The Influence of Surface Effects on the Simulation of 1.3μm InGaAsN Edge-Emitting Lasers

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Presentation Outline

- Boundary condition models
- Surface Fermi-level pinning
- Simulation tool
- Dilute nitride lasers
- Simulation results
- Conclusions and outlook

Boundary Condition Models

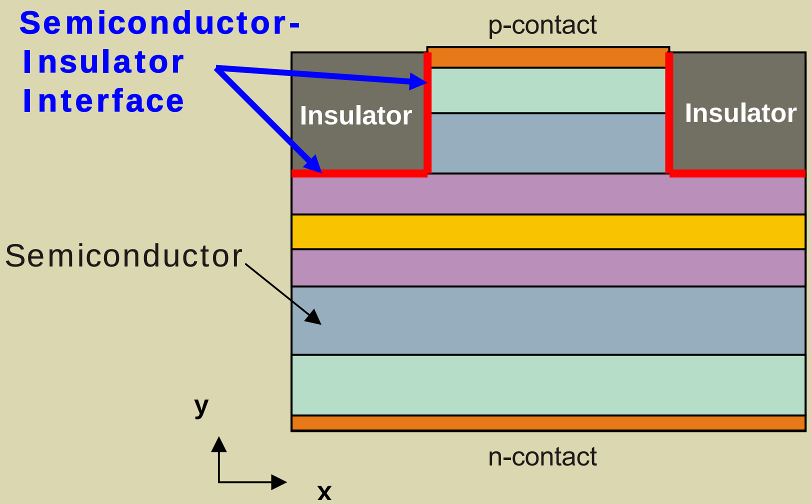
Semiconductor-insulator boundary condition models usually employ a combination of the following assumptions:

- Fixed surface charge

$$\varepsilon_0 \varepsilon_s \frac{\partial \phi}{\partial \mathbf{n}} = Q_s$$

- Fixed surface recombination velocity

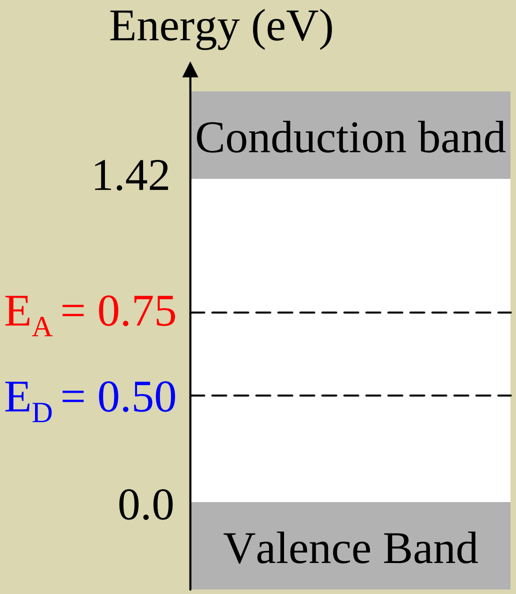
$$\mathbf{n} \cdot \mathbf{J_n} = -q v_{sr} \left(np - n_0 p_0 \right)$$
$$\mathbf{n} \cdot \mathbf{J_p} = q v_{sr} \left(np - n_0 p_0 \right)$$



These BCs suffer from the following problems:

- the equilibrium Fermi-level at the interface depends on doping type and concentration (i.e. no pinning)
- the surface charge doesn't change with recombination dynamics (e.g. no band-flattening with illumination)

Fermi-level Pinning



- Fermi-level pins at the surface of many semiconductors
- Large number of defect states at surface
- Defect states act as traps and recombination centres
  - Trapped charge causes surface band bending
  - Surface pinning affects surface recombination
- In GaAs, Fermi-level pinning is attributed to two defect levels in the bandgap of the semiconductor

Fermi-level Pinning Model

$$Q_s = qN_{TD}\left(1 - f_{TD}\right) - qN_{TA} f_{TA}$$

$$f_T = \frac{\tau_p n + \tau_n p_1}{\tau_n (p + p_1) + \tau_p (n + n_1)}$$

$$R_{surf} = \frac{np - n_1 p_1}{\tau_p (p + p_1) + \tau_p (n + n_1)}$$

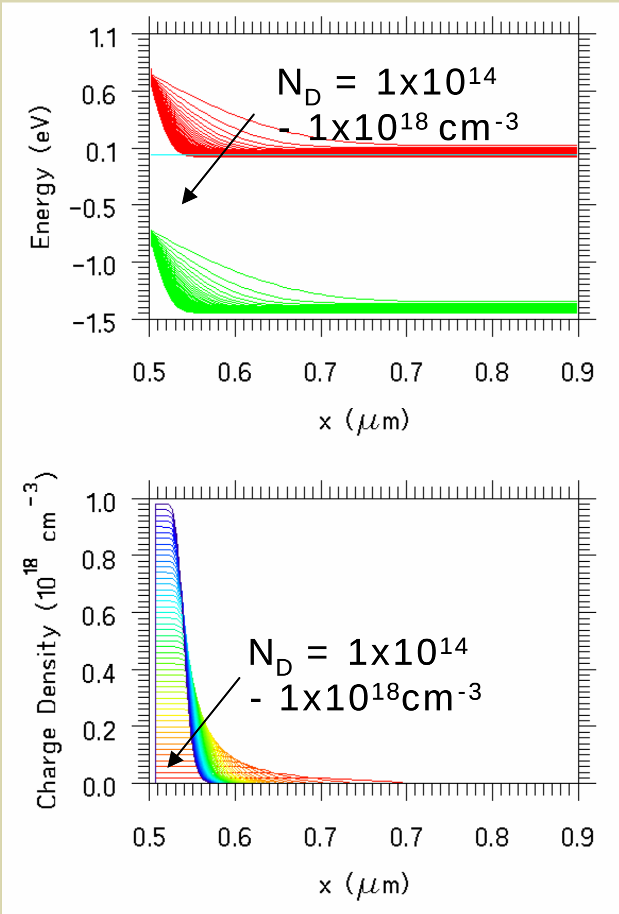
$$n_1 = N_C \exp\left(\frac{E_T - E_C}{kT}\right) \qquad \tau_n = \frac{1}{N_T \sigma_n v_{th}}$$

$$p_1 = N_V \exp\left(\frac{E_V - E_T}{kT}\right) \qquad \tau_p = \frac{1}{N_T \sigma_p v_{th}}$$

