THEORY AND MODELLING OF HIGH-FIELD CARRIER TRANSPORT IN HIGH-SPEED PHOTODETECTORS

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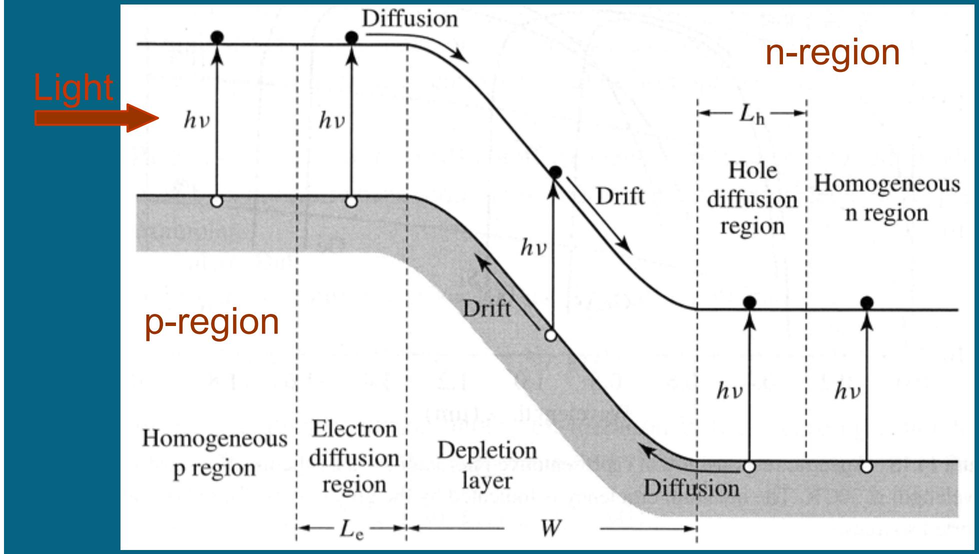
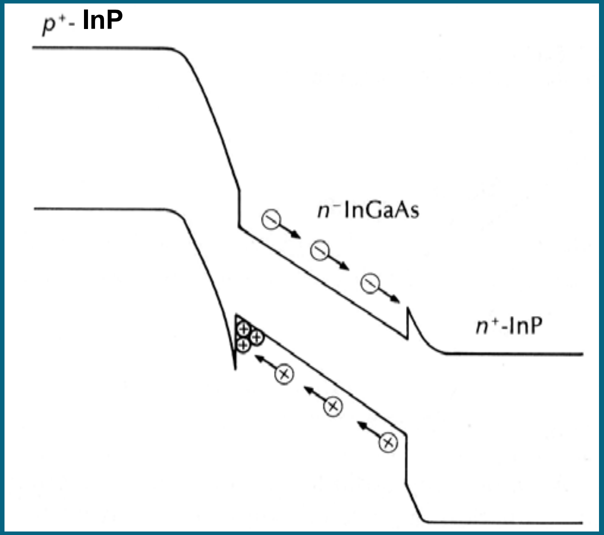
(Inter-University EPSRC UK Project - PORTRAIT)

Outline of Presentation

- New Microscopic and Macroscopic Theory of High-Field Transport in Inhomogeneous Electric Fields (Including Built-in Fields)
- Implications for Physics-Based Software Modelling Tools
- Application to p-i-n Photodiodes: Steady State and Transient
- Transient Simulation of UTC Photodiodes: New Underlying Physics, Consequences, and Interpretation of the Results
- Conclusions

High-Field Transport in Photodetectors

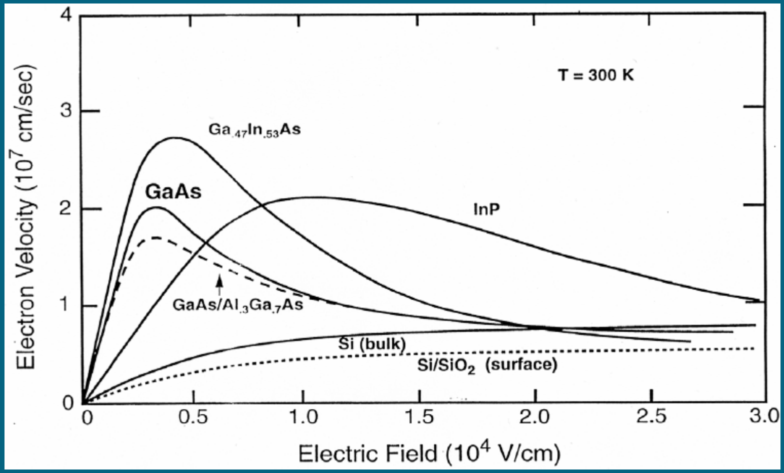


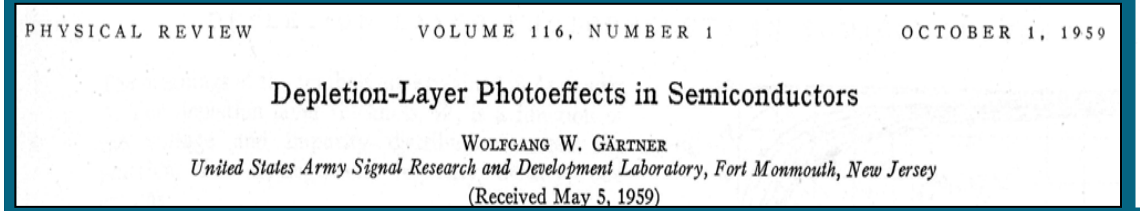


Speed of response – transient time:

$$\tau_{tr} = \frac{w}{v}, \qquad v = \mu F .$$

(Response time of electrical circuit: τ_{RC}=RC).




PHYSICAL REVIEW VOLUME 116, NUMBER 1 OCTOBER 1, 1959

Depletion-Layer Photoeffects in Semiconductors

Wolfgang W. Gärtner
United States Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey

(Received May 5, 1959)

Transient Time and Electron Dynamics in Built-in Electric Fields

TRANSIT TIME AND HIGH-FIELD MOBILITY

$$\tau_{tr} = \frac{w}{v}, \qquad v = \mu F, \qquad \mu = \frac{e\tau_p}{m^*}.$$

- In high electric fields:

$$\mu = \mu(F).$$

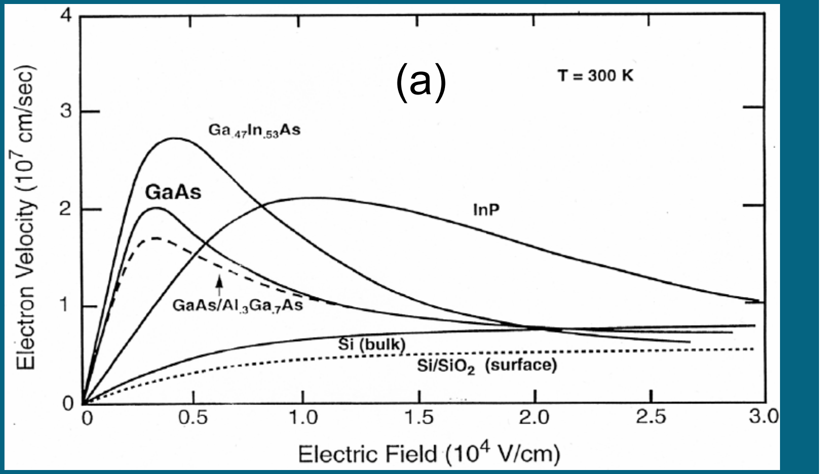
- Usually μ decreases when F increases, and drift velocity becomes <u>sub-linear</u> function of F.
- Saturation velocity and transferred electron model:

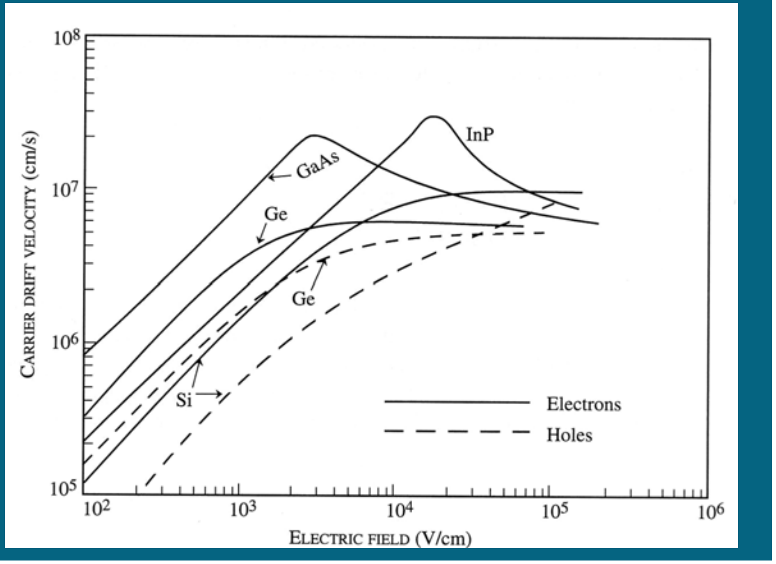
$$\mu(F) = \frac{\mu_{low}}{\left[1 + \left(\frac{\mu_{low} F}{v_{sat}}\right)^{\beta}\right]^{1/\beta}}.$$

$$\mu(F) = \frac{\mu_{low} + \left(\frac{v_{sat}}{F}\right)\left(\frac{F}{F_0}\right)^4}{1 + \left(\frac{F}{F_0}\right)^4}.$$

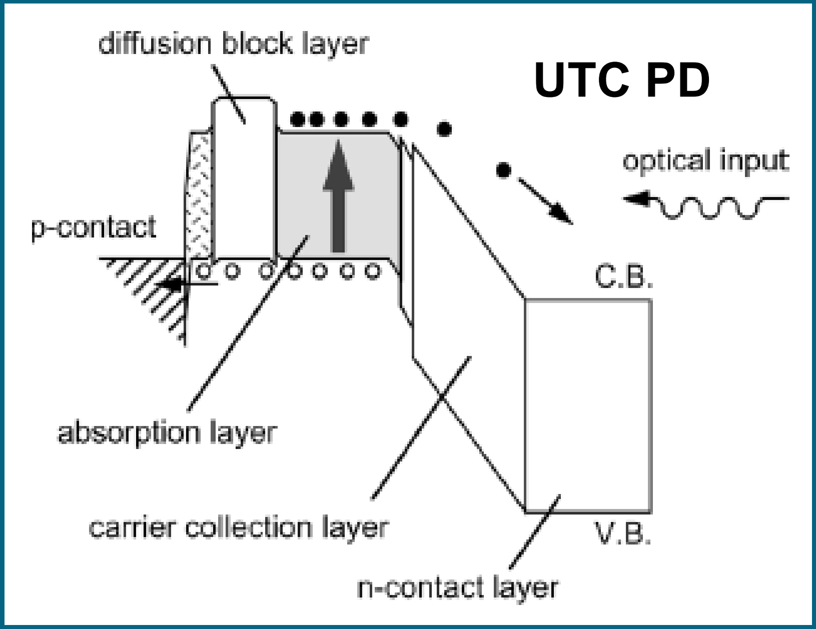
- Drift velocity and mobility of holes << then for e-ns.

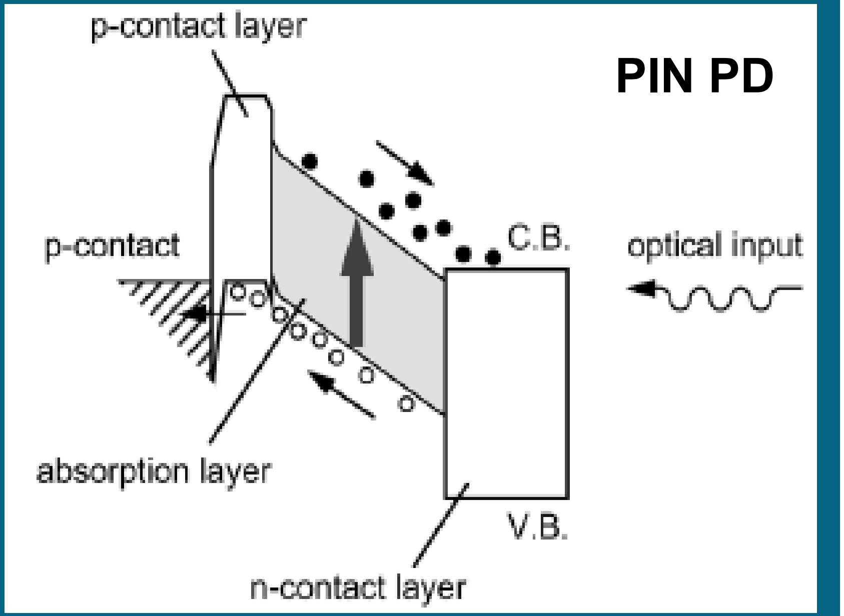
Velocity-Field Characteristics for e-ns and holes in Bulk (Homogeneous Fields)





UTC PD vs p-i-n PD





The main UTC PD features:

1. Separation of photo-absorption and high-field transport regions.
2. Only one (fastest, e-ns) type of carriers is involved in high-field transport.

The main p-i-n PD features:

1. Photo-absorption and high-field transport regions coincide.
2. Both types of carriers (electrons and holes) are involved in high-field transport.

T. Ishibashi et al, (Invited Review Paper) “High-Speed and High-Output InP-InGaAs Unitravelling-Carrier Photodiodes”, IEEE J. Select. Topics Quantum Electron, Vol. 10, 709, (2004).

Theory of Carrier Transport in Photodetectors

THE SIMPLEST (BUT NOT THE BEST!) MODEL IS THE DRIFT-DIFFUSION (DD) MODEL:

$$\frac{\partial n}{\partial t} - \frac{1}{e}\nabla_x j_n(x) = \alpha \frac{I_0}{\hbar\omega_0} e^{-\alpha x} - R(n,p),$$

$$\frac{\partial p}{\partial t} + \frac{1}{e}\nabla_x j_h(x) = \alpha \frac{P_0}{\hbar\omega_0} e^{-\alpha x} - R(n,p),$$

- The goal is to calculate e/h current densities j_n and j_h for a given optical intensity I_0 (W/cm^2), i.e. to calculate the electrical response of photo-diode, and all local parameters.

$$\nabla_x E_c(x) = \frac{e^2}{\varepsilon\varepsilon_0}[p(x) - n(x) + N_D^+(x) - N_A^-(x)],$$

$$j_n(x) = n(x)\mu_n(x)\nabla_x E_c(x) + eD_n(x)\nabla_x n(x) = n(x)\mu_n(x)\nabla_x E_{Fn}(x),$$

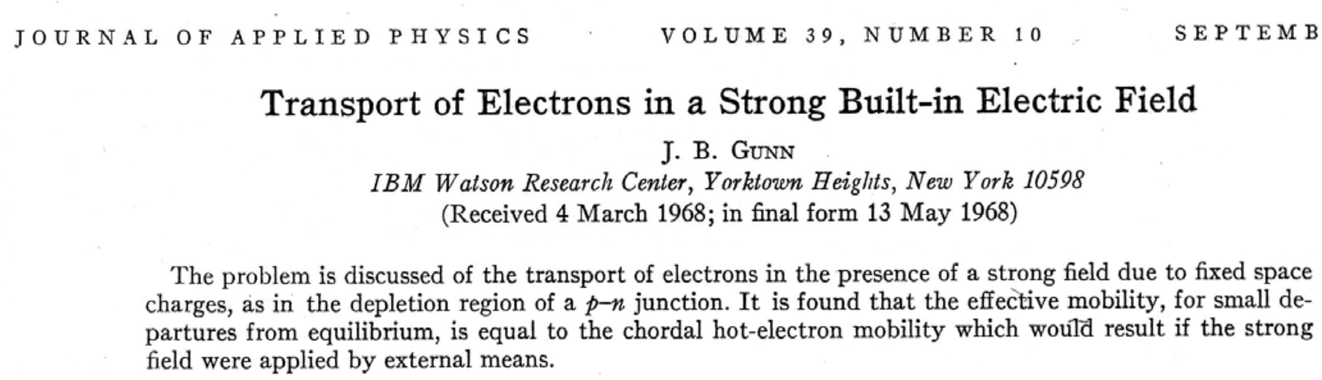
$$j_h(x) = p(x)\mu_h(x)\nabla_x E_c(x) - eD_h(x)\nabla_x p(x) = p(x)\mu_h(x)\nabla_x E_{Fh}(x),$$

$$n(x) = N_c(T_0)F_{1/2}(\eta_n(x)), \qquad \eta_n(x) = [E_{Fn}(x) - E_c(x)]/k_0T_0,$$

$$p(x) = N_v(T_0)F_{1/2}(\eta_h(x)), \qquad \eta_h(x) = [E_v(x) - E_{Fh}(x)]/k_0T_0.$$

- The feature of p-i-n and UTC PDs is the presence of strong built-in field.
- The key question is: What does define the local mobility $\mu_{n,h}(x)$?

Electron Dynamics in Built-in Electric Fields – Key Previous Results



JOURNAL OF APPLIED PHYSICS VOLUME 39, NUMBER 10 SEPTEMBER 1968

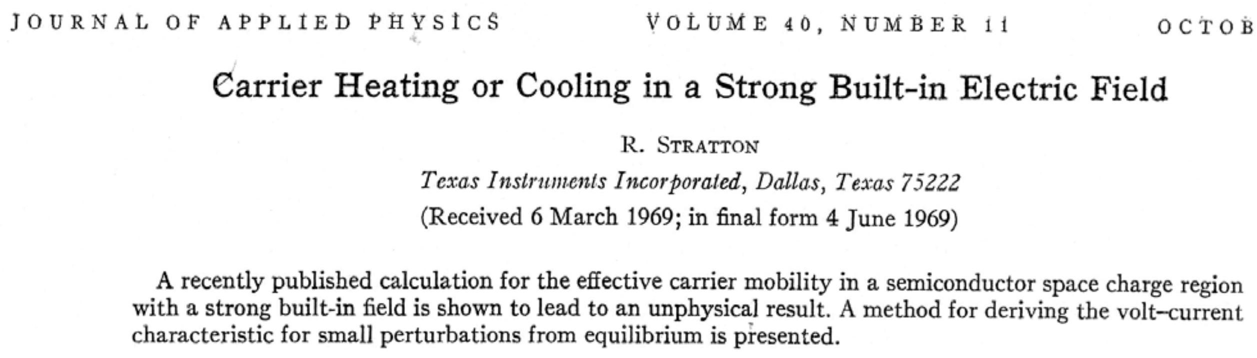
Transport of Electrons in a Strong Built-in Electric Field

J. B. GUNN
IBM Watson Research Center, Yorktown Heights, New York 10598
(Received 4 March 1968; in final form 13 May 1968)

The problem is discussed of the transport of electrons in the presence of a strong field due to fixed space charges, as in the depletion region of a *p–n* junction. It is found that the effective mobility, for small departures from equilibrium, is equal to the chordal hot-electron mobility which would result if the strong field were applied by external means.

The result:

$$\mu = \mu(F_{Buil-in}).$$



JOURNAL OF APPLIED PHYSICS VOLUME 40, NUMBER 11 OCTOBER 1969

Carrier Heating or Cooling in a Strong Built-in Electric Field

R. STRATTON
Texas Instruments Incorporated, Dallas, Texas 75222
(Received 6 March 1969; in final form 4 June 1969)

A recently published calculation for the effective carrier mobility in a semiconductor space charge region with a strong built-in field is shown to lead to an unphysical result. A method for deriving the volt–current characteristic for small perturbations from equilibrium is presented.

The result:

$$\mu = \mu_{low} .$$

- The above results are obtained for systems near the equilibrium.
- The results are in disagreement with each other. THE QUESTIONS:
- What is a correct result? What is a mobility in systems with built-in fields far from equilibrium, which mobility e.g. should be used in DD theory?

Electron Dynamics in Inhomogeneous Electric Fields (Including Built-in Fields) – New Results

- <u>Microscopic Boltzmann Kinetic Equation Based Approach:</u>

$$\left[\vec{\nabla}_r E_c(\vec{r}).\vec{\nabla}_p + \vec{v}_p.\vec{\nabla}_r\right]\Phi(\vec{p},\vec{r}) = \hat{I}\Phi(\vec{p},\vec{r}),$$

Φ(p,r) – is the distribution function.
If Φ(p,r) is known, then the current density is:

$$\vec{j}_n(\vec{r}) = \frac{-e}{V}\sum_{\vec{p}}\vec{v}\Phi(\vec{p},\vec{r}).$$

Two Physically Different Cases (Due to different role of e-e scattering):

- **<u>Case 1. High Electron Density.</u>** **<u>Case 2. Low Electron Density.</u>**

$$\Phi(\vec{p},\vec{r}) = \Phi_0(\vec{p},\vec{r}) + \Phi_1(\vec{p},\vec{r}),$$

In Case 1 $\Phi_0(\vec{p},\vec{r})$ is known:

$$\Phi_0(\vec{p},\vec{r}) = 1/\left[1+\exp[(E(\vec{p},\vec{r}) - E_F(\vec{r}))/k_o T_n(\vec{r})]\right], \quad E(\vec{p},\vec{r}) = E_{\vec{p}} + E_c(\vec{r}),$$

In Case 2 $\Phi_0(\vec{p},\vec{r})$ is unknown, and finding it presents the most difficult part.

The Main Results for Inhomogeneous Fields

- In both cases the electron dynamics is governed by the “field parameter” f(r):

$$f(\vec{r}) = \vec{\nabla}_r E_c(\vec{r}).\vec{\nabla}_r E_F(\vec{r}),$$

- The field parameter is different for e-ns and holes!

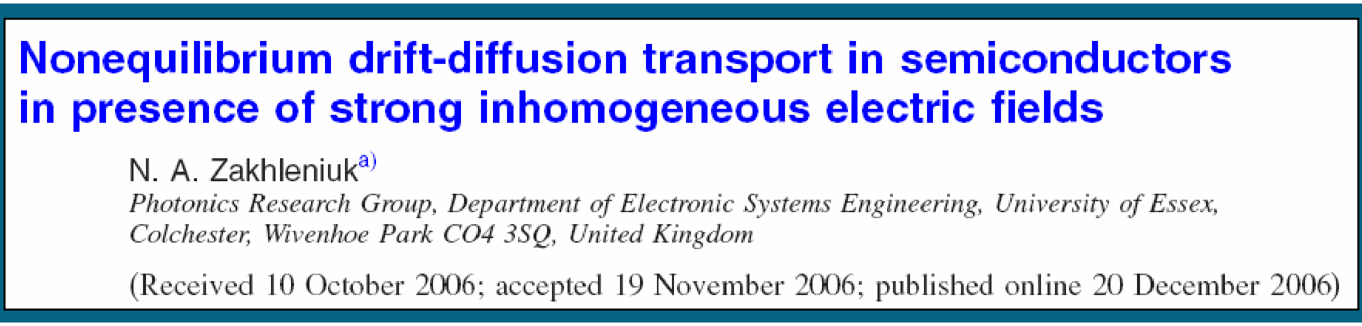
- <u>NOT</u> by the electric field $F=\nabla E_c(r)/e$ or the gradQFermi $\nabla E_F(r)$ alone! Why?

- The mobility is a function of the “field parameter”, <u>which is the driving force</u>:

$$\mu = \mu[f(\vec{r})], \qquad \underline{\text{NOT}} \qquad \mu = \mu[F(\vec{r})], \qquad \underline{\text{OR}} \qquad \mu = \mu[\nabla_{\vec{r}} E_F(\vec{r})],$$

- Within applicability of the DD theory the high-field mobility (i.e. the μ(f) dependence) can be obtained using the known results for a homogeneous field.

- However, even in the DD theory the mobility is different for cases of low and high electron density, respectively.



Nonequilibrium drift-diffusion transport in semiconductors in presence of strong inhomogeneous electric fields

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(Received 10 October 2006; accepted 19 November 2006; published online 20 December 2006)

General Results for Mobility at High and Low Carrier Densities

1. High Carrier Density:

$$\mu(\mathrm{T_n}) \Rightarrow \mu[\mathrm{R}(\mathrm{f})],\quad \mathrm{T_n} \Rightarrow \mathrm{R}(\mathrm{f}),\quad \mathrm{f}(\vec{\mathrm{r}}) = \vec{\nabla}_{\mathrm{r}}\mathrm{E_c}(\vec{\mathrm{r}}).\vec{\nabla}_{\mathrm{r}}\mathrm{E_F}(\vec{\mathrm{r}}),$$

where $\mathrm{T_n} = \mathrm{R}(\mathrm{f})$ is given by the solution of <u>simplified</u> balance equation:

$$\mu(T_n)\vec{\nabla}_r E_c(\vec{r}).\vec{\nabla}_r E_F(\vec{r}) = eW(T_n,T_o).$$

$W(T_n,T_o)$ - is the power loss function.

2. Low Carrier Density:

Const. $\mathrm{F_0}$ solution:

$$\left.\begin{matrix}\Phi_0(\vec{\mathrm{p}},\mathrm{F_0}) \\ \\ \mu(F_o)\end{matrix}\right\}$$

Substitution

$$F_o \rightarrow [f(\vec{r})/e]^{1/2}$$

Inhomogeneous field solution:

$$\left\{\begin{matrix}\Phi_0(\vec{\mathrm{p}},\mathrm{F_0}) \Rightarrow \Phi_0[\vec{\mathrm{p}},\mathrm{f}(\vec{\mathrm{r}})] \\ \\ \mu(F_o) \Rightarrow \mu[(f/e)^{1/2}]\end{matrix}\right.$$

$$f(\vec{r}) = \vec{\nabla}_r E_c(\vec{r}).\vec{\nabla}_r E_F(\vec{r}).$$

Results of the Mobility Calculations for Practically Important Cases

Case of High Electron Density:

- For a particular model with: $\mu(T_n) = \mu_o \times (T_o / T_n)$ and $W(T_n, T_o) = (3/2)k_o(T_n - T_o)/\tau_\varepsilon$ the high-field mobility is:

$$\mu(f) = \mu_o / [1/2 + \sqrt{1/4 + \alpha_o f}\,], \quad f(\vec{r}) > 0; \qquad \mu(f) = \mu_0, \quad f(\vec{r}) < 0. \quad \alpha_o = 2\mu_o \tau_\varepsilon / 3ek_o T_o.$$

Case of Low Electron Density (The saturation velocity model):

$$\mu(F_o) = \frac{\mu_o}{[1 + (\mu_o F_o / v_{sat})^\beta]^{1/\beta}} \quad \Rightarrow \quad \mu(f) = \frac{\mu_o}{[1 + (\mu_o f^{1/2}(\vec{r}) / e^{1/2} v_{sat})^\beta]^{1/\beta}}, \quad \text{if} \quad f(\vec{r}) > 0;$$

$$\mu(f) = \mu_0 \equiv \mu_{low}, \quad \text{if} \quad f(\vec{r}) < 0.$$

Application to Various Physical Situations

- Homogeneous system: $\vec{\nabla}_r E_F(\vec{r}) = \vec{\nabla}_r E_c(\vec{r}) = e\vec{F}_o$, $f = e^2 F_o^2$, $\mu[f] = \mu(F_0)$.

- Strong built-in field is present, but the system is at equilibrium: $\vec{\nabla}_r E_F(\vec{r}) = 0$, $f(\vec{r}) = 0$, $\mu[f] = \mu_{low}$.

- The diffusion current is small: $\vec{\nabla}_r E_F(\vec{r}) \approx \vec{\nabla}_r E_c(\vec{r})$, $f \approx [\vec{\nabla}_r E_c(\vec{r})]^2 = e^2 F^2(\vec{r})$, $\mu[f] = \mu[F(\vec{r})] \approx \mu[\nabla_{\vec{r}} E_F(\vec{r})]$.

- If $\vec{\nabla}_r E_c(\vec{r})$ and $\vec{\nabla}_r E_F(\vec{r})$ have the same sign (as in a reverse-biased p-n junction or illuminated p-i-n photodiode), then $f(\vec{r}) > 0$ and we have the electron heating, which however, requires not only strong electric field $\vec{\nabla}_r E_c(\vec{r})$, but also large $\vec{\nabla}_r E_F(\vec{r})$.

- If $f(\vec{r}) = \vec{\nabla}_r E_c(\vec{r}).\vec{\nabla}_r E_F(\vec{r}) < 0$ (as in forward-biased p-n junction), then the direction of the current is opposite to the direction of the electric field, and there we be carrier cooling (decrease of T_n). In this case approximately $\mu(f) \approx \mu_0$.

Application to Simulation of p-i-n Photodiode: Steady-State Analysis

DESSIS (Synopsys/ISE) tool is used for the simulation.

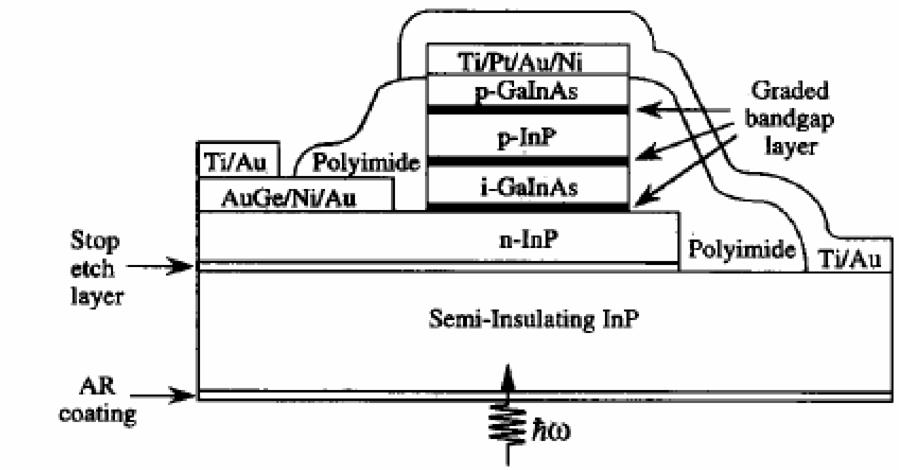
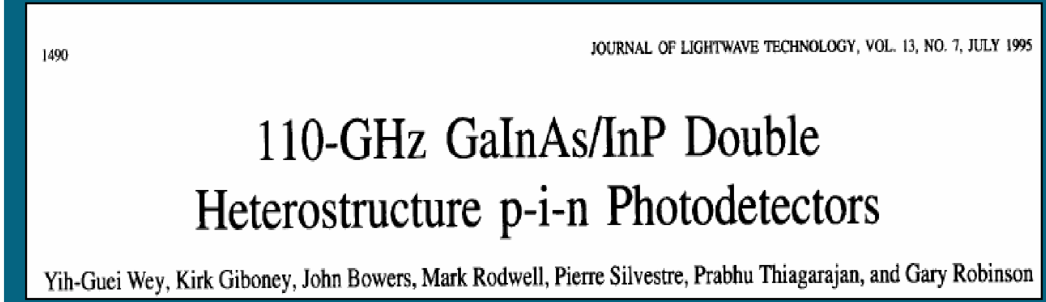


Fig. 1. Cross section of a high-speed GaInAs/InP p-i-n photodiode.


1490 JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 13, NO. 7, JULY 1995

110-GHz GaInAs/InP Double Heterostructure p-i-n Photodetectors

Yih-Guei Wey, Kirk Giboney, John Bowers, Mark Rodwell, Pierre Silvestre, Prabhu Thiagarajan, and Gary Robinson

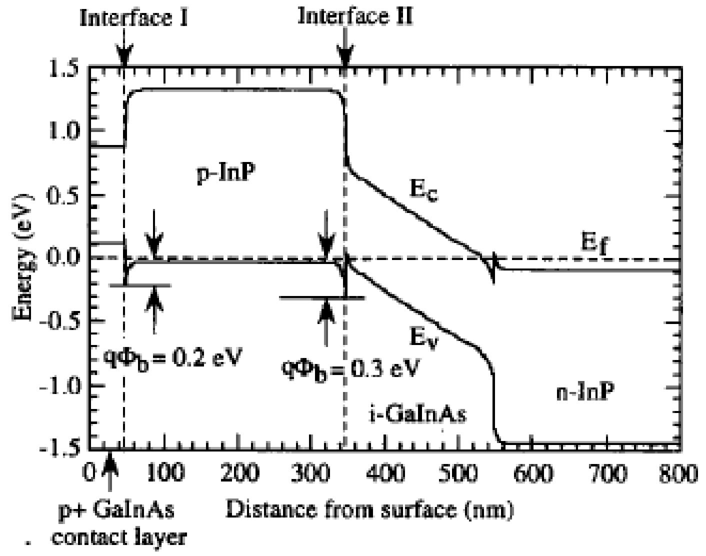
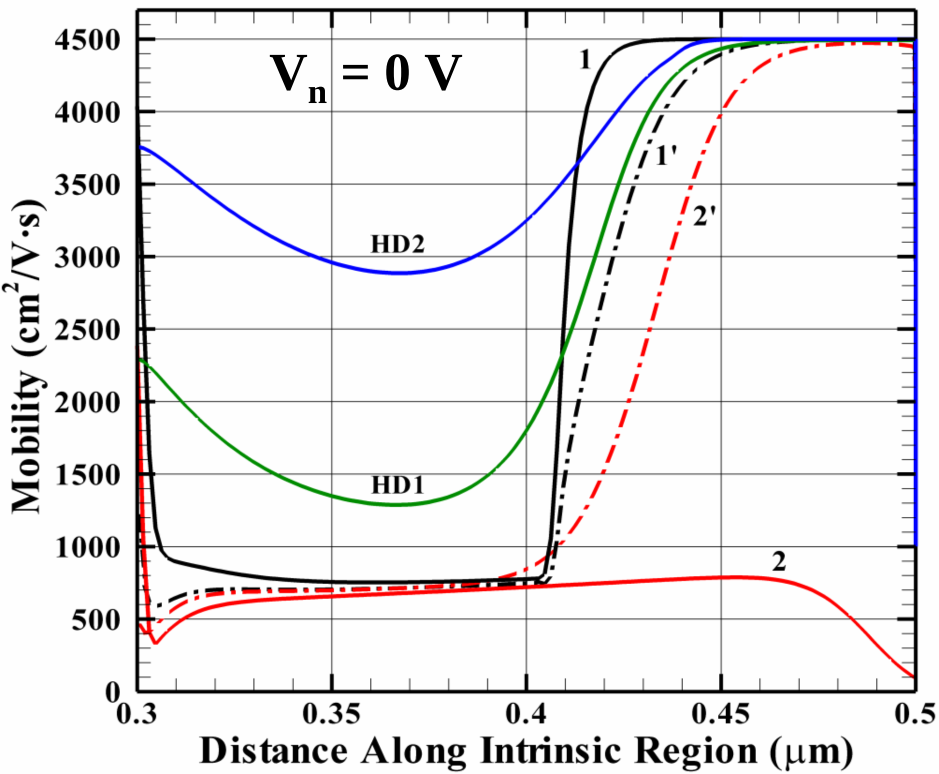


Fig. 4. Band diagram of an abrupt GaInAs/InP p-i-n photodiode.

