Progress in non-polar and semi-polar GaN VCSELs

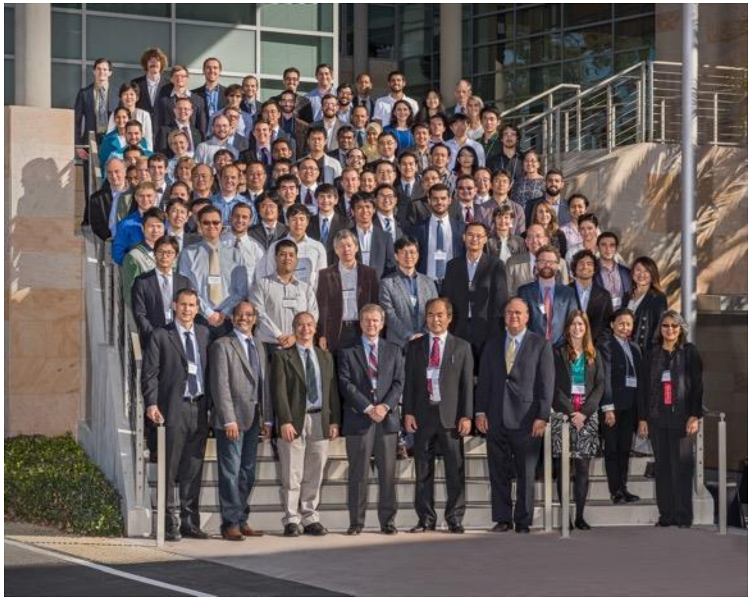
Tal Margalith

Solid-State Lighting and Energy Electronics Center (SSLEEC)

UC Santa Barbara

EPIC Meeting on VCSELs
17-18 October, 2019

SSLEEC: Premier GaN Research Center



- 9 Faculty Members
- >50 Engineers, Postdocs, and Ph.D. Students on GaN
- 4 dedicated staff
- 8 Industrial Member Companies









SSLEEC: Application-Driven Research

GaN

VCSEL

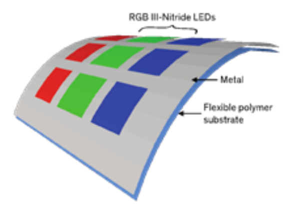
Power Devices | LEDs | Laser Diode

EV Car

PV Inverters

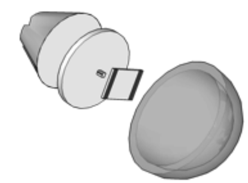
General Lighting

Micro-LED



Car Headlight

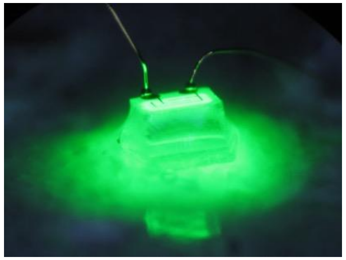
Laser Light

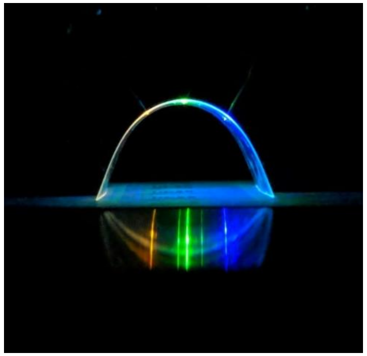


LiFi / LIDAR

Research Thrusts

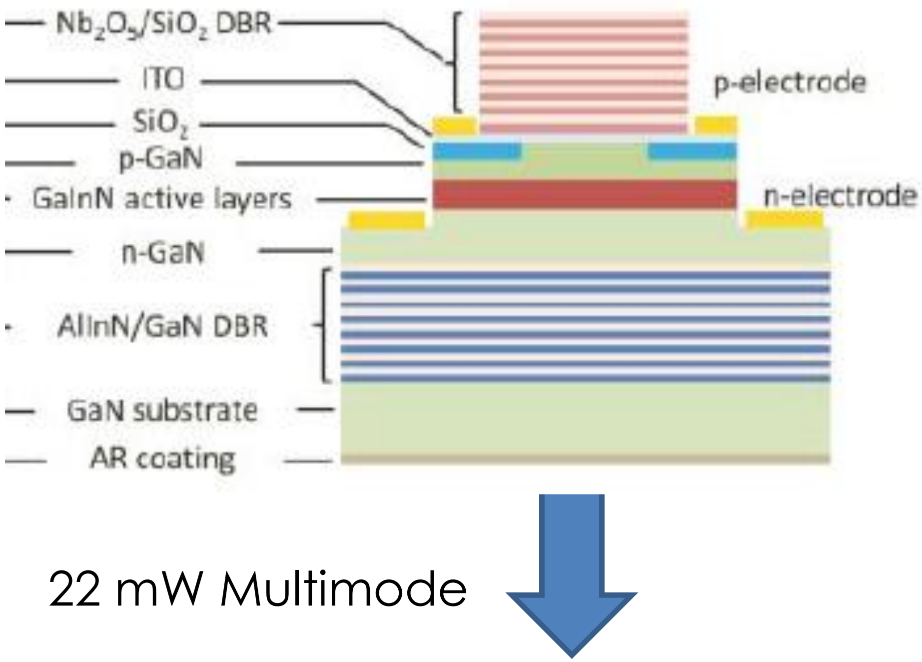
- Optoelectronics
  - Platform Technologies
    - Tunnel Junction devices
  - Broadening the GaN Spectrum
    - UV, Green, Amber LEDs
  - Application-Driven Functionality
    - HP Lasers / Laser Lighting
    - LiFi Emitters and High-Speed Photodetectors
    - LIDAR
  - Performance at a Small-Size Scale
    - µLEDs for Display, AR, and VR
    - VCSELs





