Modeling the temperature and excitation dependences of efficiency in InGaN light-emitting diodes

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III-N material system, LEDs and efficiency

Microscopic model

Efficiency versus excitation and temperature

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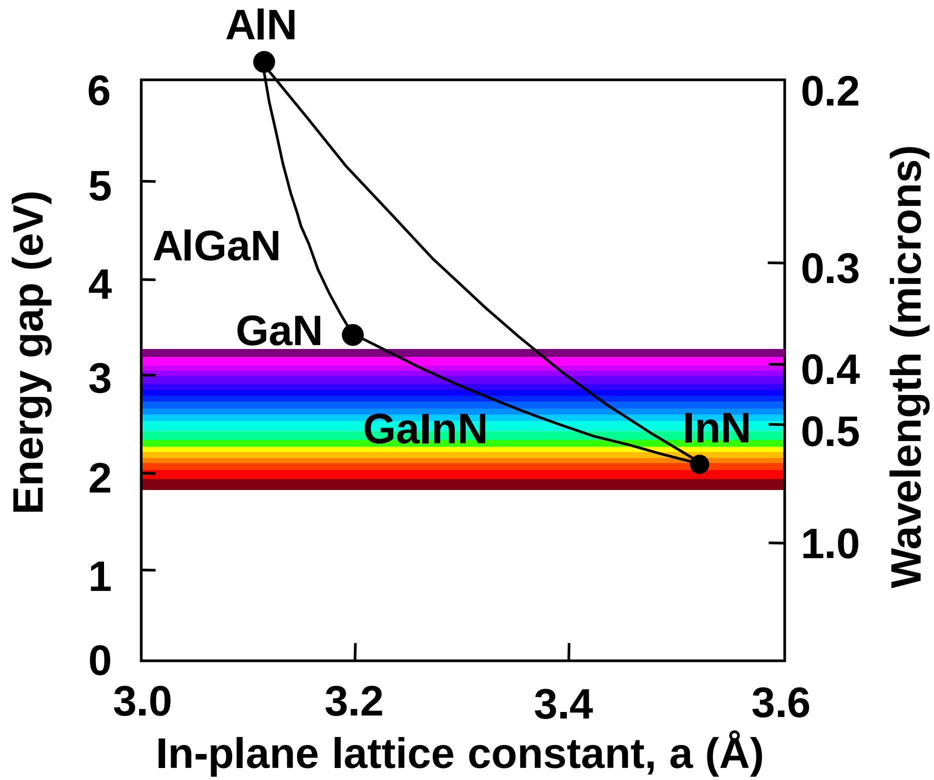
Visible and ultraviolet lasers: wide bandgap Group-III Nitrides



Interesting physics

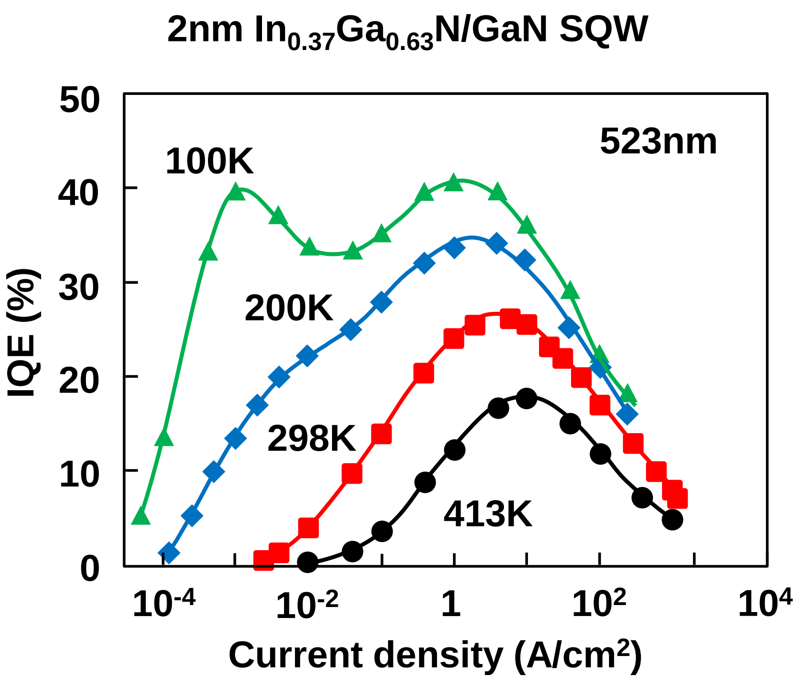
- **High exciton binding energy** ➡ **Strong many-body Coulomb effects**

