

ANALYTICAL THEORY AND NUMERICAL SIMULATION OF NON-EQUILIBRIUM TRANSPORT EFFECTS IN LASER HETEROSTRUCTURES

N.A. Zakleniuk and M.J. Adams

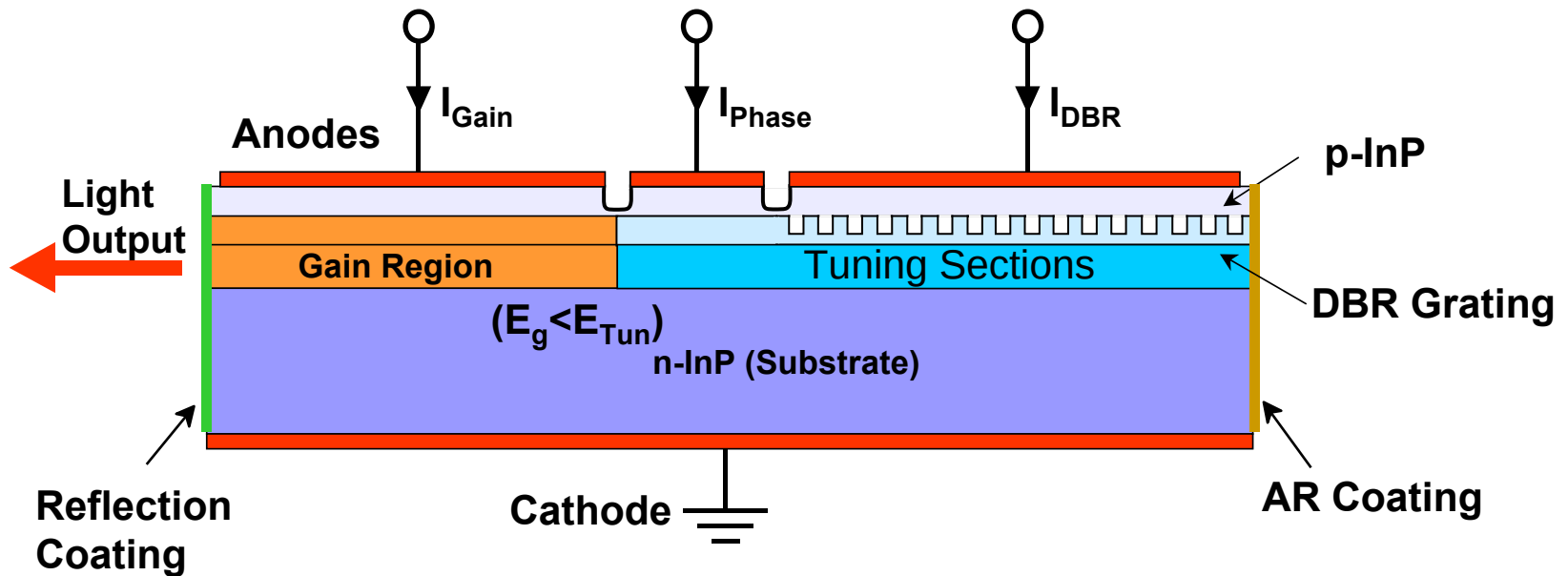
Photonics Research Group, ESE Department
University of Essex, Colchester, UK

CONTENTS

- **Surface Ridge InP/InGaAsP Laser Geometry is Considered**
- **Outline of the Model – Key Processes**
- **Analytical Theory (1D)**
- **DESSIS Simulation Below and Above Threshold**
- **Comparison of the Results**
- **Why 1D Theory is in so Good Agreement with Numerical Model**
- **Why 1D Theory is not Applicable for Reliable Analysis**
- **Conclusions**

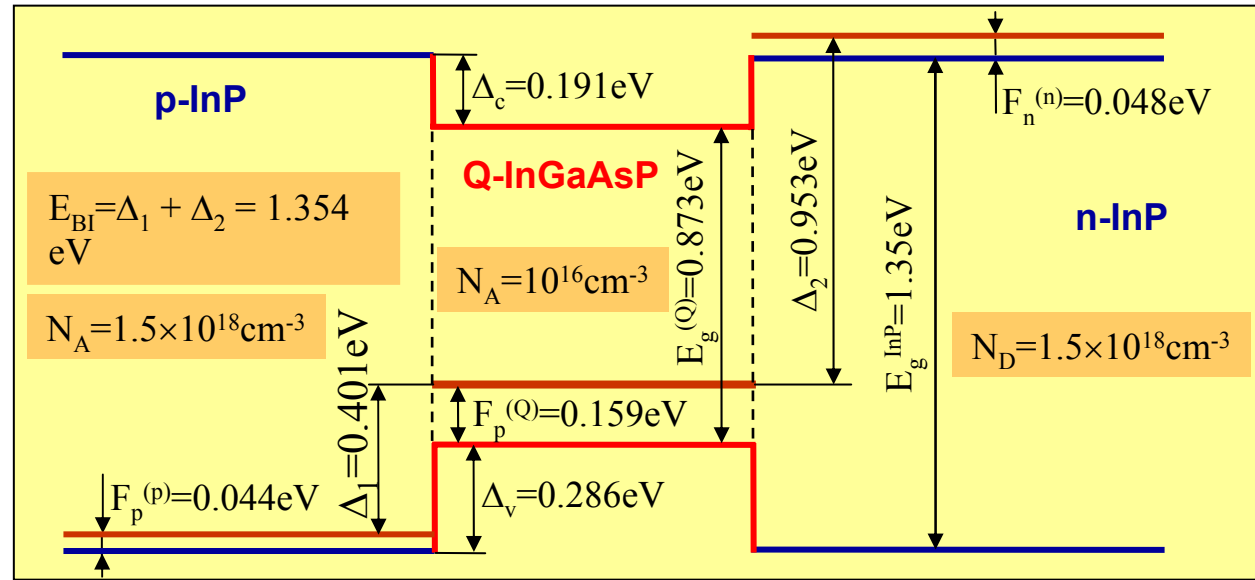
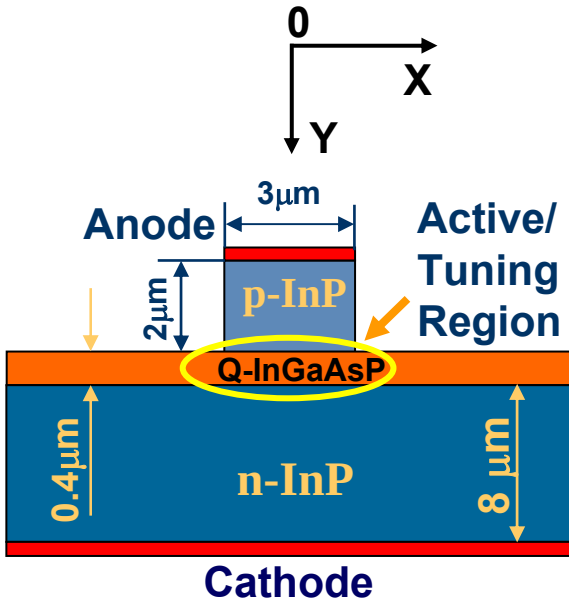
MOTIVATION

Multi-Section Tunable Laser Diode:



- Wavelength tuning is achieved via change of the electronic part of the dielectric function in the passive part of the waveguide.
- The main goal is to obtain maximum free-carrier density for a given injection currents $I_{\text{DBR}}/I_{\text{Phase}}$ or bias.

GEOMETRY AND PARAMETERS



Mobilities: InP: $\mu_n^{\text{n-InP}} = \mu_n^{\text{p-InP}} = 1250 \text{ cm}^2/\text{V}\cdot\text{s}$; $\mu_p^{\text{p-InP}} = \mu_p^{\text{n-InP}} = 100 \text{ cm}^2/\text{V}\cdot\text{s}$;

Q-InGaAsP: $\mu_n^{(Q)} = 4000 \text{ cm}^2/\text{V}\cdot\text{s}$; $\mu_p^{(Q)} = (200, 100, 50) \text{ cm}^2/\text{V}\cdot\text{s}$;

Recombination: InP: $\tau_{\text{SRH}} = 100 \times 10^{-9} \text{ s}$; Radiative: $C = 1 \times 10^{-10} \text{ cm}^3/\text{s}$; Auger: $C_n = C_p = 1 \times 10^{-30} \text{ cm}^6/\text{s}$;

Q-InGaAsP: $\tau_{\text{SRH}} = 20 \times 10^{-9} \text{ s}$; Radiative: $C = 1.2 \times 10^{-10} \text{ cm}^3/\text{s}$; Auger: $C_n = 0$, $C_p = 16 \times 10^{-29} \text{ cm}^6/\text{s}$;

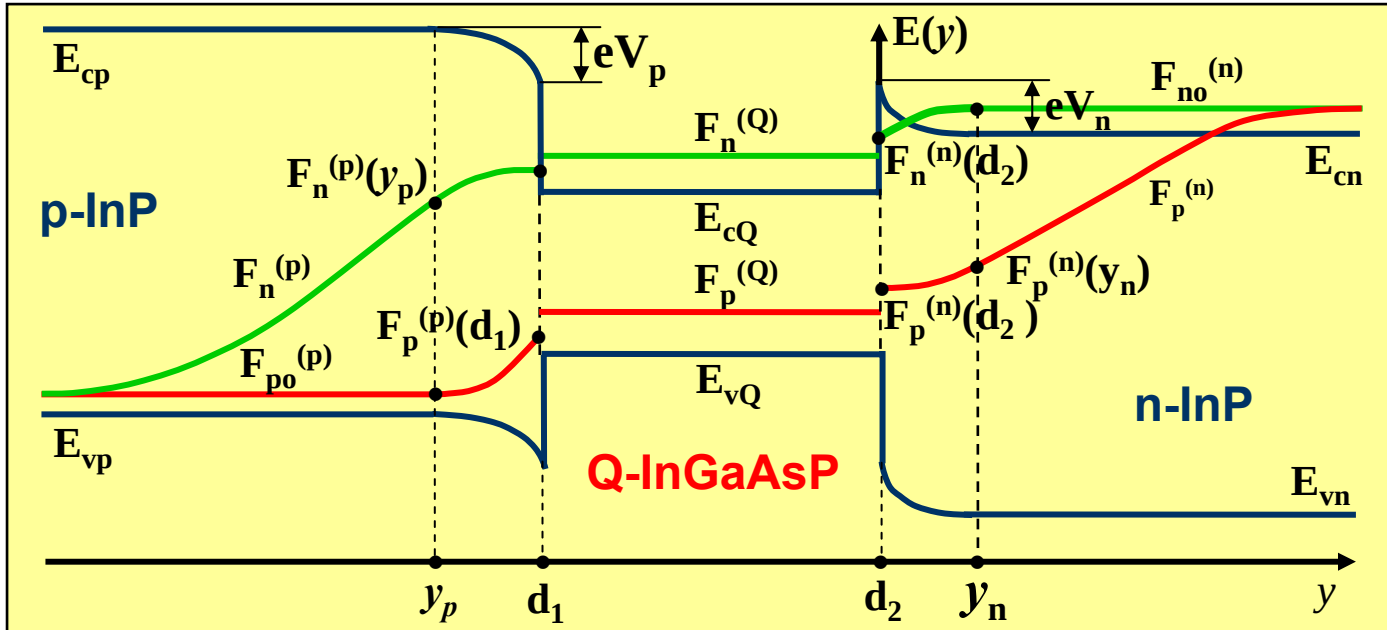
Effective masses: InP: $m_n = 0.078m_0$, $m_p = 0.7m_0$; Q-InGaAsP: $m_n = 0.052m_0$, $m_p = 0.50m_0$;

Ohmic contacts: $R = 0$; Room temperature: $T = 300 \text{ K}$; Abrupt doping profiles;

Built-in voltage: $V_{\text{bi}} = 1.35 \text{ V}$;

HETEROSTRUCTURE AT HIGH-INJECTION REGIME: THE FLAT-BAND CONDITIONS

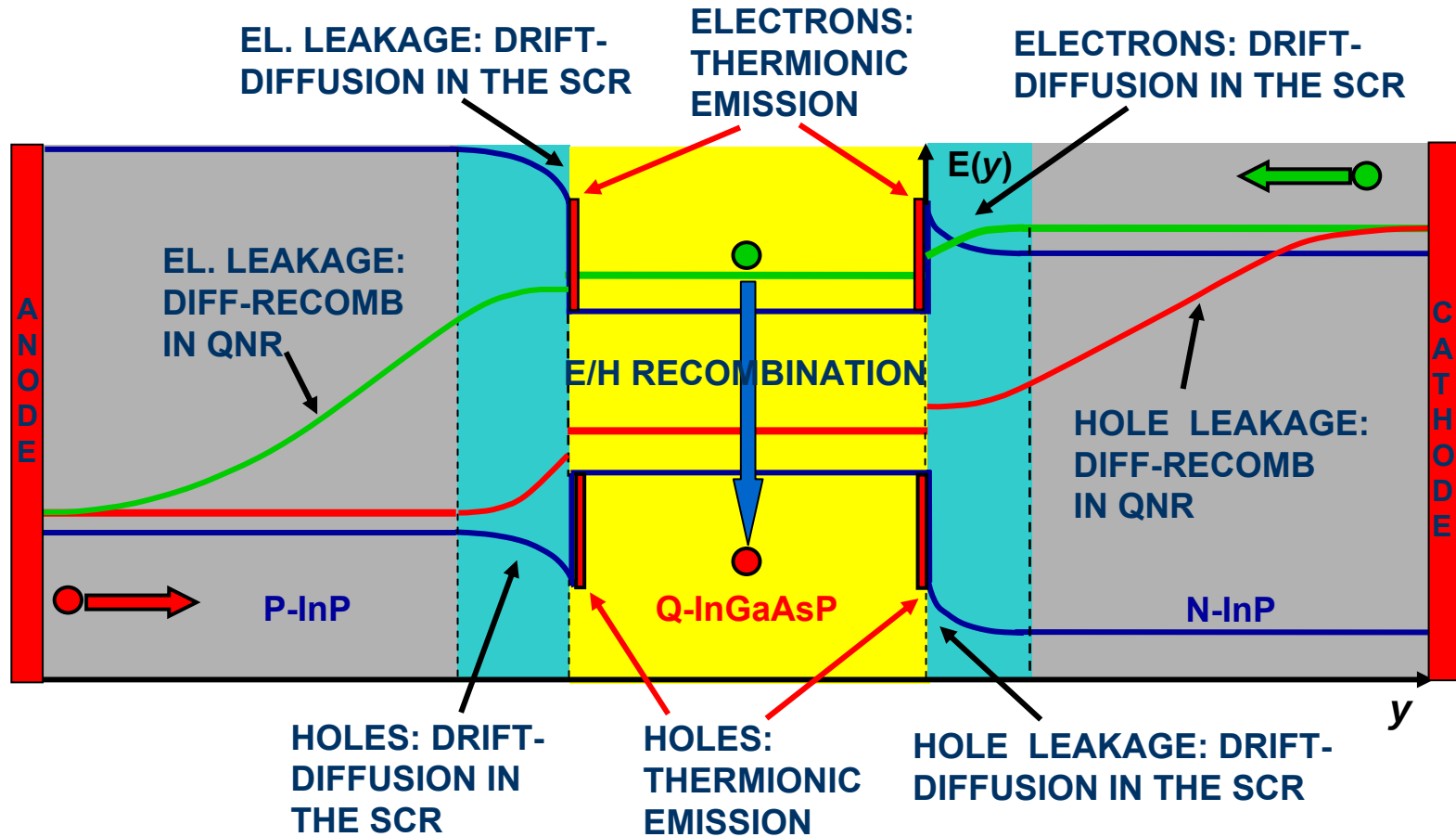
Schematic of Band Profile and e/h Quasi-Fermi Levels Used in Analytic Theory at High-Injection Regime: Most General Case



THE NECESSARY CONDITIONS (A. Grinberg, JAP 75 7669 (1994)):

1. $L_D \equiv \left(\frac{\varepsilon_Q k_o T}{4 \pi e^2 n_Q} \right)^{1/2} \ll d_Q$; (For $n \sim 10^{18} \text{ cm}^{-3}$: $L_D = 5 \text{ nm}$).
2. Voltage Drop Across Q-Layer: $e\Delta V_Q \ll k_o T$ (For $I \sim 50 \text{ mA}$, $e\Delta V_Q = 0.8 \text{ meV}$).
3. Quasi-Neutrality ($L_D \ll d_Q$) and Homogeneity ($L_{\text{Dif}} \gg d_Q$, $L_{\text{Dif}} \sim 1 \mu\text{m}$!).

BASIC TRANSPORT PROCESSES IN LASER DIODE



BASIC EQUATIONS (Electrons)

SET OF EQUATIONS FOR ELECTRON INJECTION CURRENT:

- Drift-Diffusion in the SCR in n-InP ($d_2 \leq y \leq y_n$):

$$-\frac{1}{e} \frac{dj_n^{DD}(y)}{dy} = G_n - R_n \approx 0.$$

$$j_n^{DD}(y) = \mu_n n_n(y) \frac{dF_n^{(n)}(y)}{dy}, \quad n_n(y) = N_c^{(n)} \exp\left(-\frac{E_c^{(n)}(y) - F_n^{(n)}(y)}{k_o T}\right)$$

- Boundary Conditions at n-InP/Q Interface: $j_n^{DD}(y = d_2) = j_n^{TE}.$

- Thermionic Emission Current at n-Inp/Q IF: $j_n^{TE} = -(j_n^{TE+} - j_n^{TE-}),$

$$j_n^{TE} = -A_n^* T^2 \alpha_n \exp\left(-\frac{\Delta_c + E_c^{(Q)}}{k_o T}\right) \left[\exp\left(-\frac{F_n^{(n)}(d_2^+)}{k_o T}\right) - \left(\frac{T_e}{T}\right)^2 \exp\left(-\frac{F_n^{(Q)}}{k_o T_e}\right) \right].$$

FERMI LEVEL DISCONTINUITY AT THE INTERFACE

Boundary condition at $y=d_2$ leads to the following expression:

$$F_n^{(n)}(d_2^-) =$$

$$k_o T \times$$

$$\ln \left[\frac{j_{no}^{DD} \exp \left(-\frac{F_{no}^{(n)}}{k_o T} \right) + j_{no}^{TE} \left(\frac{T_e}{T} \right)^2 \exp \left(-\frac{\Delta_c + E_c^{(Q)} - F_n^{(Q)}}{k_o T_e} \right) \exp \left(\frac{E_{cn}(d_2^-)}{k_o T} \right)}{j_{no}^{DD} + j_{no}^{TE}} \right],$$

where j_{no}^{DD} and j_{no}^{TE} are some characteristic drift - diffusion and thermionic emission currents defined on the next page.

SOLUTION OF BASIC EQUATIONS (Electrons)

ELECTRON INJECTION CURRENTS: DRIFT-DIFFUSION + TE EMISSION:

$$J_n^{(n)} = -J_{no} \left[\exp \left(- \frac{E_{co}^{(n)} - F_{no}^{(n)} + eV_n}{k_o T} \right) - \left(\frac{T_e}{T} \right)^2 \exp \left(- \frac{\Delta_c + E_c^{(Q)} - F_n^{(Q)}}{k_o T_e} \right) \right]$$

$$J_{no} = \left(\frac{1}{j_{no}^{DD}} + \frac{1}{j_{no}^{TE}} \right)^{-1} \quad \Leftarrow$$

The smallest current defines the injection bottleneck !

$$J_{no}^{DD} = eD_n \frac{N_c^{(n)}}{L_{Deb}^{(n)}} F \left(\frac{eV_n}{k_o T} \right),$$

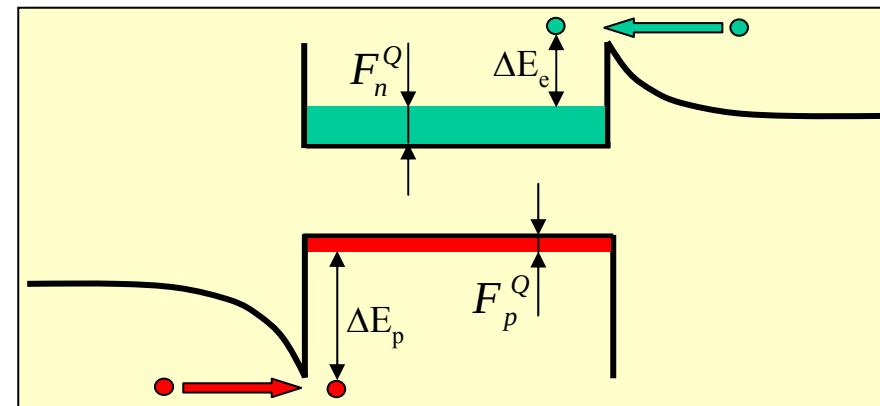
$$L_{Deb}^{(n)} = \left(\frac{\varepsilon k_o T}{4 \pi e^2 N_D^{(n)}} \right)^{1/2} \quad \text{- Debye's length}$$

$$J_{no}^{TE} = A_n^* T^2 \alpha_n = A_o^* \frac{m_n^*}{m_o} T^2 \alpha_n,$$

$$A_o^* = 120 \text{ A/cm}^2 \text{K}^2 \quad \text{- Richardson's constant}$$

Incorporation of injection heating into the model: Injection of e/h results in supply of the excess energy into the Q-layer:

$\Delta E_{e(p)} \approx 0.1\text{-}0.2 \text{ eV/carrier}$. This in turn leads to increase of the e/h temperature in Q-layer and increase of thermionic emission from the Q-layer.



