Investigation of the Impact of Polarization and Auger Recombination on the Wurtzite and Zincblende GaN-Based Green LEDs

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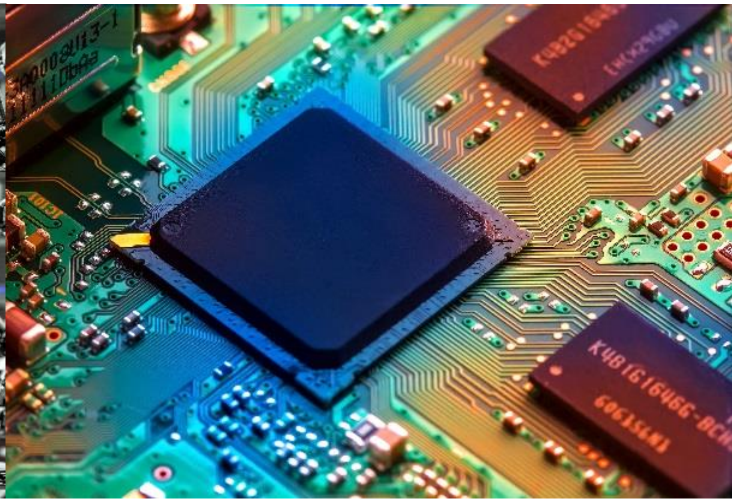
YES WE GaN



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Motivations

1. **Why we need efficient green LEDs?**
   – To generate natural white light via color mixing
   – To make semiconductor green lasers
   – To save power

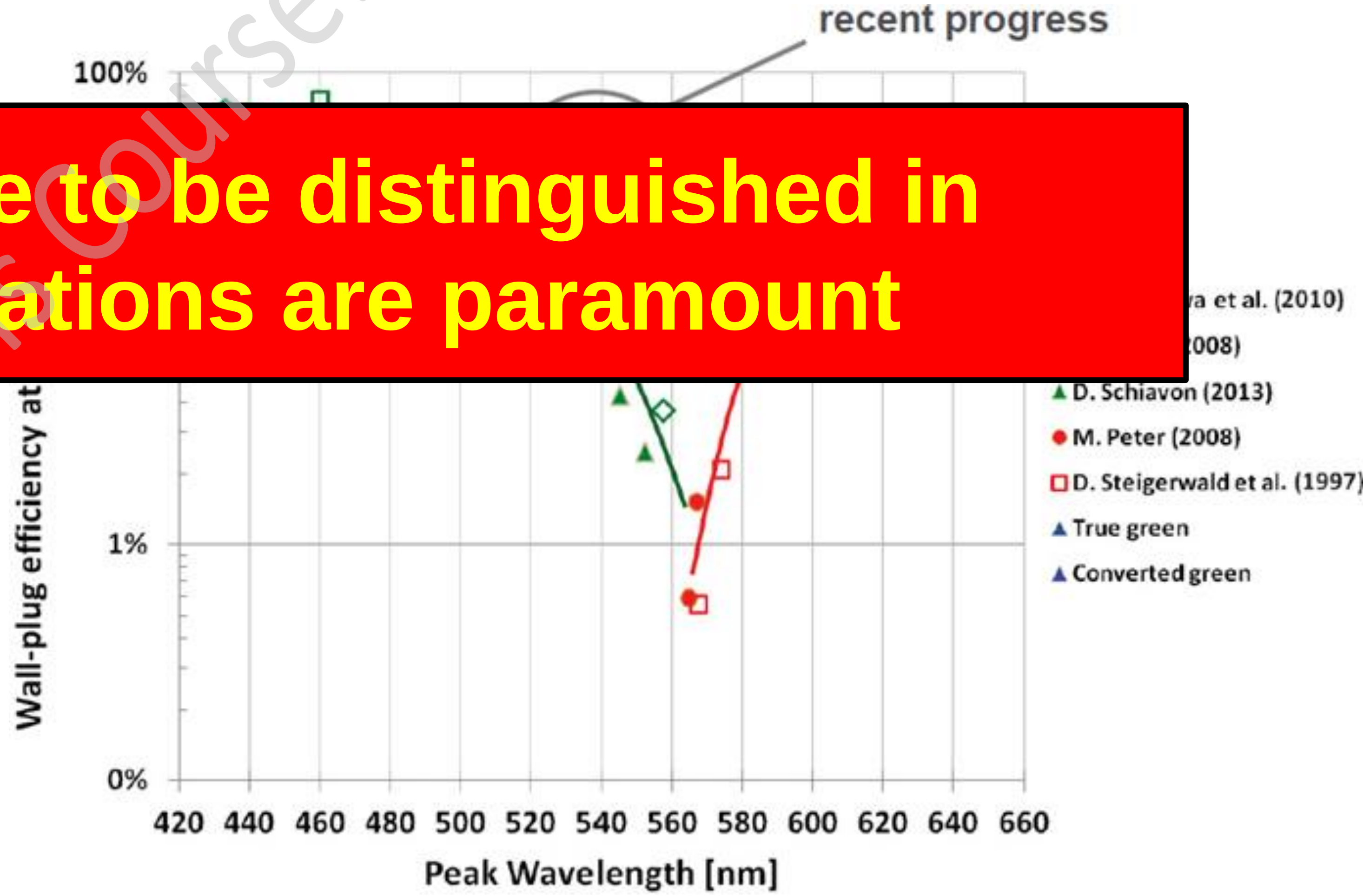
2. **Green gap**
   – Phosphor-coated blue LED → Down-conversion → Energy loss
   – Phosphide-based materials → Indirect bandgap → Low rad. rate
   – Nitride-based green LEDs → Several factors might involve

Issues of nitride-based green LEDs

- **Possible mechanisms**
  - Shockley-Read-Hall recombination
  - Auger recombination

Prohibitively impossible to be distinguished in experiments → Simulations are paramount

  - Electron leakage
- **Solution: Zincblende GaN**
  - Zero polarization
  - Smaller Auger coefficient