Parameters: InP: Mobilities: 930 (e); 85 (h);
Doping: $N_A=1.5\times10^{19}$, $N_D=3\times10^{18}$;
InGaAs: Mobilities: 4500 (e); 85 (h);
$v_{sat}=2.5\times10^{7}$ (e); 0.5×10^{7} (h);
Doping: $N_D=5\times10^{15}$; Bandgap: $E_g=0.75$ eV.
Interfaces: $\Delta E_c=0.25$ eV, $\Delta E_v=0.35$ eV.
Absorption: $\alpha=6080$ cm^{-1}; $I_0=3$ kW/cm^2;
Reverse bias: -1.5 V.
Boundary conditions: Thermionic currents.

Calculated Mobilities Using Various Models



- Large difference in the high-field mobilities for DD models using various driving forces clearly shows that μ(F) and μ(gradE$_{Fermi}$) are not equivalent.

- μ(f) from the DD theory qualitatively follows μ(T$_n$) from the HD theory. This means that DD is also able to correctly describe the HF transport, provided that the correct DF is used.

- Curves 1 and 2 obtained from DD simulation using $\mu(F) = \mu_o / \sqrt{1 + (\mu_o F / v_{sat})^2}$ with (1) $F = |\nabla_x E_F(x)/e|$ and (2) $F = |\nabla_x E_c(x)/e|$.

- Curves 1′ and 2′ are calculated mobilities using $F = [f(x)/e^2]^{1/2}$, where $f(x) = \nabla_x E_F(x).\nabla_x E_c(x)$ was obtained from the results corresponding to curves 1 and 2, respectively.

- Curves HD1 and HD2 are the results of full HD simulation using $\mu(T_n) = \mu_o (T_o / T_n)$ (HD1) and $\mu(T_n) = \mu_o / [\sqrt{1 + \kappa^2 (T_n - T_o)^2} + \kappa (T_n - T_o)]$ (HD2), where $\kappa = 3\mu_o k_o / 4e\tau_\varepsilon v_s^2$.

Hydrodynamic or Energy Balance Model

- Additional energy flux continuity (balance) equations for e-ns and holes:

$$\frac{\partial w_n}{\partial t} + \vec{\nabla} \cdot \vec{S}_n = \frac{1}{e} \vec{J}_n \cdot \vec{\nabla} E_c + \frac{w_n - w_0}{\tau_\varepsilon},$$

$$\vec{S}_n = -\frac{3}{2} \frac{k_0 T_n}{e} \left(\vec{J}_n + k_0 n \mu_n \vec{\nabla} T_n \right),$$

$$w_n = \frac{3}{2} n k_0 T_n,$$

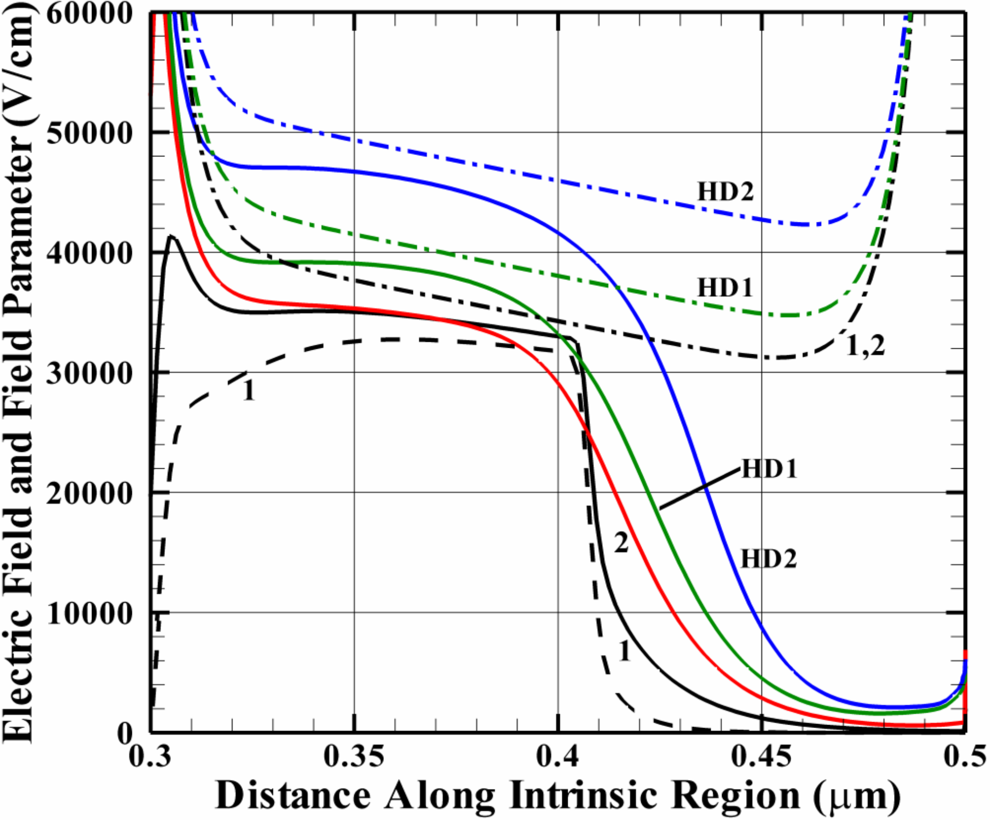
$$\mu_n = \mu_0 \times (T_0 / T_n),$$

$$\mu_n = \mu_0 / \left[\sqrt{1 + \kappa_n^2 (T_n - T_0)^2} + \kappa_n (T_n - T_0) \right], \quad \kappa_n = \frac{3}{4} \frac{k_0 \mu_0}{e \tau_\varepsilon v_s^2}.$$

- Important difference: DD model does not includes hot-electron effects, the HD model does.

- Boundary conditions at all interfaces are formulated via TE emission carrier fluxes and the carrier energy fluxes.

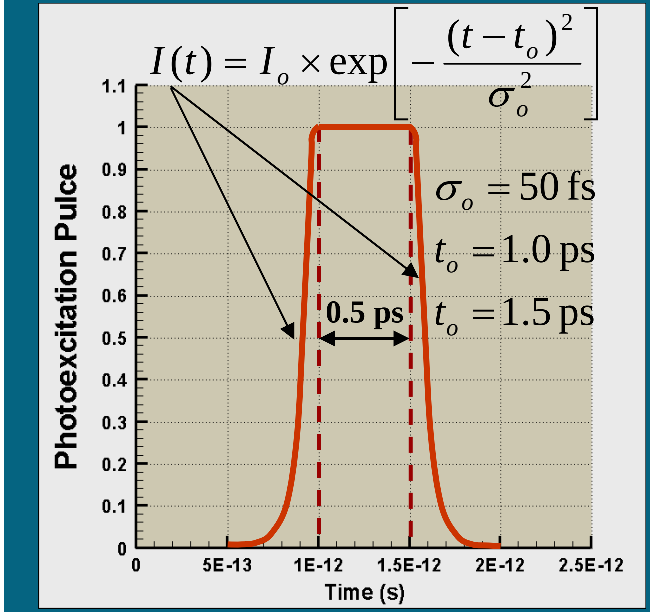
Calculated Electric Fields And Field Parameter

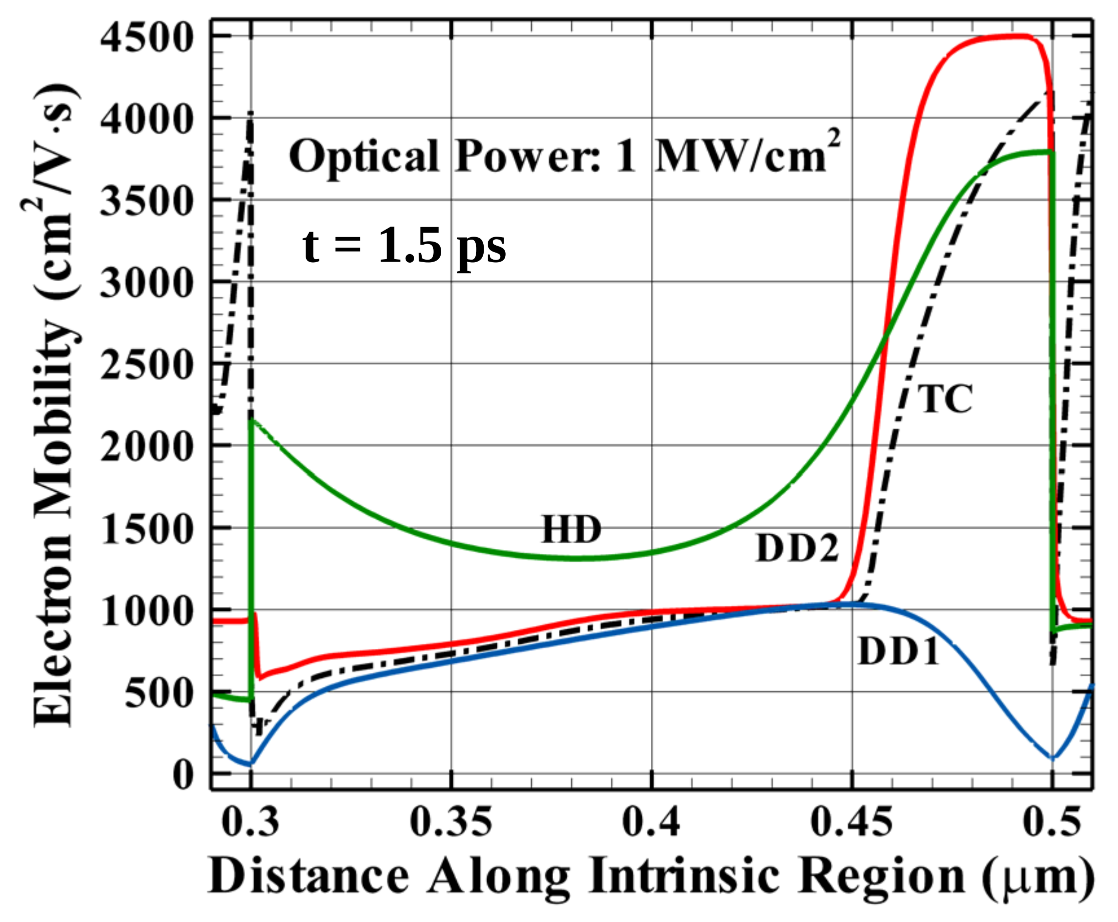


- In general the field parameter f(r) does not follow F(r) or $\nabla E_F(r)$.

- Profiles of the electric field $|\nabla_x E_c(x)/e|$ (dash-dotted lines);
- Profiles of the "field parameter" $[f(x)/e]^{1/2}$ (solid lines);
- Profile of the gradient of QFL $|\nabla_x E_F(x)/e|$ (dashed line, only curve 1 is shown).

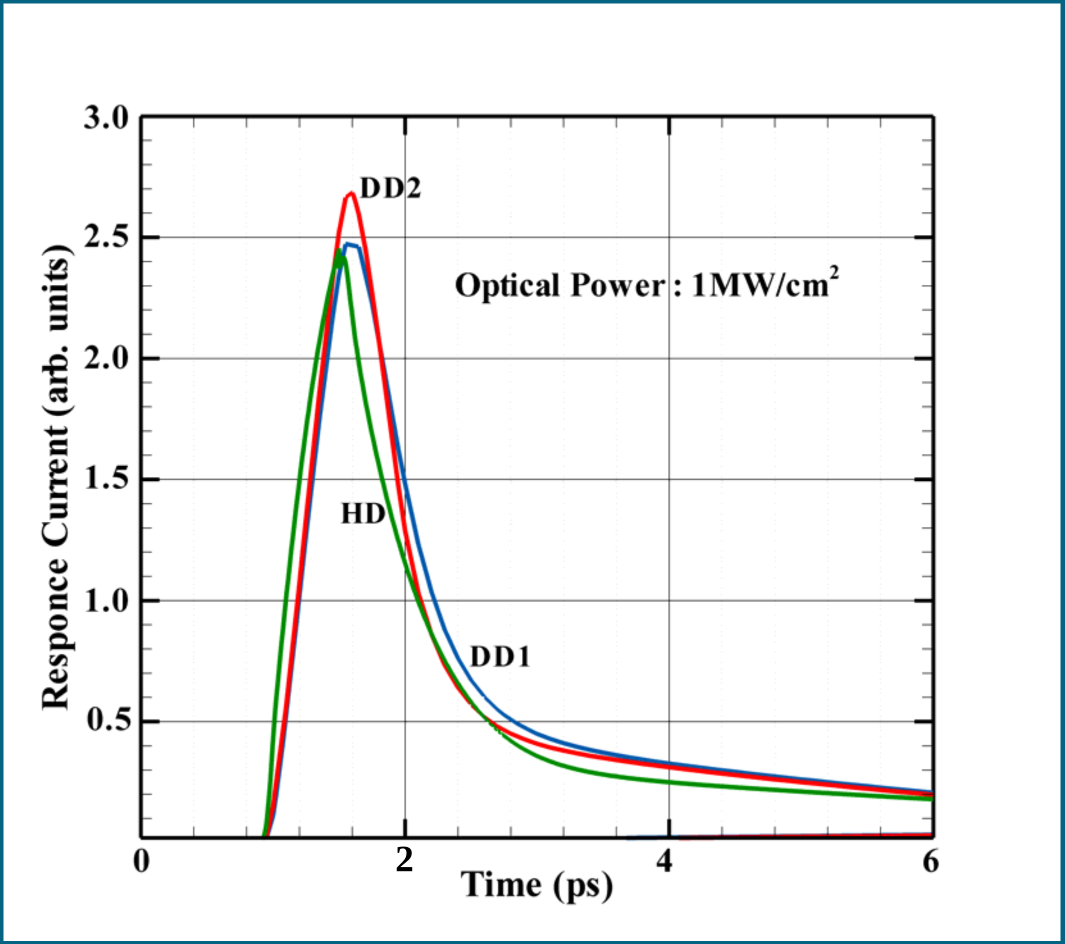
Application to Simulation of p-i-n Photodiode: Transient Analysis: Mobility





Transient mobility profiles at t=1.5 ps for various models: DD1 – F, DD2 - ∇E_F, HD – T_n, TC – Theoretical Calculations.

Application to Simulation of p-i-n Photodiode: Transient Analysis: Output Current



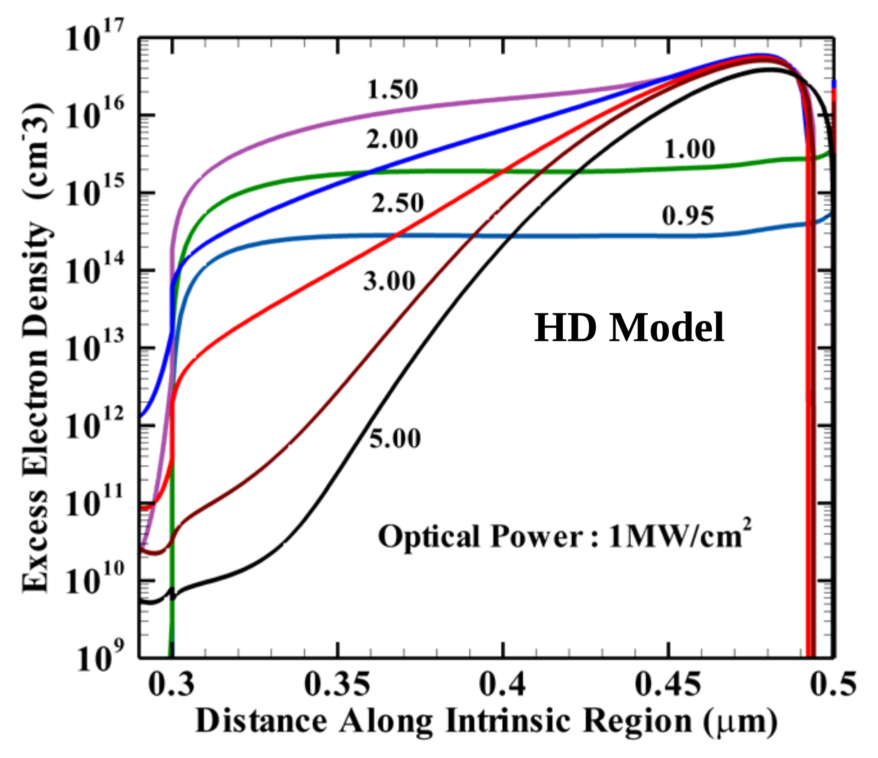
In spite of large difference in the drift mobility/velocity profiles (previous figure), the output signals are very close for all models. What is a physical reason for this result?

University of Essex

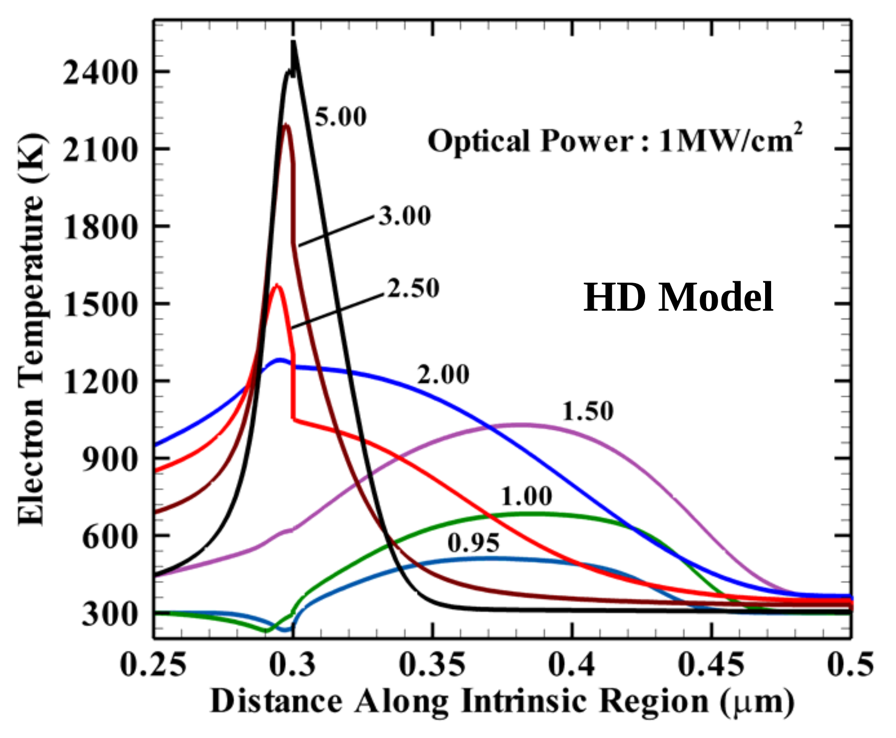
Application to Simulation of p-i-n Photodiode: Transient Analysis: Density and Temperature

Department of Computing and Electronic Systems

Excess electron density at various t.



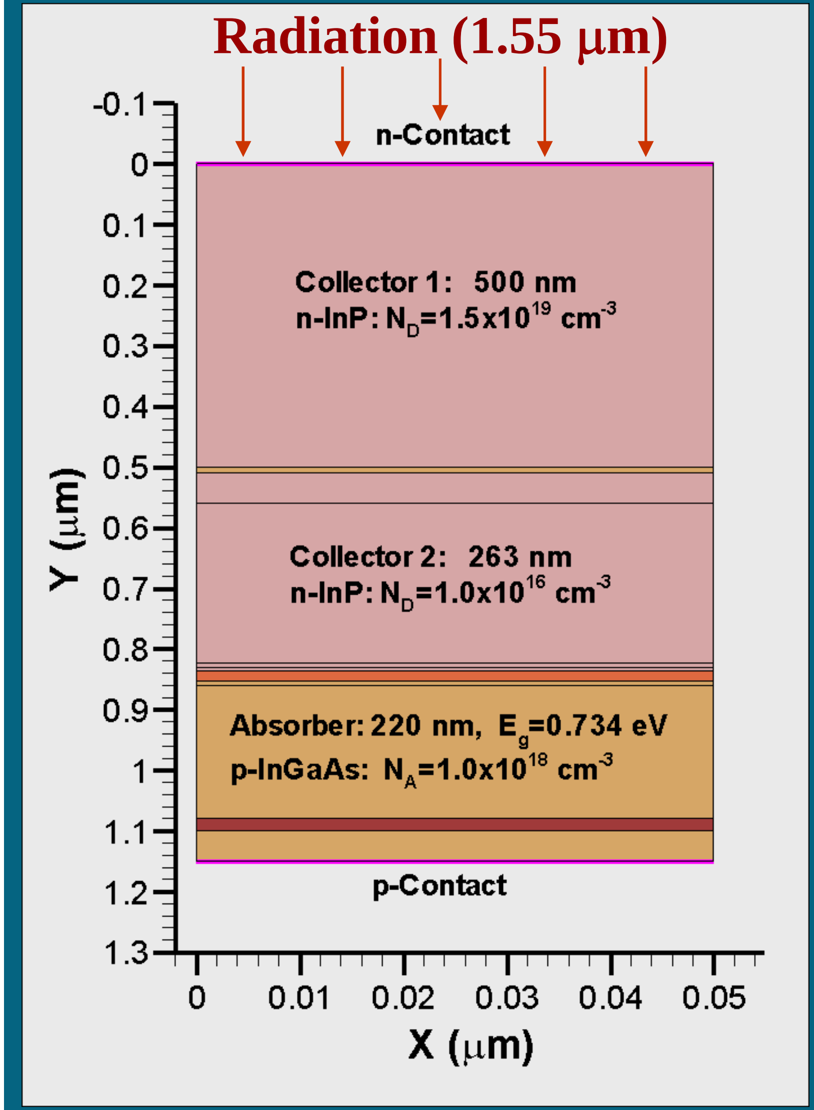
Electron temperature at various t.

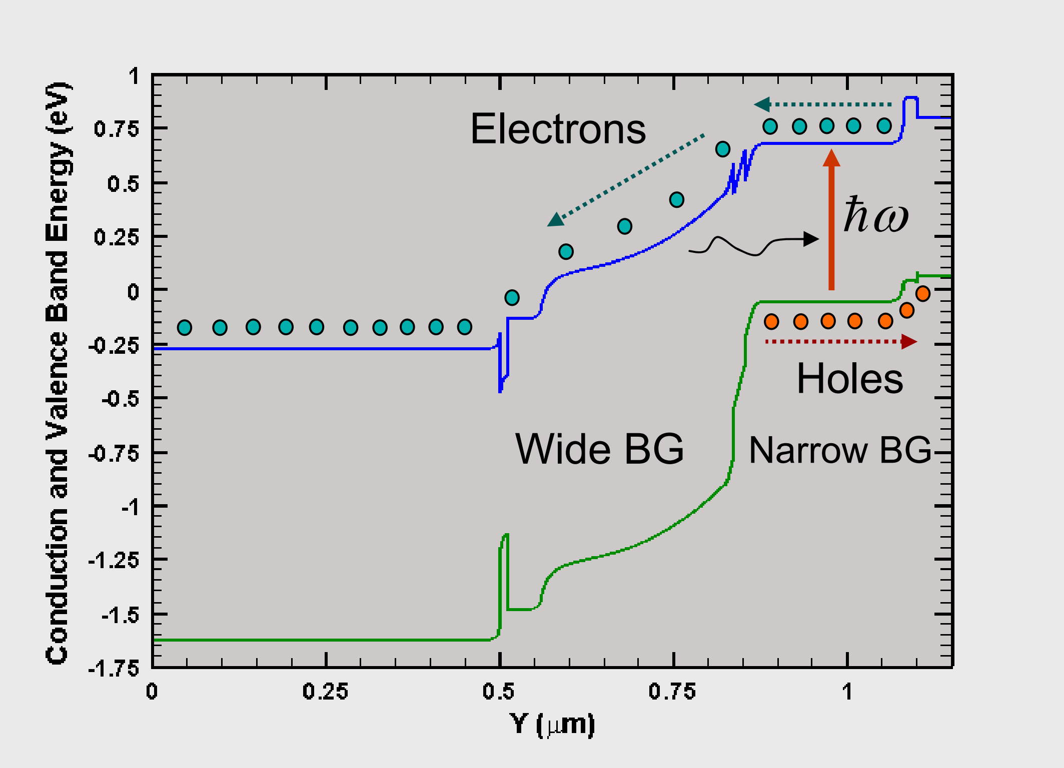


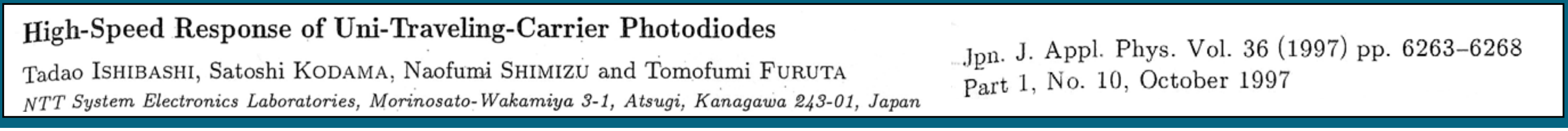
At high optical excitations the current is determined by the TE emission at the IF rather than by the high-field transport. The electron diffusion current flows away from the n-InP/InGaAs IF and it helps to counterbalance the fast drift supply of the electrons to the IF. Although the max of $T_n(x)$ is shifted away from the IF as *t* increases, at *t~2 ps* $T_n(x=0.5)=360$ K is still higher than T_0 and this explains faster response in HD model.

THEORY AND SIMULATIONS OF UTC PHOTODETECTORS

UTC Device Structure And Energy Bands







High-Speed Response of Uni-Traveling-Carrier Photodiodes

Tadao Ishibashi, Satoshi Kodama, Naofumi Shimizu and Tomofumi Furuta

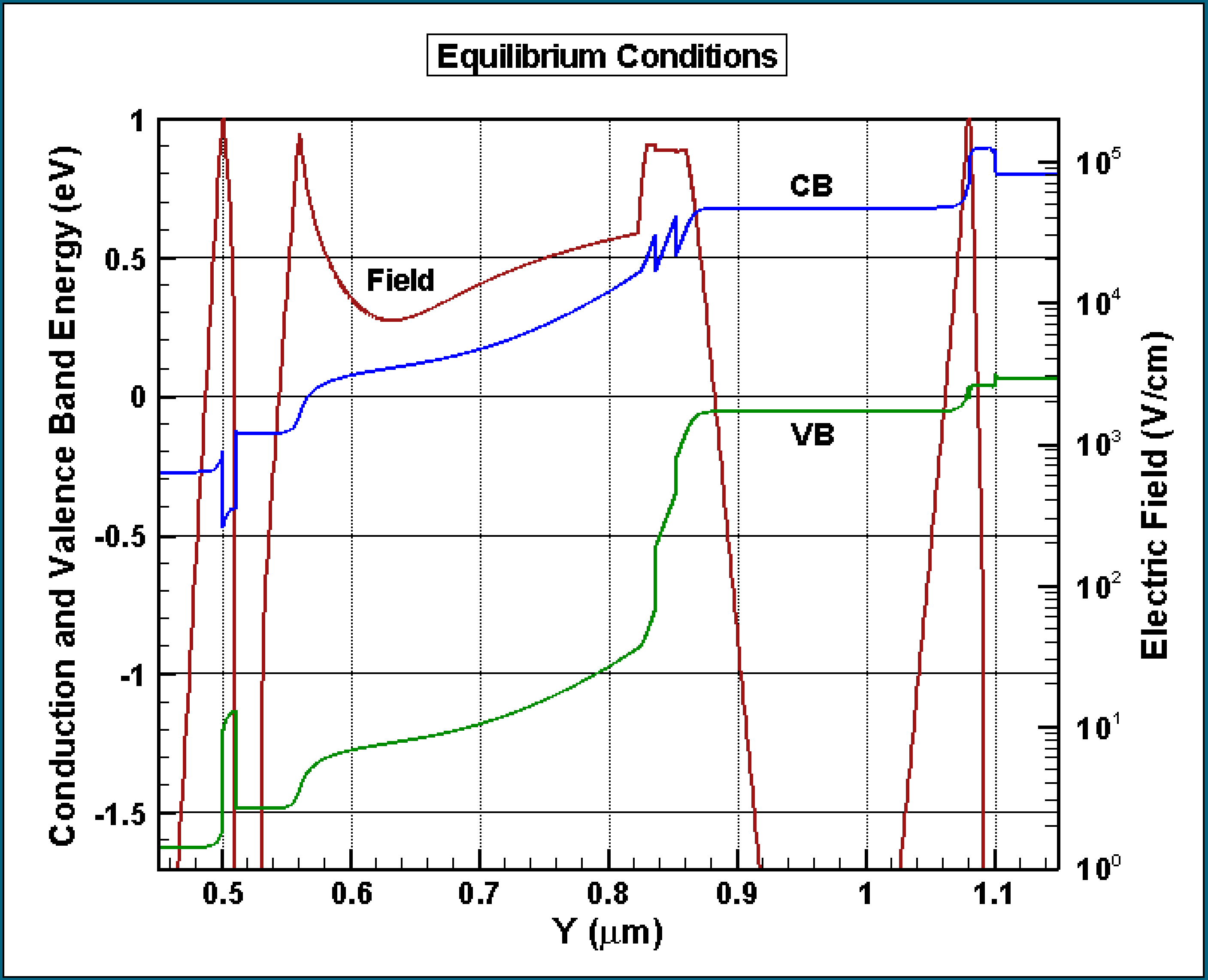
NTT System Electronics Laboratories, Morinosato-Wakamiya 3-1, Atsugi, Kanagawa 243-01, Japan