DESCRIPTION OF VERTICAL LEAKAGE CURRENTS

- **Drift-Diffusion in the SCR in p-InP ($y_p \leq y \leq d_1$):**

$$-\frac{1}{e} \frac{dj_{nl}^{DD}(y)}{dy} = G_n - R_n \approx 0.$$

$$j_{nl}^{DD}(y) = \mu_n^{(p)} n_n^{(p)}(y) \frac{dF_n^{(p)}(y)}{dy}, \quad n_n^{(p)}(y) = N_c^{(p)} \exp\left(-\frac{E_c^{(p)}(y) - F_n^{(p)}(y)}{k_o T}\right)$$

- **Boundary Conditions at Q/p-InP interface:** $j_{nl}^{DD}(y = d_1^-) = j_{nl}^{TE}.$

- **Thermionic Emission Leakage Current:** $j_{nl}^{TE} = -\left(j_{nl}^{TE}(+) - j_{nl}^{TE}(-)\right).$

- **Diffusion-Recombination Leakage Current in the QNR ($y \leq y_p$):**

$$j_{nl}^{DR} = j_{nlo}^{DR} \exp\left(-\frac{E_c^{(p)}(-\infty) - F_n^{(p)}(y_p)}{k_o T}\right),$$

- **Boundary condition at the QNR edge:** $j_{nl}^{DD}(y = y_p) = j_{nl}^{DR}(y = y_p).$

EXPRESSIONS FOR ELECTRON LEAKAGE CURRENTS

$$J_{nl}^{(p)} = -J_{nlo} \left[\left(\frac{T_e}{T} \right)^2 \exp \left(- \frac{\Delta_c + E_c^{(Q)} - F_n^{(Q)}}{k_o T_e} \right) \right] \exp \left(- \frac{eV_p}{k_o T} \right)$$

$$J_{nlo} = \left(\frac{1}{J_{nlo}^{TE}} + \frac{1}{J_{nlo}^{DD}} + \frac{1}{J_{nlo}^{DR}} \right)^{-1}$$

The Smallest Current Defines the Leakage !

$$J_{nlo}^{TE} = A_n^* T^2 \alpha_n \exp \left(\frac{eV_p}{k_o T} \right)$$

- **Thermionic Emission Leakage Current.**

$$J_{nlo}^{DD} = e D_n^{(p)} \frac{N_c^{(p)}}{L_{Deb}^{(p)}} R \left(\frac{eV_p}{k_o T} \right)$$

- **Drift-Diffusion Leakage Current.**

$$j_{nlo}^{DR} = e \frac{D_n^{(p)}}{L_n^{(p)}} N_c^{(p)} \coth \left(\frac{d_p}{L_n^{(p)}} \right)$$

- **Diffusion-Recombination Leakage Current.**

SET OF EQUATION FOR ACTIVE LAYER

•Continuity Equation in Q-layer:

$$-\frac{1}{e} \frac{dJ_n}{dy} = -R^{(Q)}(n, p)$$

•Electron Recombination Current:

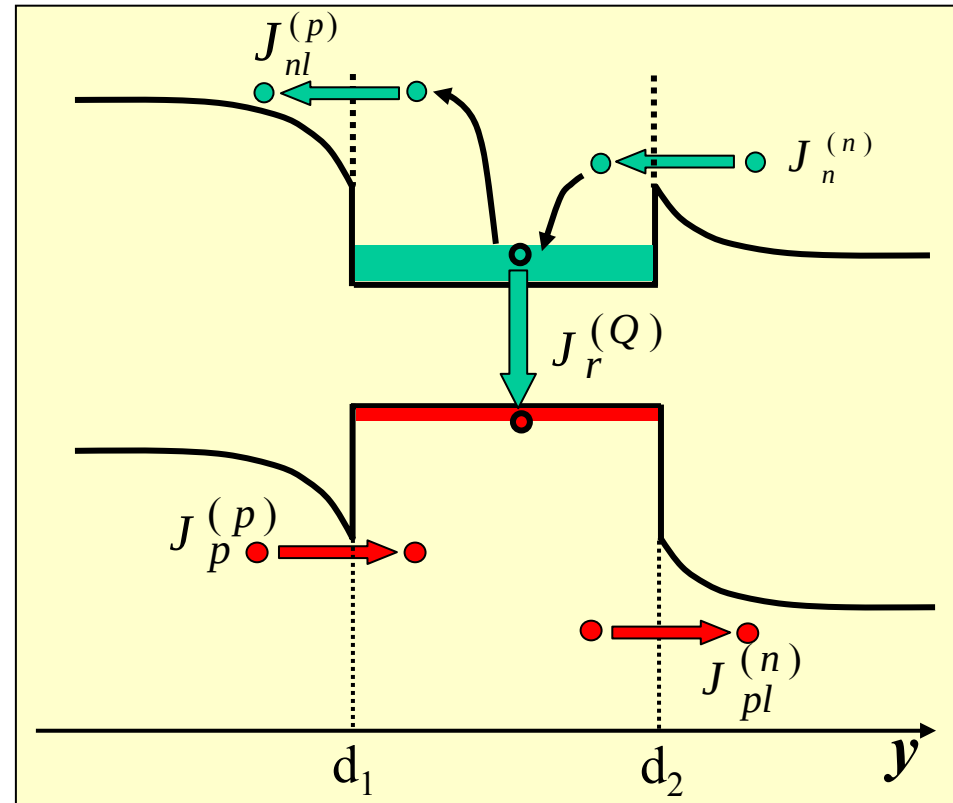
$$J_r = J_n^{(n)} - J_{nl}^{(p)}$$

•Total Recombination Current:

$$J_r^{(Q)} = -ed_Q R^{(Q)}(F_n^{(Q)}, F_p^{(Q)})$$

•Charge Quasi-Neutrality:

$$n^{(Q)}(F_n^{(Q)}) = p^{(Q)}(F_p^{(Q)})$$



The set of similar equations/expressions are derived for the injection and leakage currents of the holes.

The obtained equations contain three unknown variables:

The height of the barriers V_n and V_p , and the electron Fermi level F^Q .

SET OF EQUATION FOR V_n , V_p , $F_n^{(Q)}$

- The obtained equations contain three unknowns: eV_n , eV_p , and $F_n^{(Q)}$.
- Therefore there should be three equations:
 - $J_n^{(n)}(V_n, F_n^{(Q)}) - J_{nl}^{(p)}(V_p, F_n^{(Q)}) = J_r^{(Q)}(F_n^{(Q)})$
 - $J_p^{(p)}(V_p, F_n^{(Q)}) - J_{pl}^{(n)}(V_n, F_n^{(Q)}) = J_r^{(Q)}(F_n^{(Q)})$
 - $eV = E_g^{InP} + [F_{no}^{(n)} - E_{co}^{(n)}] + [E_{vo}^{(p)} - F_{po}^{(p)}] - eV_n - eV_p$
- The third equation was obtained using the flat-band conditions (see energy band diagram).

INCORPORATION OF LASING REGIME

$$J_n^{(n)} - J_n^{(p)} = -ed \left[R_{ps}(n) - G(n, \omega) P_k \right],$$

$$J_p^{(p)} - J_p^{(n)} = -ed \left[R_{ps}(n) - G(n, \omega) P_k \right],$$

$$n = n_{th} \quad \Leftrightarrow \quad G(n_{th}, \omega_p) = c_g \alpha_L(n_{th}),$$

$$\omega = \omega_p \quad \Leftrightarrow \quad \partial G(n, \omega) / \partial \omega = 0,$$

$$G(n, \omega) = c_g \alpha(\omega) \left[F_n(\omega) + F_p(\omega) - 1 \right],$$

$$J_o = J_n^{(n)} - J_p^{(n)}, \quad J_o = J_p^{(p)} - J_n^{(p)},$$

$$\Rightarrow P_k(J_o).$$

(A. Grinberg, 1994)

NUMERICAL VALUES OF CHARACTERISTIC CURRENTS FOR InP/InGaAsP LASER

$$J_{no} = \left(\frac{1}{j_{no}^{DD}} + \frac{1}{j_{no}^{TE}} \right)^{-1} \quad J_{nlo} = \left(\frac{1}{J_{nlo}^{TE}} + \frac{1}{J_{nlo}^{DD}} + \frac{1}{J_{nlo}^{DR}} \right)^{-1}$$

$$J_{no}^{DD} = 8.404 \cdot 10^6 \text{ (A / cm}^2\text{)} \times F \left(\frac{eV_n}{k_o T} \right); \quad J_{po}^{DD} = 10.5 \cdot 10^6 \text{ (A / cm}^2\text{)} \times F \left(\frac{eV_p}{k_o T} \right).$$

$$J_{no}^{TE} = 8.631 \times 10^5 \text{ (A/cm}^2\text{)}; \quad J_{po}^{TE} = 5.397 \times 10^6 \text{ (A/cm}^2\text{)}.$$

$$J_{nlo}^{DD} = 8.404 \cdot 10^6 \text{ (A / cm}^2\text{)} \times R \left(\frac{eV_p}{k_o T} \right); \quad J_{plo}^{DD} = 10.5 \cdot 10^6 \text{ (A / cm}^2\text{)} \times R \left(\frac{eV_n}{k_o T} \right).$$

$$J_{nlo}^{TE} = 8.631 \times 10^5 \text{ (A/cm}^2\text{)}; \quad J_{plo}^{TE} = 5.397 \times 10^6 \text{ (A/cm}^2\text{)}.$$

$$J_{nlo}^{DR} = 1.575 \times 10^4 \text{ (A / cm}^2\text{)} \quad J_{plo}^{DR} = 3.241 \times 10^4 \text{ (A / cm}^2\text{)}$$

$$J_r^{(Q)} = 0.61 \times 10^2 \left(\frac{\text{A}}{\text{cm}^2} \right) \left[\tilde{A}_{\text{SRH}} \times \tilde{n} + \tilde{B}_{\text{Rad}} \times \tilde{n}^2 + \tilde{C}_{\text{Aug}} \times \tilde{n}^3 \right], \quad n = \tilde{n} \times 10^{17} \text{ cm}^{-3}$$

$$A = \tilde{A} \times 10^8 \text{ s}^{-1}; \quad B = \tilde{B} \times 10^{-10} \text{ cm}^3/\text{s}; \quad C = \tilde{C} \times 10^{-29} \text{ cm}^6/\text{s}. \quad (\tilde{A}=1, \quad \tilde{B}=2, \quad \tilde{C}=16).$$

SIMPLIFIED ANALYTICAL I(V) CHARACTERISTICS OF DH LASER DIODE

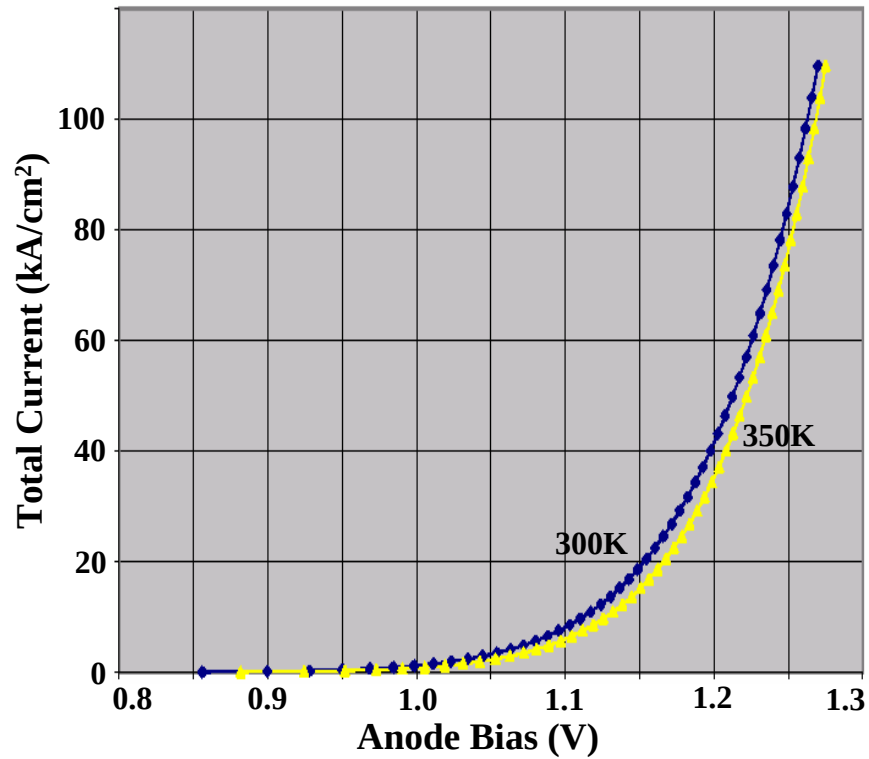
APPROXIMATIONS:

- Neglecting Leakage Currents
- Neglecting Injection Heating
- Assuming Thermionic Emission is a bottleneck

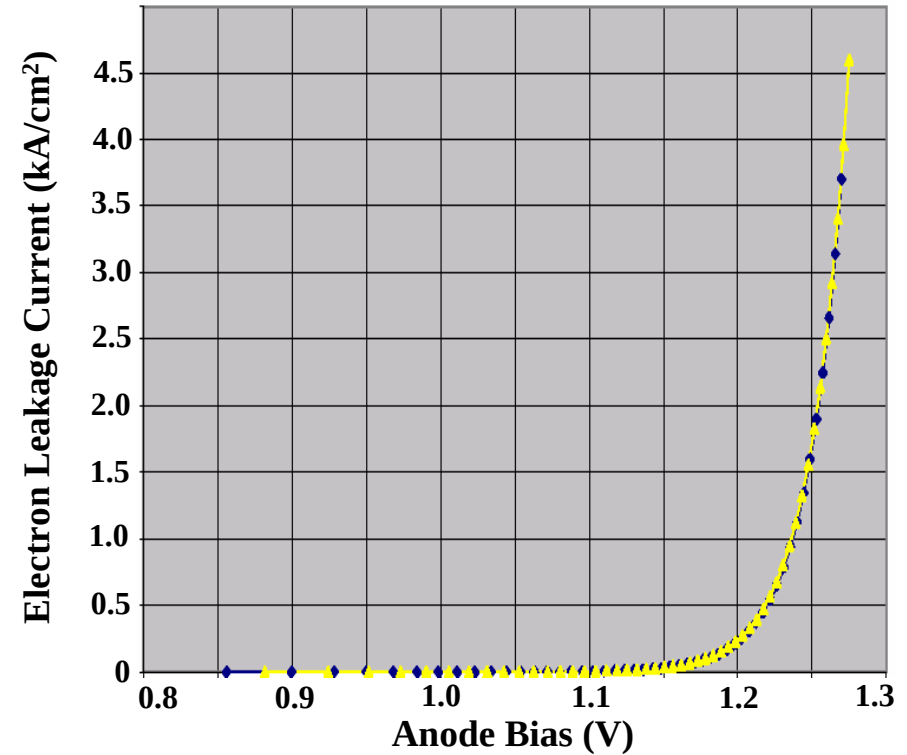
$$J = \sqrt{A_n A_p} T^2 e^{-\frac{E_g^{\text{InP}}}{2k_o T}} \left[1 - e^{-\frac{\Delta_c + F_n^{(n)} - F_n^{(Q)} - eV_n}{k_o T}} \right]^{1/2} e^{\frac{eV}{2k_o T}}.$$

RESULTS FROM ANALYTICAL THEORY: I-V CHARACTERISTICS

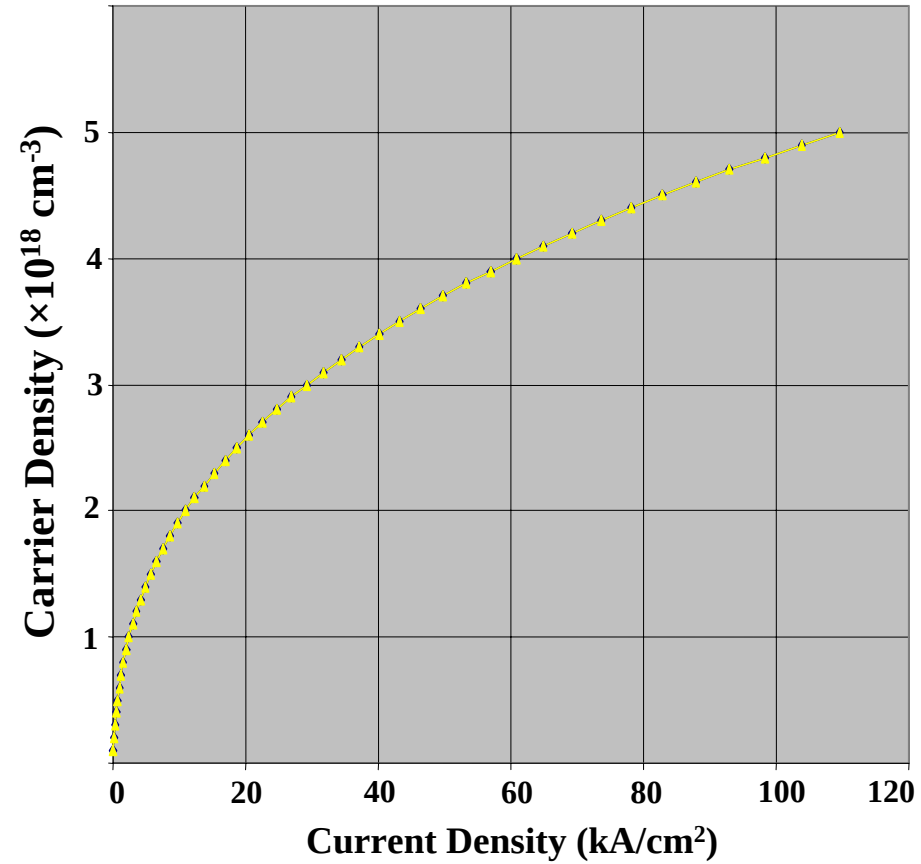
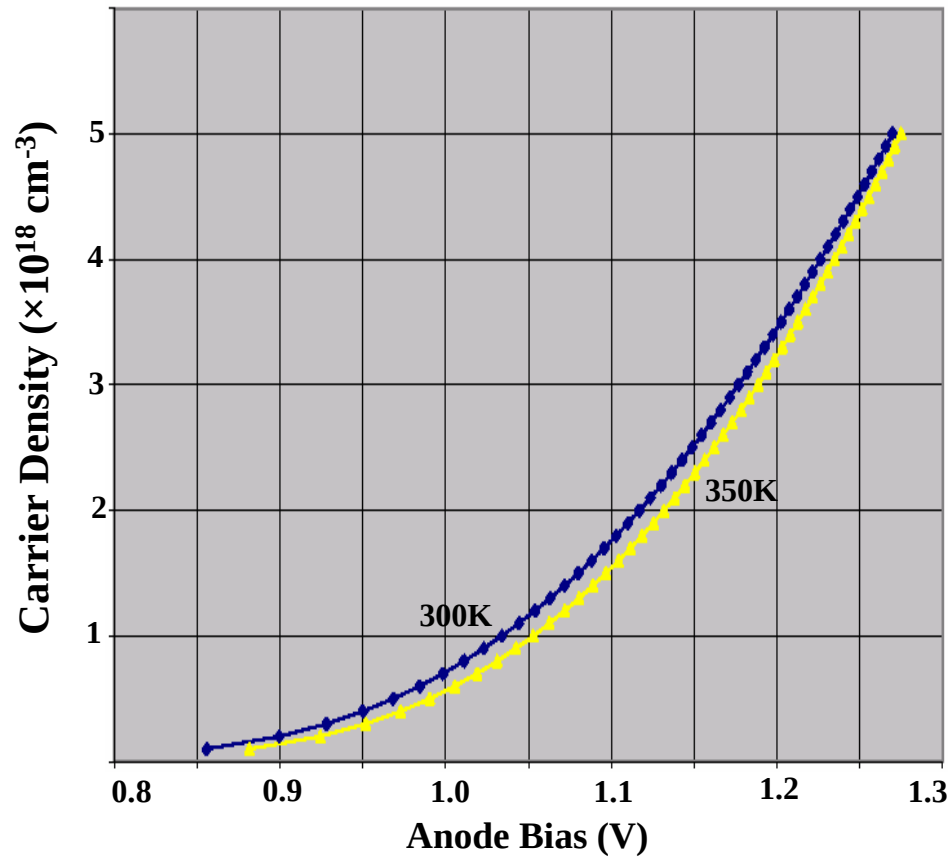
I-V Characteristics



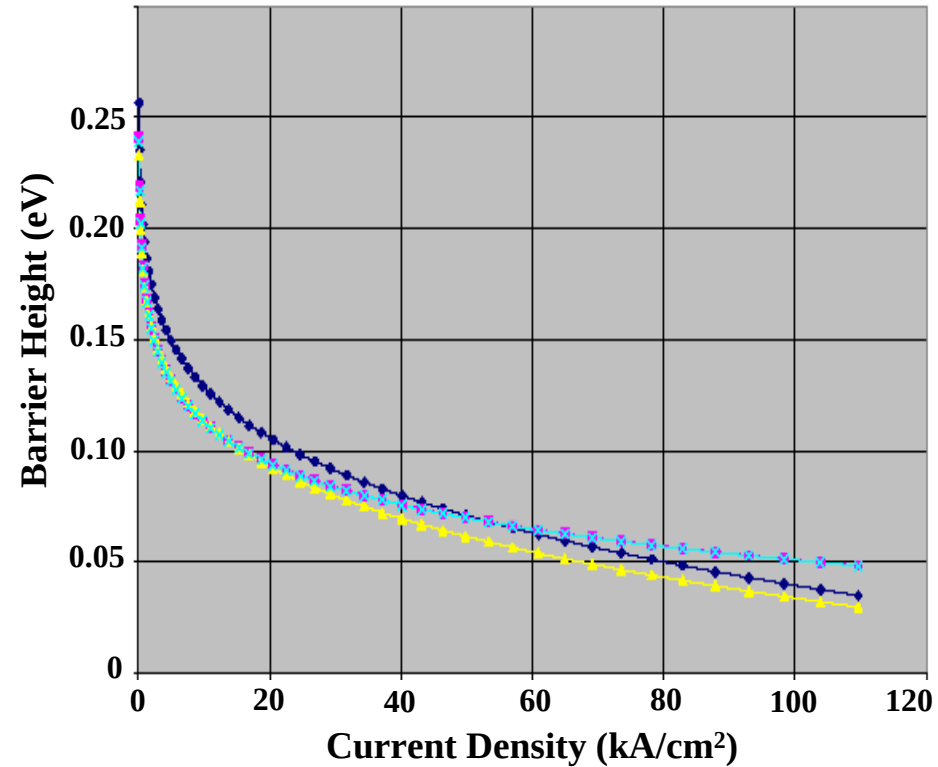
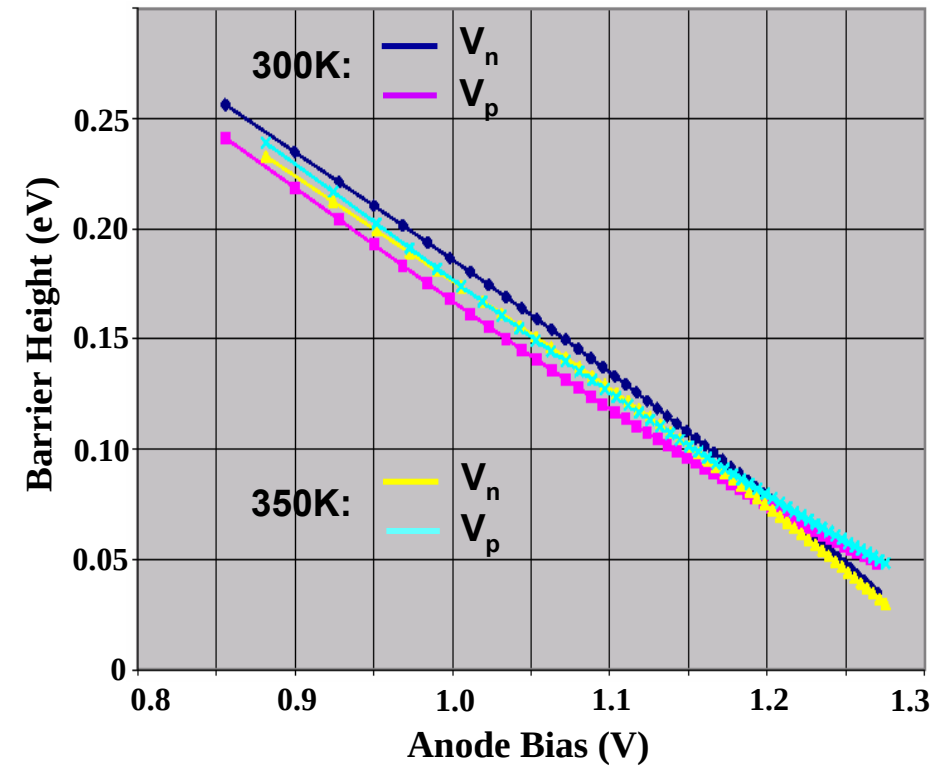
Vertical Leakage Current