- III-N-Based RF/Power Electronics

State of the Art VCSEL



22 mW Multimode

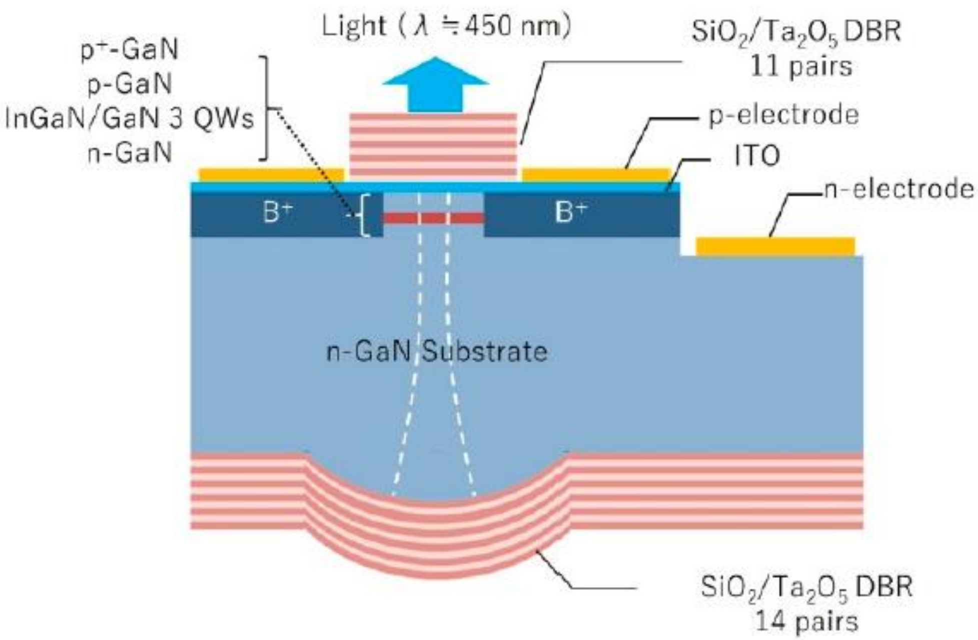
Advantages
- Short cavity = single frequency
- No substrate removal or thinning

Disadvantages
- Very long growth time (~12 hrs)
- Narrow DBR stop band = low MFG yield
- Poor lateral mode control with wider apertures
- Neither DBR permits heat flow

(Stanley Elec., Meijo Univ.),
Kuramoto, et al., Proc. SPIE vol. 11145, 1114501-73 (2019)

State of the Art VECSEL

15 mW Multimode



Sony
H. Nakajima, APEX 12, 084003 (2019)