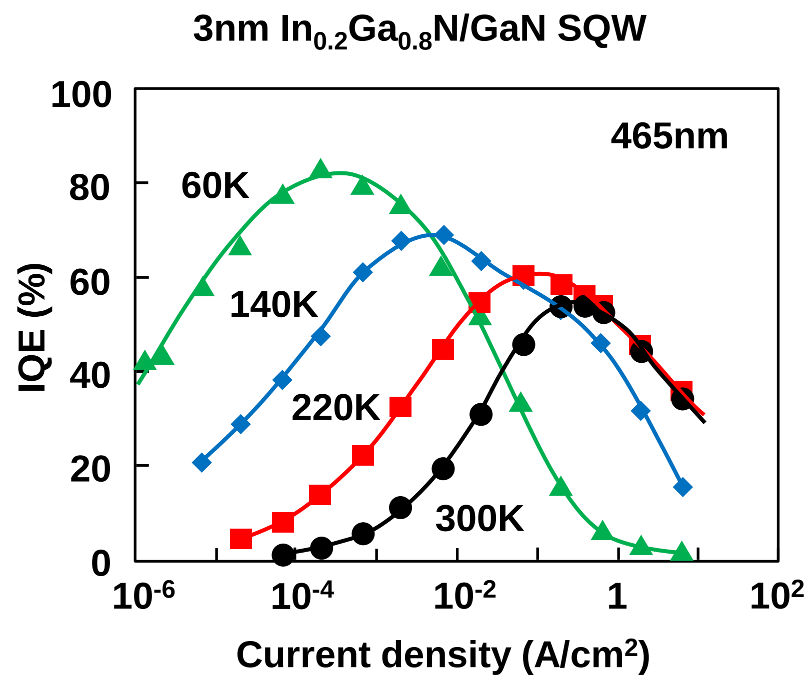
  (23meV for GaN vs. 5meV for GaAs) Chow, Knorr, Koch, Appl. Phys, Lett. **67**, 754 (1995)

- **Wurtzite crystal symmetry** ➡ **Strong quantum confined Stark effect**

Important applications: visible and ultraviolet lasers and LEDs

Experiment





Possible efficiency droop mechanisms

- **Auger losses**
- **Carrier leakage**
- **Non capture**
- **Defect**
- **Junction heating**

Considerations for model

- **Systematic, unbiased accounting of mechanisms**
- **Possibility of multiple contributing mechanisms (simultaneous or sequential)**
- **Possibility of different mechanisms for different experimental configurations**
- **Minimization of free parameters**

Hader, Moloney, Koch, APL 99, 181127 (2011)
Fujiwara, Jimi, Kaneda, Phys. Status Solidi C 6, S812 (2009); Laubsch, et al, Phys. Status Solidi C 6, S913 (2009)