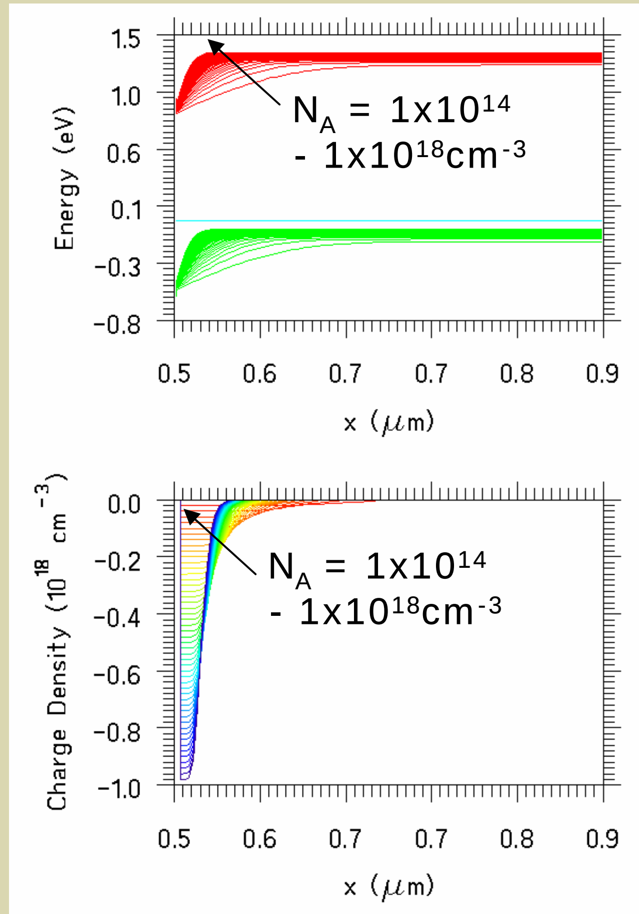
References: *W. E. Spicer et al., J. Vac. Sci. Technol. B, Vol. 6, pp. 1245-1251, 1988*
R. B. Darling, Phys. Rev. B Vol. 43, No. 5, pp. 4071-83, 1991

Surface Fermi-level pinning (Equilibrium)

- Surface band-bending of n- and p- GaAs at equilibrium



n-type



p-type

➔ Surface Fermi-level nearly independent of dopant type / concentration.

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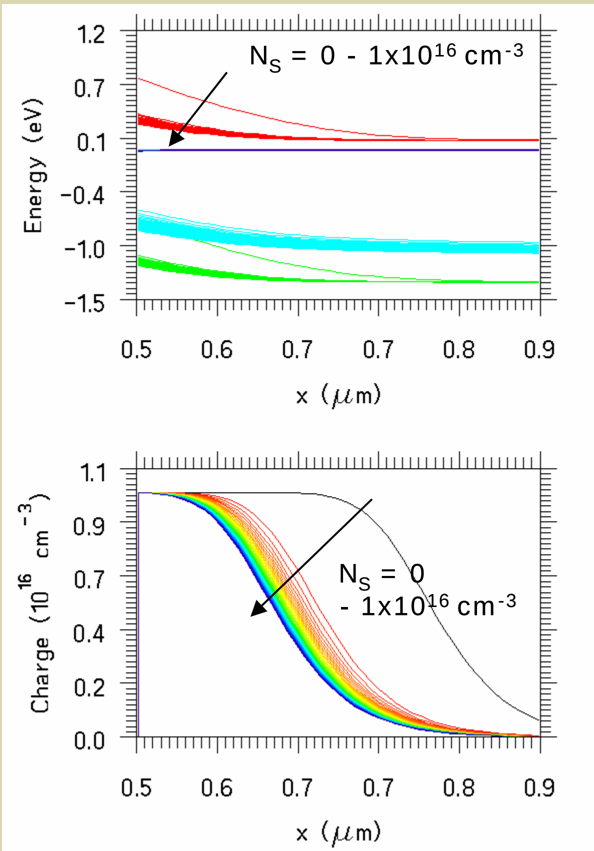
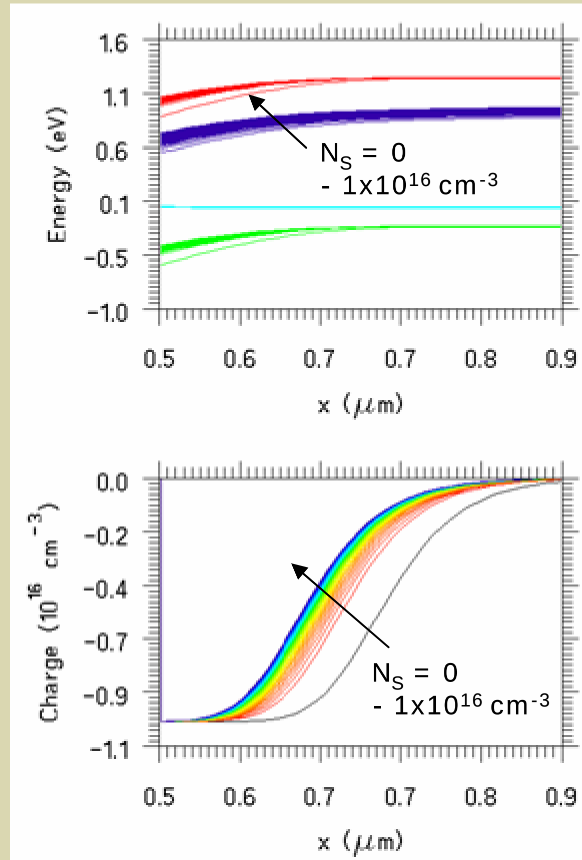
Surface Fermi-level pinning (Non-Equilibrium)

- Surface band-bending of n- and p- GaAs as a function of optical illumination
- N_A / N_D = $1\text{x}10^{16}$ cm^{-3}, $N_S = \Phi_s/v_g$ = 0 – $1\text{x}10^{16}$ cm^{-3}



