ECE-656: Fall 2009

Lecture 35: Ballistic Transport

Professor Mark Lundstrom
Electrical and Computer Engineering
Purdue University, West Lafayette, IN USA

first: let's finish up L34

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

temporal vs. spatial transients

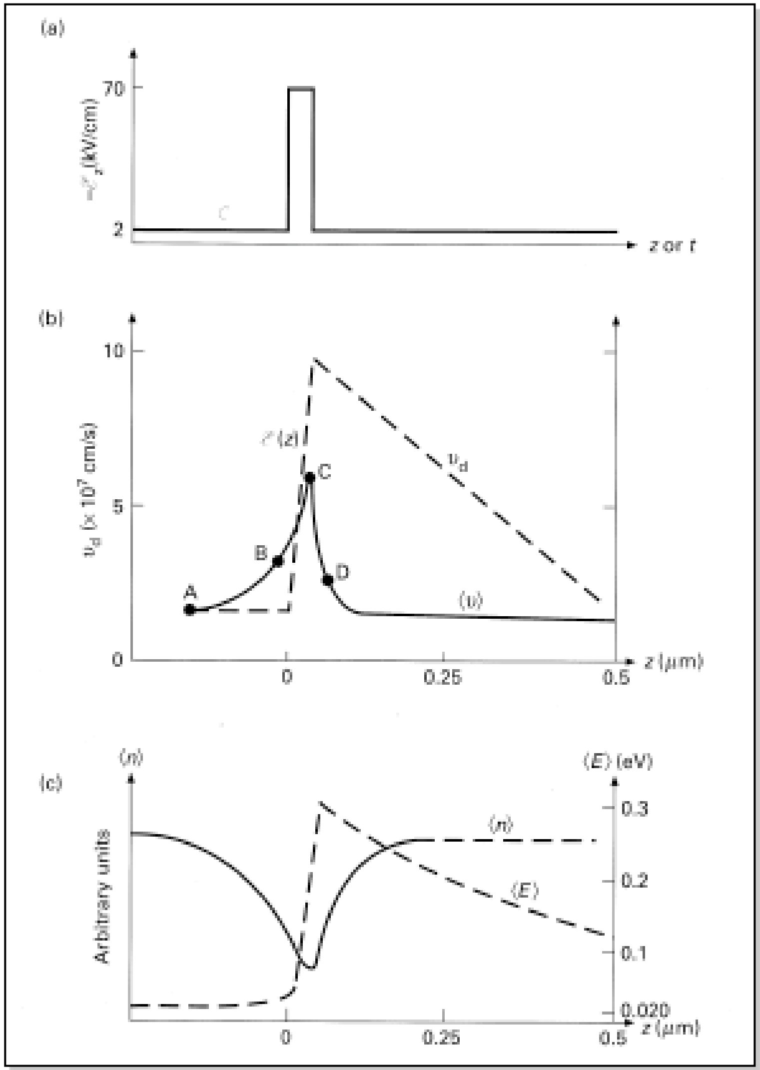


Fig. 8.13 (a) Applied electric field in time and space. (b) Average velocity versus position for a pulse applied in space (solid line) and time (dashed line). (c) Steady-state carrier density (solid line() and energy (dashed line.) The results were obtained by Monte Carlo simulation of electron transport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

p. 340 of Lundstrom

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

can VO be maintained over large distances?