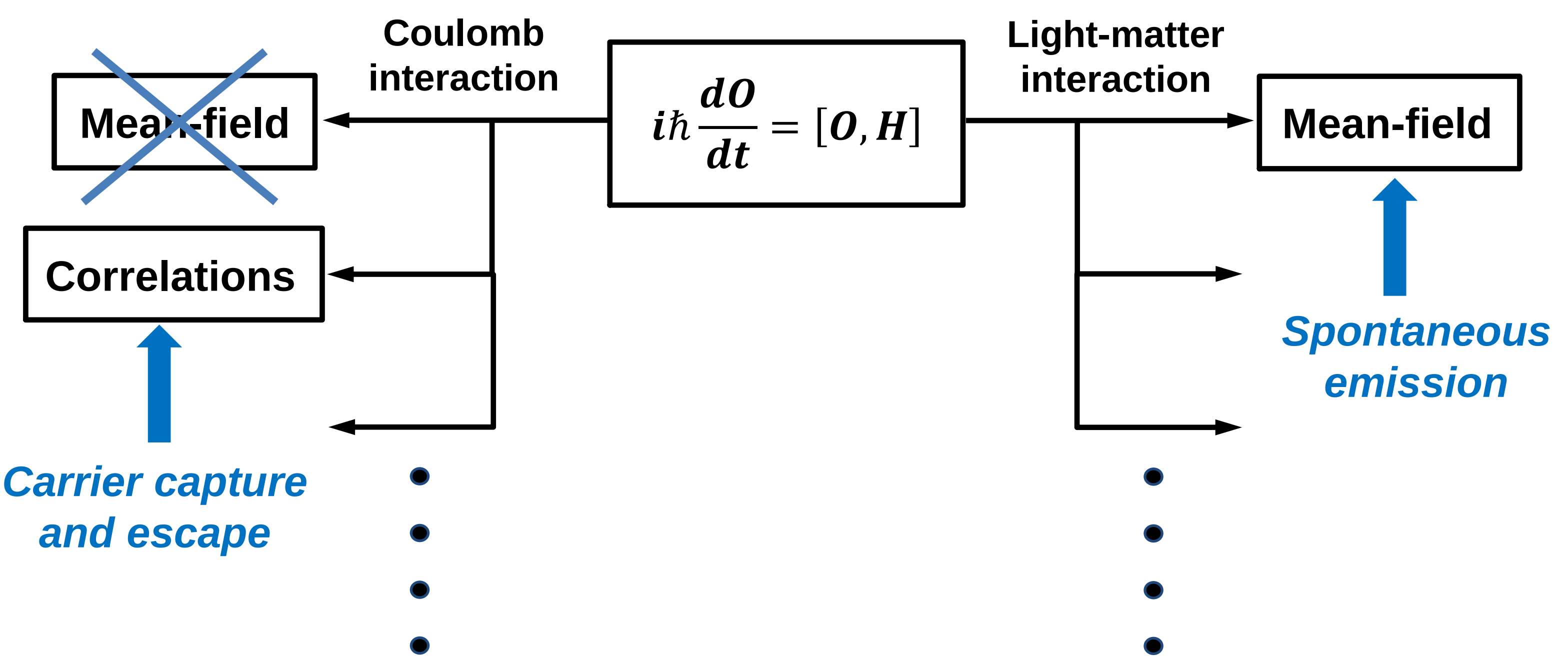
Approach

Hamiltonian

$$\mathbf{H} = \overbrace{\sum_i \varepsilon_i^e a_i^\dagger a_i + \sum_j \varepsilon_j^h b_j^\dagger b_j + \sum_q \hbar\Omega_q c_q^\dagger c_q}^{\text{Single-particle energies}} \overbrace{- \sum_{i,j,q} \wp_{ij} \sqrt{\frac{\hbar\Omega_q}{V\epsilon_b}} \left(a_i b_j c_q^\dagger + c_q b_j^\dagger a_i^\dagger \right)}^{\text{Light-matter interaction}}$$

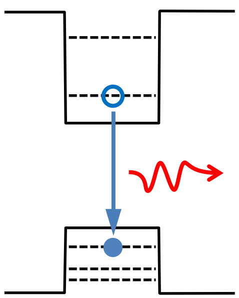
+ Coulomb interaction

Hiesenberg Picture



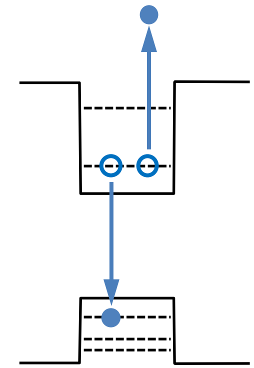
Model

Spontaneous emission (>ns)

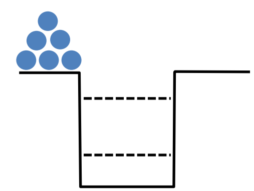


$$\frac{dn_{\sigma,\alpha_\sigma,k_\perp}}{dt} = \overbrace{n_{\sigma,\alpha_\sigma,k_\perp}\sum_{\alpha_{\sigma'}} b_{\alpha_\sigma,\alpha_{\sigma'},k_\perp} n_{\sigma',\alpha_{\sigma'},k_\perp}} - \overbrace{A n_{\sigma,\alpha_\sigma,k_\perp}}^{\text{Defect loss (SRH)}}$$
$$-\gamma_{c-c}\left[n_{\sigma,\alpha_\sigma,k_\perp} - f\left(\varepsilon_{\sigma,k_\perp},\mu_\sigma,T\right)\right]$$
$$-\gamma_{c-p}\left[n_{\sigma,\alpha_\sigma,k_\perp} - f\left(\varepsilon_{\sigma,k_\perp},\mu_\sigma^L,T_L\right)\right]$$
$$-\gamma_{ag}\left[n_{\sigma,\alpha_\sigma,k_\perp} - f\left(\varepsilon_{\sigma,k_\perp},\mu_{ag},T_{ag}\right)\right]$$

Auger

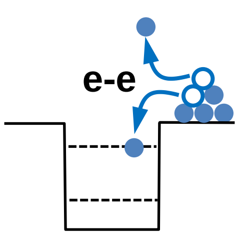


Carrier injection

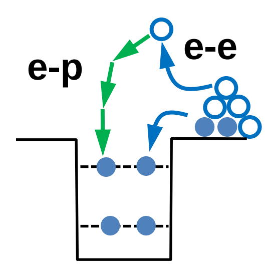


$$\frac{dn_{\sigma,k}^b}{dt} = \overbrace{-b_k n_{e,k}^b n_{h,k}^b} + \overbrace{\frac{J}{eN_\sigma^p} f\left(\varepsilon_{\sigma,k}^b,\mu_\sigma^p,T_p\right)\left(1-n_{\sigma,k}^b\right)}^{\text{Carrier injection}} - An_{\sigma,k}^b$$
$$-\gamma_{c-c}\left[n_{\sigma,k}^b - f\left(\varepsilon_{\sigma,k}^b,\mu_\sigma,T\right)\right]$$
$$-\gamma_{c-p}\left[n_{\sigma,k}^b - f\left(\varepsilon_{\sigma,k}^b,\mu_\sigma^L,T_L\right)\right]$$
$$-\gamma_{ag}\left[n_{\sigma,k}^b - f\left(\varepsilon_{\sigma,k}^b,\mu_{ag},T_{ag}\right)\right]$$

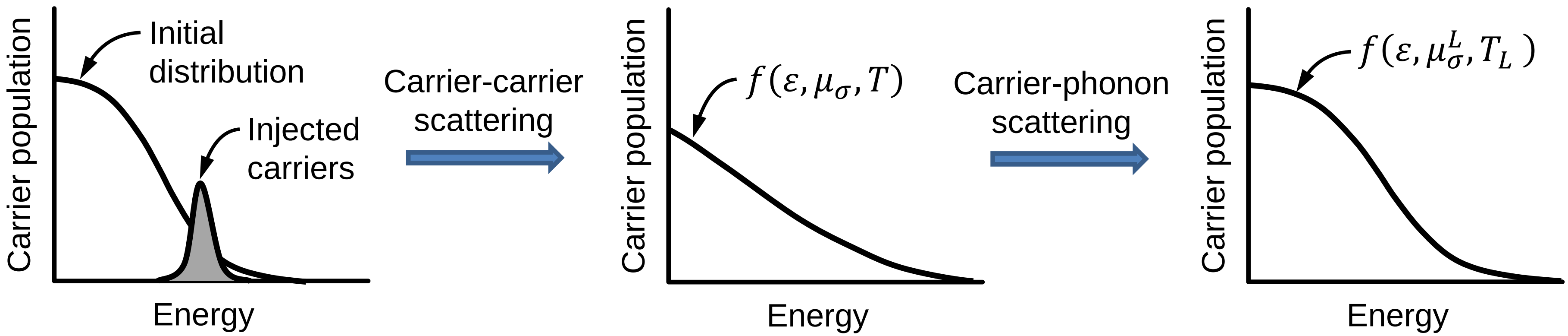
Carrier-carrier (100fs)

