ECE 656: Electronic Transport in Semiconductors Fall 2017

Non-local Carrier Transport in Devices

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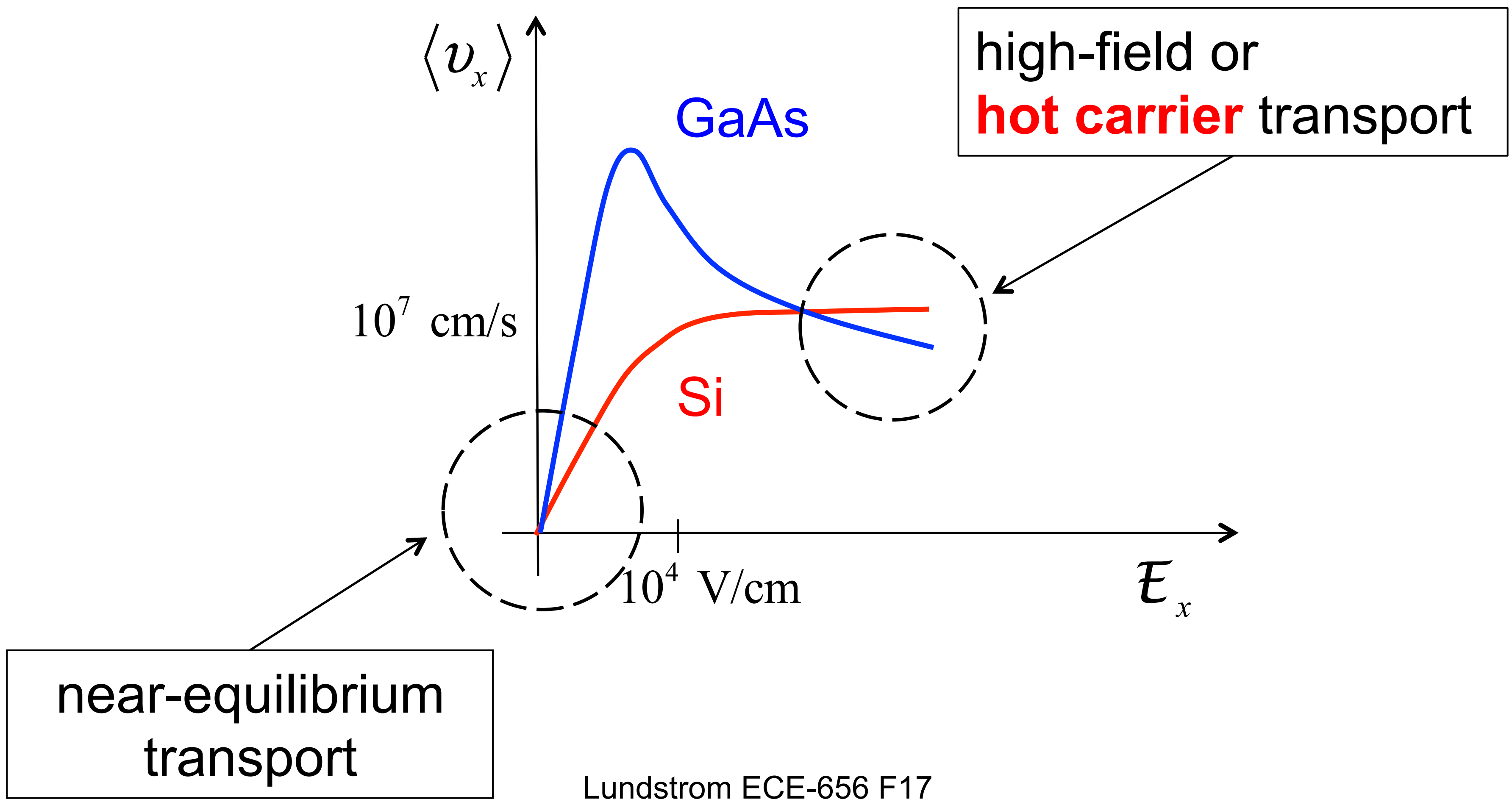
11/28/17

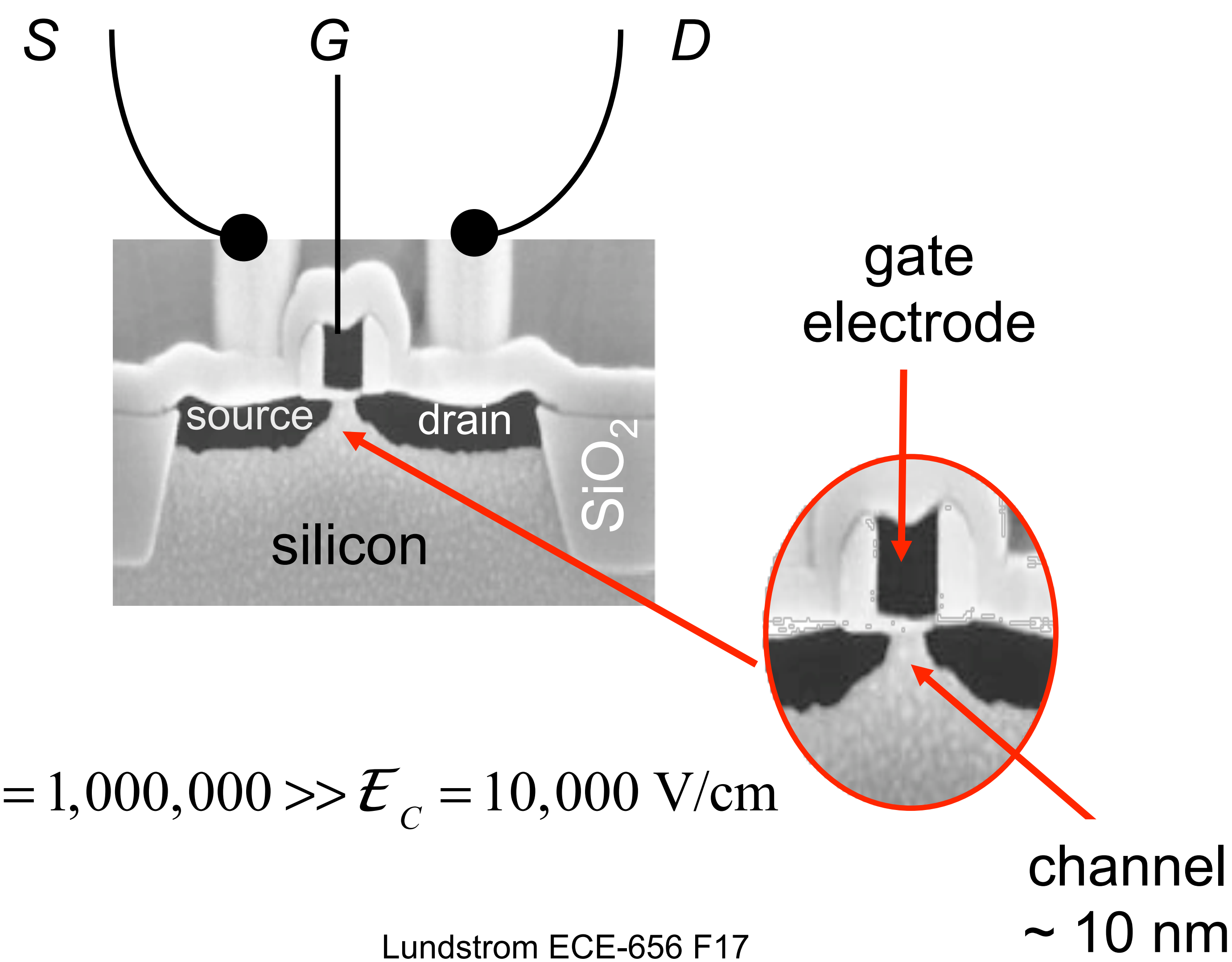
PURDUE UNIVERSITY

Velocity vs. field characteristics of **bulk** semiconductors

(***bulk*** semiconductors assumed)

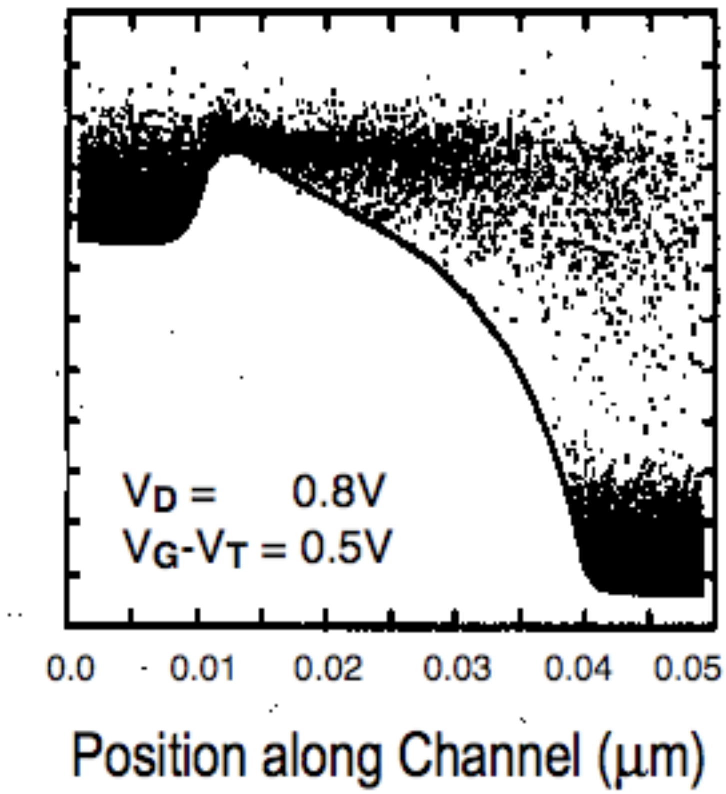


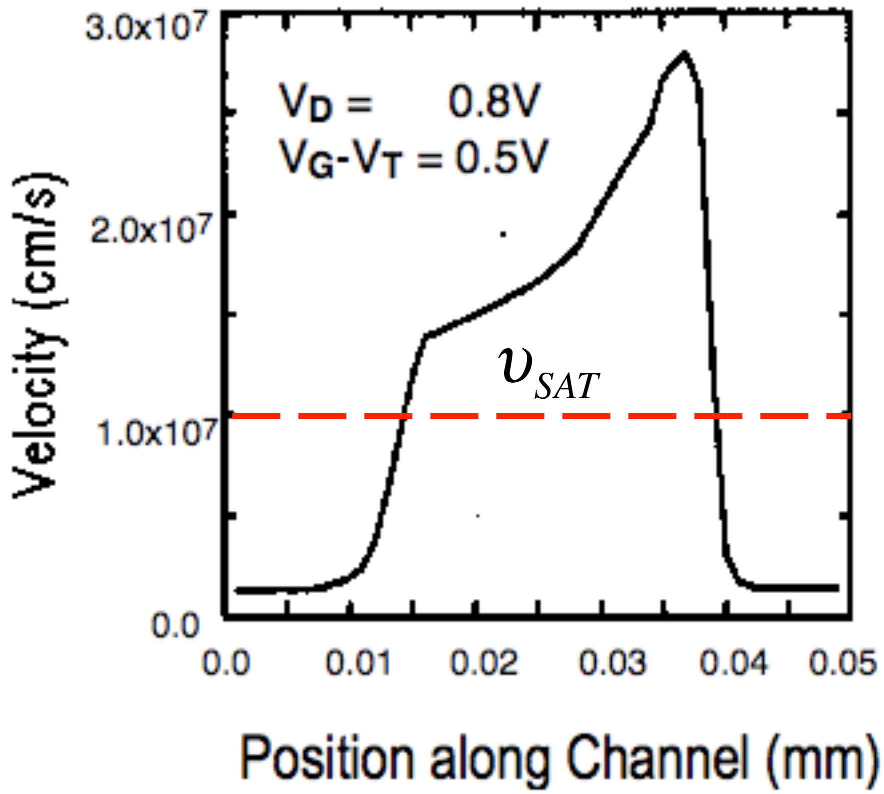
Nanoscale MOSFETs 2017



$$\mathcal{E} \simeq \frac{1\ \mathrm{V}}{10\ \mathrm{nm}} = 1{,}000{,}000 >> \mathcal{E}_C = 10{,}000\ \mathrm{V/cm}$$

