III-V and Group IV Epitaxy for Low Energy Optoelectronics

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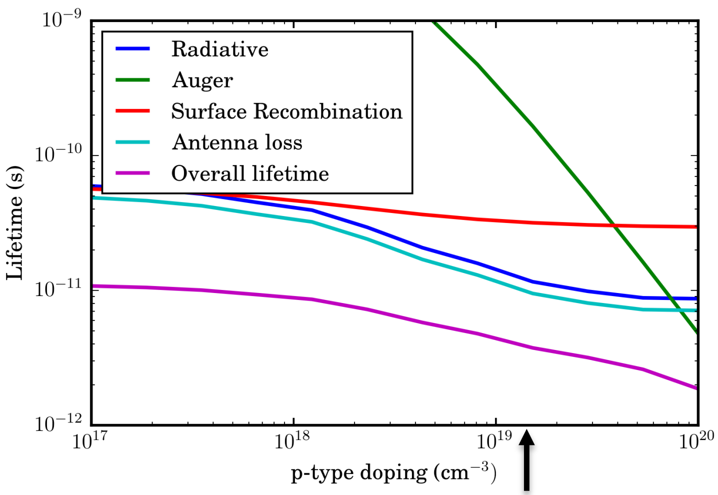
Outline

- Materials for optical link
- HBT integration for high performance communication
- Likely application for these technologies

Active region p-doping analysis from UC Berkeley



Target

Assumptions:

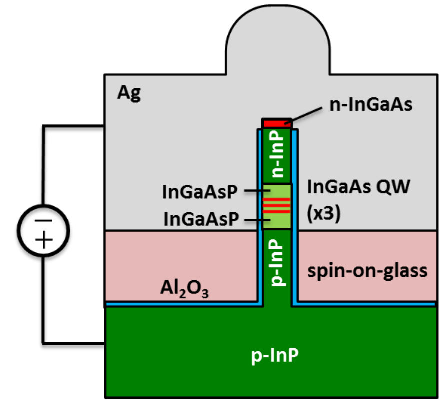
(1) Surface recombination velocity = 3e4 cm/s

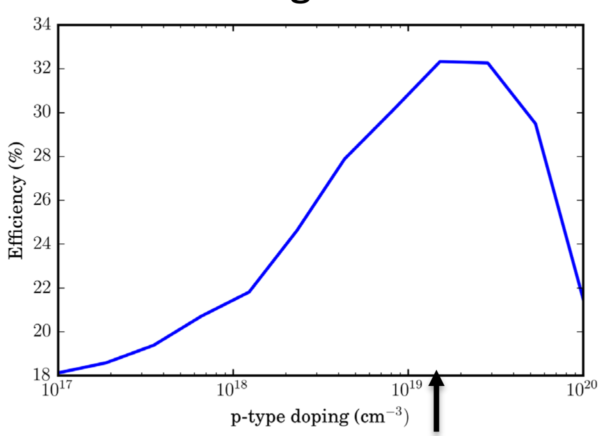
(2) Auger recombination coefficient = 2e-29 cm-6s-1

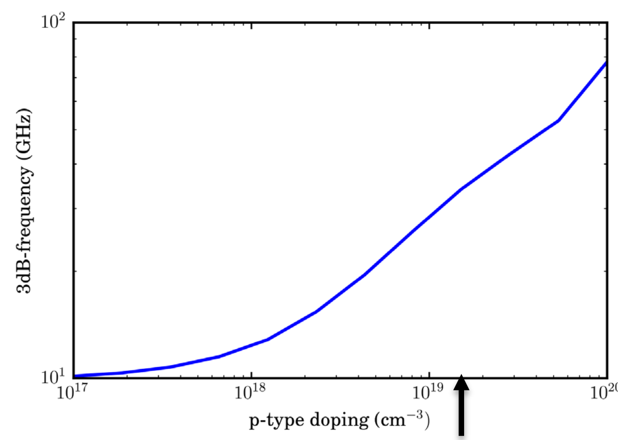
(3) Sp. Em. Enhancement = 640, Antenna Efficiency = 45% Q-factor = 37