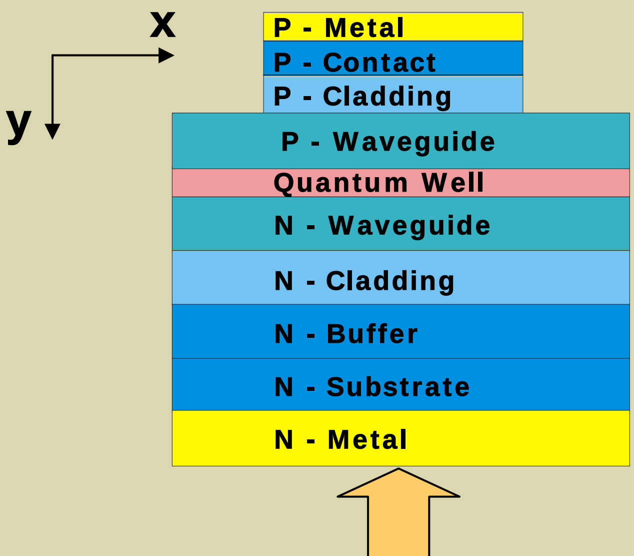
n-type



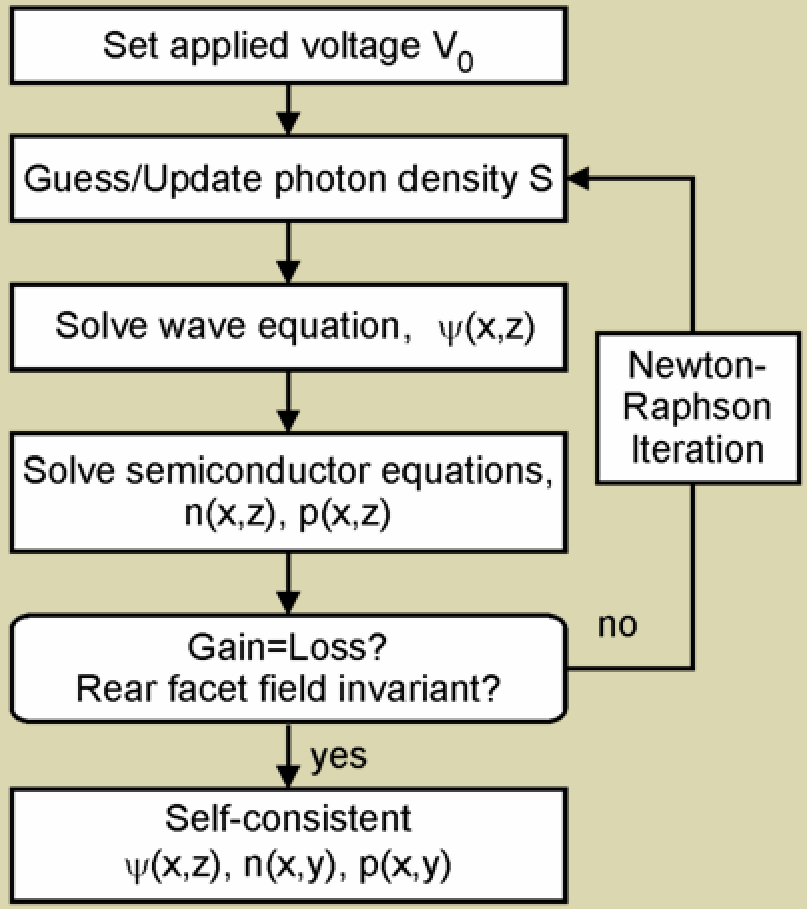
p-type

➔ Illumination changes the depletion width and flattens the band-bending.

Simulation Software



2D XY electrical-thermal solver
- Drift-diffusion equation
- Poisson equation
- QW capture-escape equations
- Accurate surface BC's
- BAC + (4x4) **k·p** model



Dilute Nitride Lasers

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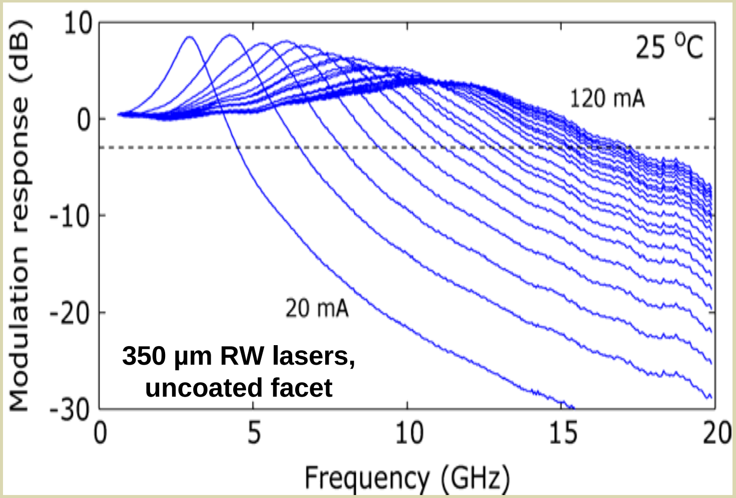
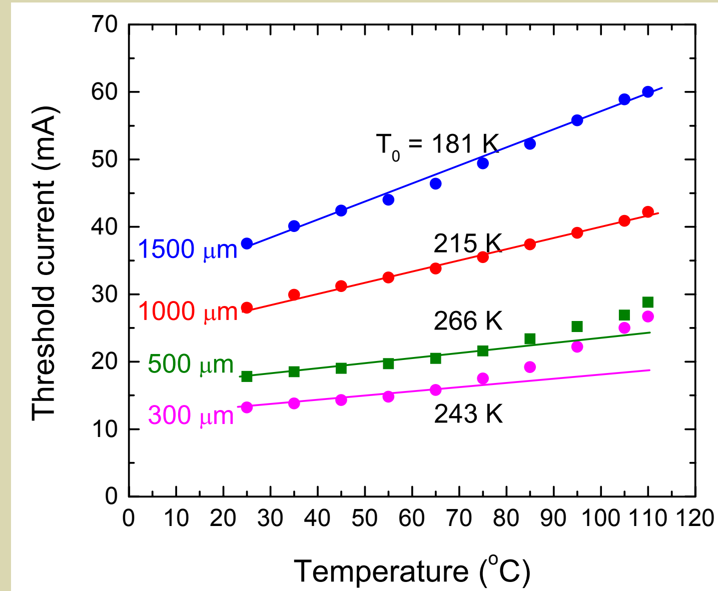