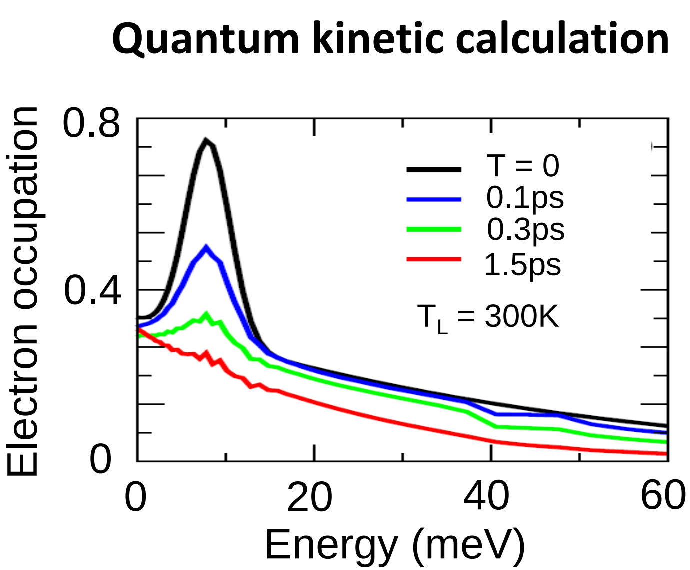


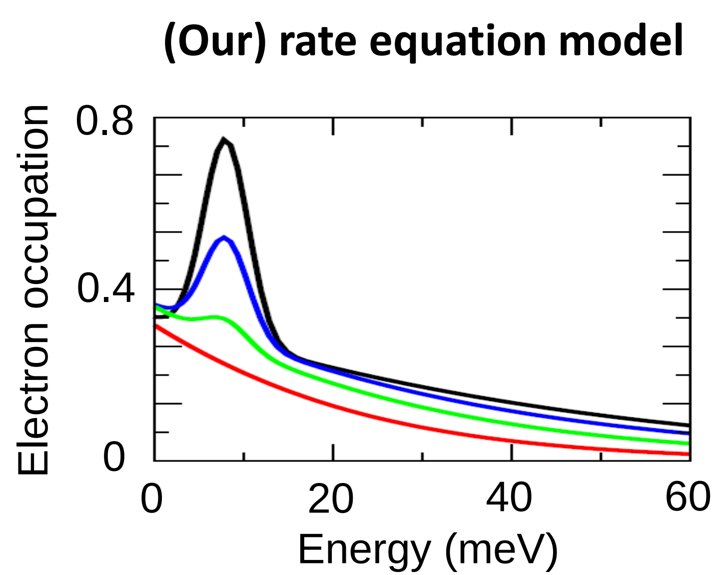
Carrier-phonon (<1ps)



Asymptotic carrier distributions







Numerical analysis

1

Bandstructure

a) Solve k·p and Poisson equations for given range of carrier densities

b) Tabulate energy dispersions and transition matrix elements versus carrier density

