

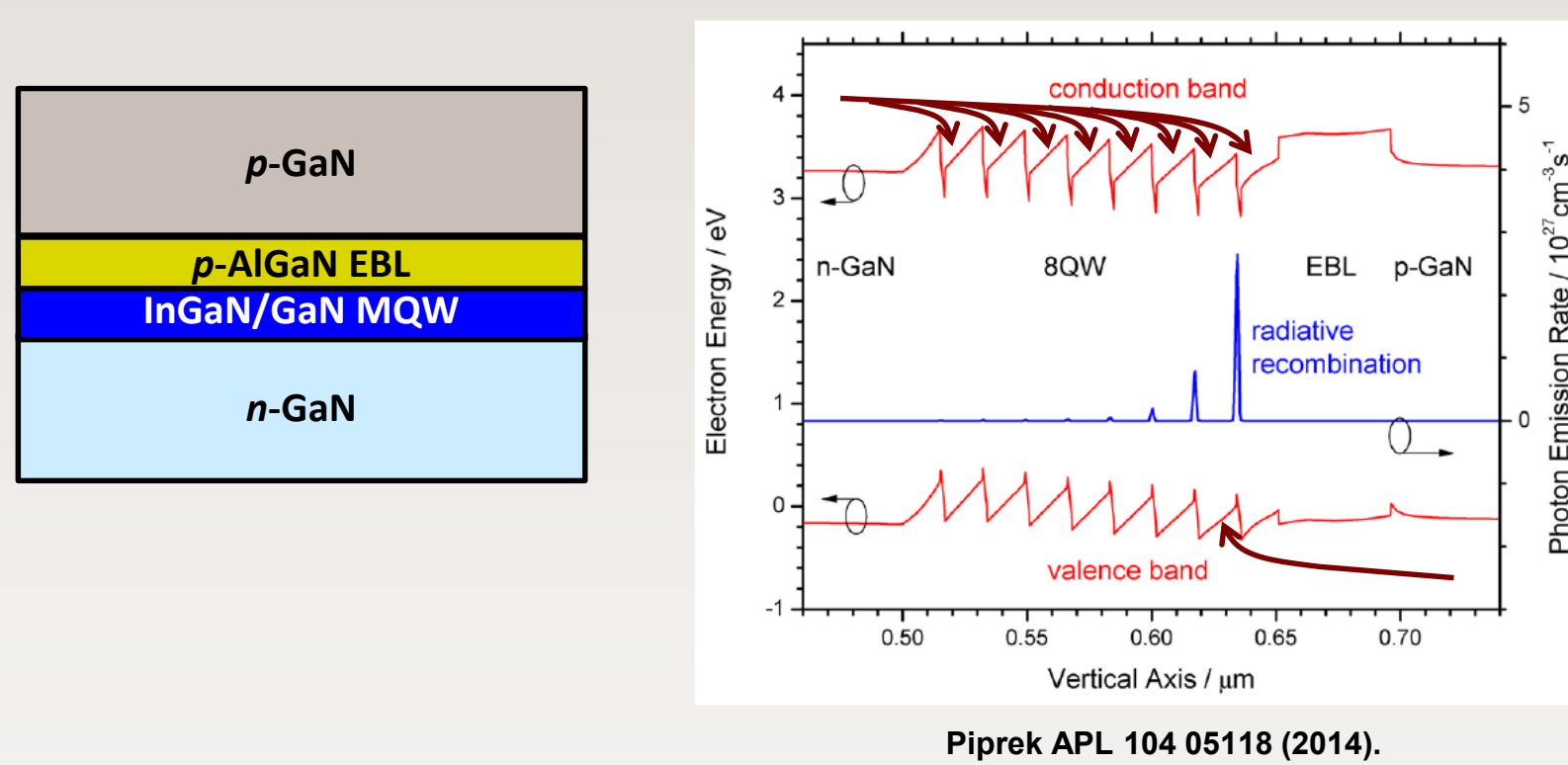
Tunneling-Enabled High-Efficiency High-Power Multi Junction LEDs