RESULTS FROM ANALYTICAL THEORY: CARRIER DENSITY

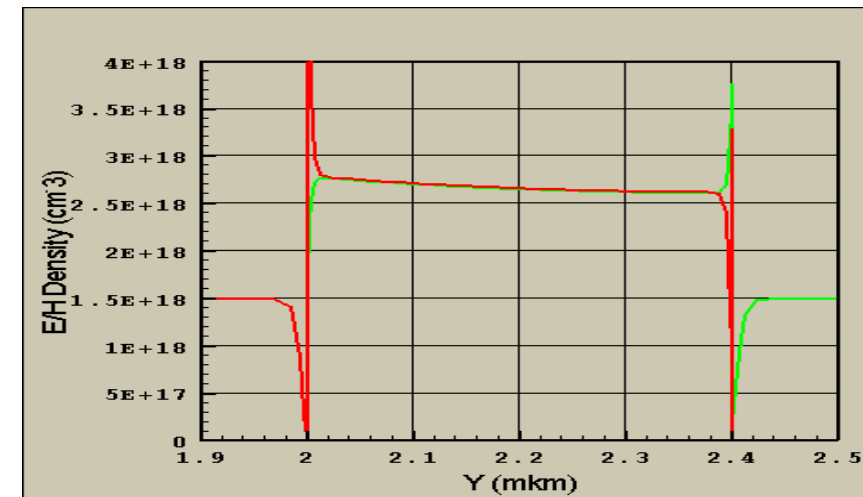
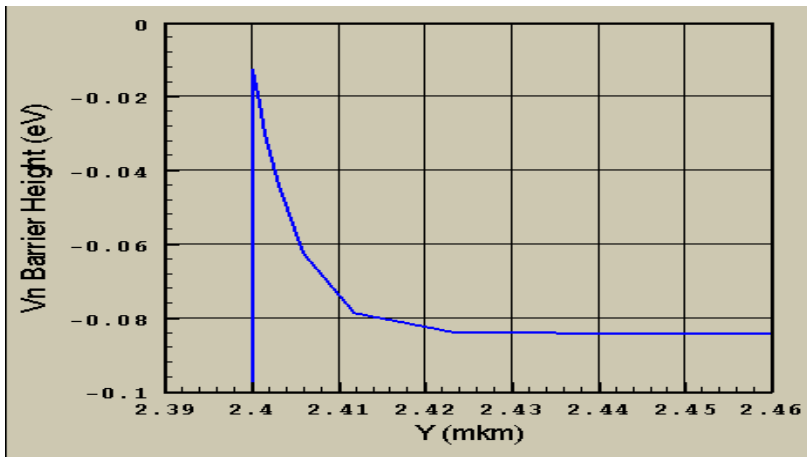
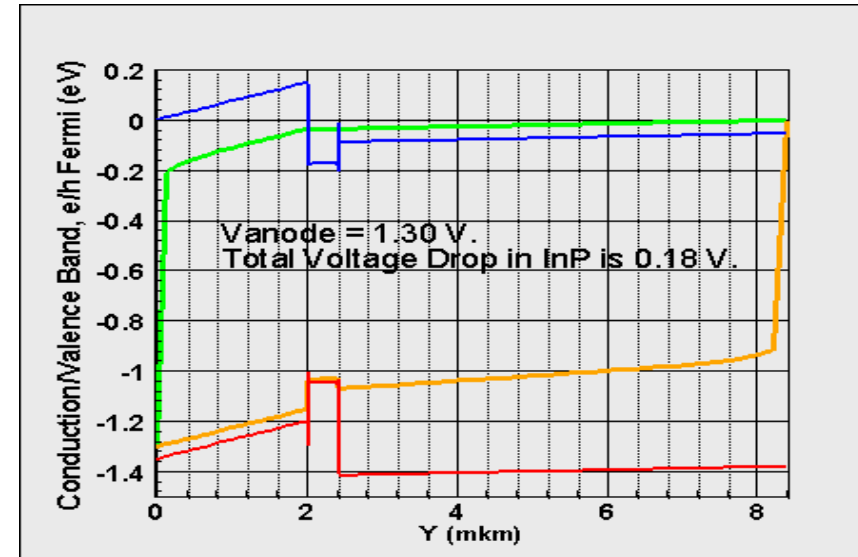
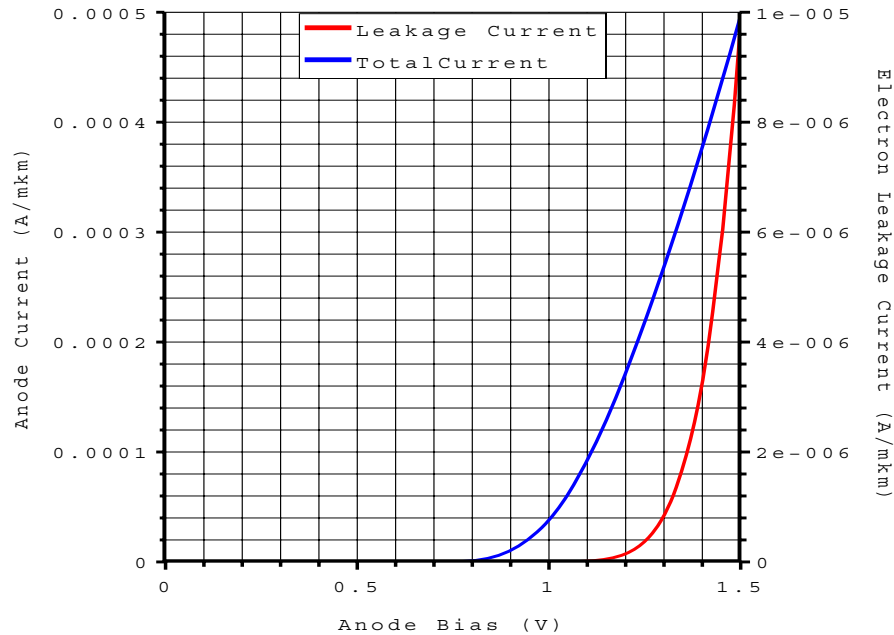


RESULTS FROM ANALYTICAL THEORY: V_n , V_p BARIERS



DESSIS SIMULATION – IDEAL 1D CASE

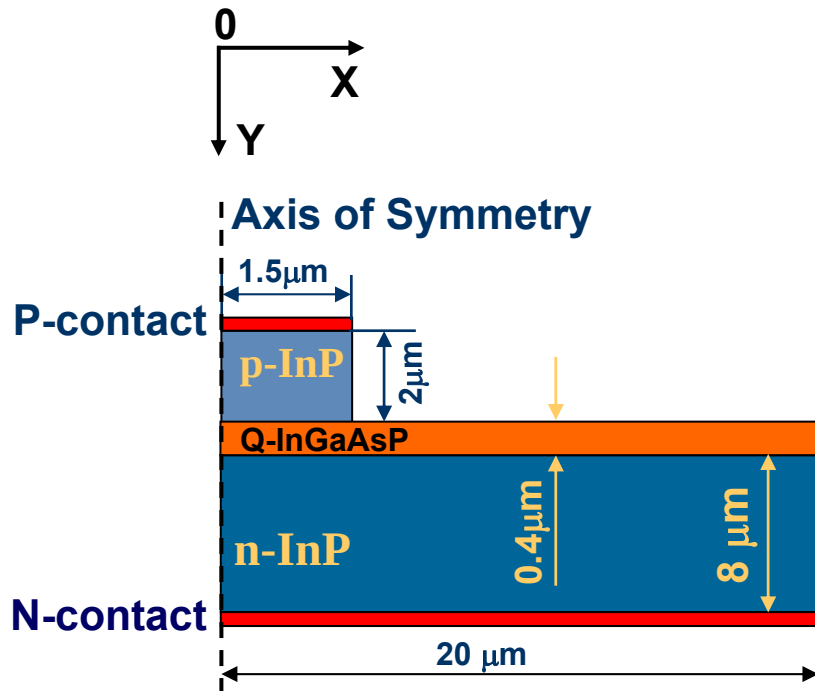
There is a very good agreement with analytical results if voltage drop in InP is taken into account.



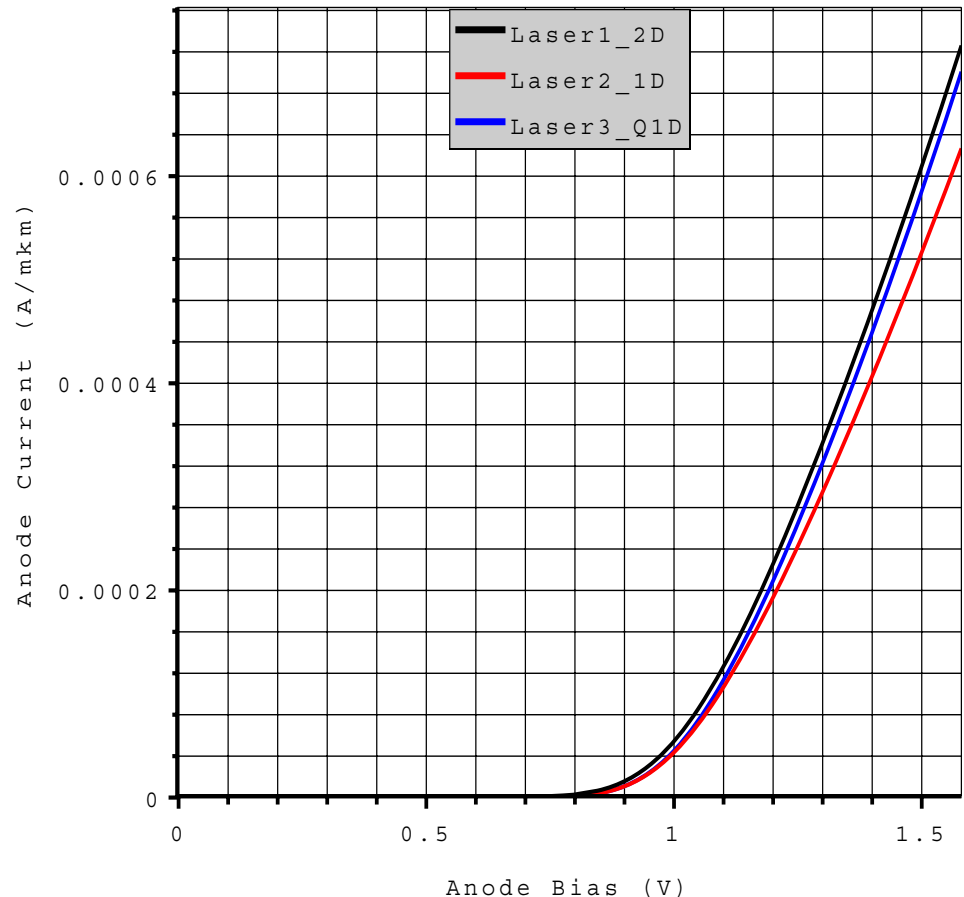
DESSIS – 2D SIMULATION (Below Threshold)

Results for three different geometries with the same material parameters:

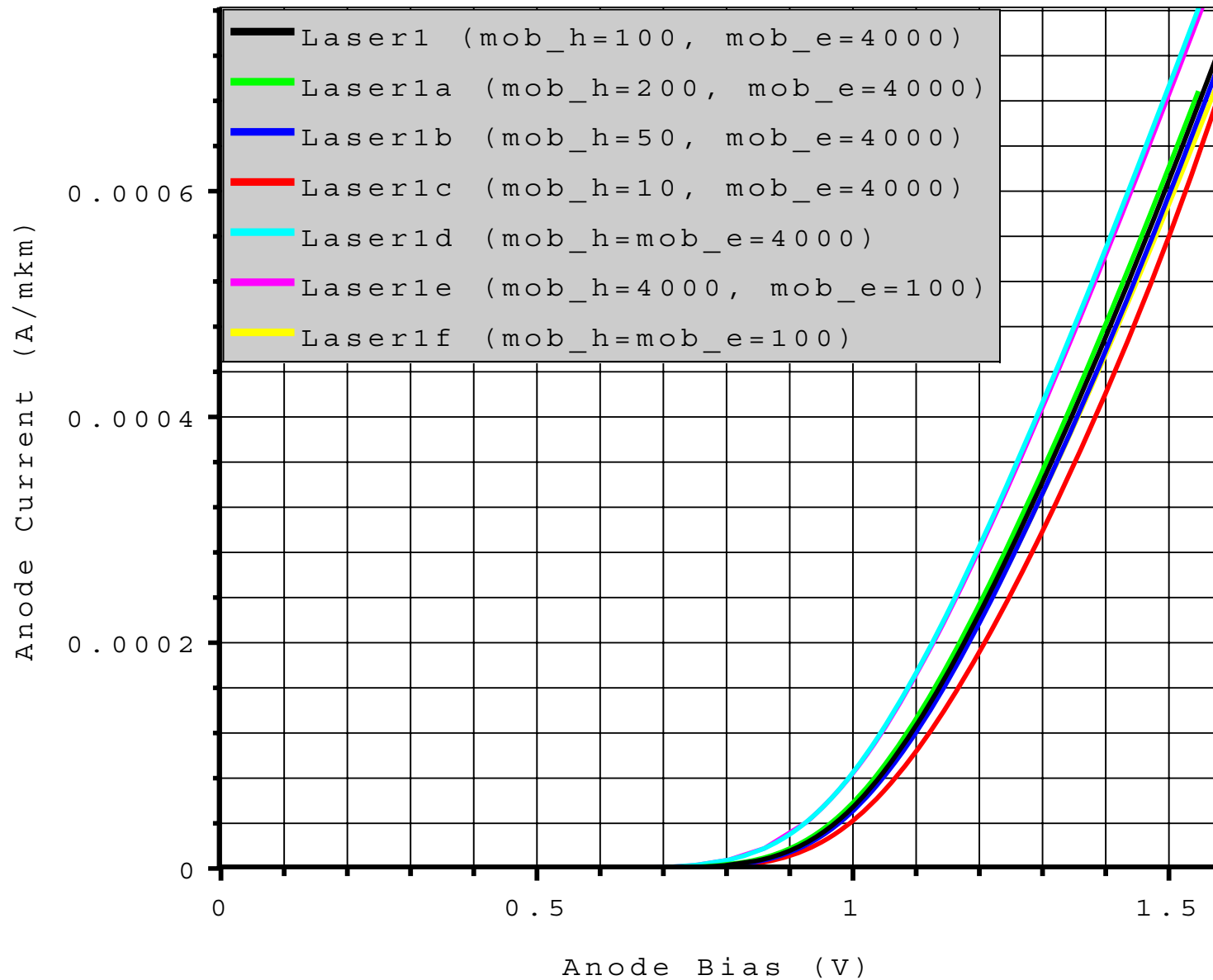
- 2D (as in the Figure);
- 1D (hypothetical device of constant width $w=3\mu\text{m}$);
- Quasi-1D (Q-InGaAsP width is $w=3\mu\text{m}$)



The I-V characteristics are almost identical for biases below 1.5 V.

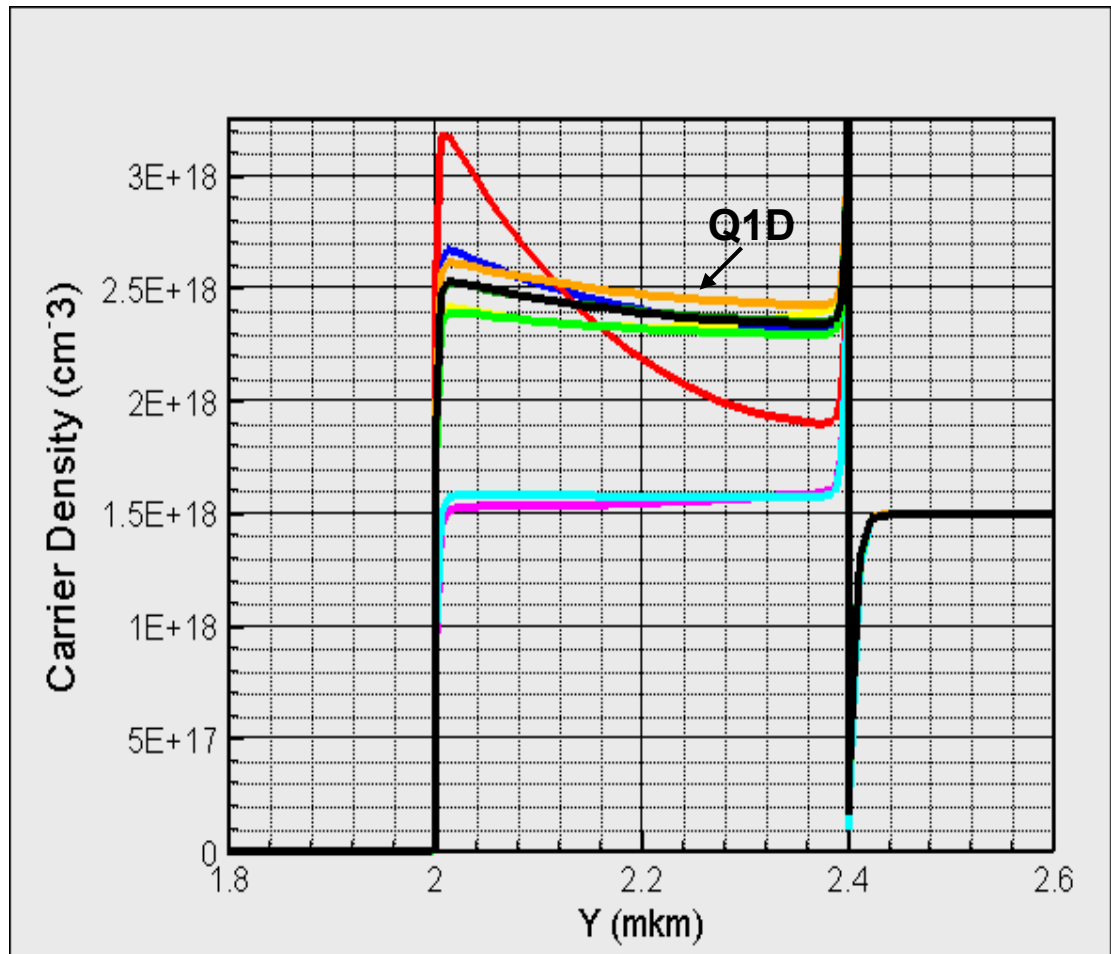
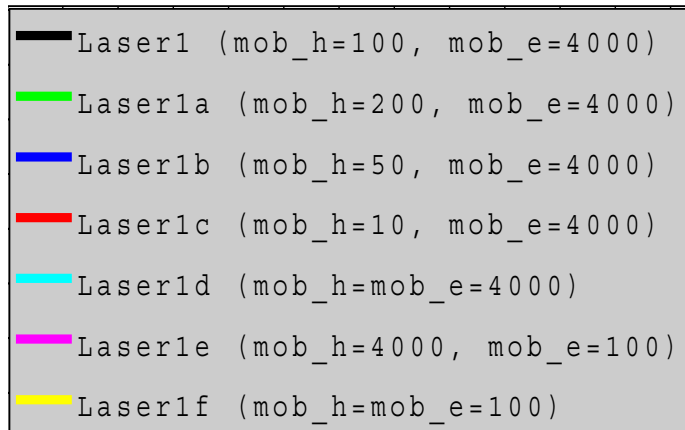