Jpn. J. Appl. Phys. Vol. 36 (1997) pp. 6263–6268
Part 1, No. 10, October 1997

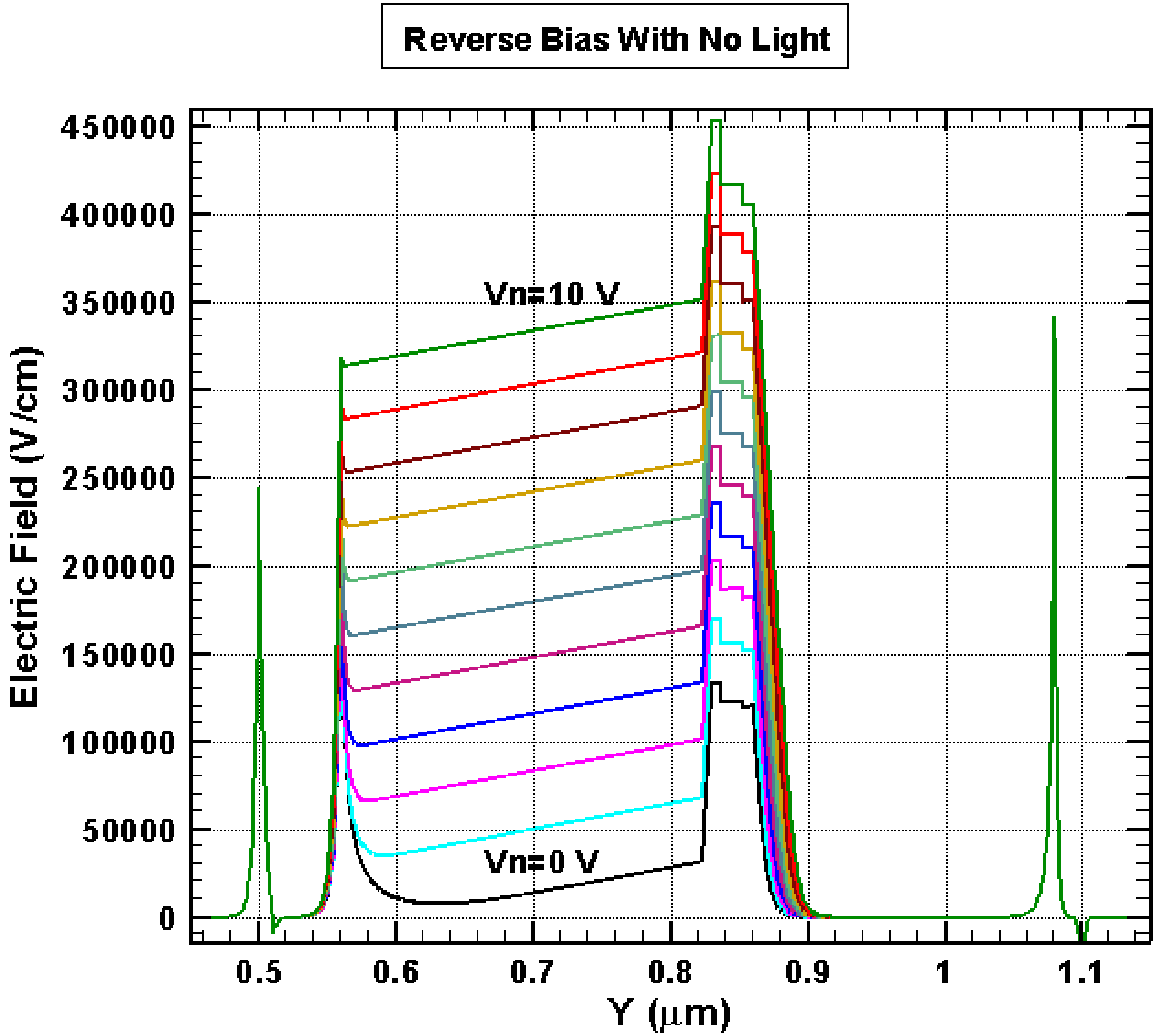
University of Essex

Built-in Electric Field

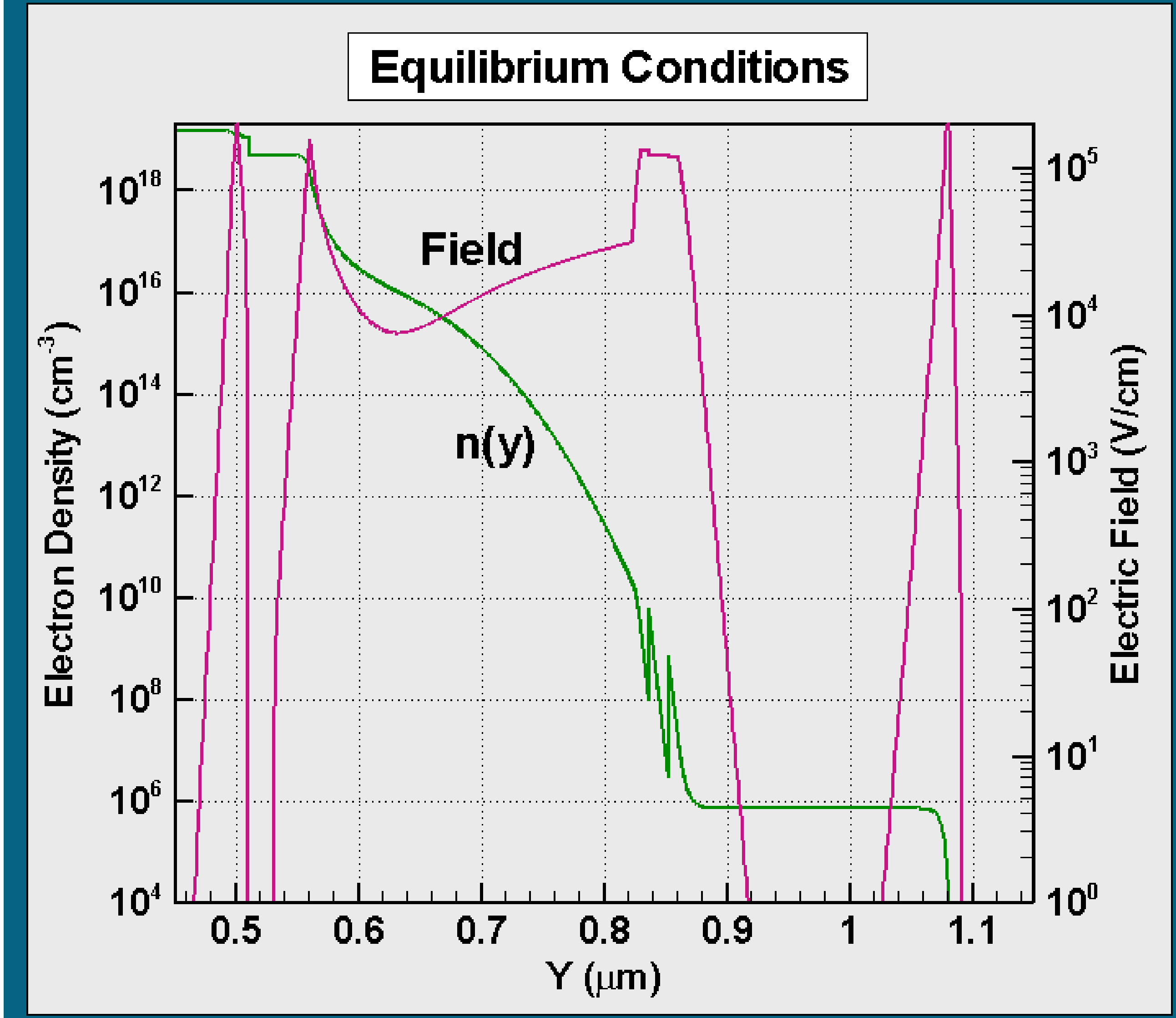
Department of Computing and Electronic Systems



Variation of Electric Field with Bias



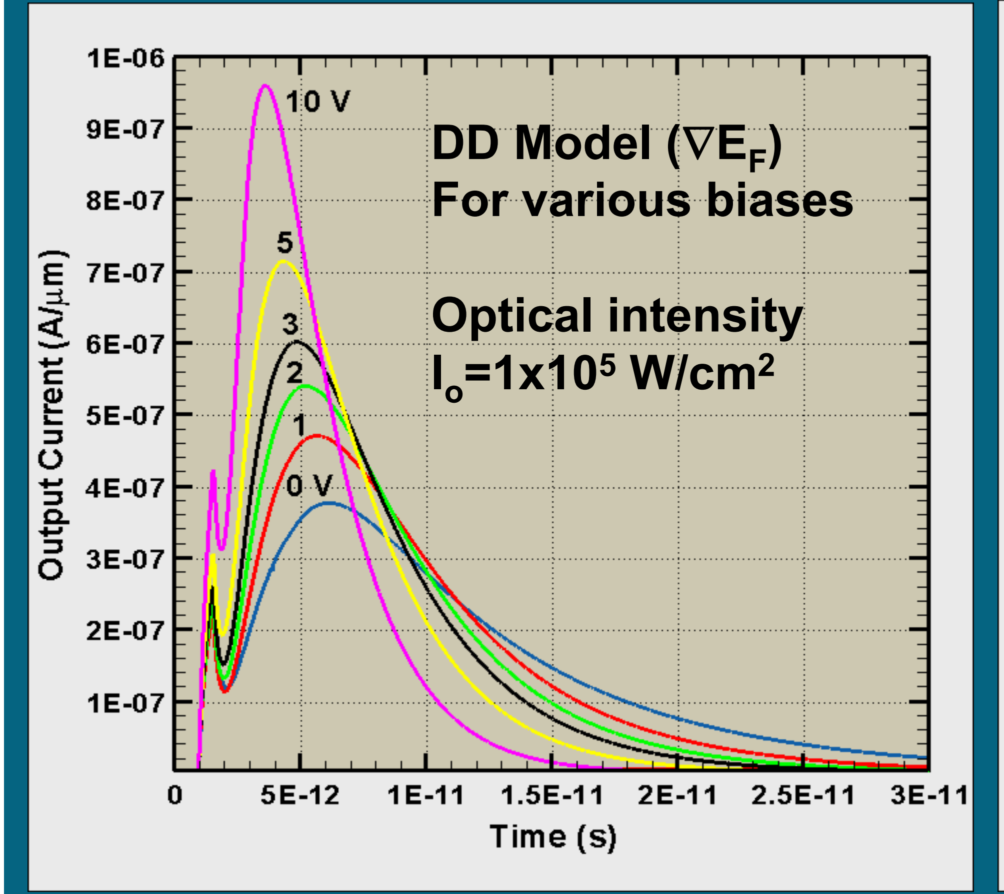
Strong Electric Field and Strong Gradient

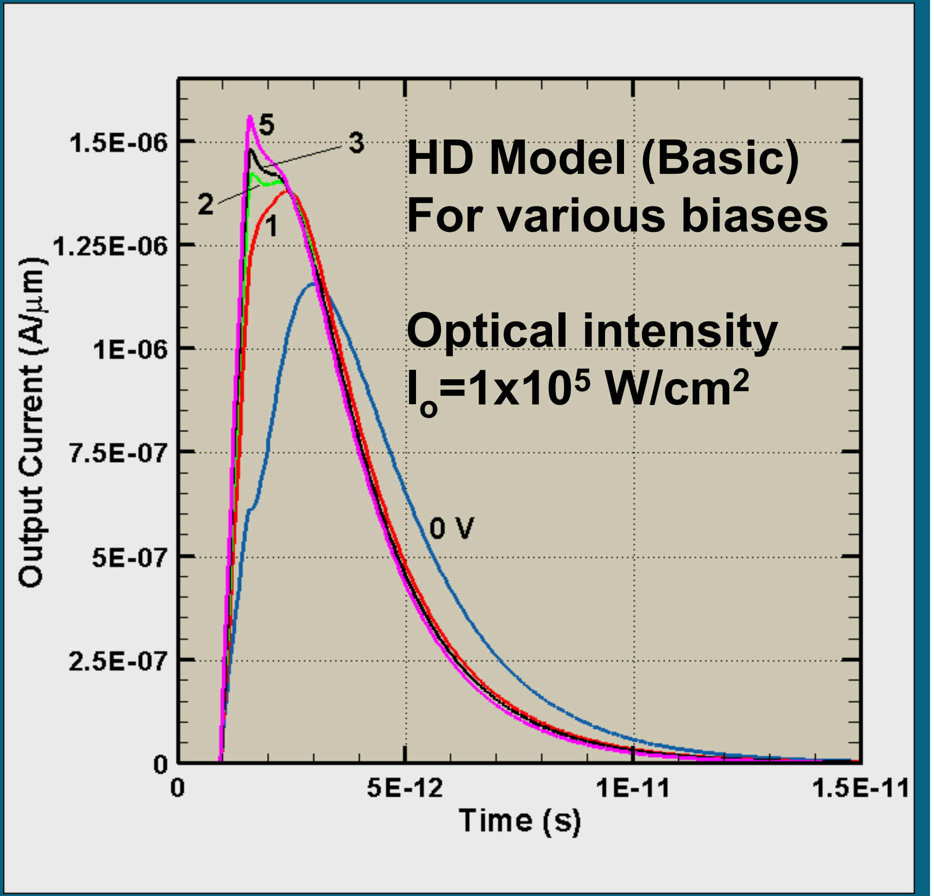


- **When equilibrium is violated, the high-field carrier dynamics is determined by the joint action of F (∇E_c) and ∇n, NOT by the electric field alone. This is the physical reason behind introduction of the field parameter f(r):**

$$f(\vec{r}) = \vec{\nabla}_r E_c(\vec{r}).\vec{\nabla}_r E_F(\vec{r}),$$

Photocurrent Response in DD and HD Models





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Direct Comparison of HD and DD Responses at V_n=0 V and V_n=5 V

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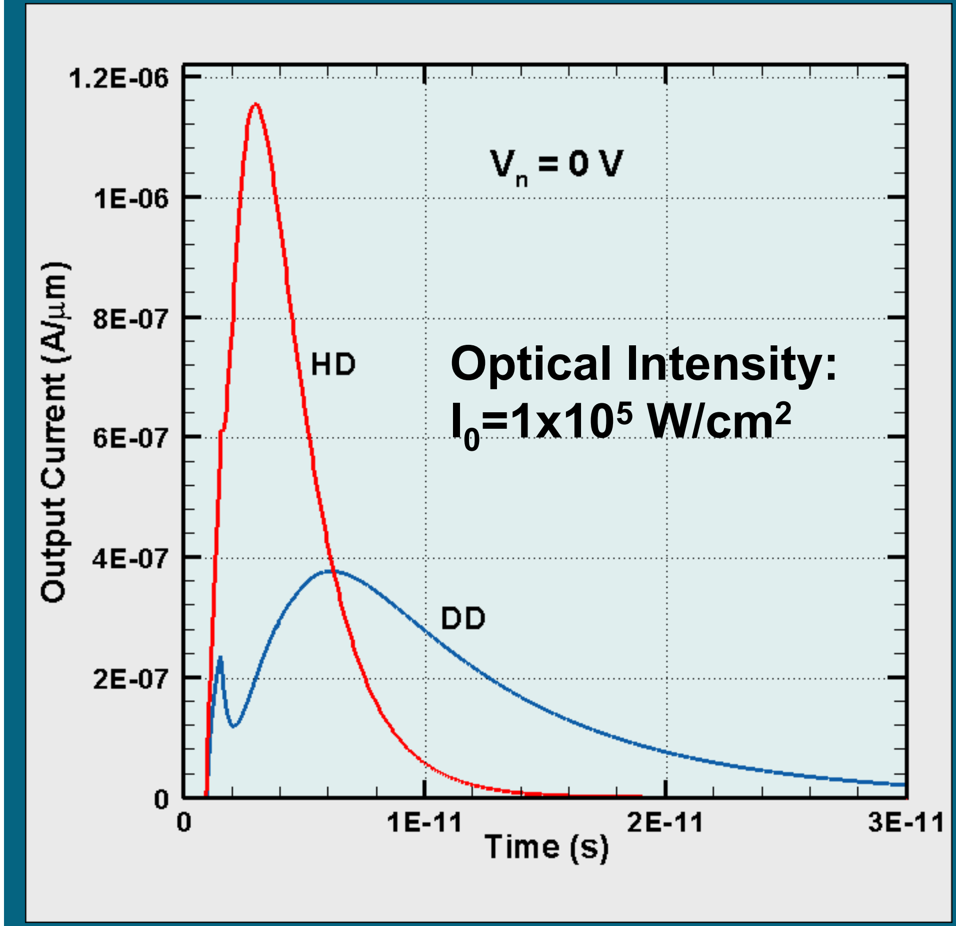
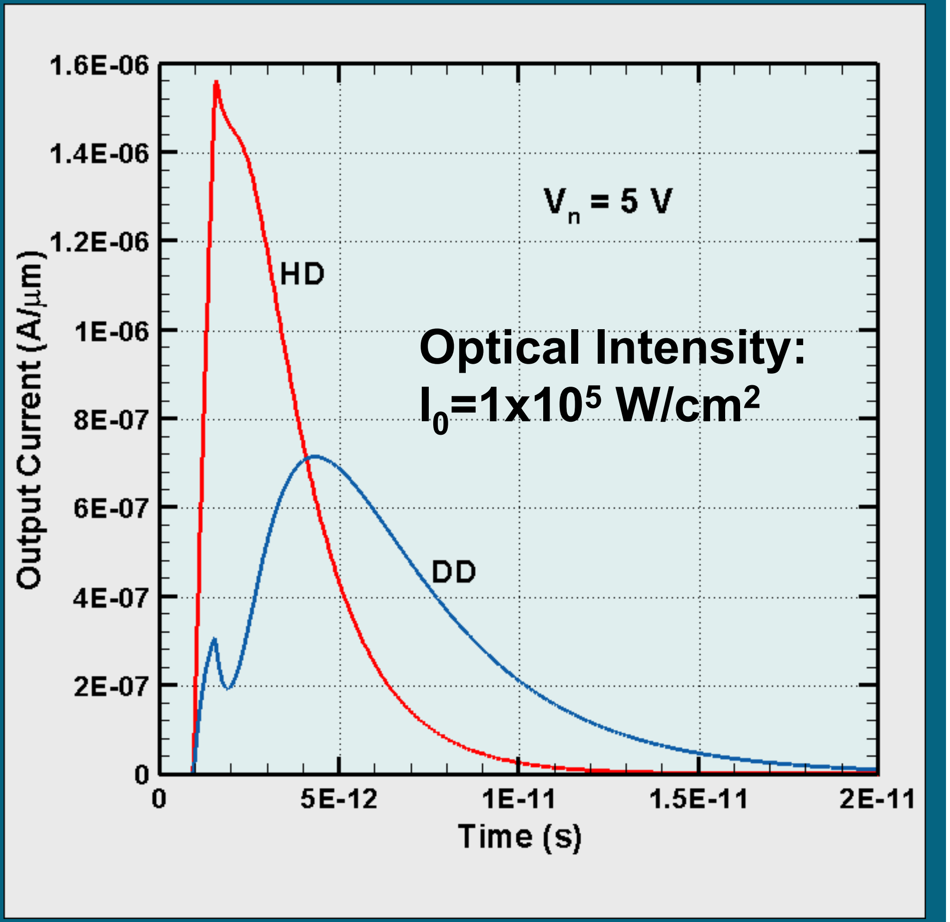
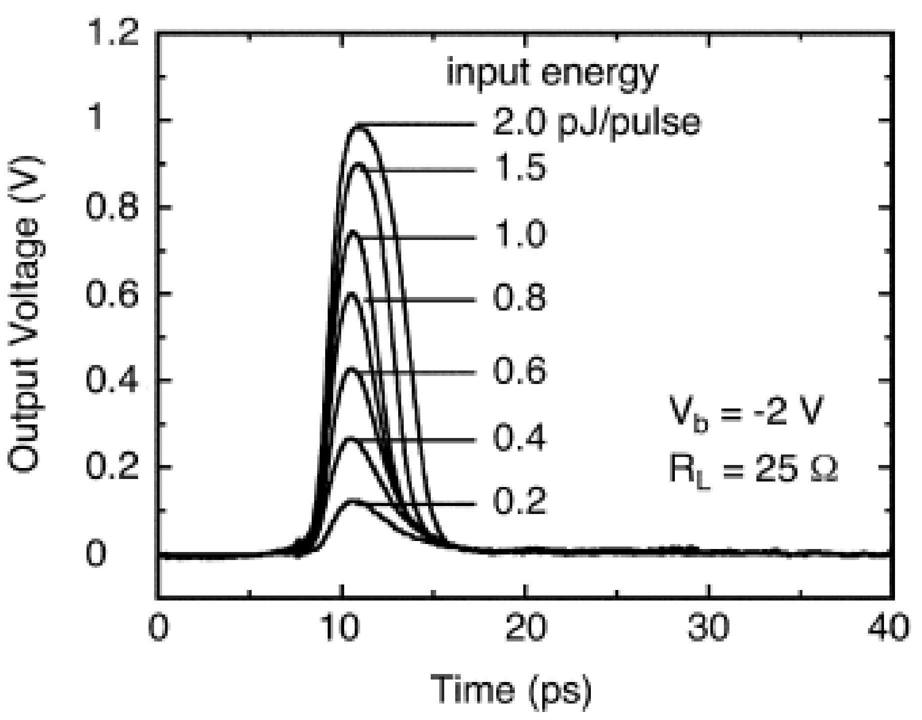
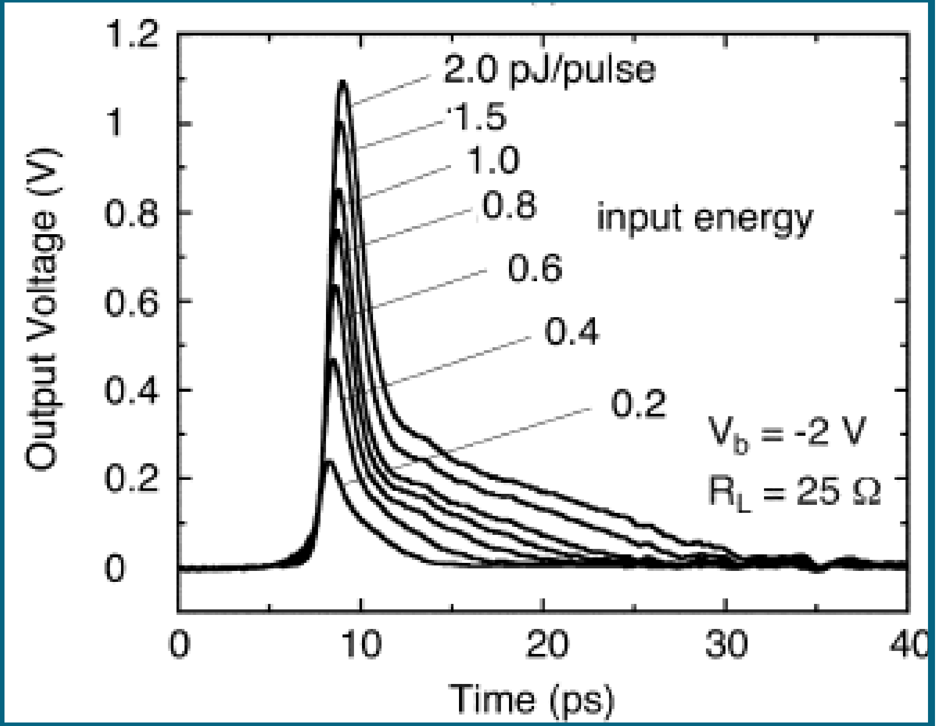




Comparison with the Experiment

T. Ishibashi et al, (Invited Review Paper) “High-Speed and High-Output InP-InGaAs Unitravelling-Carrier Photodiodes”, IEEE J. Select. Topics Quantum Electron, Vol. 10, 709, (2004).

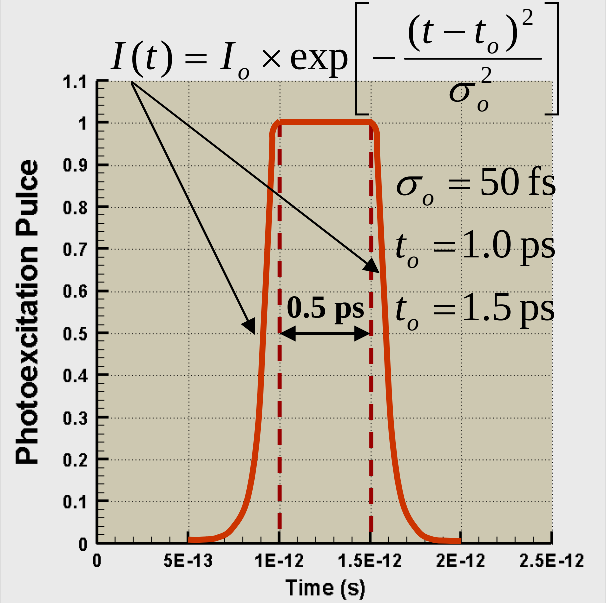


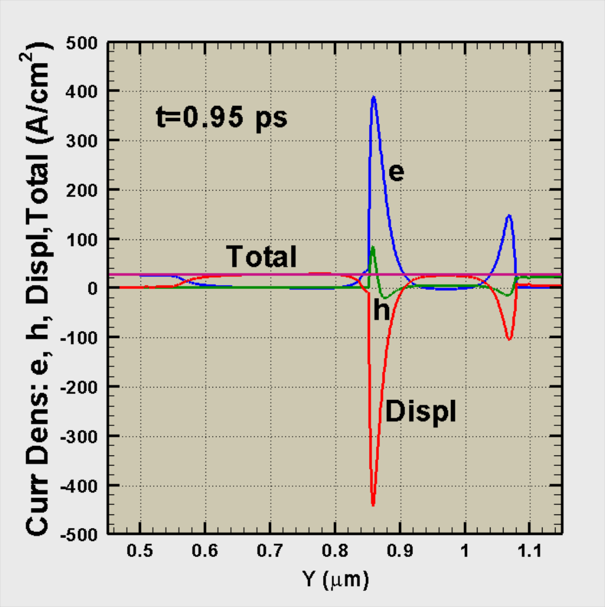


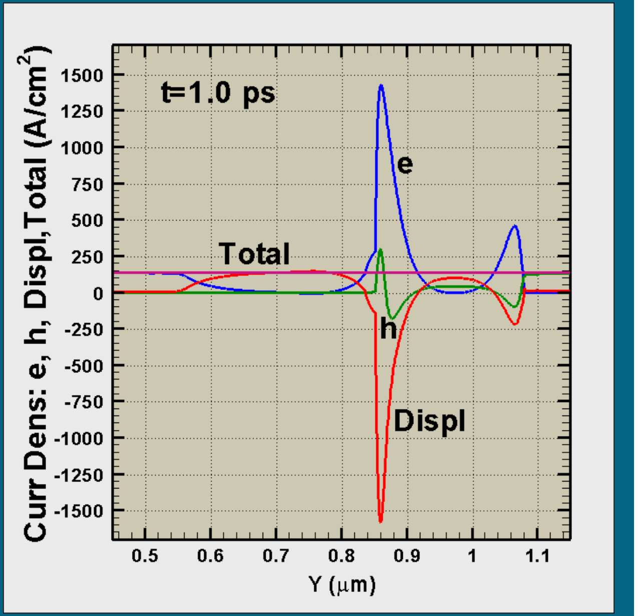
Response of UTC PD (A=2500 μm^2) to 1.55 μm incident pulse with FWHM=0.4 ps. (2pJ input energy corresponds to intensity ≈ I_o=1x10^5 W/cm^2). The experiment is well described with the HD model, but not with the DD model.

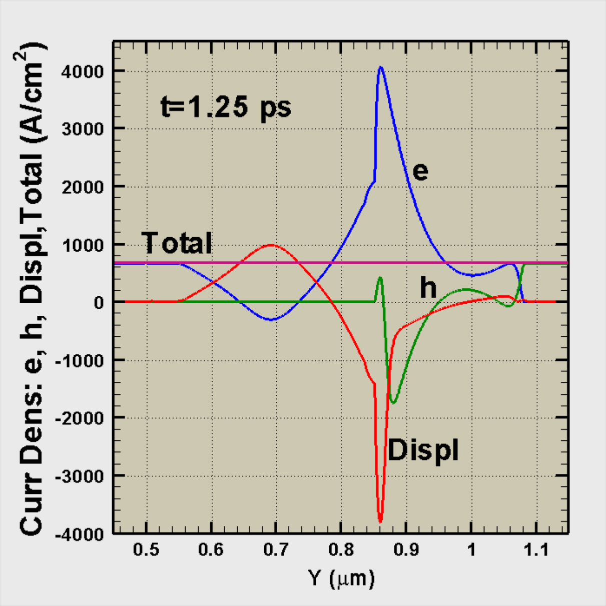
(For comparison: Photoresponse of a p-i-n PD. The experimental curves are well described by the simulation results with the DD or the HD models).

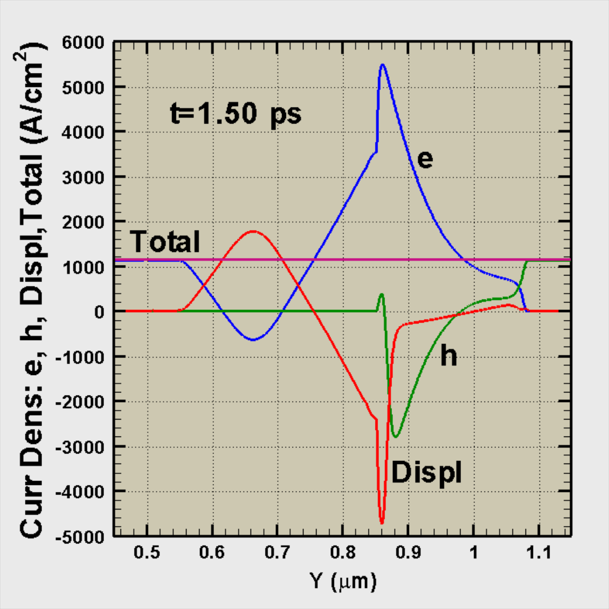
Transient Current Profiles Across the Device from the HD Model: $I_o=10^5$ W/cm^2 (V_n=0 V)

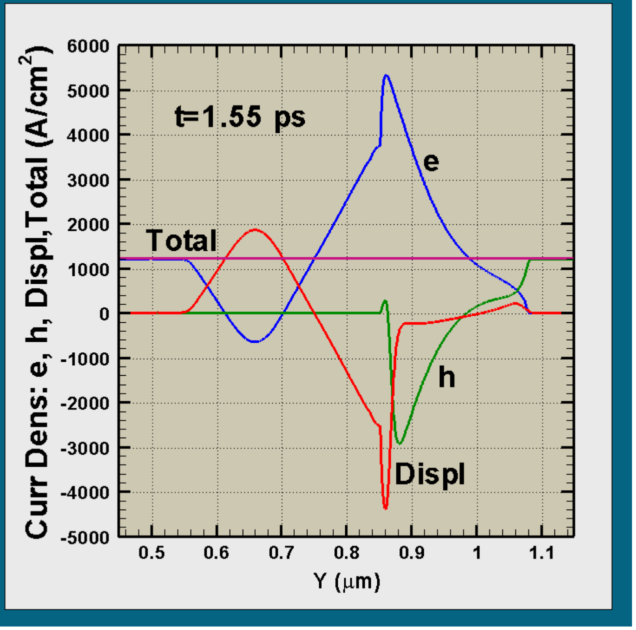




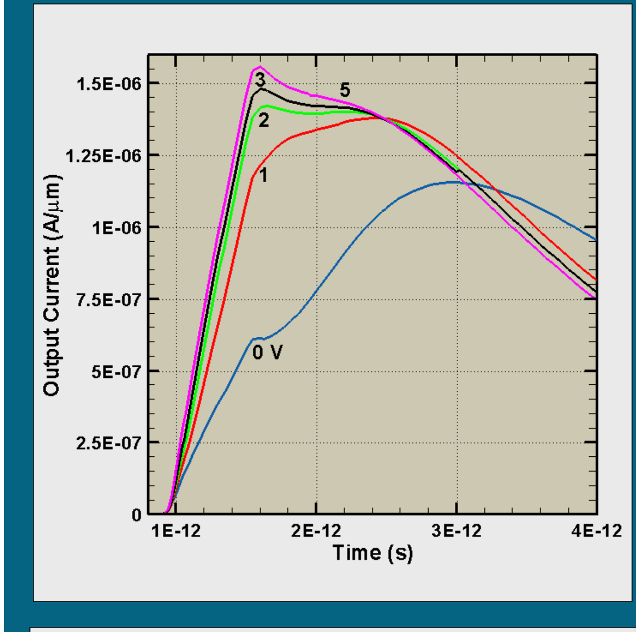


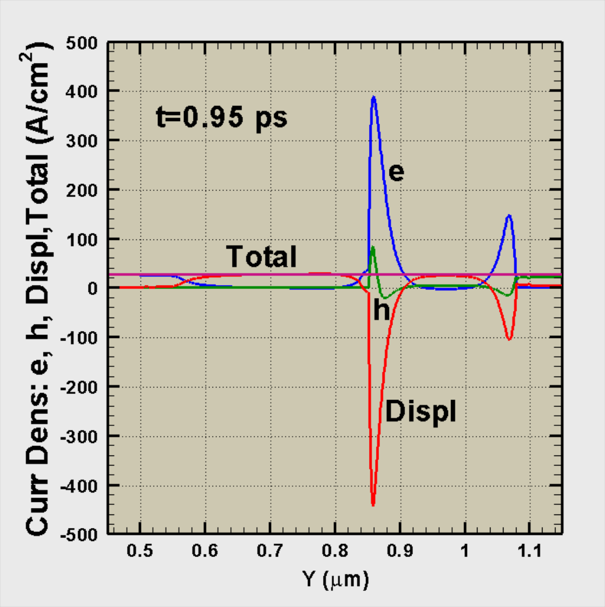


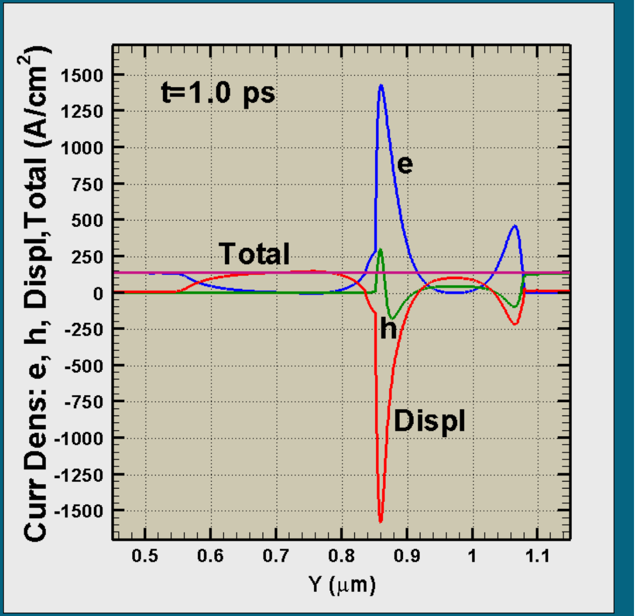


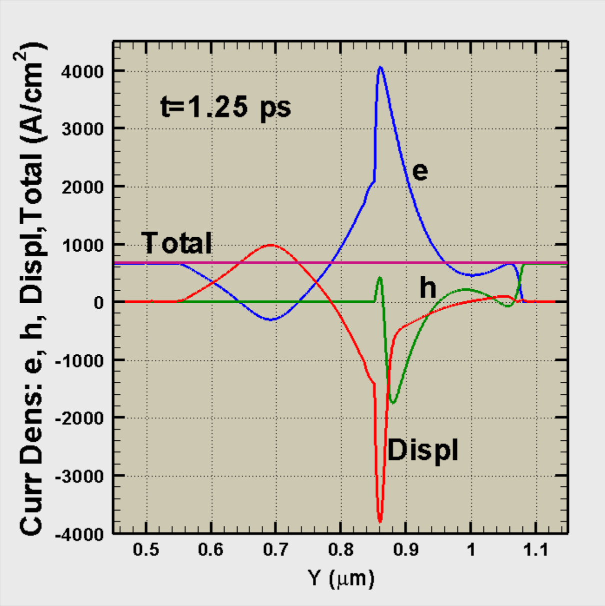


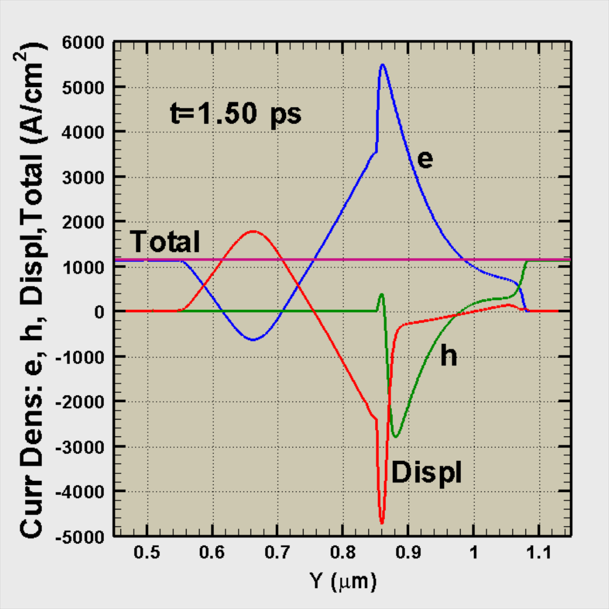
Transient Current Profiles Across the Device from HD Model: $I_o=10^5$ W/cm^2 (V_n=0 V)

