High Speed and Low Dark Current InGaAs Photodiodes on CMOS-Compatible Silicon by Heteroepitaxy

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Abstract: High speed InGaAs photodiodes were realized on (001) Si by direct heteroepitaxy, demonstrating low dark current, high responsivity, a bandwidth of 11 GHz and up to 30 Gbps operation at a wavelength of 1550 nm.

OCIS codes: (160.1890) Detector materials; (040.5160) Photodetectors; (200.4650) Optical interconnects

1. Introduction

The demand for high speed photodiodes (PDs) has dramatically increased due to the emergence of 5G technology, the Internet of things and growth of data centers and optical interconnects. Indium gallium arsenide (InGaAs) PDs are widely used in optical communications and sensing applications. Relative to silicon (Si), indium phosphide (InP) substrates, used for InGaAs PDs, are much more expensive and are limited to 4-inch diameter. Germanium (Ge) PDs realized on Si are commercially available and can be fabricated on 8-inch and 12-inch wafers. These are used primarily for the telecommunications O-band, due to limited responsivity at longer wavelengths, and suffer from high dark current [1]. Recently, direct heteroepitaxy of III-V semiconductors on Si substrates has gained significant traction, in particular for monolithically integrating optical gain into silicon photonics [2,3]. We have previously demonstrated 1550 nm InP lasers on CMOS-compatible (001) Si substrates [4]. InP-on-Si templates demonstrating record low surface defect density were realized by nano-V-groove patterned Si, compositional grading, dislocation filters, and thermal cycle annealing [5]. In this work, we have advanced the InP-on-Si template technology and subsequently demonstrated mesa InGaAs PDs with low dark current and high bandwidth. We previously reported single InGaAs PIN PDs on non-compatible miscut Si [6]. The ability to realize InGaAs PDs on CMOS-compatible Si substrates by direct heteroepitaxy can enable high performance at low cost. Here, top-illuminated proof-of-concept high speed InGaAs PDs with ground-single-ground pads were realized on standard (001) Si by heteroepitaxy. PDs with various diameters demonstrate dark currents as low as 1.02 nA at 1 V reverse bias and room temperature operation. A bandwidth of 11 GHz and up to 30 Gbps open eye diagrams were demonstrated. A responsivity as high as 0.7 A/W was measured at 1550 nm. The PDs on Si perform similar to nearly identical devices fabricated on native InP substrates, thereby suggesting the potential for realizing high performance InGaAs PDs while leveraging CMOS fabrication techniques.

2. Epitaxial growth and device fabrication

The InP-on-Si template was grown on (001) Si by metalorganic chemical vapor deposition. The dislocation density for the template is approximately 2×10^{8} cm^{-2}. The template includes a 2-µm-thick GaAs on V-groove patterned Si (GoVS), and a 2.7-µm-thick InP buffer. Three periods of $In_{0.7}Ga_{0.3}As/InP$ strained layer superlattices were embedded in the InP to serve as dislocation filters. Details of the template development were reported in [4].

