

Monolithic indium arsenide quantum dots on silicon optoelectronics

Researchers develop photodetectors with low dark current and comparable performance to germanium devices.

Researchers based in USA, Taiwan and China have monolithically integrated photodetectors (PDs) and lasers using indium arsenide (InAs) quantum dot (QD) in indium gallium arsenide/aluminium gallium arsenide (InGaAs/AlGaAs) well/barrier active structures on silicon [Yating Wan et al, Optics Express, vol25, p27715, 2017]. The devices operated in the 1260-1360nm O-band of wavelengths.

The researchers hope that their work will help to combine the economies of scale of silicon with the high optoelectronic efficiency of III-V materials for photonic integrated circuits. In particular, the InAs QD photodetector showed much reduced dark current compared with germanium-based photodetectors on silicon.

The team from University of California Santa Barbara (UCSB), Taiwan's National Central University, Hong Kong University of Science and Technology (HKUST) and Hewlett Packard Labs in the USA report, "to the best of our knowledge, the first characterization of high-speed performance and the first demonstration of the on-chip photodetection for this QD-on-silicon system."

The researchers see the monolithic integration of photodetectors and lasers on silicon as a means to

create power monitors or amplifiers for pre-amplified receivers.

The GaAs-on-silicon template was prepared using metal-organic chemical vapor deposition (MOCVD). The silicon substrate was V-grooved to allow aspect ratio trapping of dislocations. Further cyclic annealing and strain-balancing layers further reduced the dislocation density to $7 \times 10^7/\text{cm}^2$.

The template was used in molecular beam epitaxy (MBE) to create photodiodes with an active region consisting of seven stacks of InAs dots-in-wells (DWELLS), sandwiched between 1.4 μm layers of n- and p-AlGaAs. The epitaxial structure also included 500nm n-GaAs bottom contact layers, and a 300nm GaAs cap. Plan-view transmission electron microscopy of one layer of QDs gave an estimate of 6×10^{10} dots/ cm^2 .

Device fabrication (Figure 1) consisted of inductively coupled etching of 20 $\mu\text{m} \times 50\mu\text{m}$ mesas; deposition of palladium/titanium/palladium/gold and palladium/germanium/gold p- and n-contacts, respectively; atomic layer deposition (ALD) of aluminium oxide and sputtering of silicon dioxide passivation; via the opening and deposition of 1.5 μm titanium/gold

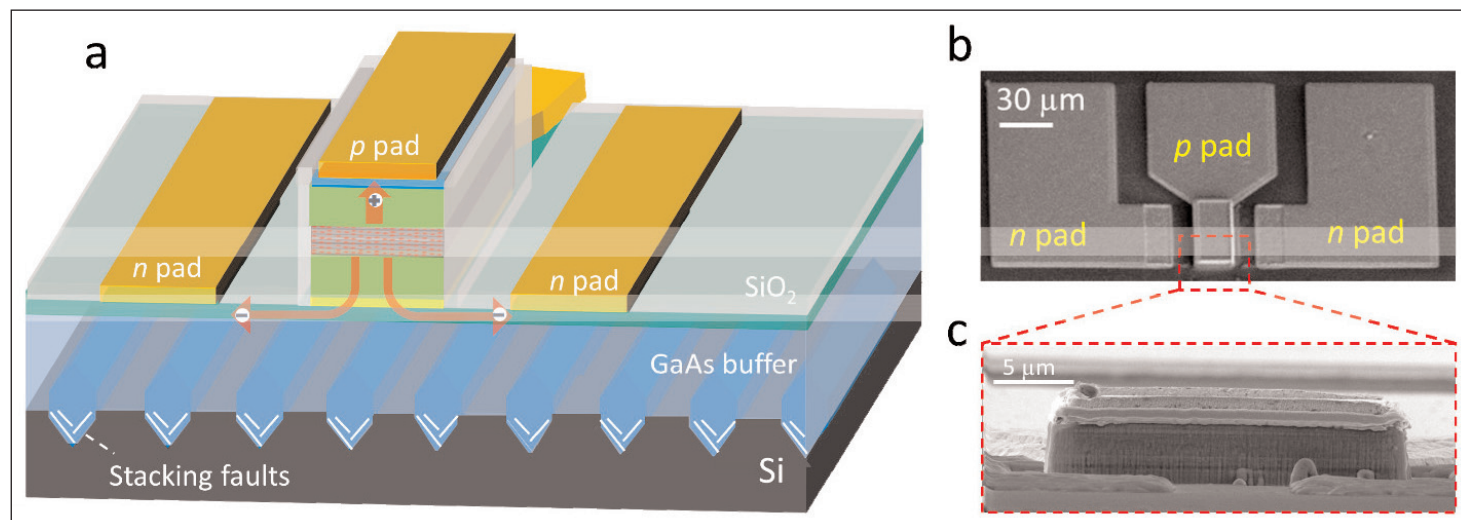


Figure 1. (a) Schematic of fabricated photodetector on V-grooved substrate; (b) top-view and (c) cross-sectional view scanning electron microscope images.