(4) Bulk SRH ignored

(5) Injection carrier density = 1.5e18cm-3





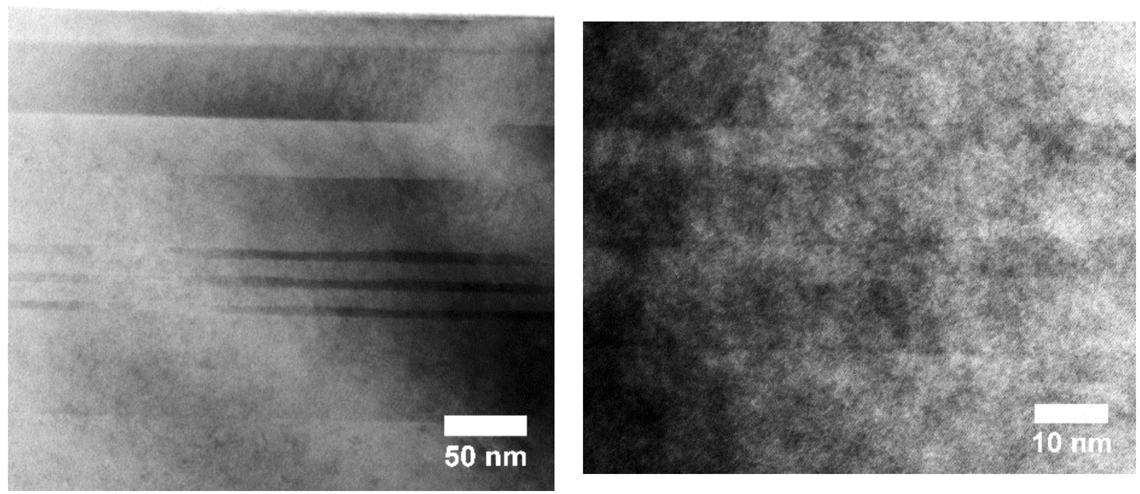


Growth of undoped LED structure

LED structure schematic:

InGaAs top contact	40 nm
InP top contact	30 nm
InGaAsP barrier	40 nm
InGaAs QW	6 nm
InGaAsP barrier	10 nm
InGaAs QW	6 nm
InGaAsP barrier	10 nm
InGaAs QW	6 nm
InGaAsP barrier	60 nm
InP bottom contact	300 nm
InP (substrate)	

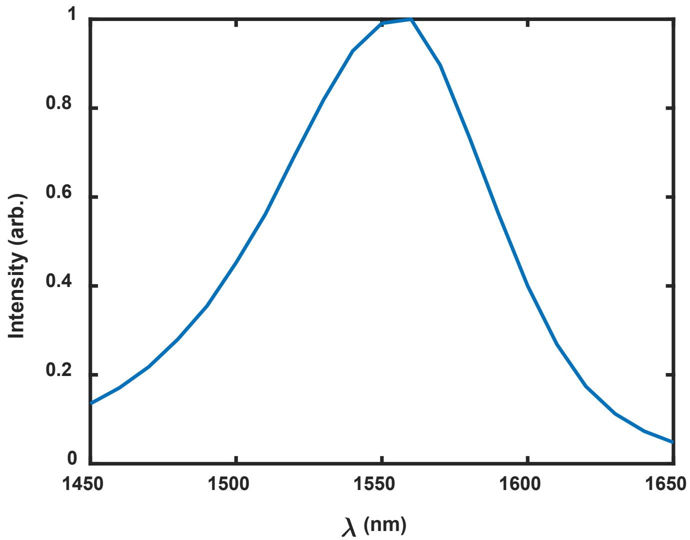
XTEM



HT = 200 kV, (110) on pole

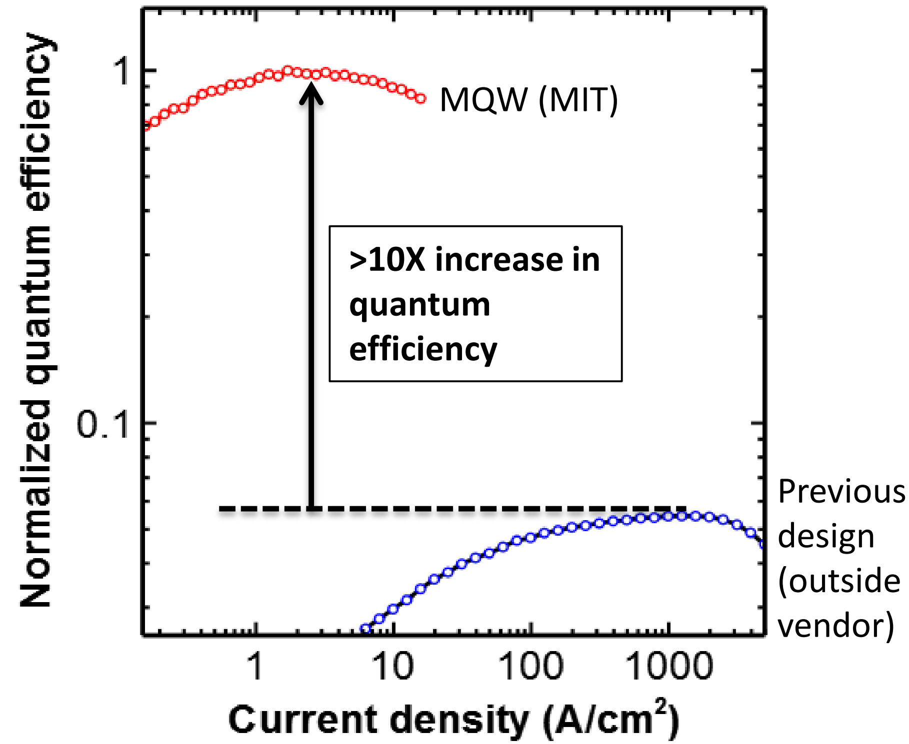
Luminescence of undoped LED structure

PL of blanket film



1550 nm target

Quantum efficiency (large-area LEDs, UC Berkeley)



LED structure with Zn p-type doping

undoped active region:

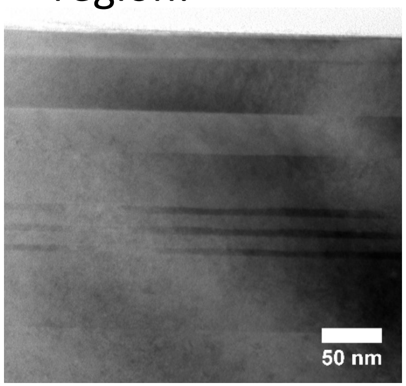
p+ active region (Zn doping ~ 5 x 10^{18}):

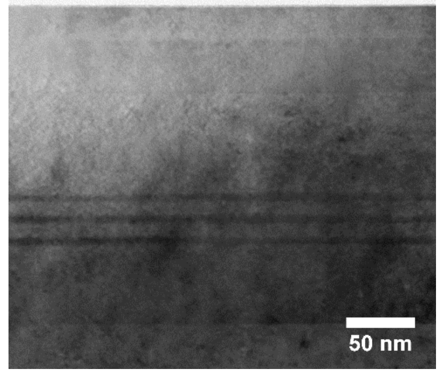
InGaAs contact

InP contact

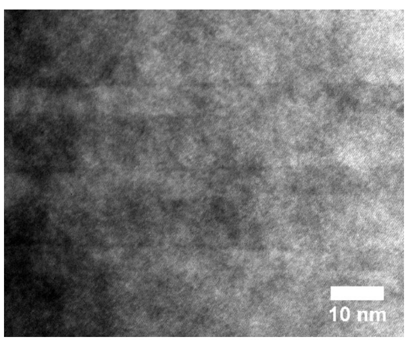
InGaAs/InGaAsP MQW

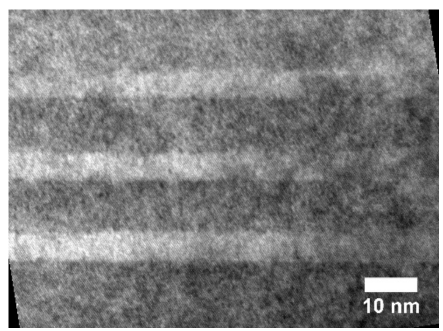
InP contact



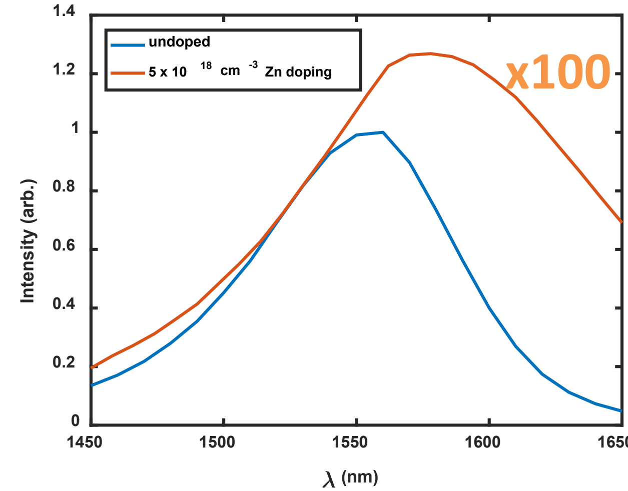


InGaAs/InGaAsP MQW

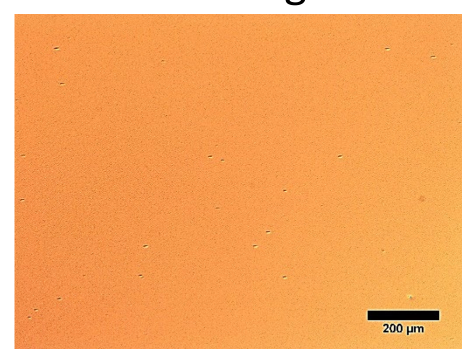