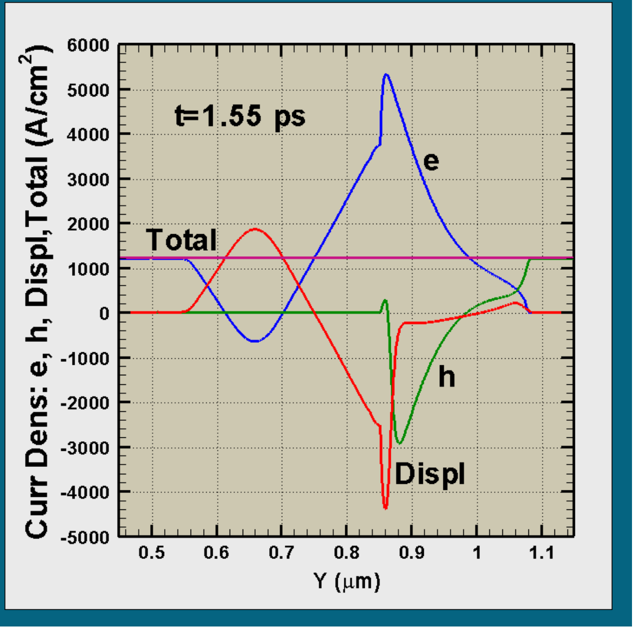




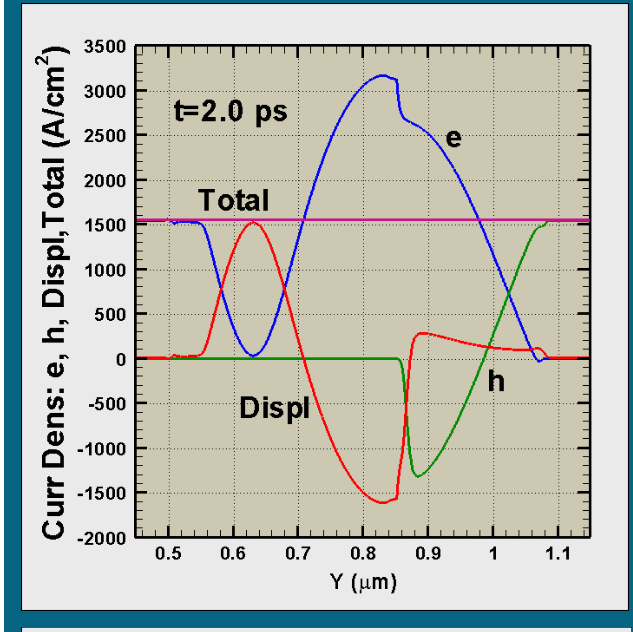


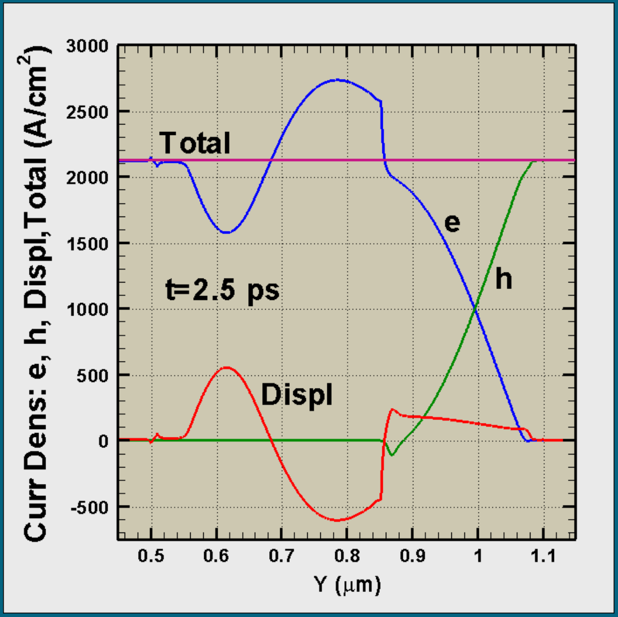


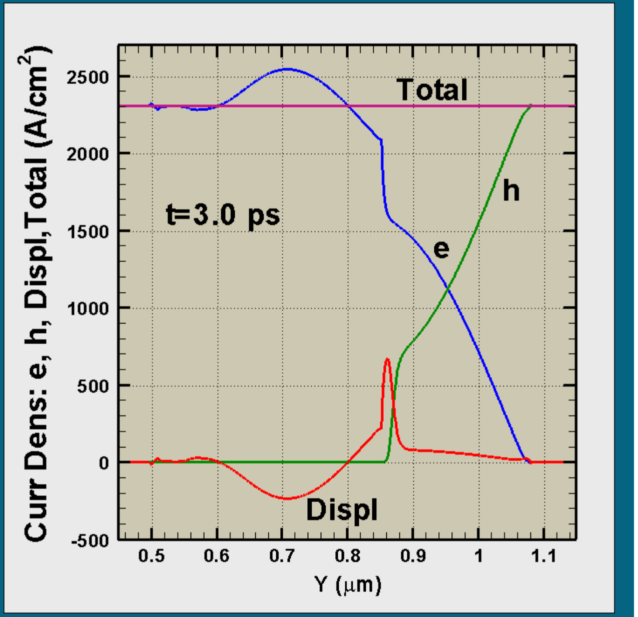


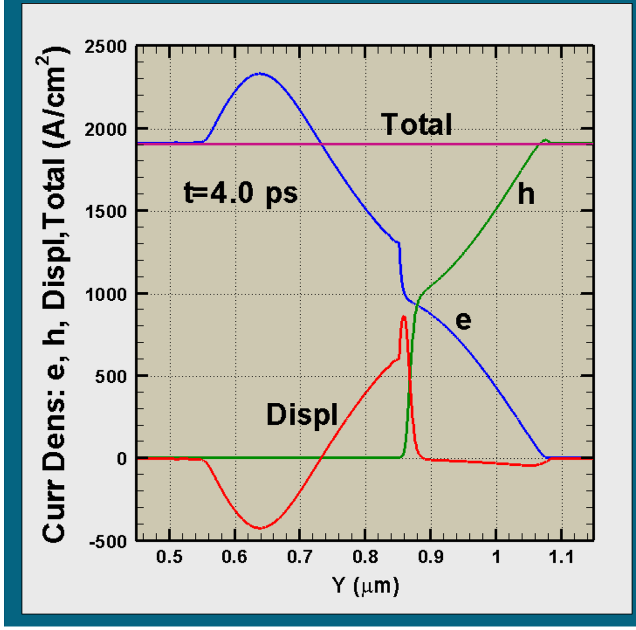


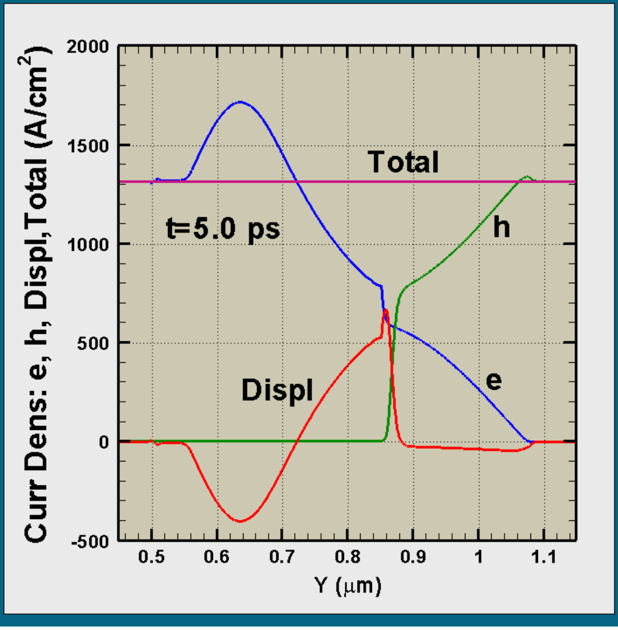
Transient Current Profiles Across the Device from the HD Model: $I_o=10^5$ W/cm^2 (V_n=0 V) - Continued

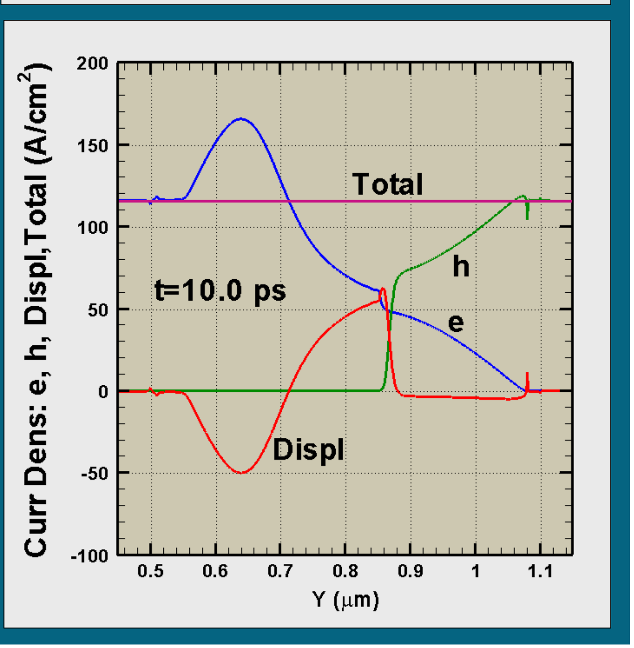












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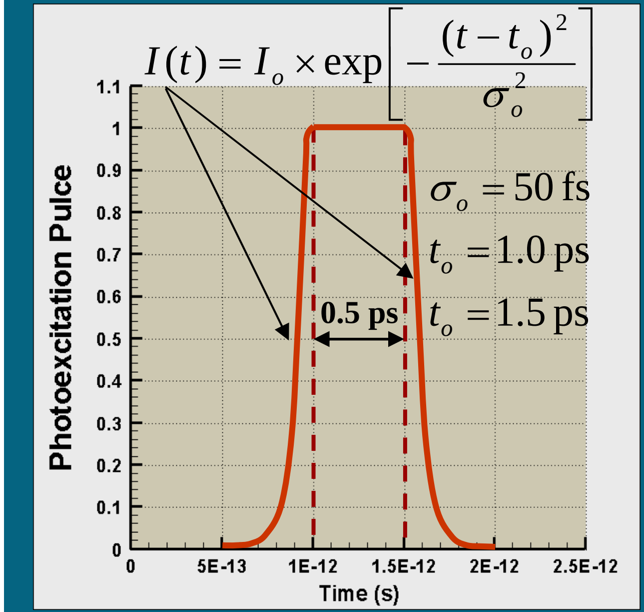
Transient Current Profiles Across the Device from the HD Model: $I_o = 10^5$ W/cm² ($V_n = 1$ V)

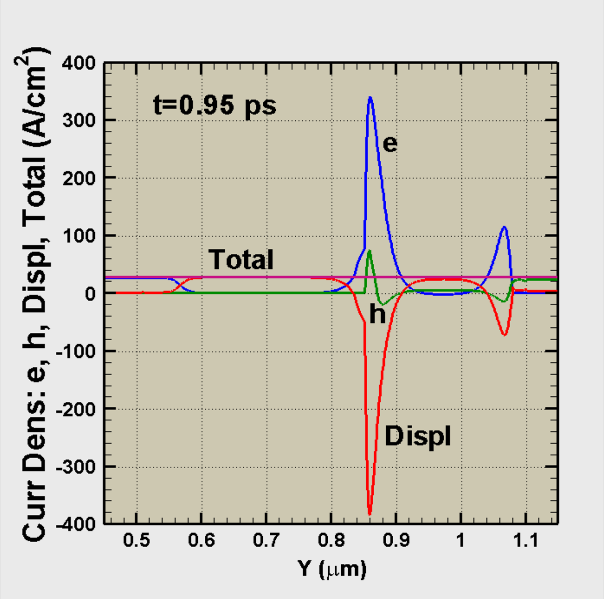


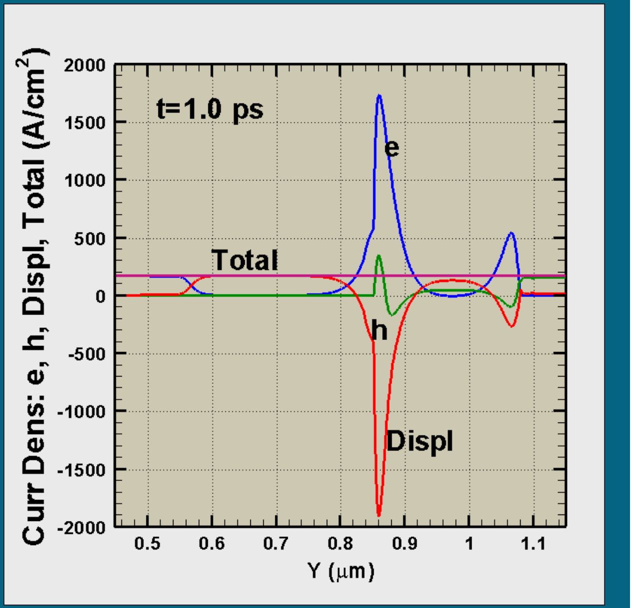
$$I(t) = I_o \times \exp\left[-\frac{(t - t_o)^2}{\sigma_o^2}\right]$$

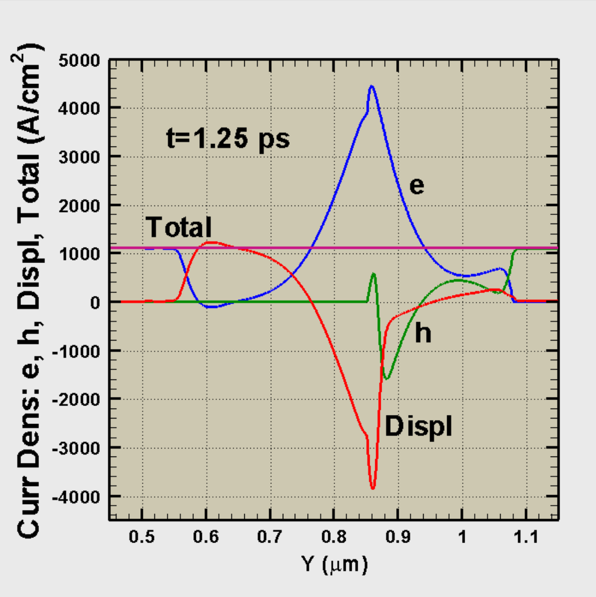
$\sigma_o = 50$ fs

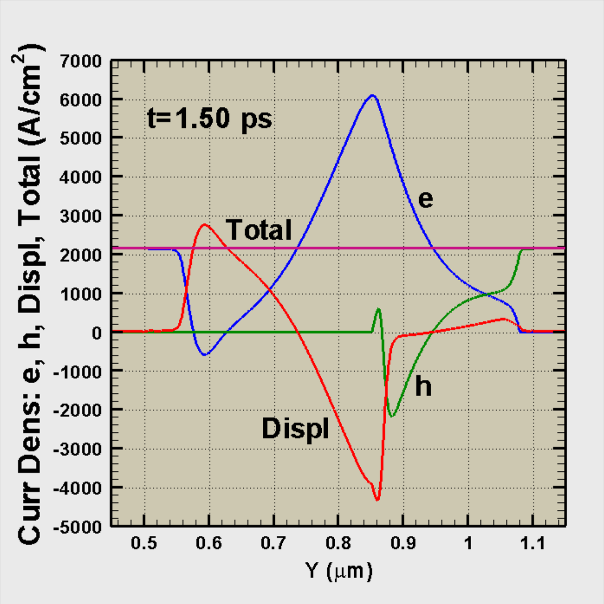
$t_o = 1.0$ ps

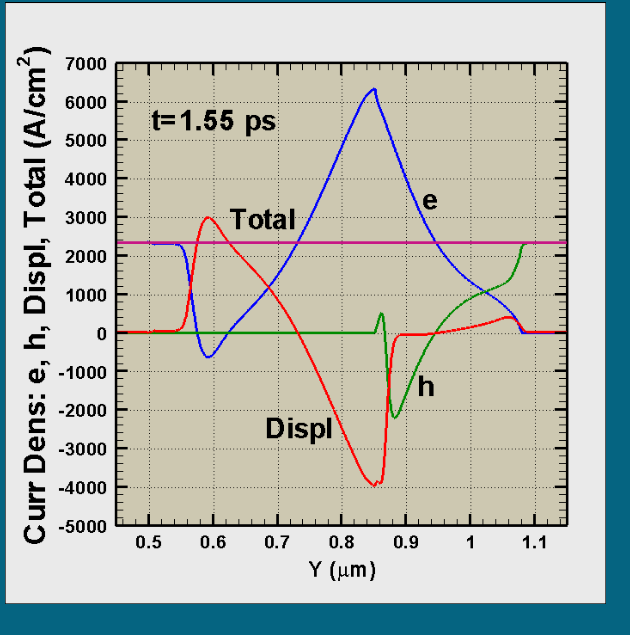
$t_o = 1.5$ ps











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Transient Current Profiles Across the Device from the HD Model: $I_o=10^5$ W/cm^2 (V_n=1 V)

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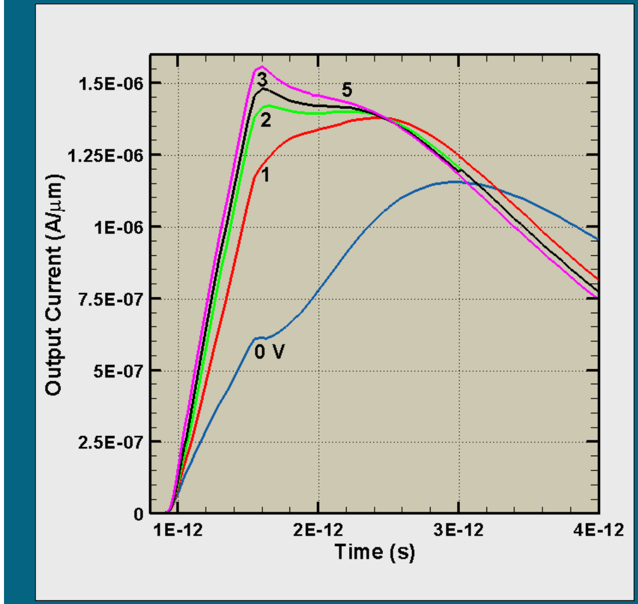
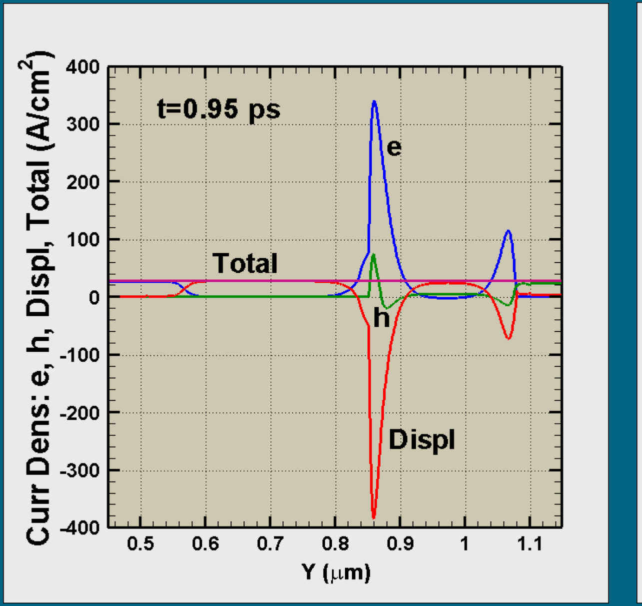
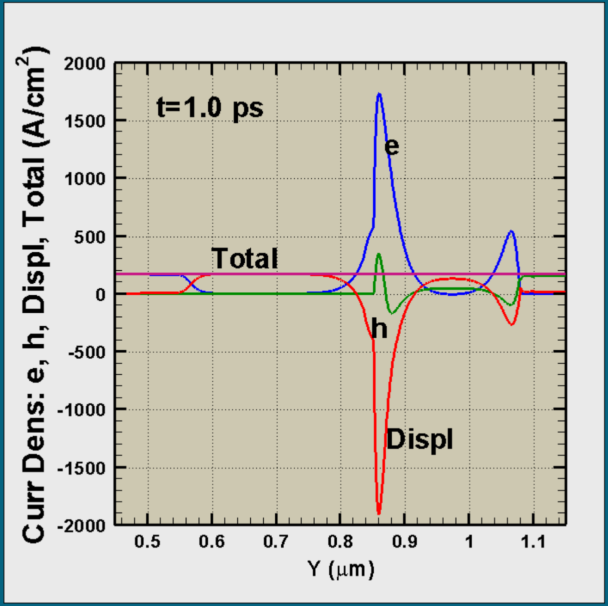
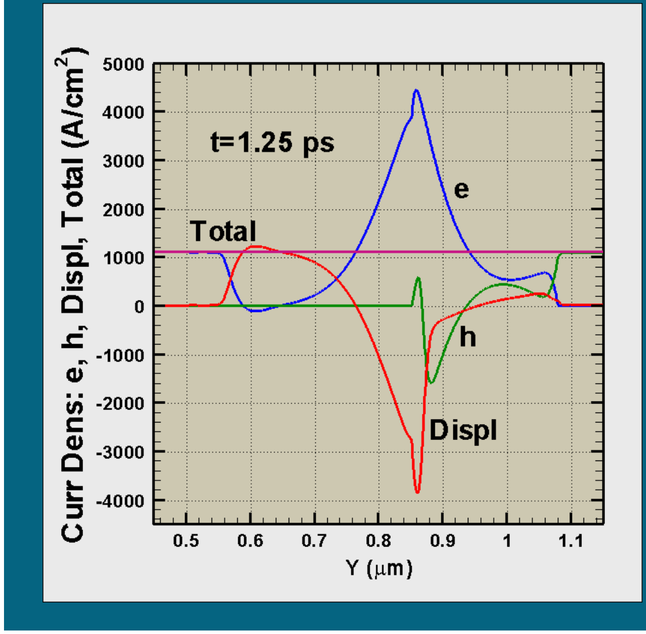
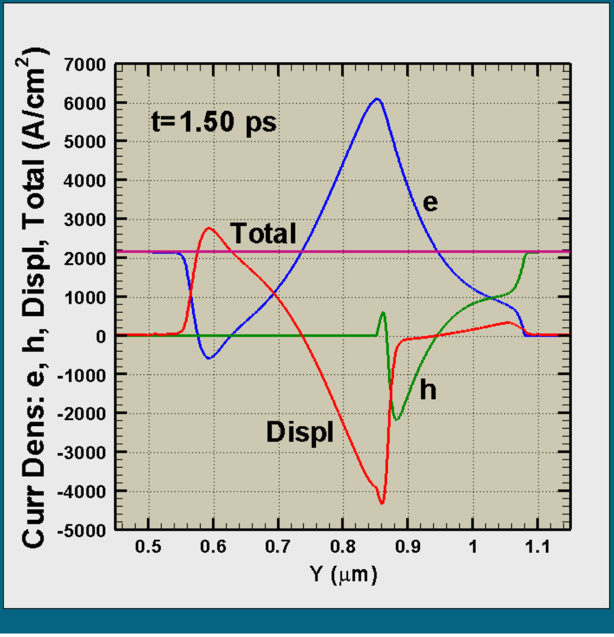
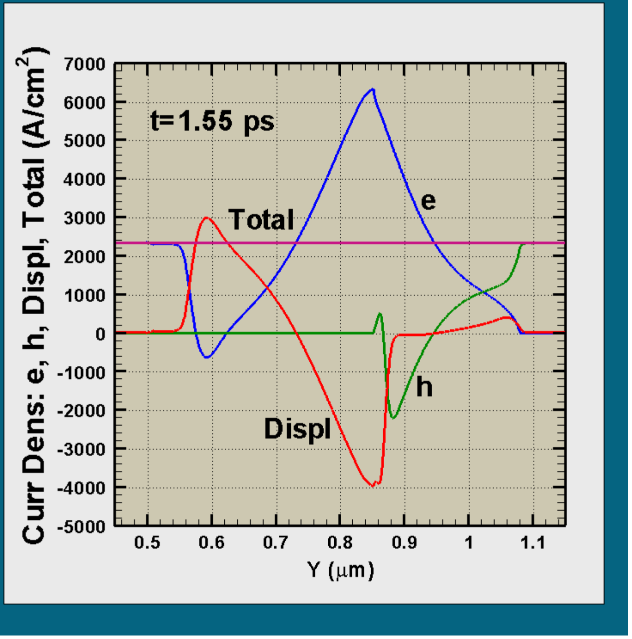




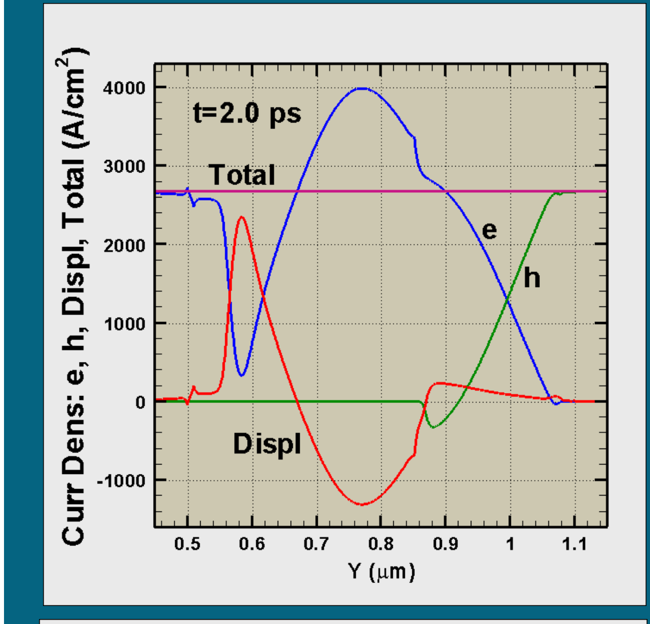


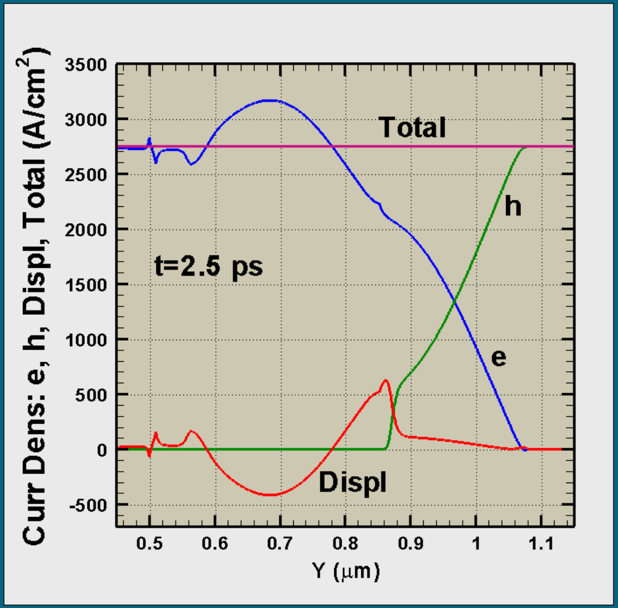


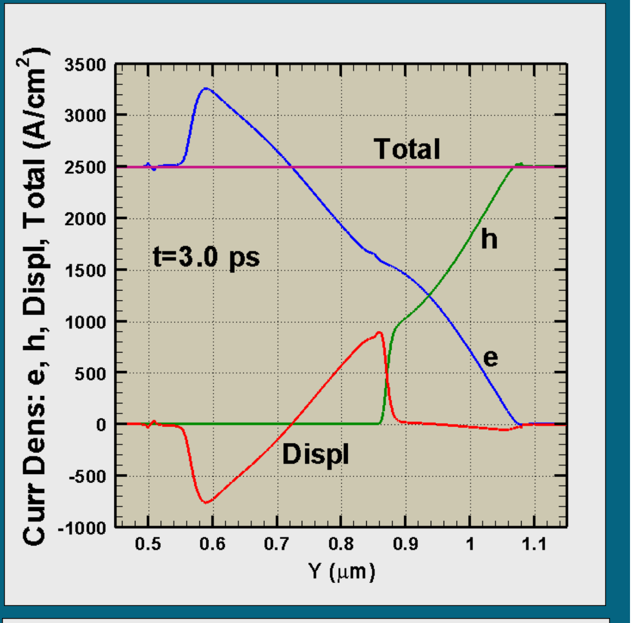


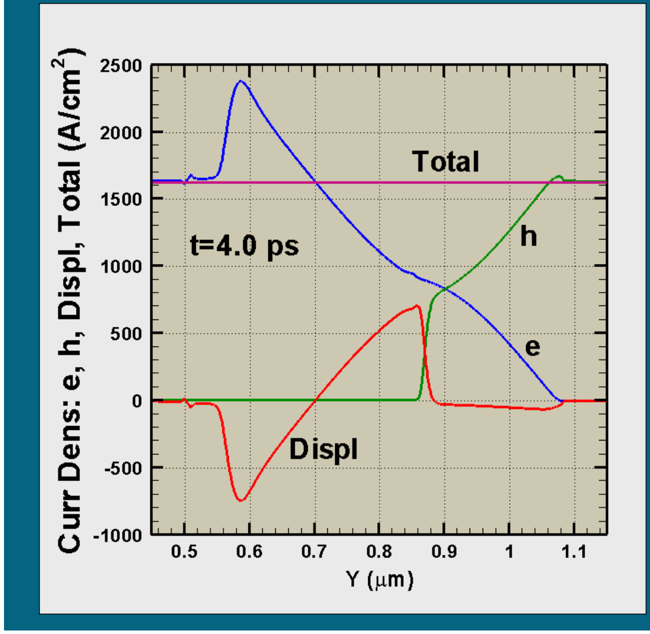


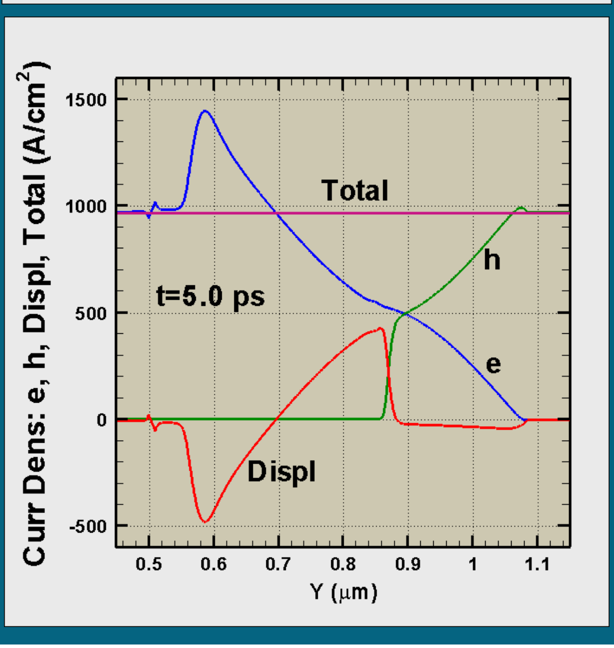
Transient Current Profiles Across the Device from the HD Model: $I_o=10^5$ W/cm^2 (V_n=1 V) - Continued