Quantum-Corrected DD Model

1. Poisson Equation: $\nabla \cdot \left(\varepsilon_0 \nabla \phi + \vec{P}\right) = -q\left(p - n + N_D - N_A + n_p\right),$

2. Schrödinger Equation:

$$-\frac{\hbar^2}{2m^*}\nabla^2 \psi_i + e\phi\psi_i = E_i \psi_i \qquad n = 2\sum_i f\left(E_i - E_F\right)\left|\psi_i\right|^2$$

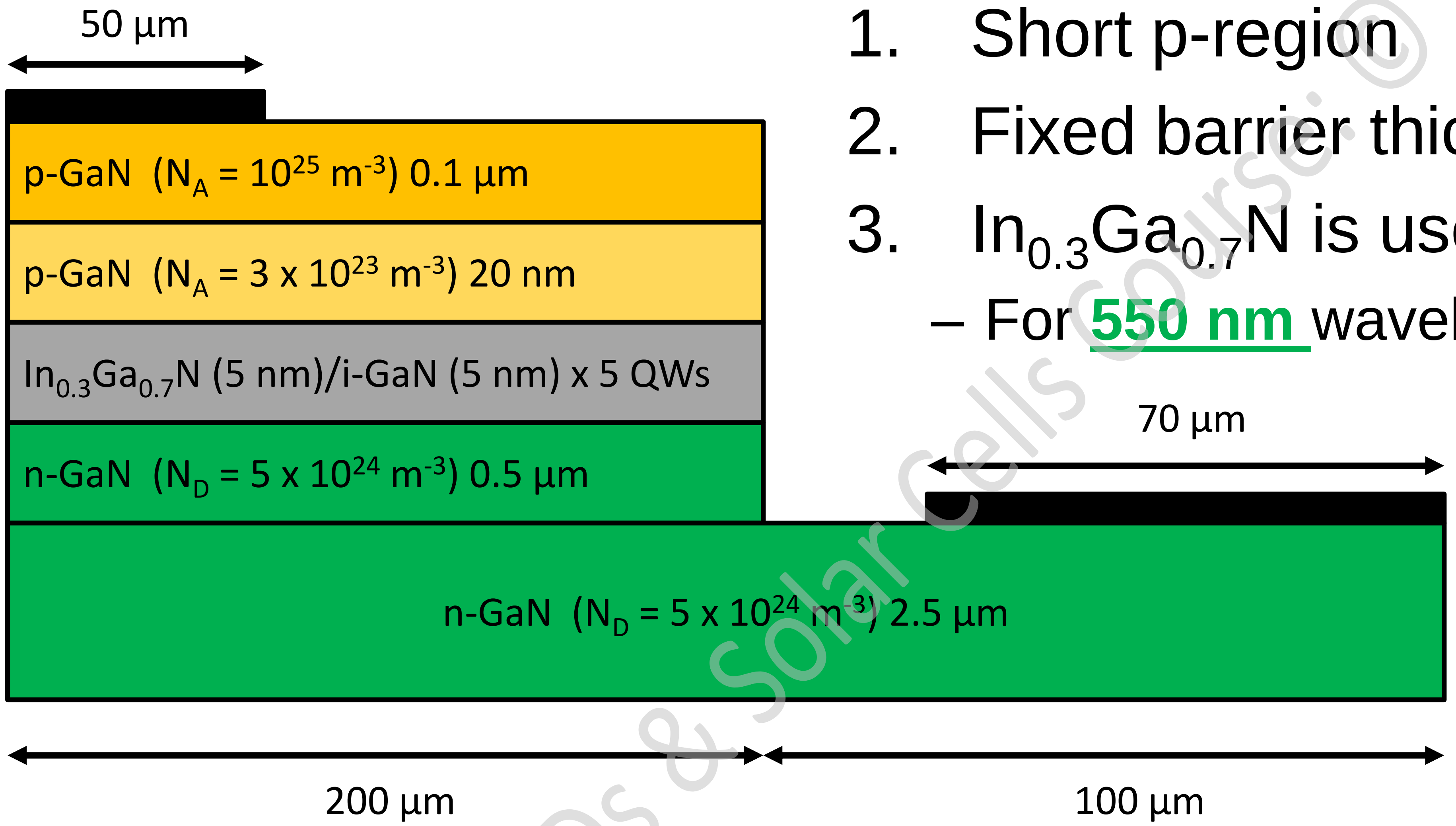
3. Drift-Diffusion Equations:

$$\vec{J}_n = q\mu_n n\vec{E} + qkT\mu_n \nabla n,$$
$$\vec{J}_p = q\mu_p p\vec{E} - qkT\mu_p \nabla p,$$