“Non-local transport” in nanoscale MOSFETs

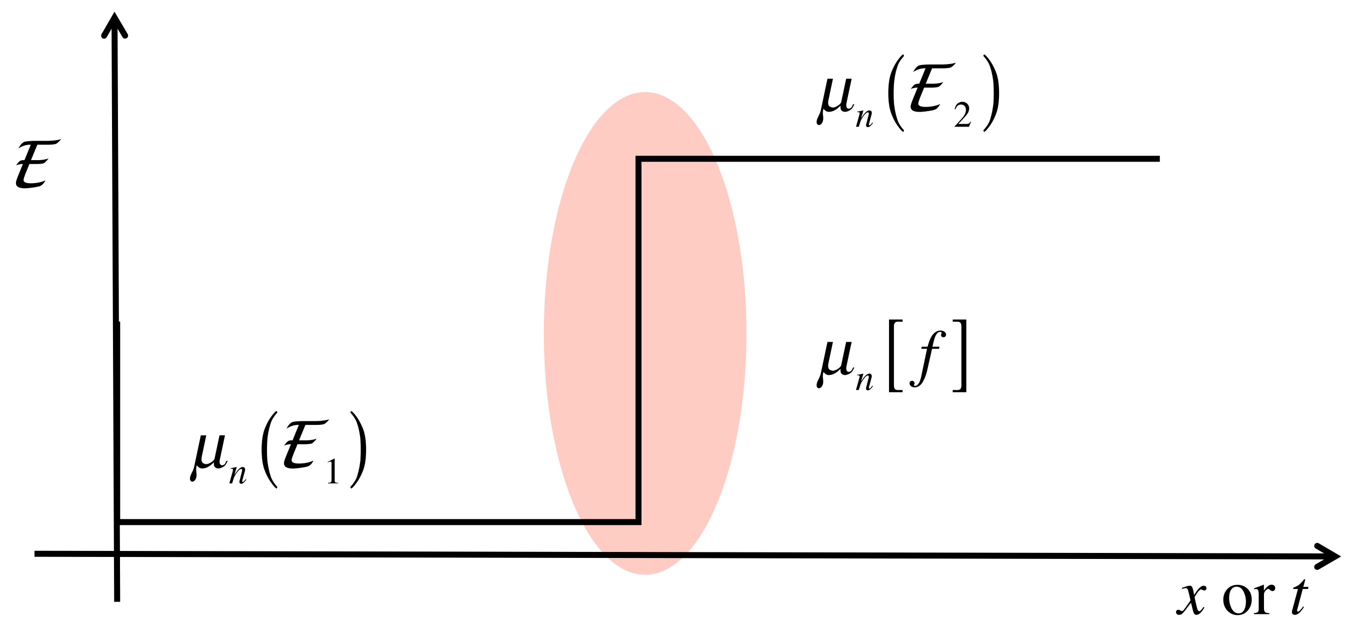




Frank, Laux, and Fischetti, IEDM Tech. Dig., p. 553, 1992

Non-local transport

Rapidly varying electric fields lead to "off-equilibrium", "non-local" or "non-stationary" transport effects that cannot be described with (local) field-dependent field dependent transport parameters.



Analysis techniques

1) Field-dependent mobility:

$$J_{nx} = nq\mu_n(\mathcal{E})\mathcal{E}_x + qD_n(\mathcal{E})\frac{dn}{dx}$$

Local electric field

2) Energy transport:

$$J_{nx} = nq\mu_n(u)\mathcal{E}_x + 2\mu_n(u)\frac{d(nu)}{dx}$$

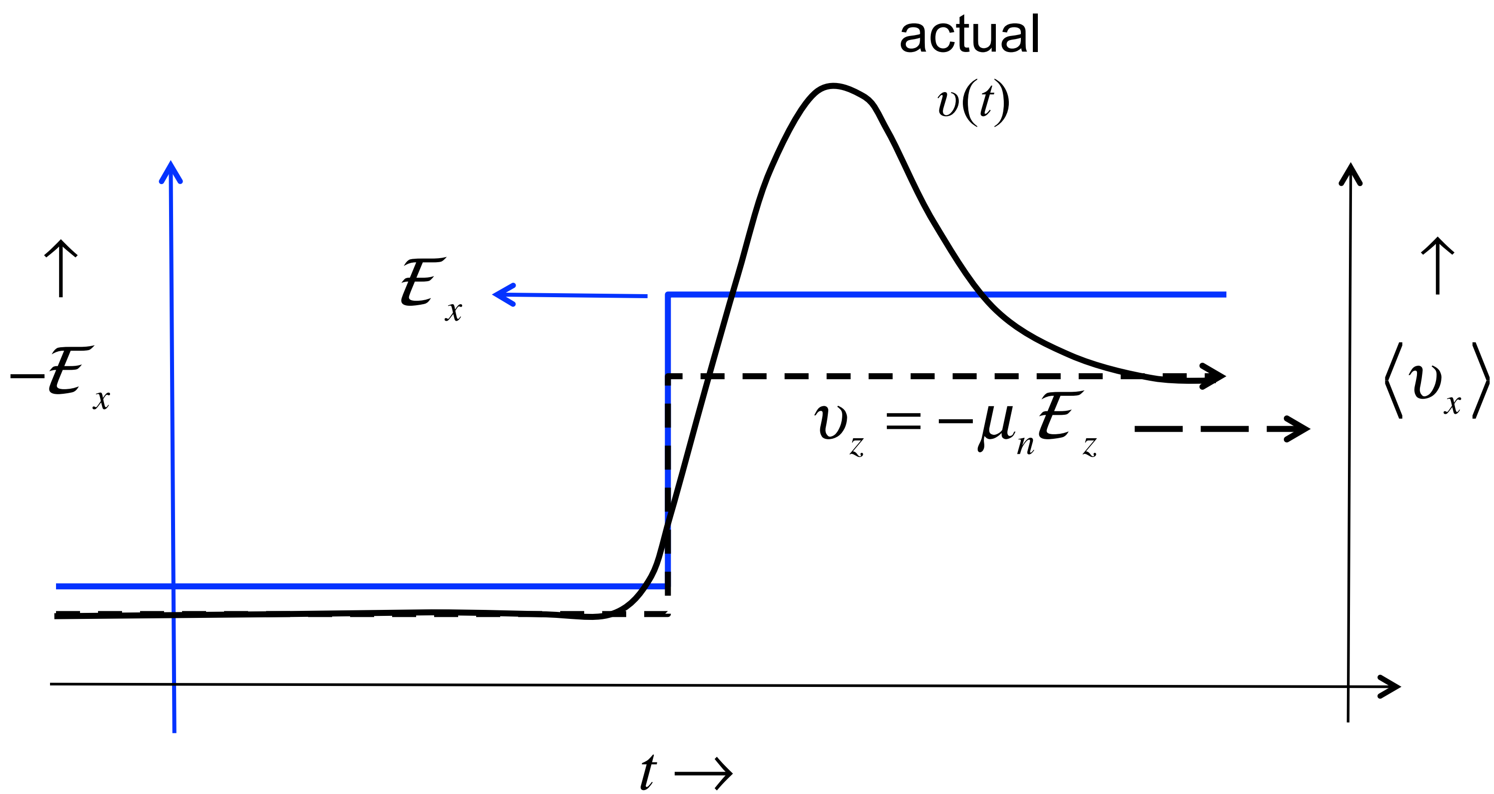
Local kinetic energy

3) Monte Carlo simulation: Full BTE

Outline

1) **Velocity overshoot**
2) Steady-state, spatial transients
3) Heterojunction launching ramps
4) Repeated velocity overshoot?
5) Questions?

Rapidly varying electric fields



Velocity overshoot

$p_{dx} = \langle p_x \rangle$ Let's find an equation for the ave. *x*-directed momentum.

$$\frac{\partial P_x}{\partial t} = -\frac{\partial (2W_{xx})}{\partial x} - nq\mathcal{E}_x - \frac{P_x}{\langle \tau_m \rangle} \qquad P_x = nm^* \upsilon_{dx} = np_{dx}$$

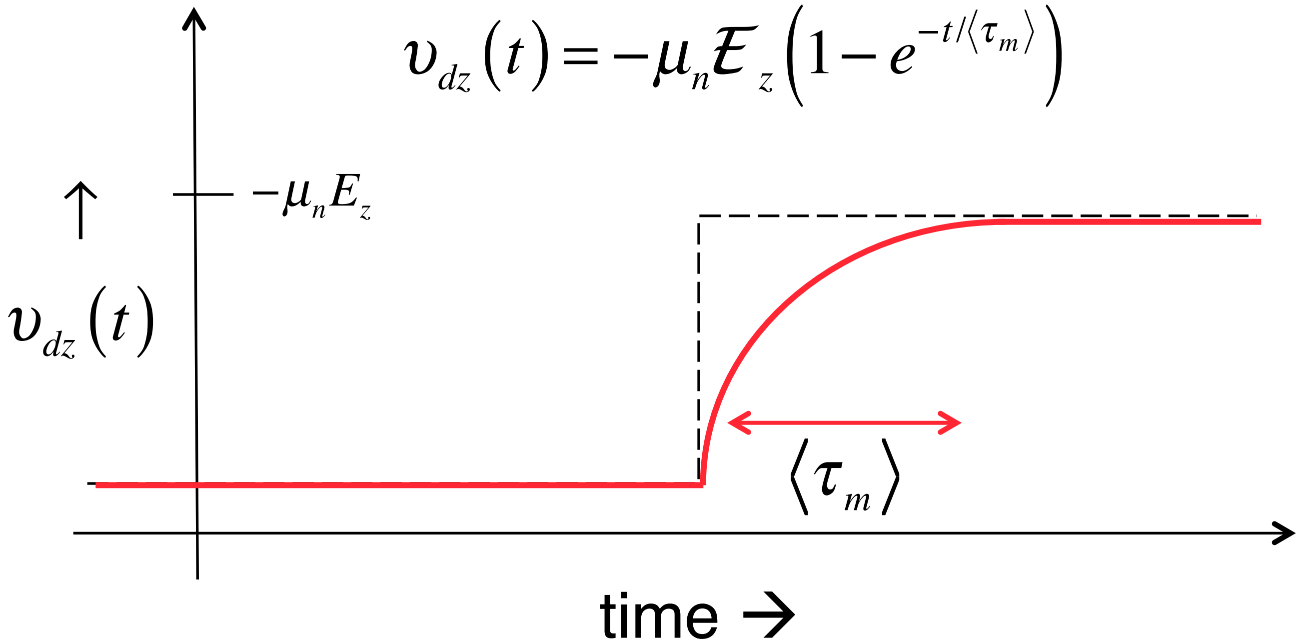
$$\frac{dp_{dx}}{dt} \approx -q\mathcal{E}_x - \frac{p_{dx}}{\langle \tau_m \rangle}$$

(ignores diffusion)

$$\upsilon_{dx}(t) = -\mu_n \mathcal{E}_x \left(1 - e^{-t/\langle \tau_m \rangle}\right)$$

Velocity overshoot

$$\upsilon_{dz}(t) = -\mu_n \mathcal{E}_z \left(1 - e^{-t/\langle \tau_m \rangle}\right)$$



But, μ_n is not constant: $\mu_n(T_e)$

Velocity overshoot

$u = \langle E - E_C \rangle$

Let's find an equation for the ave. kinetic energy

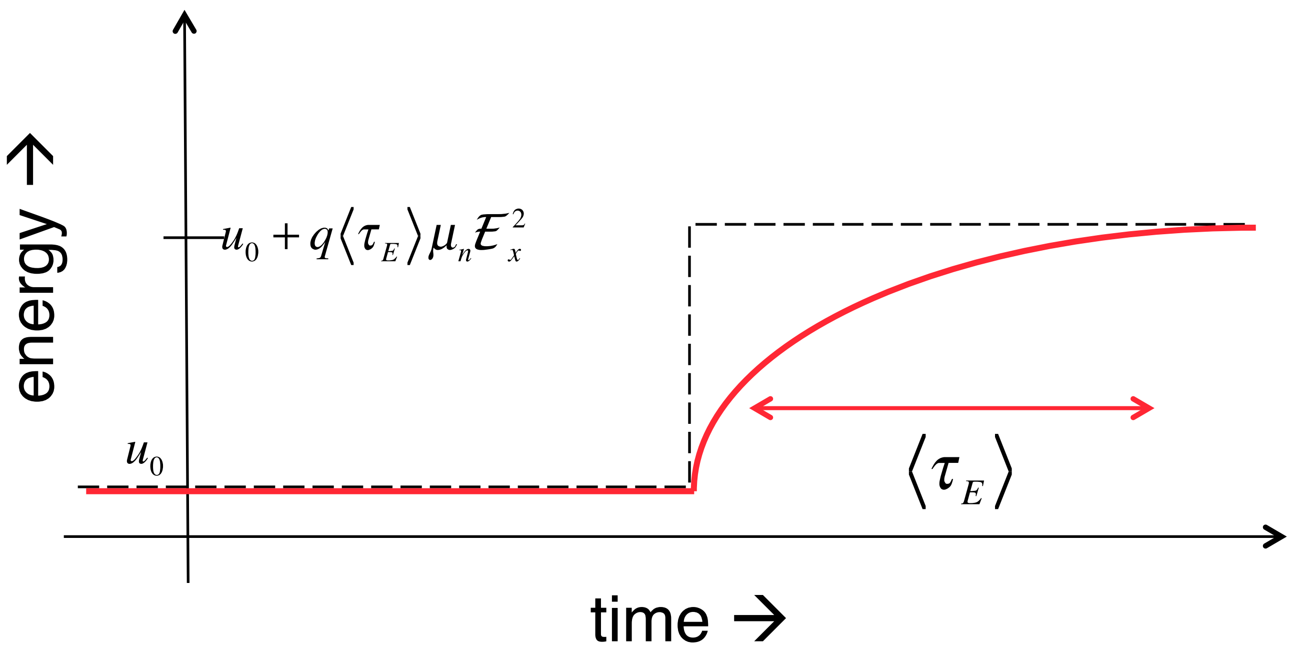
$$\frac{du}{dt} = -q\upsilon_{dx}\mathcal{E}_x - \frac{(u - u_0)}{\langle \tau_E \rangle}$$