2

Solve for carrier population distributions

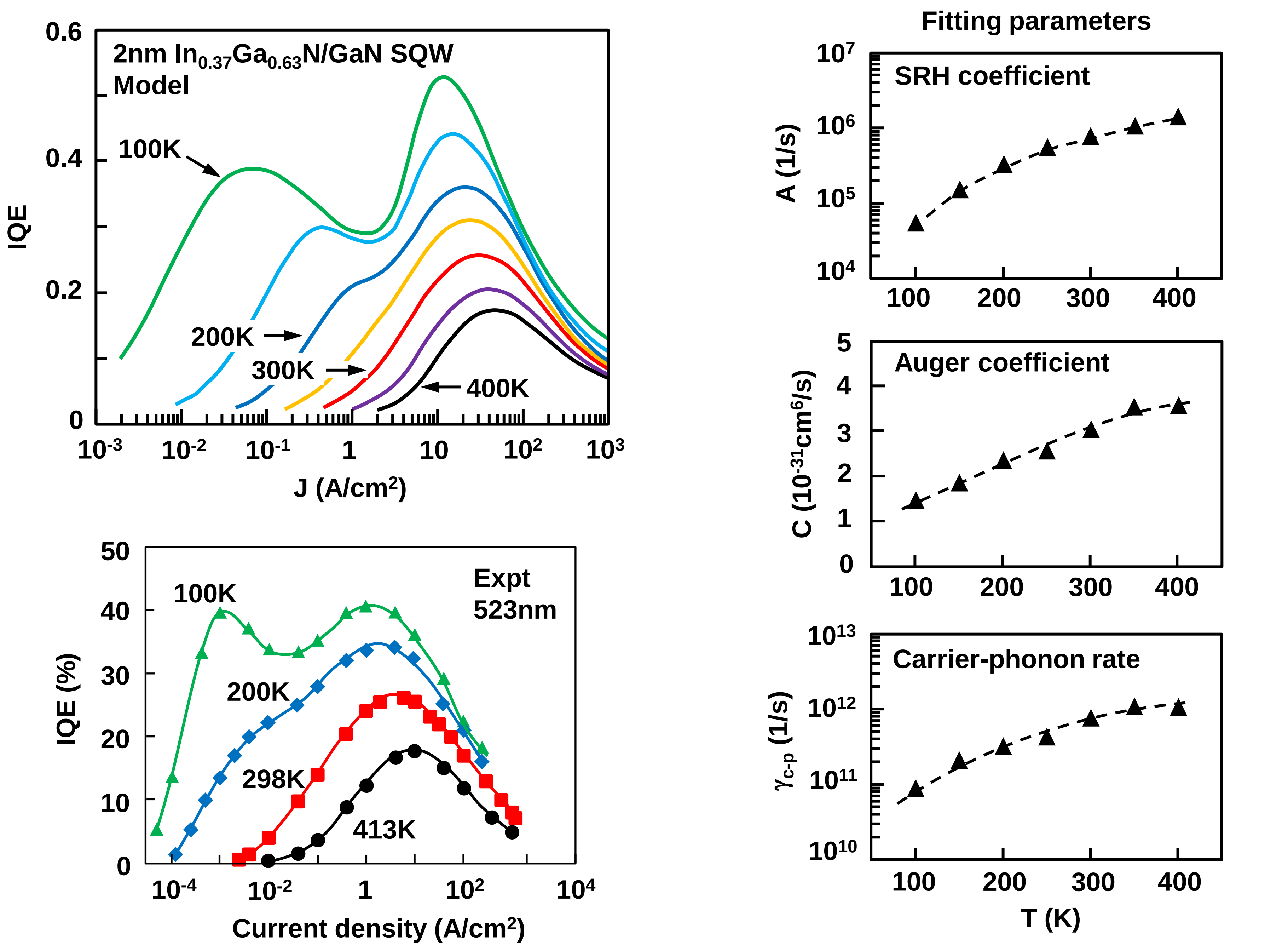
Solve kinetic equations with bandstructure properties and asymptotic Fermic-Dirac distributions updated at each time step

