

InGaAs Photodiode Array on Silicon by Heteroepitaxy

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Abstract: InGaAs photodiode arrays were realized on Si by heteroepitaxy, demonstrating a dark current as low as 5.71 nA at -1 V and responsivity as high as 0.64 A/W at 1550 nm and at room temperature. © 2021 The Author(s)

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1. Introduction

While silicon (Si) detectors are limited to the visible and near infrared (NIR) regime, indium gallium arsenide (InGaAs) extends into the short wave infrared (SWIR) and also demonstrates higher sensitivity. InGaAs SWIR detectors are widely applicable to optical communications, imaging, and spectroscopy, but are also enabling for emerging applications including commercial lidar (light detection and ranging); SWIR extends into eye safe wavelengths, allowing for significantly higher optical power and therefore longer range. While InGaAs SWIR detectors clearly outperform Si, their manufacturing is not as mature. The substrates used, namely indium phosphide (InP), are much more expensive than Si and are limited to 4-inch diameter or less. Lastly, InGaAs SWIR detector arrays are typically attached to read out integrated circuits (ROICs) through flip-chip based hybridization. This is characteristic of lower throughput and yield, further increasing cost. InGaAs detectors, therefore, have not penetrated the higher volume or emerging markets that are dominated by Si complementary metal oxide semiconductor (CMOS) image sensors.

Recently, direct heteroepitaxy of III-V semiconductors on Si substrates has gained significant interest, in particular for monolithically integrating optical into silicon photonics [1,2]. We have previously demonstrated 1550 nm InP lasers on CMOS-compatible (001) Si substrates [3]. InP-on-Si templates demonstrating record low surface defect density were realized by leveraged nano-V-groove patterned Si, dislocation filters, and thermal cycle annealing [4]. In this work, we have advanced the InP-on-Si template technology and subsequently demonstrated mesa InGaAs photodiode arrays on Si with performance comparable to InGaAs arrays on native InP. The ability to realize InGaAs SWIR detector arrays on CMOS-compatible Si substrates by direct heteroepitaxy can enable higher performance at low cost, as well as novel device structures. We previously reported single InGaAs PIN photodiodes on miscut Si [5]. Here, top-illuminated proof-of-concept 8×8 InGaAs photodiode arrays were realized on CMOS-compatible (001) Si by heteroepitaxy, and are compared to identical devices on a native InP substrate. On Si, photodiodes with 40- μm diameter demonstrate a dark current as low as 5.71 nA at 1 V reverse bias, corresponding to a dark current density of only 0.45 mA/cm². A responsivity of 0.64 A/W was measured at 1550 nm. Identical devices on InP demonstrate a dark current density of 0.20 mA/cm² and responsivity of 0.57 A/W. The comparable performance for the arrays on Si suggests the potential for realizing SWIR detector arrays using highly manufacturable CMOS fabrication methods.

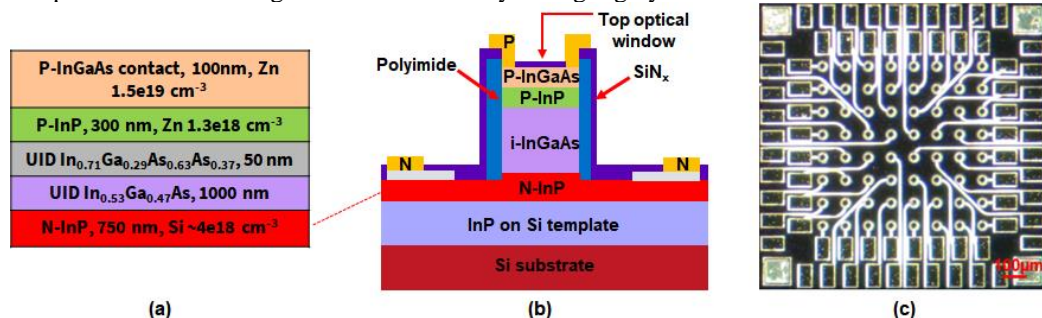


Fig. 1. (a) Epitaxial layer details for InGaAs PIN on InP-on-Si template. (b) Cross-section schematic of mesa photodiode structure. (c) Top view image microscope image of fabricated 8×8 InGaAs PIN array with pixel diameter of 40 μm on Si.