(ignores diffusion)

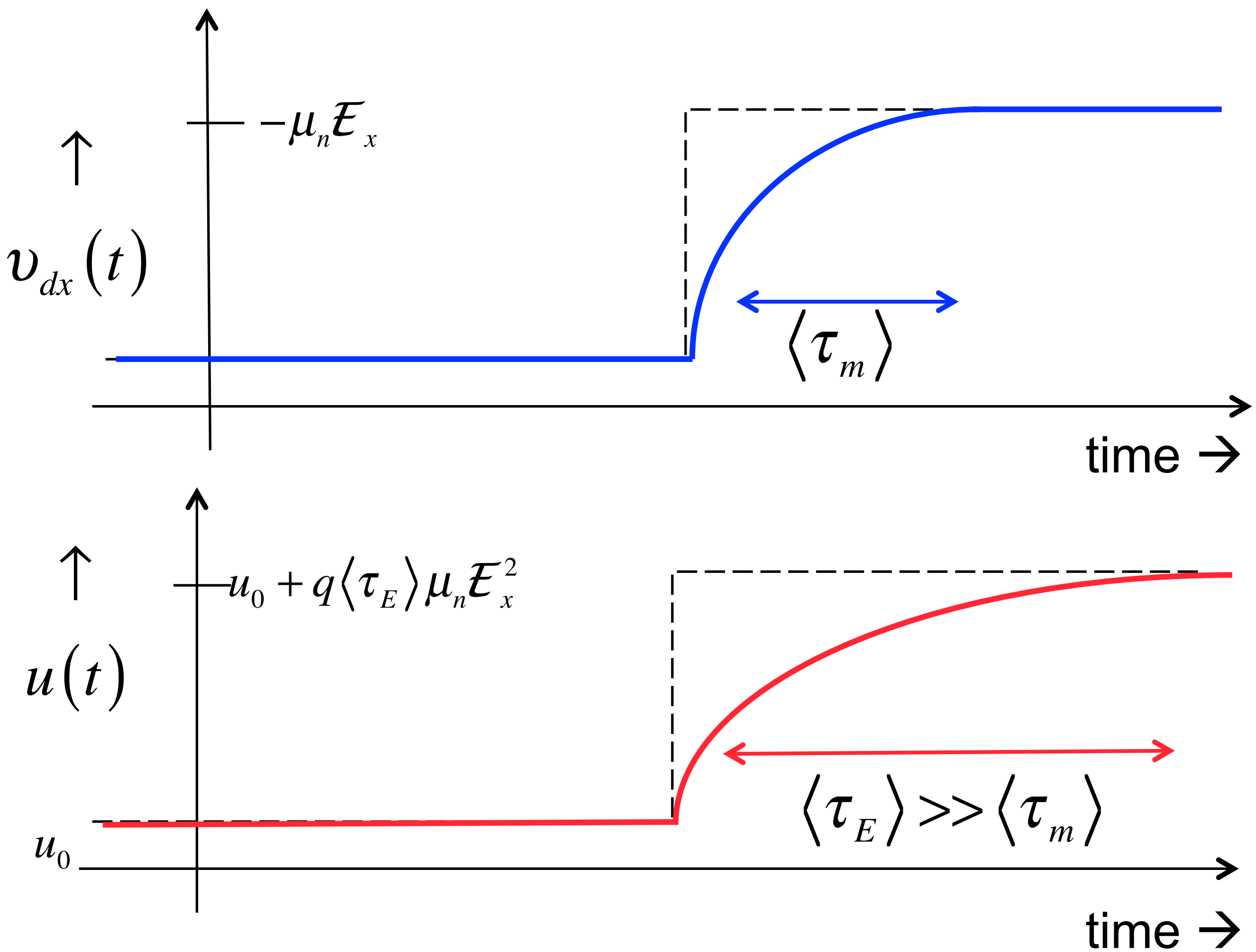
$$u(t) = u_0 + q\langle \tau_E \rangle \mu_n \mathcal{E}_x^2 \left(1 - e^{-t/\langle \tau_E \rangle}\right)$$

Velocity overshoot

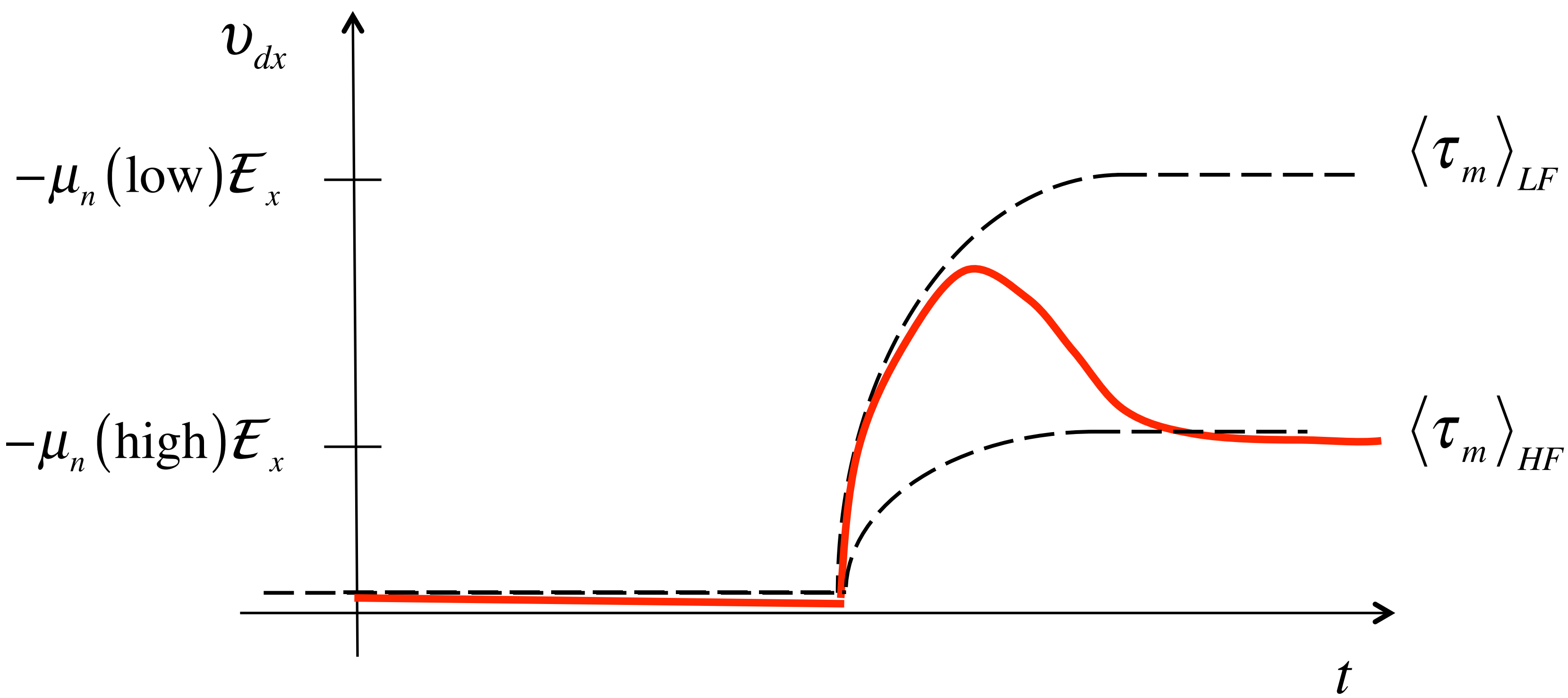
$$u(t) = u_0 + q\langle \tau_E \rangle \mu_n \mathcal{E}_x^2 \left(1 - e^{-t/\langle \tau_E \rangle}\right)$$



Velocity overshoot



Velocity overshoot



Temporal velocity overshoot

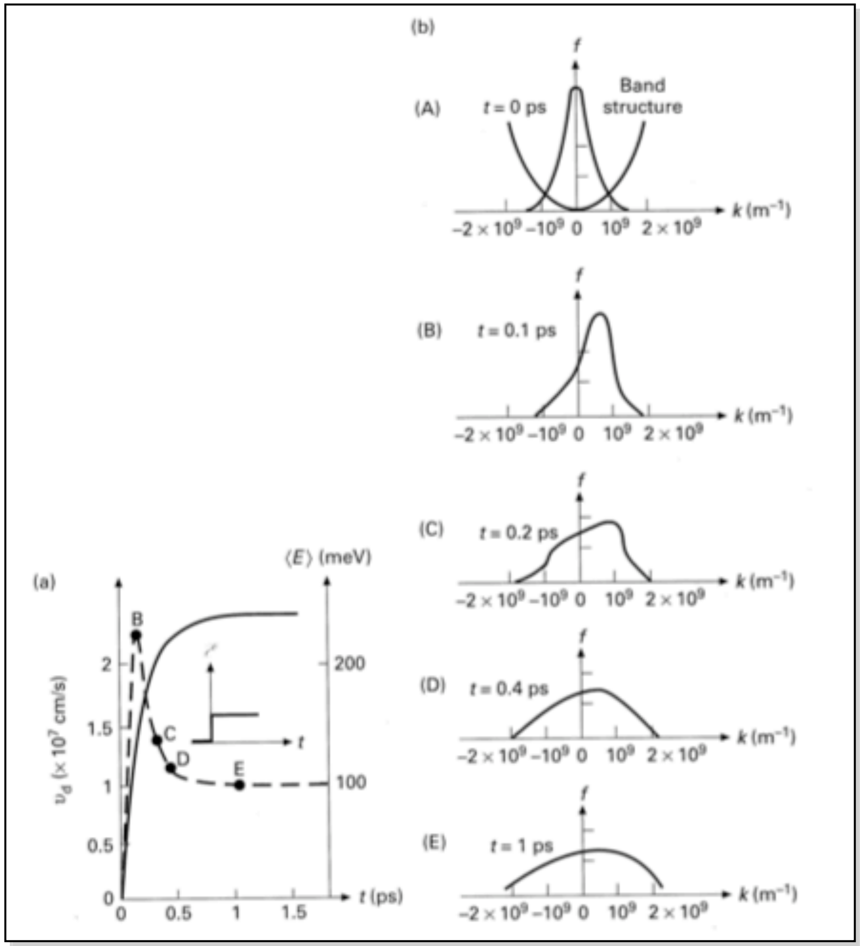


Fig. 8.9 Evolution of the distribution function during a velocity overshoot transient.

The average drift velocity and energy are shown in (a), and the evolution of the corresponding distribution function is shown in (b).

The results were obtained by Monte Carlo simulation of electron transport in silicon by E. Constant [8.10].