3

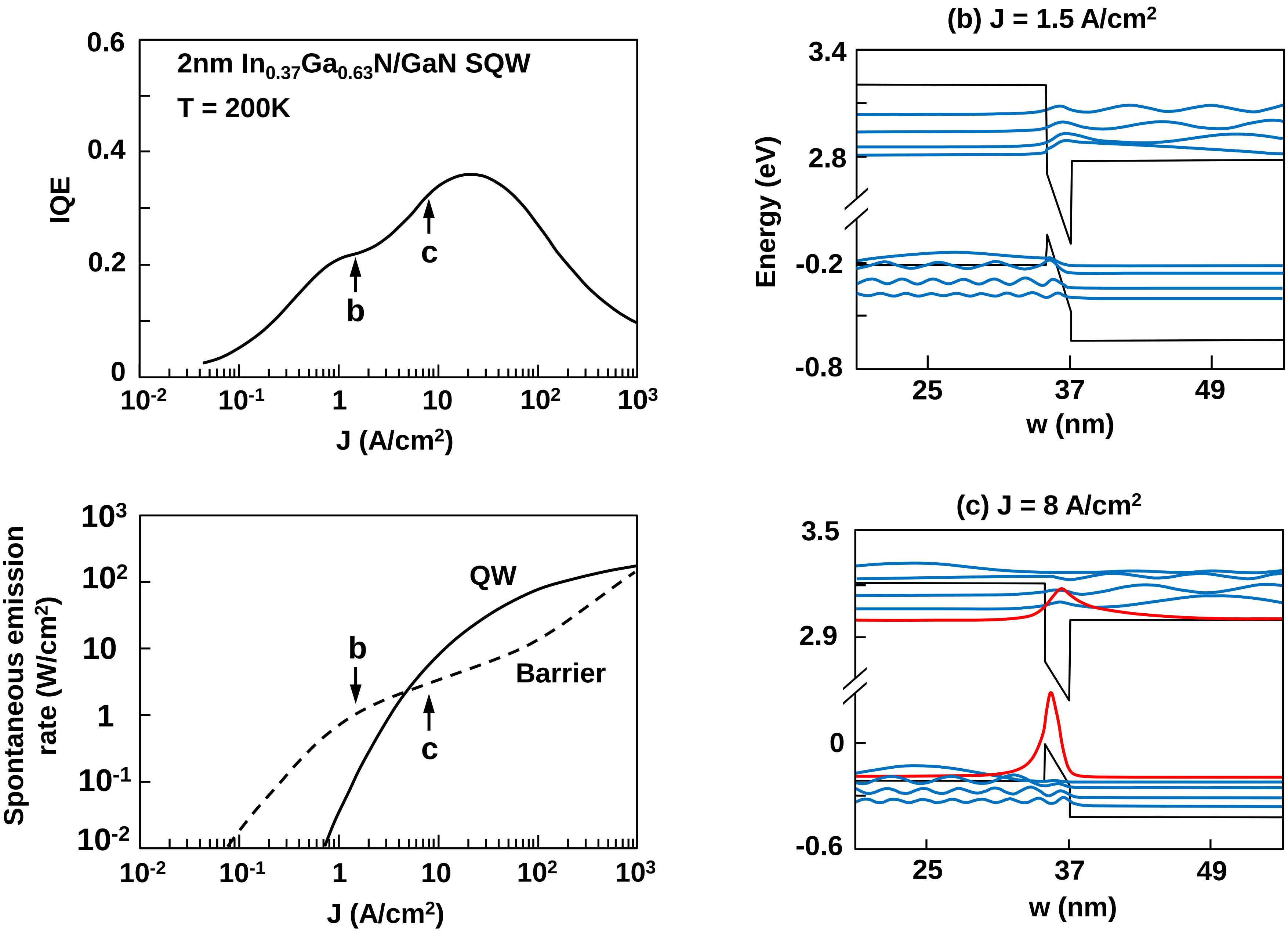
Compute efficiency

$$IQE = \frac{e}{JS}\left(\sum_{\alpha_e,\alpha_h,k_\perp} b_{\alpha_e,\alpha_h,k_\perp} n_{e,\alpha_e,k_\perp} n_{h,\alpha_h,k_\perp} + \sum_{k} b_k n^b_{e,k} n^b_{h,k}\right)$$

