InP quantum dots for dislocation-tolerant, visible light emitters on Si

P. Dhingra,[1] Y. Sun,[1,3] S. Fan,[1] R. D. Hool,[2] M. L. Lee[1+]
[1] *Dept. of Electrical and Computer Engineering, University of Illinois, Urbana, IL, USA*
[2] *Dept. of Material Science and Engineering, University of Illinois, Urbana, IL, USA*
[3] *Dept. of Electrical Engineering, Yale University, New Haven, CT, USA*

We present the first demonstration of InP quantum dots (QDs) on Si showing room-temperature, visible photoluminescence (PL) intensity nearly identical to samples grown on GaAs. The past few years have seen tremendous progress in the development of 1.3 μm InAs quantum dot (QD) lasers on Si with low threshold current density and high reliability despite threading dislocation densities (TDD) of ~10^7 cm^{-2} [1]. The high luminescence efficiency of InAs QDs on Si can be attributed to lateral carrier confinement of the QDs and high QD density, ~3 orders of magnitude higher than the TDD. Epitaxial InP QDs embedded in $(Al_xGa_{1-x})_{0.52}In_{0.48}P$ can also be grown on GaAs and have recently been used to demonstrate red and near-infrared lasers with low threshold current density [2]. Here, we show that the apparent dislocation-tolerance of InAs QDs on Si also extends to InP QDs on Si, making them an ideal candidate for low-cost visible and near-infrared lasers and light emitting diodes (LEDs).

We grew InP/AlGaInP QD PL structures on bulk GaAs and GaAs/Si virtual substrates using MBE. GaAs/Si virtual substrates were grown on commercially available GaP/Si (001) templates using a 3.6 μm thick $GaAs_xP_{1-x}$ step-graded buffer. Cross-sectional transmission electron microscope (XTEM) images of samples grown on both GaAs and GaAs/Si were nearly identical, showing coherently strained InP QDs capped by a smooth InGaP QW. Planar-view cathodoluminescence (CL) maps showed essentially no dislocations for the sample grown on GaAs, as expected. In contrast, a TDD of 3.3×10^7 cm^{-2} was observed for the sample grown on GaAs/Si. Atomic force microscopy (AFM) showed a high QD density of 1.3×10^{11} cm^{-2} on both substrates, which is several orders of magnitude greater than the TDD in the active region. We performed room-temperature PL measurements to characterize the emission wavelength and intensity of InGaP QWs and InP QDs grown on both GaAs and GaAs/Si virtual substrates. The integrated intensity of the InGaP QW sample grown on GaAs/Si is ~9× lower than the QW on GaAs due to the high TDD. In contrast, the integrated intensity of InP QDs on Si is ~16× higher than the InGaP QW on Si and within 15% of InP QDs grown on GaAs, showing the high dislocation tolerance of InP QDs. In conclusion, we show that high density InP/AlGaInP QDs can be grown on Si with similar structural and optical properties as growth on bulk GaAs, paving a pathway towards low-cost, integrated light emitters with potential applications ranging from micro-LEDs to optogenetics.

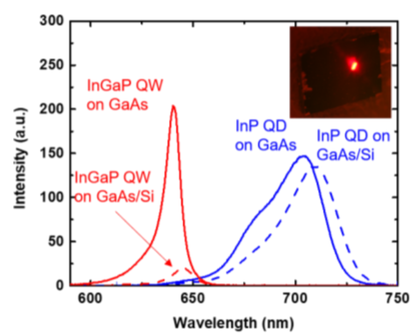

Figure 1: PL of InP QDs on GaAs/Si and GaAs showing similar integrated intensity and far greater dislocation tolerance compared to InGaP QWs. (inset: photo of PL from InP QDs/Si with green laser filtered out, sample size = 1.5 cm × 2 cm)

[1] Jung, ACS Photonics, **5**, 1094 (2018)
[2] Lutti, Electron Lett., **5**, 247 (2005)
+ Author for correspondence: mllee@illinois.edu