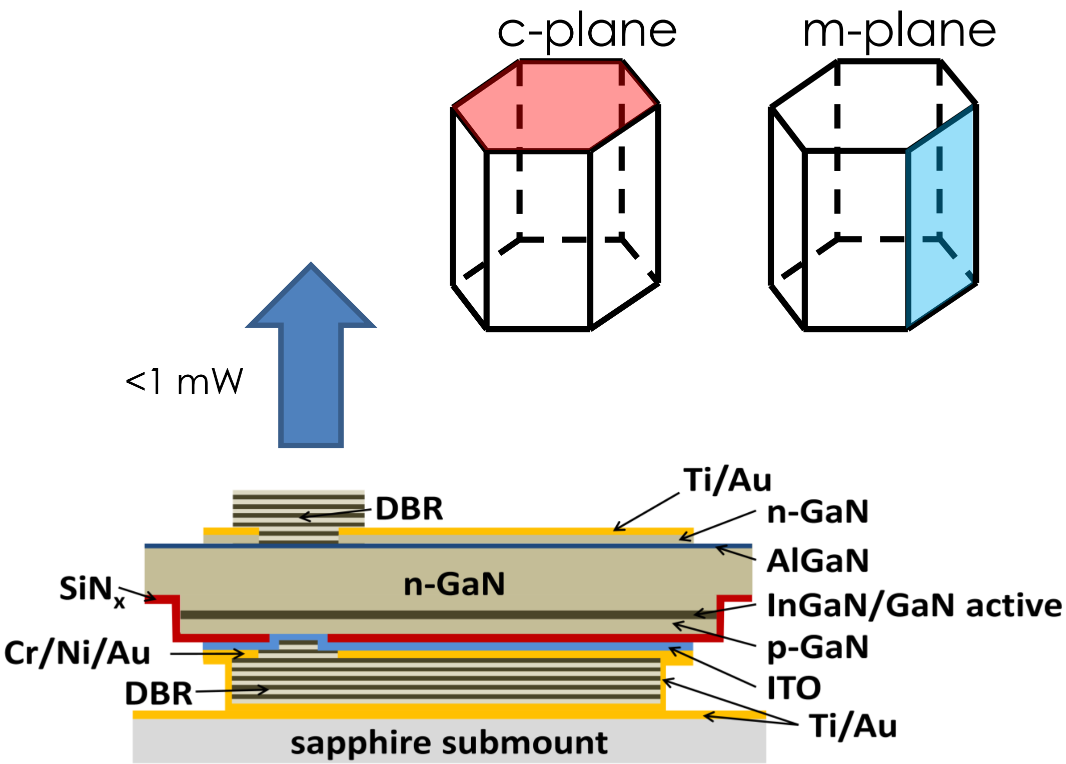
Advantages

- Long cavity insures a lasing mode near gain peak
  - Higher MFG yield, looser temp control
  - Wider dynamic range, but NOT necessarily higher power
- No DBR barrier to heat flow
- Mode control in large area VCSEL

Disadvantages

- Mirror alignment with current aperture
- Mirror size may limit array density
- Long photon lifetime limits modulation speed
- Substrate thinning or transfer needed

UCSB Focus: Nonbasal, Polarized VCSEL



Advantages

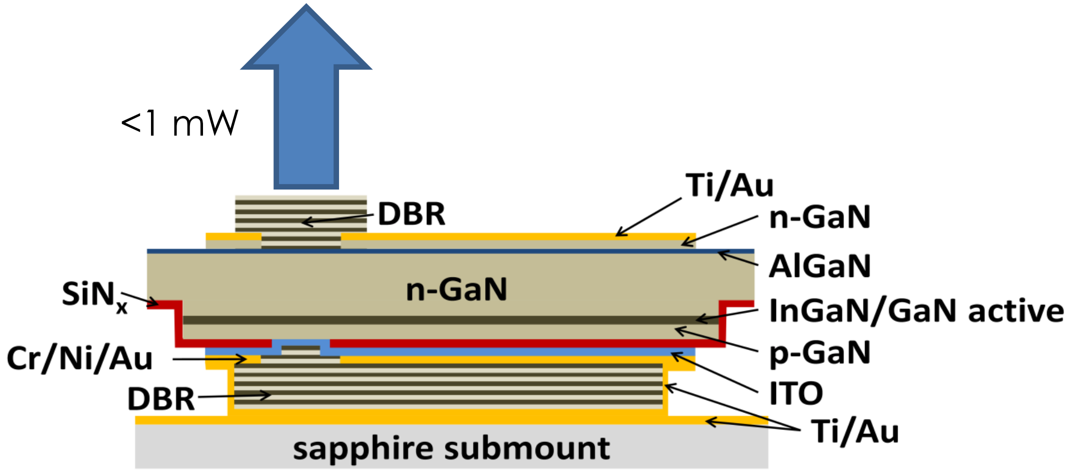
- Polarized output locked to crystal axis
- Higher gain coefficient than c-plane

Disadvantages

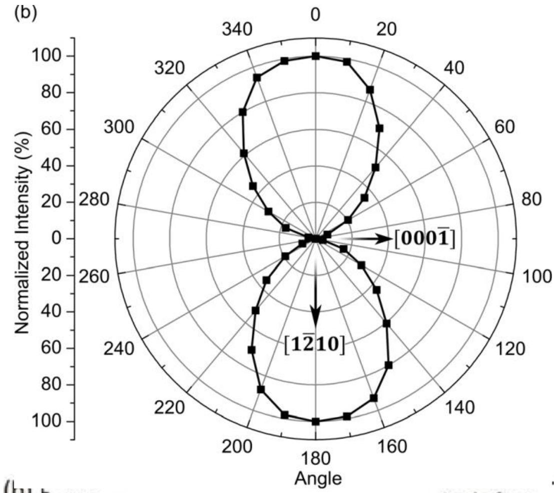
- Substrate removal needed
- Poor lateral mode with wider apertures (parallel mirrors)
- Neither DBR permits heat flow

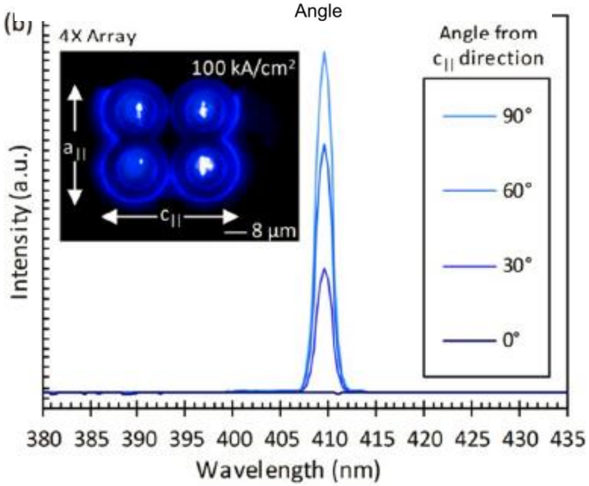
UCSB
Holder, Appl. Phys. Lett. 105, 031111 (2014)