IQE versus current density for different lattice temperatures

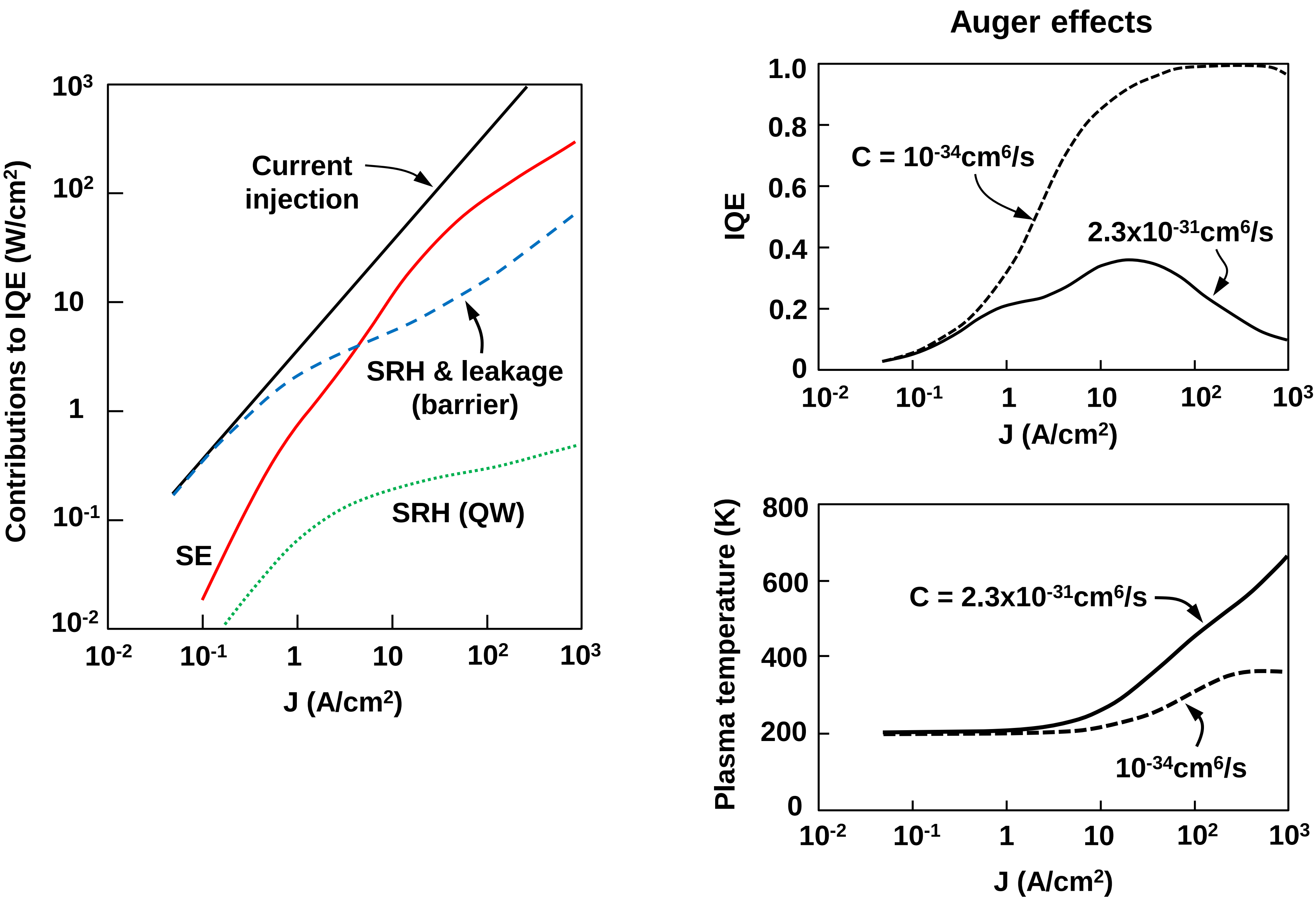


Spontaneous emission from QW and barrier states



Contributions to IQE

2nm $In_{0.37}Ga_{0.63}N$/GaN SQW, T = 200K



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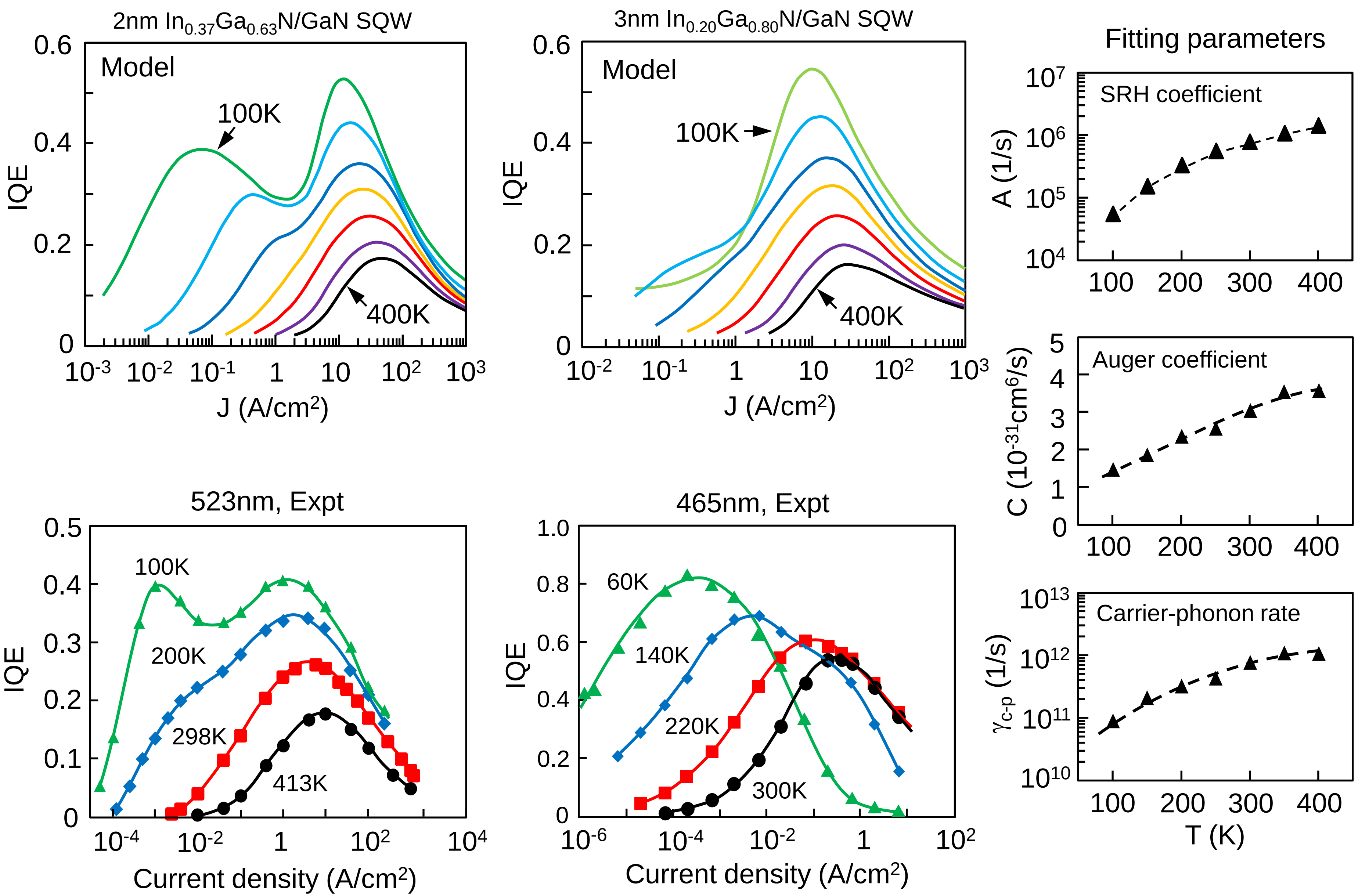