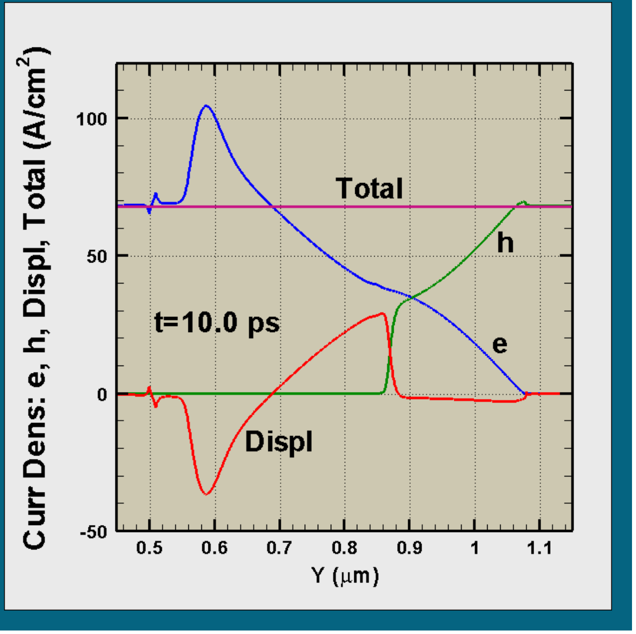




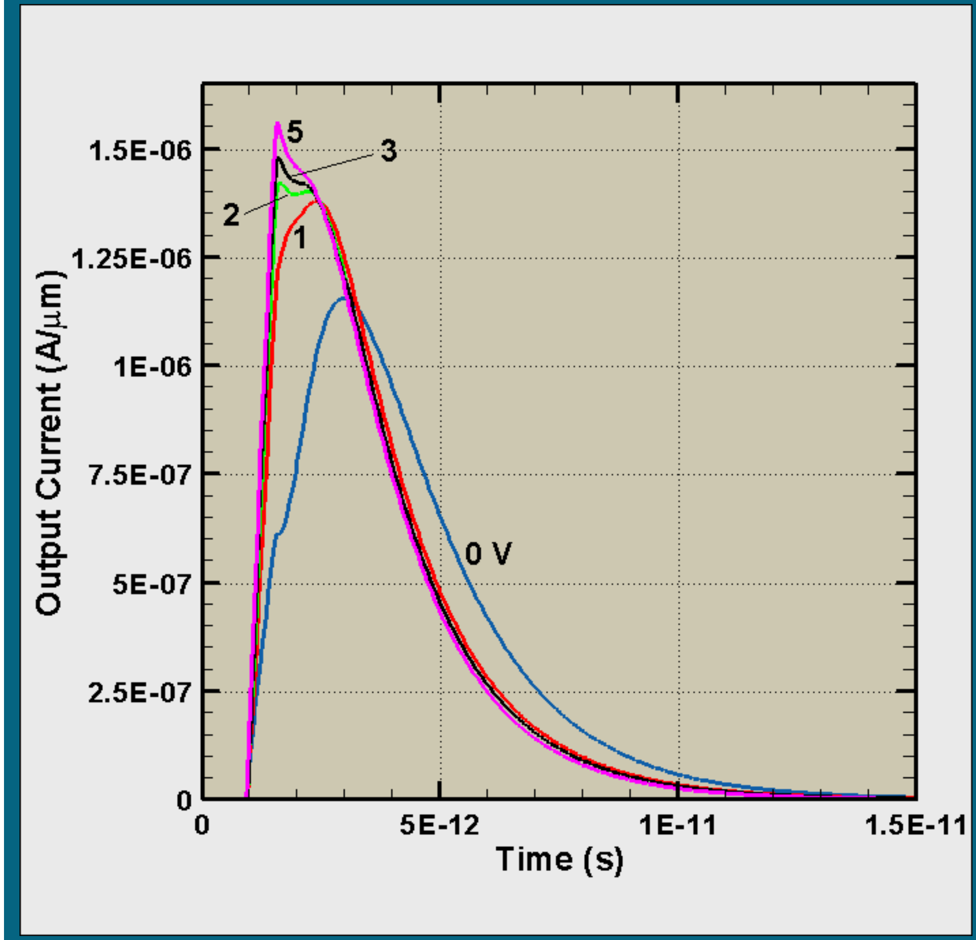


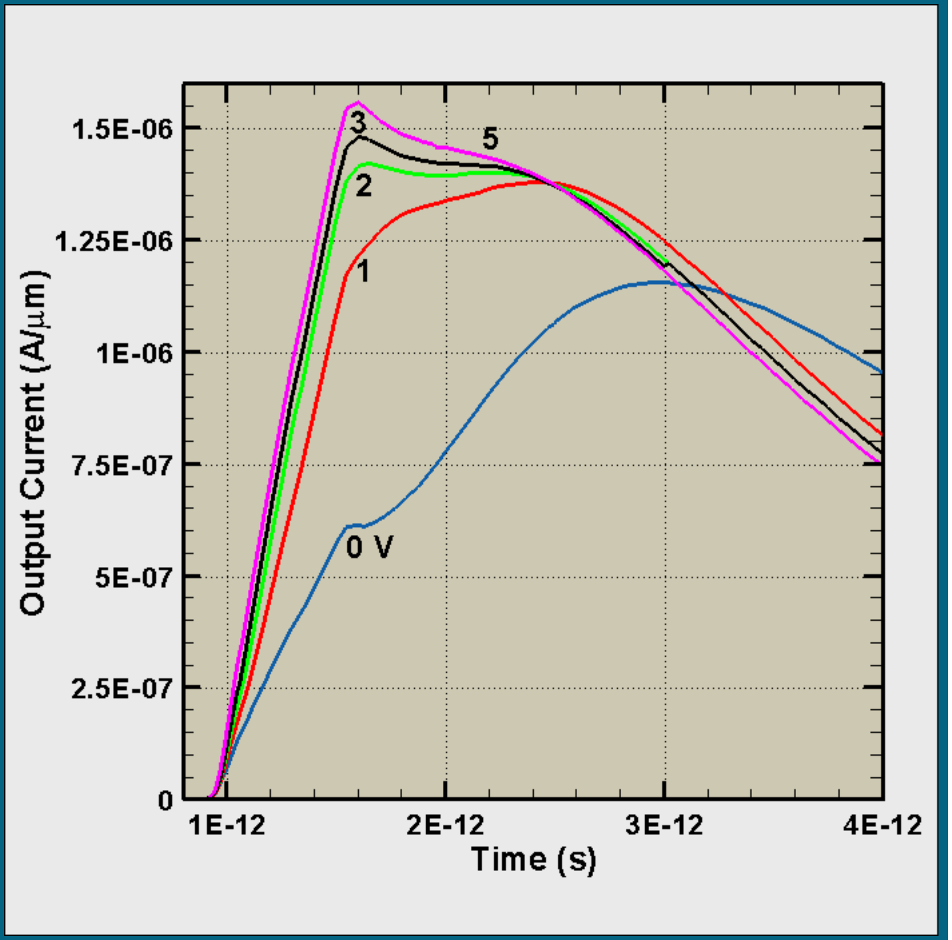




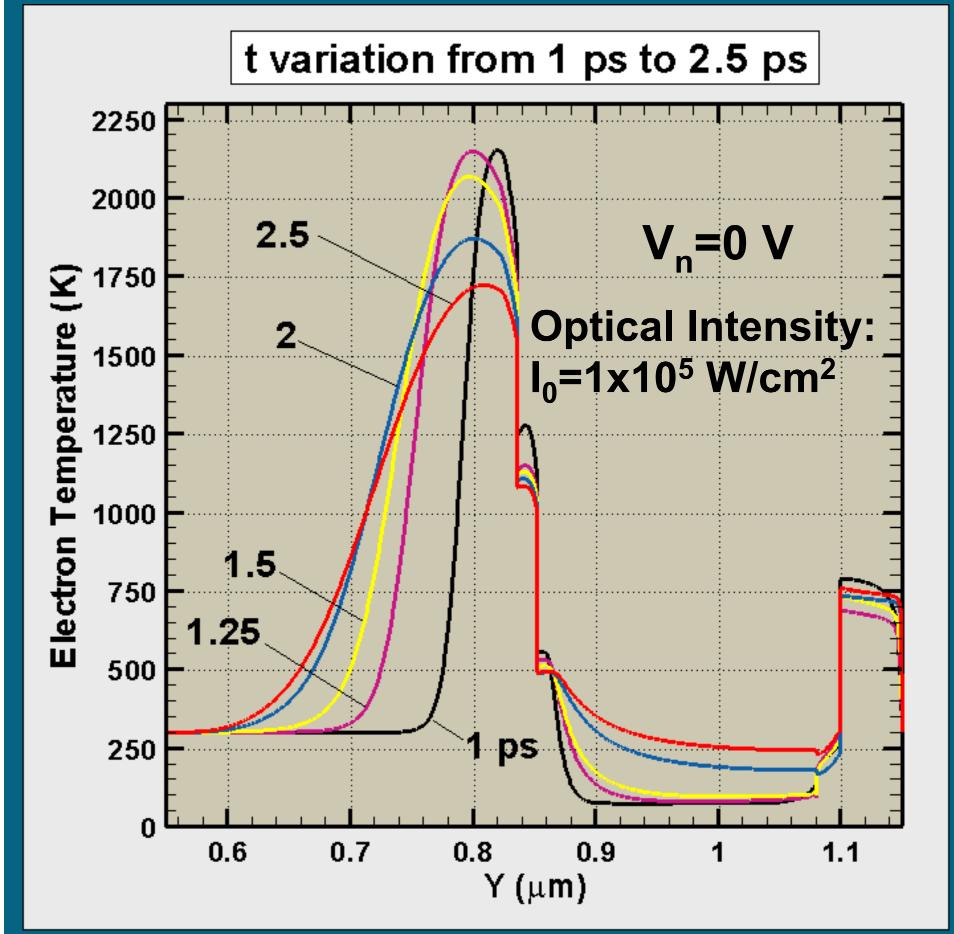


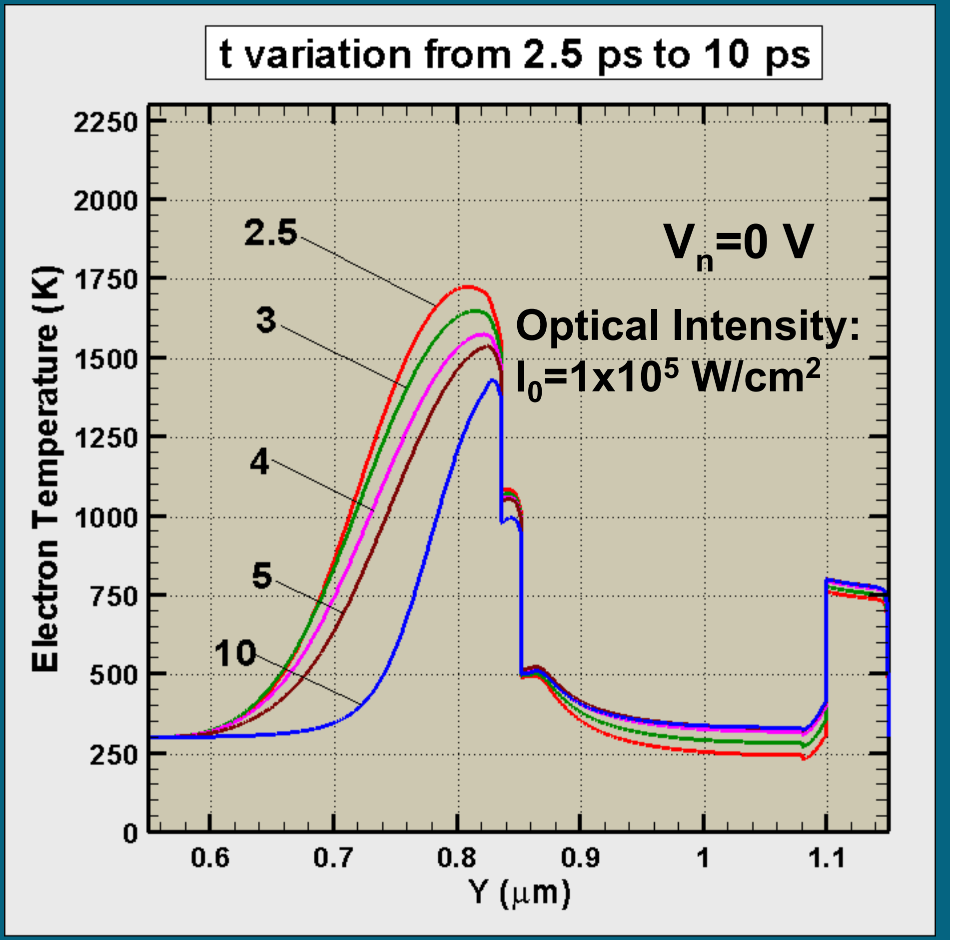
Effect of Bias on Photoesponse: HD, I=1x10^5 W/cm^2



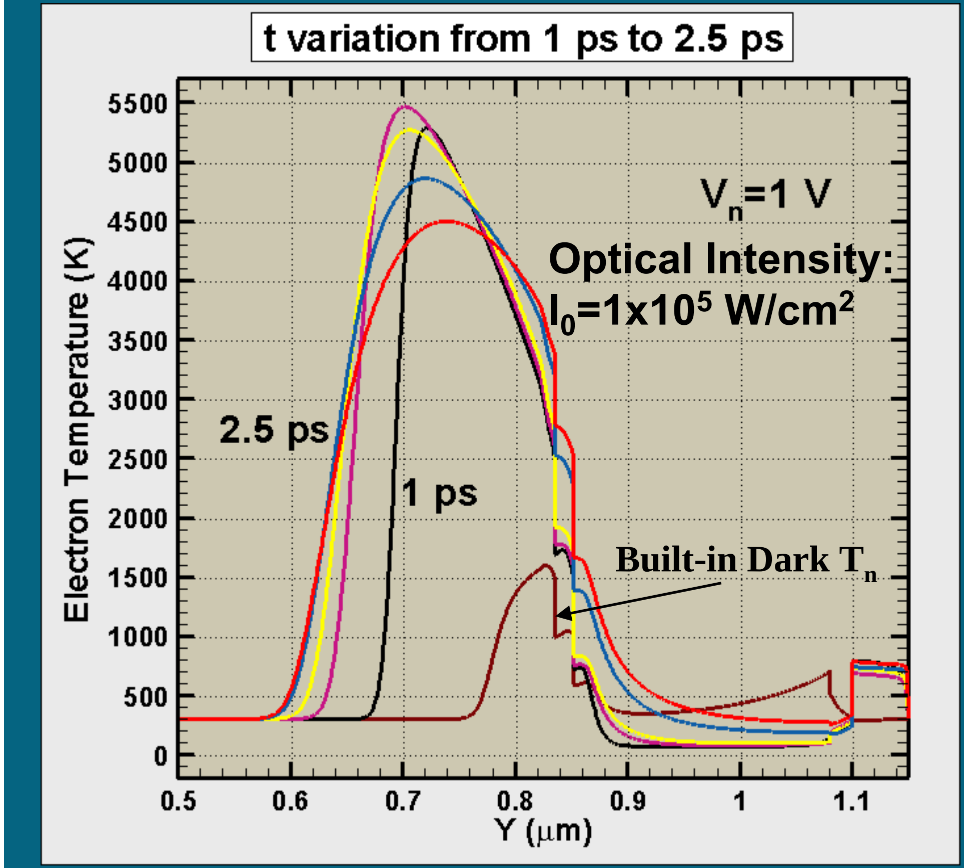


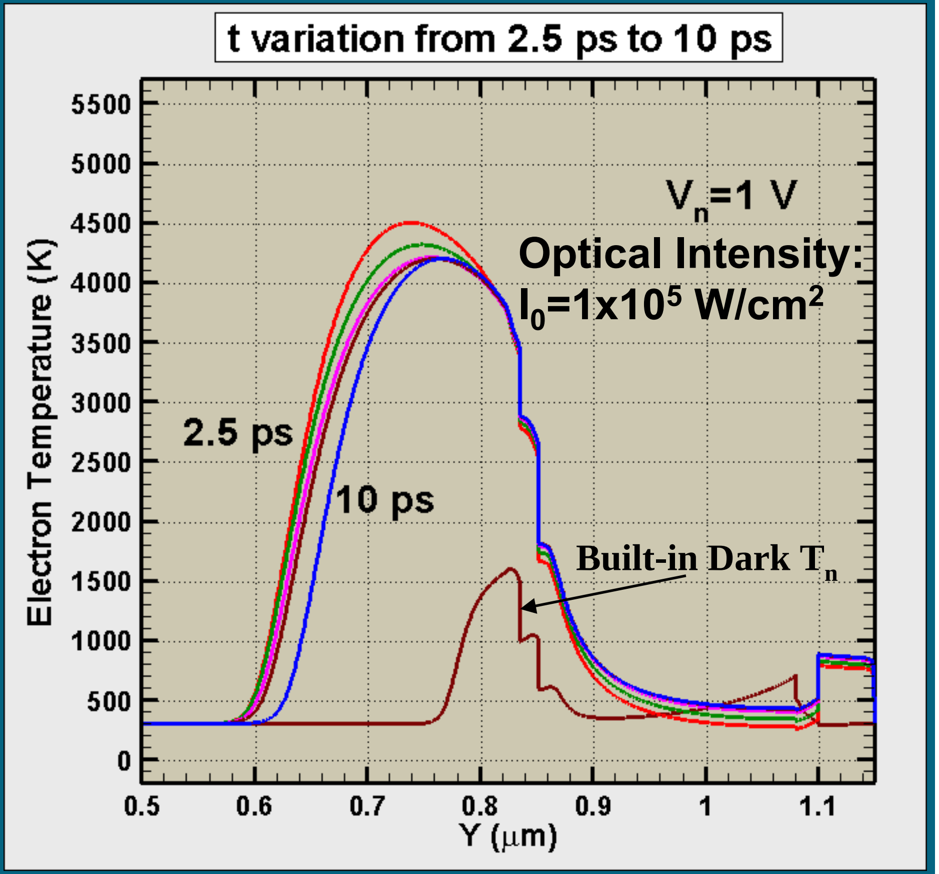
Evolution of Electron Temperature at V_n=0 V


t variation from 1 ps to 2.5 ps

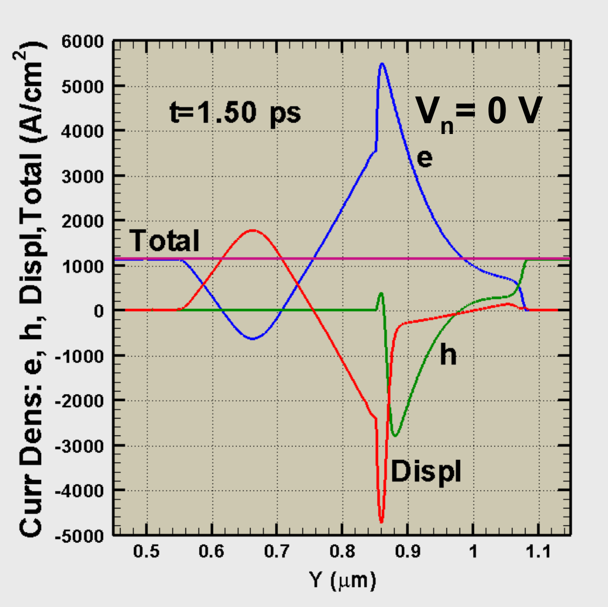

t variation from 2.5 ps to 10 ps

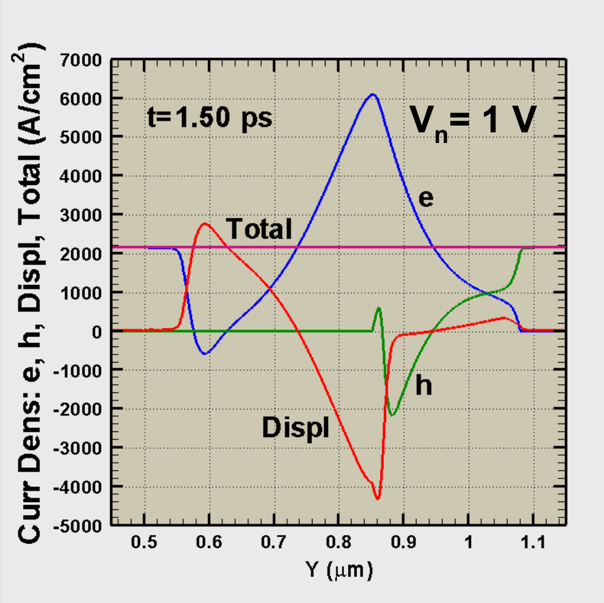
Evolution of Electron Temperature at V_n=1 V

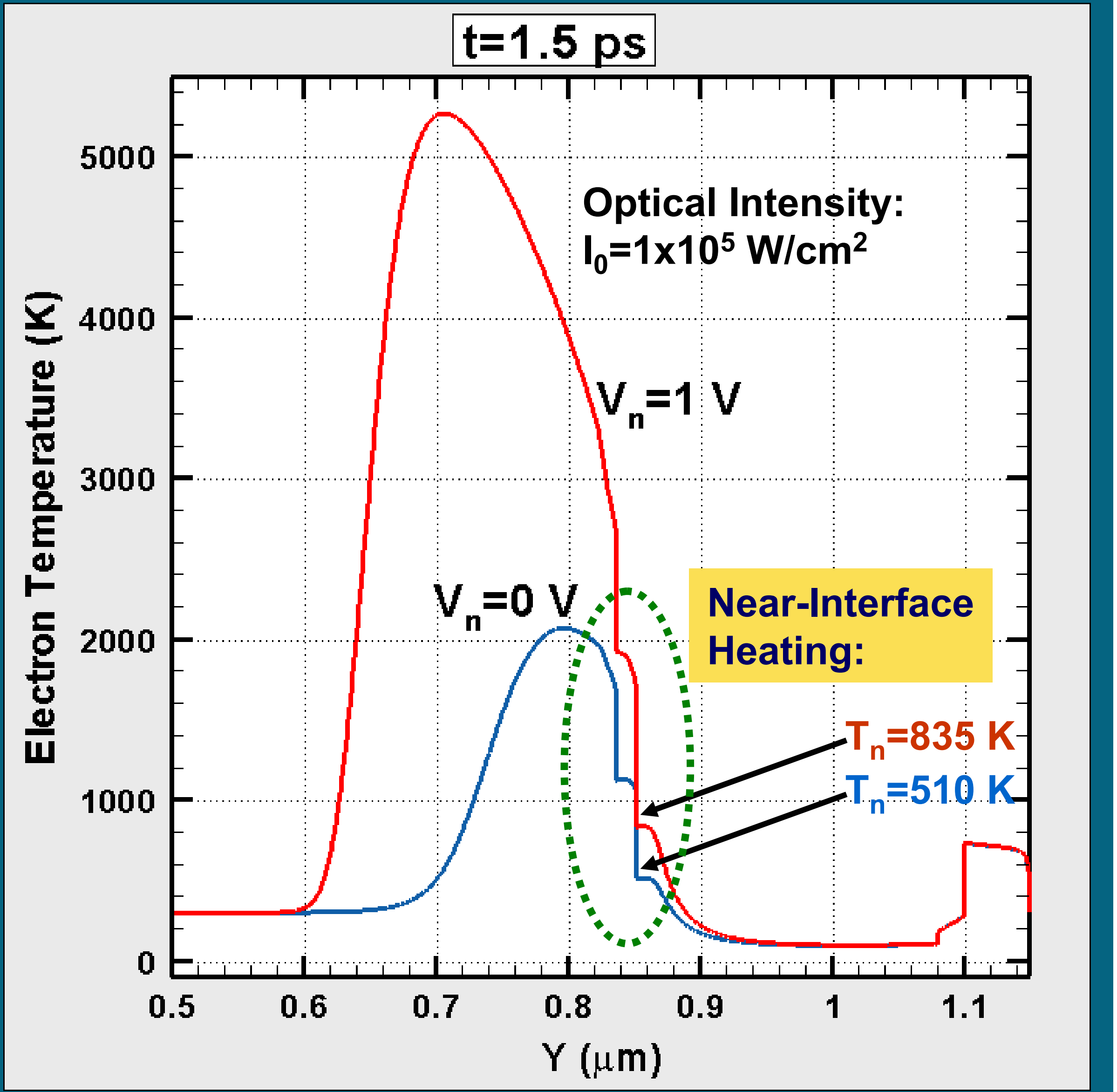




Physical Reason for Increase of Photocurrent with Increase of the Bias V_n – Increase of TE Current



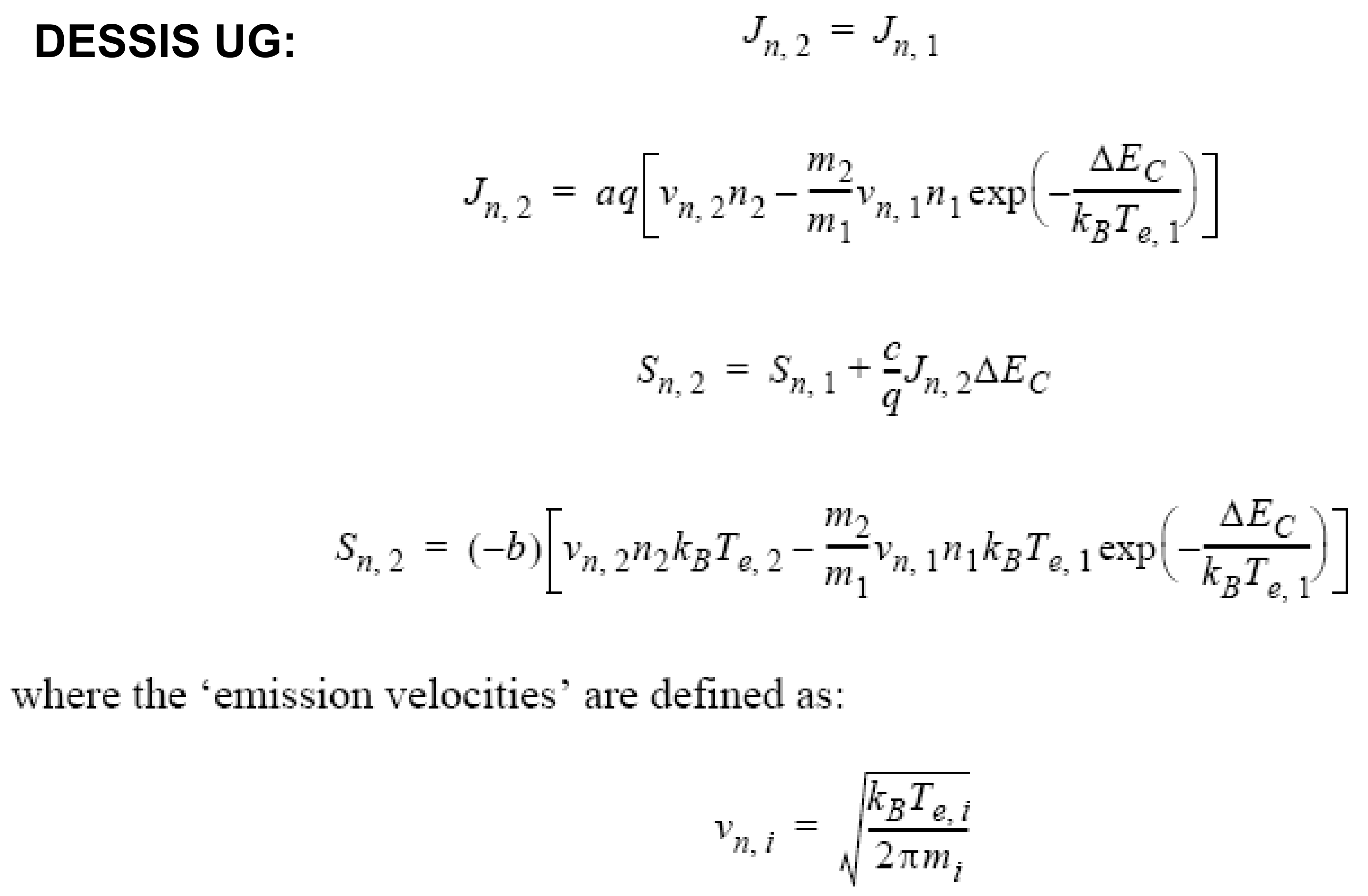




Optical Intensity:
I_0=1x10^5 W/cm^2

Near-Interface Heating:

Thermionic Emission Current from the Absorber



DESSIS UG:

$$J_{n,2} = J_{n,1}$$

$$J_{n,2} = aq\left[v_{n,2}n_2 - \frac{m_2}{m_1}v_{n,1}n_1\exp\left(-\frac{\Delta E_C}{k_B T_{e,1}}\right)\right]$$

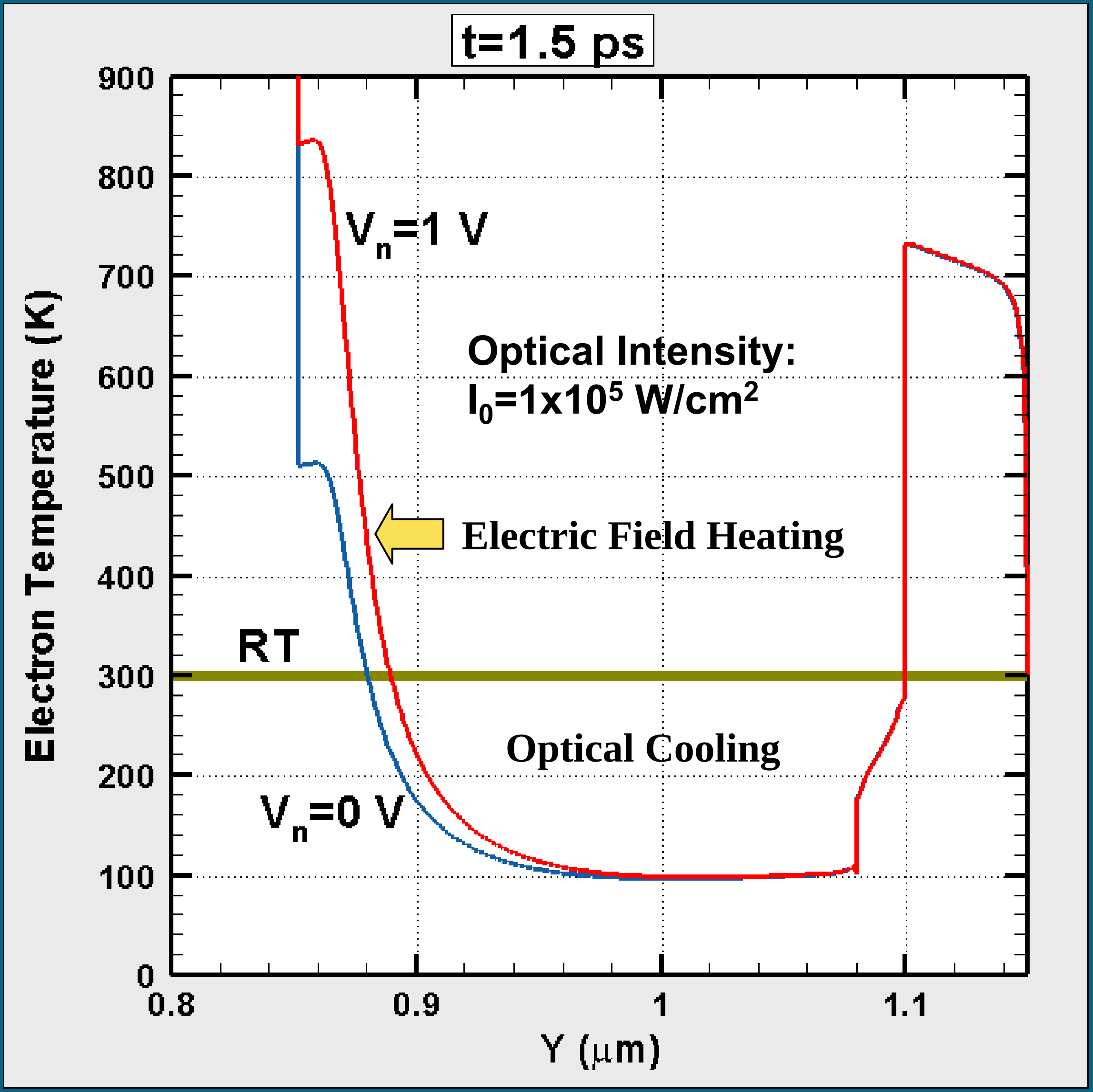
$$S_{n,2} = S_{n,1} + \frac{c}{q}J_{n,2}\Delta E_C$$

$$S_{n,2} = (-b)\left[v_{n,2}n_2k_BT_{e,2} - \frac{m_2}{m_1}v_{n,1}n_1k_BT_{e,1}\exp\left(-\frac{\Delta E_C}{k_B T_{e,1}}\right)\right]$$