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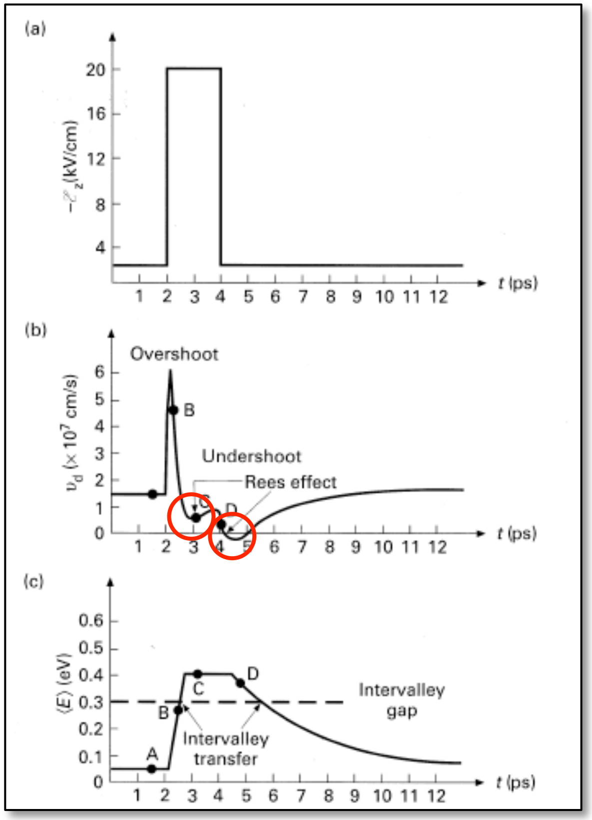
Rees effect (GaAs)



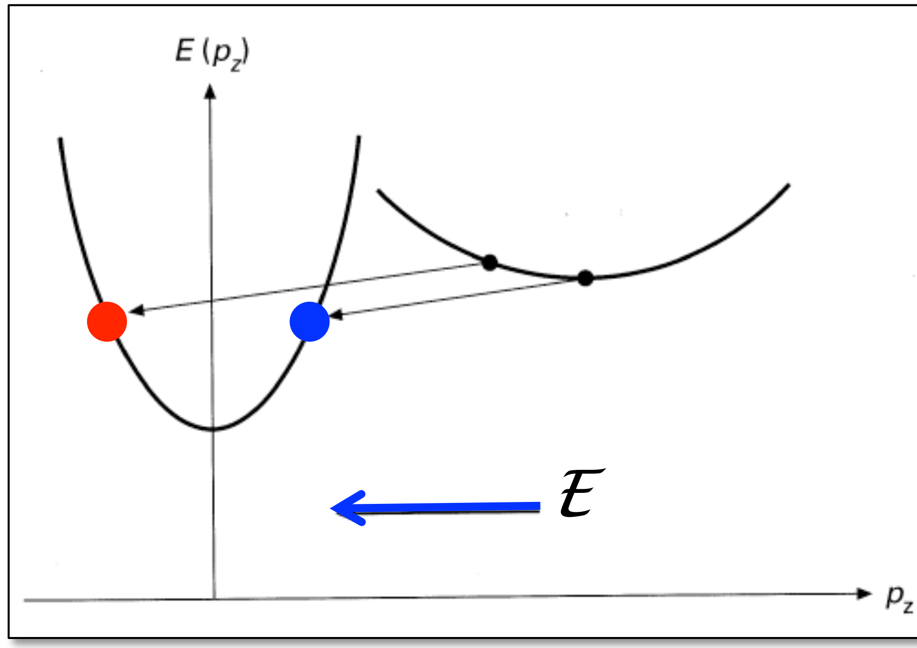


Fig. 8.10 (a) Applied electric field vs. time. (b) Ave. drift velocity vs. time. (c) Ave. electron energy vs. time. (Monte Carlo simulations from E. Constant [8.10].

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Outline

1) Velocity overshoot

2) Steady-state, spatial transients

3) Heterojunction launching ramps

4) Repeated velocity overshoot?

5) Questions?

Diffusion effects

$$\frac{dp_{dx}}{dt} = -q\mathcal{E}_x - \frac{p_{dx}}{\langle \tau_m \rangle}$$

$$\frac{du}{dt} = -q\upsilon_{dx}\mathcal{E}_x - \frac{(u - u_0)}{\langle \tau_E \rangle}$$

$$\frac{dP_x}{dt} = -\frac{d(2W_{xx})}{dx} - qn\mathcal{E}_x - \frac{P_x}{\langle \tau_m \rangle}$$

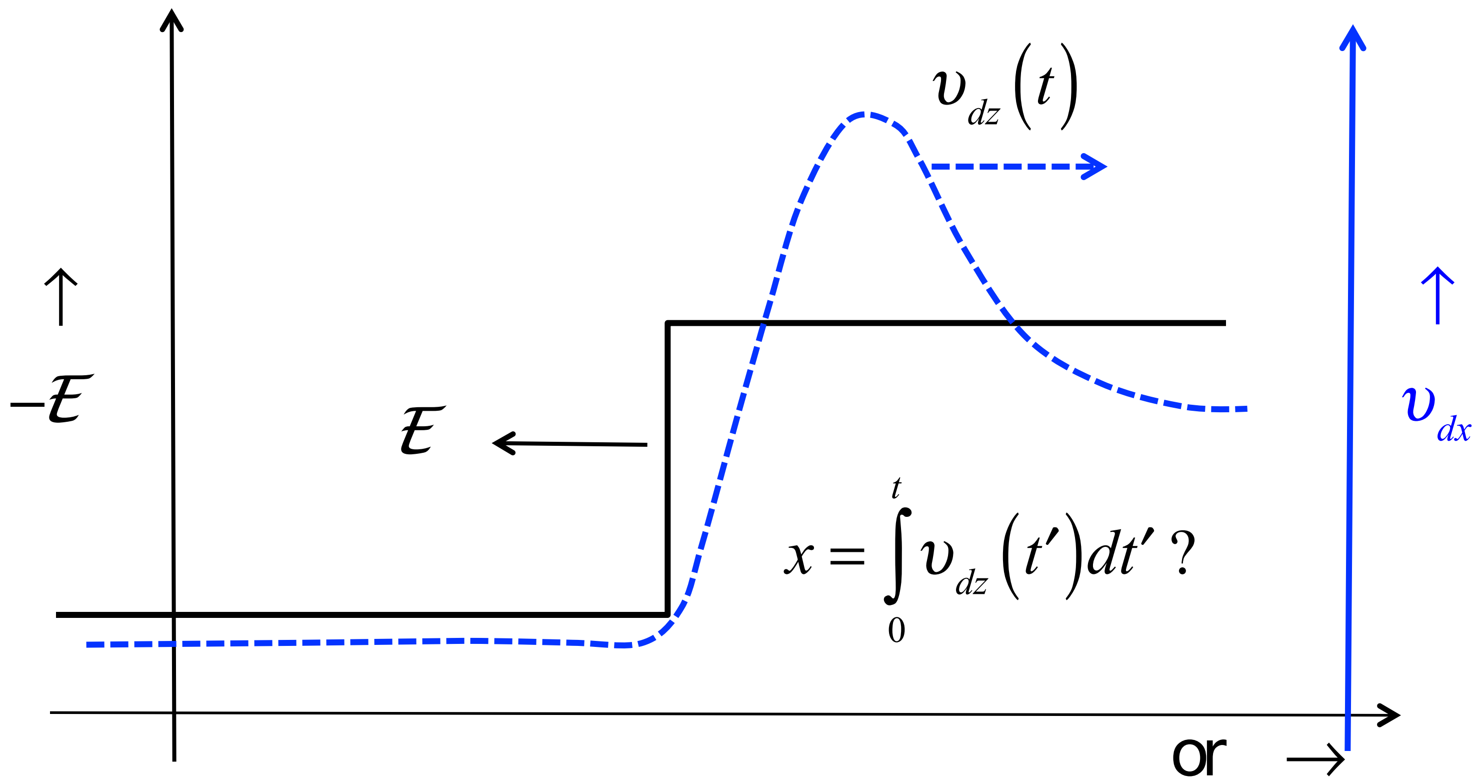
$$P_x = n\langle p_x \rangle = np_{dx}$$

$$\frac{dW}{dt} = -\frac{d(F_W)}{dx} + J_x\mathcal{E}_x - \frac{W - W_0}{\langle \tau_E \rangle}$$

$$W = n\langle E(p) \rangle = nu$$

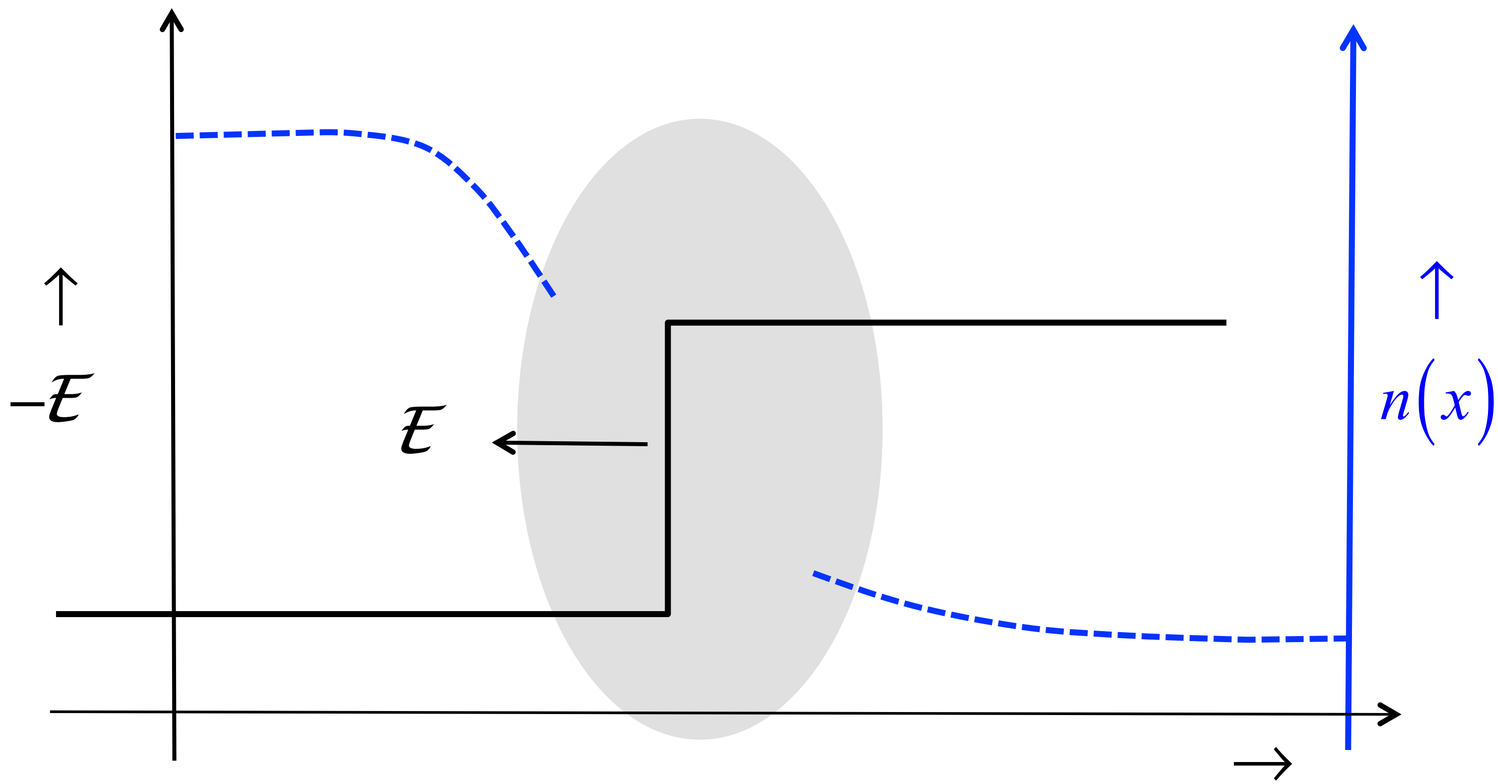
What effect do these spatial gradients have?