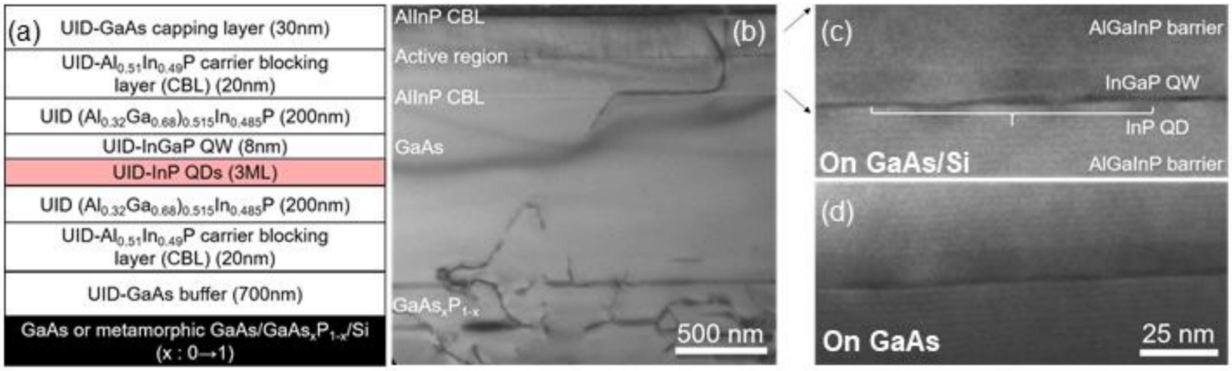

Figure 1: (a) InP QD structure for PL experiments, (b) Low- and (c) high-magnification XTEM image of InP QD active region on GaAs/Si. (d) XTEM of active region on GaAs showing nearly identical morphology. (b) taken with $g = \langle 004 \rangle$ and (c)-(d) taken with $g = \langle 002 \rangle$ two-beam conditions. Same scale bar for (c) and (d).

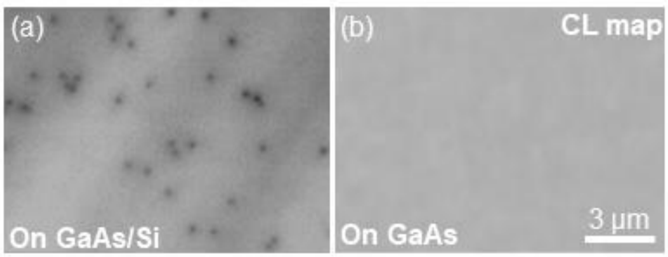

Figure 2: CL image of InP QD active region co-grown on (a) GaAs/Si showing TDD = 3.3×10^7 cm^{-2} (dark spots), and (b) GaAs. Same scale bar for (a) and (b).

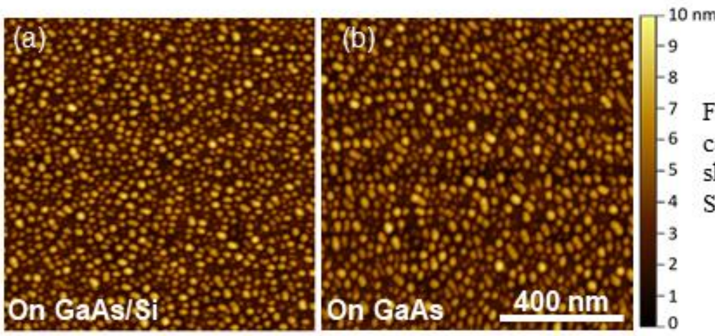

Figure 3: AFM of 3 ML InP QDs simultaneously co-grown on (a) GaAs/Si and (b) GaAs. Both show very high dot density of $\sim 1.3 \times 10^{11}$ cm^{-2}. Same scale bar for (a) and (b).

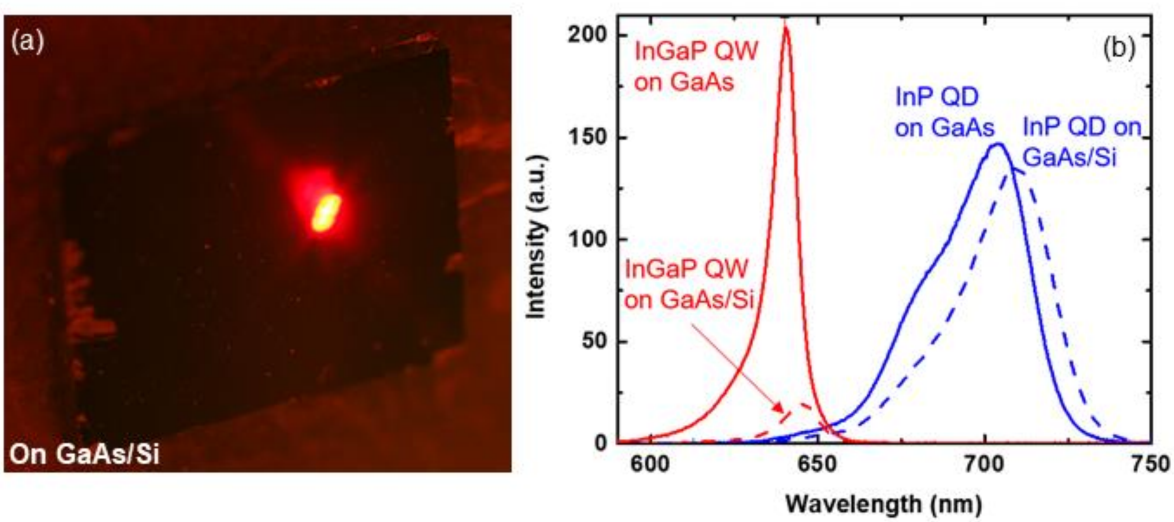

Figure 4: (a) Photo of PL from InP QDs on GaAs/Si at RT with green laser filtered out, sample size = 1.5 cm × 2 cm (b) PL of InP QDs on GaAs/Si and GaAs showing similar integrated intensity and far greater dislocation tolerance compared to InGaP QWs.