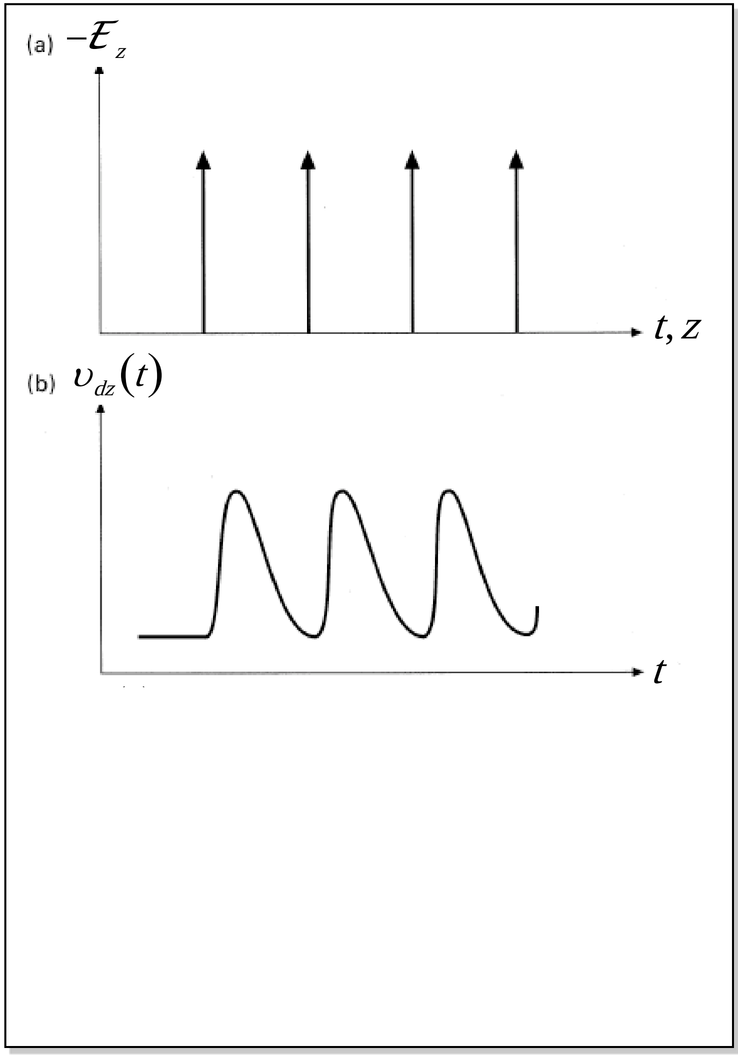


Fig. 8.14 (a) A series of electric field impulses in time or space. (b) Expected average velocity versus time profile. (c) Expected steady-state velocity vs. position profile.