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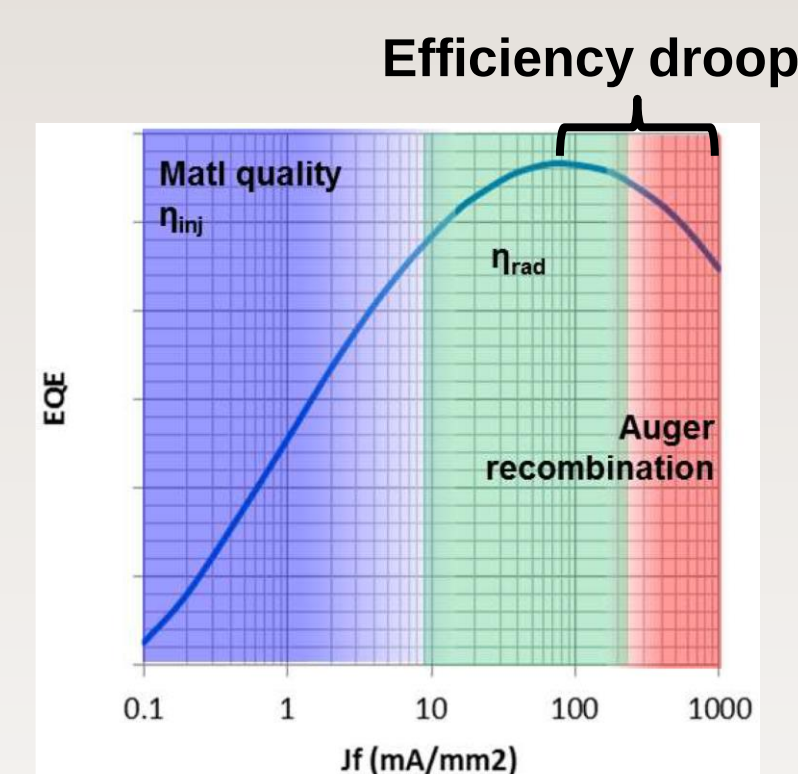
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LEDs suffer efficiency droop at high current density

Standard “1x8” LED



Current droop

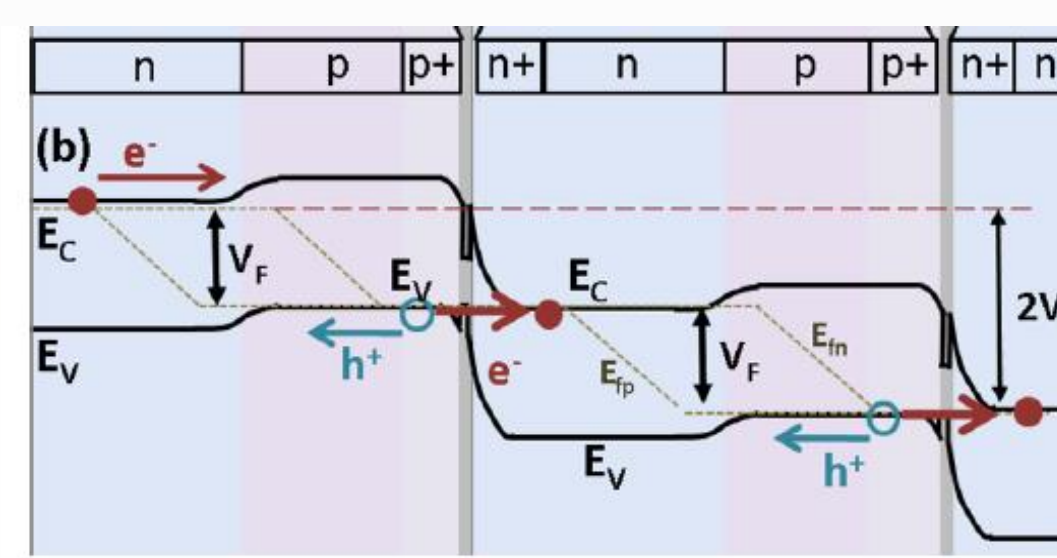
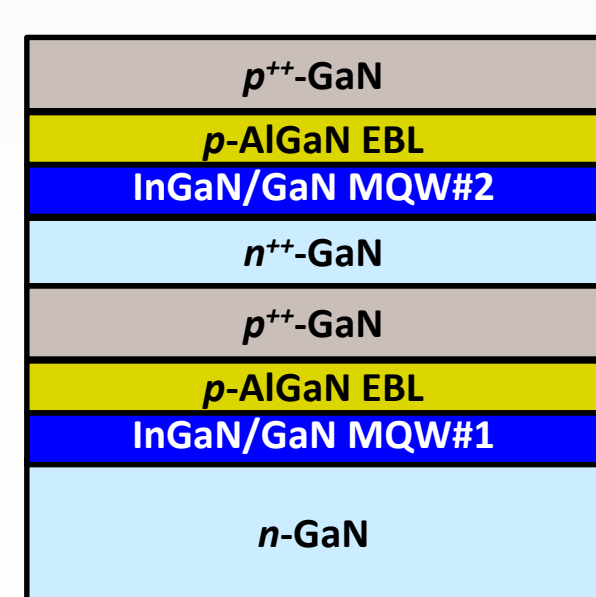