UCSB Focus: Nonbasal, Polarized VCSEL



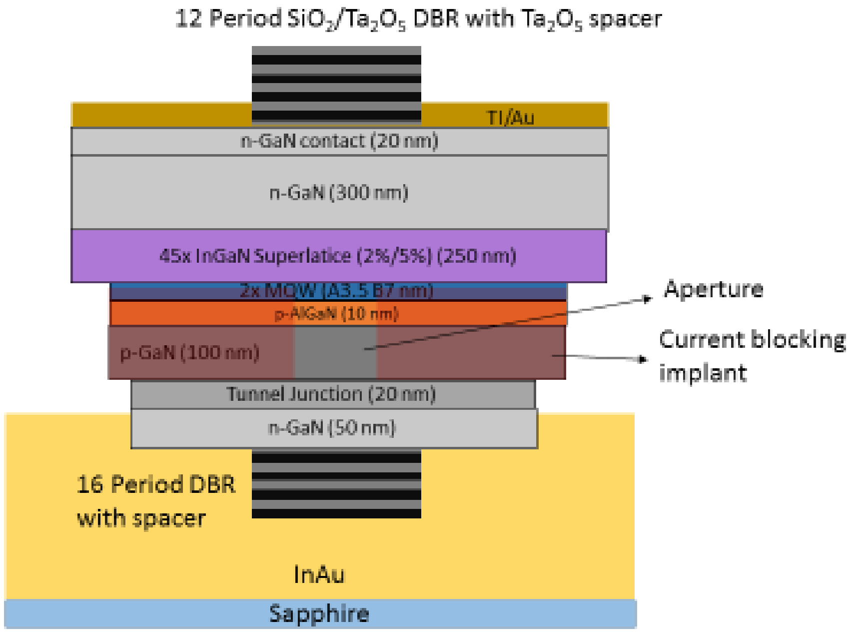
UCSB
Holder et al., APL 105, 031111 (2014)
J. Leonard, III-N VCSELs, Dissertation (2016)