4. Current Continuity Equations:

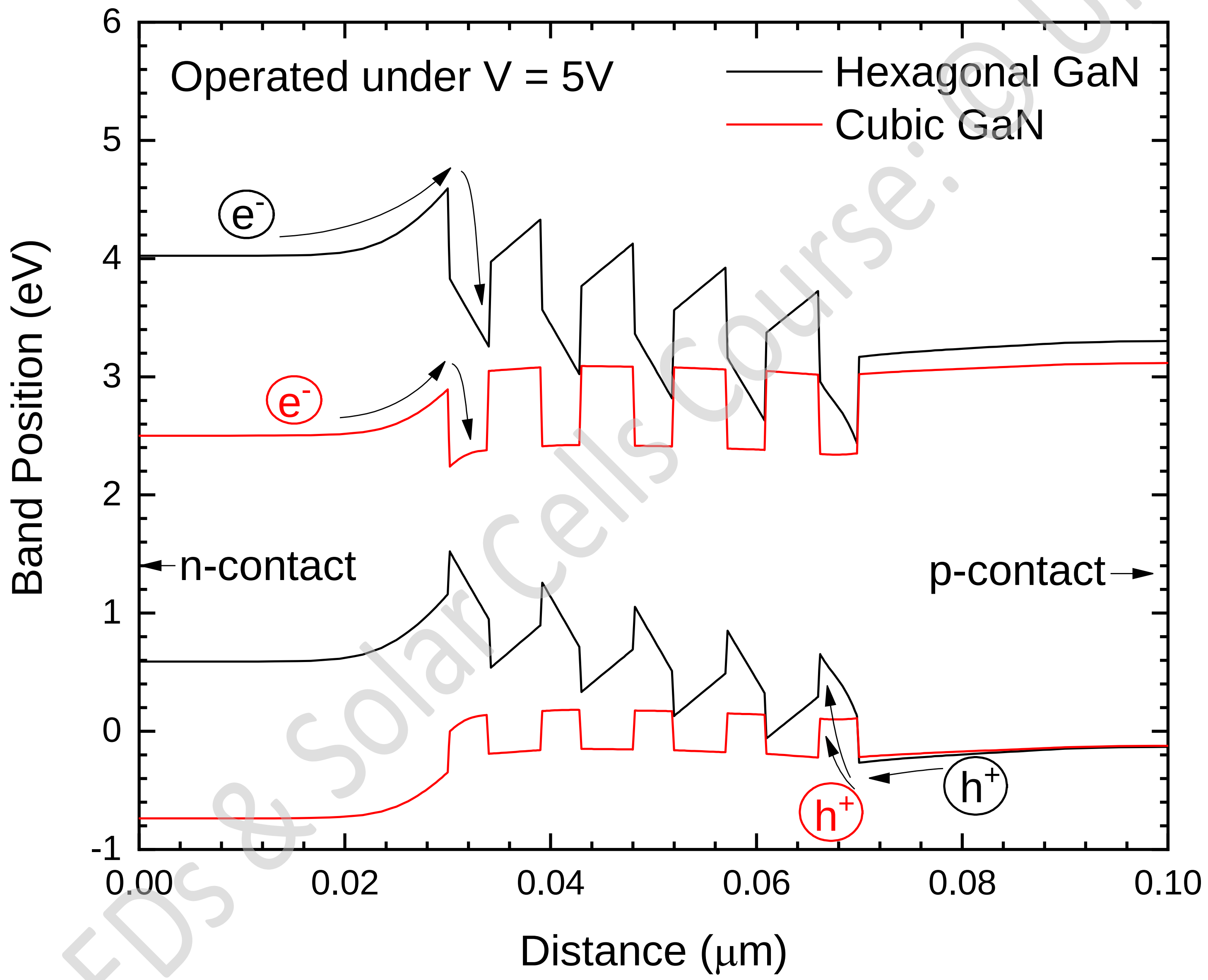
$$\frac{1}{q}\nabla \cdot \vec{J}_n = R^n{}_{SRH} + R_{Rad} + R_{Auger},$$
$$-\frac{1}{q}\nabla \cdot \vec{J}_p = R^p{}_{SRH} + R_{Rad} + R_{Auger}.$$