Auger recombination causes current droop in InGaIn LEDs

- Hole “pile up” at p-side QW causes high carrier density and Auger recombination
- Improve hole distribution to mitigate current droop

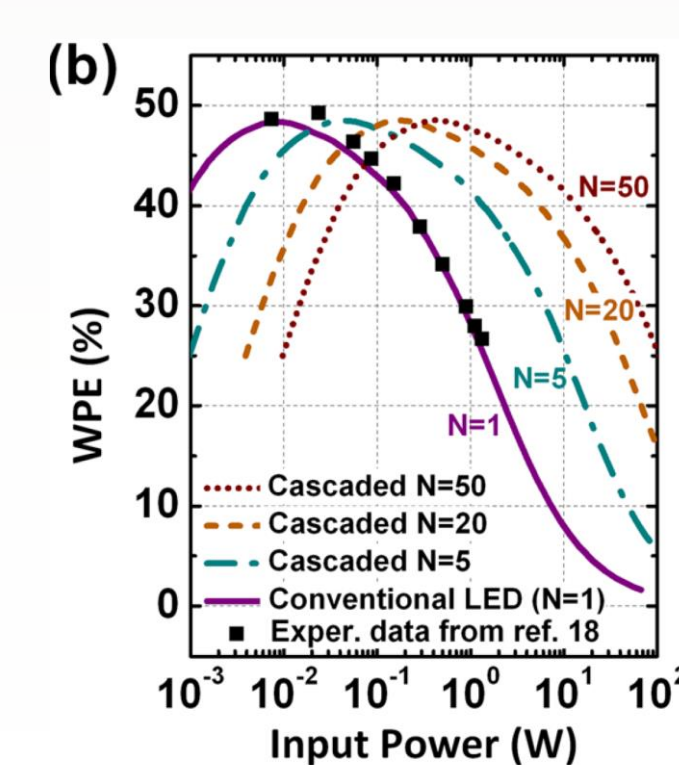
Mitigate current droop using multi-junction LEDs

TJ-enabled MJ-LED



Akyol et al., APL 103 081107 (2013).

Reduced current droop



Akyol et al., APL 103 081107 (2013).

Stacking MQWs reduces current density needed for high output power

- Tunnel junctions (TJs) act as a distributed hole injector
- Mitigates current droop by improving light output at same current density