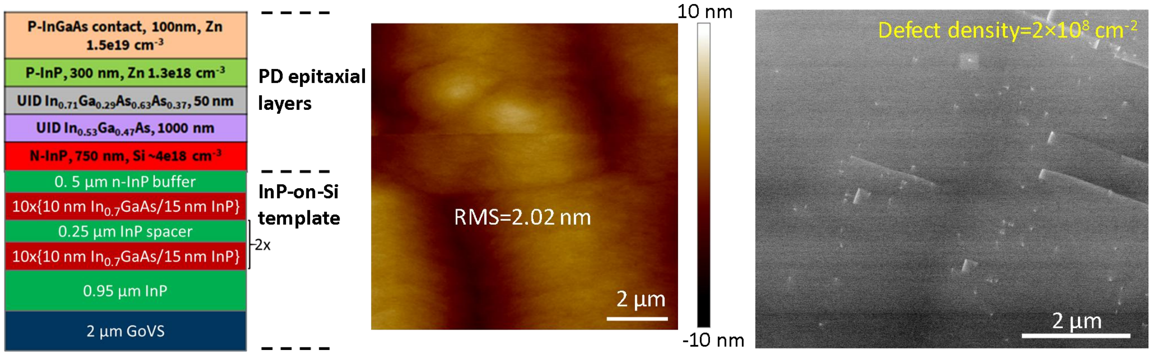

Fig. 1. (a) Epitaxial structure for PD on Si. Corresponding (b) 10×10 µm^2 AFM scan and (c) ECCI measurement of the as-grown PD surface.

The epitaxial structure for the InGaAs PIN PD grown on the InP-on-Si template is presented in Fig. 1(a). Figure 1(b) and 1(c) demonstrate the surface morphology and surface defects of the as-grown PD on Si, characterized by atomic force microscopy (AFM) and electron channeling contrast imaging (ECCI), respectively. A smooth surface was obtained with the roughness as low as 2 nm. The final surface defect density is 2×10^8 cm^{-2}, indicating no extra misfit dislocations generated within the 1-µm-thick InGaAs absorption layer.

A cross-section schematic of the mesa PD structure is shown in Fig. 2(a). Mesas were defined by chlorine based inductively coupled plasma reactive ion etching. Photosensitive polyimide was applied and patterned to the mesas to passivate sidewalls. Silicon nitride (SiN_x) encapsulation was applied following curing of the polyimide. The thickness of the SiN_x was chosen to increase the photon sensitivity, thereby providing a single-layer anti-reflection (AR) coating. Ring shaped p-metal contacts enable top-side illumination. Ni/AuGe/Ni/Au was employed for n-metal contacts, and Ti/Pt/Au for p-metal contacts. A 3D schematic of the high speed InGaAs PD on silicon is depicted in Fig. 2(b). The 5-µm-thick polyimide layer, below the p-metal, assists to reduce parasitic capacitance. Devices with mesa diameters of 10, 15, 20, 25, 30 and 40 µm were fabricated. A top-view microscope image of fabricated InGaAs PDs on Si is shown in Fig. 2(c).

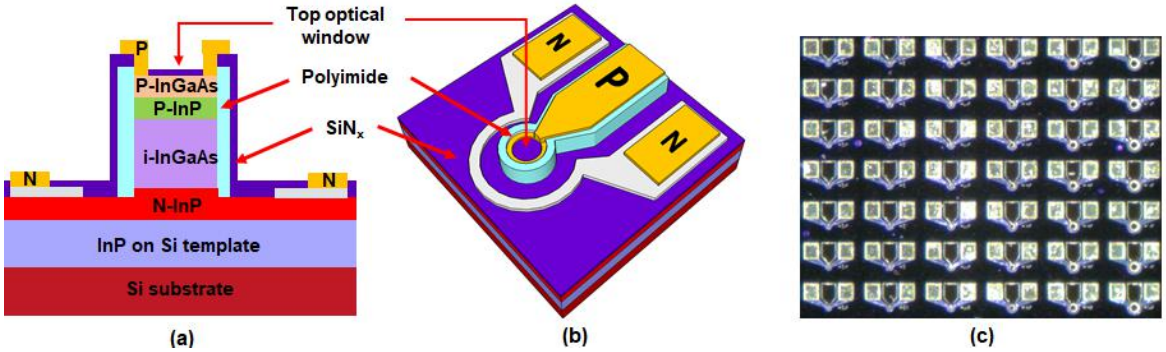

Fig. 2. (a) Cross-section schematic of mesa PD structure. (b) 3D schematic of high speed InGaAs PD on Si. (c) Top view microscope image of fabricated InGaAs PDs on Si.

3. Measurement results

Fabricated devices were characterized near room temperature (~22°C) without cooling. Current-voltage (IV) characteristics and dark current results for devices with various mesa diameters are summarized in Fig. 3(a) and (b). A dark current density as lows as 1 mA/cm^2 at 1 V reverse bias was measured for 40 µm diameter devices.