Device Structure – 5QWs



1. Short p-region
2. Fixed barrier thickness: 5 nm
3. $In_{0.3}Ga_{0.7}N$ is used for QWs
   – For **550 nm** wavelength

Exemplification of Band Diagrams

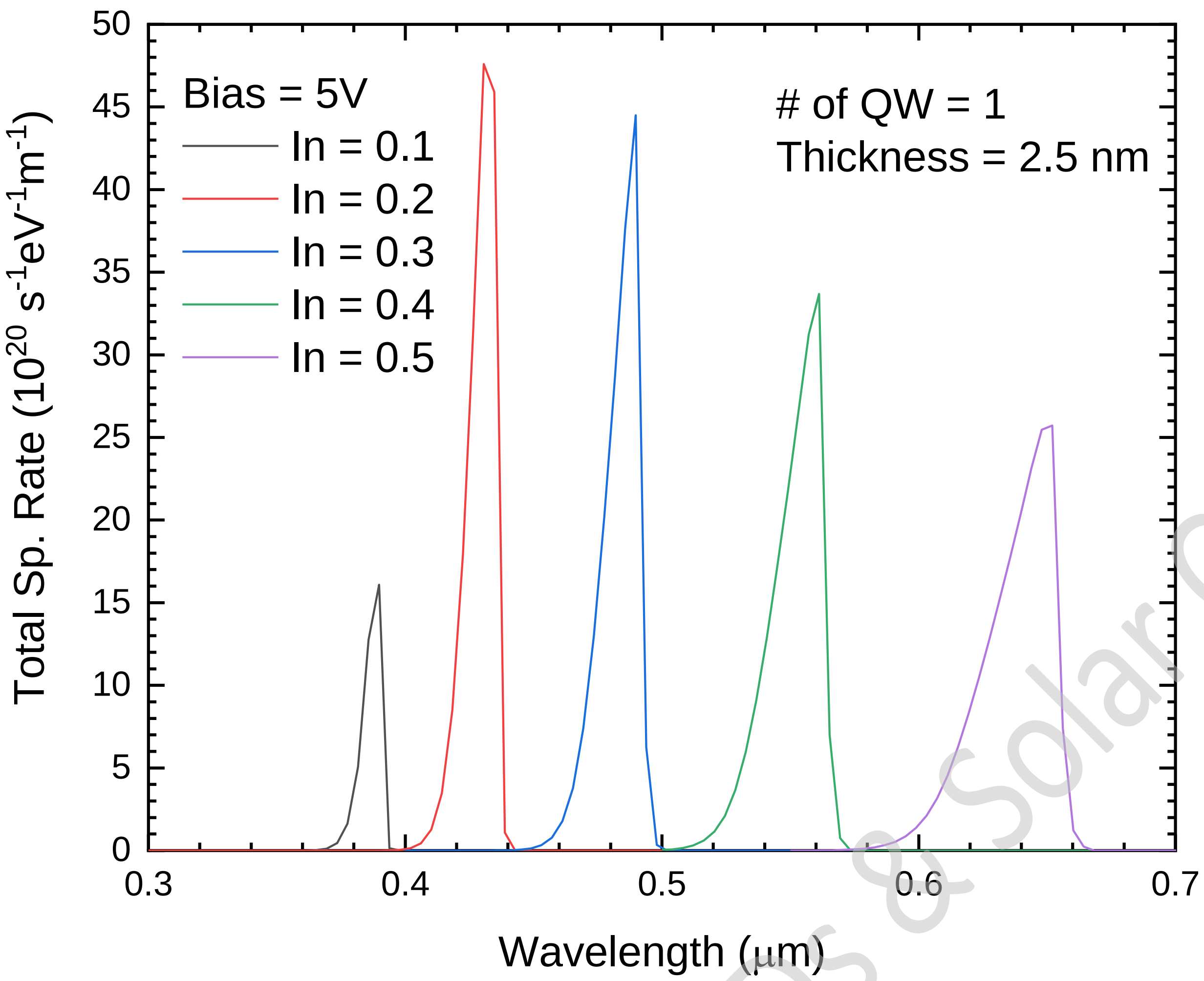


Green Gap Analysis

Identify the major mechanisms

- ❑ **Single QW**
- ❑ **Thickness: 2.5 nm**
- ❑ **Varying In mole fraction**

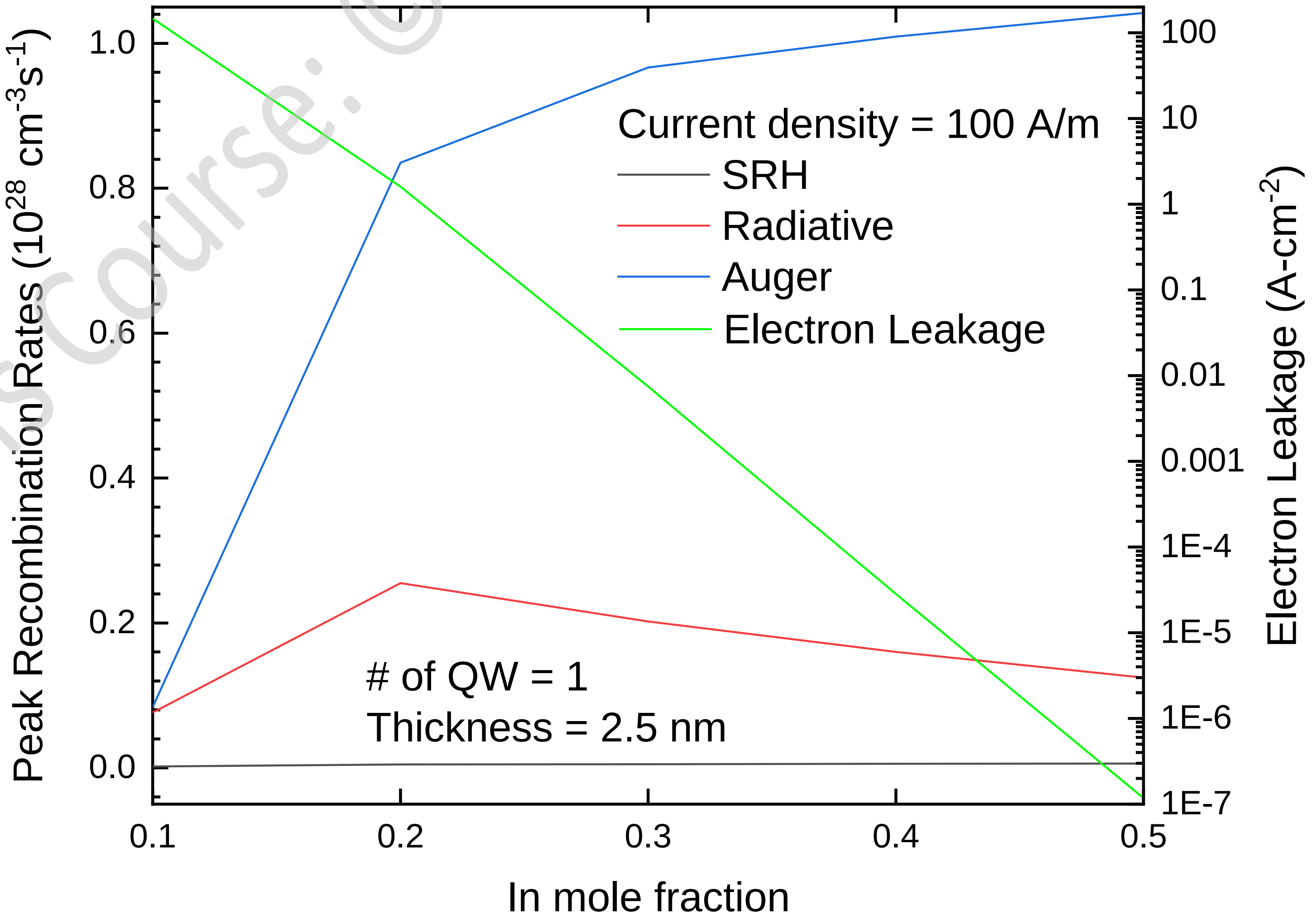
Spontaneous Emission