PL of Blanket Films

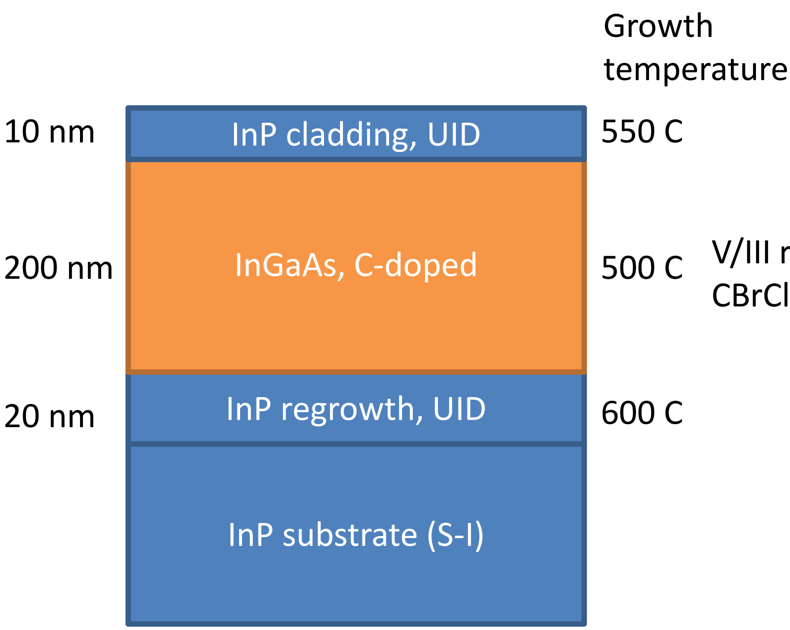


DIC Image

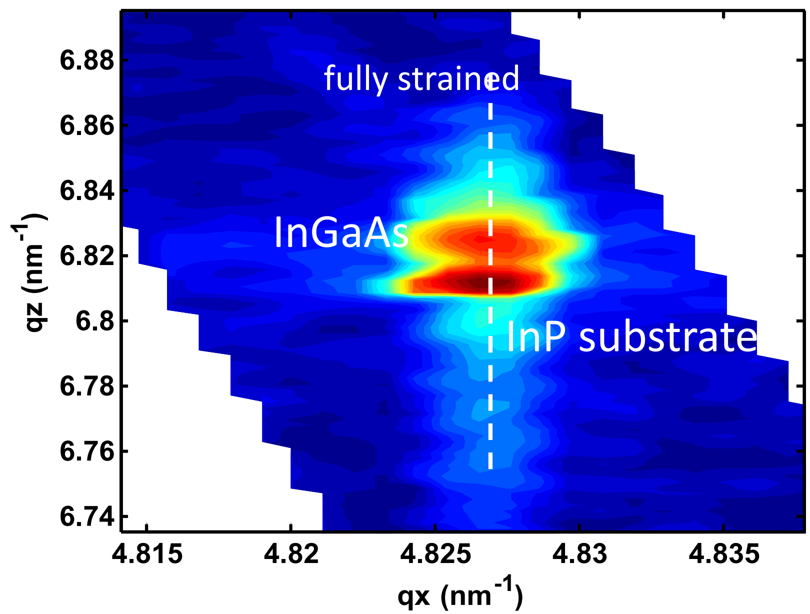


poor EL and IV characteristics for fabricated LED

Lattice matched growth



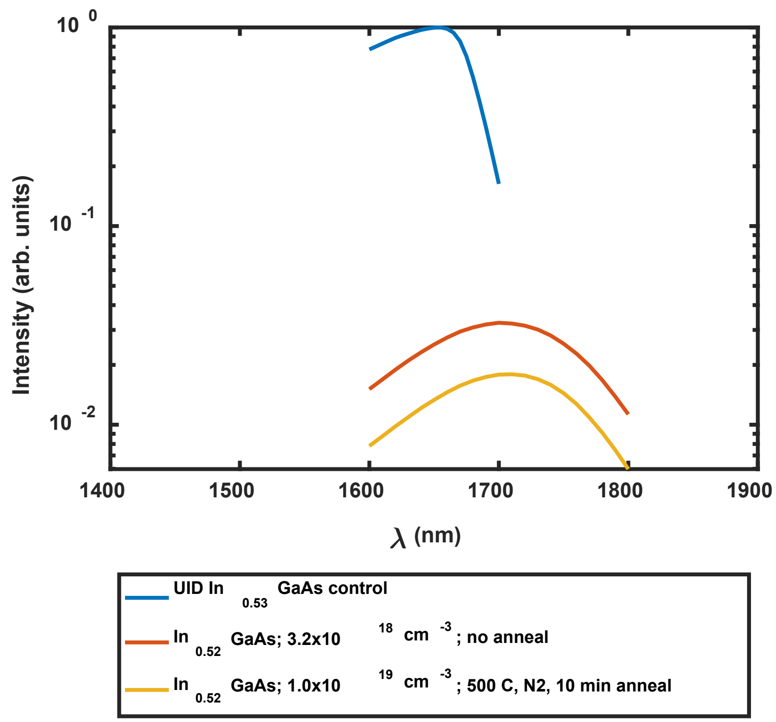
V/III ratio = 4
$CBrCl_3$ ratio = 9%



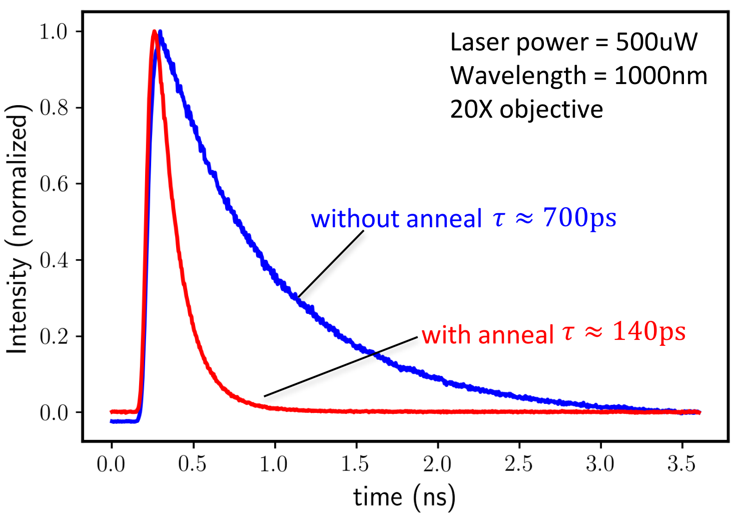
In fraction = 52.2%

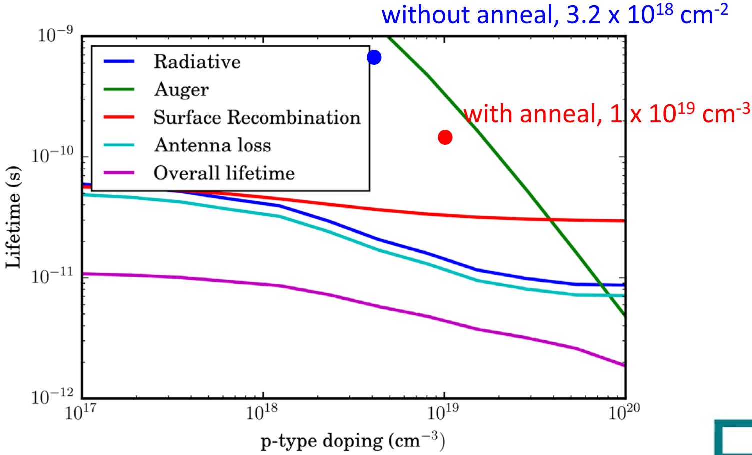
