treated them with Tetra-n-butylammonium iodide (TBAI) to enhance their mobility and n-doping characteristics. As the hole transport and electron blocking layer, we employed QDs featuring a 0.94 µm absorption peak treated with 1,2-ethanedithiol (EDT) for p-doping. Two layers of 1.3 µm QDs were incorporated to mitigate surface-trap-induced leakage current. This reduced the dark current more than ten times. The BI-QDPD shows a dark current density of 2.8 mA/cm² and a responsivity of 0.19 A/W (external quantum efficiency, EQE, of 11.2%) under a -3 V bias, as illustrated in Figure 1c. The relatively low EQE can primarily be attributed to the incomplete absorption caused by the thin absorption layer.

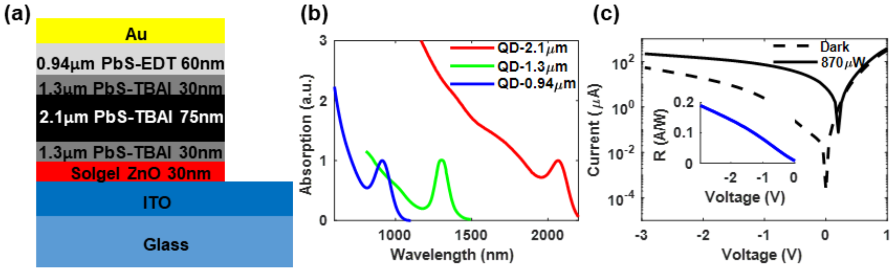

Figure 1. Structure and characterization of BI-QDPDs. (a) Device structure of the photodiode. (b) Absorption spectra for three types of QDs used, dispersed in n-octane. (c) Dark current and photocurrent of the photodiode with an area of 1.77 mm^2. The photocurrent was measured at 2.1 µm with a peak power density of 220 mW/cm^2.

Integration on Waveguides

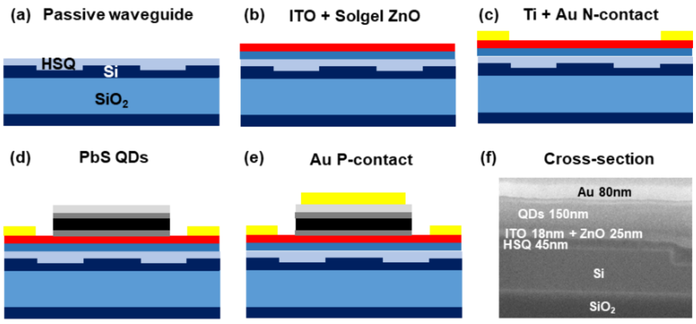

Figure 2. Processing steps to fabricate WG-QDPDs. (a) Si rib waveguide patterning and top cladding deposition. (b) ITO and ZnO electron transport layer deposition and patterning. (c) N-contact metal patterning with photoresist and liftoff. (d) QD film patterning with PMMA resist and liftoff. (e) P-contact metal patterning with PMMA resist and liftoff. (f) Cross-section of the integrated photodiode.

The process flow we used to integrate the QDPD on waveguides is shown in Figure 2a-e. The waveguides were defined on 220 nm silicon-on-insulator substrates with a 70 nm shallow etch. To achieve a smooth surface, a 45 nm flowable oxide (hydrogen silsesquioxane) was applied to planarize the waveguide. The QDPD stack was then integrated on top for evanescent absorption. A 20 nm ITO layer was sputtered as the bottom electrode. It was patterned with HCl-based wet etching. The ZnO layer was deposited using a sol-gel method and patterned with a dilute HCl solution. Ti/Au was placed on the side as the n-contact pad using a lift-off technique. The QD stacks were deposited layer by layer and lifted off simultaneously to achieve the desired pattern. Finally, 100 nm Au is deposited on top as p-contact pad. The cross-section of the fabricated WG-QDPD is shown in Figure 2(f).

Characterization

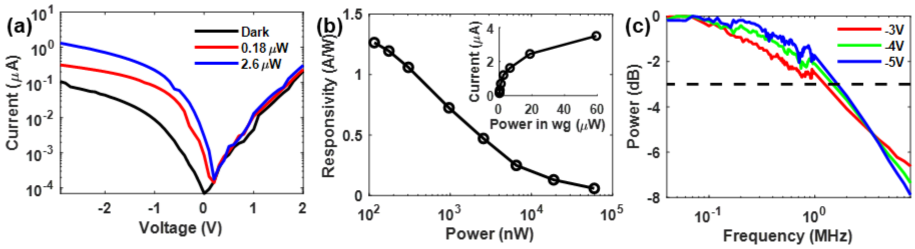

Figure 3. Response of the WG-QDPD. (a) I-V curves of integrated photodiodes under dark condition and illumination at 2.1 µm. (b) Responsivity vs. optical power at -3V bias voltage. Inset: photo-current vs. optical power with bias voltage of -3V. (c) Bandwidth of integrated photodiodes.

We characterized the WG-QDPDs using a 2.1 µm laser. The optical power in the waveguide was calibrated by measuring the coupling efficiency of the grating coupler for a reference waveguide without QDPDs. The WG-QDPD shows a low dark current of 106 nA at -3 V, as illustrated in Figure 3a. Considering a WG-QDPD width of 30 µm and a length of 200 µm, the dark current density (1.8 mA/cm^2) is in line with the measurements obtained on the BI-QDPDs. The responsivity reaches 1.3 A/W (EQE of 74.8%) at low optical power level of 116 nW, as shown in Figure 3b. The significantly higher EQE compared to BI-QDPDs is attributed to increased absorption during propagation within the waveguides. The photo-current increases nonlinearly with optical power, a phenomenon we attribute to QDPD saturation due to high series resistance, as previously observed in other work [6]. The speed of the fabricated WG-QDPD was measured at 1.55 µm, exhibiting a bandwidth of 1.1 MHz, as shown in Figure 3(c). While this bandwidth may not be as high as that of III-V photodiodes, it meets the requirements of many sensing applications.