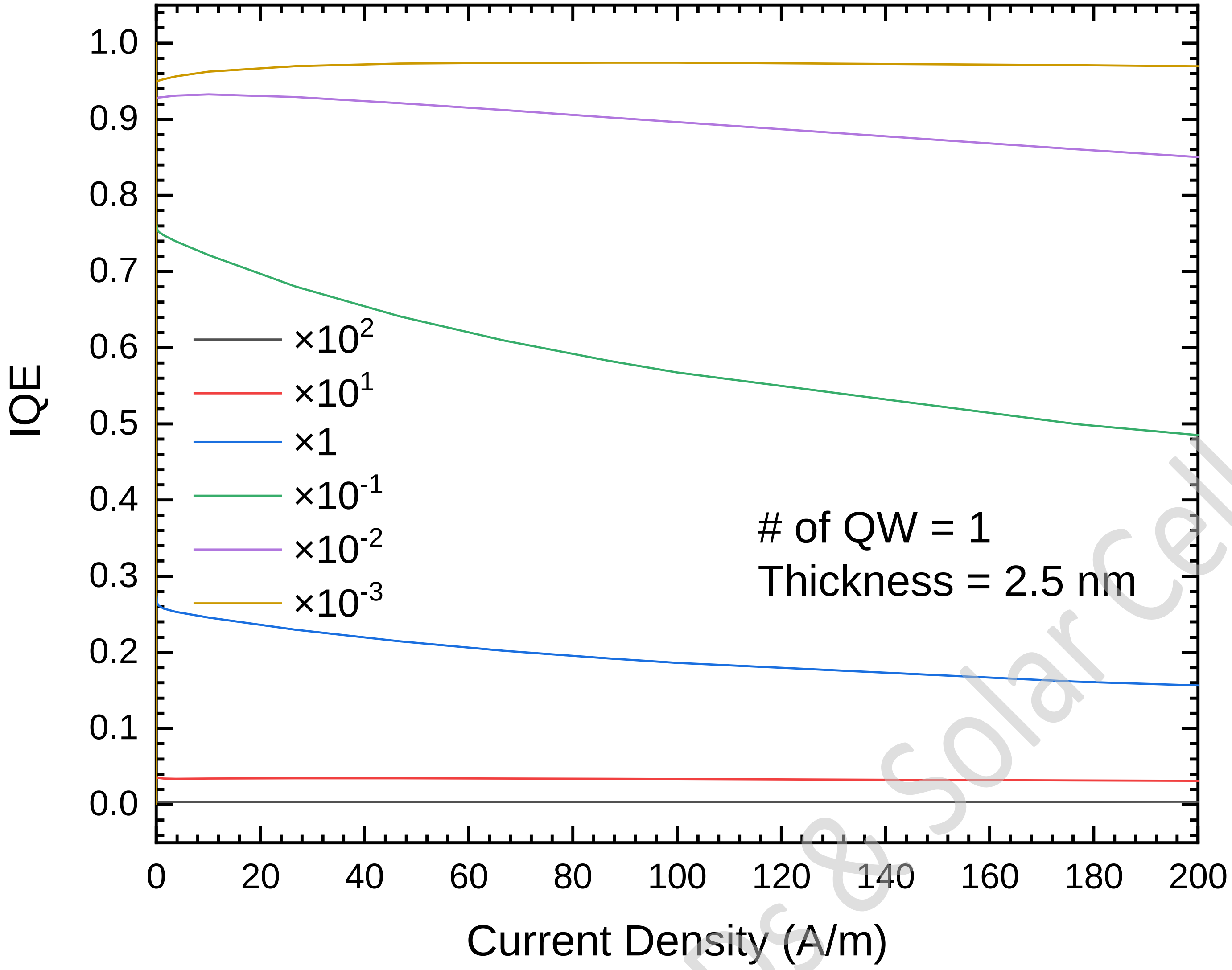
- The increase of In mole fraction
  - – Deeper QW
  - – Increases wavelength emission
  - – Decreases spontaneous emission rate
  - – Why?

Recombination Processes and Leakage

- ❑ In mole fraction = 0.1
  - – Shallow QW
  - – Strong electron leakage
- ❑ In mole fraction > 0.2
  - – Higher electron density
    - • Auger recomb. increases
  - – Stronger QCSE
    - • Radiative recomb. drops