Temporal vs. spatial transients



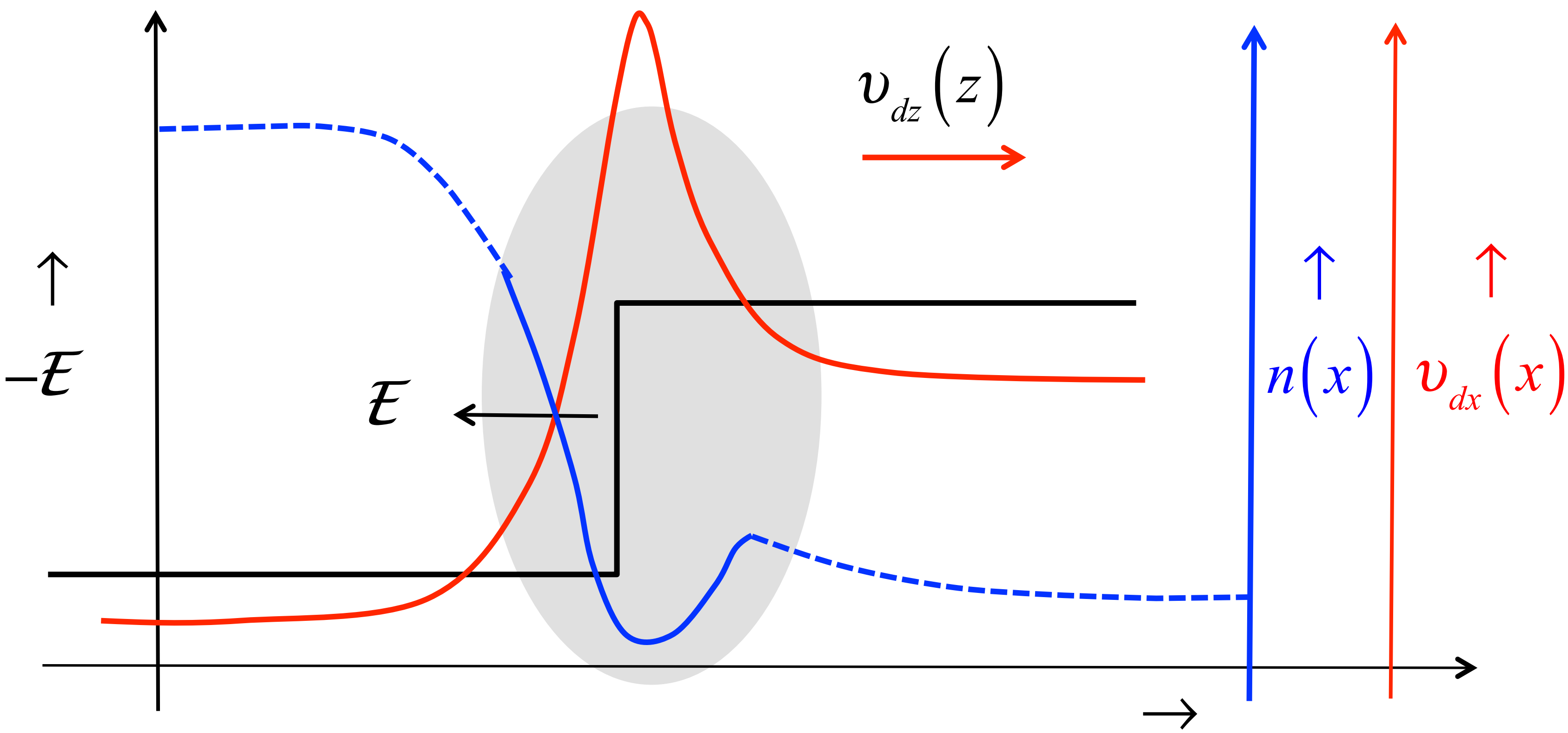
Question: If we change the horizontal axis to distance, what does the steady-state velocity vs. position characteristic look like?

Carrier density vs. position



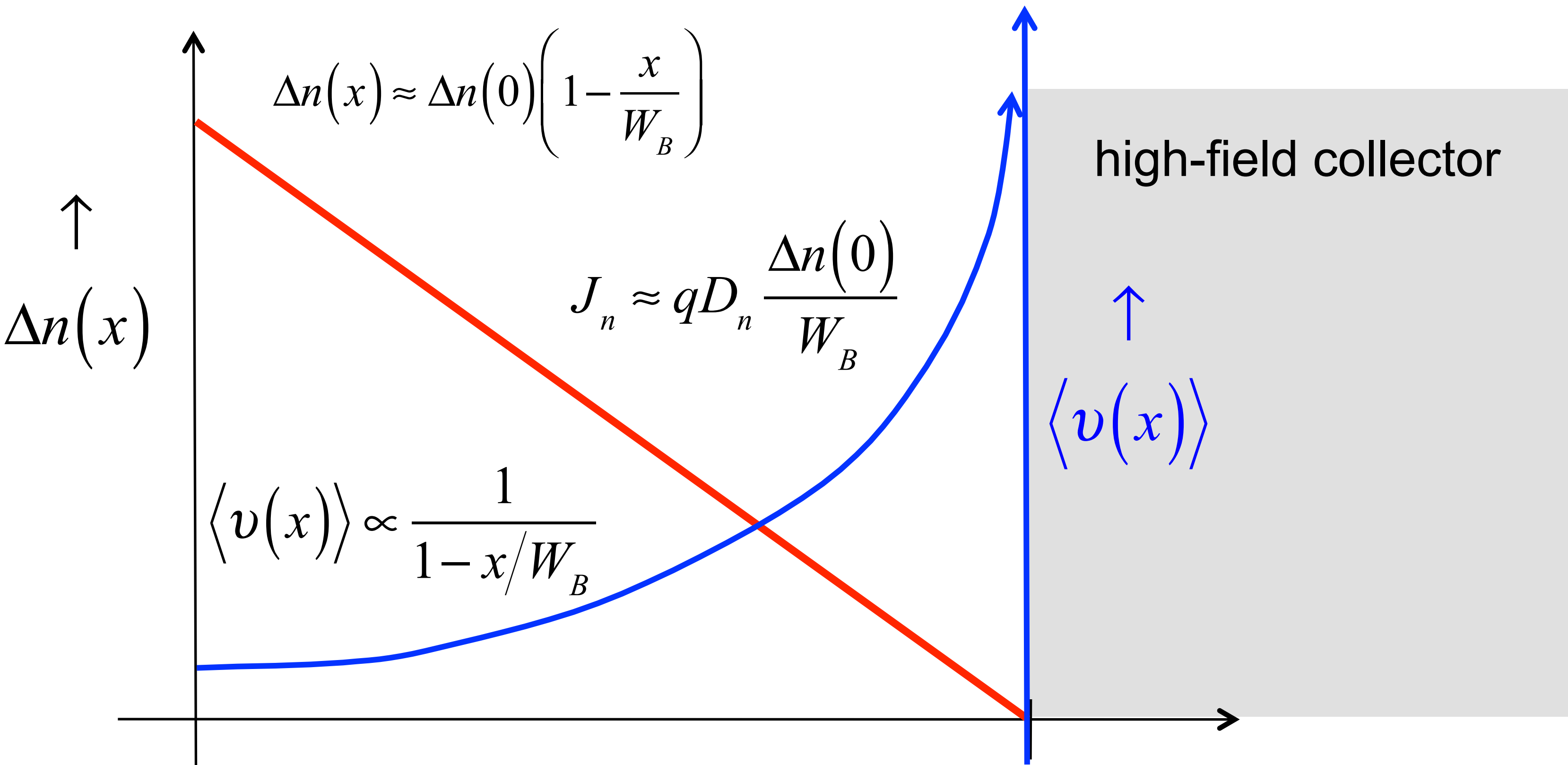
Steady-state current is constant: $J_{nx} = n(x) q \langle \upsilon_x(x) \rangle$

Carrier velocity vs. position



Expect strong diffusion effects.

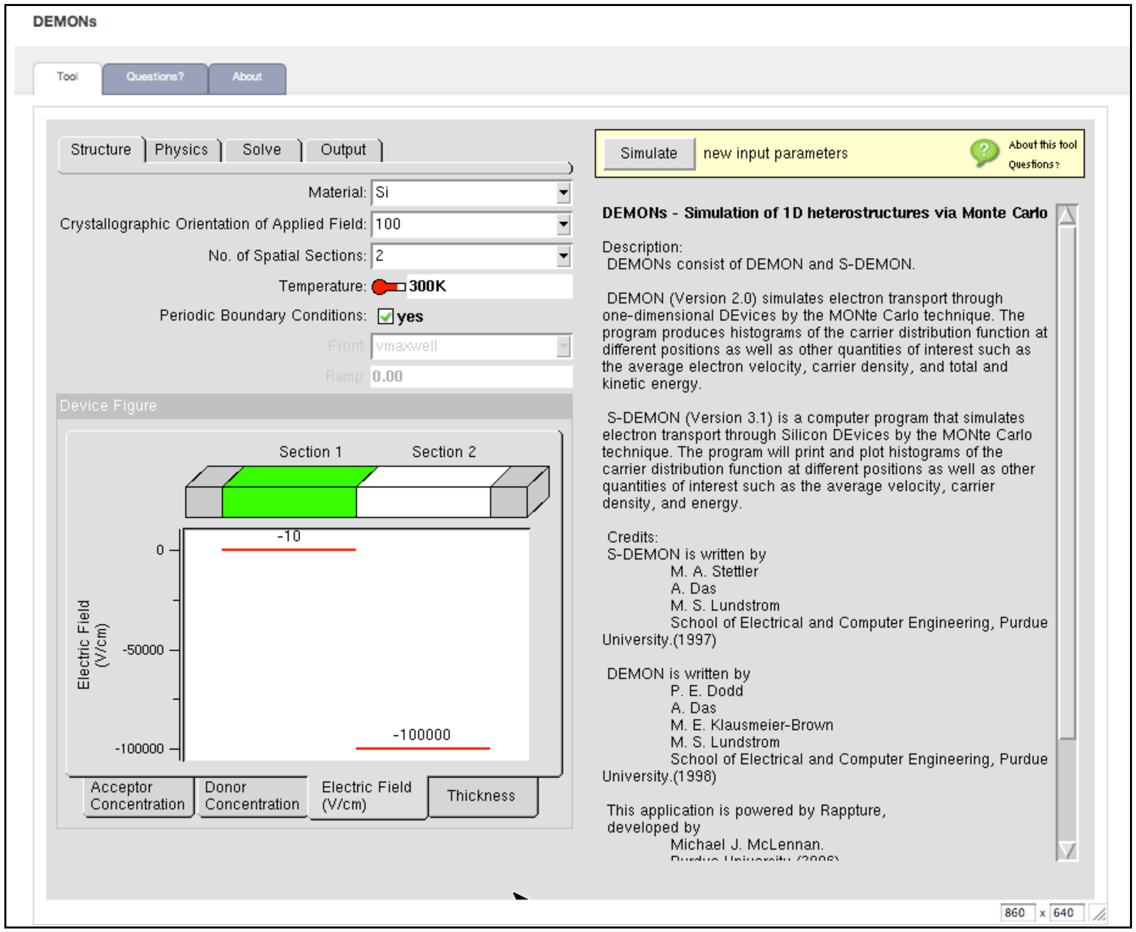
A familiar example



$$J_{nx} = n(x)q\langle \upsilon_x(x) \rangle$$

Example Monte Carlo simulations

DEMONs

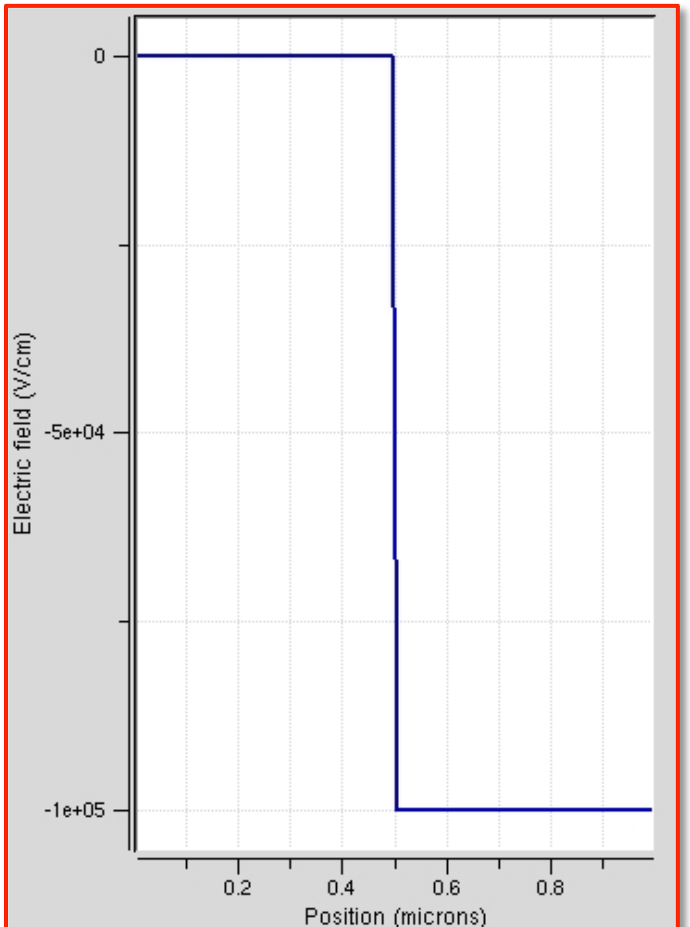


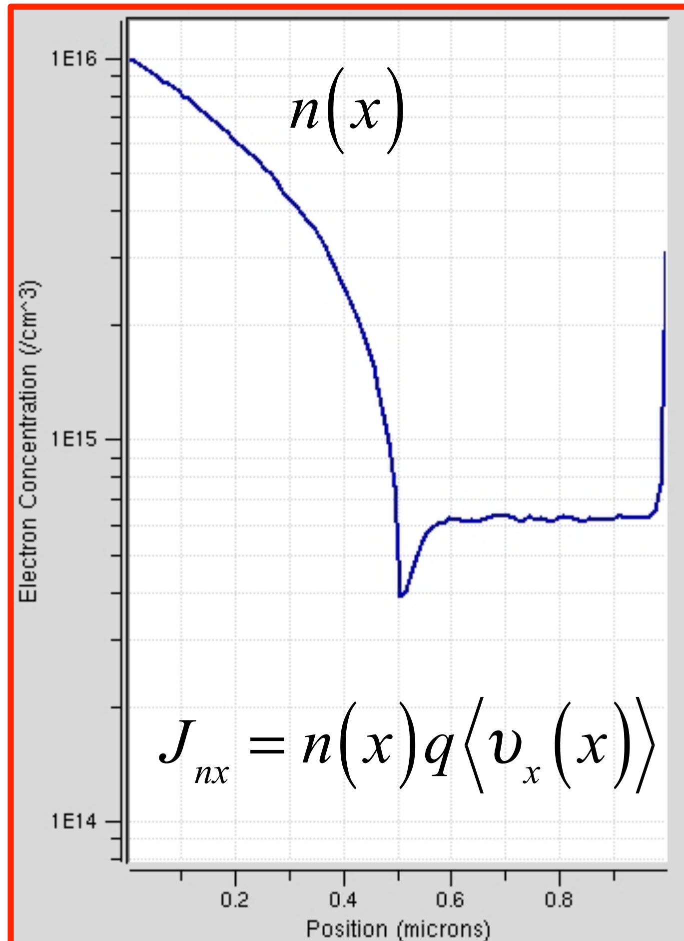
1D, steady-state Monte Carlo simulation for Si and GaAs