EFFECT OF ELECTRON/HOLE MOBILITIES IN Q-LAYER ON I-Vs



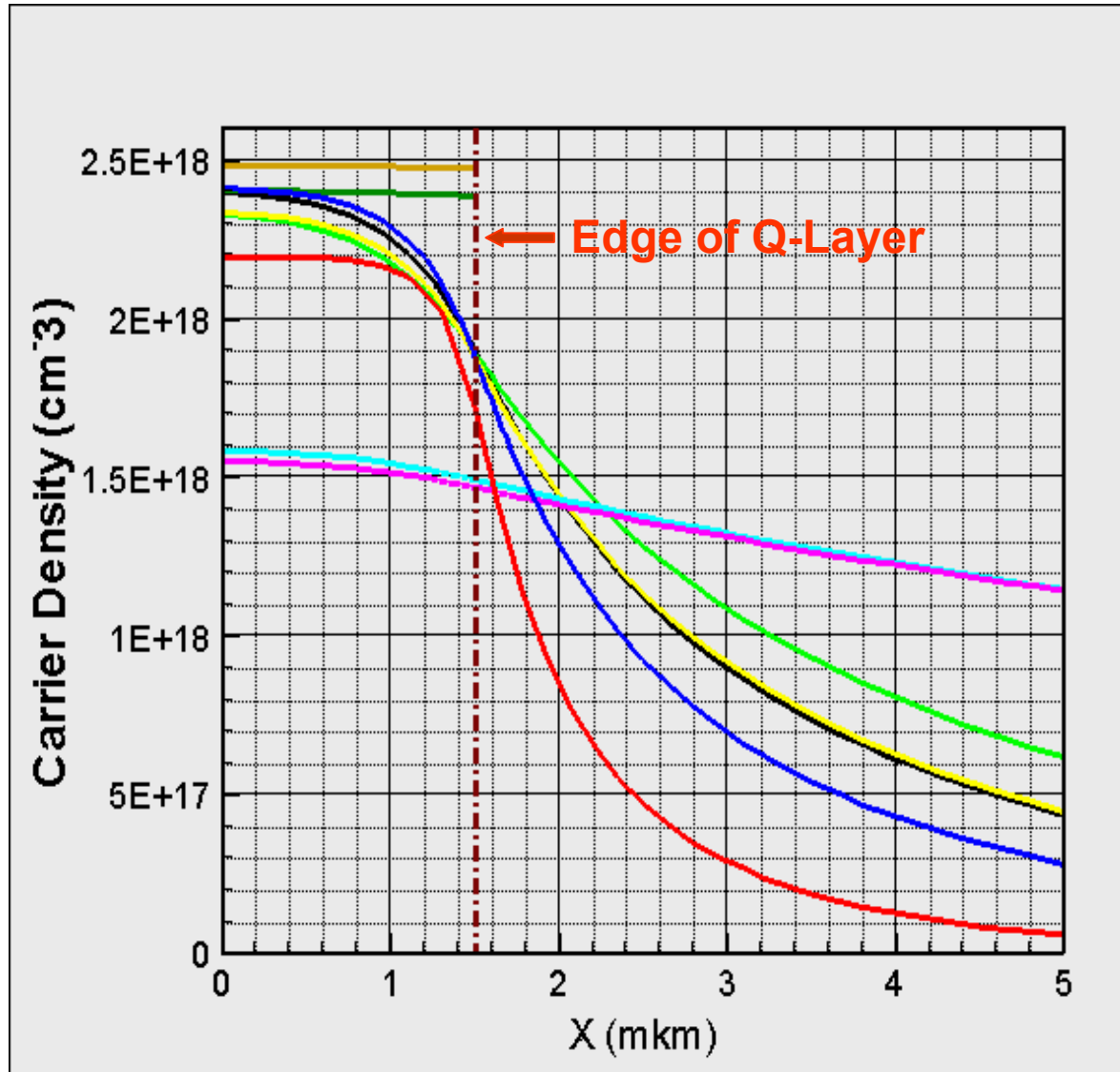
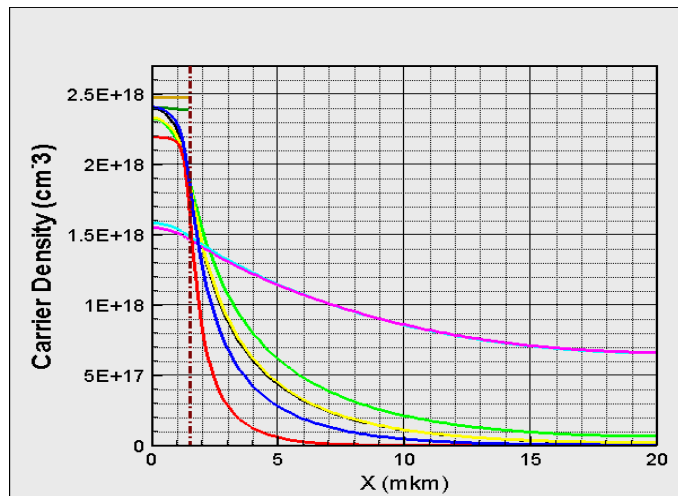
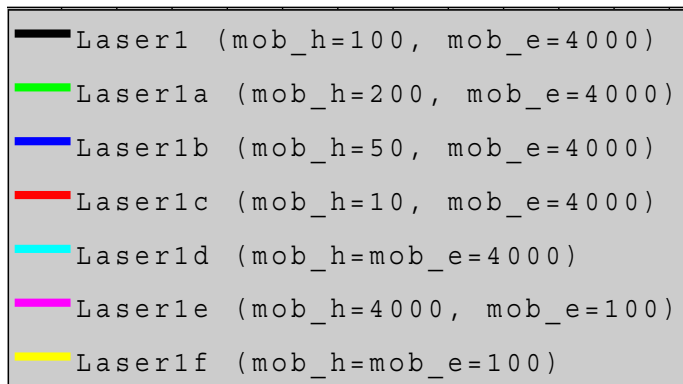
EFFECT OF ELECTRON/HOLE MOBILITIES IN Q-LAYER CARRIER DISTRIBUTION

**Distribution of the carriers
along Y-direction in the
cross-section plane
at $X=0.075\mu\text{m}$.**



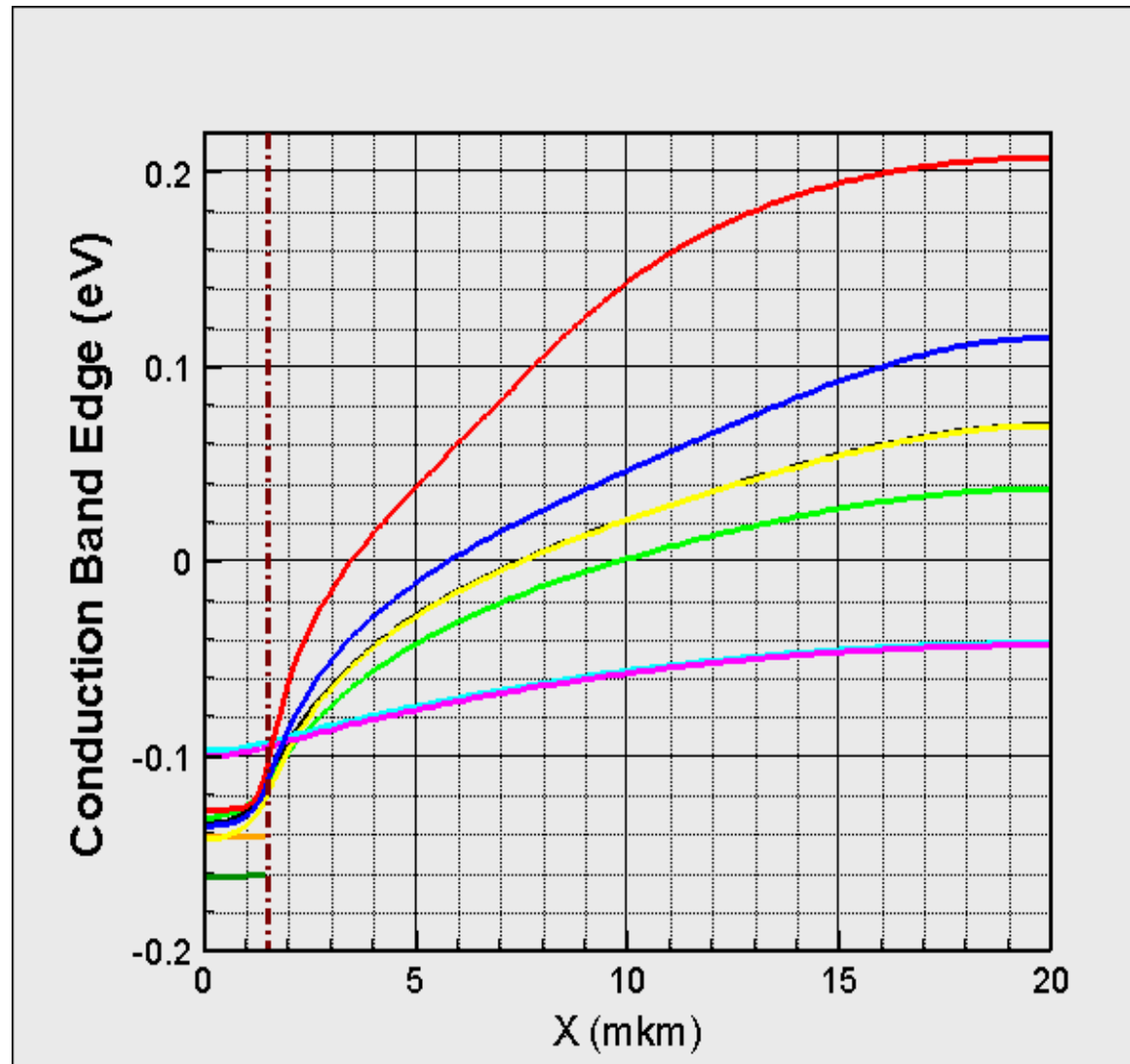
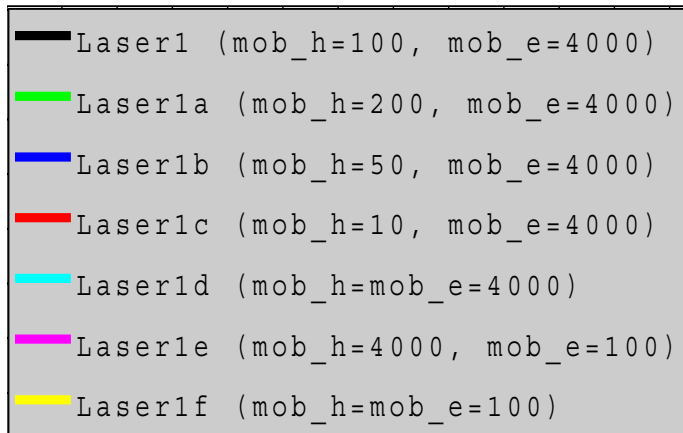
EFFECT OF ELECTRON/HOLE MOBILITIES IN Q-LAYER ON CARRIER DISTRIBUTION

Distribution of the carriers along X-direction in the cross-section plane at $Y=2.2\mu\text{m}$ (middle of Q).



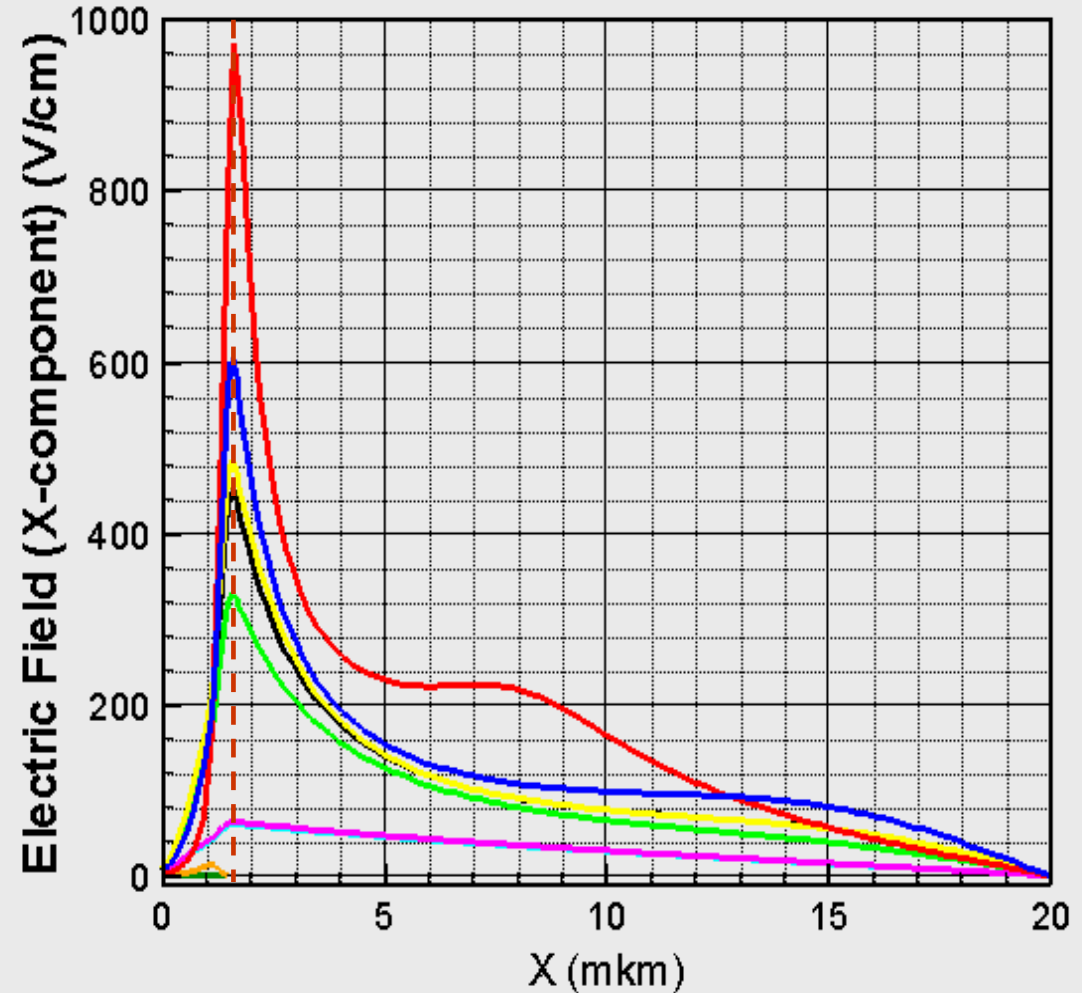
CONDUCTION BAND PROFILE ALONG Q-LAYER

Conduction band profile
along X-direction in the
cross-section plane
at $Y=2.2\mu\text{m}$ (middle of Q).



BUILT-IN ELECTRIC FIELD IN Q-LAYER: X-COMPONENT

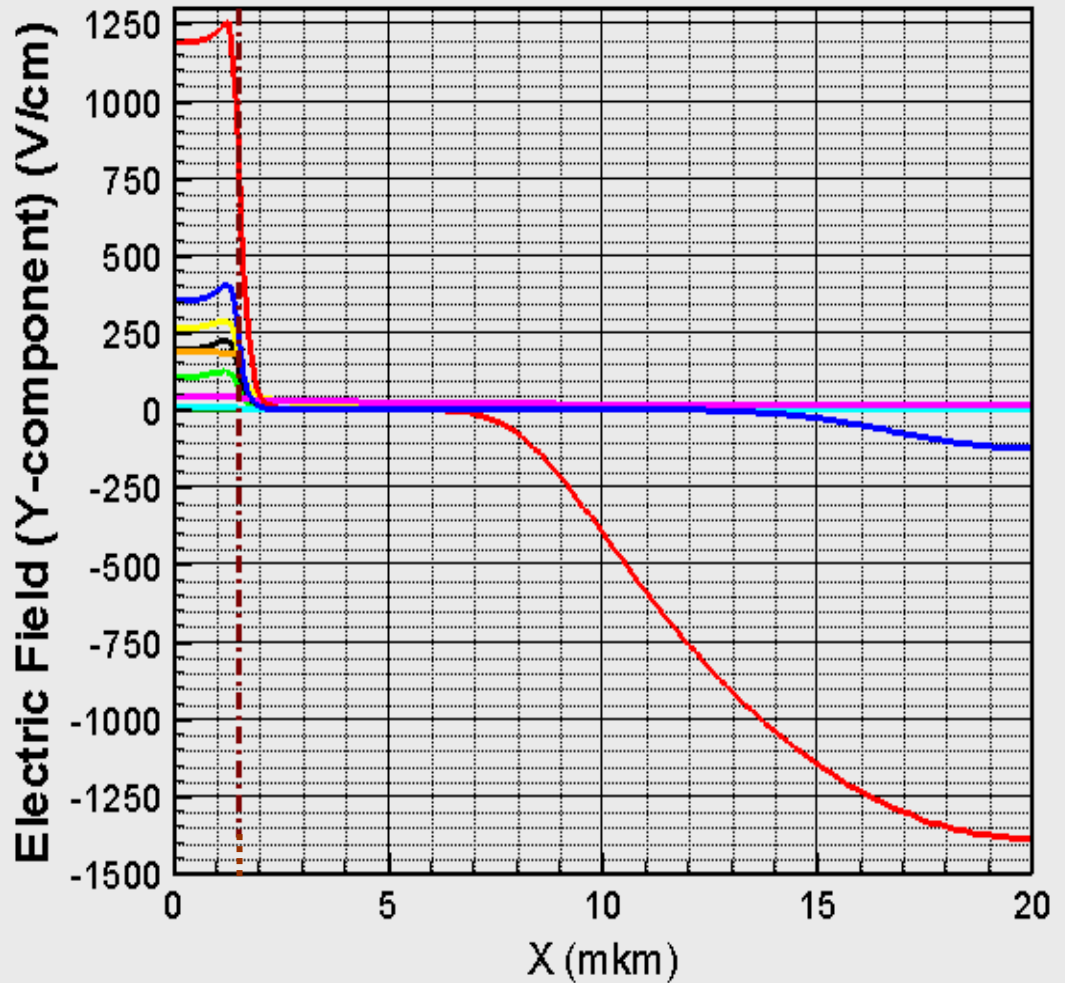
**Built-in electric field (E_x)
along X-direction in the
cross-section plane
at $Y=2.2\mu\text{m}$ (middle of Q).**



— Laser1 (mob_h=100, mob_e=4000)
— Laser1a (mob_h=200, mob_e=4000)
— Laser1b (mob_h=50, mob_e=4000)
— Laser1c (mob_h=10, mob_e=4000)
— Laser1d (mob_h=mob_e=4000)
— Laser1e (mob_h=4000, mob_e=100)
— Laser1f (mob_h=mob_e=100)

BUILT-IN ELECTRIC FIELD IN Q-LAYER: Y-COMPONENT

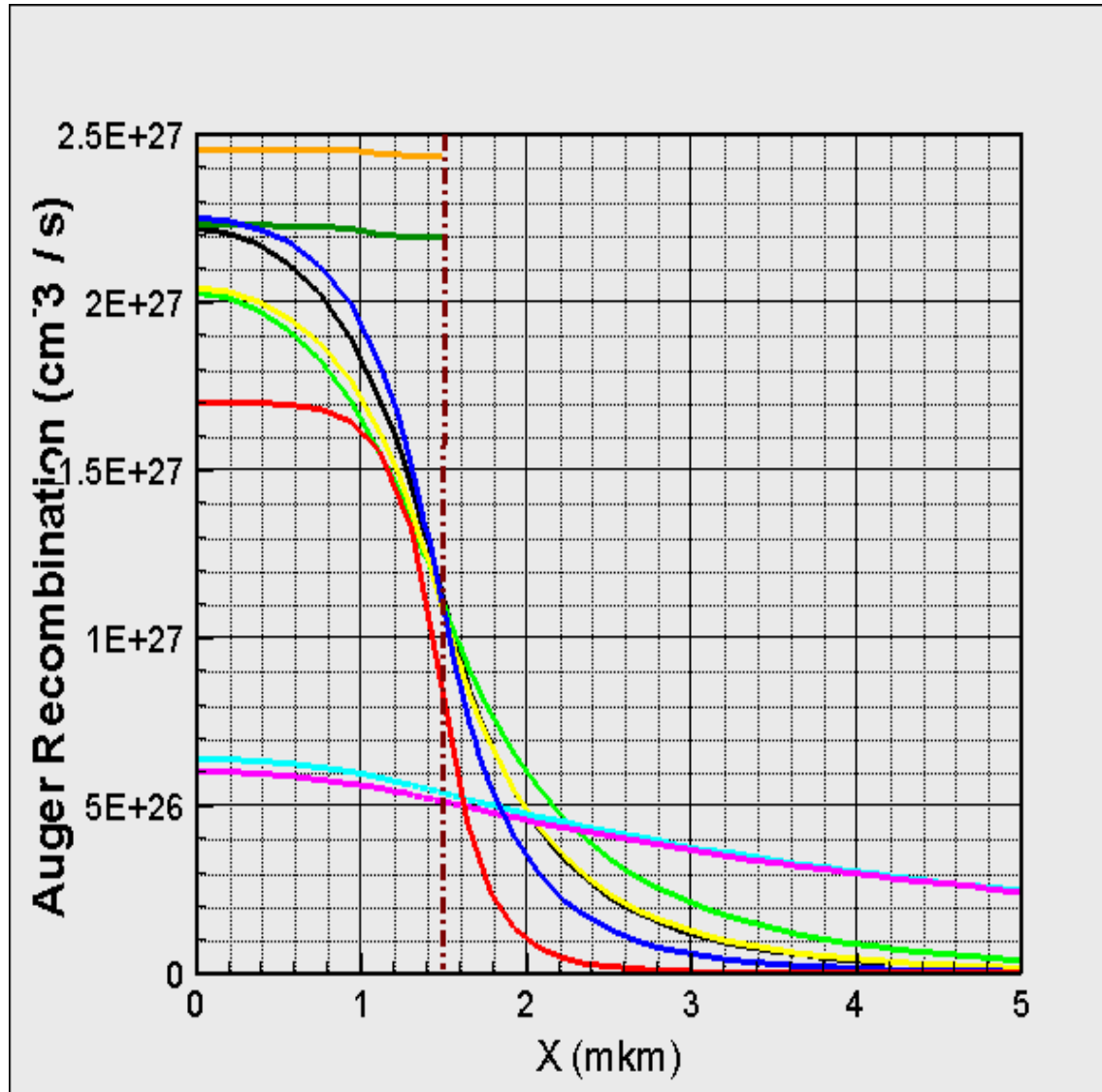
Built-in electric field (E_y)
along X-direction in the
cross-section plane
at $Y=2.2\mu\text{m}$ (middle of Q).