p. 340 of Lundstrom

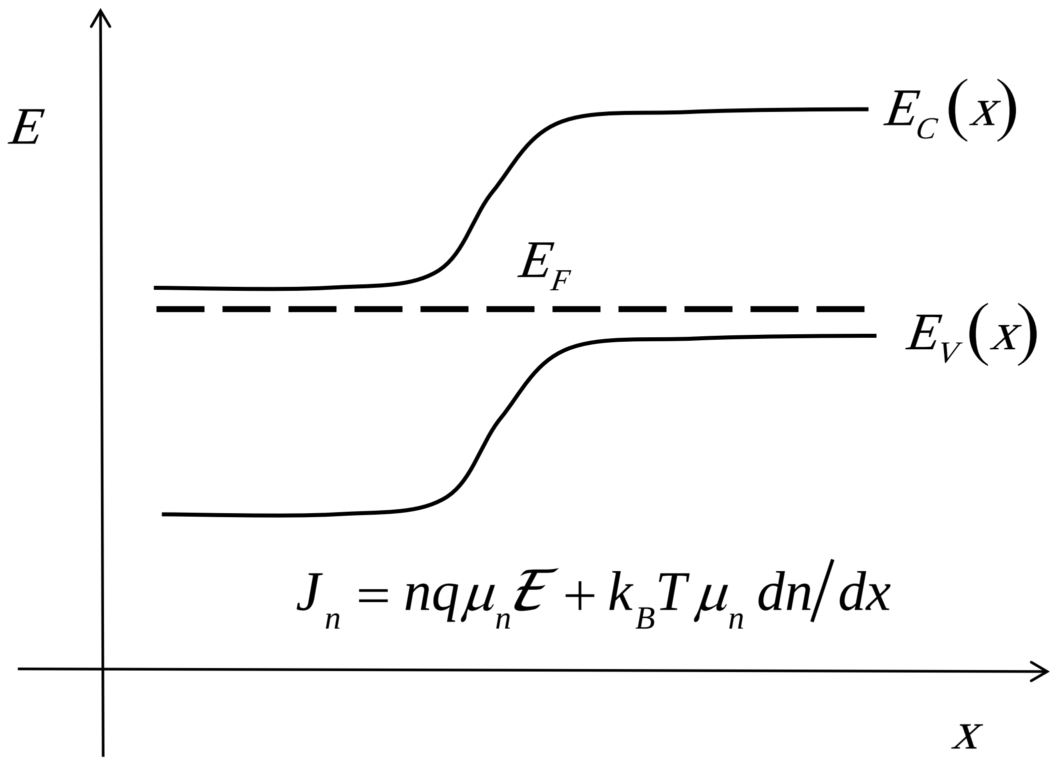
outline

1) Schottky barriers

2) Transport across a thin base

3) High-field collectors

a familiar problem with strong gradients



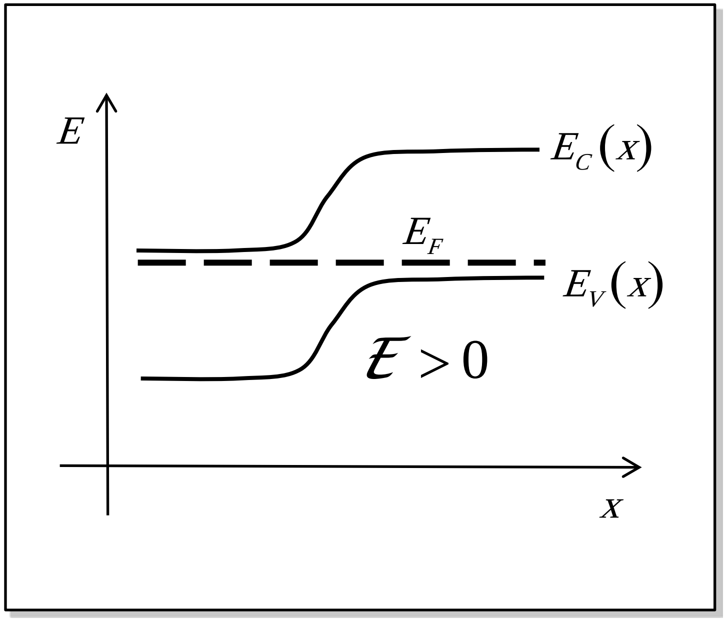
Should we use a field-dependent mobility?

$$\mu_n(\mathcal{E}) = \frac{\mu_n^o}{\sqrt{1+\left(\mathcal{E}/\mathcal{E}_C\right)^2}} \ ?$$

pn junction: energy balance

$$J_n \mathcal{E} \approx \frac{3}{2} \frac{n k_B \left(T_e - T_L\right)}{\left\langle \tau_E \right\rangle}$$ (ignores diffusion)

$$\frac{T_e}{T_L} = 1 + \left(\frac{\mathcal{E}}{\mathcal{E}_C}\right)^2 \qquad \mathcal{E}_C^2 = \frac{3 n k_B T_L \mathcal{E} / 2}{\left\langle \tau_E \right\rangle J_n}$$



1) equilibrium:

$$J_n = 0 \qquad \mathcal{E}_C \to \infty$$

$$T_e \to T_L \qquad \mu_n \to \mu_n^o$$

pn junction: under bias

$$\frac{T_e}{T_L} = 1 + \left(\frac{\mathcal{E}}{\mathcal{E}_C}\right)^2 \qquad \mathcal{E}_C^2 = \frac{3nk_B T_L \mathcal{E}/2}{\langle \tau_E \rangle J_n}$$

2) forward bias:

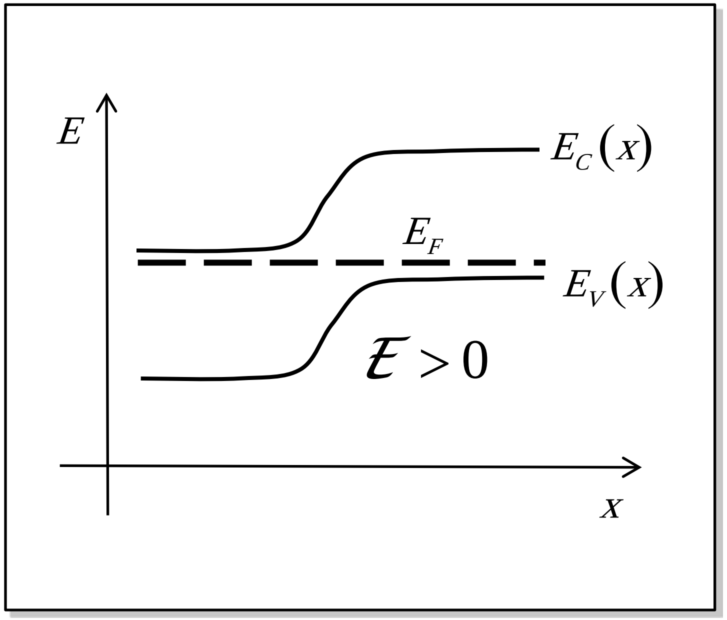
$$J_n < 0 \qquad \mathcal{E}_C^2 < 0$$

$$T_e < T_L \qquad \mu_n > \mu_n^o$$

3) reverse bias:

$$J_n > 0 \qquad \mathcal{E}_C^2 > 0$$

$$T_e > T_L \qquad \mu_n < \mu_n^o$$



FB: $J_n g\mathcal{E} < 0$ cooling

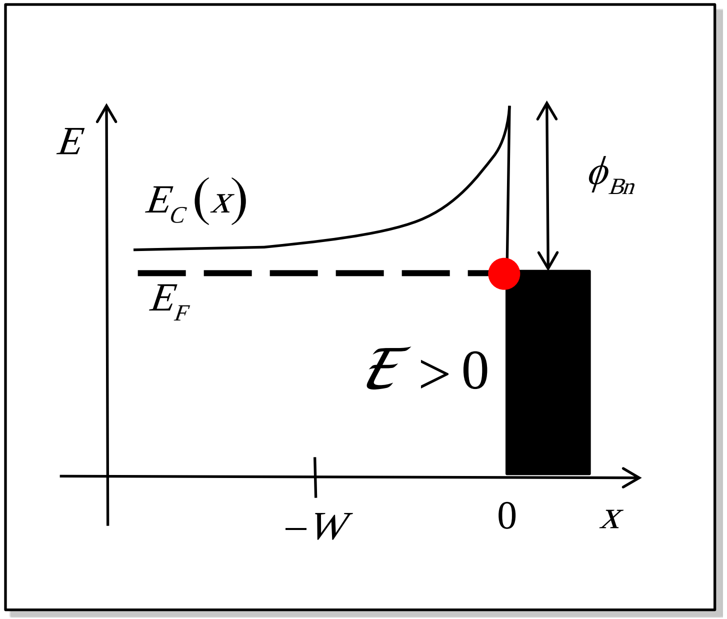
RB: $J_n g\mathcal{E} > 0$ heating

Schottky barriers: diffusion theory

solve:

$$J_n = nq\mu_n \mathcal{E} + k_B T \mu_n \, dn/dx$$

$$n(0) = n_0 \qquad n(-W) = N_D$$



result:

$$J(V_A) = qN_D \mu_n \mathcal{E}(0) e^{-q\phi_{Bn}/k_B T}\left(e^{qV_A/k_B T} - 1\right)$$

$$\mu_n \le \mu_n^o$$

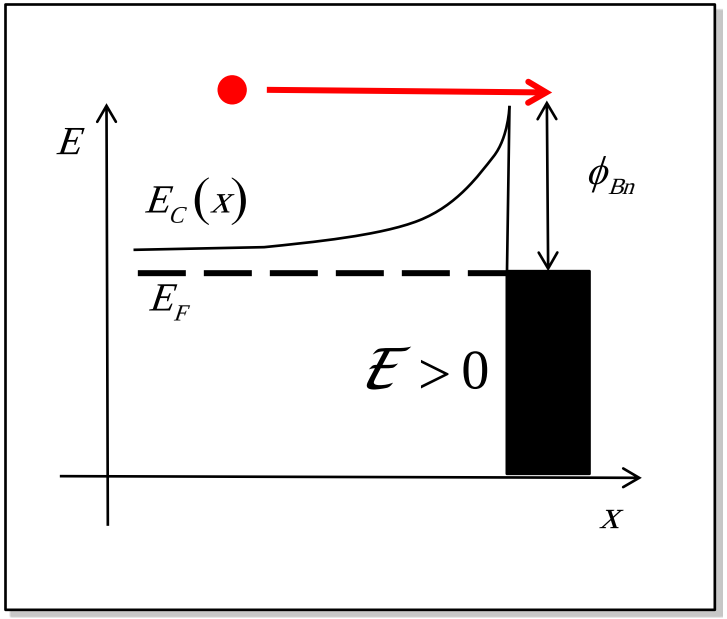
Schottky barriers: TE theory

assume:

ballistic transport

result:

$$J(V_A) = q\frac{N_D}{2}\upsilon_T e^{-q\phi_{Bn}/k_BT}\left(e^{qV_A/k_BT} - 1\right)$$