Piecewise constant electric field profiles.

http://nanohub.org/resources/1934

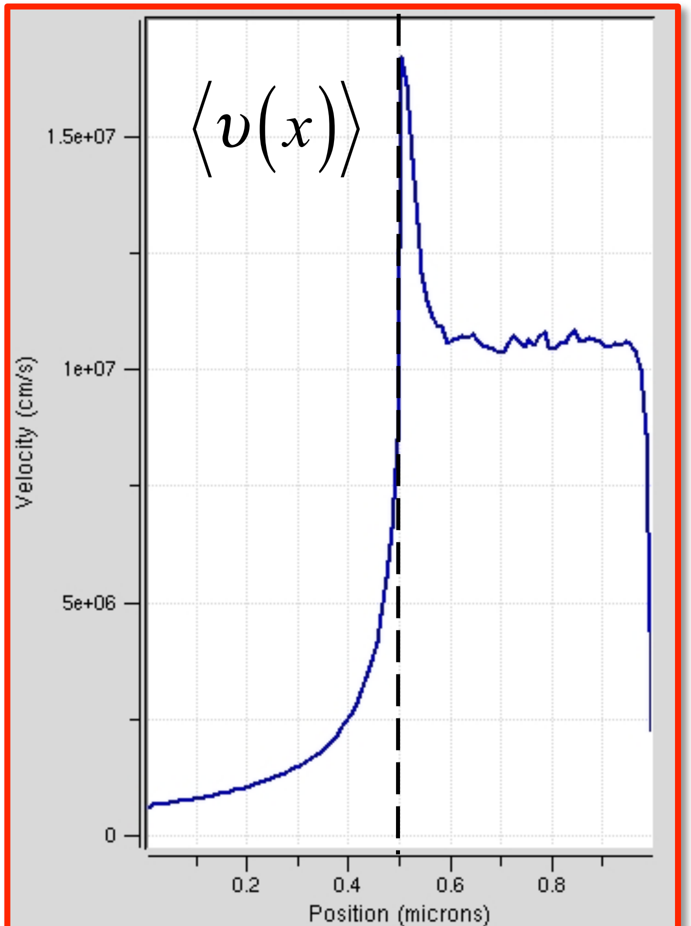
Low-high field structure

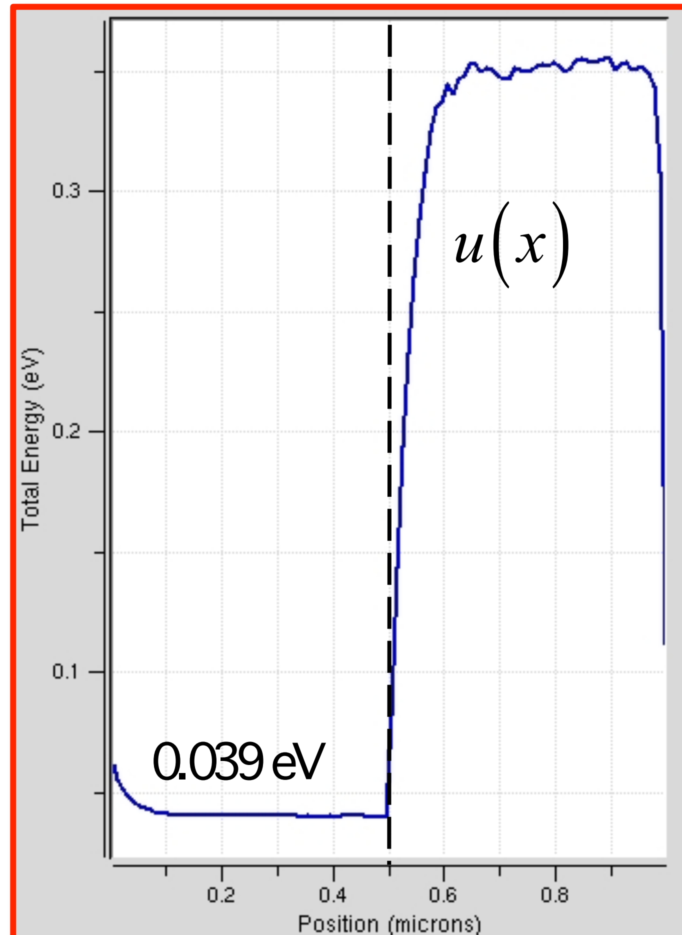




periodic boundary conditions

Low-high field structure

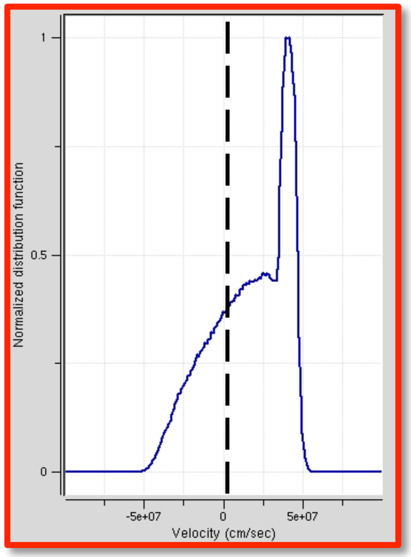


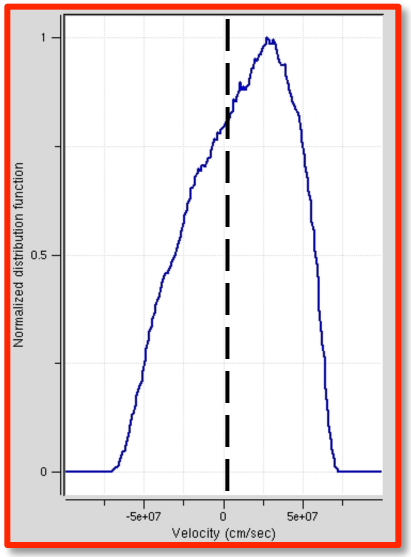


periodic boundary conditions

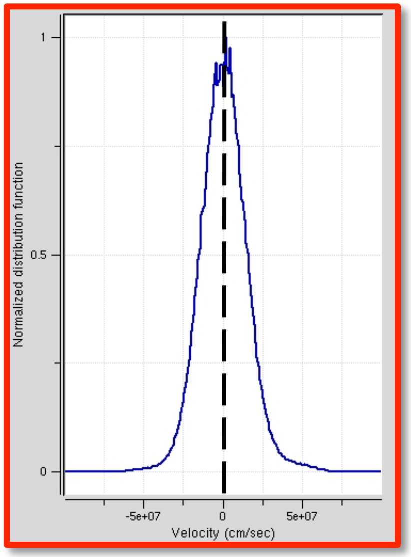
Velocity histograms

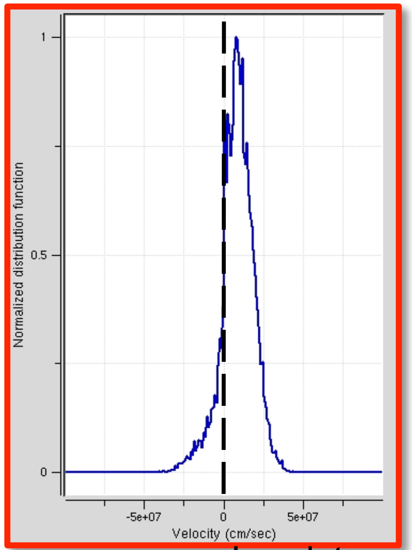
$\mathcal{E} = -10^5 \text{ V/cm}$





$\mathcal{E} = -10 \text{ V/cm}$

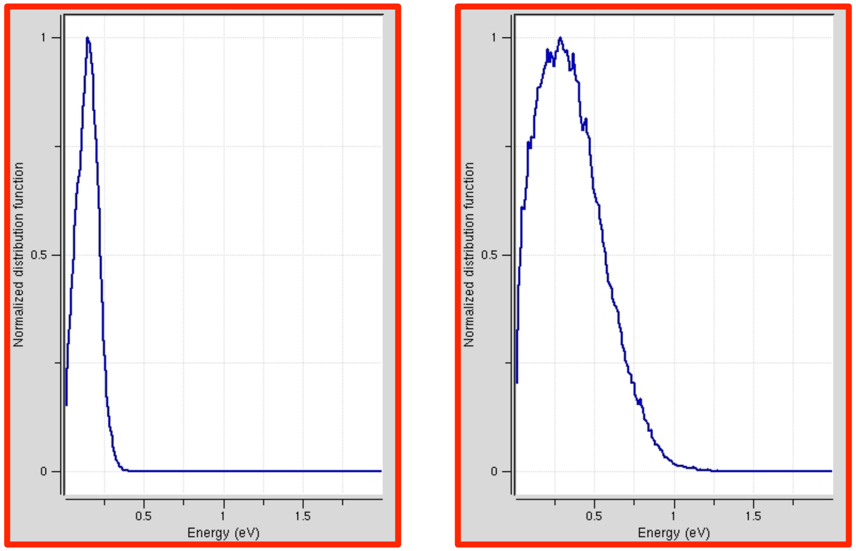




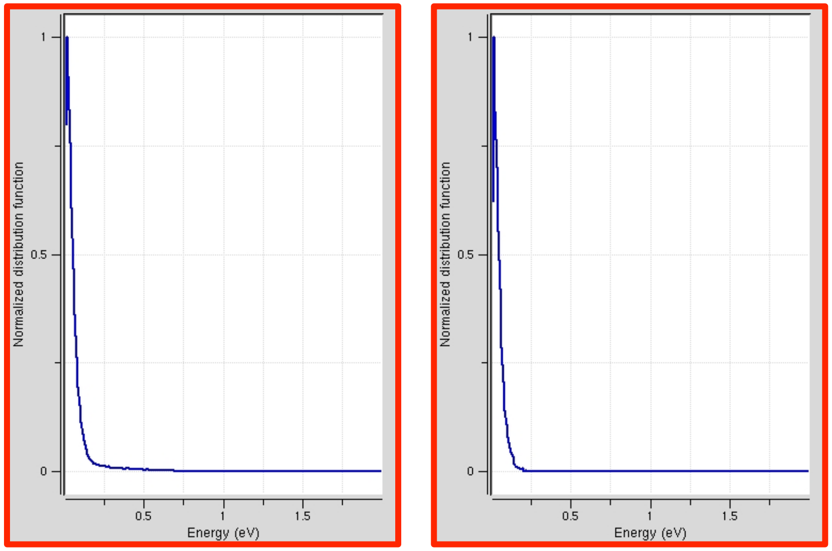
Energy histograms

$$n(E) = f(E)D(E)$$

$$\mathcal{E} = -10^5 \text{ V/cm}$$

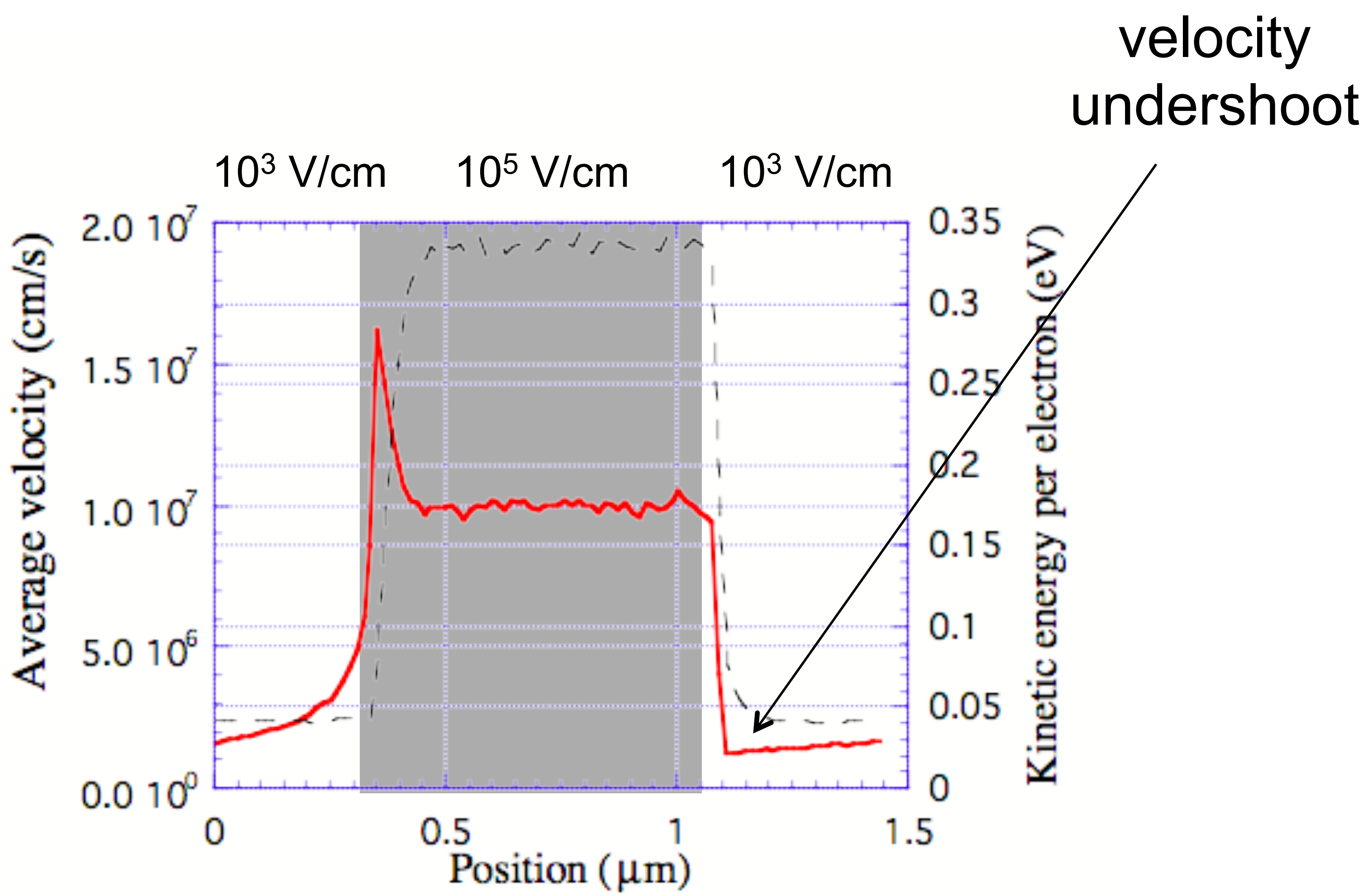


$$\mathcal{E} = -10 \text{ V/cm}$$

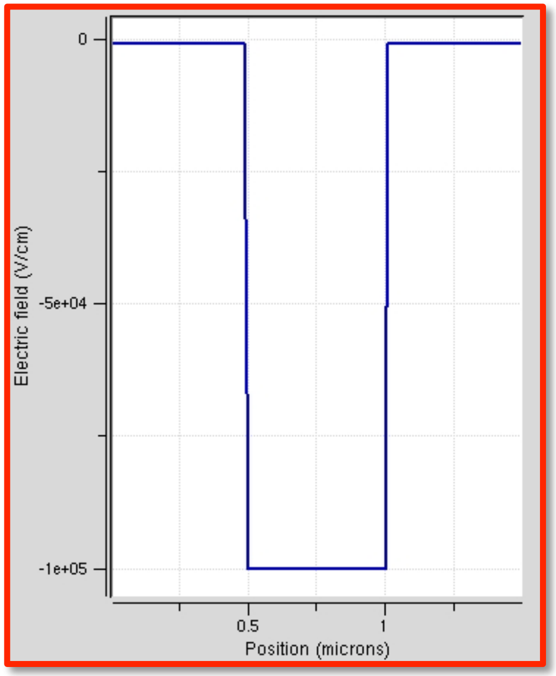


$$n(E) \propto e^{-E/k_BT}\sqrt{E}$$

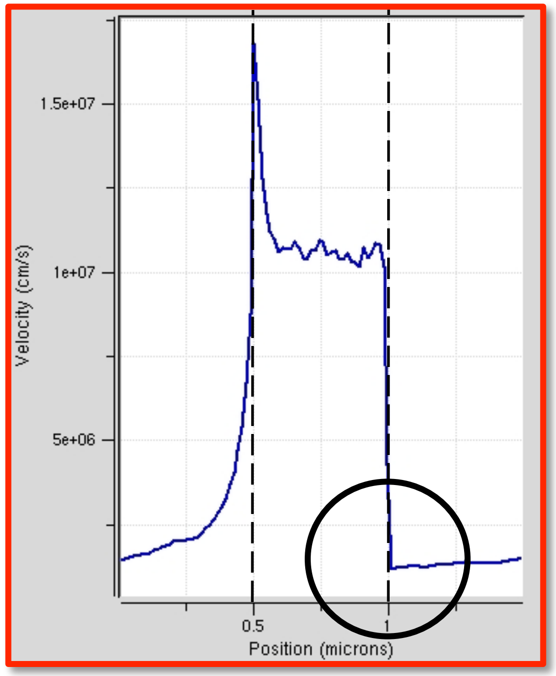
S.S. velocity overshoot in silicon



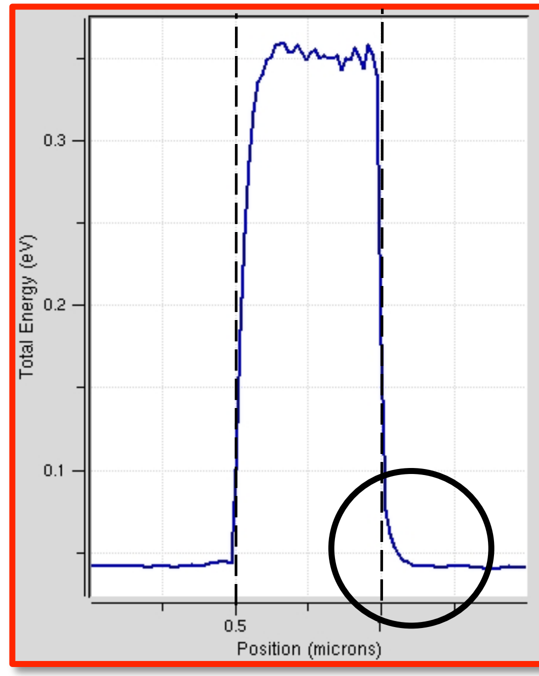
Low-high-low field structure



periodic boundary conditions

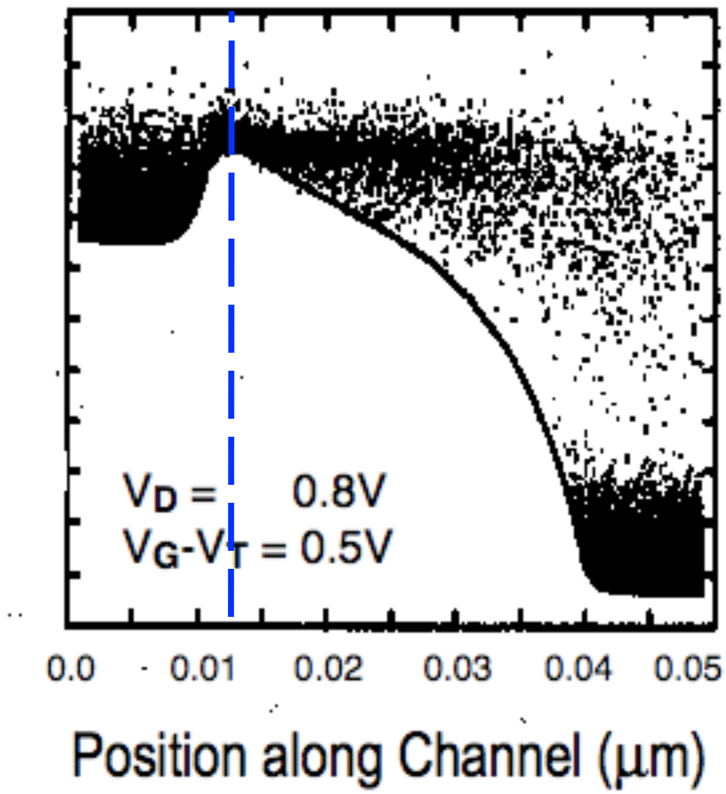


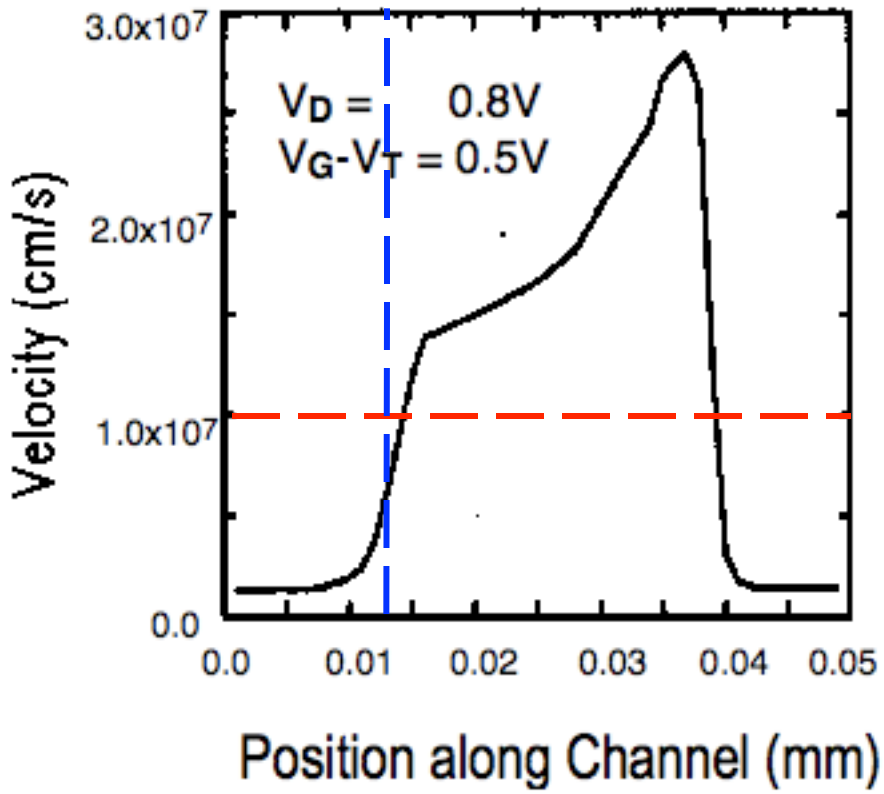
velocity undershoot



$u(x) > u_0$

Off-equilibrium nanoscale MOSFETs





Frank, Laux, and Fischetti, IEDM Tech. Dig., p. 553, 1992