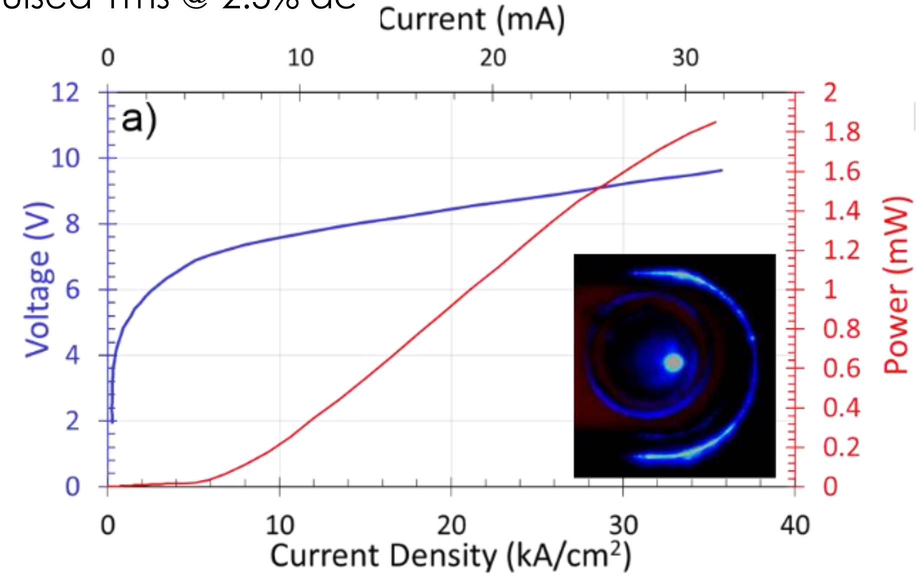


J. Leonard Dissertation 2016

445 nm Semipolar TJ VCSEL with Ion-Implanted Aperture



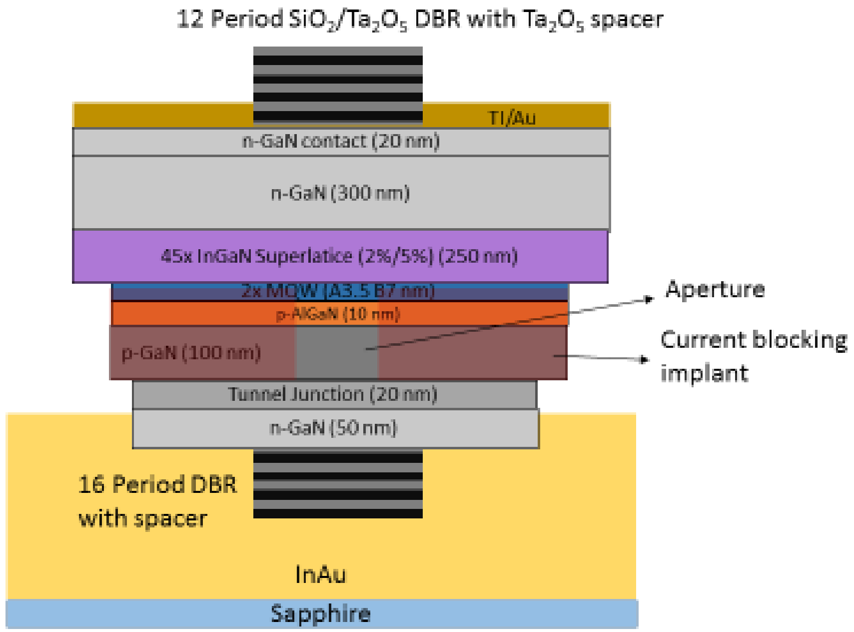
5 λ cavity
12 µm dia.
Pulsed 1ms @ 2.5% dc



- Tunnel junction intracavity current spreader
- 12 µm ion-implanted aperture, single transverse mode
- Poor bond-> limited to 50% duty cycle

Kearns, et al., Optics Express 27, 23707 (2019)

445 nm Semipolar TJ VCSEL with Ion-Implanted Aperture



Calculated VCSEL Parameters

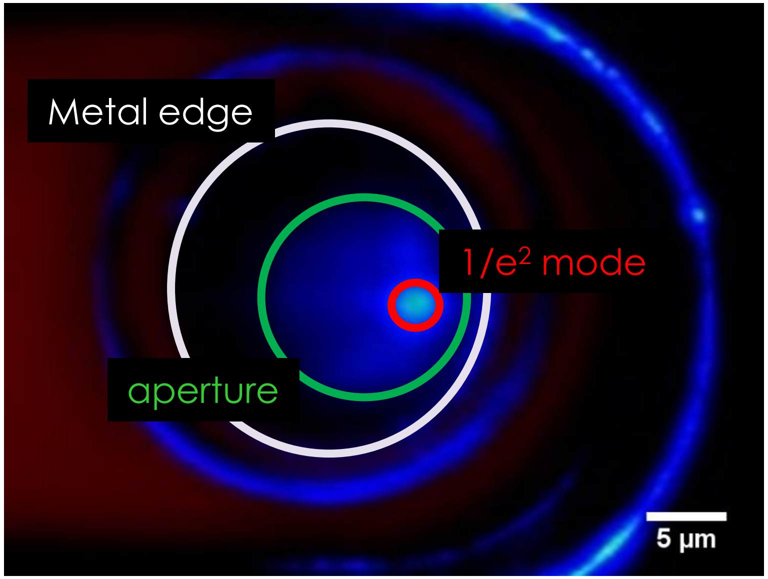
Internal Loss: $\alpha_i = 13\ cm^{-1}$
Mirror Loss: $\alpha_m = 3\ cm^{-1}$
Scattering Loss: $\alpha_s = 5\ cm^{-1}$
Injection Efficiency: $\eta_i = 0.68$
Topside Emission: $F_1 = 0.5$
Excess Loss: $\boldsymbol{\alpha_e = 7\ cm^{-1}}$

- Tunnel junction intracavity current spreader
- 12 μm ion-implanted aperture, single transverse mode
- Poor bond-> limited to 50% duty cycle

Kearns, et al., Optics Express 27, 23707 (2019)

Loss Analysis

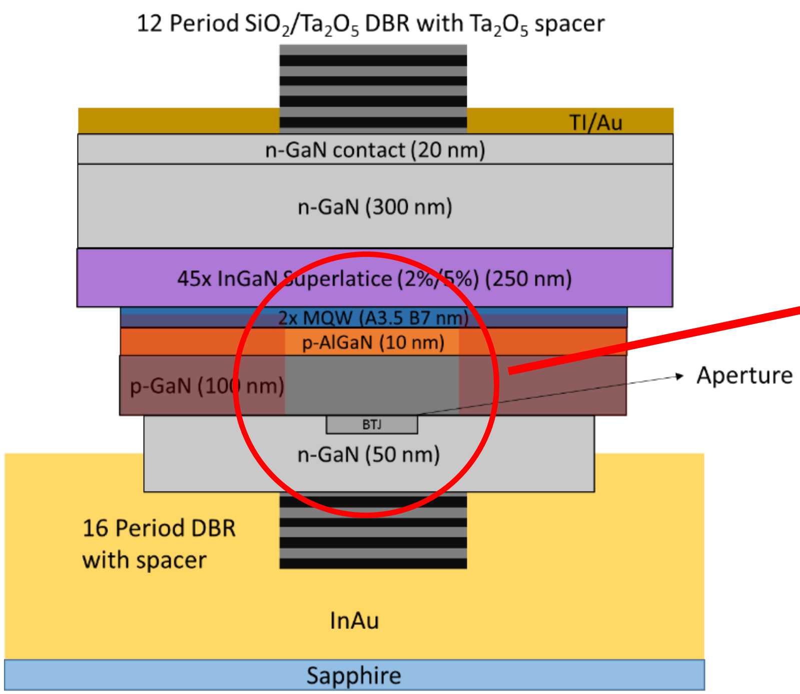
- Implant Overlap
  - Al ion implantation at 10^{14} cm^{-2}
  - Absorption: 1400 cm^{-1}
  - Contribution: 1 cm^{-1} (0.6-2 cm^{-1})
- Metal Overlap
  - Ti/Au (20/500 nm)
  - Effective Penetration: 100 nm
  - 〈 $_{Ti}$=8.6 × 10^5 cm^{-1}
  - 〈 $_{Au}$=5.4 × 10^5 cm^{-1}
  - Contribution: 6 cm^{-1} (3-12 cm^{-1})