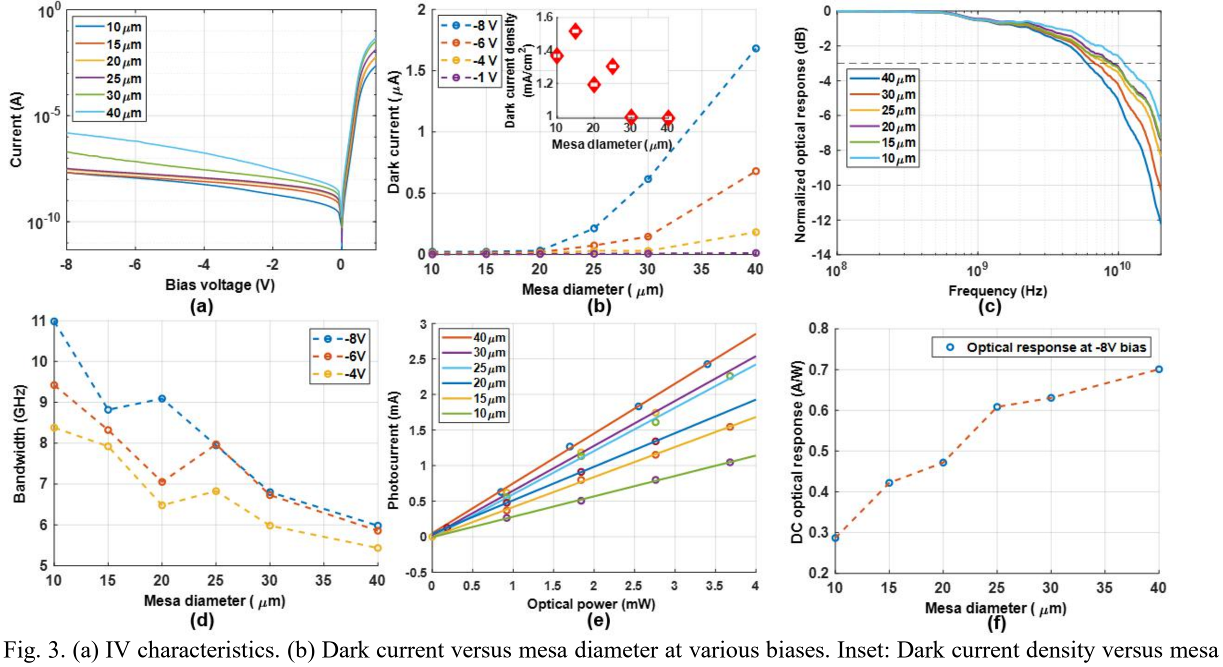

Fig. 3. (a) IV characteristics. (b) Dark current versus mesa diameter at various biases. Inset: Dark current density versus mesa diameter at 1 V reverse bias. (c) Measured RF frequency response at 8 V reverse bias. (d) 3-dB bandwidth versus mesa diameter at various bias voltages. (e) Photocurrent characteristics at 1550 nm wavelength and 8 V reverse bias. (f) Measured optical response for PDs on Si versus mesa diameter at 8 V reverse bias.

The RF response was measured using a network analyzer with an integrated laser source. A single mode fiber was used to couple laser light from the network analyzer to the PDs, and a high-speed probe was used to bias the PD and measure the DC photocurrent and response. The 3-dB bandwidth was extracted for all devices at various bias voltages. The frequency response at -8 V for PDs with different mesa diameters are shown in Fig. 3(c). As shown in Fig. 3(d), a bias voltage of -8 V yielded the highest bandwidth. The responsivity of the PDs was also measured at 1550 nm at a bias voltage of -8 V. The DC photocurrent level was recorded and is reported as a function of optical power in Fig. 3(e). The responsivity values for various mesa diameters were extracted and are shown in Fig. 3(f). For the PD with 40 µm mesa diameter, the responsivity is 0.7 A/W.