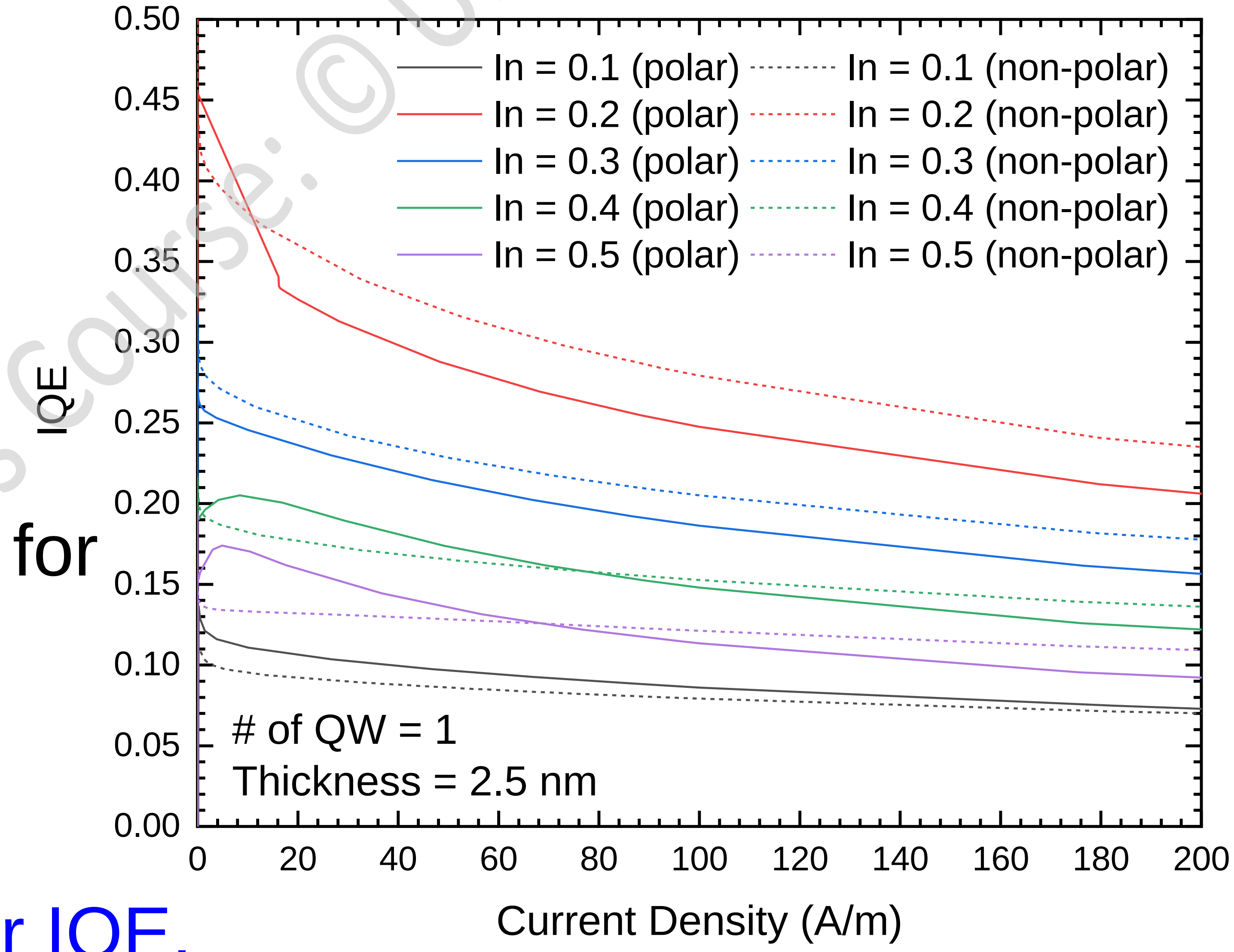
Impact of Auger Coefficient



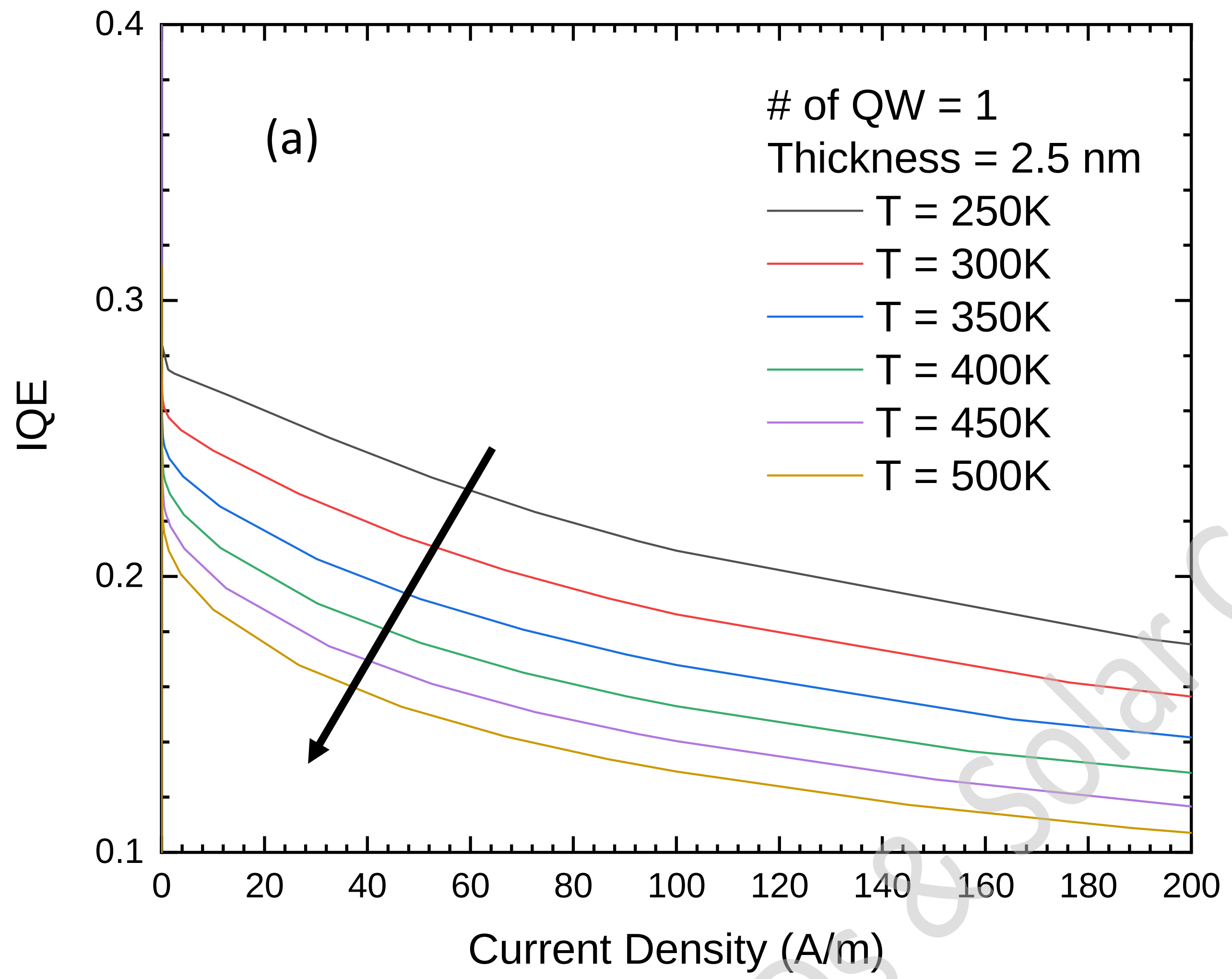
- Default: 2.96×10^{-30} cm^{-6}s^{-1}
- Reduced by an order
  - – Double IQE
  - – Gain an extra 40% efficiency
- Reduced by more than two orders
  - – Droop-free performance
- Material engineering is necessary.