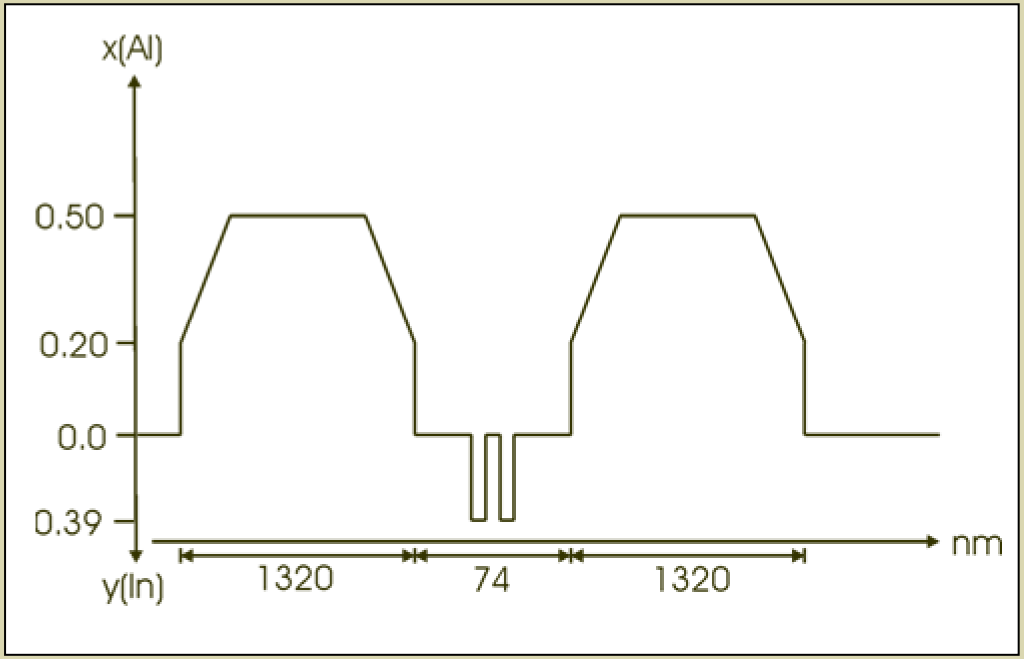


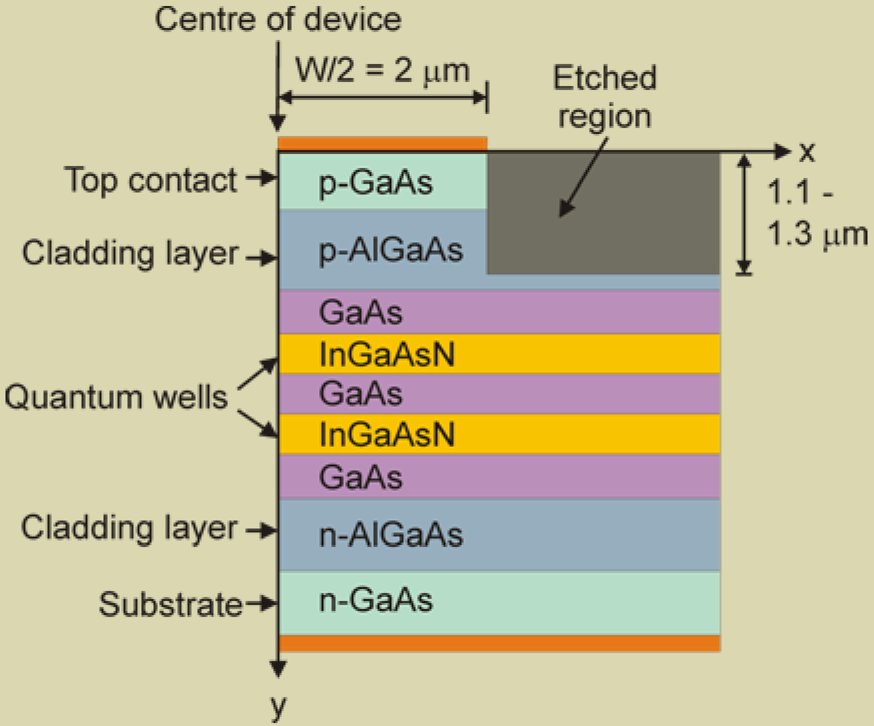
- Bandgap energy reduction – Longer wavelength
- Large conduction band offset – High T_0
- Low-cost alternative to InP for access networks
- 17 GHz maximum modulation bandwidth
- Characteristic temperature = 181-266 K (20-70°C)