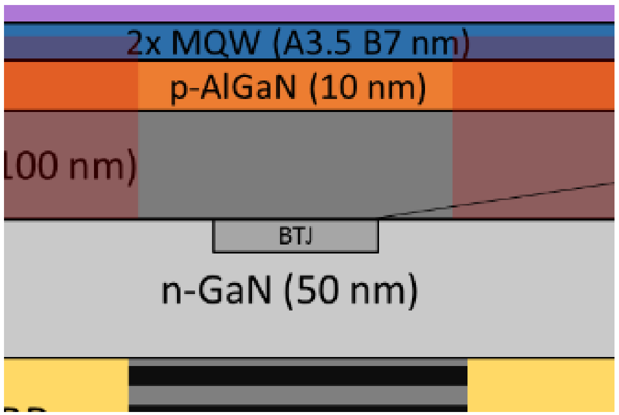


Off-centered optical mode can account for the observed excess loss

Kearns, et al., Optics Express 27, 23707 (2019)

450 nm Semipolar Buried TJ VCSELs

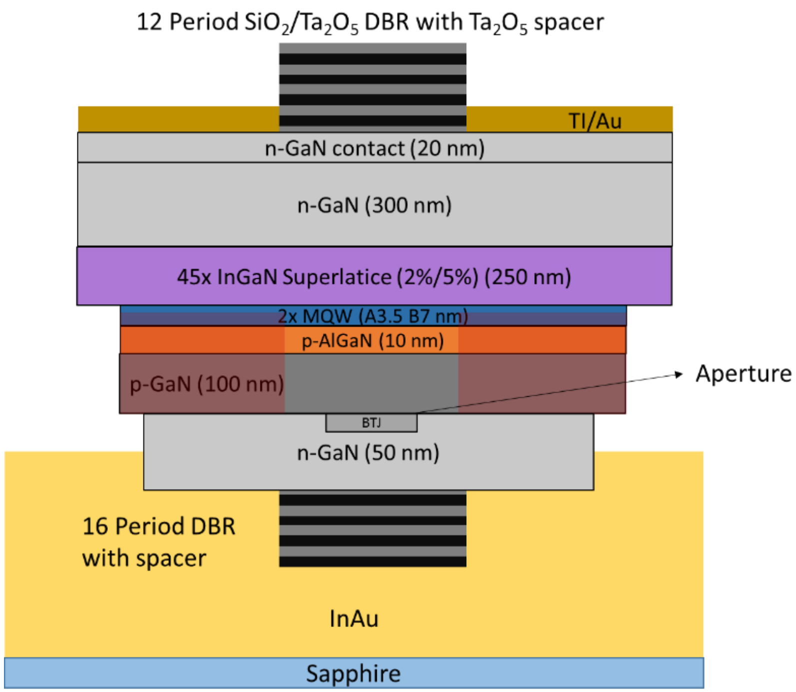


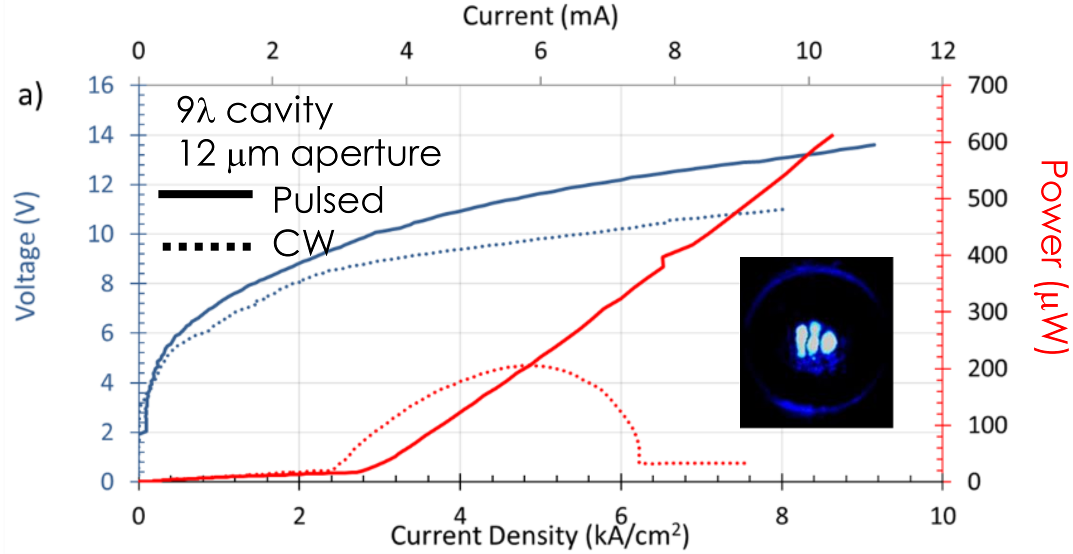


- Buried tunnel junction design avoids implant loss
- Provides optical and current confinement