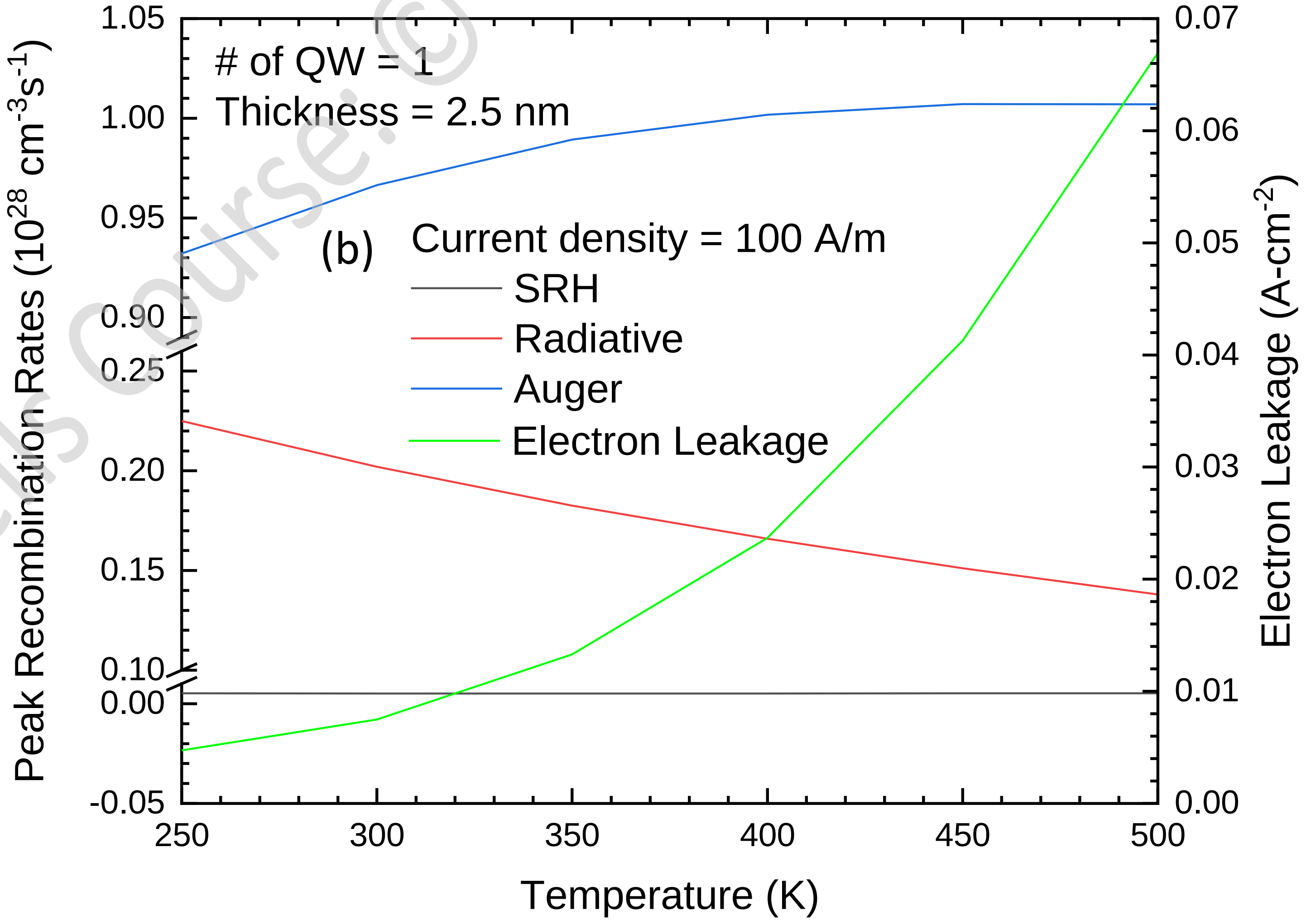
Impact of Polarization

- Low carrier injection
  - Triangular QW is formed
  - Better carrier localization
  - Only works for narrow QW
- Impact of polarization is stronger for
  - Thick QW
  - High carrier injection
- Zero polarization leads to a better IQE.