Reference: *Y.Q. Wei et al., Optics Express, Vol. 14, pp. 2753-2759, 2006*

Device Structure

- 7nm $In_{0.39}Ga_{0.61}AsN_{0.012}$/GaAs DQW
- 4x400 μm^2 Ridge Waveguide



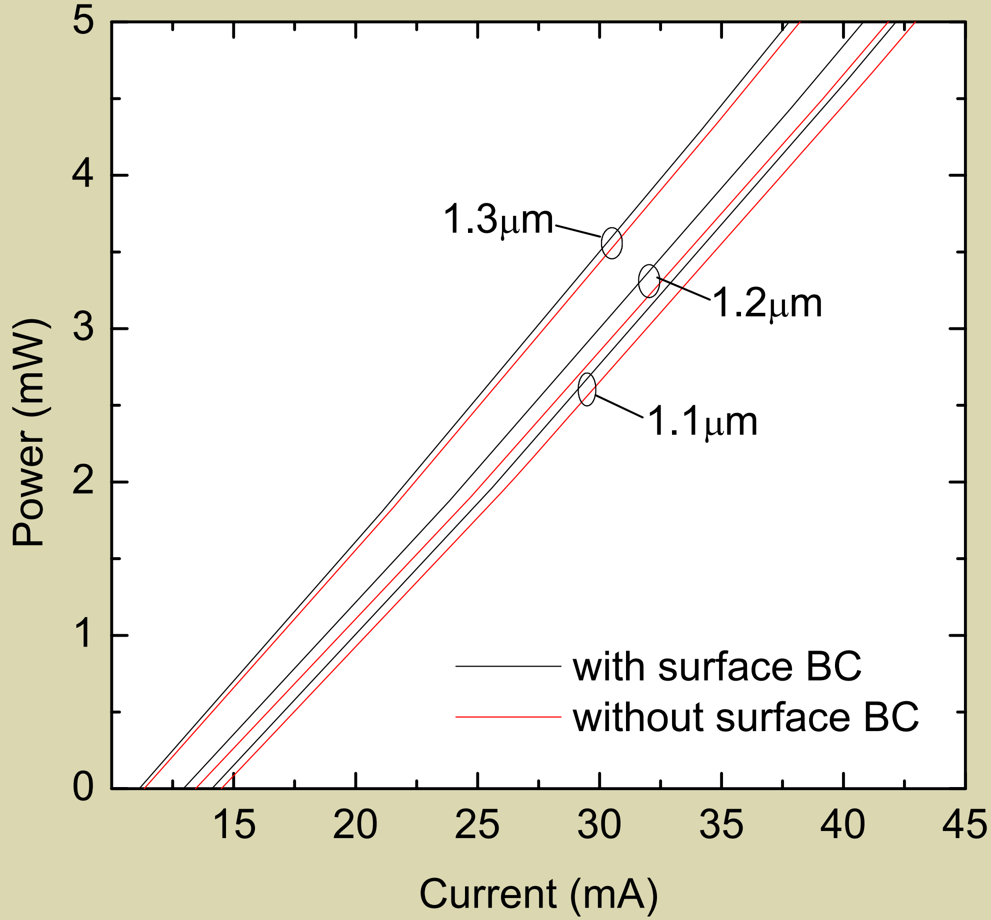


Reference: *Y.Q. Wei et al., Appl. Phys. Lett., Vol. 88, 051103, 2006.*

Power-Current Characteristic

Surface trap parameters:

- Donor
  - E_D = 0.50 eV
  - N_{TD} = 1×10^{13} cm^{-2}
  - $\sigma_{nD} = \sigma_{pD}$ = 1×10^{-16} cm^2
- Acceptor
  - E_A = 0.75 eV
  - N_{TA} = 1×10^{13} cm^{-2}
  - $\sigma_{nA} = \sigma_{pA}$ = 1×10^{-16} cm^2



➔ Surface band-bending reduces current spreading and threshold current

Vertical Current Density Distribution

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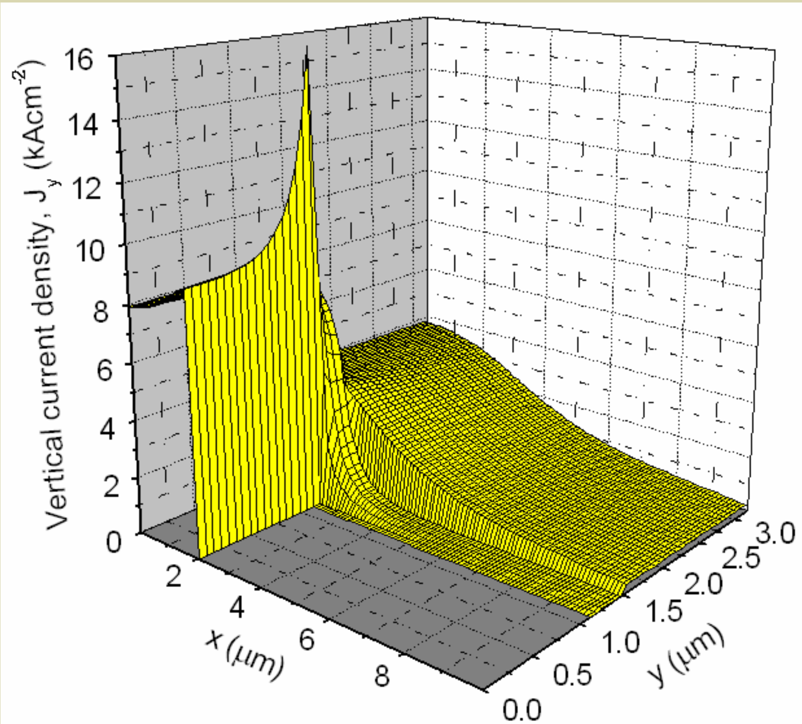
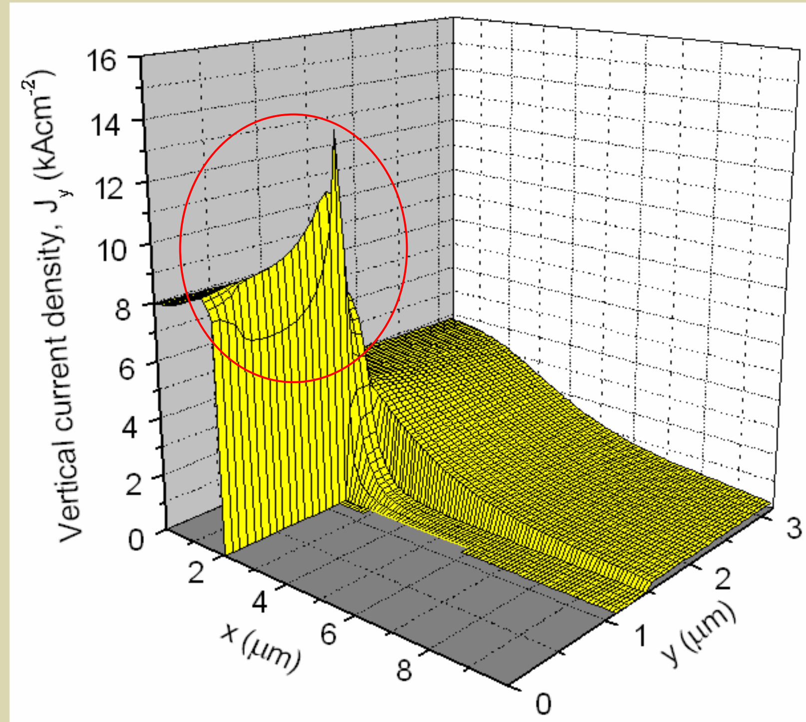
- Etch depth = 1.2μm