2. Epitaxial Growth and Device Fabrication

InP-on-Si template was first grown on (001) Si by metalorganic chemical vapor deposition. The dislocation density for the template is approximately $3 \times 10^8 \text{ cm}^{-2}$. The template growth procedure includes a 2 μm GaAs on V-groove patterned Si (001) substrates, and a 2.7- μm -thick InP buffer grown on top. Three-stack of $\text{In}_{0.7}\text{Ga}_{0.3}\text{As}/\text{InP}$ strained layer superlattices were embedded in the InP to serve as dislocation filters. Growth details have been reported in

[3,4]. The epitaxial layer details for the InGaAs PIN photodiodes grown on the InP-on-Si template and native n-type InP substrate are presented in Fig. 1(a). Identical photodiode arrays were fabricated both on Si and InP. A cross-section schematic of the mesa photodiode structure is shown in Fig. 1(b). Following dry etching, the mesas were passivated with polyimide and silicon nitride (SiN_x). Ring shaped p-metal contacts enable top-side illumination. Ni/AuGe/Ni/Au was employed for n-metal contacts, Ti/Pt/Au for p-metal. Arrays with pixel diameter of 20 μm , 30 μm , and 40 μm were fabricated, all with a pitch of 100 μm . A top-view microscope image of a fabricated 64-pixel InGaAs arrays on Si with 40 μm pixels is shown in Fig. 1(c).

3. Photodiode Array Characterization

Fabricated devices were characterized near room temperature ($\sim 22^\circ\text{C}$) without cooling. The dark current at 1 V reverse bias was extracted for all 64 pixels of each array on both InP and Si and the results are summarized in Fig. 2(a), (b) and (c). A normal distribution fitting was applied to each dataset and the mean value (μ), standard deviation (α), and yield are reported. Although the dark current for the arrays on Si is slightly higher, the overall performance, distribution, and yield are quite similar. Figure 2(d) shows the current-voltage (IV) characteristics for pixels with the lowest dark current on Si and InP substrates. For the devices on Si, the corresponding dark current density at 1 V reverse bias for 20, 30 and 40 μm diameter devices are 0.69, 0.56 and 0.45 mA/cm^2 , respectively. For devices on InP, those values are 0.14, 0.13 and 0.20 mA/cm^2 , respectively. The corresponding typical responsivities at 1550 nm are shown in Fig. 2(e). The responsivity values are generally higher for devices on Si and this could be attributed to reflection at the III-V/Si interface.

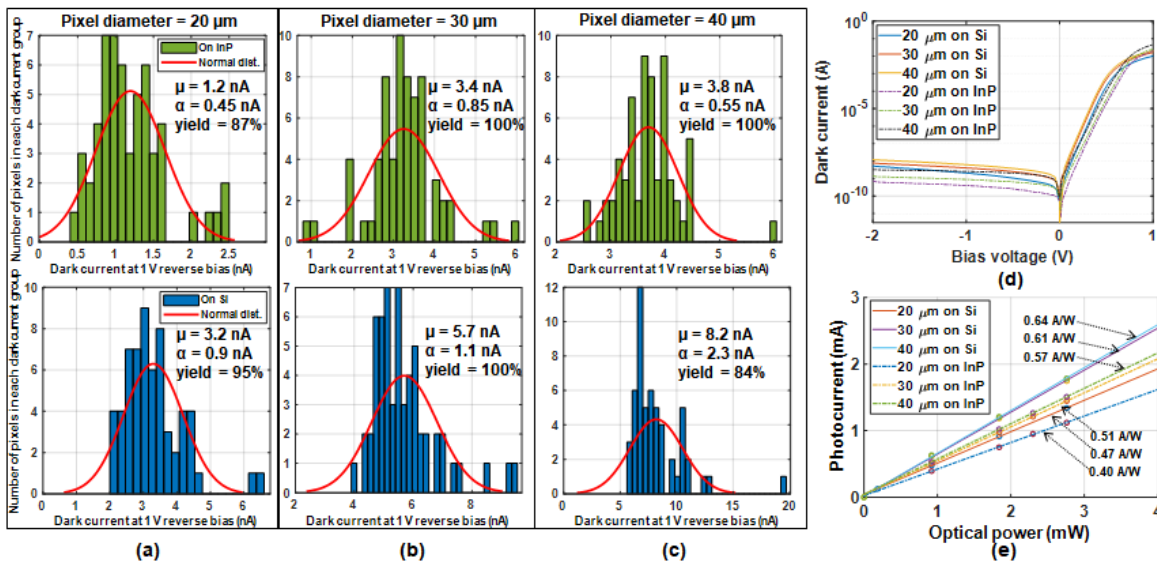


Fig. 2. Histogram plot of array on InP (top) and on Si (bottom) with pixel diameter of (a) 20 μm , (b) 30 μm , and 40 μm . (d) IV characteristics. (e) Responsivity characteristics at 1550 nm wavelength and 1 V reverse bias.

4. Conclusion

Top-illuminated mesa InGaAs photodiode arrays were realized both on CMOS-compatible (001) Si, by direct heteroepitaxy, and on native InP. Devices yield low dark current for both Si and InP, comparable to other similar mesa photodiodes reported in the literature on InP. A responsivity of 0.64 A/W at 1550 nm was measured for devices on Si. The dark current distribution and fabrication yield were similar for both Si and InP, indicating high potential for realizing high performance InGaAs SWIR detector arrays on Si substrates with heteroepitaxy.

5. Acknowledgements

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