— Laser1 (mob_h=100, mob_e=4000)
— Laser1a (mob_h=200, mob_e=4000)
— Laser1b (mob_h=50, mob_e=4000)
— Laser1c (mob_h=10, mob_e=4000)
— Laser1d (mob_h=mob_e=4000)
— Laser1e (mob_h=4000, mob_e=100)
— Laser1f (mob_h=mob_e=100)

REDISTRIBUTION OF AUGER RECOMBINATION RATE

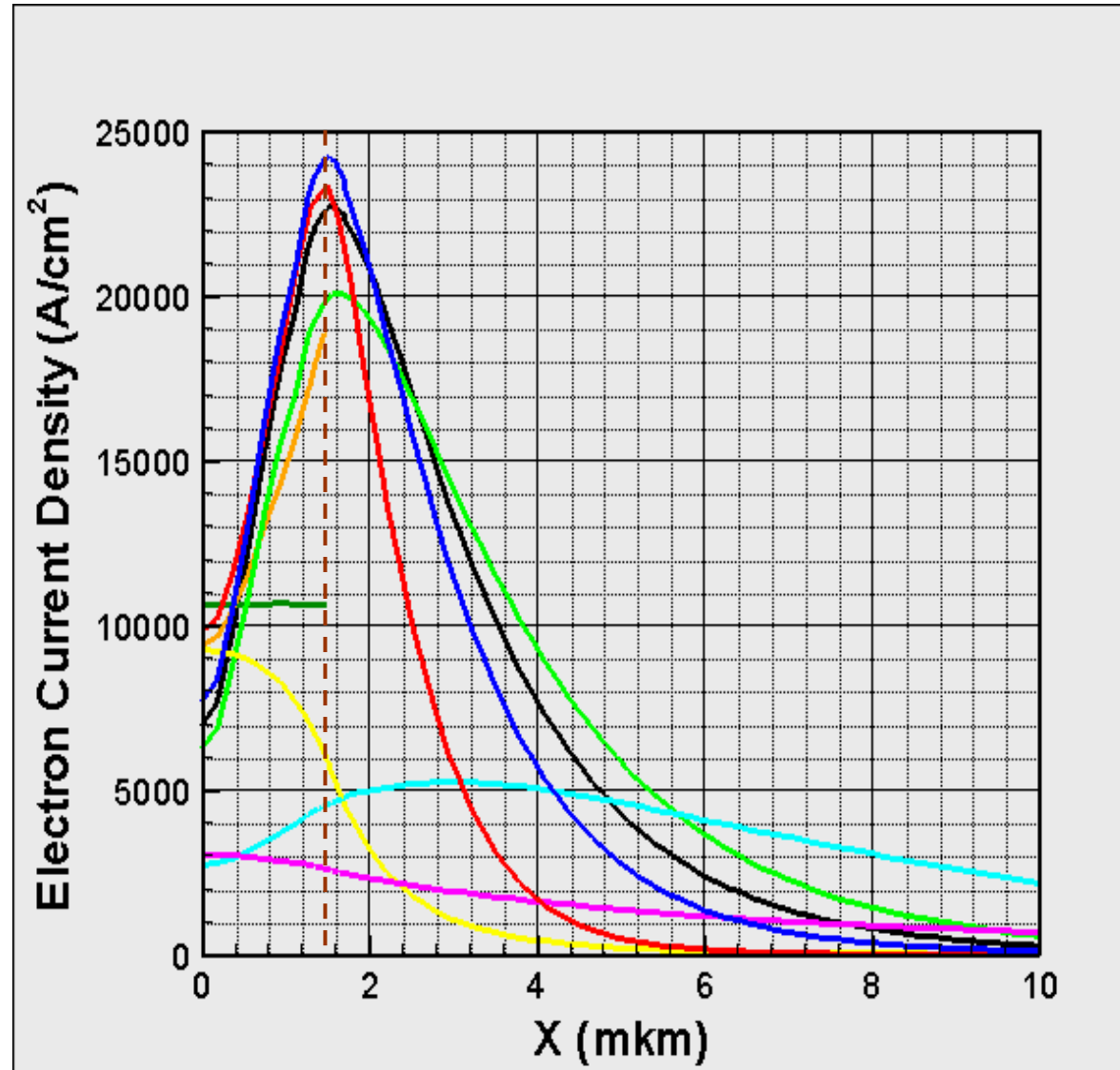
**Auger recombination rate
along X- direction in the
cross-section plane
at $Y=2.2\mu\text{m}$ (middle of Q).**



— Laser1 (mob_h=100, mob_e=4000)
— Laser1a (mob_h=200, mob_e=4000)
— Laser1b (mob_h=50, mob_e=4000)
— Laser1c (mob_h=10, mob_e=4000)
— Laser1d (mob_h=mob_e=4000)
— Laser1e (mob_h=4000, mob_e=100)
— Laser1f (mob_h=mob_e=100)

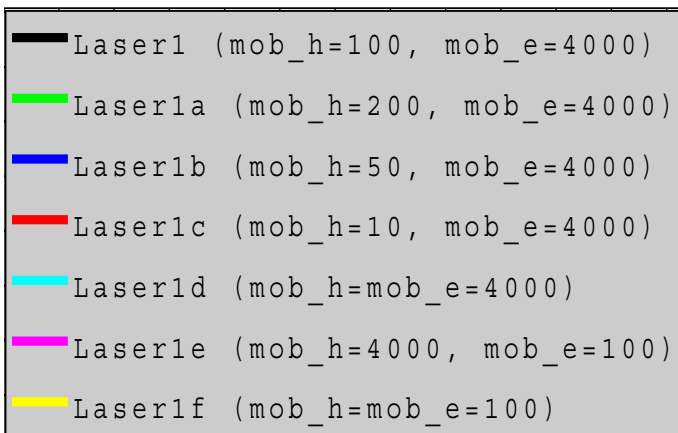
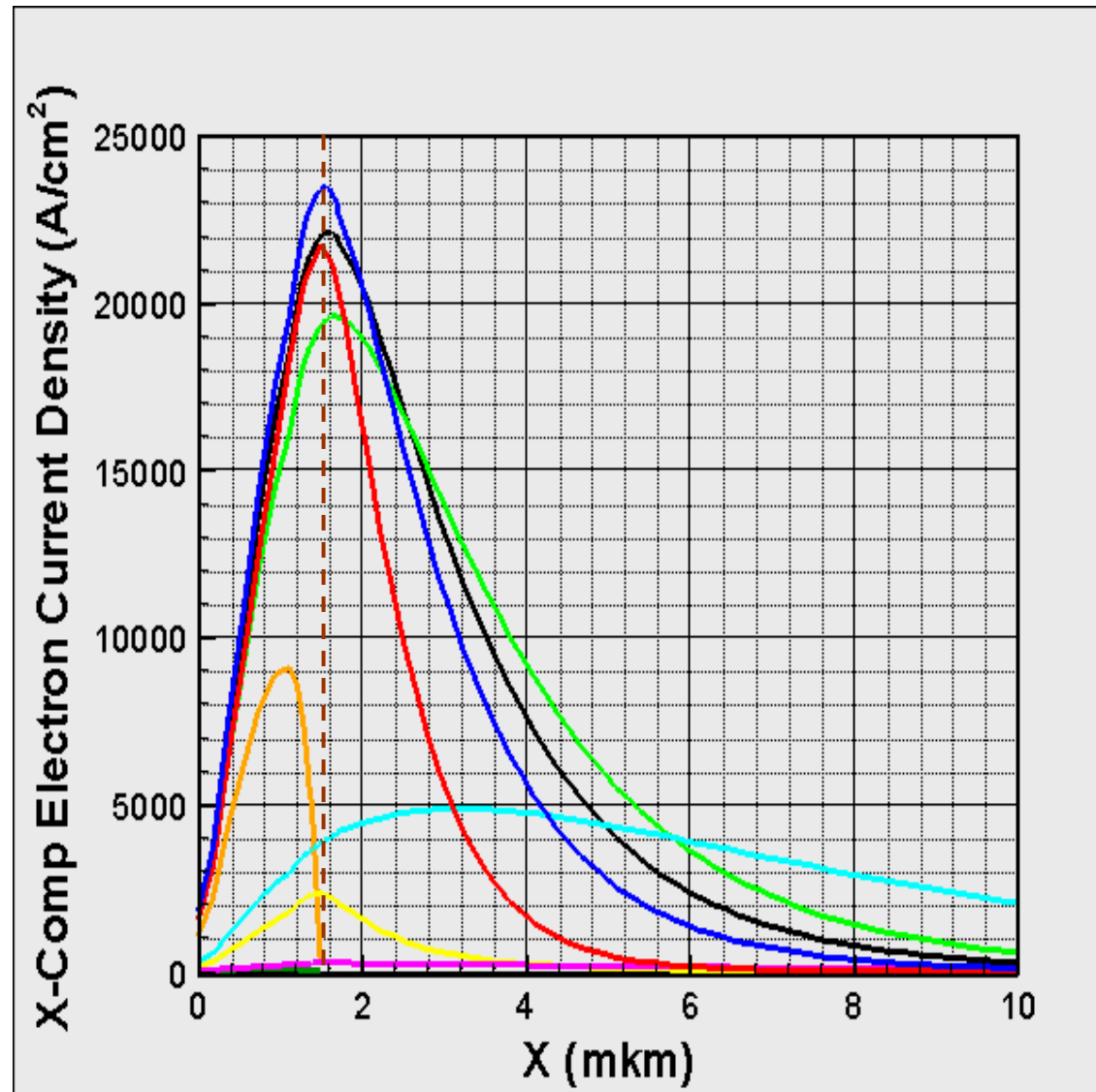
DISTRIBUTION OF ELECTRON CURRENT DENSITY IN Q-LAYER: ABSOLUTE VALUE

Total electron current density along X- direction in the cross-section plane at $Y=2.2\mu\text{m}$ (middle of Q).



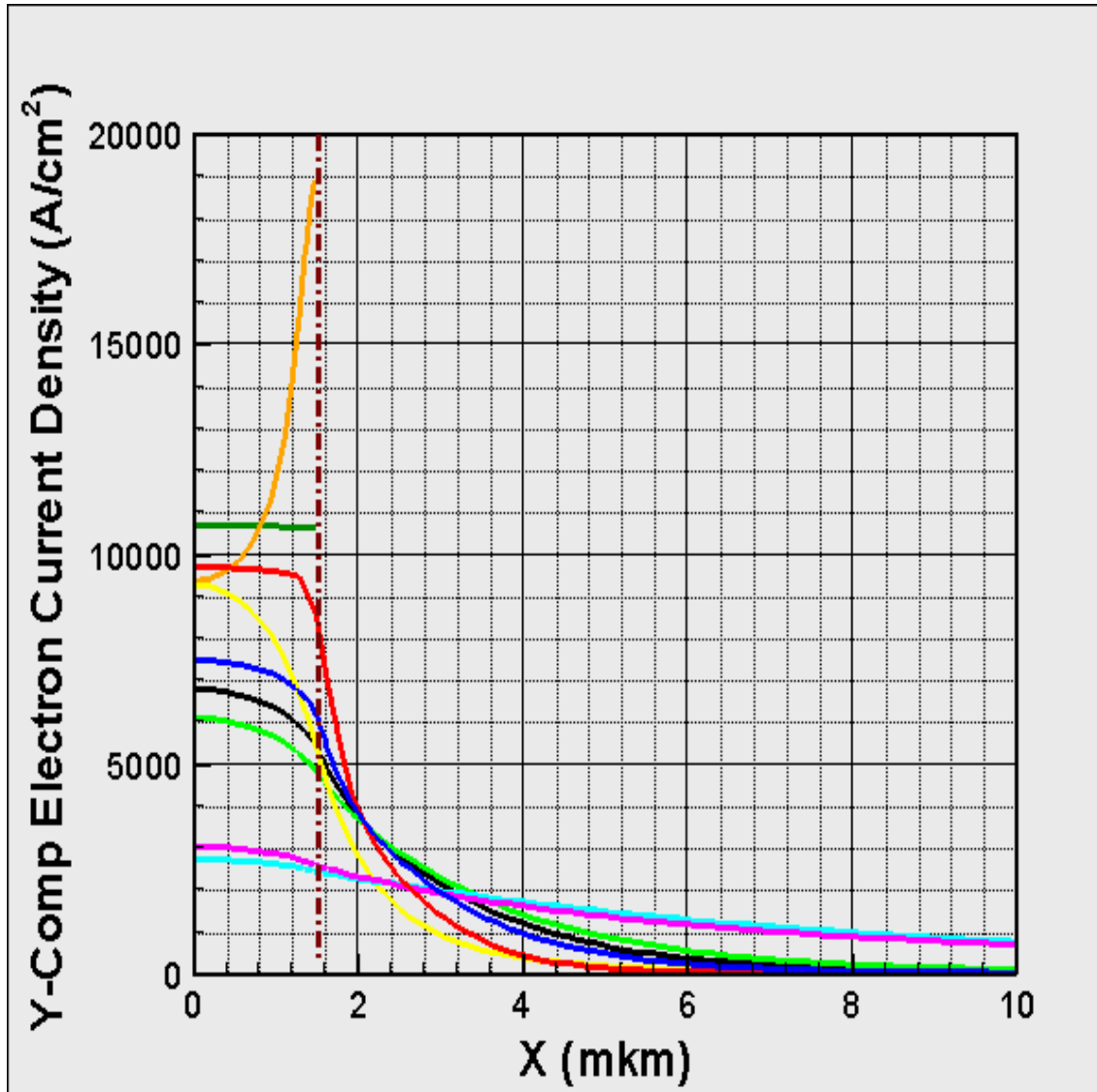
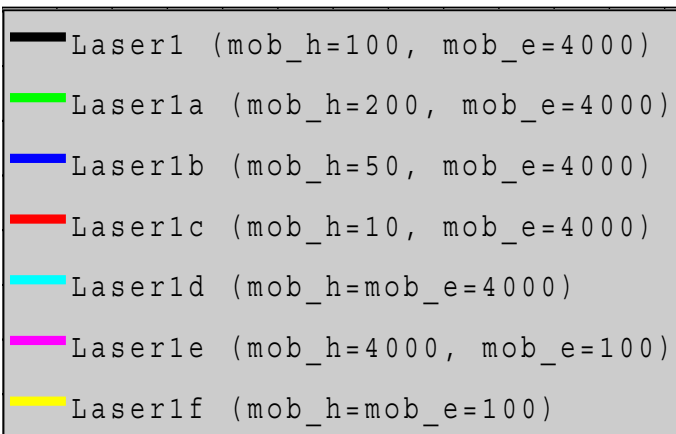
DISTRIBUTION OF ELECTRON CURRENT DENSITY IN Q-LAYER: LONGITUDINAL COMPONENT

**X-component of eCurrent
density along X- direction in
the cross-section plane
at $Y=2.2\mu\text{m}$ (middle of Q).**



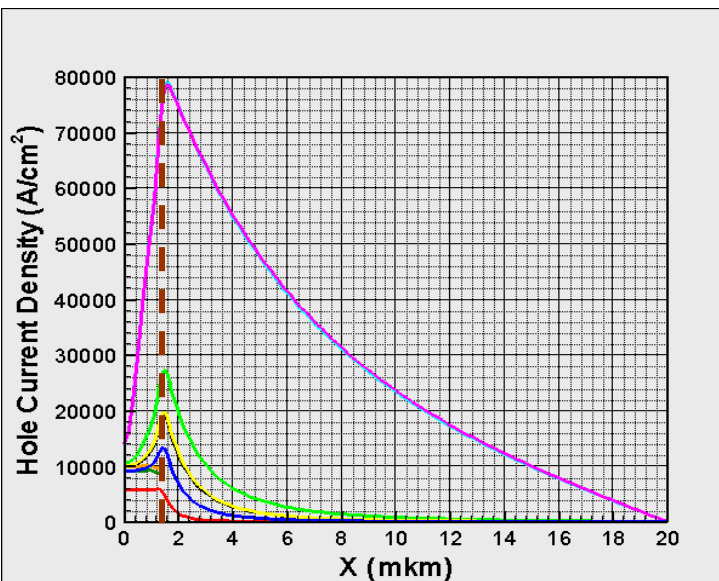
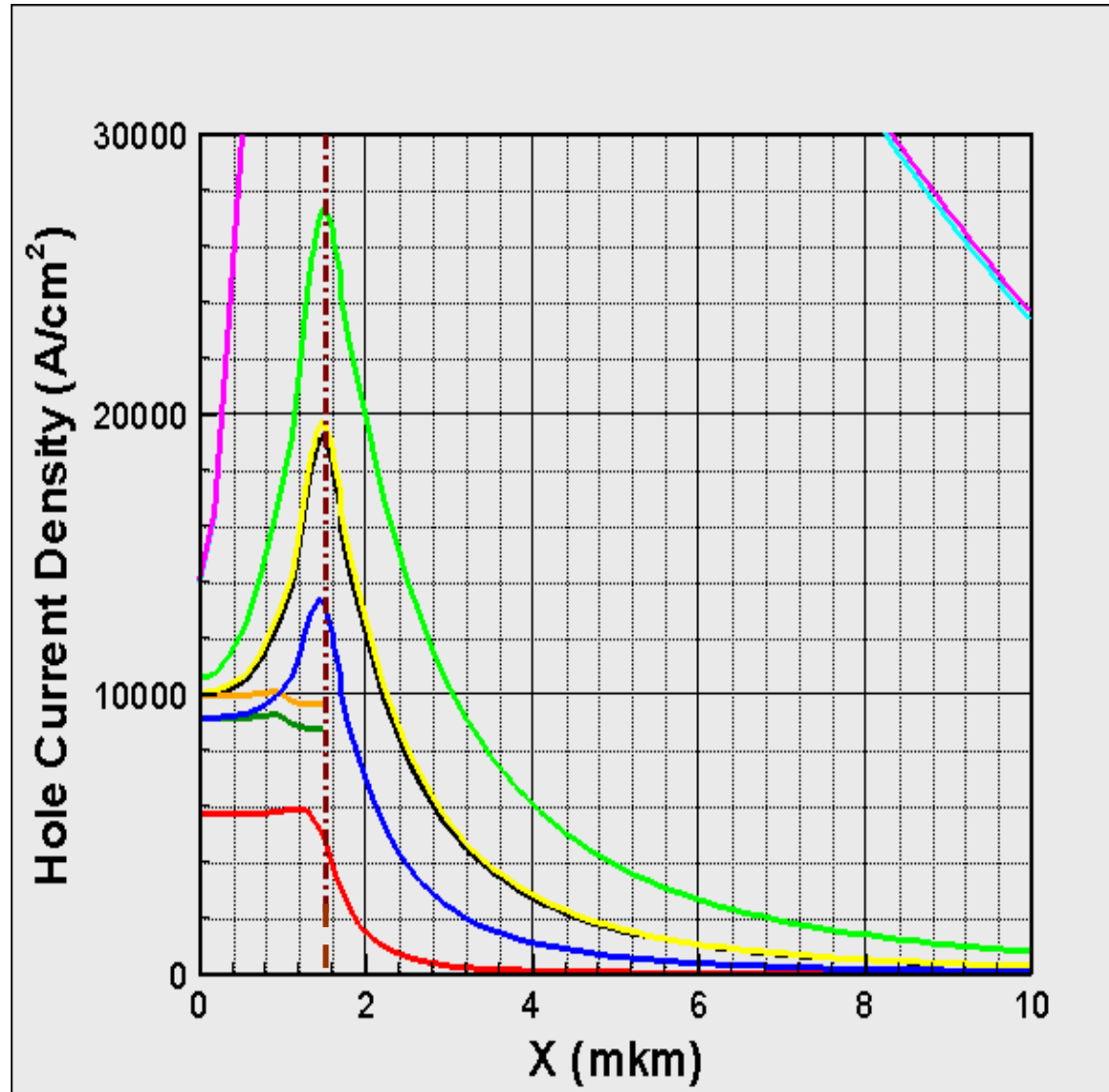
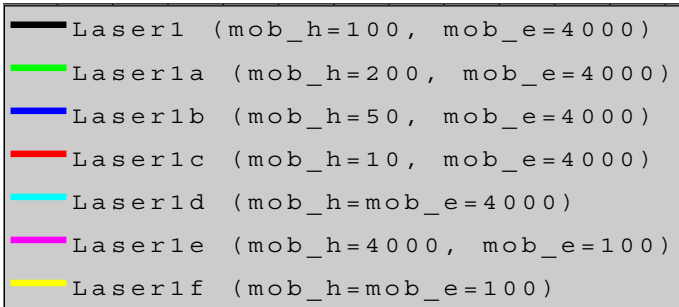
DISTRIBUTION OF ELECTRON CURRENT DENSITY IN Q-LAYER: NORMAL COMPONENT

**Y-component of eCurrent
density along X- direction in
the cross-section plane
at $Y=2.2\mu\text{m}$ (middle of Q).**



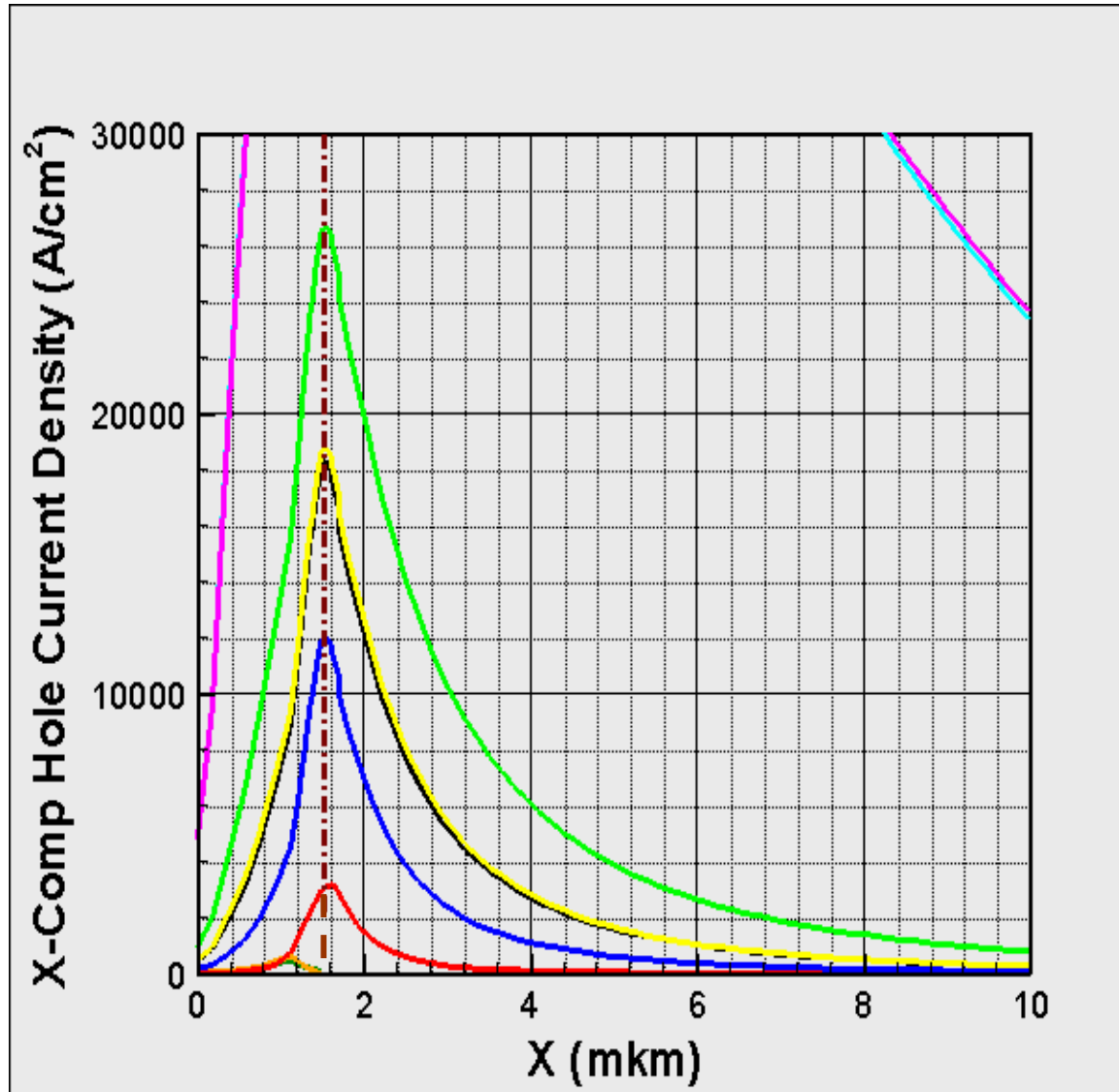
DISTRIBUTION OF ELECTRON CURRENT DENSITY IN Q-LAYER: ABSOLUTE VALUE

Total hole current density along X- direction in the cross-section plane at $Y=2.2\mu\text{m}$ (middle of Q).