Without surface BC



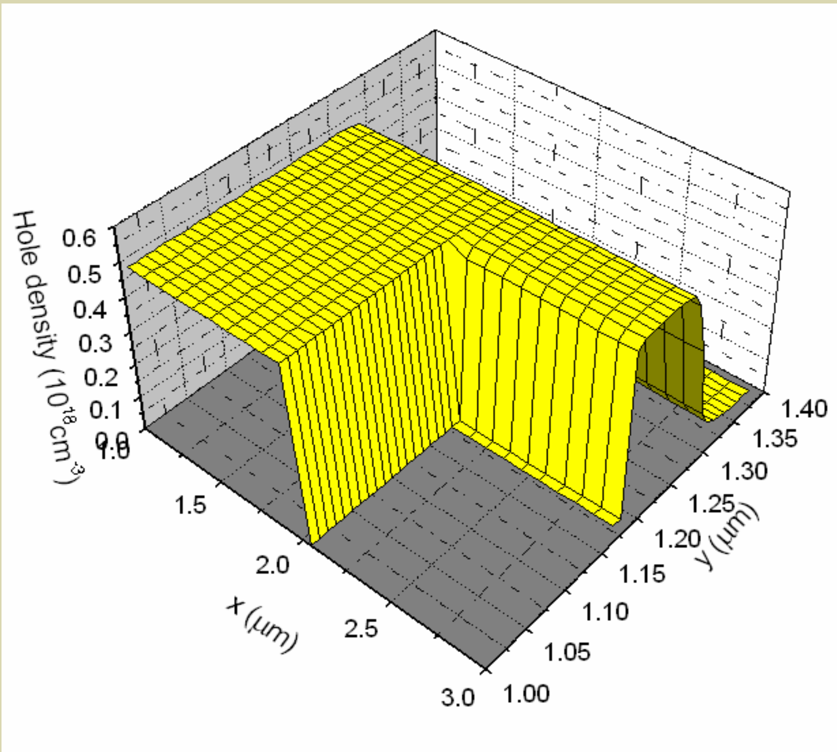
With surface BC

➔ Reduced current density at vertical edge of ridge

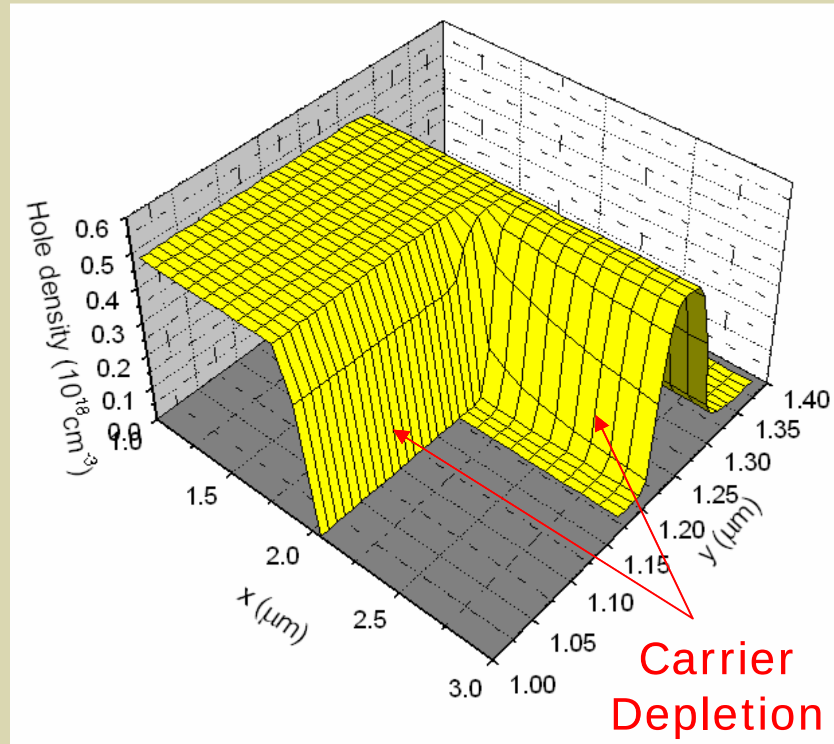
➔ Less current spreading means fewer carriers need to be supplied