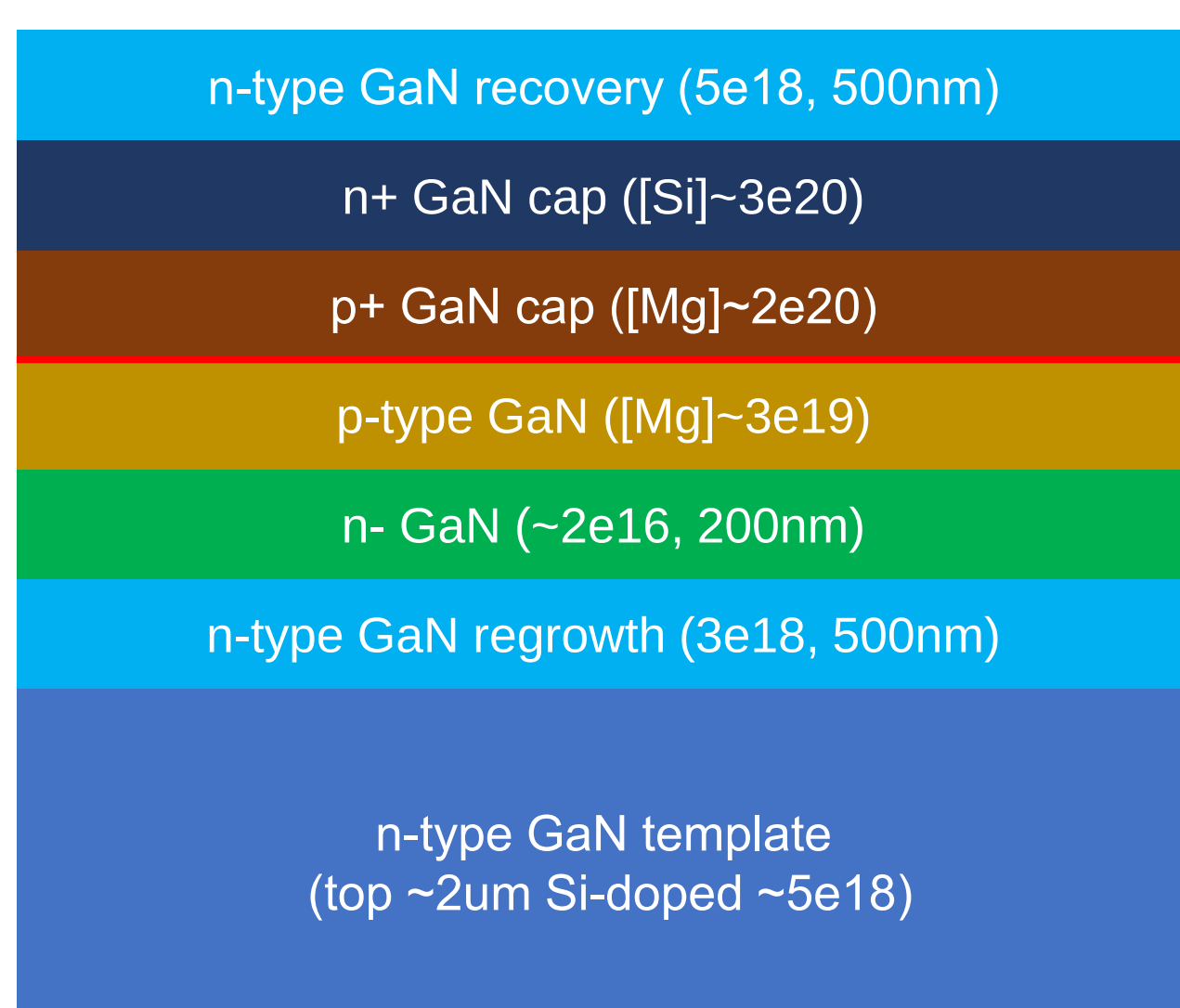
Technical approach

All-MOCVD MJ-LED

- All-MOCVD solution is optimum techno-economic solution
- Enables rapid adoption by LED industry
- High reward but also high risk due to immature MOCVD TJ technology