DISTRIBUTION OF ELECTRON CURRENT DENSITY IN Q-LAYER: LONGITUDINAL COMPONENT

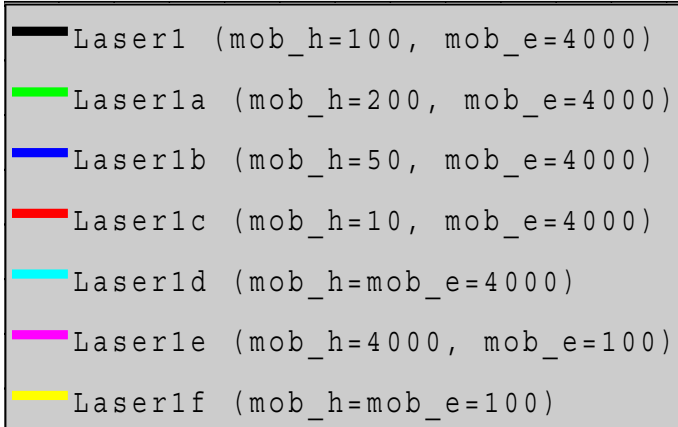
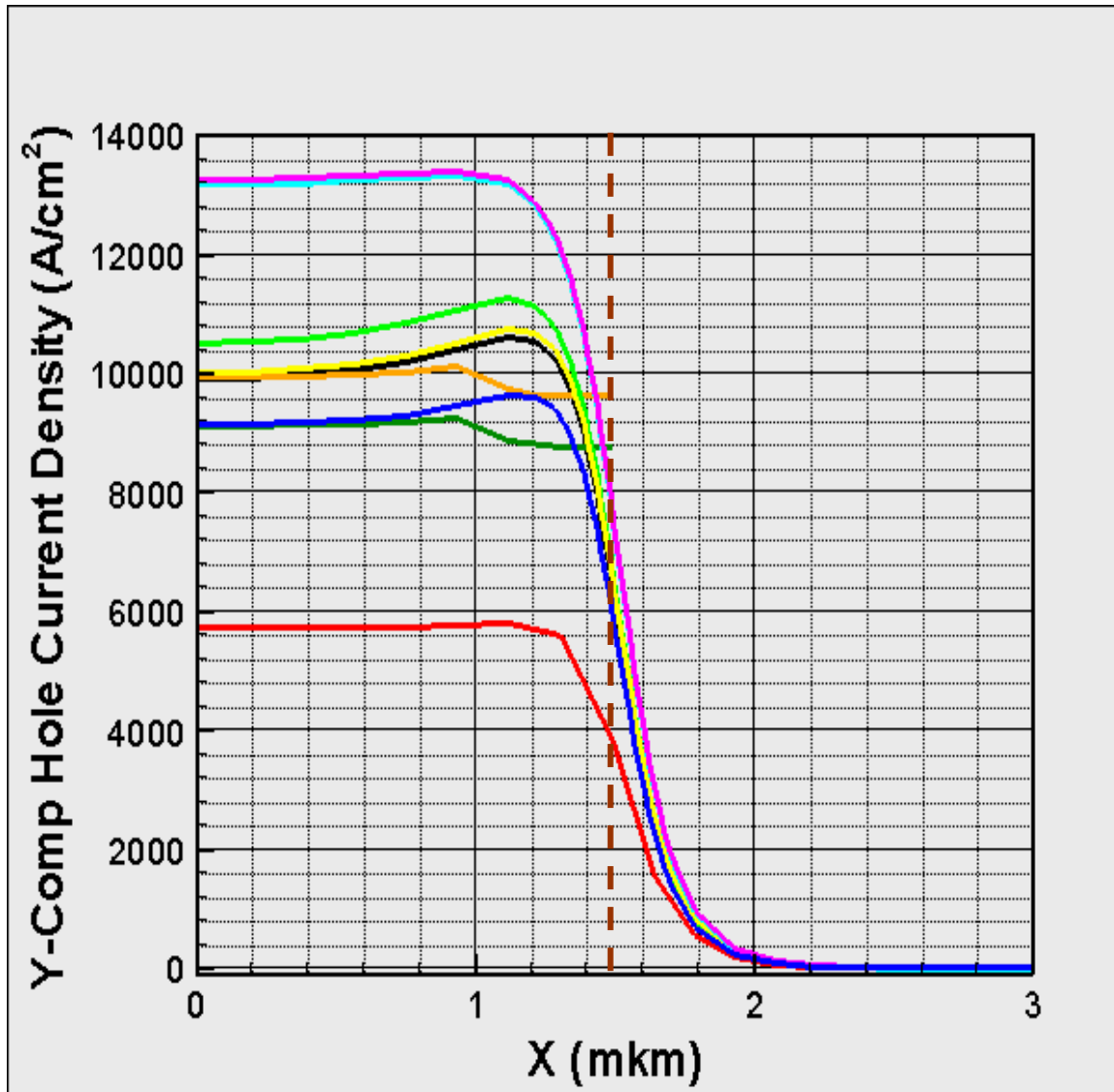
X-component of hole current density along X- direction in the cross-section plane at $Y=2.2\mu\text{m}$ (middle of Q).



- Laser1 (mob_h=100, mob_e=4000)
- Laser1a (mob_h=200, mob_e=4000)
- Laser1b (mob_h=50, mob_e=4000)
- Laser1c (mob_h=10, mob_e=4000)
- Laser1d (mob_h=mob_e=4000)
- Laser1e (mob_h=4000, mob_e=100)
- Laser1f (mob_h=mob_e=100)

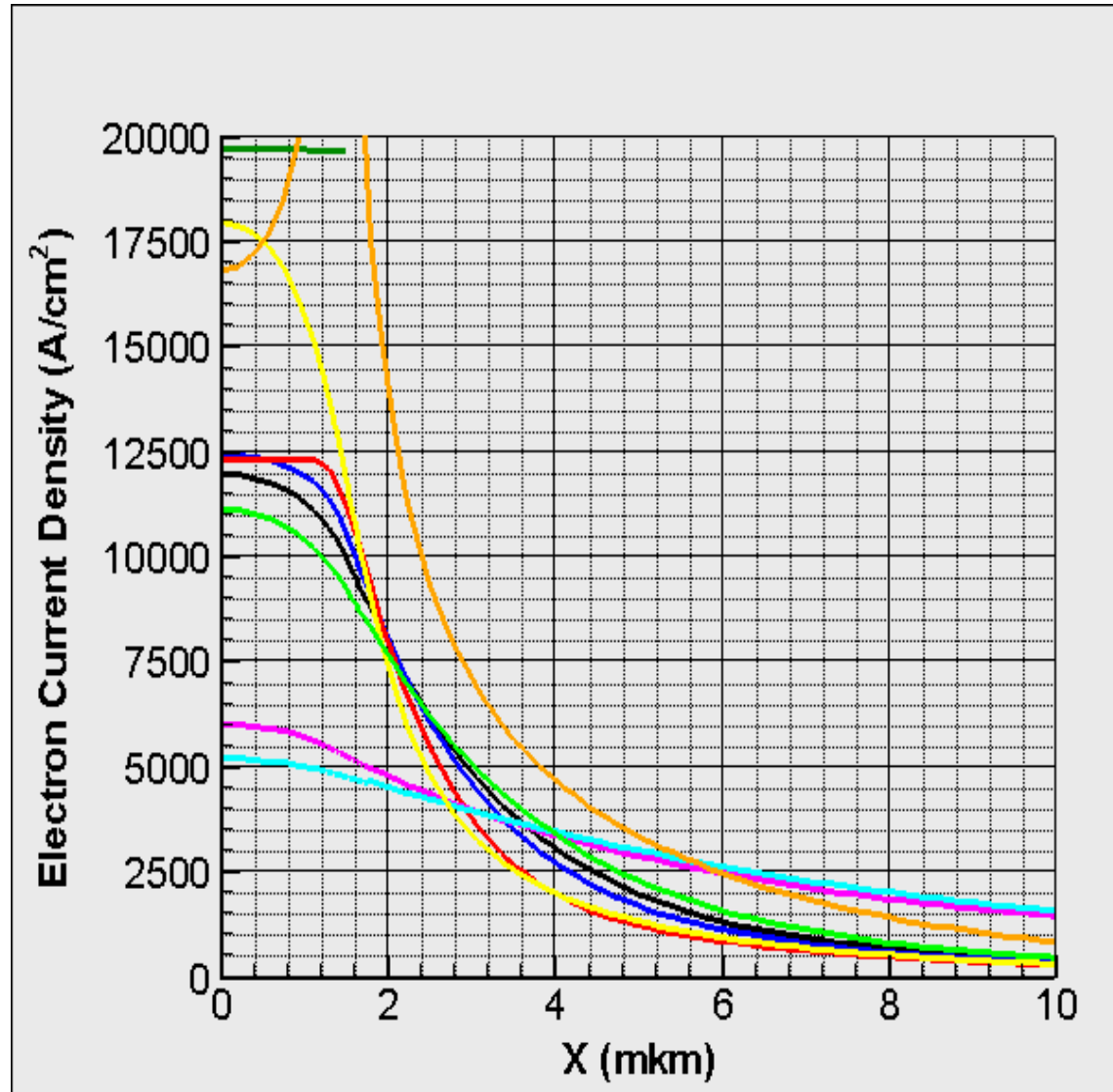
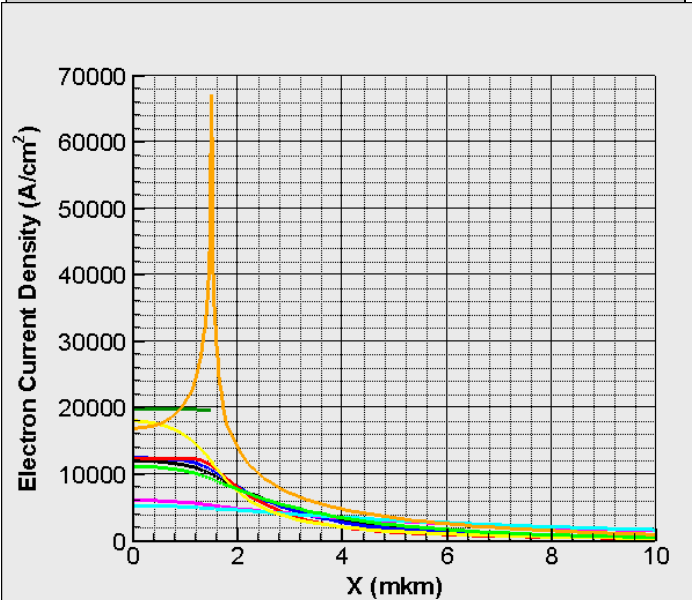
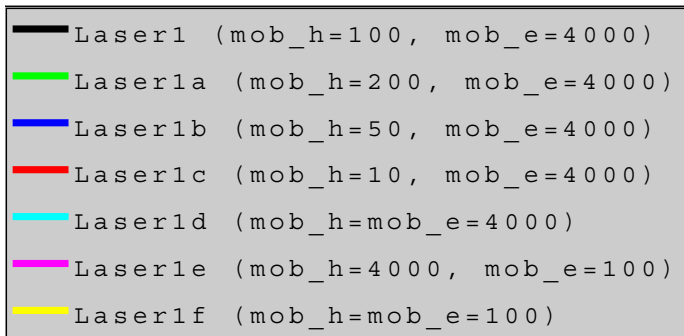
DISTRIBUTION OF ELECTRON CURRENT DENSITY IN Q-LAYER: NORMAL COMPONENT

Y-component of hole current density along X- direction in the cross-section plane at $Y=2.2\mu\text{m}$ (middle of Q).

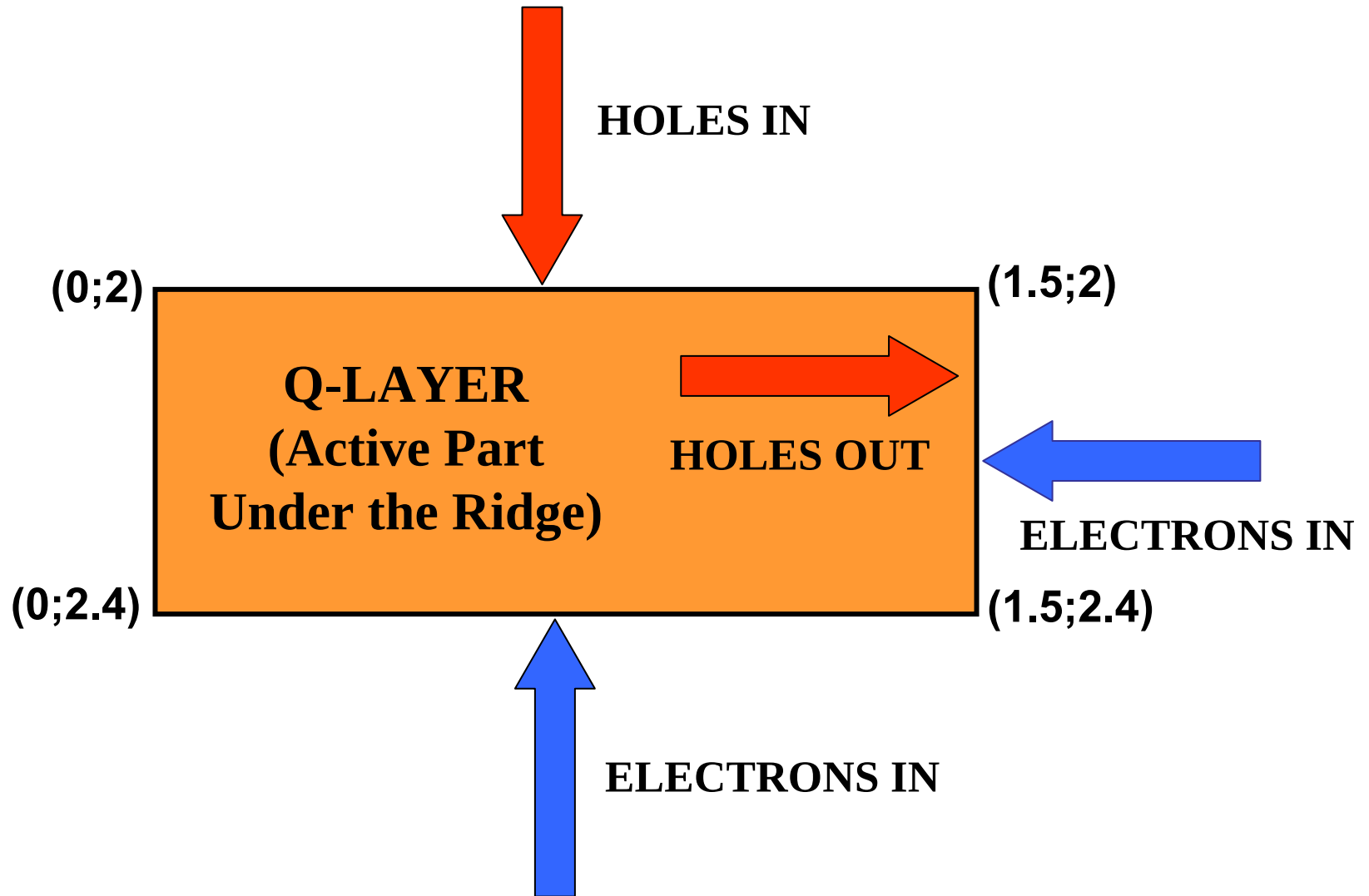


ELECTRON CURRENT DISTRIBUTION IN n-InP

Total electron current density along X- direction in the cross-section plane at $Y=2.405\mu\text{m}$ (n-inP/Q IF).



CALCULATION OF VERTICAL LEAKAGE CURRENTS

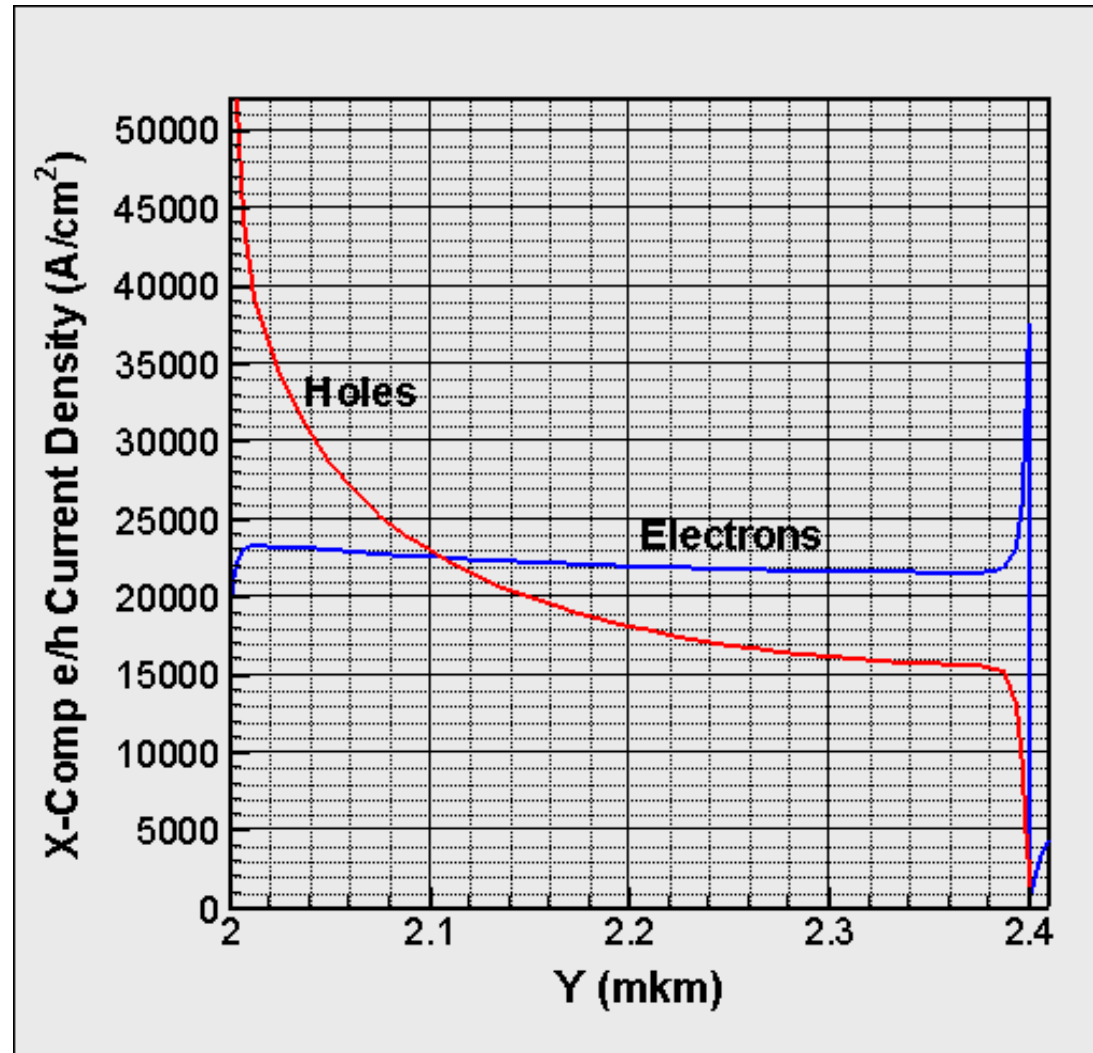


LONGITUDINAL ELECTRON AND HOLE CURRENTS AT THE RIGHT EDGE OF Q-LAYER

Laser1:

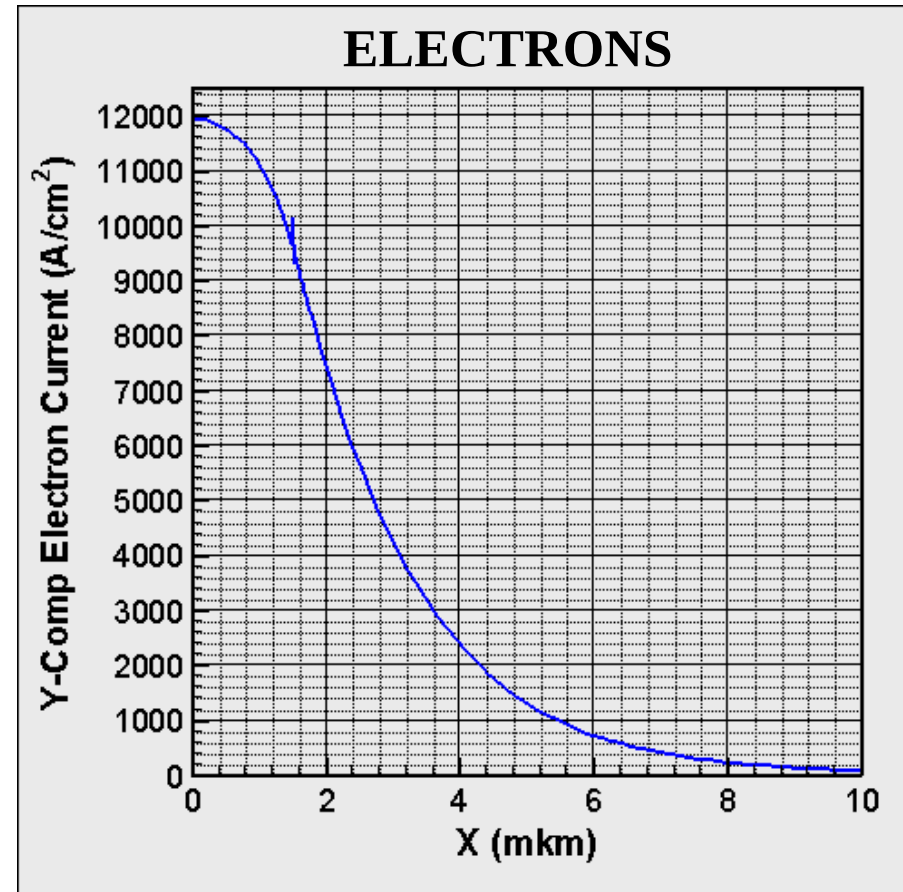
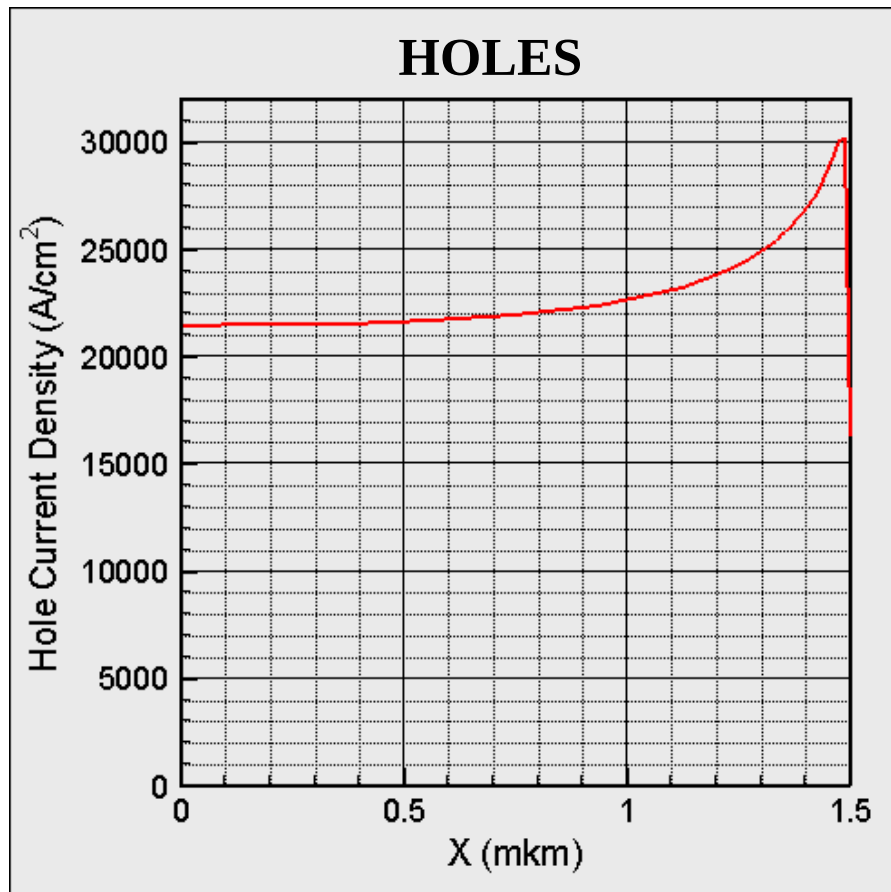
$\mu_n=4000 \text{ cm}^2/\text{Vs}$, $\mu_p=100 \text{ cm}^2/\text{Vs}$

**Distribution of X-components
of e/h current density along
in the cross-section plane
at $X=1.501 \text{ }\mu\text{m}$.**



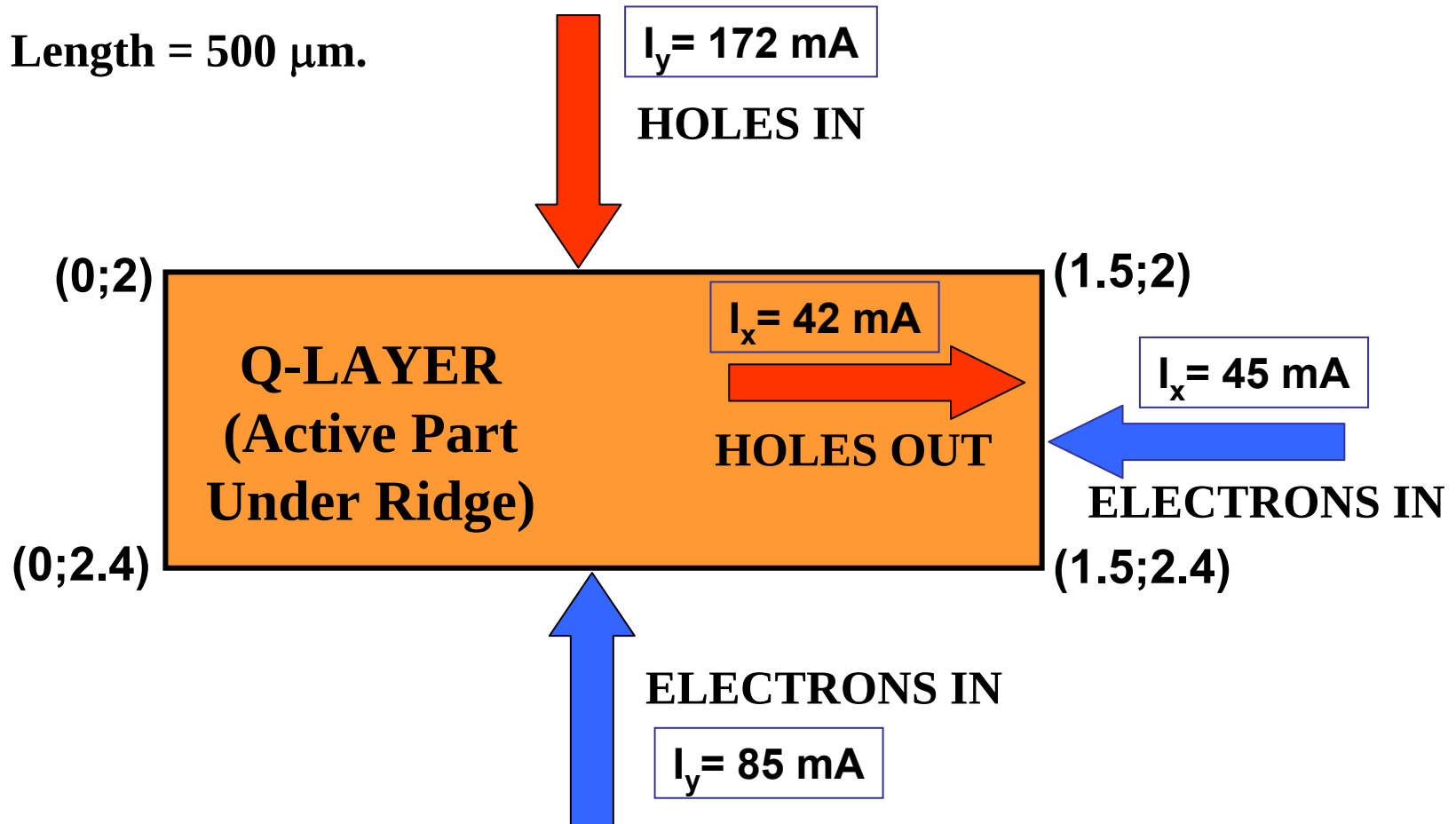
NORMAL ELECTRON AND HOLE CURRENTS AT THE TOP AND BOTTOM OF Q-LAYER

Laser1: Y-component of the hole current density in the cross-section plane $Y=1.999 \mu\text{m}$ (in p-InP just above Q), and Y-component of the electron current density in the cross-section plane $Y=2.399$ (in n-InP just below Q):



ESTIMATED VALUES OF ALL CURRENTS

Cavity Length = 500 μm .

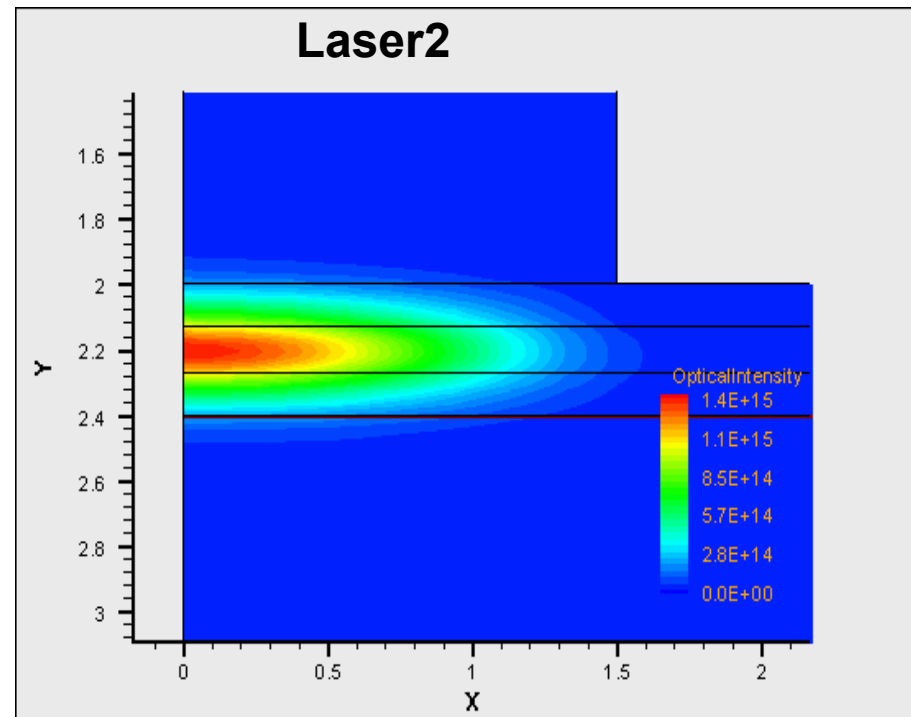
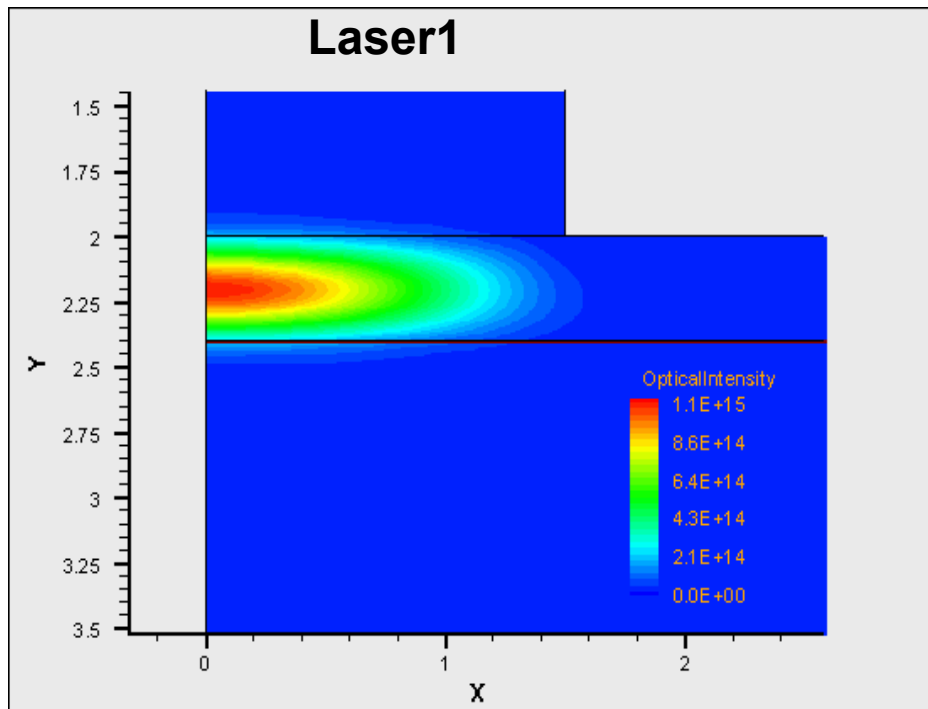


The currents and their ratios strongly depend on the hole mobility in Q-Layer. When hole mobility decreases the ratio of $I_x(\text{electron})/I_x(\text{hole})$ increases and the ratio of $I_x(\text{hole})/I_y(\text{hole})$ decreases.

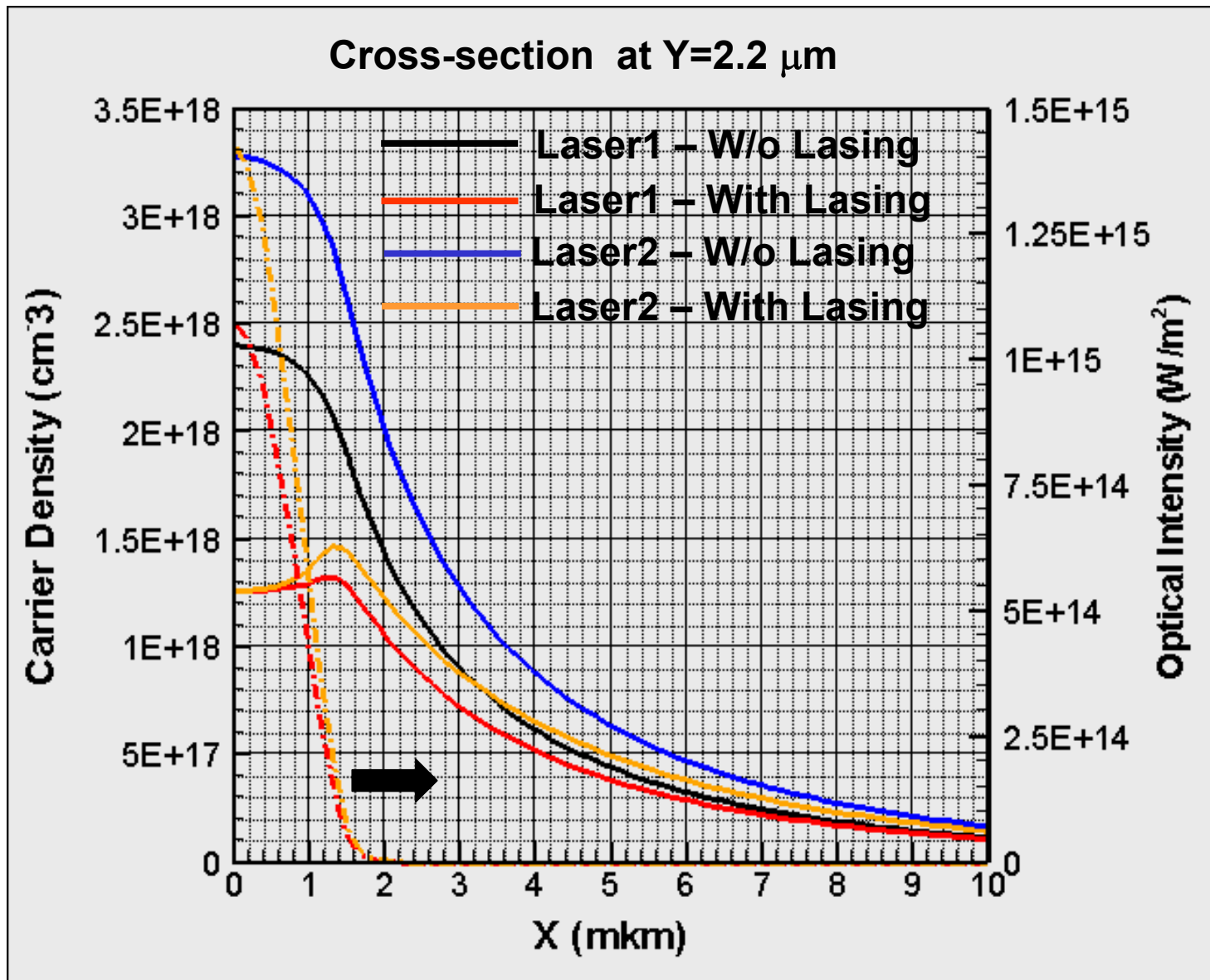
EFFECT OF LASING

We consider two geometries:

- Laser1 with the active layer bandgap of 0.873 eV and with the thickness 0.4 μm .
- Laser2 has the same material parameters as Laser1, but the active layer band-gap is 0.8 eV and the thickness is 0.14 μm . The rest of Q-layer is a symmetric SCH. The total thickness of Q-Layer is also 0.4 μm .

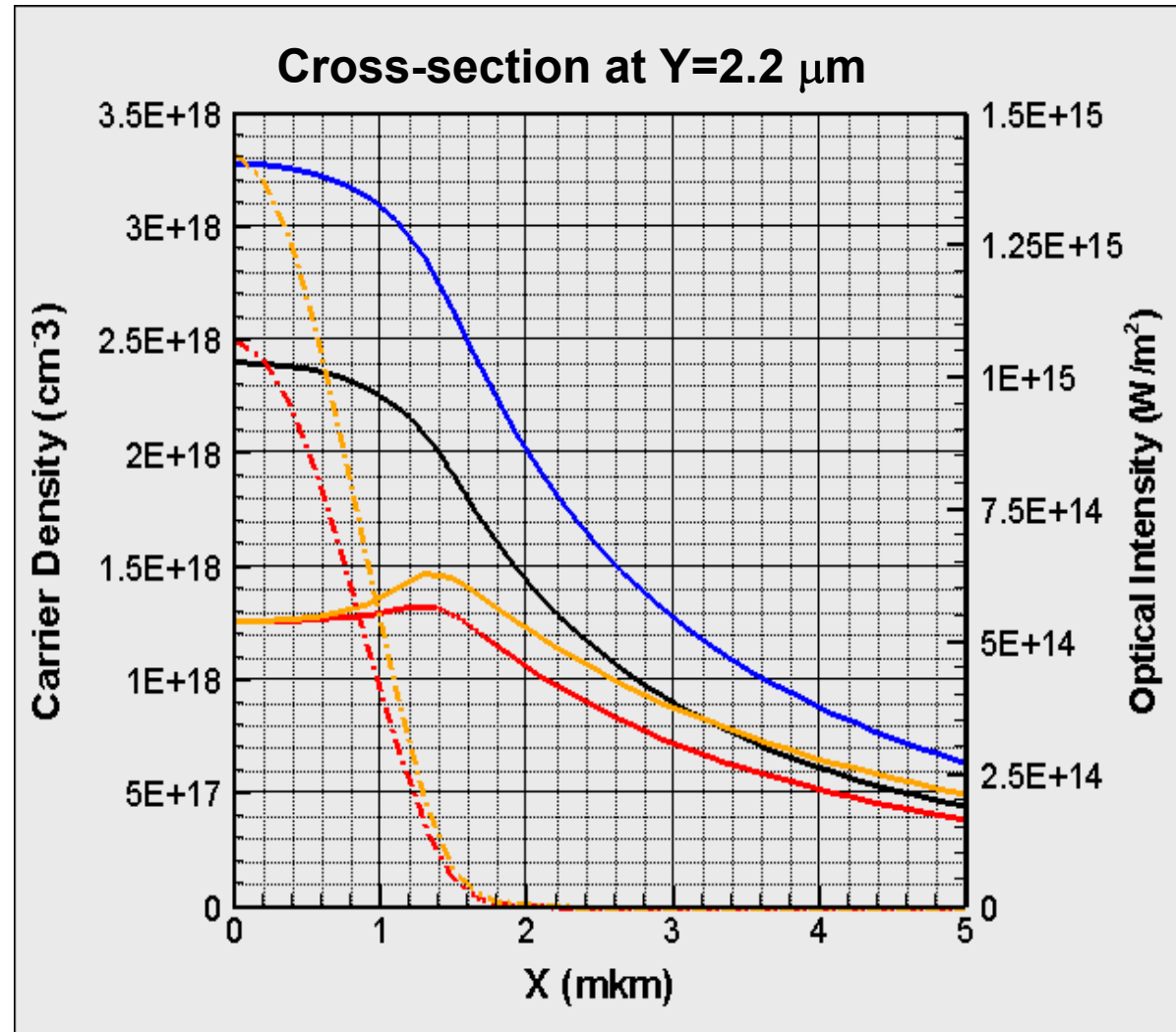


EFFECT OF LASING ON ELECTRON-HOLE PLASMA

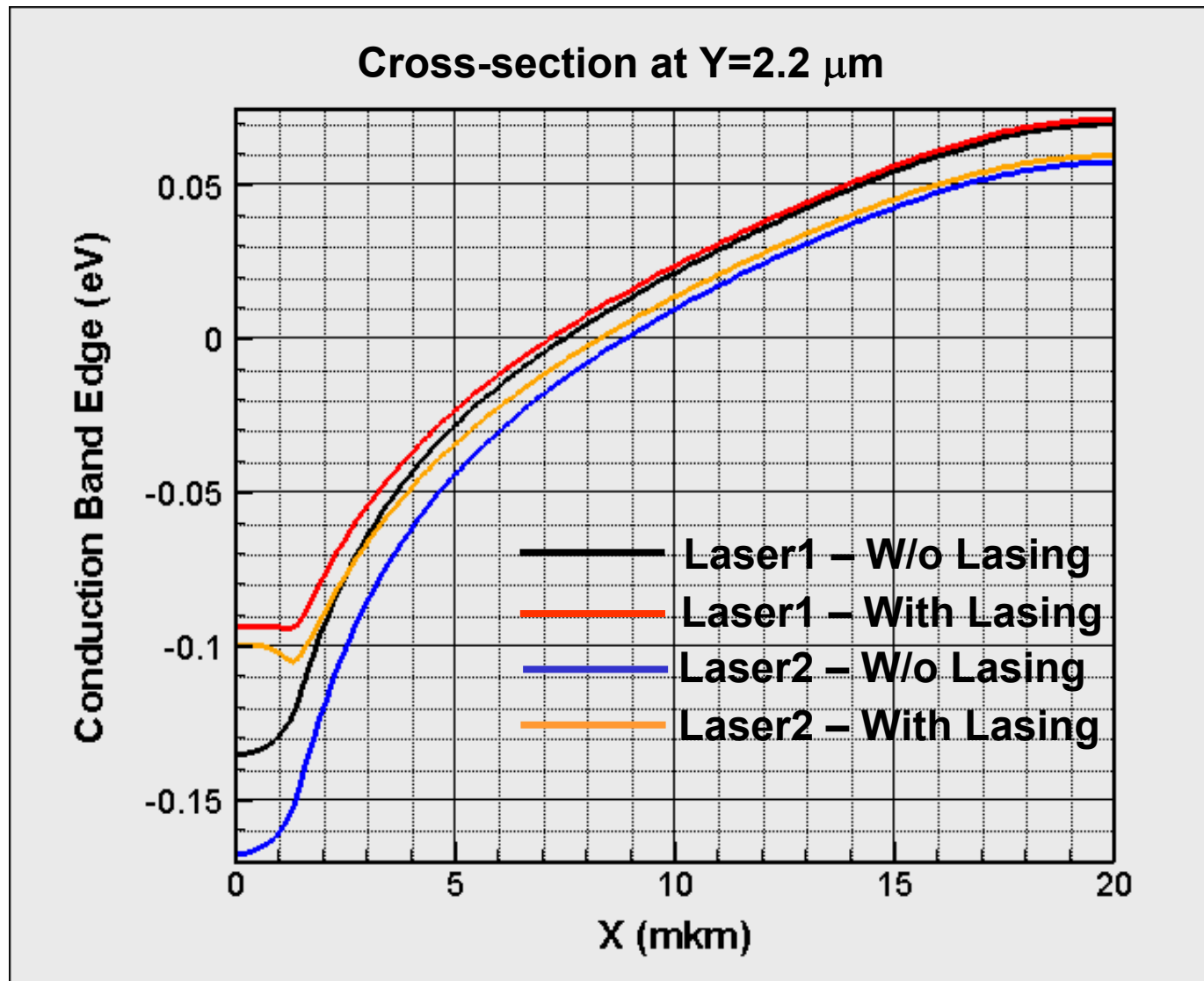


THE SAME (Larger Scale)