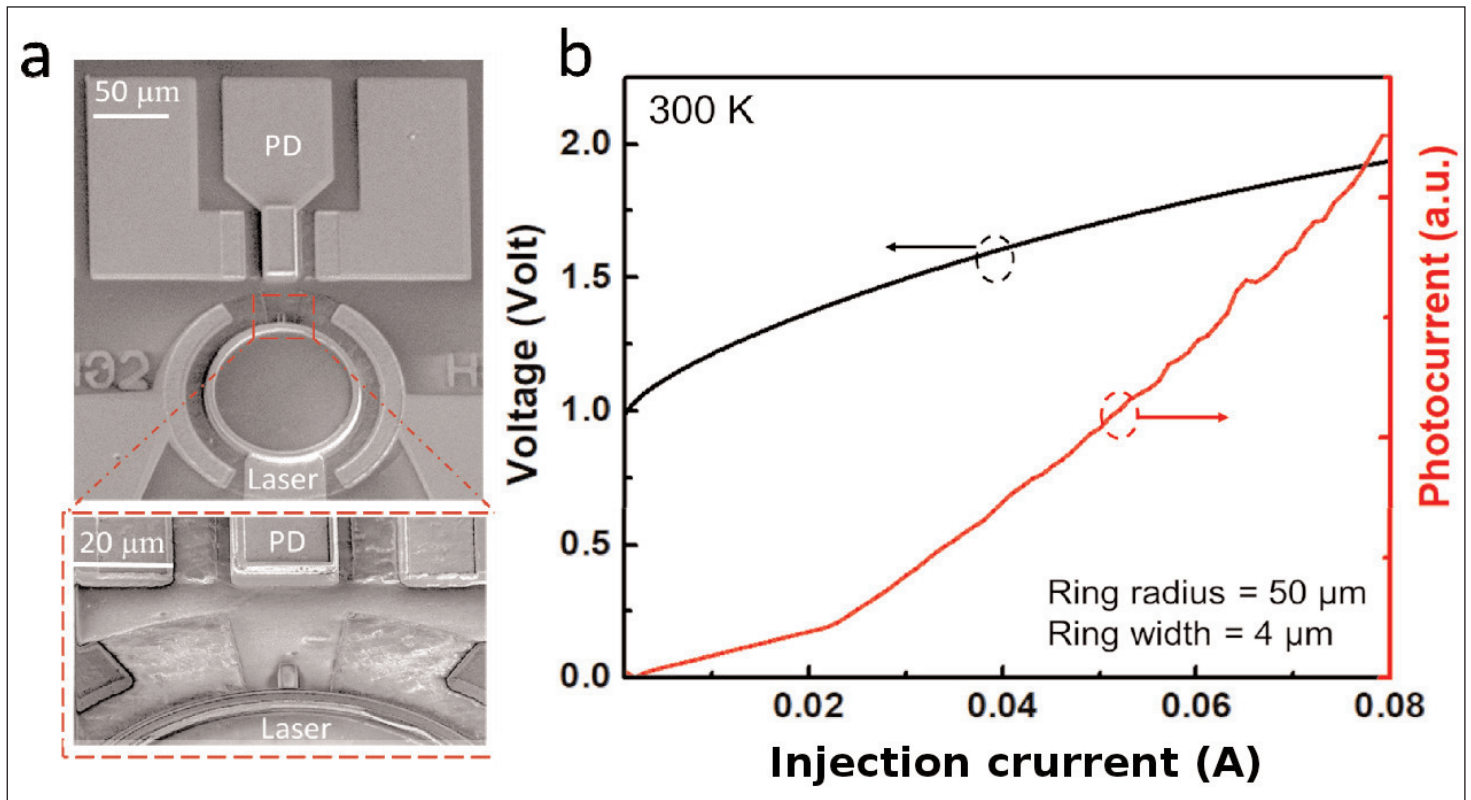


Figure 2. (a) Top-view of fabricated free-space coupled laser-photodetector system; (b) measured laser voltage and detector photocurrent as a function of injection current.

ground-signal-ground measurement pads; and, dicing and polishing of photodiode facets without an anti-reflective coating.

The dark current ranged from 0.8nA to 18nA under reverse biases of -1V and -5V, respectively. Given the 10^{-5}cm^2 device area, 1nA corresponds to a current density of $0.1\text{mA}/\text{cm}^2$. The researchers point out that $0.08\text{mA}/\text{cm}^2$ dark-current density is “two orders of magnitude lower than the competing Ge-on-Si PDs with thin Ge or SiGe buffer layers (typically in the order of $10\text{mA}/\text{cm}^2$).” They attribute the improvement to high crystalline quality, low dislocation density, shorter diffusion lengths, and good sidewall passivation.

Coupling a $1.3\mu\text{m}$ laser source into a photodetector facet with a lensed fiber gave a responsivity

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of more than $0.3\text{A}/\text{W}$ over the 1240–1340nm spectral range. At 1250nm wavelength, the responsivity was $0.33\text{A}/\text{W}$ with bias conditions ranging from -1V to -6V. The researchers estimate the facet reflection at around 30% and the coupling loss at 3dB, corresponding to a corrected photodetector responsivity of $0.94\text{A}/\text{W}$. High-quality Ge-on-SOI waveguide photodetectors have been reported with $\sim 1\text{A}/\text{W}$ responsivity. “The extracted internal responsivity ($0.9\text{A}/\text{W}$) corresponds to 90% internal efficiency,” the team adds.

The frequency performance was measured and model parameters extracted that suggest a (resistance) \times (capacitance)-limited 3dB bandwidth of $\sim 2.9\text{GHz}$. The measured 3dB device bandwidth was slightly lower at 2.3GHz. The researchers attribute the lower value to carrier trapping effects of the QDs.

The researchers also integrated the photodetector with a neighboring micro-ring laser (Figure 2). UCSB has been developing lasers on a similar InAs QD platform (www.semiconductor-today.com/news_items/2017/oct/ucsb_131017.shtml). The ring had a $1\mu\text{m}\times 9\mu\text{m}$ waveguide to scatter light through free space to the neighboring photodetector. The ring measured $50\mu\text{m}$ outer radius with $4\mu\text{m}$ mesa width. The laser threshold was around 21mA, according to the photodetector measurement. A more integrated arrangement (with the laser and photodetector connected by a waveguide) is presently being developed. ■

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