p = 3.2×10^{18} cm^3

Post-growth N_2 anneal: effect on PL intensity and lifetime



Time-resolved (UC Berkeley)





Decrease in intensity/lifetime after post-growth anneal → increased Auger recombination due to higher hole concentration

A Science & Technology Center

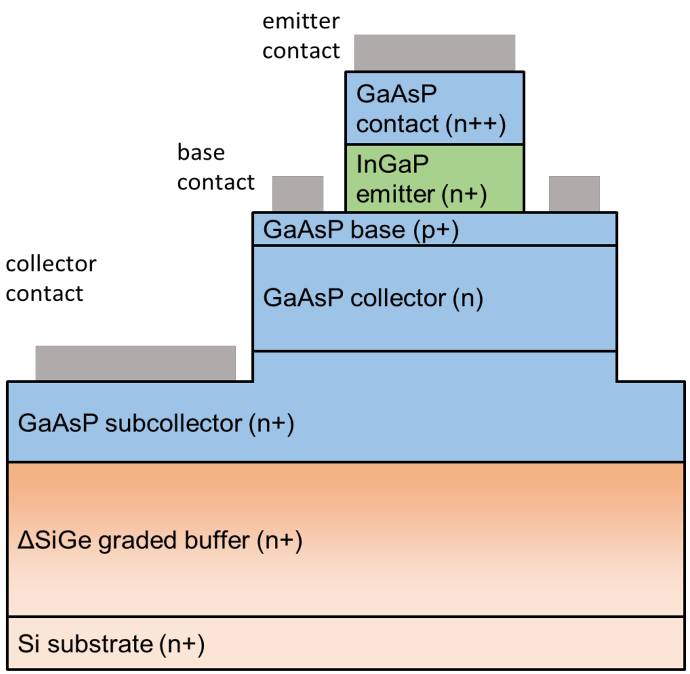
Center for Energy Efficient Electronics Science