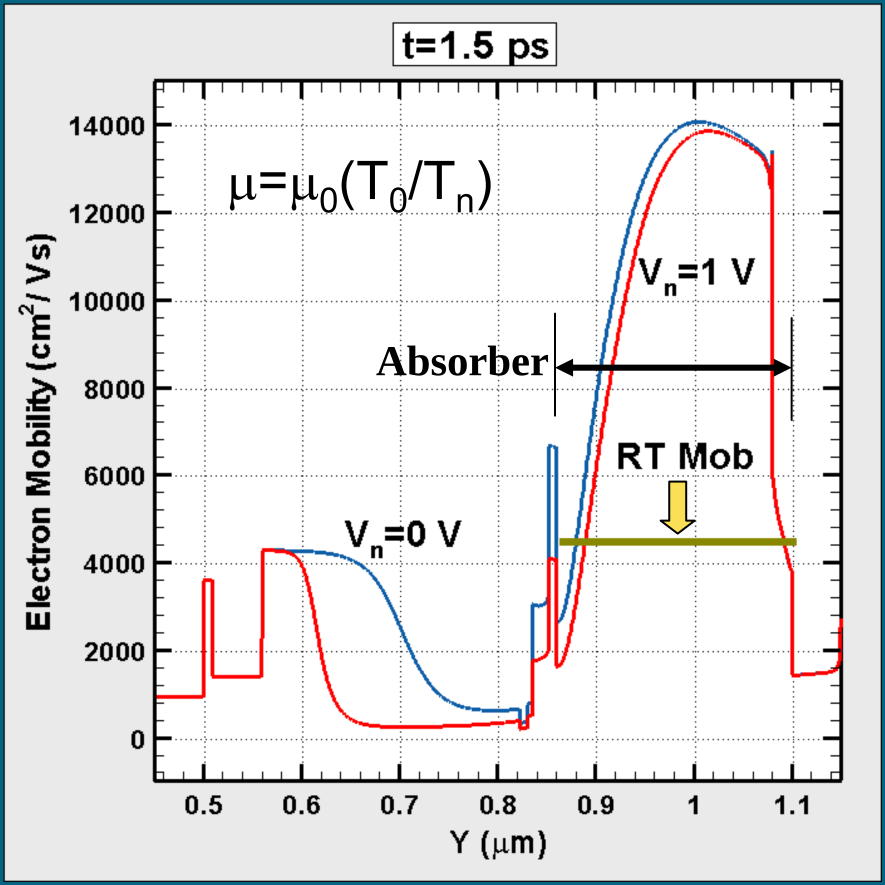
where the ‘emission velocities’ are defined as:

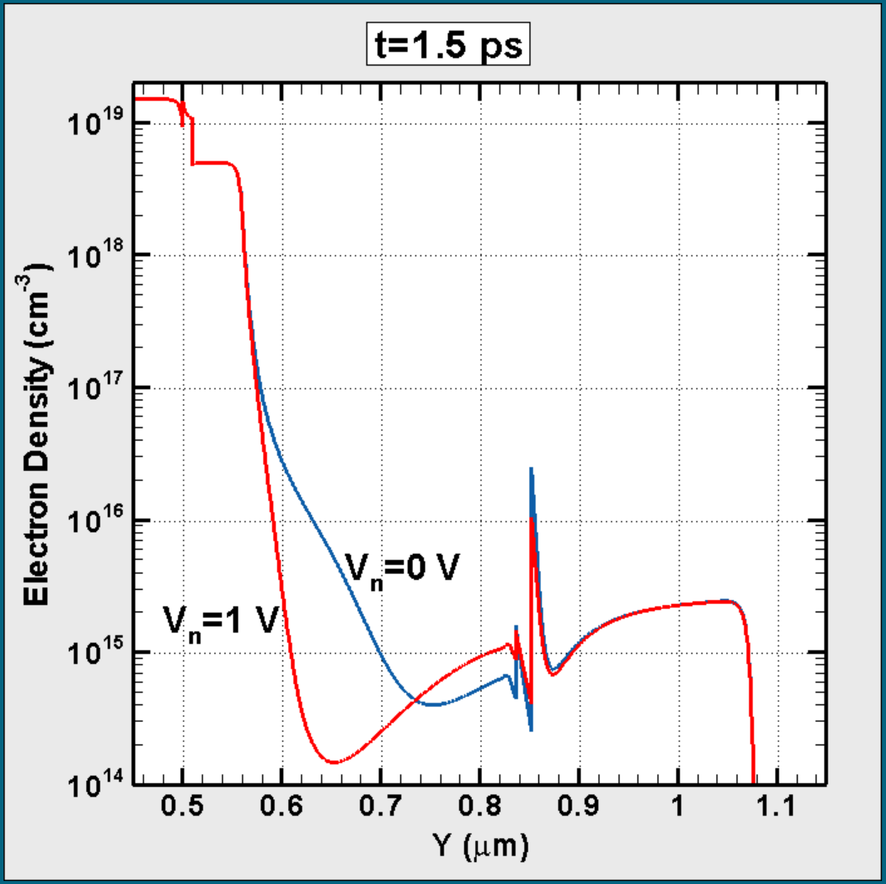
$$v_{n,i} = \sqrt{\frac{k_B T_{e,i}}{2\pi m_i}}$$

Transient Optical Cooling of Carriers in Absorber

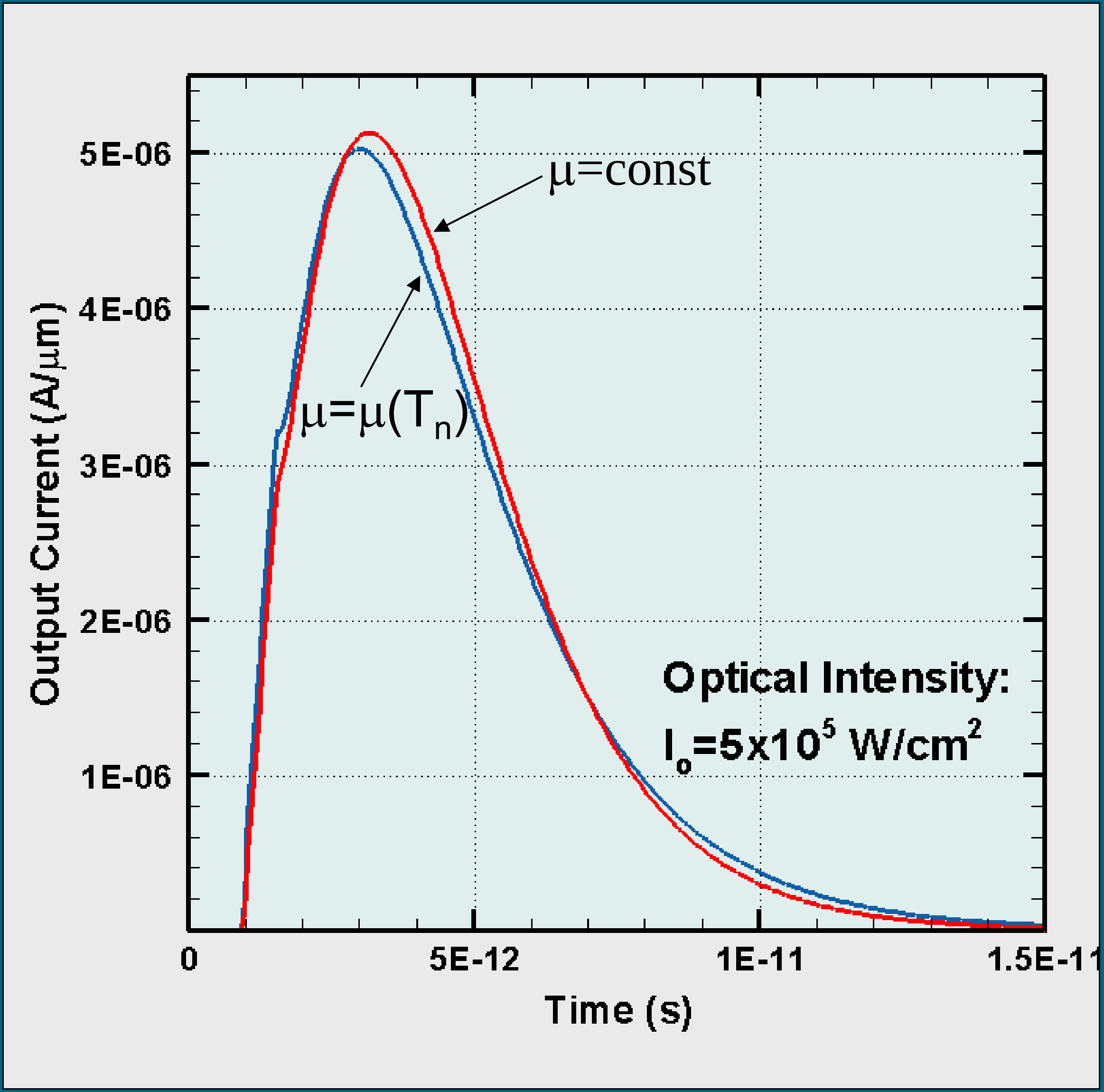


Electron Density and Electron Mobility at the Cooling

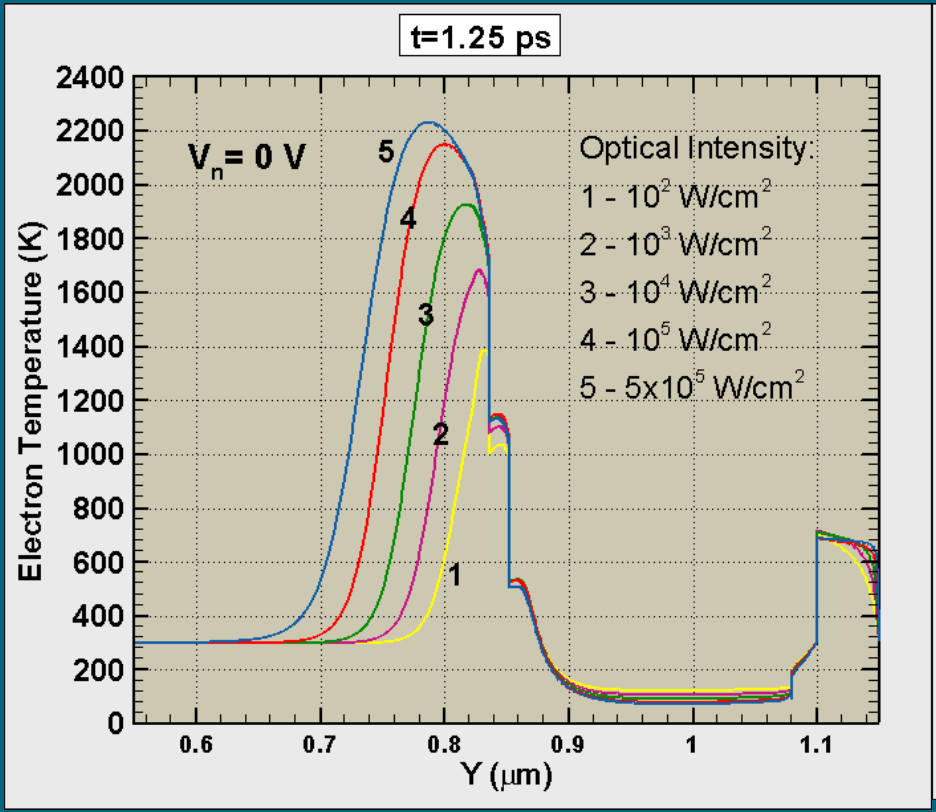


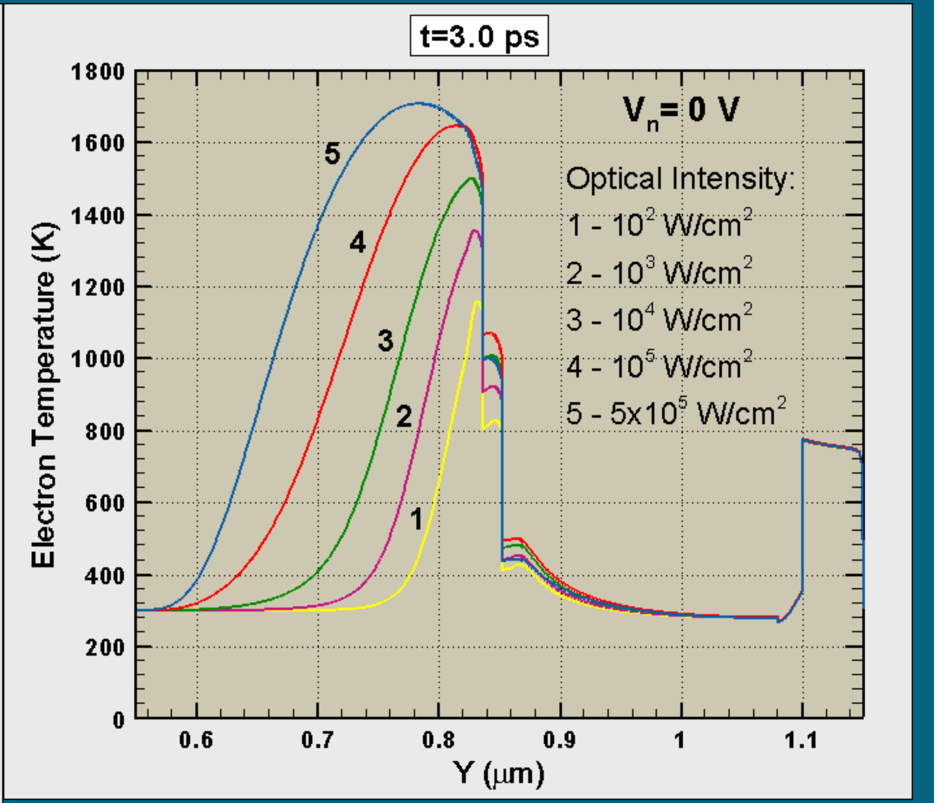


Effect of the Mobility in Absorber on Photoresponse

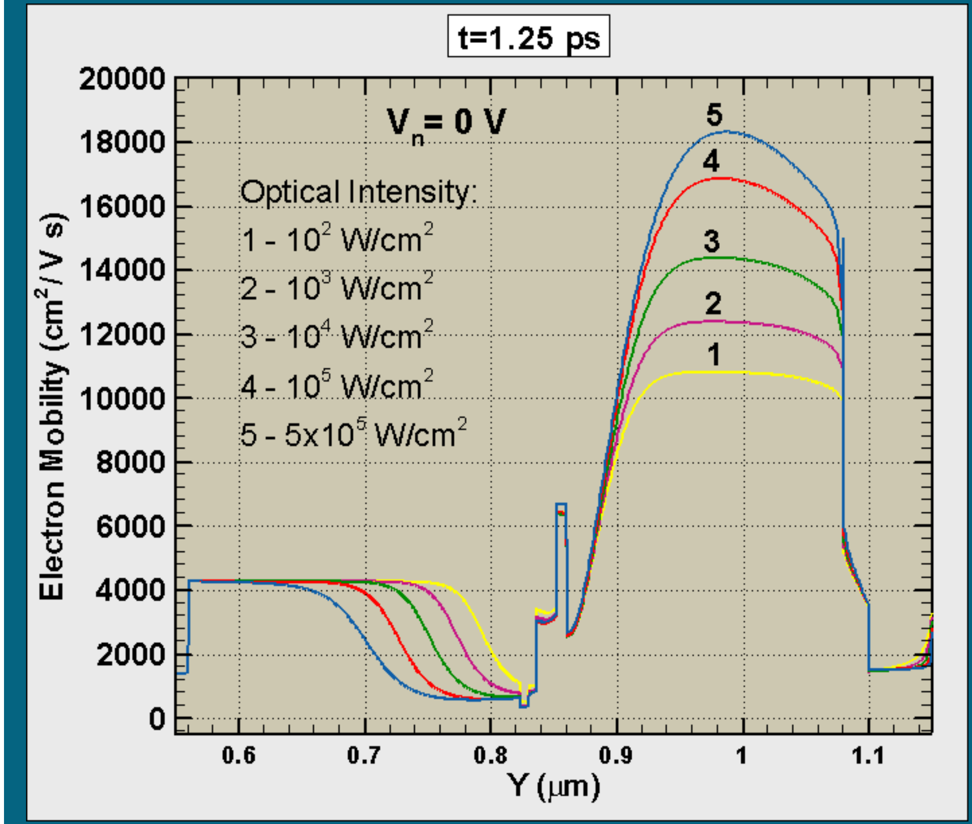


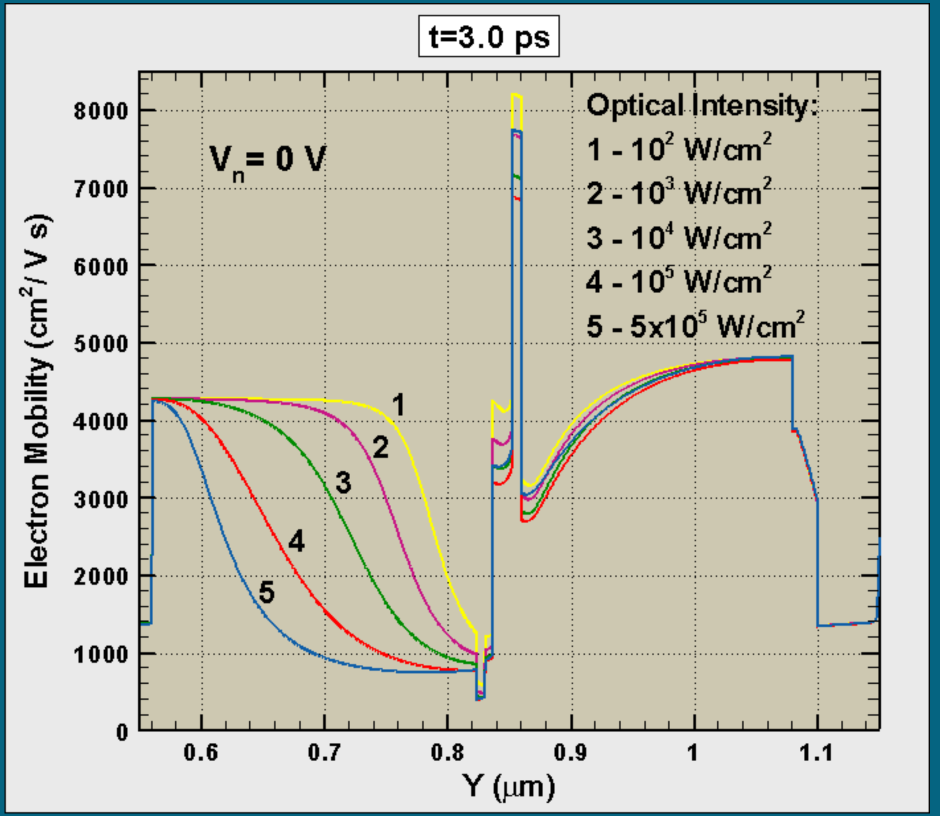
Effect of the Optical Intensity on the Electron Temperature



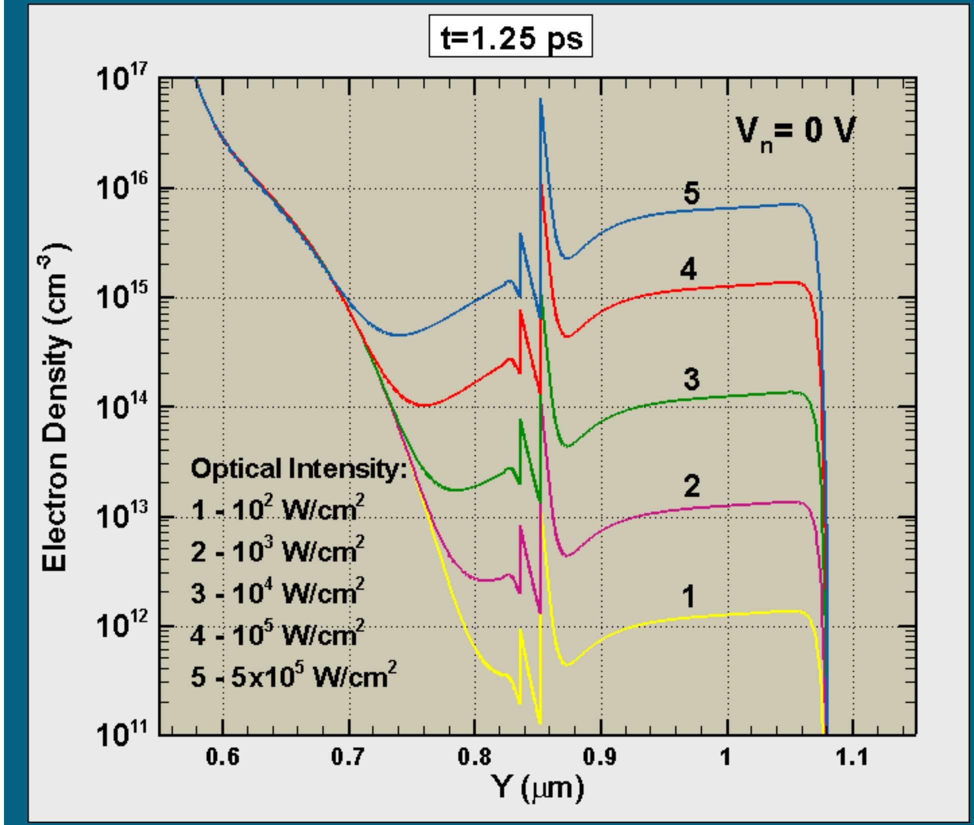


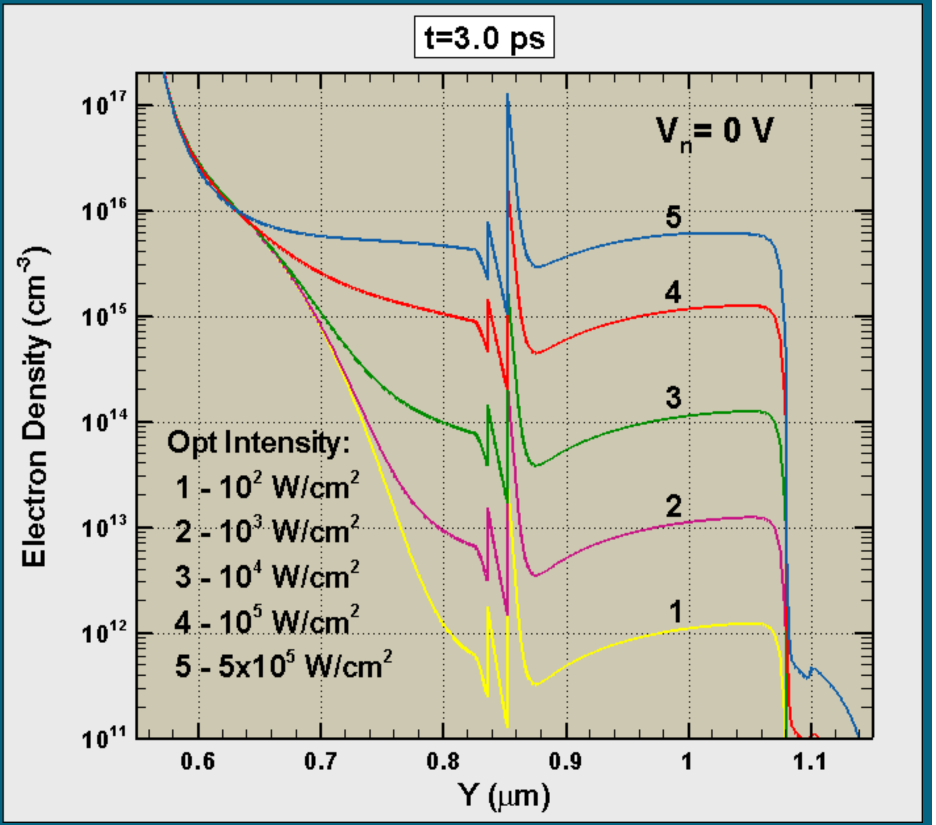
Effect of the Optical Intensity on the Electron Mobility





Effect of the Optical Intensity on the Electron Density



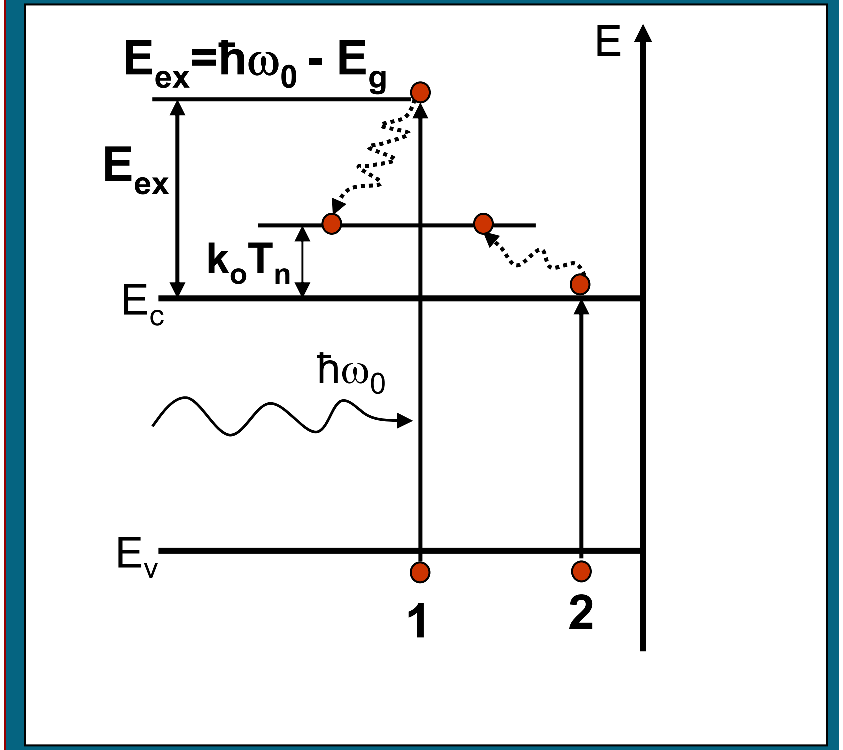


Physics of Transient Carrier Cooling in Absorber

- Process 1 – Excess of the excitation energy goes in part to the lattice (via the phonon emission) and in part into the electron system (via the e-e scattering). These processes are very fast (~10 fs).

- Process 2 – There is no energy excess and the energy is taken from the lattice in order to heat the electron up to the mean energy k_0T_n. This process is slower than the first one and it is governed by the energy relaxation time τ_ε).

- The cooling below T_n (or even below T_0) is possible only for a Process 2.



Mathematics of Transient Carrier Cooling in Absorber

$$\frac{\partial n}{\partial t} - \frac{1}{e}\nabla_x j_n(x) = \alpha\frac{I_0}{\hbar\omega_0}e^{-\alpha x} - R(n,p),$$

$$\frac{\partial p}{\partial t} + \frac{1}{e}\nabla_x j_h(x) = \alpha\frac{P_0}{\hbar\omega_0}e^{-\alpha x} - R(n,p).$$

$$\frac{\partial w_n}{\partial t} + \vec{\nabla}\cdot\vec{S}_n = \frac{1}{e}\vec{J}_n\cdot\vec{\nabla}E_c + \frac{w_n - w_0}{\tau_\varepsilon}.$$

- **Where is the term $\propto \alpha I_0$ in the energy balance equation, which describes the optical energy supply?**

- **In order to obtain this term the Boltzmann equation must be modified in the first instance, since the above equations were obtained from the BE (as the moments):**

$$\left[\vec{\nabla}_x E_c(x).\vec{\nabla}_{p_x} + \vec{v}_{p_x}.\vec{\nabla}_x\right]\Phi(\vec{p},x) = \hat{I}\Phi(\vec{p},x) + \alpha\frac{I_0}{\hbar\omega_0}e^{-\alpha x}\frac{1}{g(E)}\delta[E-(\hbar\omega_0 - E_g)].$$

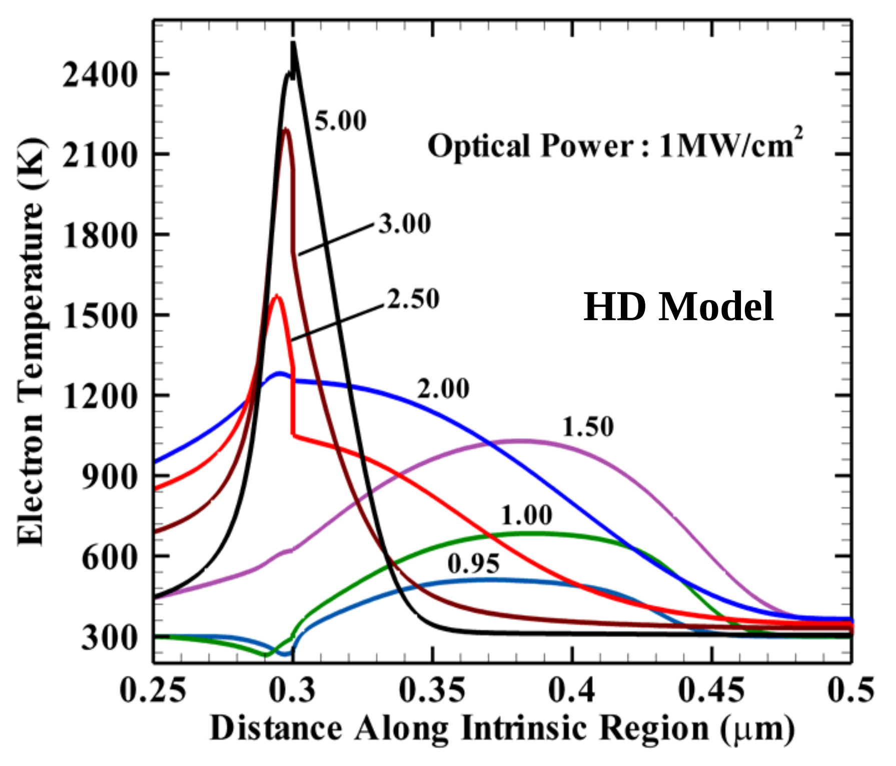
- **Integration of the latter equation (…×E) results in the following EB equation:**

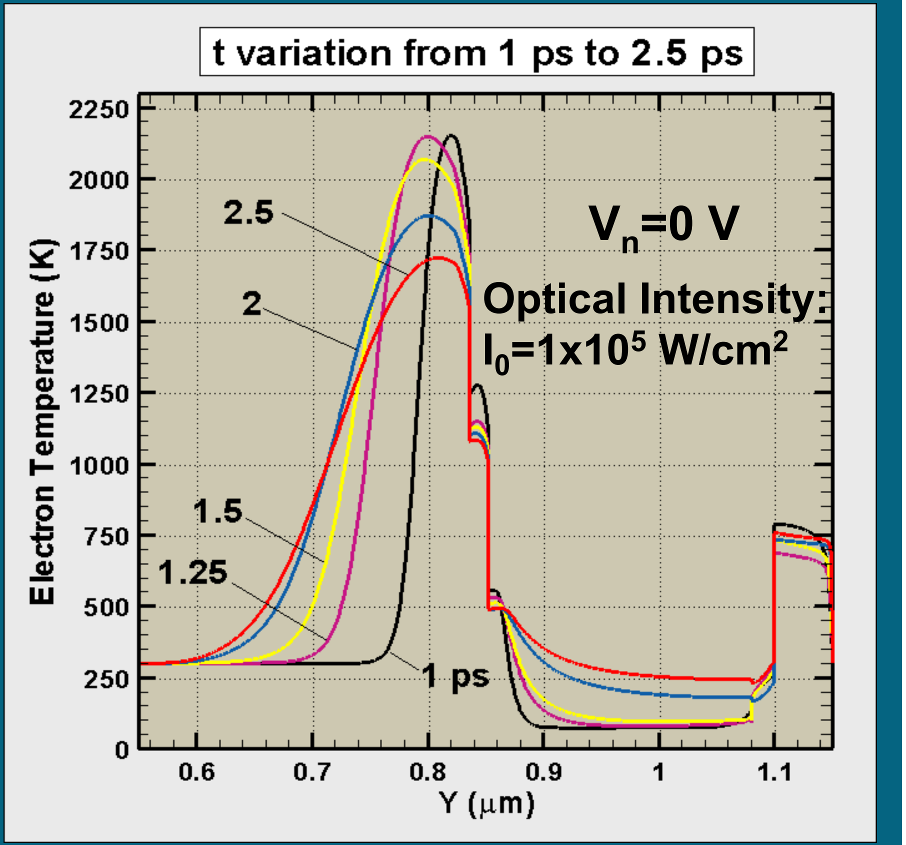
$$\frac{\partial w_n}{\partial t} + \vec{\nabla}\cdot\vec{S}_n = \frac{1}{e}\vec{J}_n\cdot\vec{\nabla}E_c + \frac{w_n - w_0}{\tau_\varepsilon} + \alpha\frac{I_0}{\hbar\omega_0}e^{-\alpha x}\Lambda_{eff}(\hbar\omega_0 - E_g).$$

- **The absence (erroneous!) of the last term from the energy balance equation means that the resulting equation describes a very particular case of photo excitation: $\hbar\omega_0=E_g$. This corresponds to Process 2 and is the real reason for the cooling.**