Thermal Effect – 250K to 500K

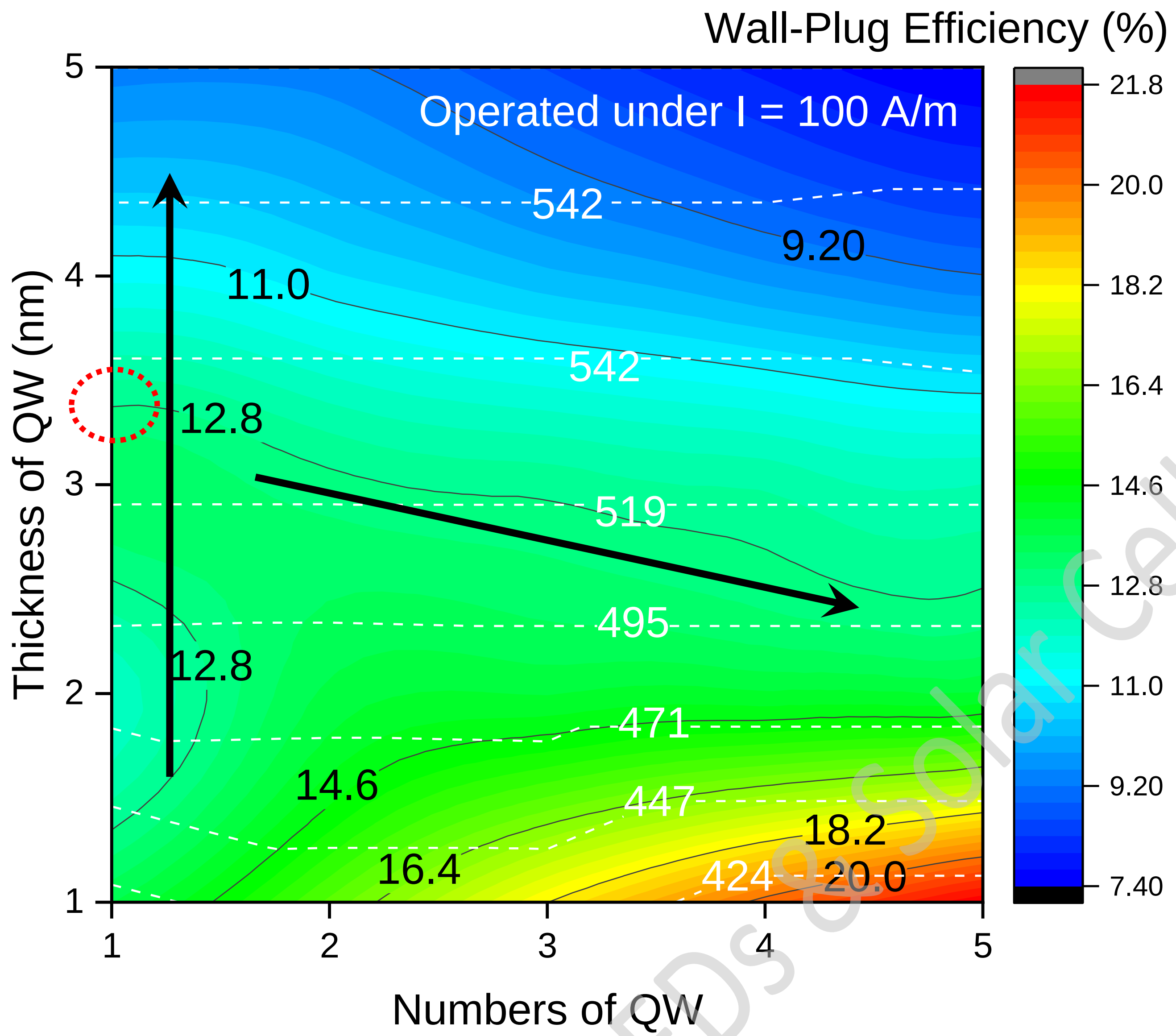




Optimization of Wurtzite GaN-based Green LEDs

- # of QW: 1 - 5
- Thickness: 1 - 5 nm
- In mole fraction: 0.3

Wall-Plug Efficiency

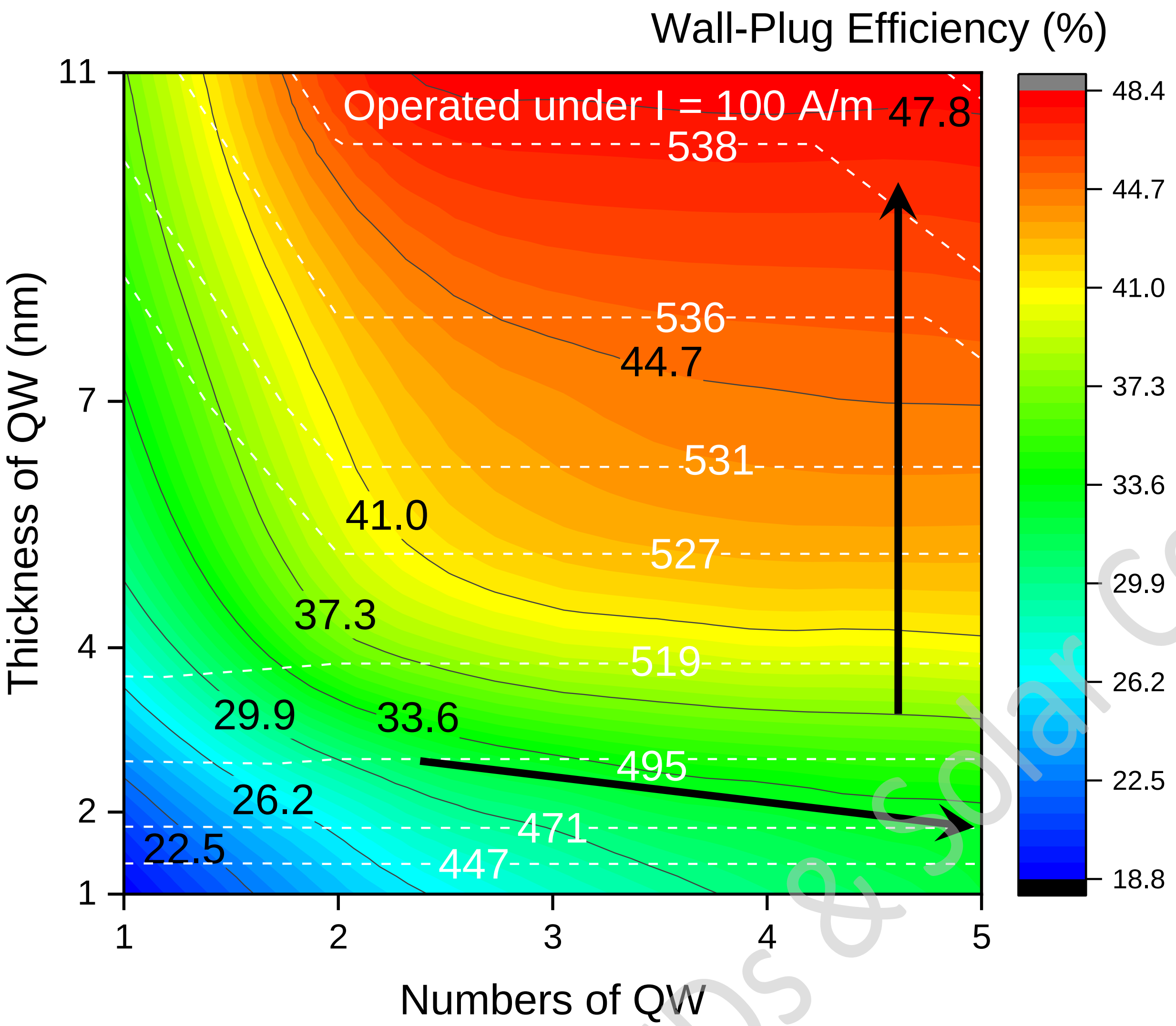


- Green emission ($\lambda > 500\ nm$)
  - Thickness > 3 nm
- Issue of thick QW
  - Polarization
  - Low radiative rate
- Issue of multiple QWs
  - Higher resistance
- Optimal efficiency
  - Under 100 A/m carrier injection
  - **12.8%**

Optimization of Zincblende GaN-based Green LEDs

- # of QW: 1 - 5
- Thickness: 1 - 11 nm
- In mole fraction: 0.3

Wall-Plug Efficiency



- ❑ Green emission ($\lambda > 500\ nm$)
  - Thickness > 3 nm
- ❑ Thick QW
  - Higher electron concentration
  - Higher radiative recombination
- ❑ Multiple QWs
  - Higher resistance
- ❑ Optimal efficiency
  - Under a constant current of 100 A/m
  - **47.8%** (3.7 times higher than 12.8%)

Conclusion

1. Auger recombination and polarization are the key to bridge green gap.

2. The highest wall-plug efficiency of wurtzite GaN-based green LEDs under 100 A/m carrier injection is 12.8%.

3. Yet, the highest wall-plug efficiency of zincblende GaN-based green LEDs under the same condition is 47.8% even though it has the same Auger coefficient.

Thank you very much for your attention

Q&A

2 mins