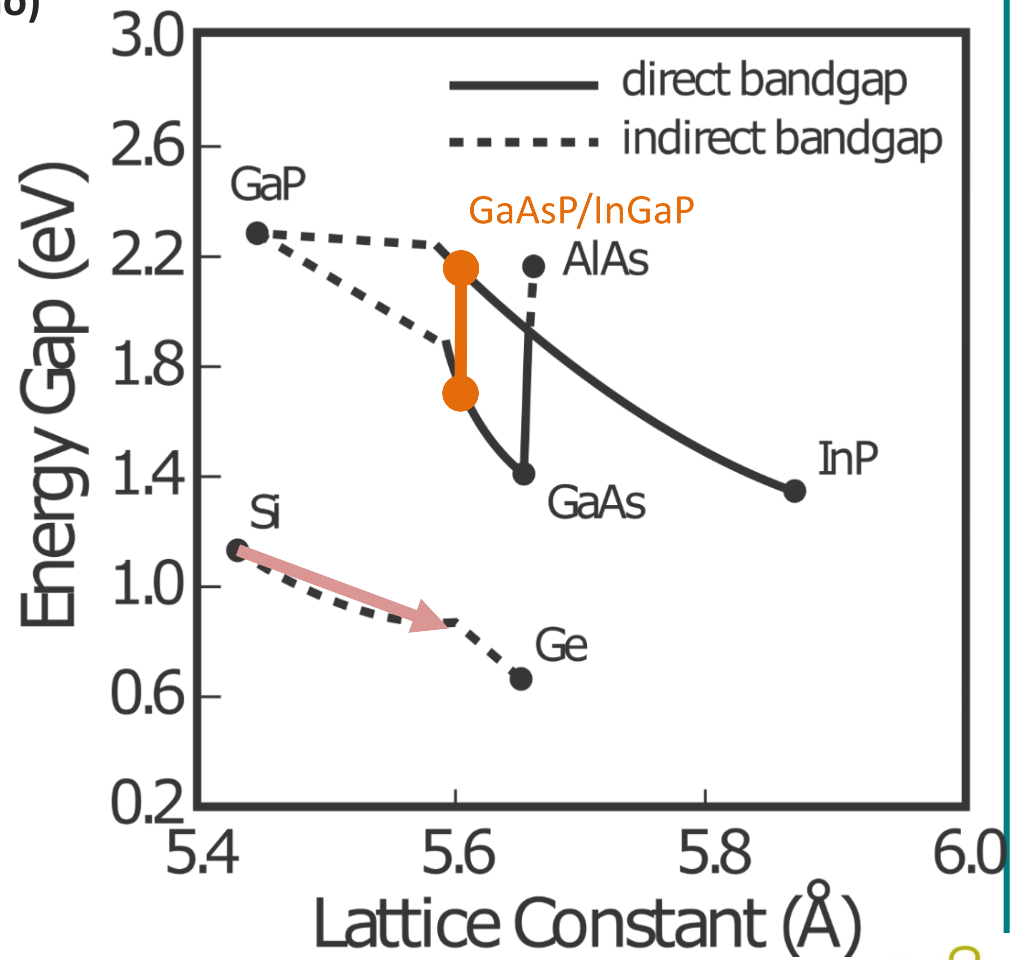
InGaAs LED structures: conclusions

- Demonstrated undoped InGaAs/InGaAsP LED structure with good morphology and high quantum efficiency
- Grew C-doped InGaAs with $p > 1 \times 10^{19}$ cm^{-3} and recombination limited by Auger recombination
- Future work
  - Grow InGaAsP cladding layers at similar growth conditions as C-doped InGaAs
  - Grow and characterize InGaAs/InGaAsP LED structure with high p-type doping
  - Fabricate and test antenna-enhanced LED structure with heavily-doped active region (UC Berkeley)

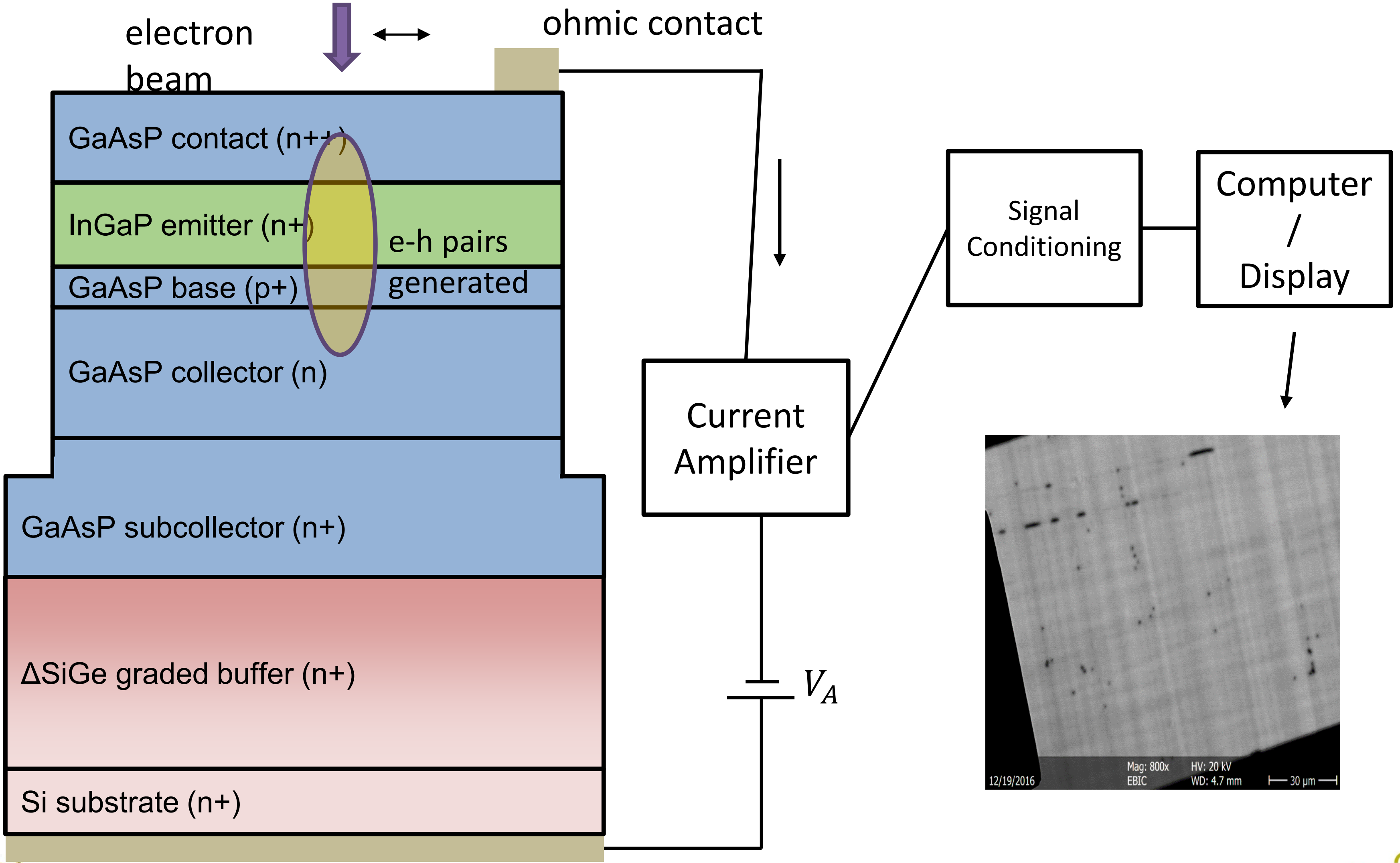
GaAsP/InGaP HBT on Si

- heterojunction bipolar transistor (HBT):
  - high frequency (& independent of litho)
  - high power efficiency