Comparison of p-i-n and UTC

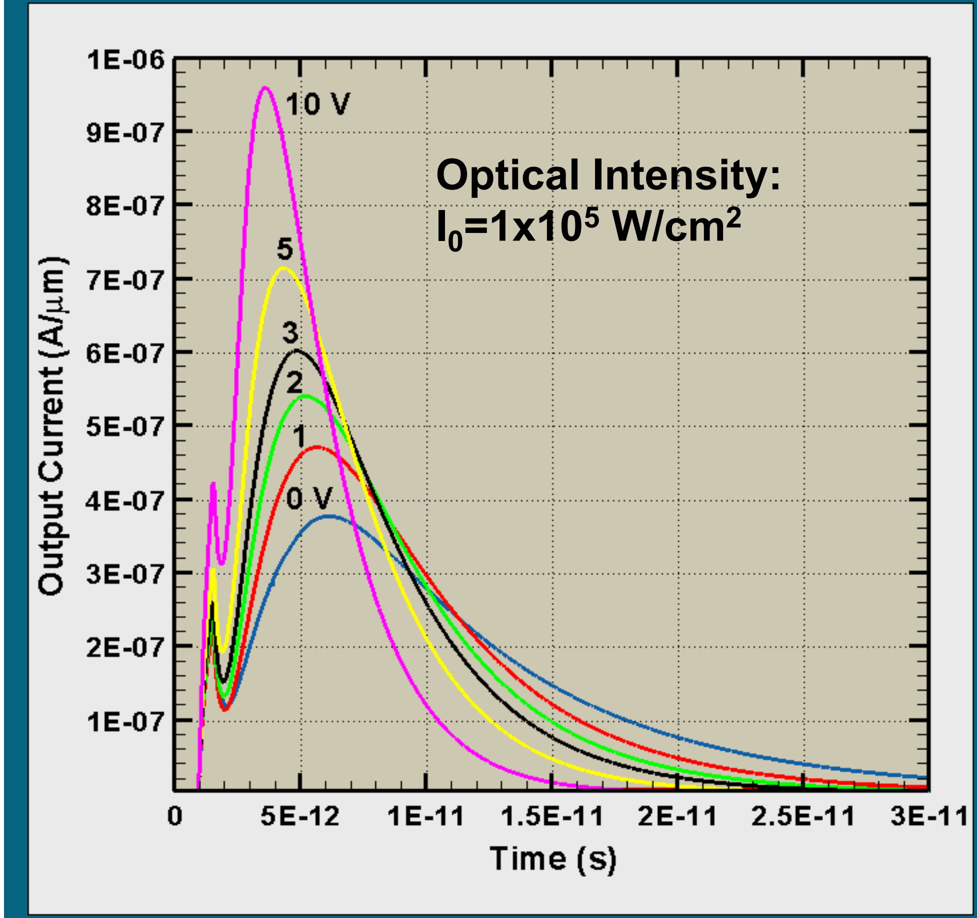
Temperature Profiles

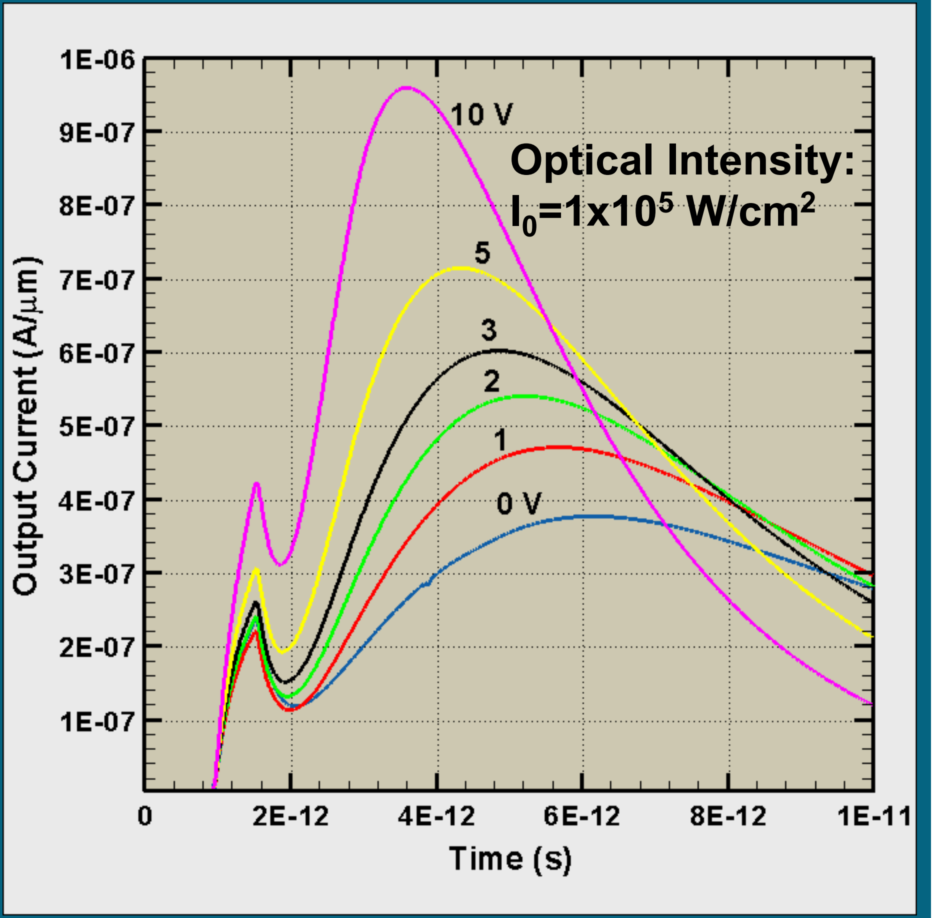




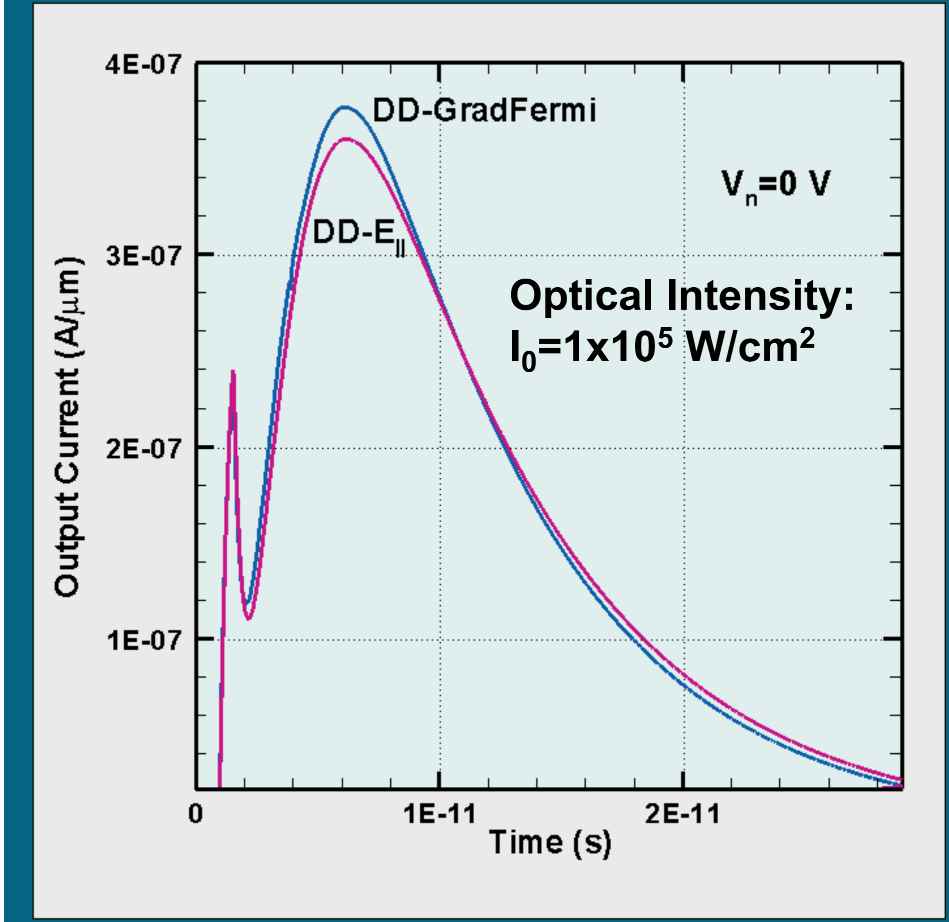
Results from DD Modelling of the UTC PD

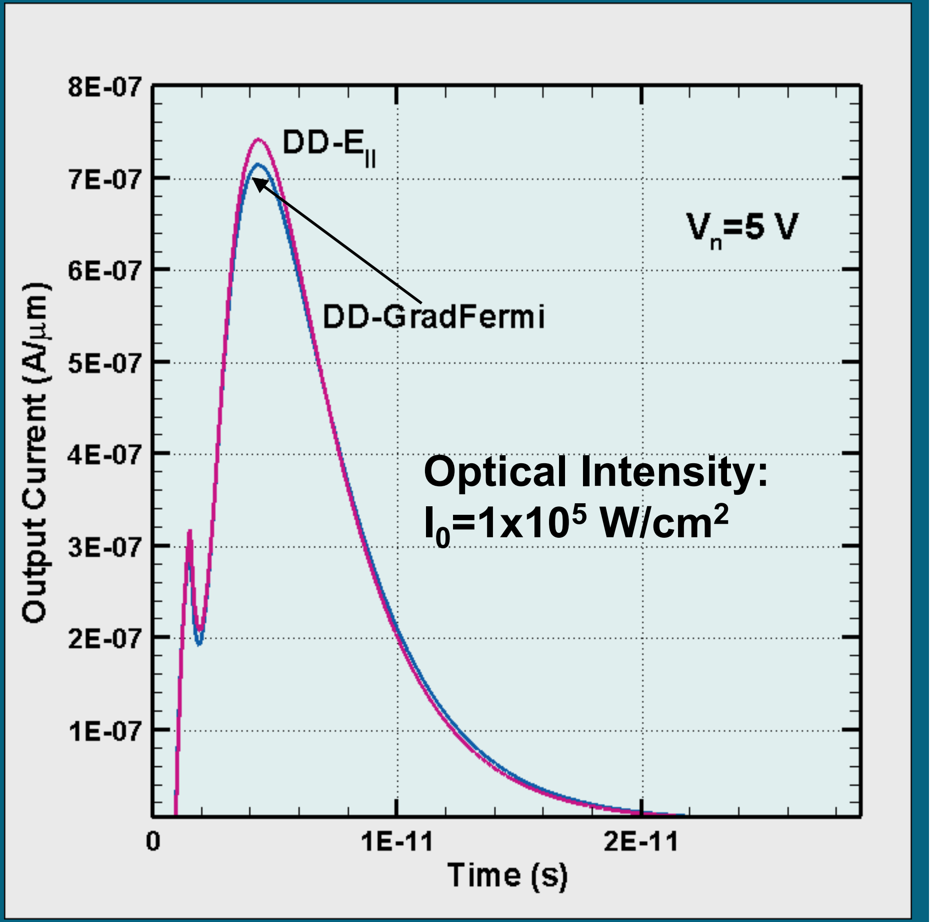
Effect of Bias on Photoresponse in the DD Model



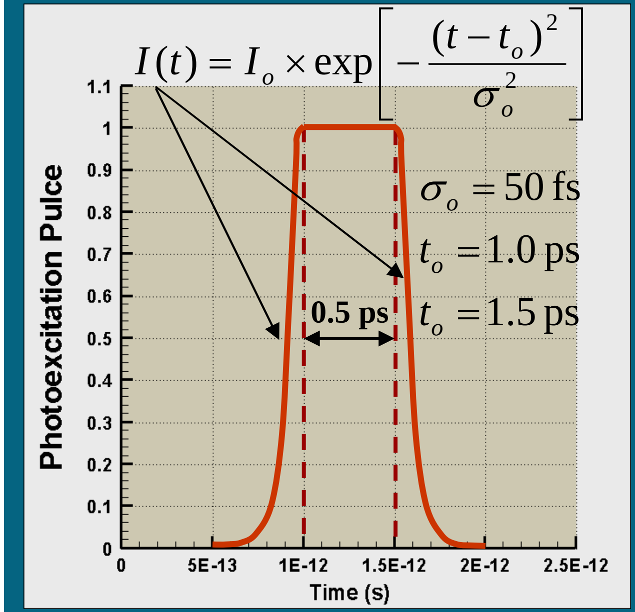


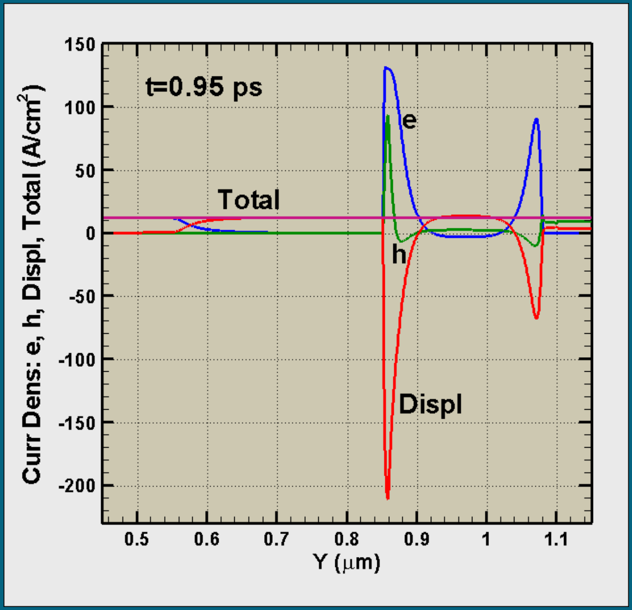
Effect of Different Driving Forces on Photoresponse

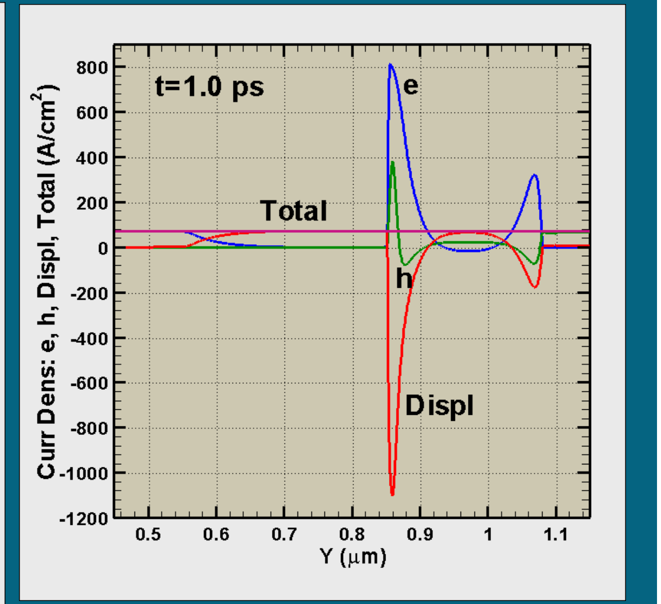


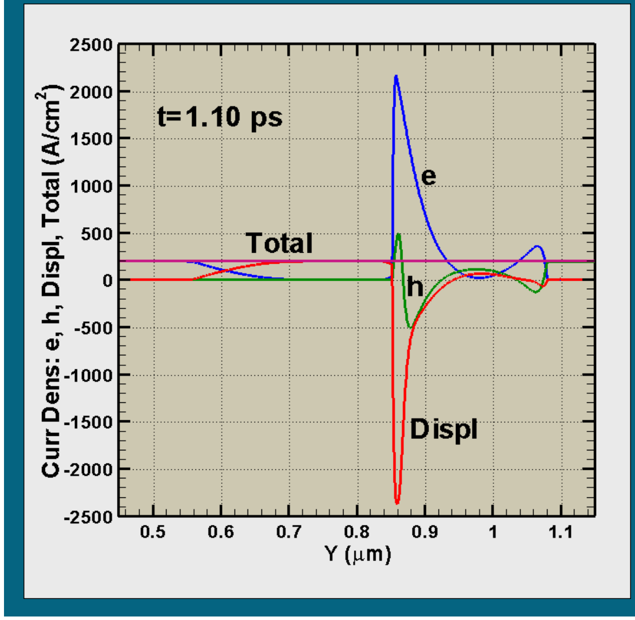


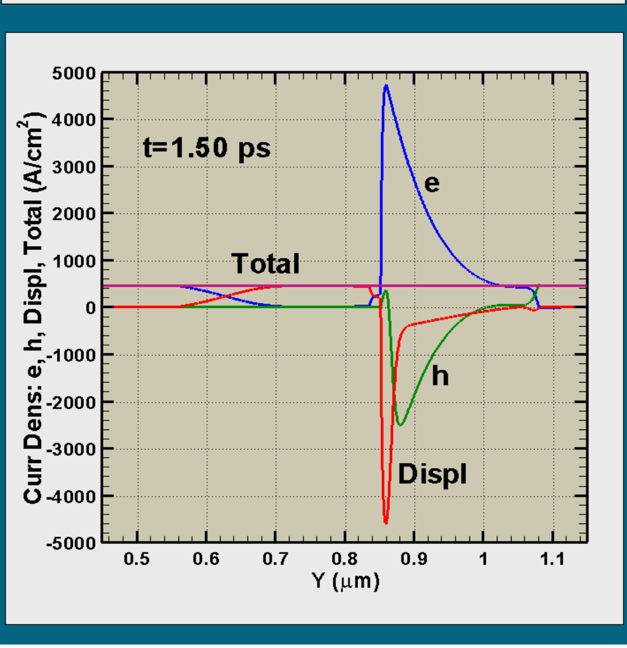
Transient Output Currents from DD Model (I_0=1x10^5 W/cm^2, V_n=0 V)

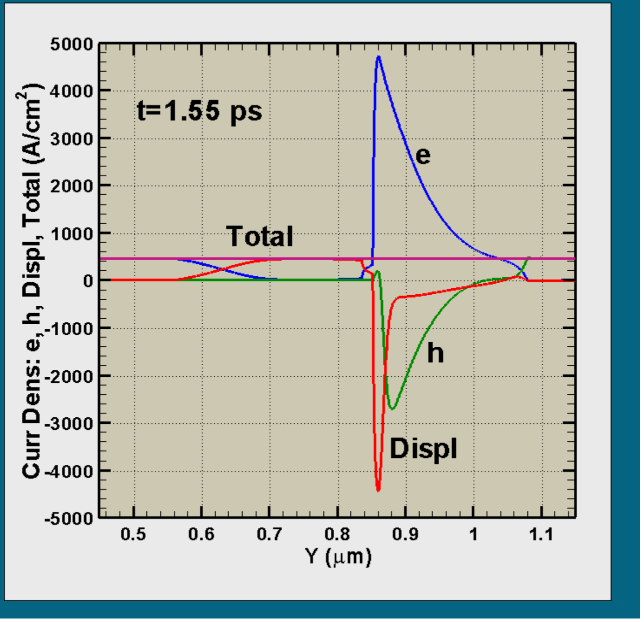












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Transient Output Currents from DD Model (I_0=1x10^5 W/cm^2, V_n=0 V)

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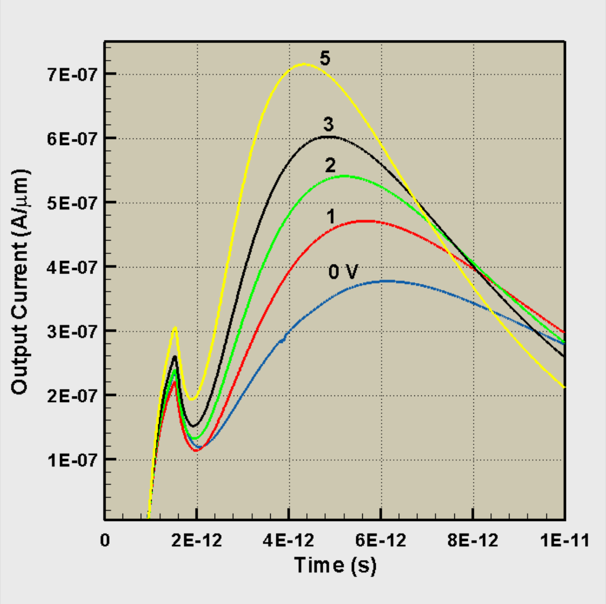
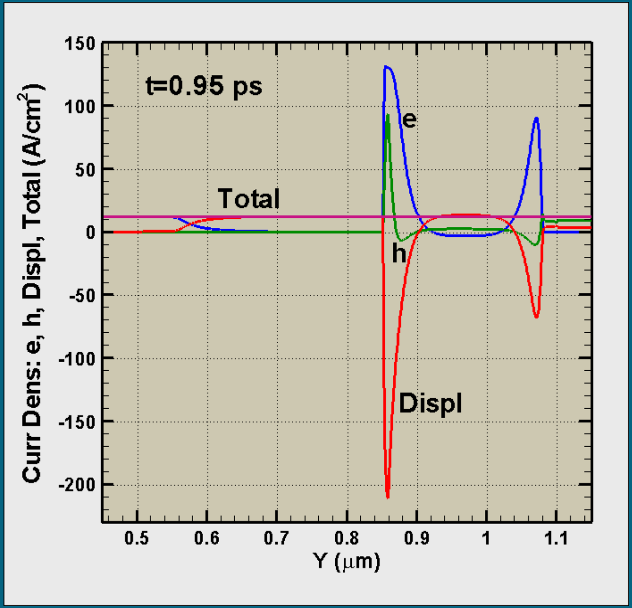
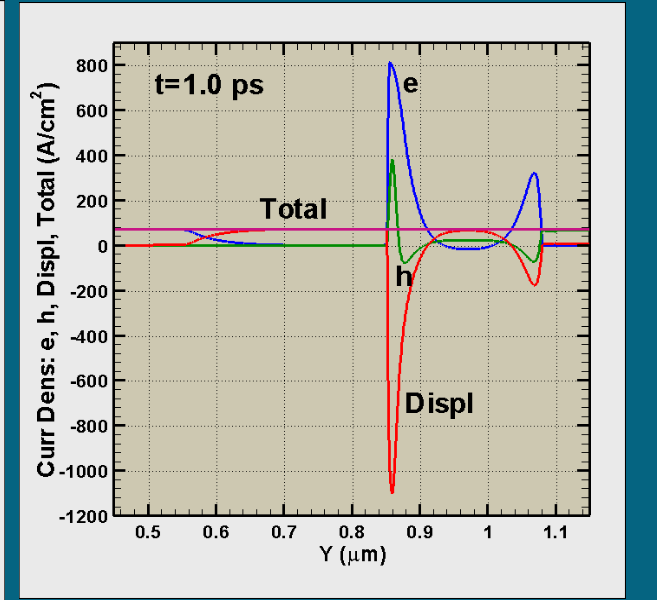
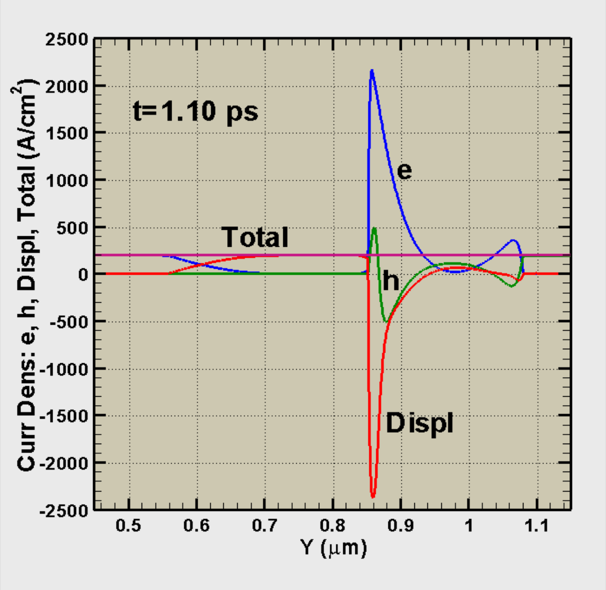
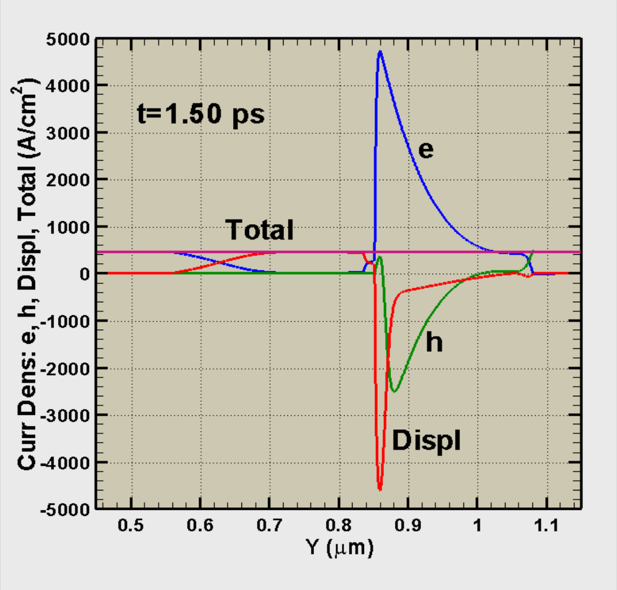
Computing and
Electronic Systems

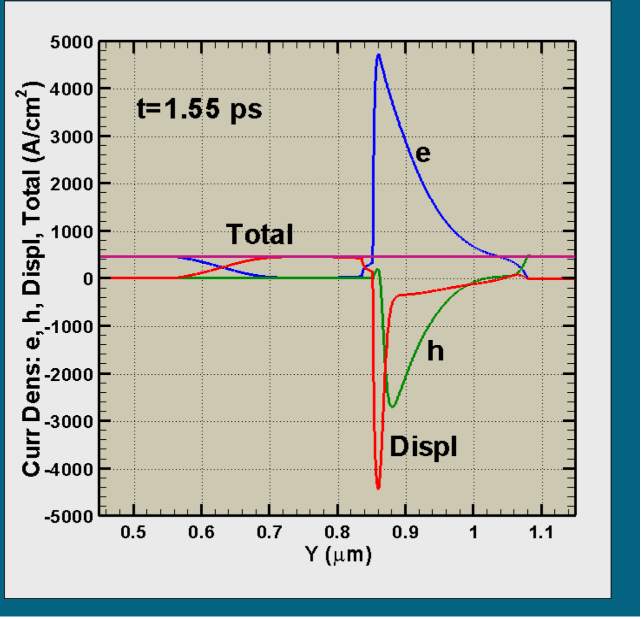




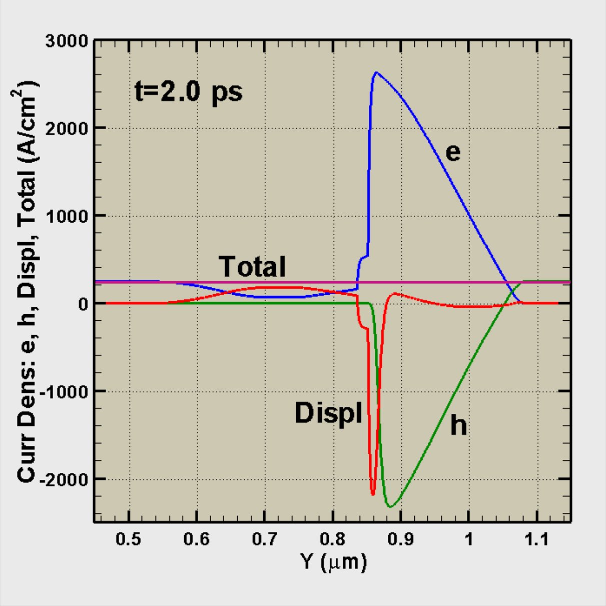


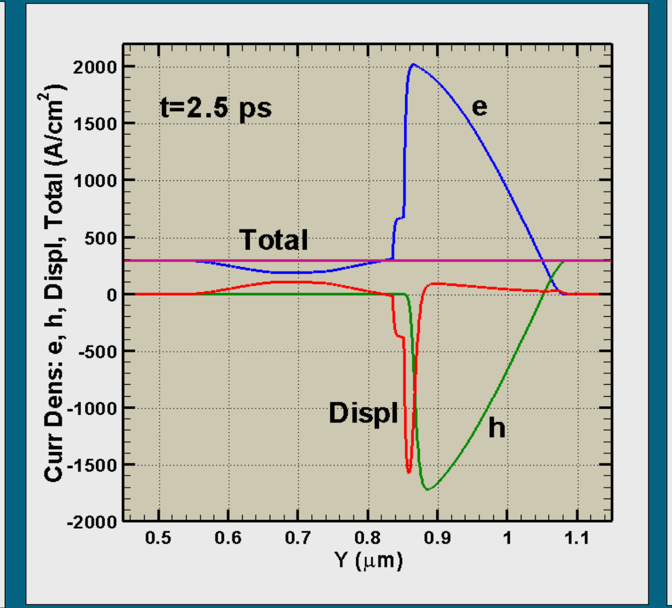


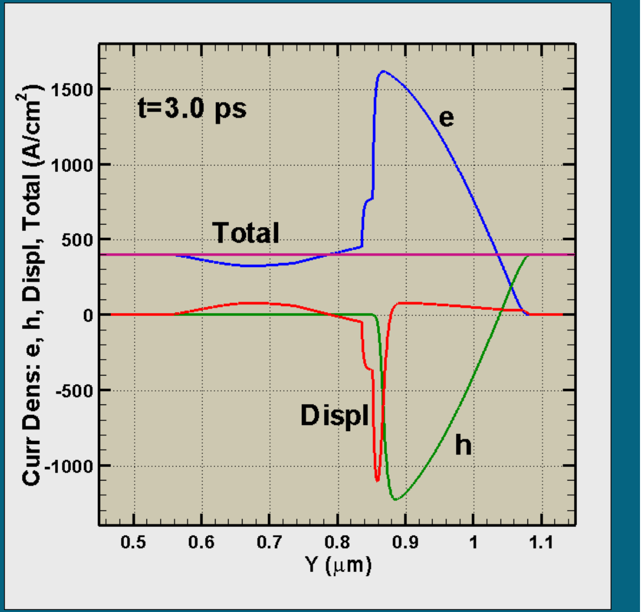


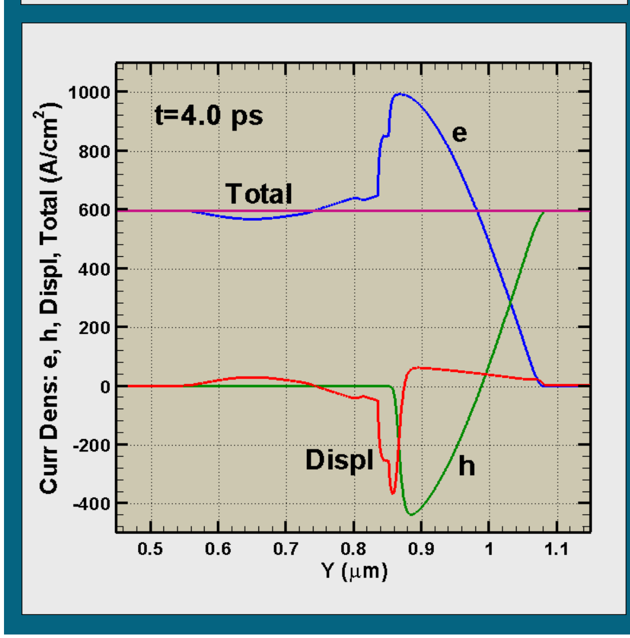


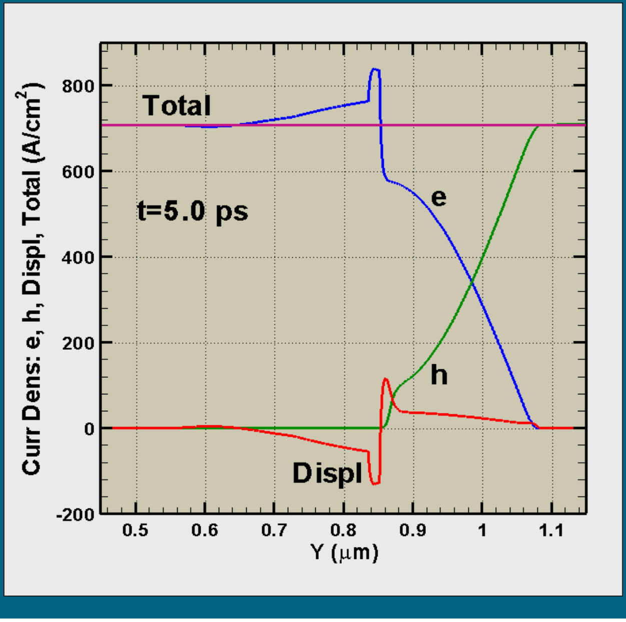
Transient Output Currents from DD Model (I_0=1x10^5 W/cm^2, V_n=0 V) - Continued