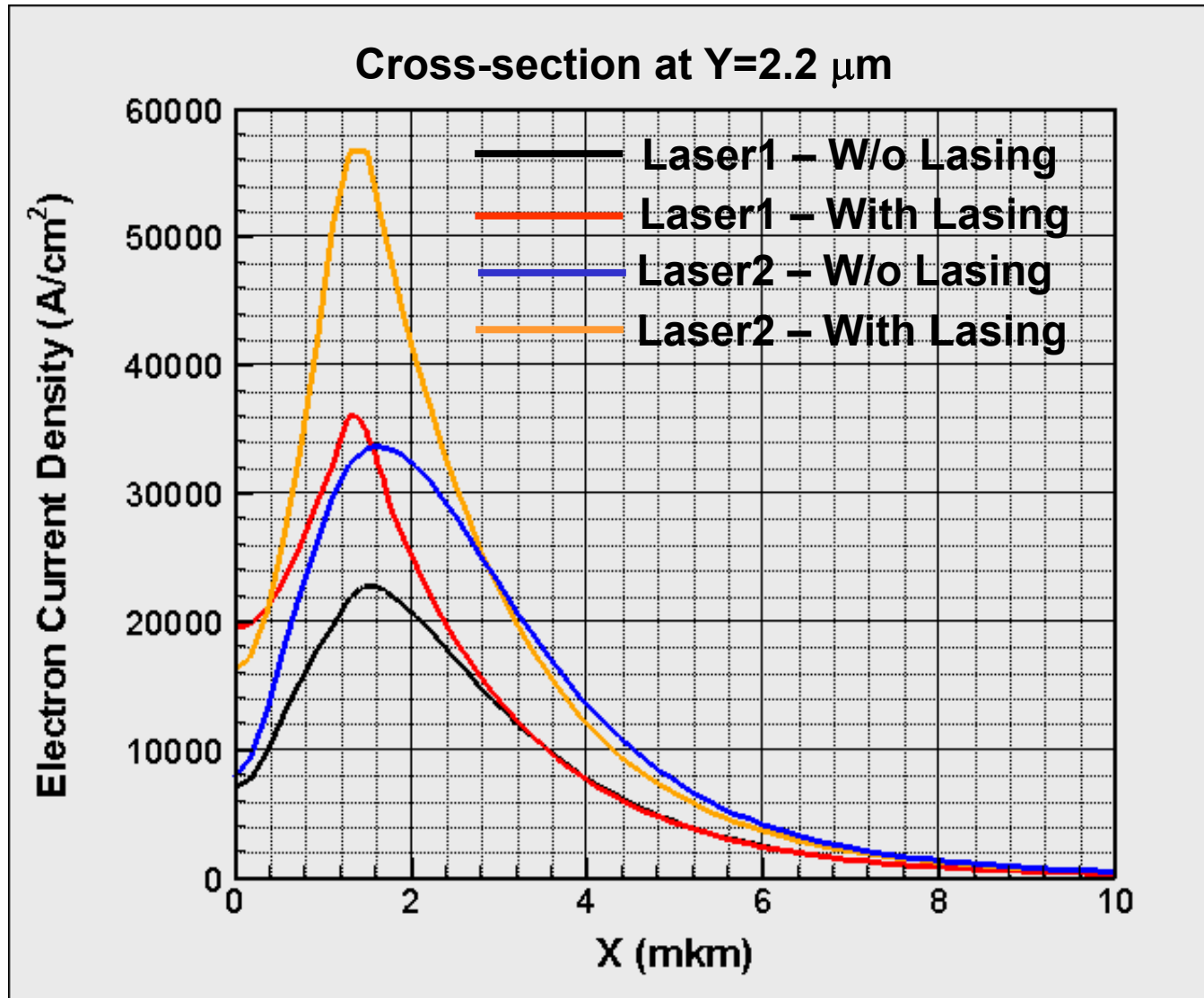
- Laser1 – W/o Lasing
- Laser1 – With Lasing
- Laser2 – W/o Lasing
- Laser2 – With Lasing



EFFECT OF LASING ON BAND EDGES



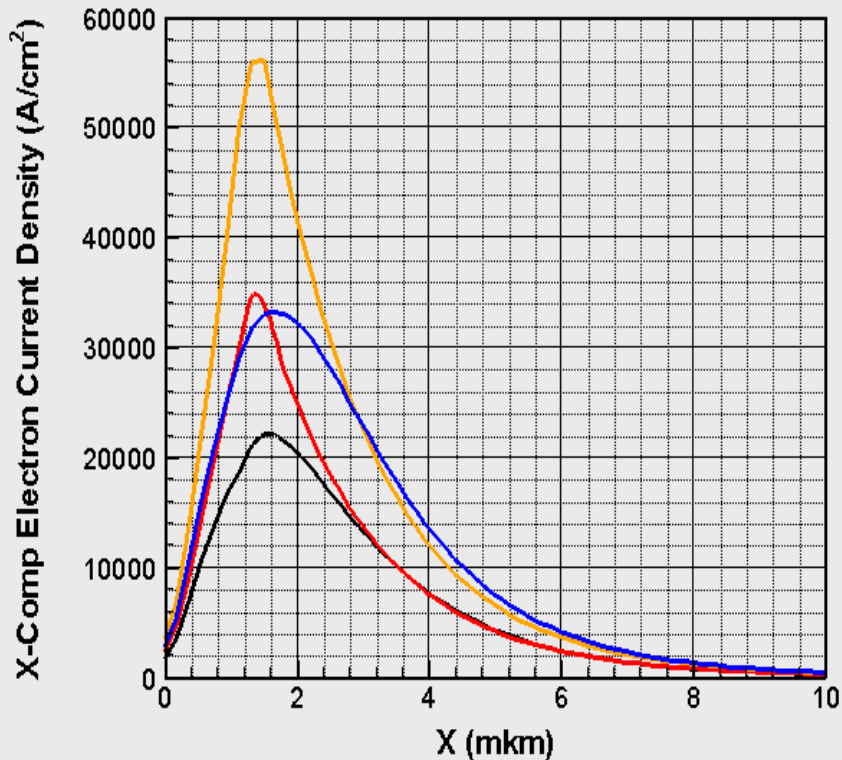
EFFECT OF LASING ON TOTAL ELECTRON CURRENT DENSITY IN Q-LAYER



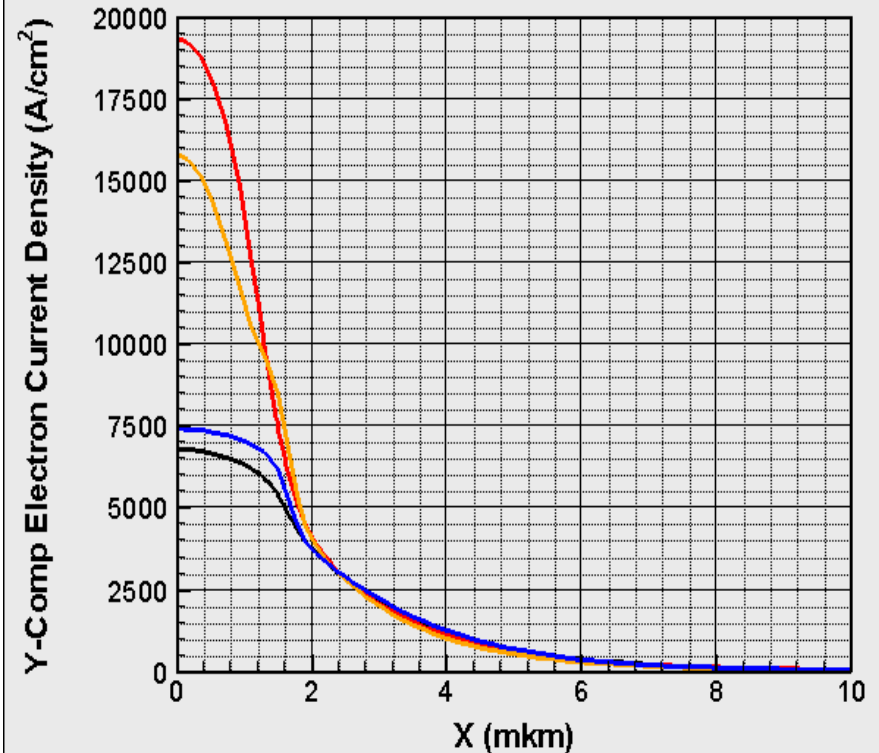
EFFECT OF LASING ON X- AND Y-COMPONENTS OF ELECTRON CURRENT DENSITY IN Q-LAYER

Electrons: Cross-section at $Y=2.2\text{ }\mu\text{m}$

X-component

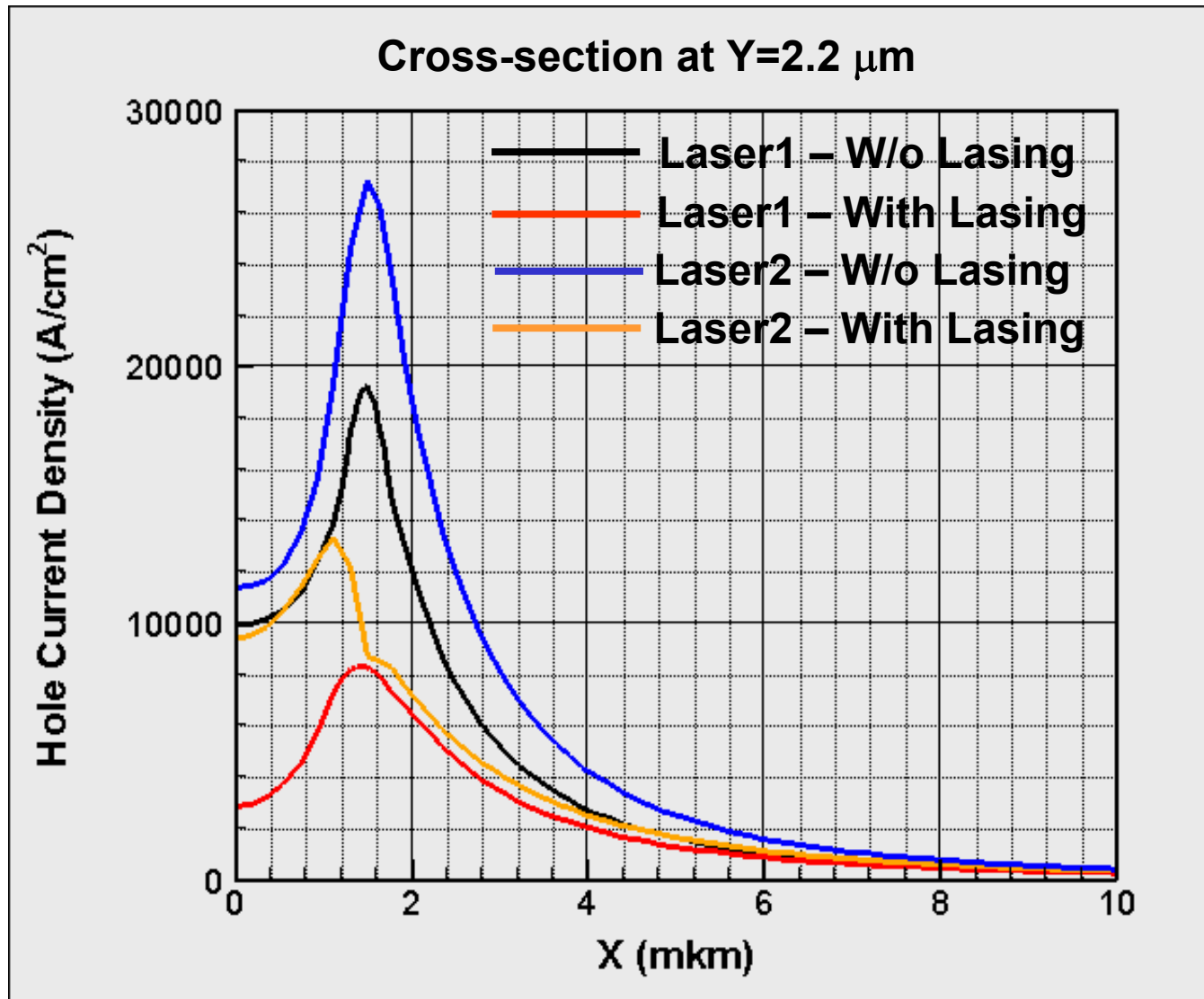


Y-component



- Laser1 – W/o Lasing
- Laser1 – With Lasing
- Laser2 – W/o Lasing
- Laser2 – With Lasing

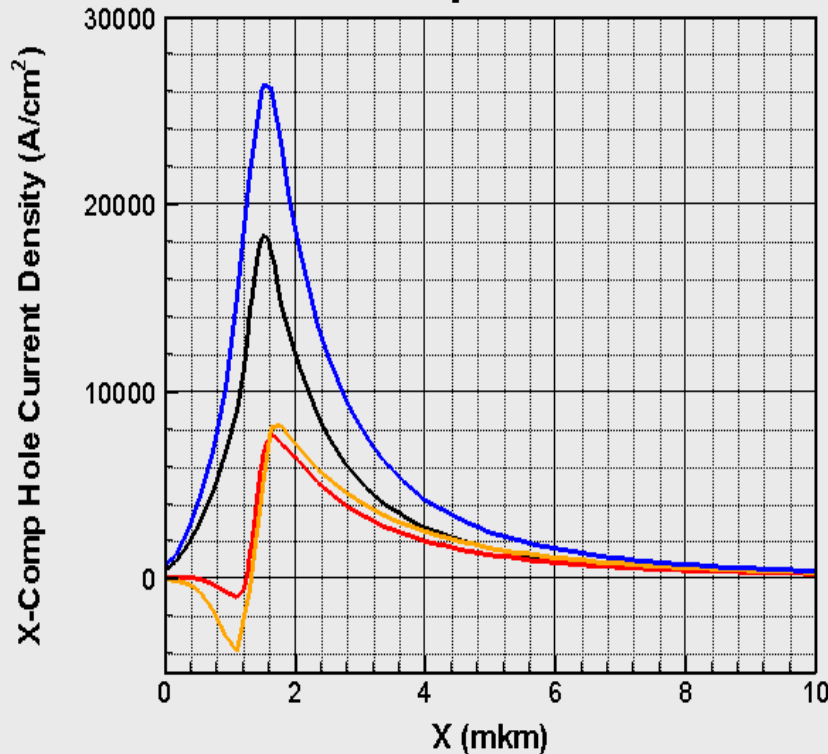
EFFECT OF LASING ON TOTAL HOLE CURRENT DENSITY IN Q-LAYER



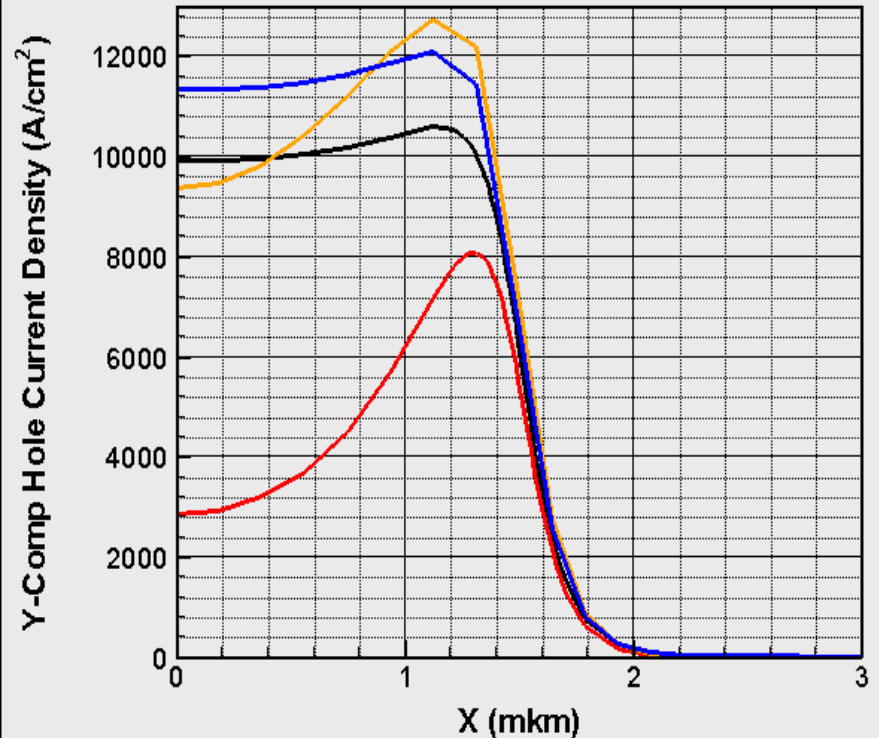
EFFECT OF LASING ON X- AND Y-COMPONENTS OF HOLE CURRENT DENSITY IN Q-LAYER

Holes: Cross-section at $Y=2.2\text{ }\mu\text{m}$

X-component



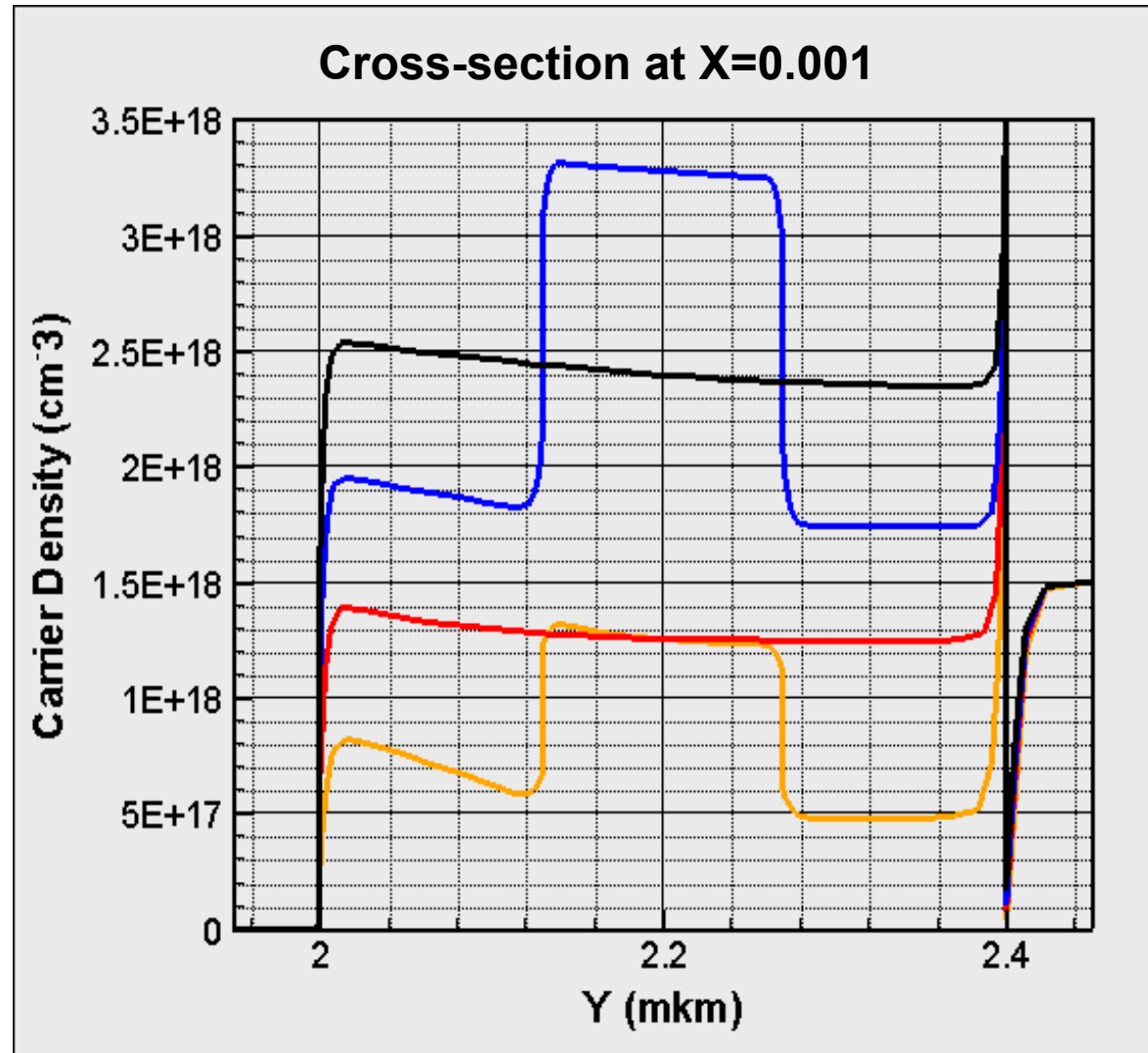
Y-component



- Laser1 – W/o Lasing
- Laser1 – With Lasing
- Laser2 – W/o Lasing
- Laser2 – With Lasing

EFFECT OF LASING ON CARRIER DISTRIBUTION ACROSS Q-LAYER

- Laser1 – W/o Lasing
- Laser1 – With Lasing
- Laser2 – W/o Lasing
- Laser2 – With Lasing



SUMMARY

- **Analytical 1D macroscopic theory of carrier transport in lasers provides very good approximation for calculation of I-V characteristics.**
- **The 1D theory is helpful in evaluation of the bottle-necks of the electron injection and vertical leakage currents.**
- **The theory has good agreement with corresponding results from numerical modelling (here we used DESSIS – Synopsys/ISE).**
- **However, in spite of good agreement, the 1D theory is absolutely inapplicable for reliable analysis of carrier distributions, energy band and electric field profiles.**
- **The applicability of 1D approximation becomes even more problematic above threshold when lasing has very strong effect.**

THANK YOU VERY MUCH!