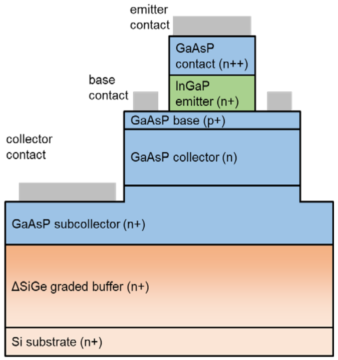




EBIC measurements of GaAsP HBTs



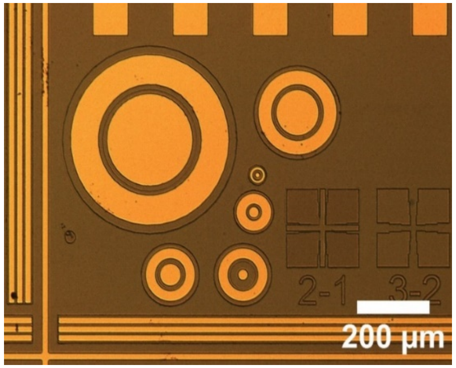
Experimental loop



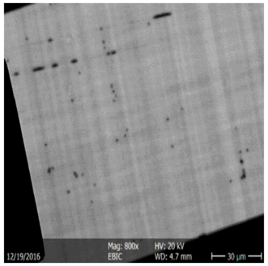
Design Structure

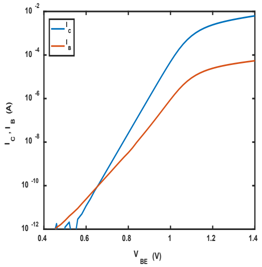
Epitaxial Growth (MOCVD)

Fabricate HBTs



EBIC + Electrical Measurements



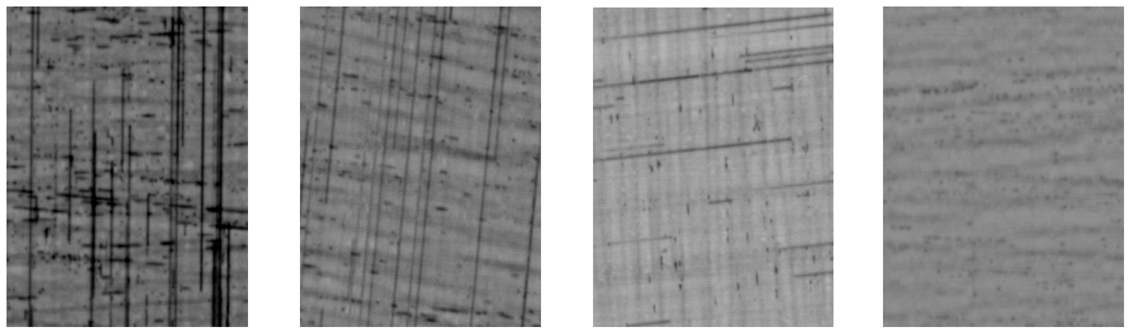


Iterative approach to improved defect density

Modification	C base doping	Zn base doping	improved InGaP calibration	thick subcollector layer

EBIC

30 µm

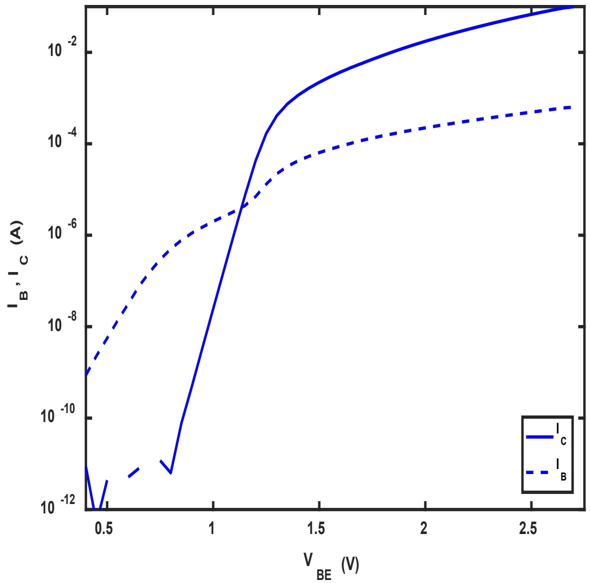


Misfit Dislocation Density	1900 cm^{-1}	900 cm^{-1}	600 cm^{-1}	$< 1\ cm^{-1}$

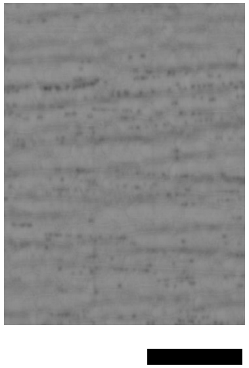
High current gain demonstrated on Si substrate

Modification C base doping → Zn base doping → improved InGaP calibratio n → thick subcollec tor layer