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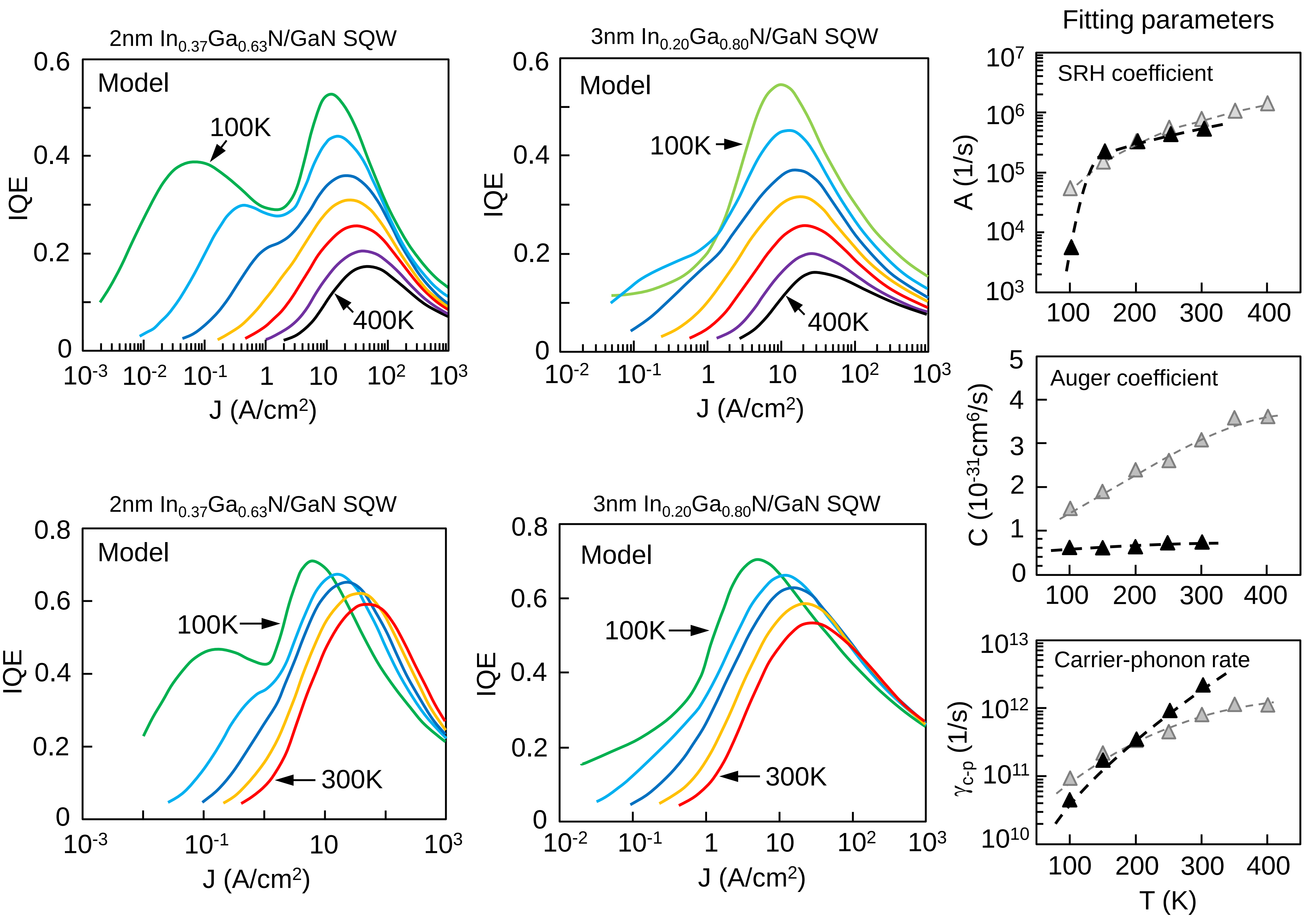

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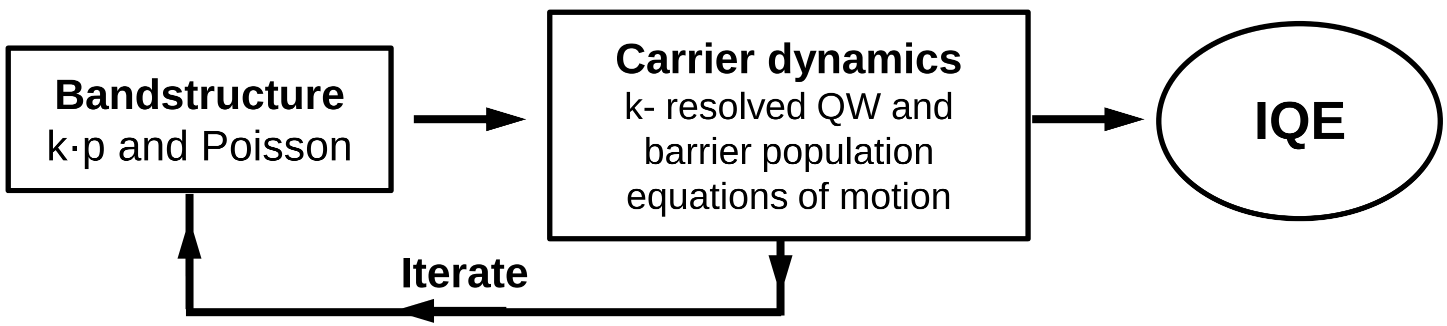

Possible efficiency droop mechanisms

- Auger losses → C -- carrier-carrier scattering rate
- Defect → A -- carrier-carrier scattering rate
- Carrier leakage
- Non capture
- Junction heating

→ $\gamma_{c\text{-}c}$ -- carrier-carrier scattering rate

$\gamma_{c\text{-}p}$ -- carrier-carrier scattering rate

- Band structure → k·p and Poisson Eqs → Growth sheet

Bulk material parameters