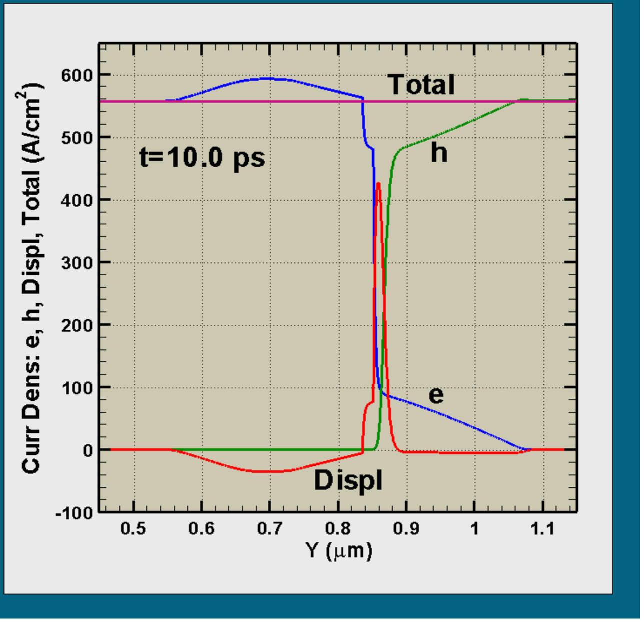




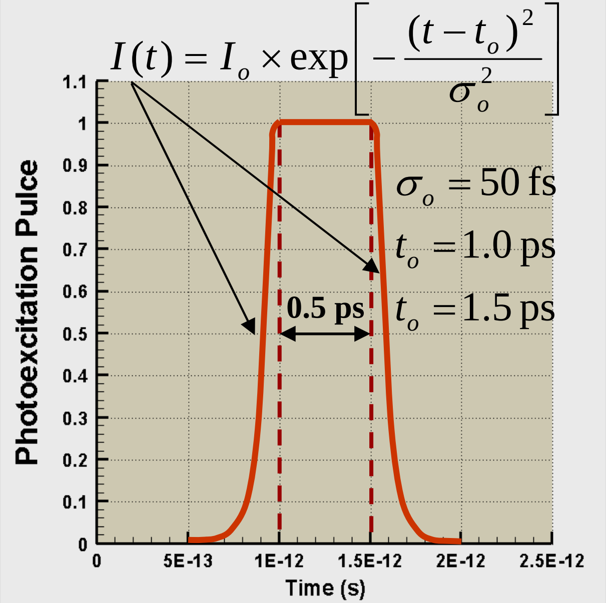








Transient Output Currents from DD Model ($I=1\times10^5$ W/cm^2, V_n=5 V)

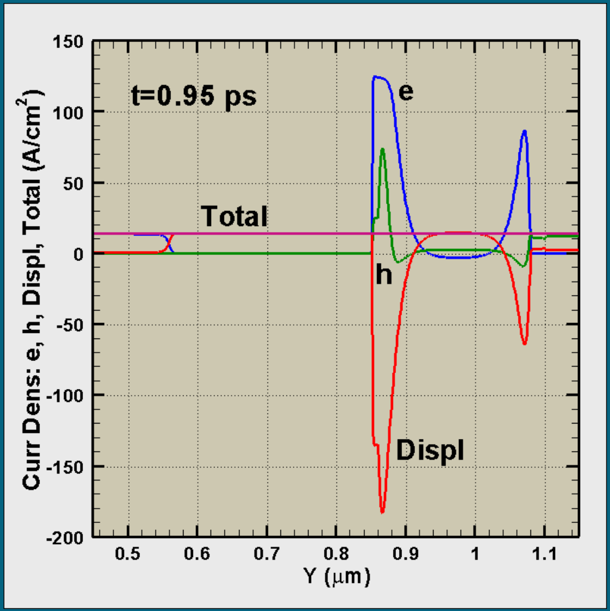


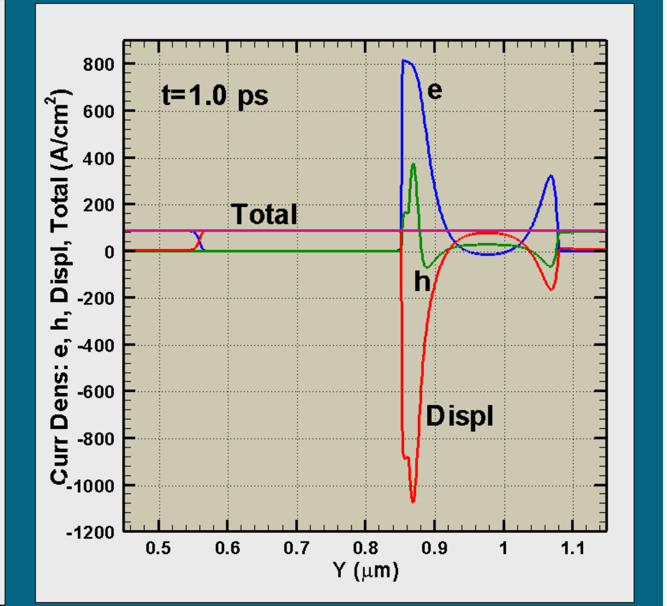
$$I(t) = I_o \times \exp\left[-\frac{(t-t_o)^2}{\sigma_o^2}\right]$$

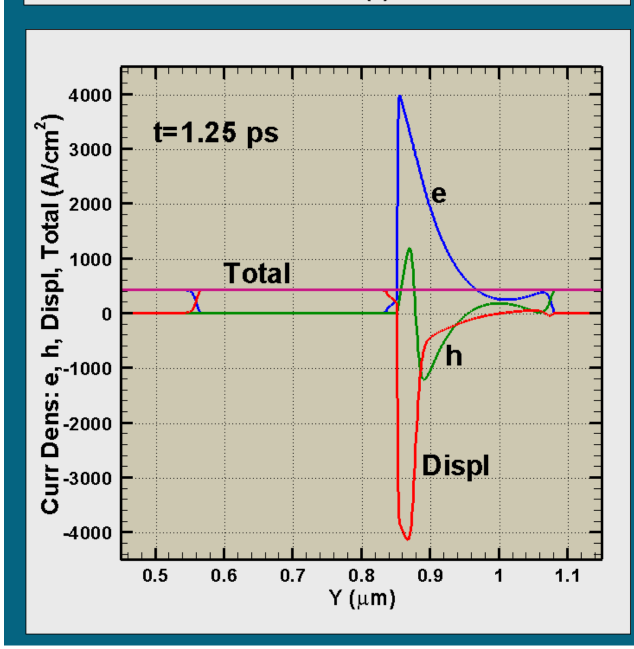
$\sigma_o = 50$ fs

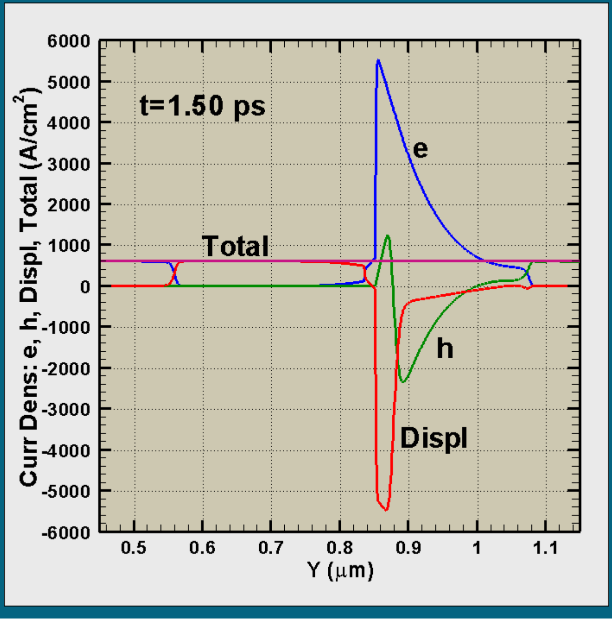
$t_o = 1.0$ ps

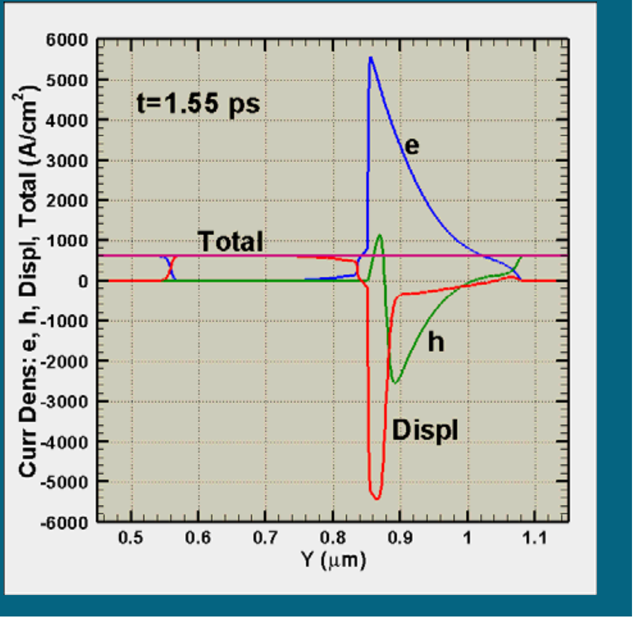
$t_o = 1.5$ ps



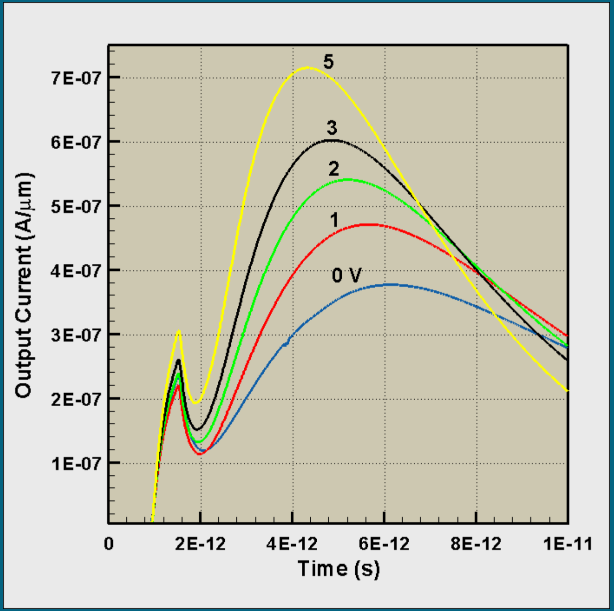


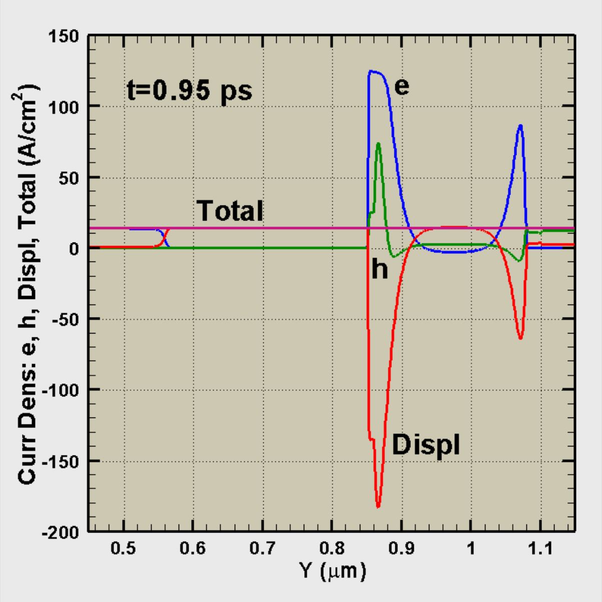


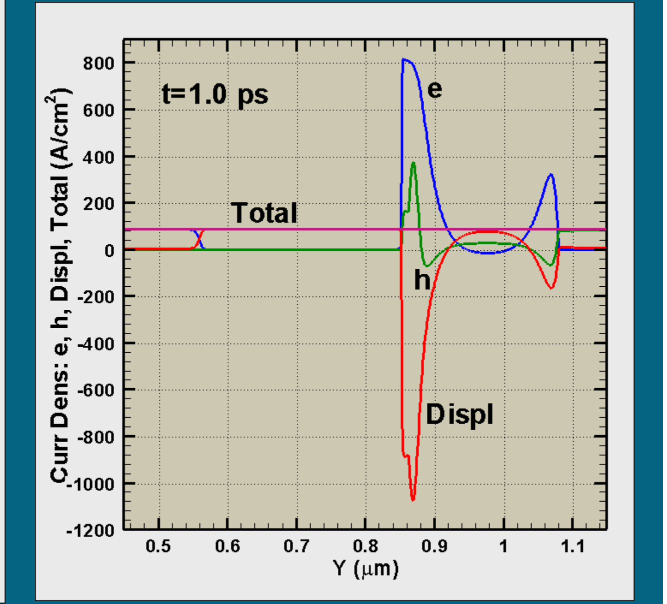


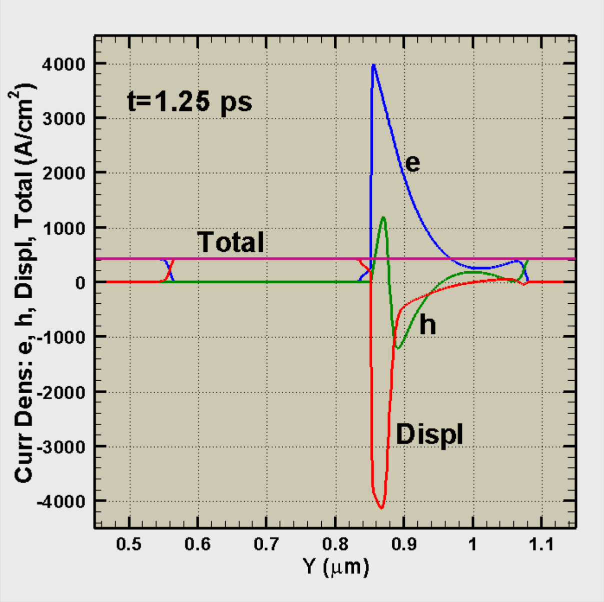


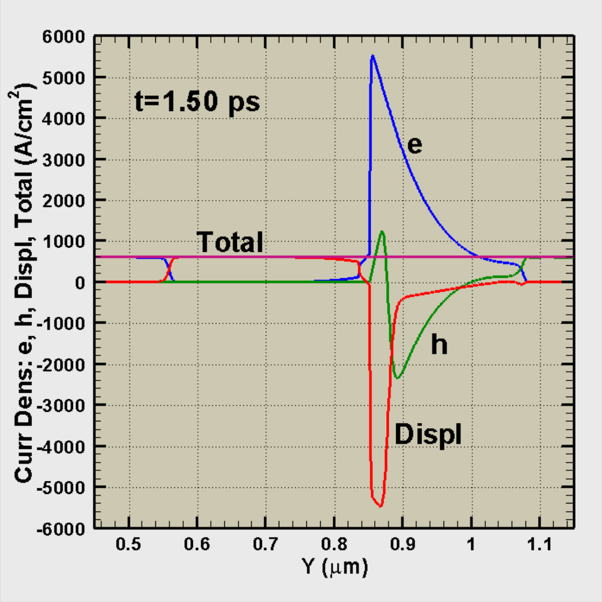
Transient Output Currents from DD Model (I=1x10^5 W/cm^2, Vn=5 V)

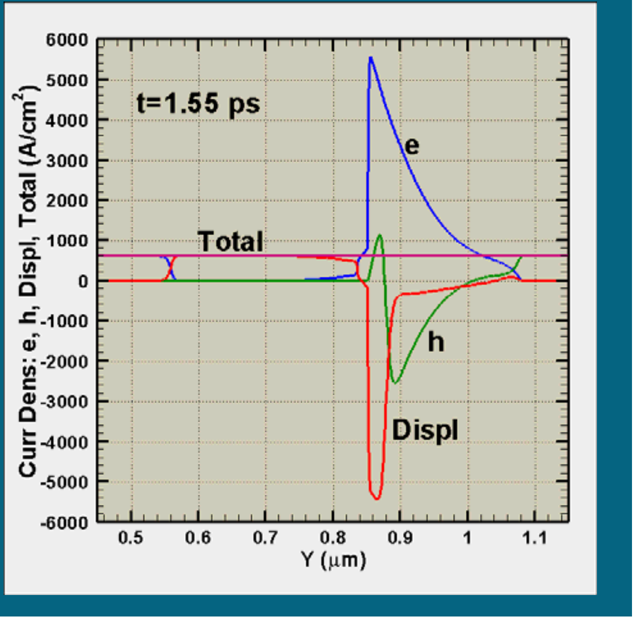




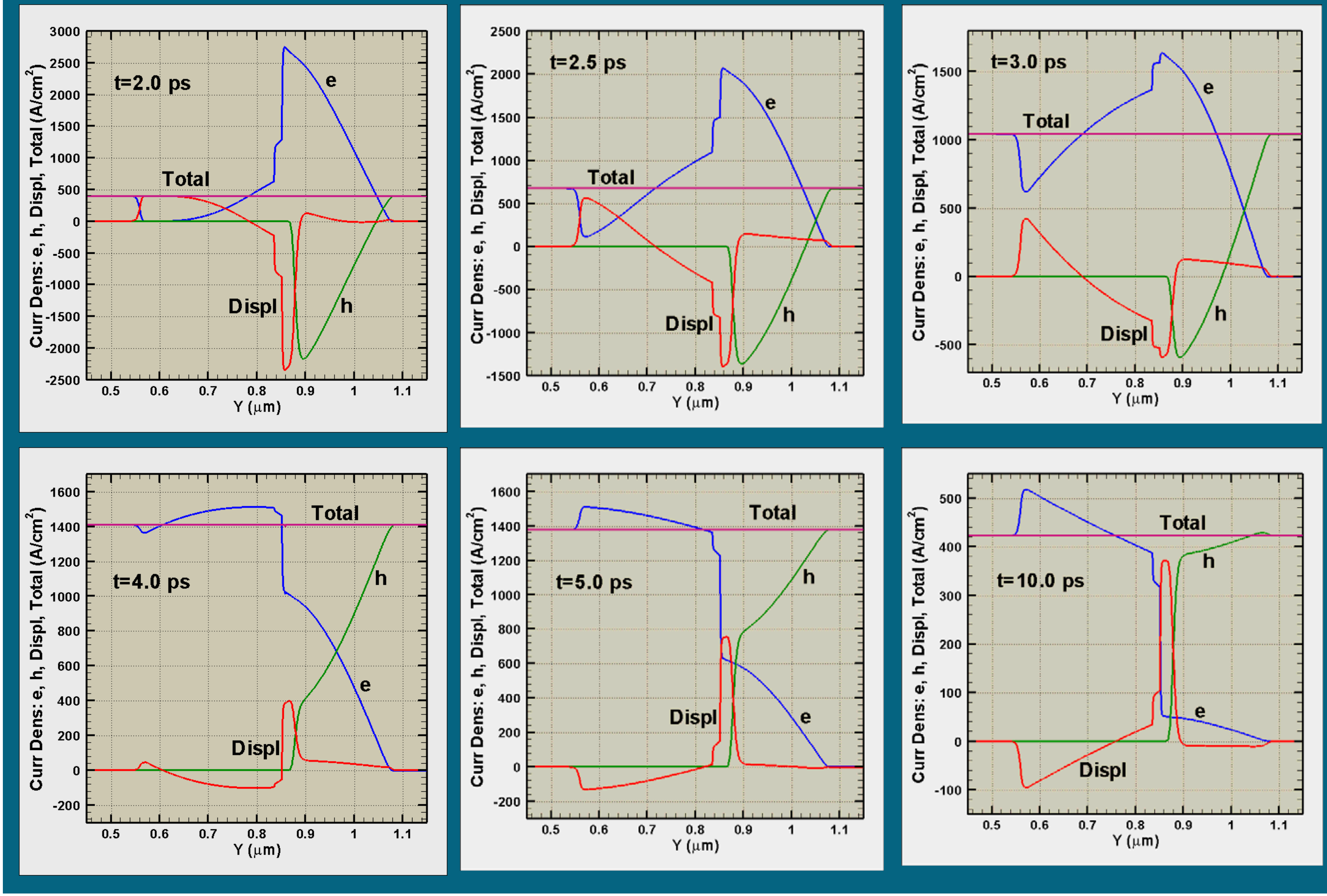




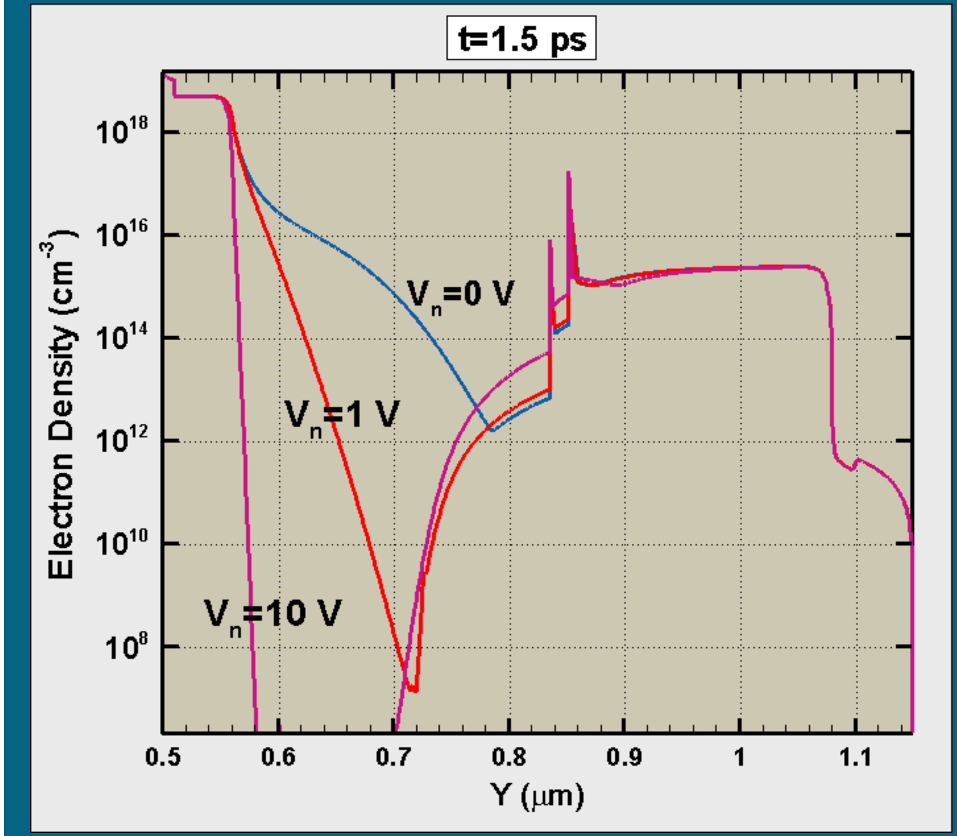


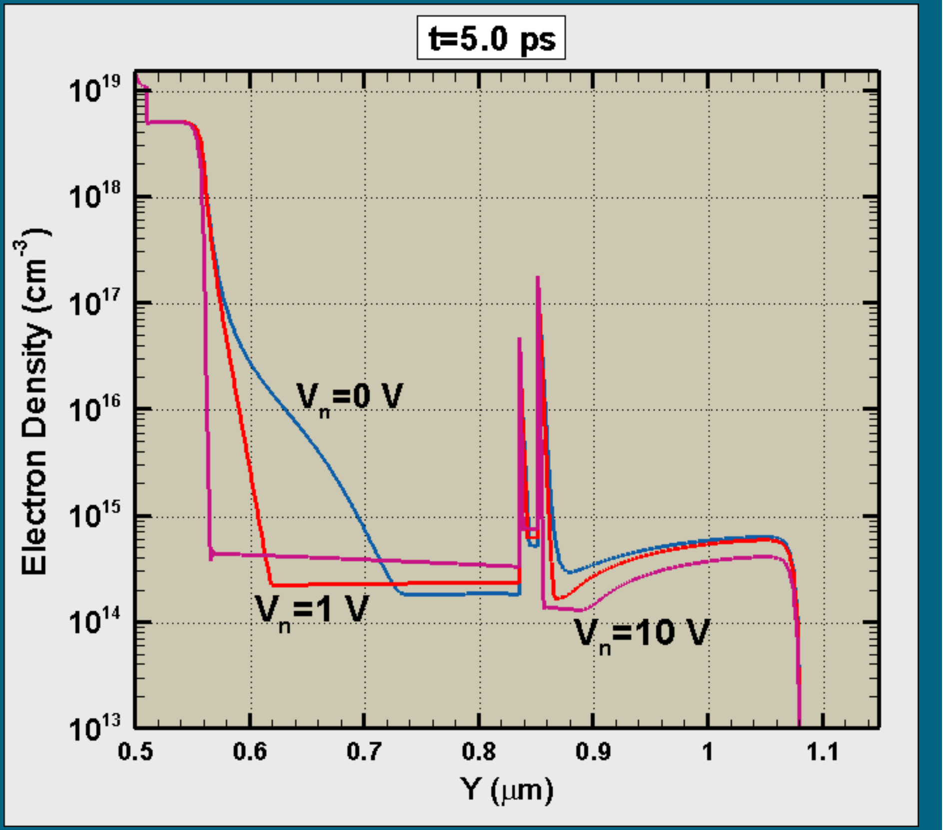


Transient Currents from DD Model (I=1x10^5 W/cm^2, V$_n$=5 V) - Continued

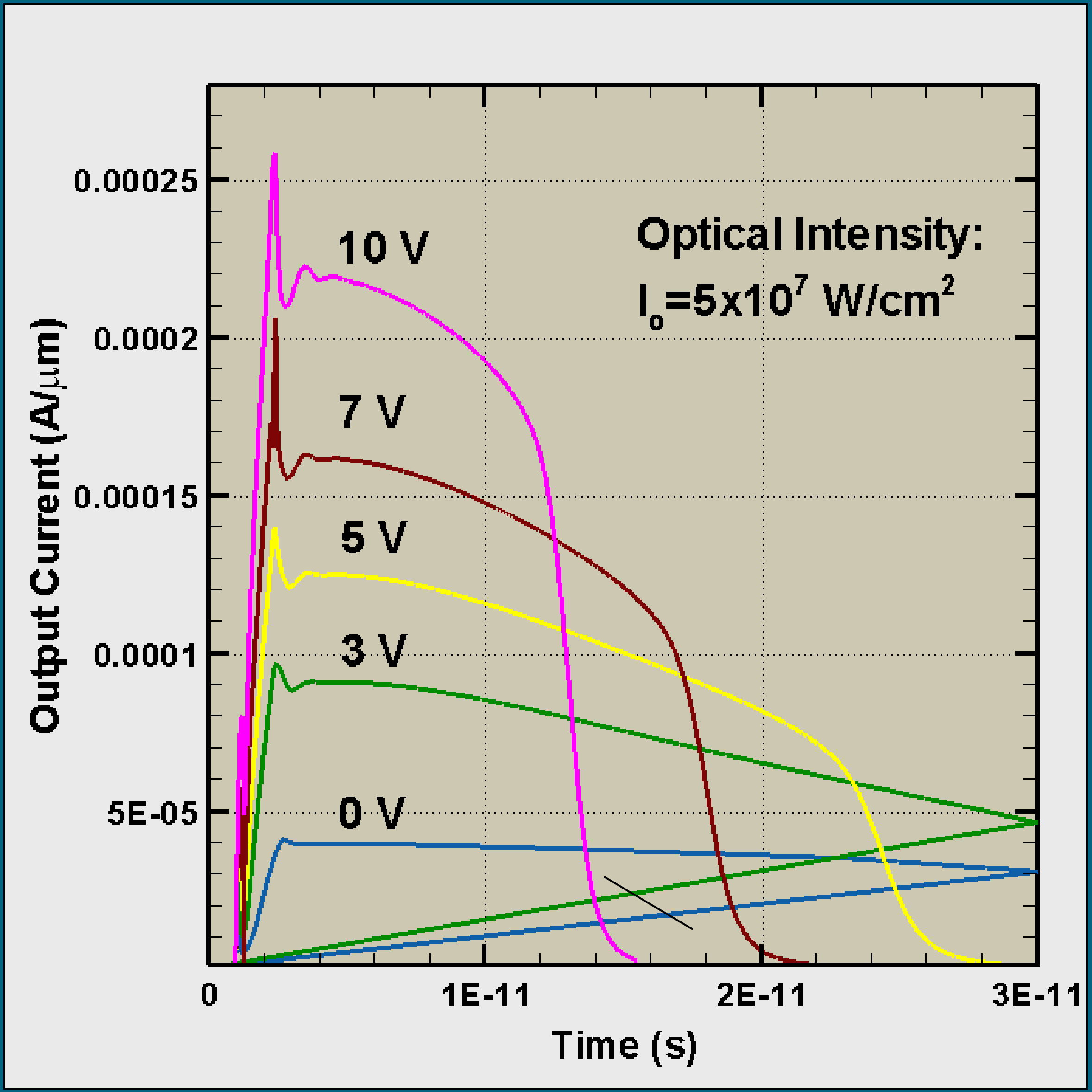


Electron Density from DD Model (V_n=0V, 1V, and 10V at t=1.5 ps

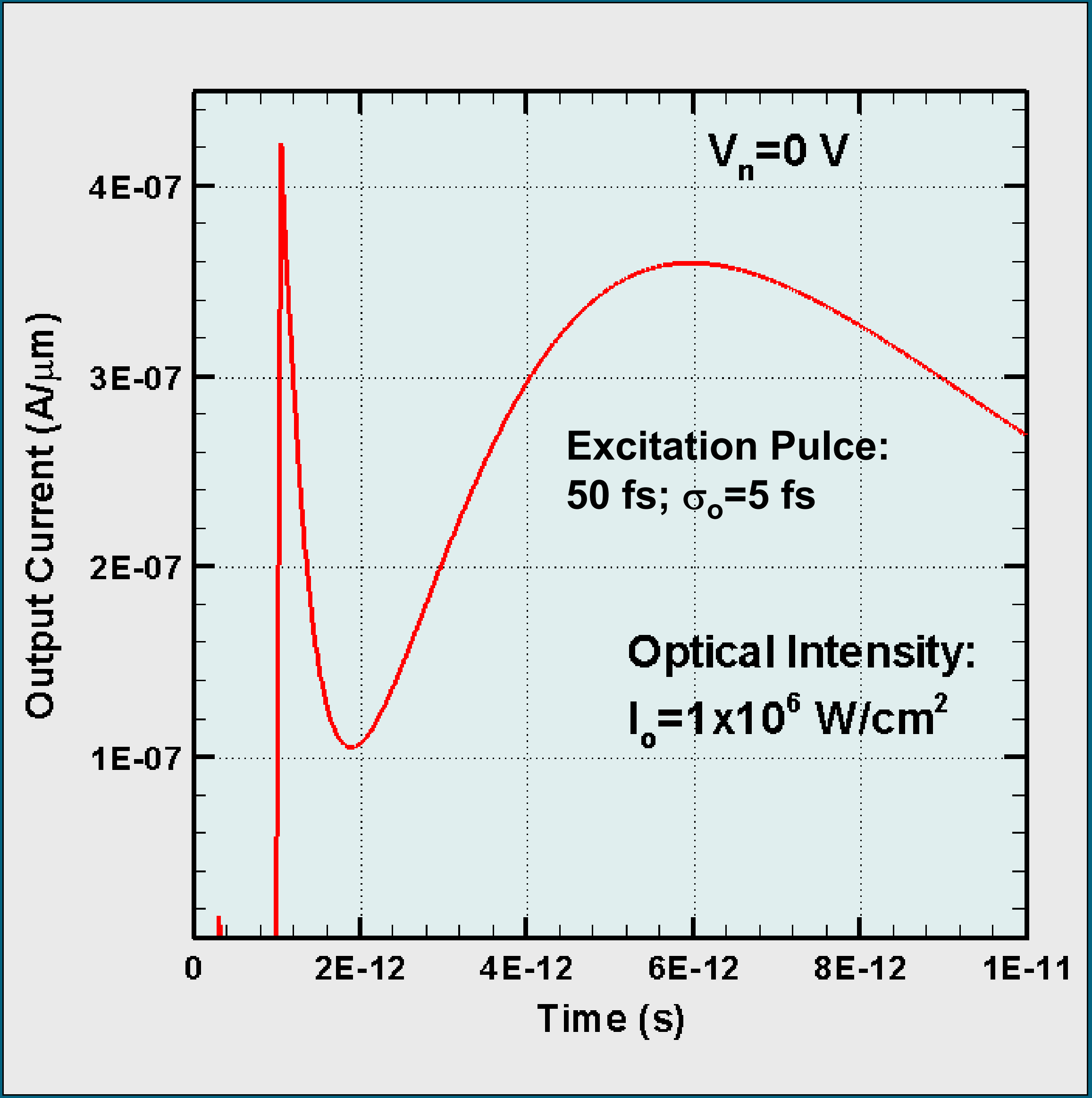




Output Currents from DD Model at Very High Photoexcitation Level for Various Biases



Effect of the Photoexcitation Pulse Duration on the Output Current for DD Model



CONCLUSIONS

- In case of spatially-inhomogeneous electric fields, which are typical for most of semiconductor devices, the driving force for carrier drift mobility in the drift-diffusion model is the fieldp parameter:

$$f(\vec{r}) = \vec{\nabla}_r E_c(\vec{r}).\vec{\nabla}_r E_F(\vec{r}): \quad \mu = \mu(f).$$

- The available mobility models, like v_{sat} or transferred electrons, must be modified respectively, in order to include the field parameter.

- In the high-speed photodetectors the hot-electrons effects are of paramount importance for the fast transient responses.

- The HD model must be used for simulation of p-i-n or UTC photodetectors, since it includes the hot-electron effects.

- For devices with photoexcitation the optical sources (optical heating/cooling) must be included in the energy balance equations.

- The key role of the near-interface field-heating of the carriers in the absorber is shown in the fast response of the UTC PDs.