Temporal vs. spatial transients

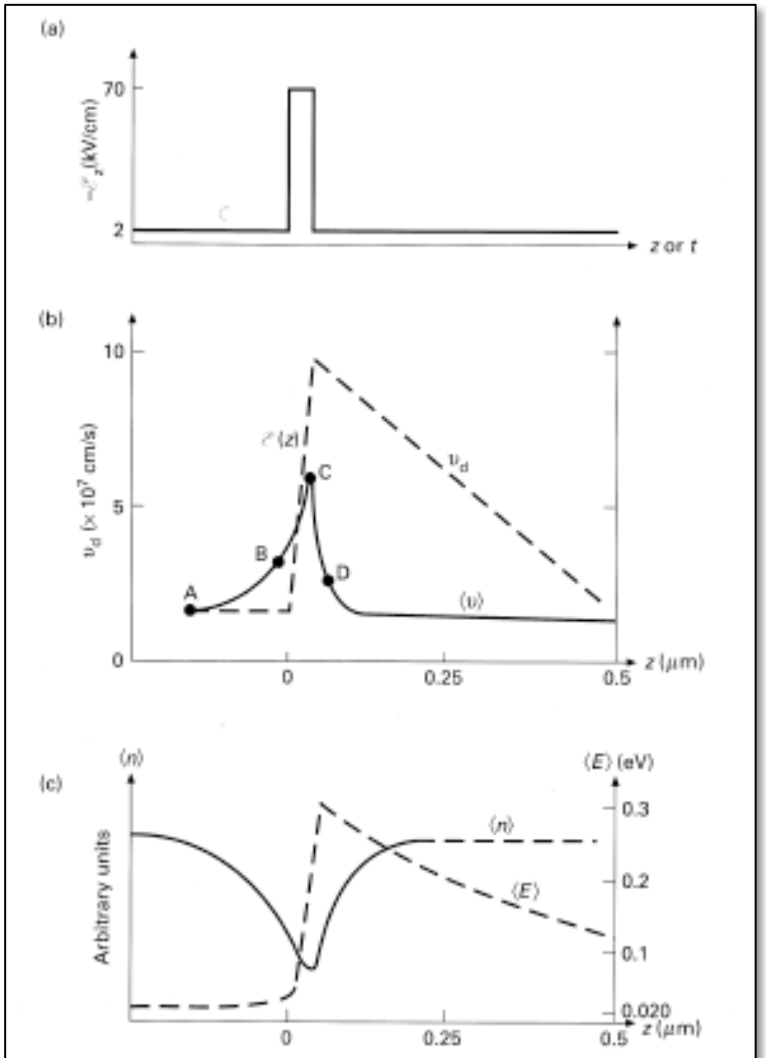


Fig. 8.13 (a) Applied electric field in time and space. (b) Average velocity versus position for a pulse applied in space (solid line) and time (dashed line). (c) Steady-state carrier density (solid line() and energy (dashed line.) The results were obtained by Monte Carlo simulation of electron transport in GaAs by E. Constant [8.10].

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$$z = \int_0^t \upsilon(t')\,dt'$$

Outline

1) Velocity overshoot
2) Steady-state, spatial transients
3) **Heterojunction launching ramps**
4) Repeated velocity overshoot?
5) Questions?

Ballistic launching ramps in HBTs

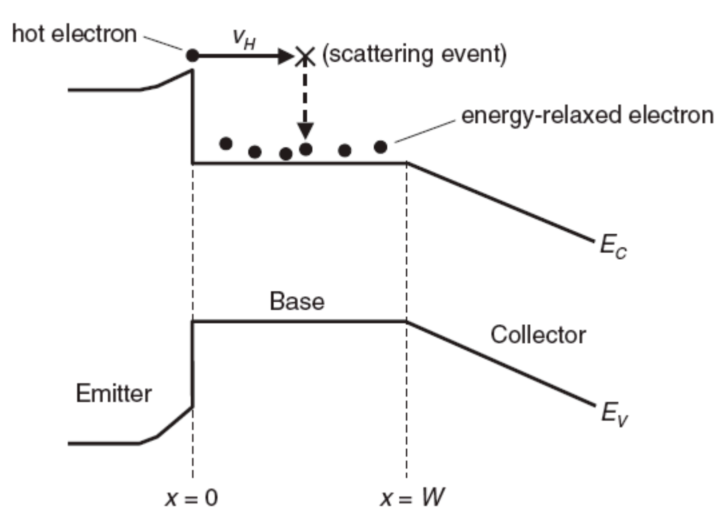


Fig. 1. Modeling of electron transport in the base of InP/InGaAs HBTs. A hot electron having a constant velocity of $v_H = 1 \times 10^8$ cm/s is assumed to be thermalized to an energy-relaxed electron after one scattering event. The energy-relaxed electron has a diffusivity D_T and a recombination life time τ_T.

Hiroki Nakajima, *Jap. J. of Appl. Phys.*, **46**, pp. 485–490, 2007.

Question: How do we experimentally tell whether base transport is ballistic or diffusive?

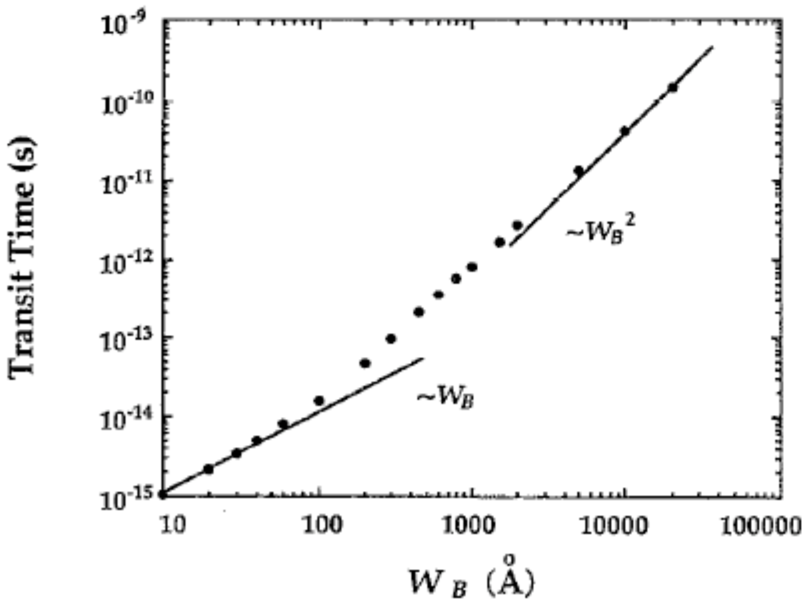