Successful activation of buried p-GaN:Mg layers

TJ device structure



Electroluminescence of TJ device

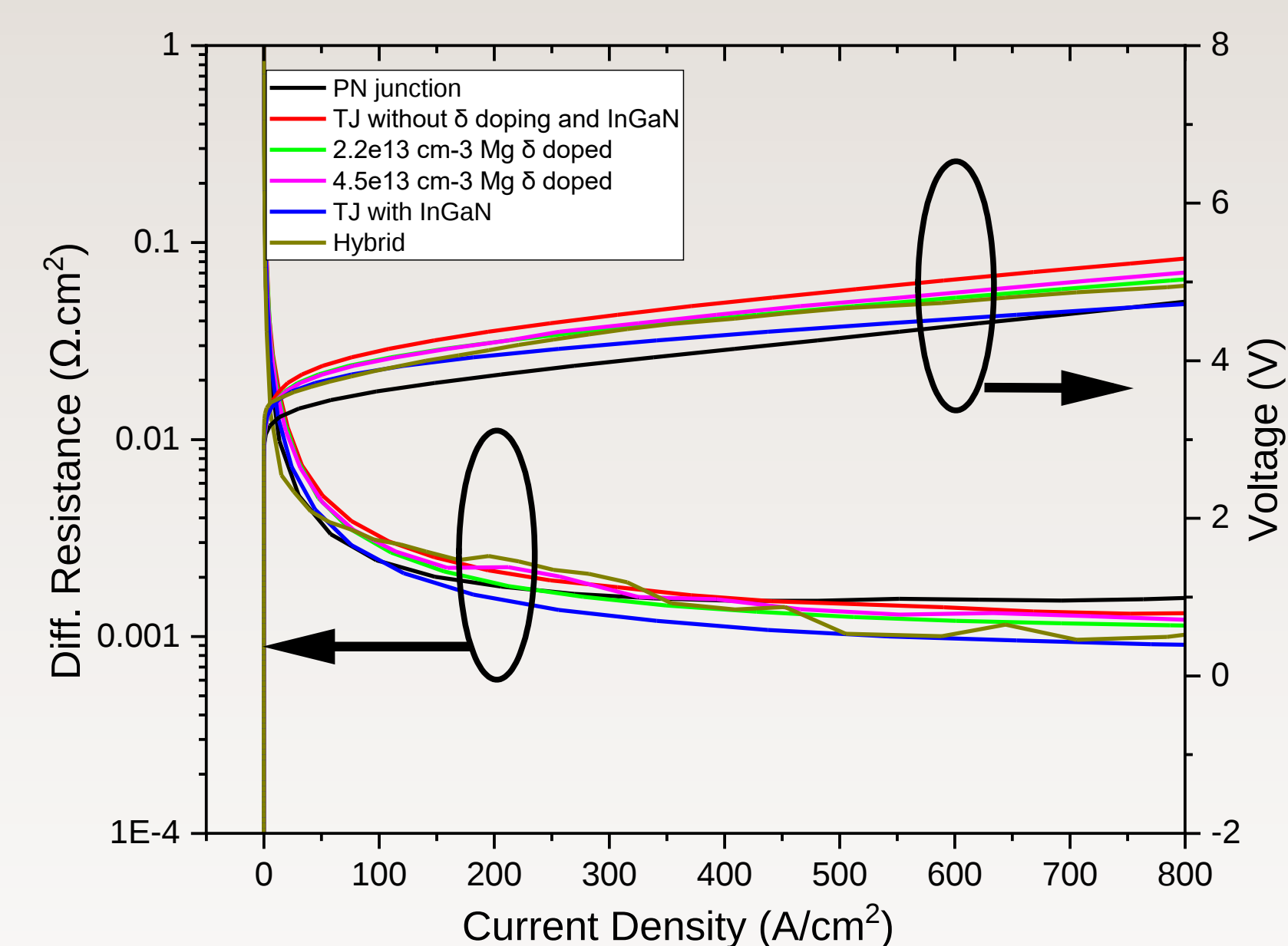
1.0 A/cm² 2.5 A/cm² 5.0 A/cm² 10.0 A/cm²



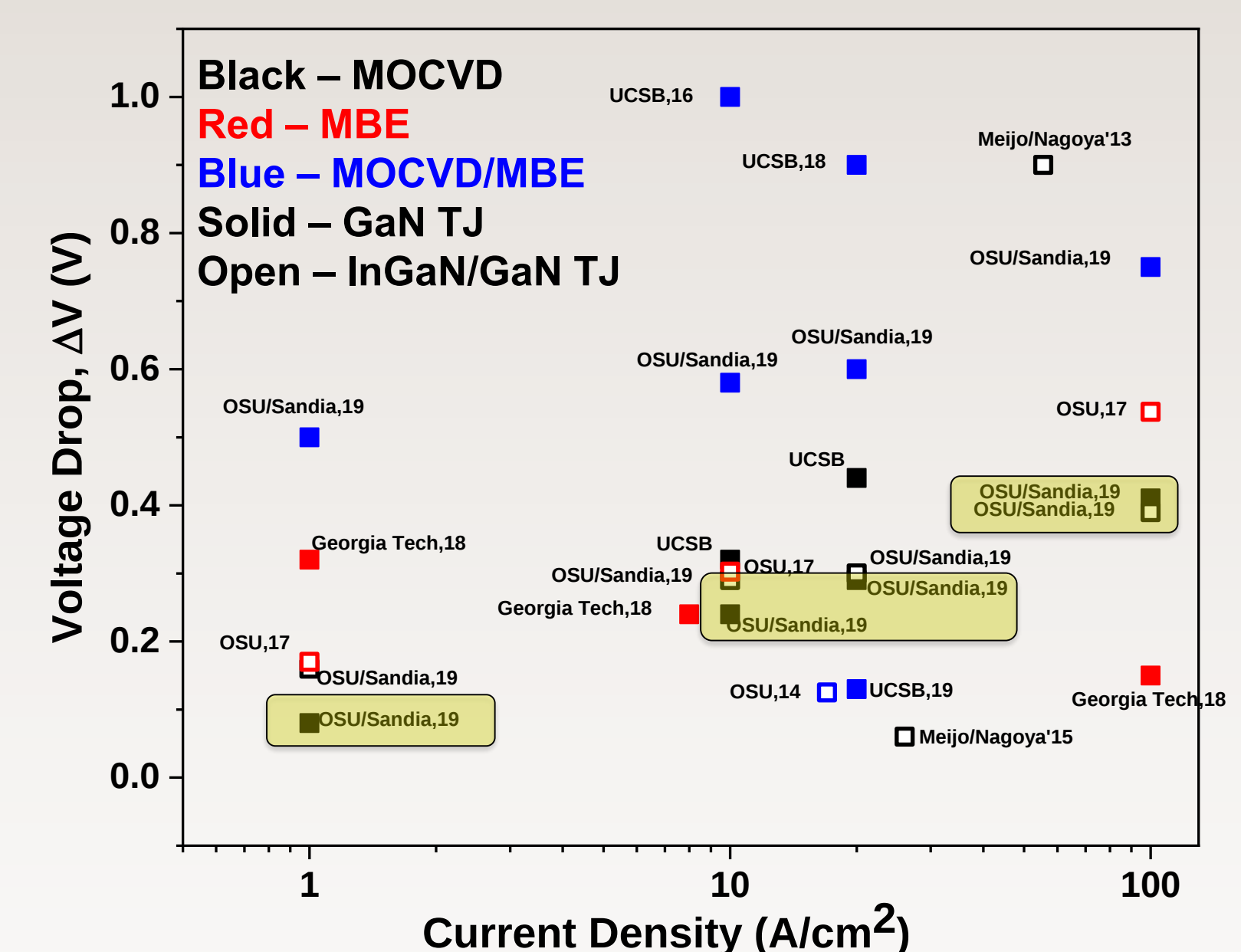
- Standard rapid thermal anneal conditions (900 °C, 30 min) activates buried p-GaN
- Lateral H diffusion to sidewall effective for 105 μm mesas