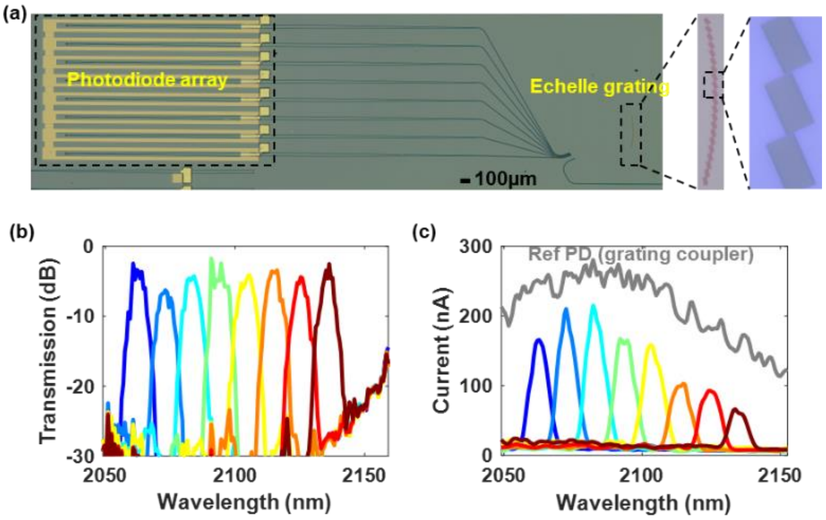

Figure 4. Integrated spectrometer with a QDPD array and a planar concave grating. (a) Top view of the spectrometer. Light is injected from the grating coupler on the right side. (b) Transmission spectrum of the planar concave grating. (c) Response of QDPDs from eight channels and a reference waveguide (gray line).

To demonstrate the scalability of our proposed QDPD integration on silicon waveguides, we combined a WG-QDPD array with an eight-channel planar concave grating (PCG), as shown in Figure 4(a). The transmission spectrum of PCG was measured prior to QDPD integration, which covers the wavelength from 2063 nm to 2135 nm, with a cross-talk less than -20 dB and insertion loss less than 3 dB, as shown in Figure 4(b). After the integration of the QDPD array, the photo-response of each channel was measured at -1 V bias by sweeping the wavelength of input laser. The response of the QDPD array aligns with the spectrum of the grating coupler (gray line in Figure 4c), as measured from a reference WG-QDPD.

Conclusion

In this work, we have demonstrated the integration of 2.1 µm PbS QDPDs on silicon waveguides. The WG-QDPD shows a low dark current of 106 nA, a high responsivity of 1.3 A/W and a bandwidth of 1.1 MHz at -3 V reverse bias. To further demonstrate the scalability of the proposed integration approach, we have showcased a compact spectrometer operating around 2.1 µm, using an eight-channel planar concave grating and a WG-QDPD array. We believe that QDPD technology holds significant promise for cost-effective photodetection in silicon photonics beyond 1.6 µm, especially for sensing applications.

This work was supported by: European Research Council (ERC) under the innovation program grant agreement No. 884963 (ERC AdG NARIOS), FWO-Vlaanderen for research funding (FWO projects G0B2921N and G0C5723N), and China Scholarship Council (CSC Grant 201906120023).

References

[1] R. Wang *et al.*, "III–V-on-silicon photonic integrated circuits for,spectroscopic sensing in the 2–4 µm wavelength range," *Sensors (Switzerland)*, vol. 17, no. 8, 2017, doi: 10.3390/s17081788.

[2] R. Wang *et al.*, "2 µm wavelength range InP-based type-II quantum well photodiodes heterogeneously integrated on silicon photonic integrated circuits," *Opt Express*, vol. 23, no. 20, p. 26834, 2015, doi: 10.1364/oe.23.026834.

[3] A. Gassenq, N. Hattasan, L. Cerutti, J. B. Rodriguez, E. Tournié, and G. Roelkens, "Study of evanescently-coupled and grating-assisted GaInAsSb photodiodes integrated on a silicon photonic chip," *Opt Express*, vol. 20, no. 11, p. 11665, 2012, doi: 10.1364/oe.20.011665.

[4] C.-H. Liu, R. Bansal, C.-W. Wu, Y.-T. Jheng, and G.-E. Chang, " GeSn Waveguide Photodetectors with Vertical p–i–n Heterostructure for Integrated Photonics in the 2 µm Wavelength Band ," *Adv Photonics Res*, vol. 3, no. 7, p. 2100330, Jul. 2022, doi: 10.1002/adpr.202100330.

[5] T. Nakotte *et al.*, "Colloidal quantum dot based infrared detectors: extending to the mid-infrared and moving from the lab to the field," *J Mater Chem C Mater*, vol. 10, no. 3, pp. 790–804, 2022, doi: 10.1039/d1tc05359k.

[6] C. Pang *et al.*, "Integrated PbS Colloidal Quantum Dot Photodiodes on Silicon Nitride Waveguides," *ACS Photonics*, Nov. 2023, doi: 10.1021/acsphotonics.3c00945.