Answer: Look at the base current.

$$I_B \propto \frac{t_t}{\tau_n}$$

ballistic: $t_t = W_B / \upsilon_{ball}$

diffusive: $t_t = W_B^2 / 2D_n$

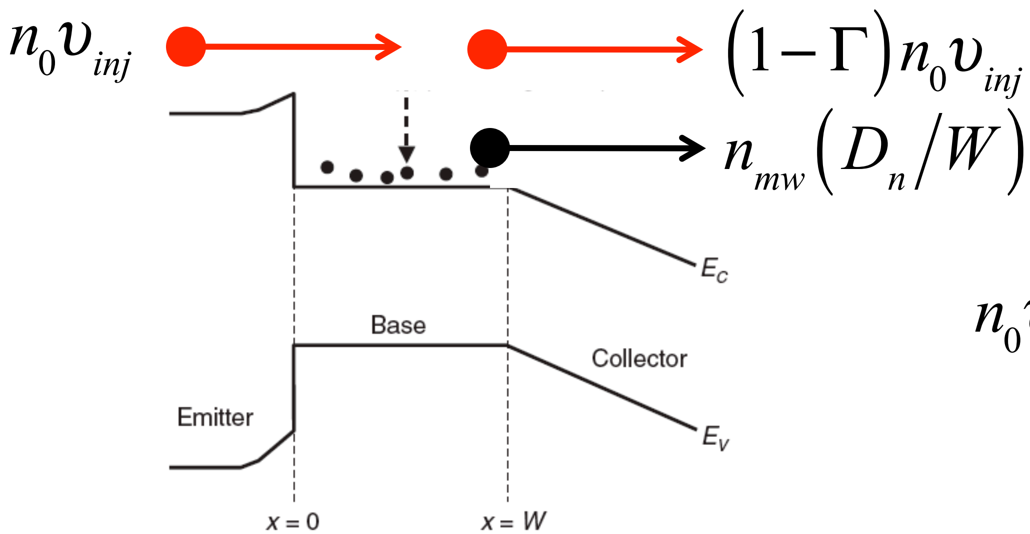
Base transit time scaling



~80% traverse a 300A base ballisticaly or quasi-ballisticaly

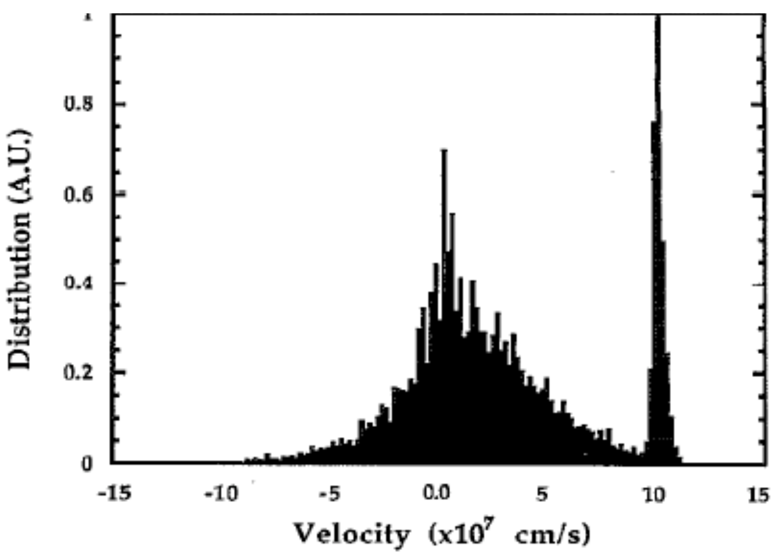
P.E. Dodd and M.S. Lundstrom, "Minority electron transport in InP/InGaAs heterojunction bipolar transostors," *Appl. Phys. Lett*., **61**, 27,1992

Base transit time scaling



$$n_0 \upsilon_{inj} = (1-\Gamma) n_0 \upsilon_{inj} + n_{mw} (D_n / W)$$

$$\frac{n_{mw}}{n_0} = \Gamma \frac{\upsilon_{inj}}{(D_n / W)}$$



Dodd and Lundstrom, *APL*, **61**, 27,1992

Outline

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Can VO be maintained over large distances?

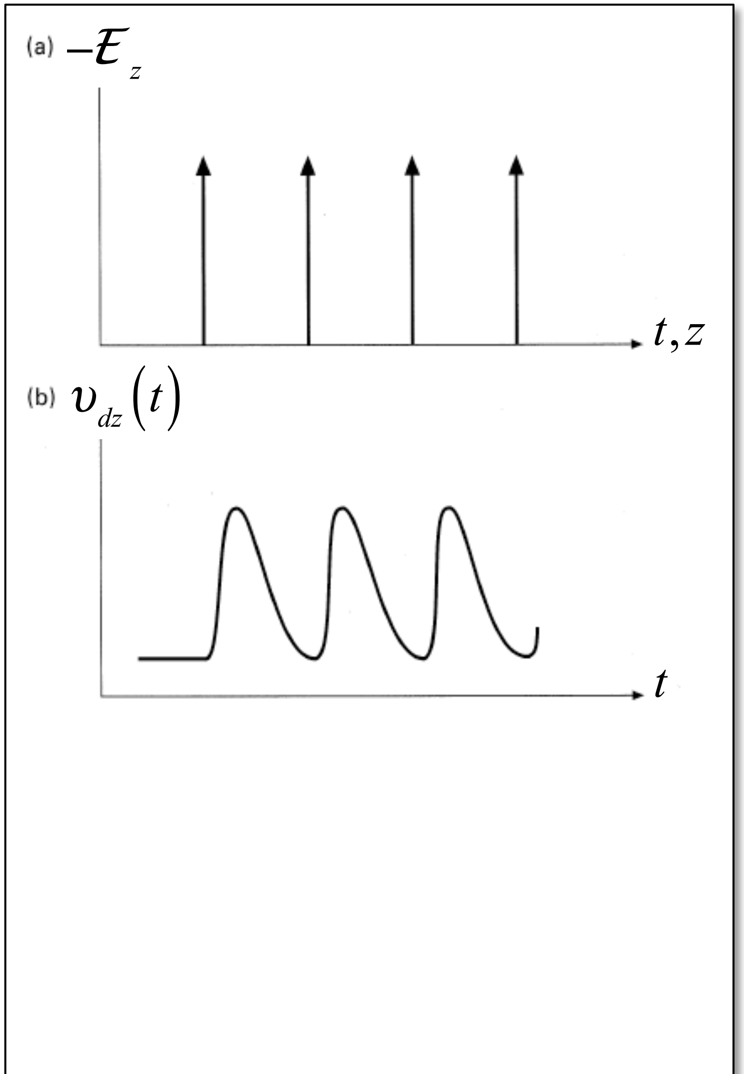

Fig. 8.14 (a) A series of electric field impulses in time or space. (b) Expected average velocity versus time profile. (c) Expected steady-state velocity vs. position profile.

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Questions

1) Velocity overshoot
2) Steady-state, spatial transients
3) Heterojunction launching ramps
4) Repeated velocity overshoot?
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