Kearns et al., PSS-a, in review (2019)

Buried TJ VCSEL

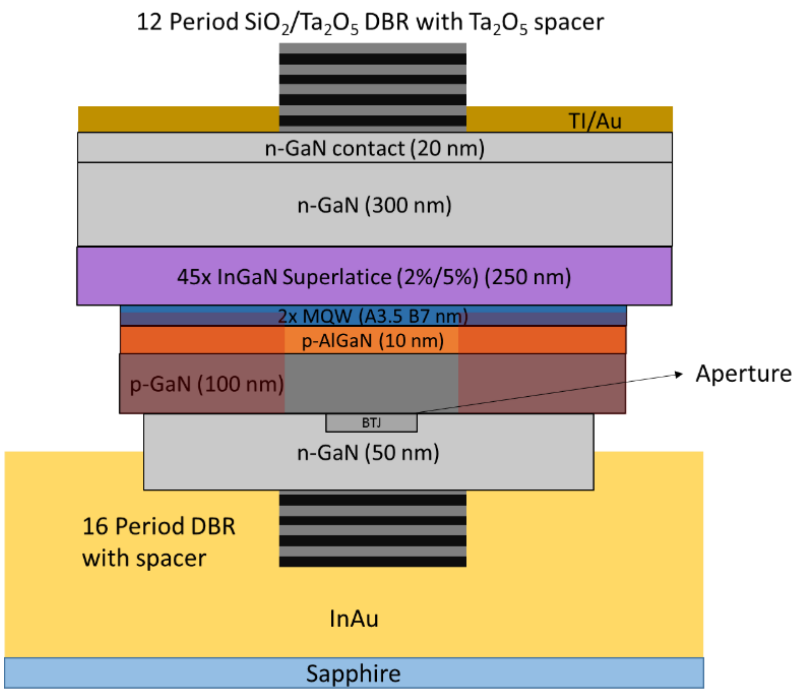




- Buried tunnel junction current and optical aperture
- Implant distant from active region for reduced loss

Kearns et al., PSS-a, in review (2019)

Buried TJ VCSEL



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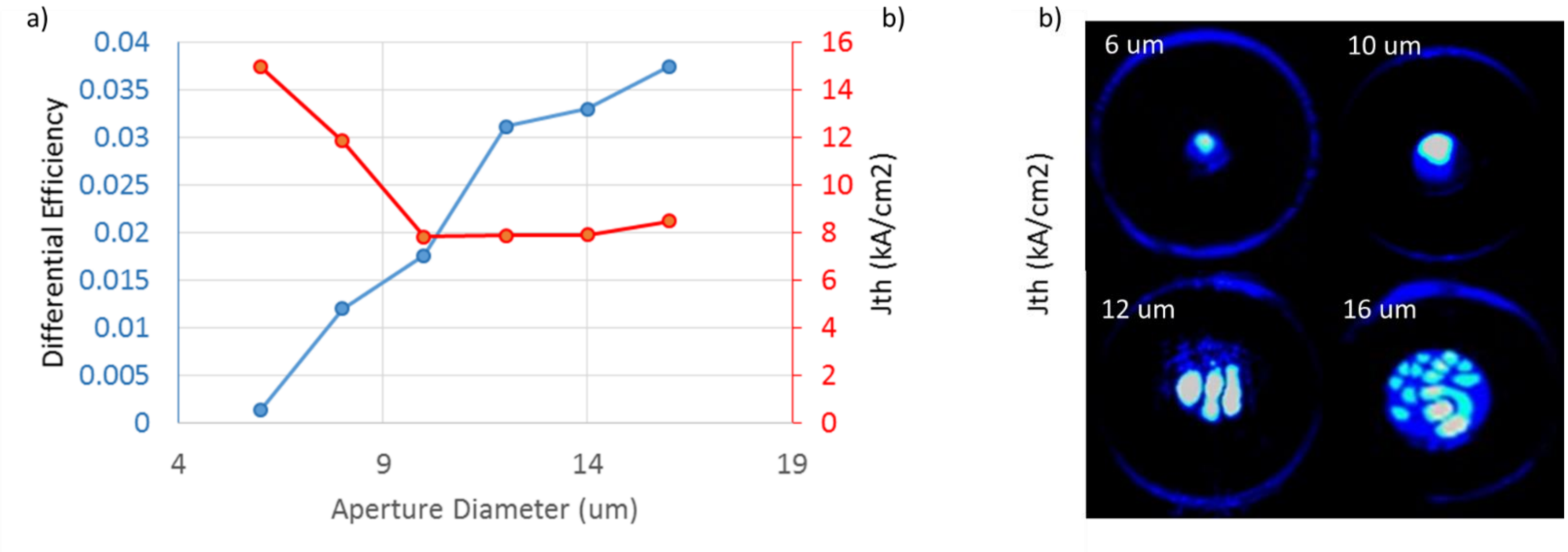
Scattering Loss:	$\langle_s = 8\ cm^{-1}$
Injection Efficiency:	$|_i = 0.68$
Topside Emission:	$F_1 = 0.5$
Excess Loss:	$\boldsymbol{\langle_e \approx 0\ cm^{-1}}$