Hole Density Distribution

- Etch depth = 1.2μm



Without surface BC

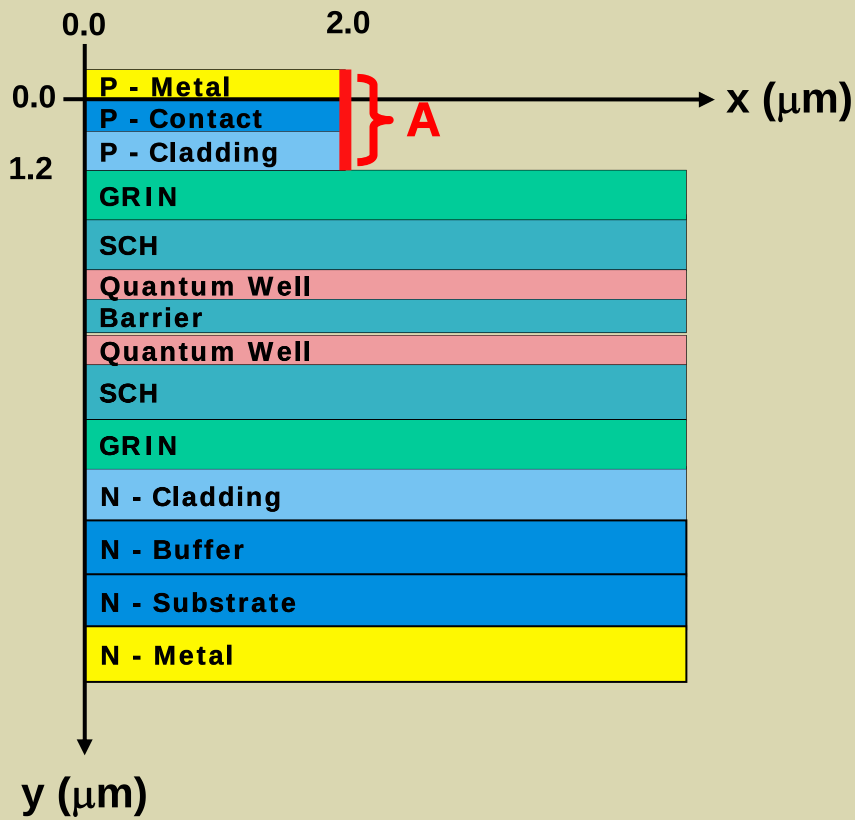


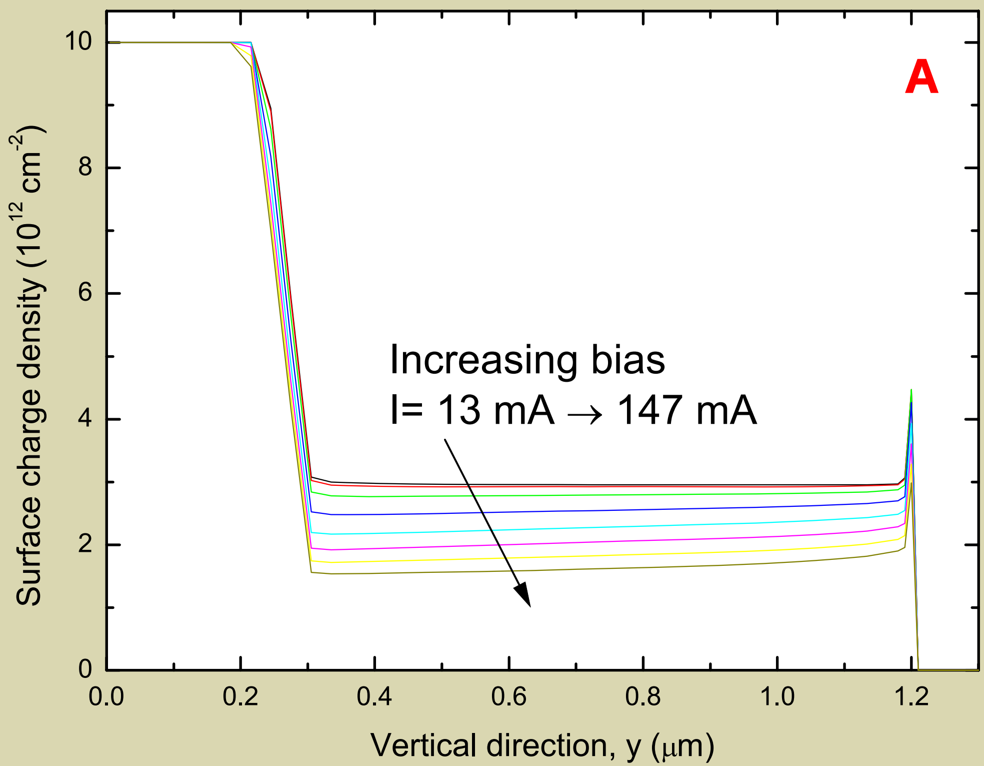
With surface BC

➔ Surface Fermi-level pinning depletes the p-region beneath the etch

Surface Charge Density Distribution (Vertical Edge)