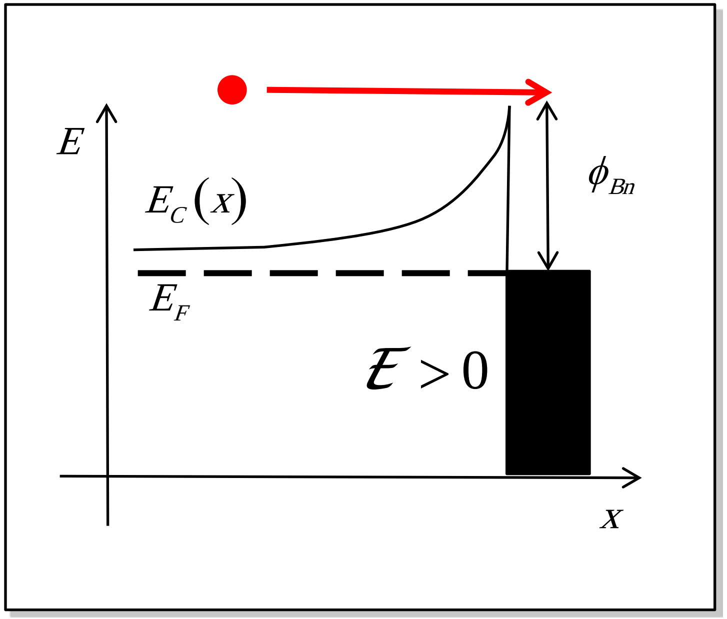
DD fails when: $\mu_n \mathcal{E}(0) > \frac{\upsilon_T}{2}$

but why, what went wrong?

Schottky barriers: aside

TE result:

$$J(V_A) = q\frac{N_D}{2}\upsilon_T e^{-q\phi_{Bn}/k_BT}\left(e^{qV_A/k_BT} - 1\right)$$



This result can be easily obtained by solving the ballistic BTE.
See Lecture 13.