Achieved low resistivity MOCVD TJs

MOCVD TJ I-V and differential resistivity



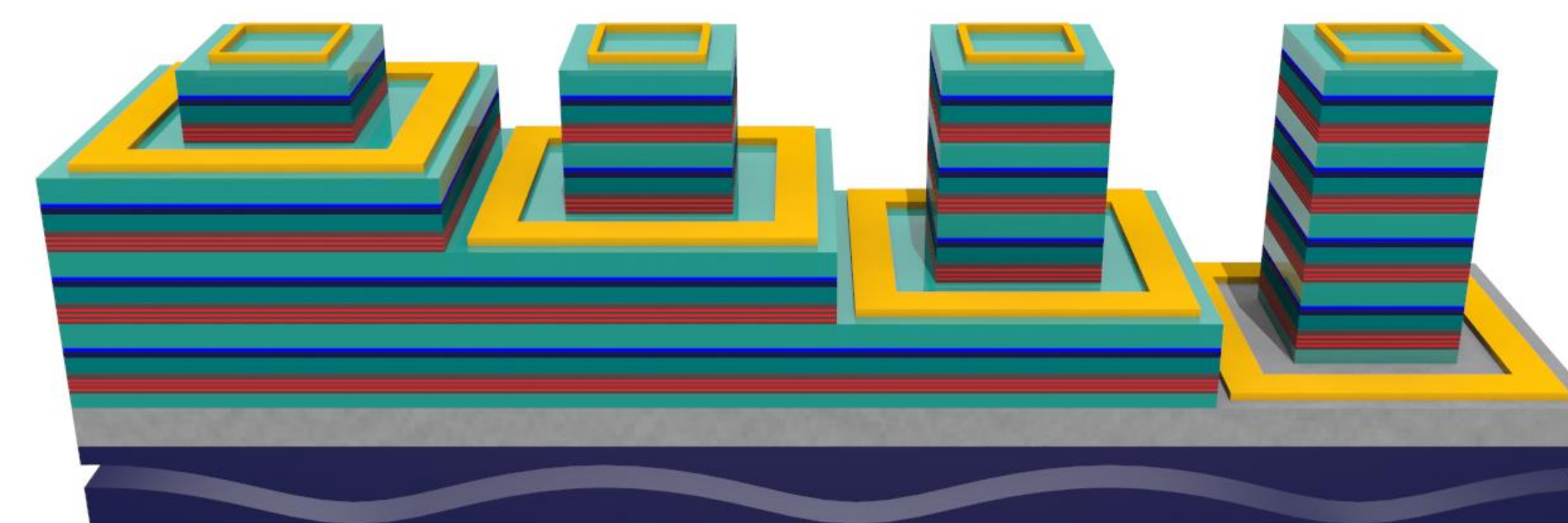
Comparison to previous results



- Various designs achieved $\rho < 2 \text{ m}\Omega\cdot\text{cm}^2$ at low current density relevant to LEDs
- Voltage penalty of TJ relative to standard p-n junction among the lowest reported for all-MOCVD device