- Etch depth = 1.2μm

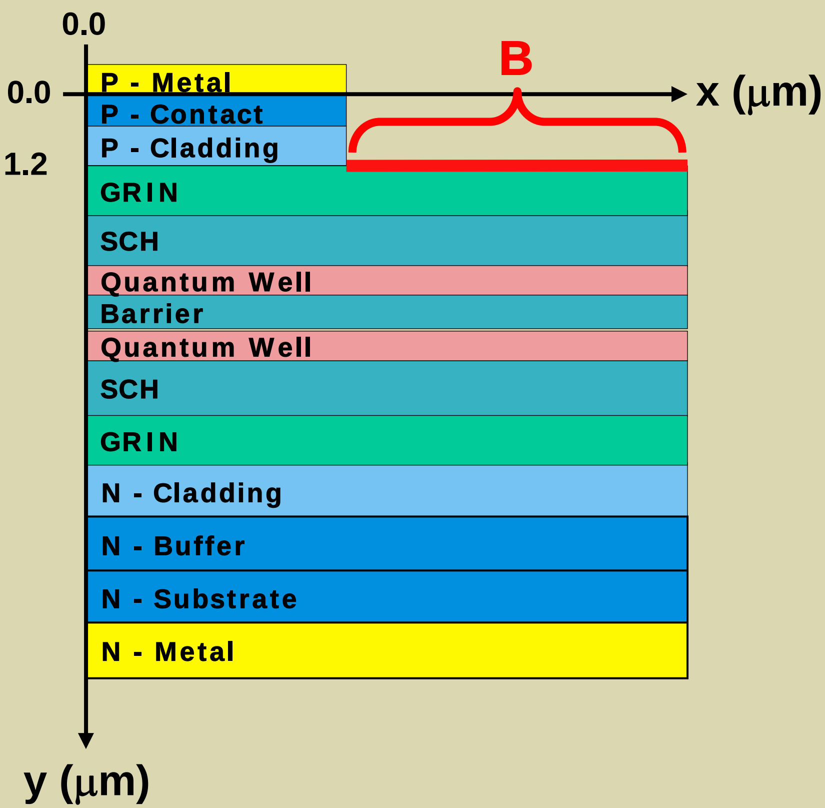


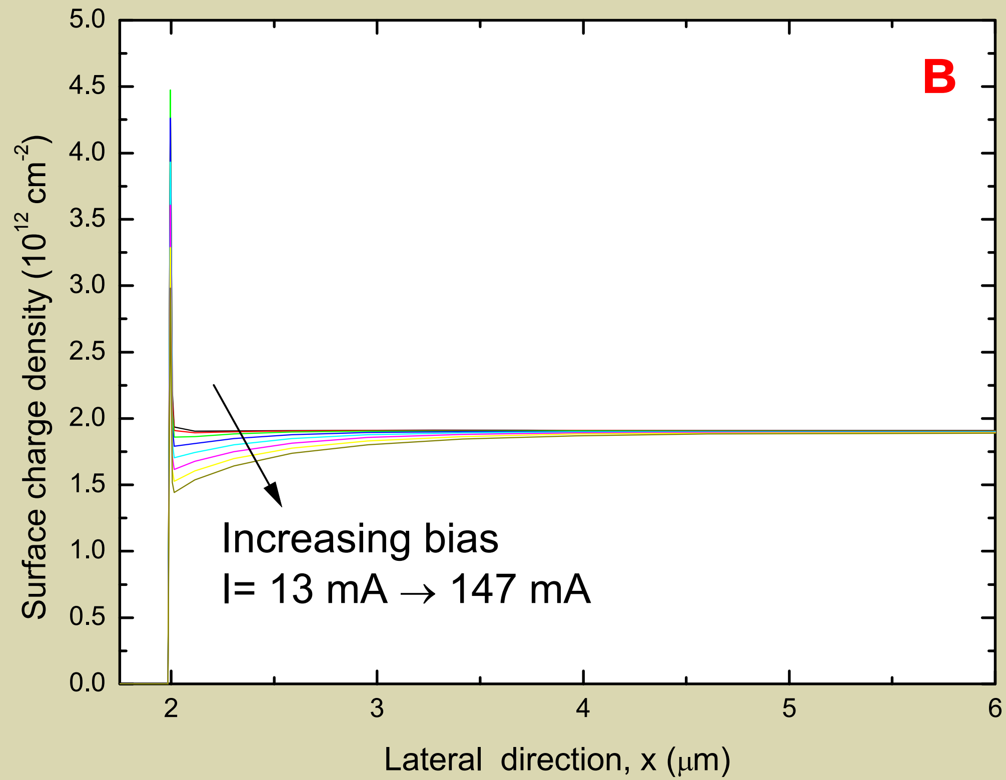


➔ Surface charge (& depletion) depend on bias & position

Surface Charge Density Distribution (Lateral Edge)

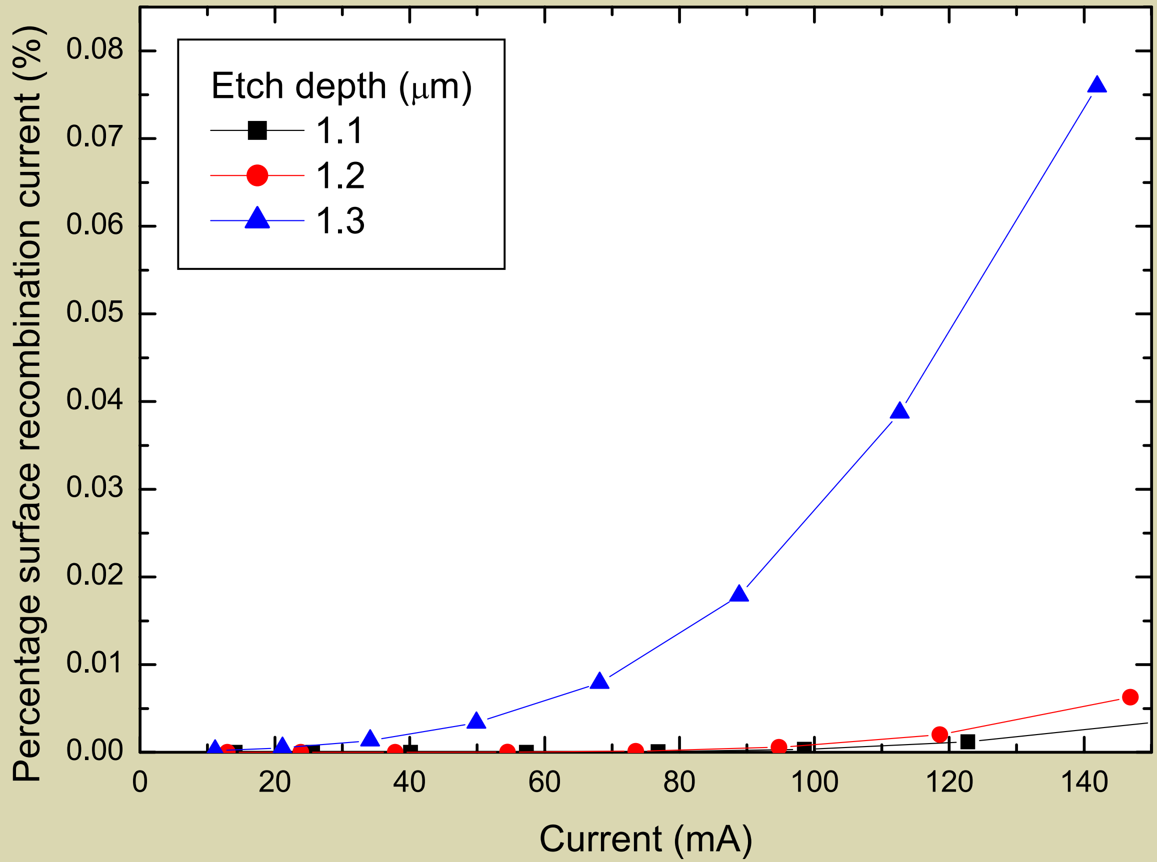
- Etch depth = 1.2μm





➔ **Surface depletion decreases with bias – lateral conductivity increases**

Surface Recombination Current



- Surface recombination integrated over surface

➔ Surface recombination current is small, but increases with etch depth and bias

Conclusions

- Accurate surface boundary condition implemented into a comprehensive laser diode simulator
- The assumption of a constant surface charge is inappropriate – distribution of charge is a nontrivial function of position and bias
- In ridge waveguide lasers, surfa electrostatics in vicinity of the su
- Surface recombination current is
- Surface recombination dynamics laser structures
- Proper surface BC's do not need