Non-return-to-zero eye patterns were measured to demonstrate the high-speed performance of the InGaAs PDs on Si. The signal from a pattern generator with pseudo-random bit sequence word length of $2^{31} - 1$ was used to modulate a 1550 nm single mode laser source with a lithium niobate ($LiNbO_3$) modulator. The data rate was varied from 10 Gbps to 30 Gbps. The DC bias voltage and polarization were adjusted to maximize the measured PD photocurrent. The total optical power received was approximately -3 dBm for all measurements. Eye diagrams for devices with mesa diameters of 10, 20 and 40 µm are reported in Fig. 4(a), (b) and (c) respectively.

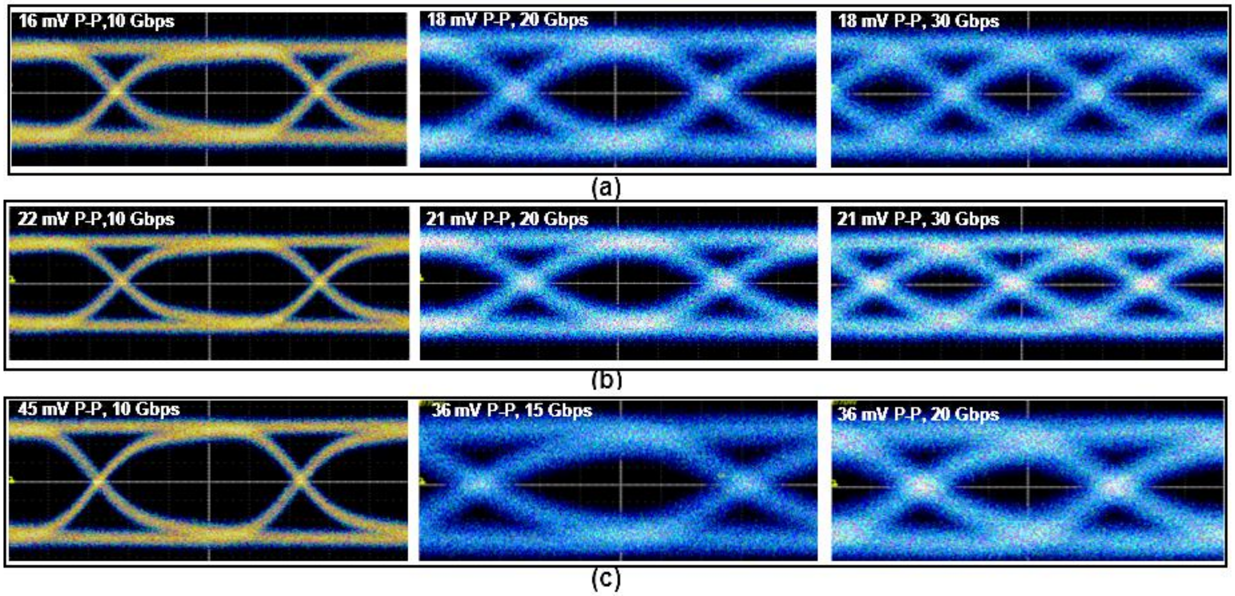

Fig. 4. (a) Measured eye diagrams for device diameters of (a) 10 µm, (b) 20 µm and (c) 40 µm. The received V_{P-P} and the data rate are provided for each received eye.

4. Conclusion

High speed top-illuminated mesa InGaAs PDs were realized on CMOS-compatible (001) Si by direct heteroepitaxy. Devices yield low dark current, a responsivity as high as 0.7 A/W, and a bandwidth as high as 11 GHz at 1550nm. Up to 30 Gbps was achieved, indicating the potential for realizing high-performance InGaAs PDs on Si substrates.

4. Acknowledgements

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