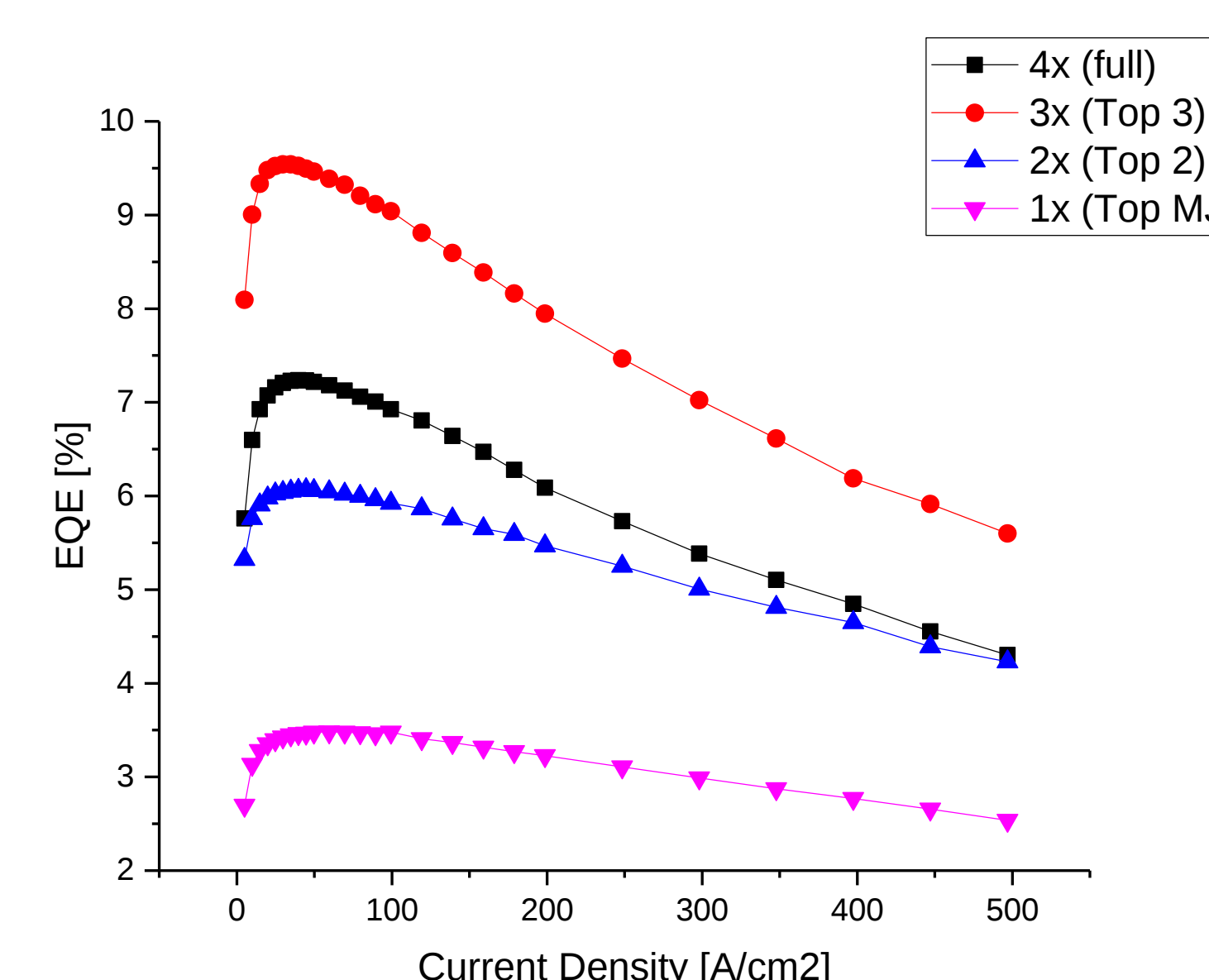
TJ-enabled multi-junction LEDs

Multi-junction LED processing to test 1x, 2x, 3x, 4x devices individually

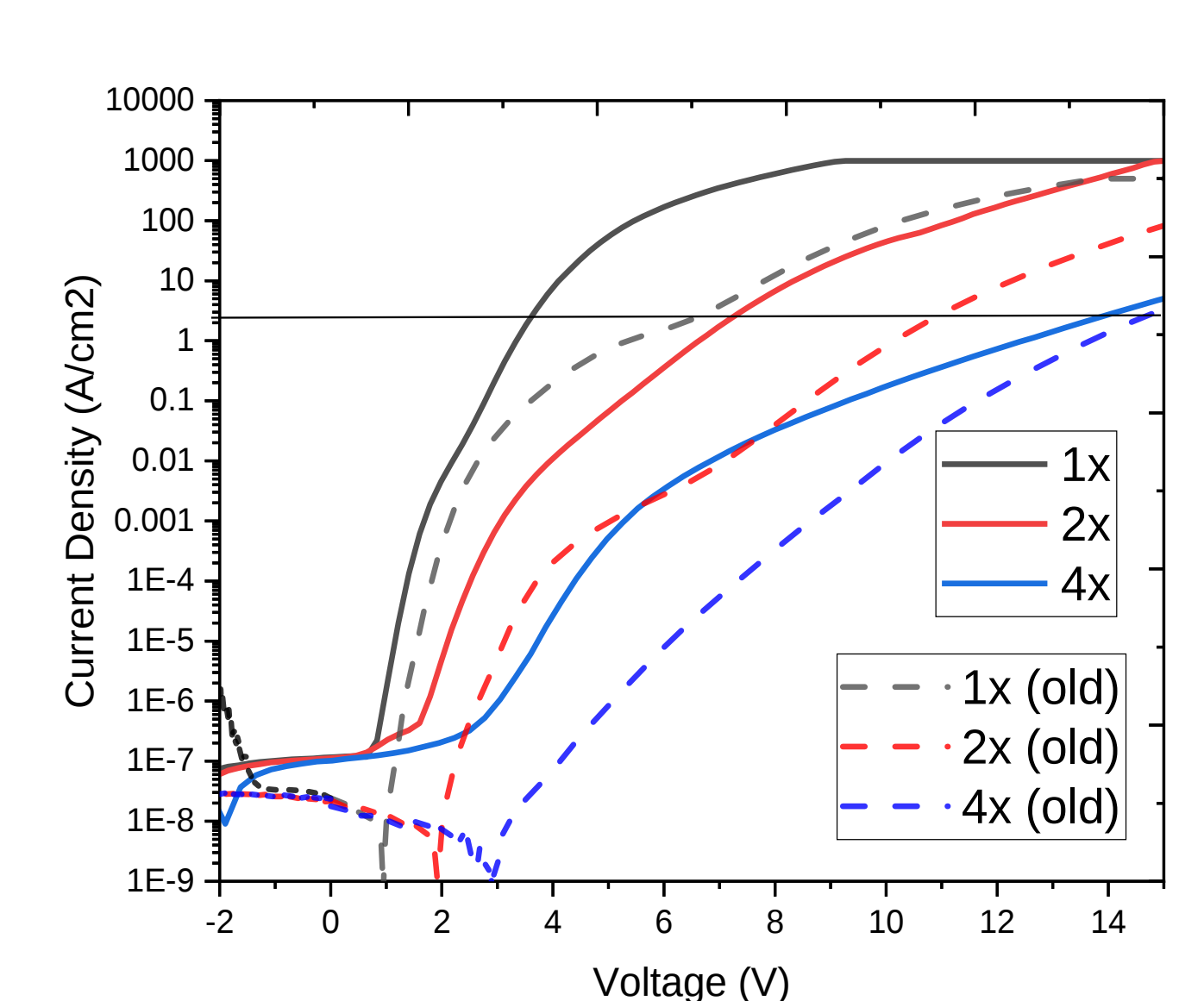


Device stack	Voltage drop at 2.5 A/cm ² (new condition)	Voltage drop at 2.5 A/cm ² (Old condition)
1x	3.6	6.6
2x	7.2	10.9
4x	13.9	14.6

On-wafer multi-junction EQE (old activation condition)



Improved multi-junction LED turn-on voltage with new activation condition



- Multi-junction LEDs show linear EQE scaling for up to 3x junctions
- Absolute EQE low due to on-wafer testing w/o light extraction techniques
- Greatly reduced turn-on voltage using new activation conditions

Summary and Next Steps

- Achieved sufficiently low ρ TJs for a 3x MJ-LED
- All-MOCVD GaN ρ_{TJ} among lowest reported
- Demonstrated linear EQE and turn-on voltage scaling in multi-junction LEDs