- Buried tunnel junction current and optical aperture
- Implant distant from active region for reduced loss

Kearns et al., PSS-a, in review (2019)

BTJ VCSEL Aperture Dependence

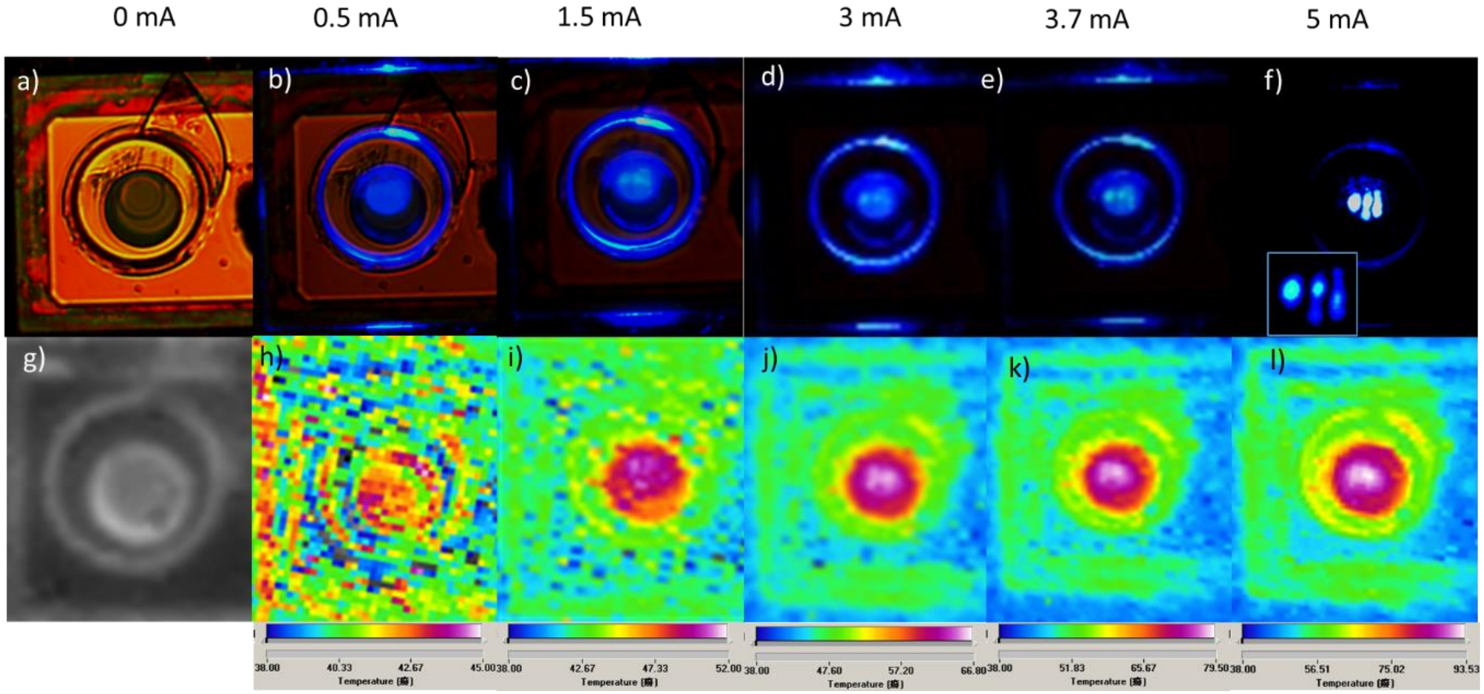


- $1/e^2$ lasing area used in J_{th} calculation: all spots apparently pumped the same
- No quantitative explanation for increase in differential efficiency
- Filamentary modes not centered in aperture

Kearns et al., PSS-a, in review (2019)

Nonuniform Current Injection

Semipolar BTJ VCSEL



- Correlation Between Thermal Map and Laser Emission

Future Work

- Manufacturability
  - Tighten processes
    - PEC (substrate removal without roughness)
    - Bonding (voltage)
    - BTJ activation (voltage)
- R&D
  - Determine root cause of filamentation
    - Address intrinsic epi-driven (or contact-driven) inefficiency
  - Heat management – longer cavity
  - Hybrid approach between best-in-class designs?

Thank You

This presentation was presented at EPIC Meeting on VCSELs Technology and Applications 2019

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