60 µm diameter HBT



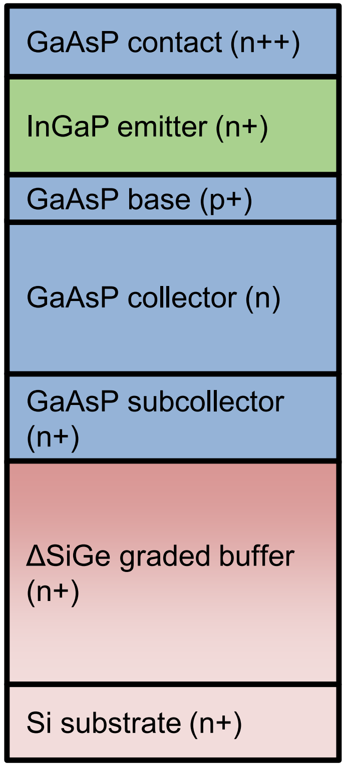
β = 156



30 µm

= 3.7 × 10^6 cm^{-2}

< 1 cm^{-1}

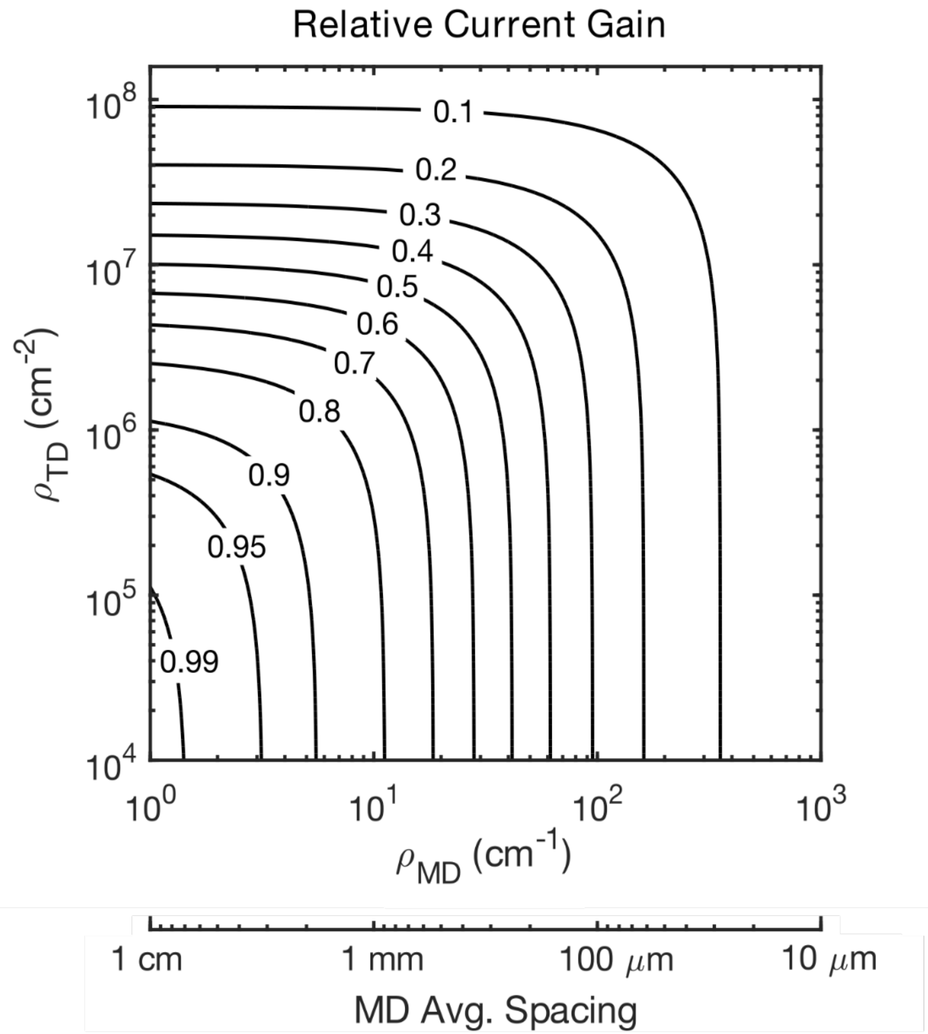


C. Heidelberger and E. Fitzgerald, *J. Appl. Phys.*, under review

“Current Gain Map”

- combined models for threading and misfit dislocations

- misfit dislocations have pronounced effect on current gain, even at low densities



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Applications/Market: Is Computing a Target Market?

- 28nm likely to be 'last profitable node' for non-monopolistic market participants?
  - De-integration occurring for performance and market reasons
  - Computing cores will be mature for a decade or more
  - Data center 'farms' or even 'cities'
    - Key necessary innovations obscured by monopolistic corporate structure
    - University research likely irrelevant to key problems without an informing paradigm
  - Communication and power management take front-seat
    - Within-data-center more important for silicon ICs because of market size
    - i.e. telecom thinking must leave silicon photonics (i.e. = telecom photonics)
- What to do in next decade or two?
  - Disruptive* path suggests key silicon technology (with new added value in materials) to appear in communication, lighting, and power management ICs; new era of ASICs
    - Nothing to do with data centers, computing, etc. initially
    - Grow in other markets for decades, then spill back into computing
      - Real 5G wireless
      - Visible integrated optoelectronics
    - Old silicon nodes (and 200mm) are playground and commercialization for innovation

*Actual Christensen definition, not Valley term