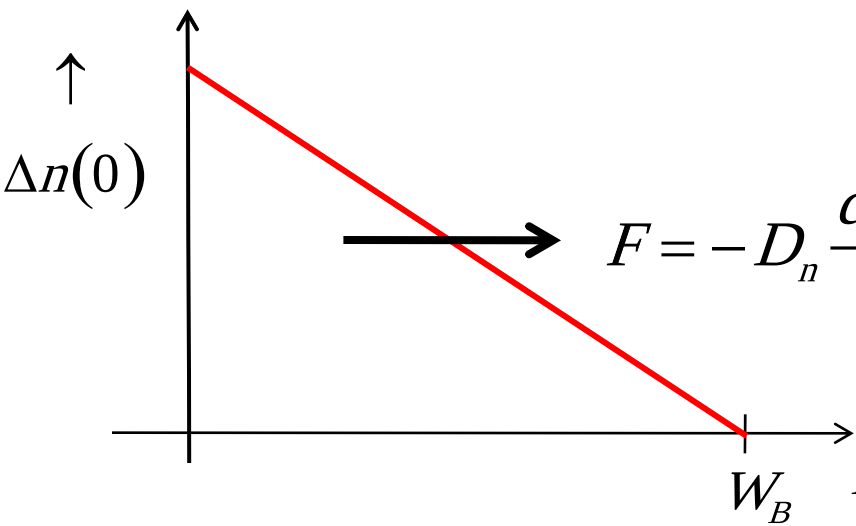
outline

1) Schottky barriers

2) Transport across a thin base

3) High-field collectors

diffusion across a thin base



$$F = -D_n \frac{d\Delta n}{dx}$$

$$F = D_n \frac{\Delta n(0)}{W_B} = \Delta n(0)\,\upsilon_{diff}$$

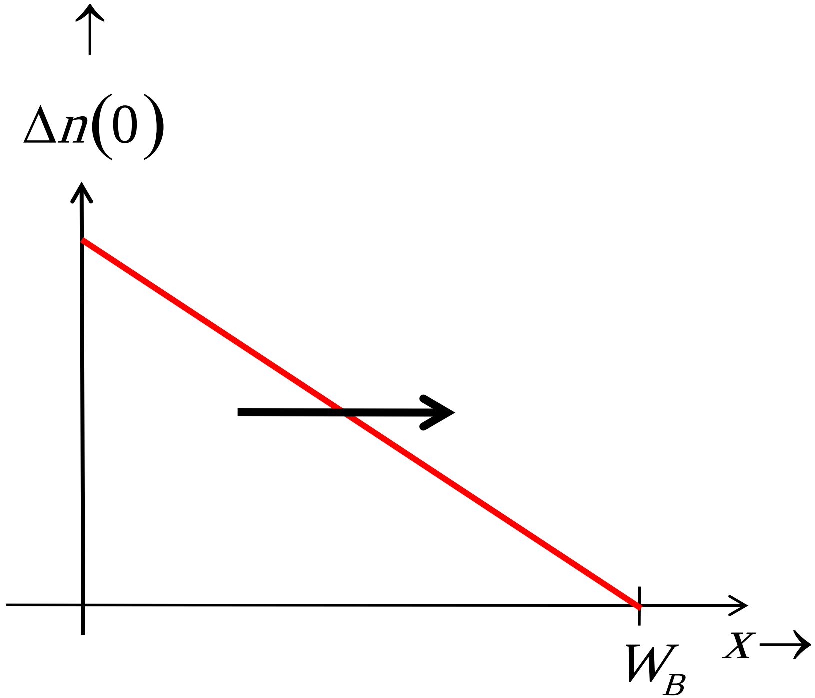
$$\upsilon_{diff} = \frac{D_n}{W_B} << \upsilon_T$$

$$D_n = \frac{\upsilon_T \lambda_0}{2}$$

$$W_B >> \lambda_0$$

Fick’s Law describes diffusion across bases that are many mfps long.

why does DD fail?



$$J_n = nq\mu_n \mathcal{E} + 2\mu_n\, d\left(nu_{xx}\right)/dx$$

$$u_{xx} = \frac{k_B T}{2} + \frac{1}{2} m^* \upsilon_{dx}^2 \qquad J_{nx} = -qn\upsilon_{dx}$$

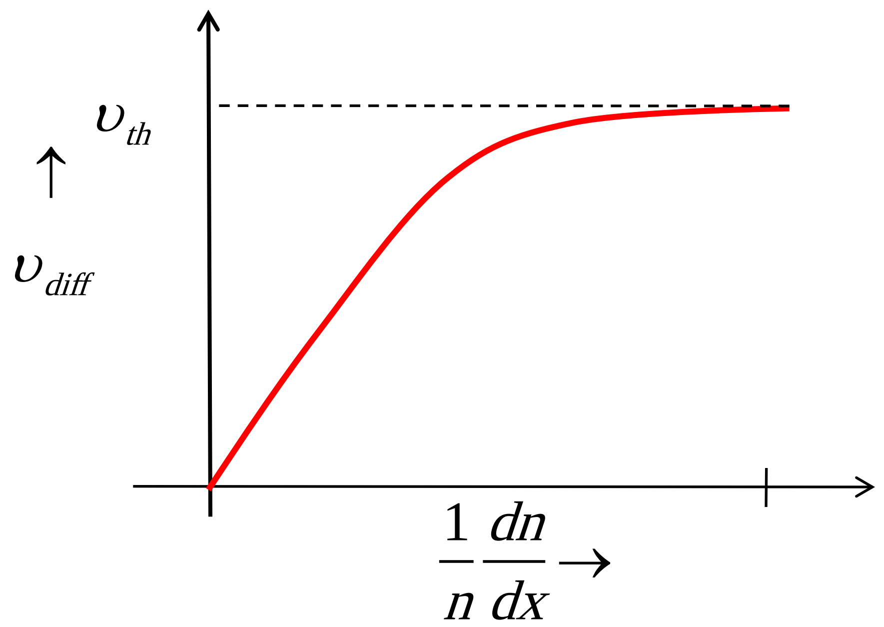
$$J_{nx}^2 + \frac{n^2 q^2}{2\mu_n m^* \left(dn/dx\right)} J_{nx} - \frac{n^2 q^3 D_n}{2\mu_n m^*} = 0$$

$i)\quad dn/dx \rightarrow 0 \qquad J_{nx} \rightarrow qD_n\, dn/dx$

$ii)\quad dn/dx \rightarrow \infty \qquad J_{nx} \rightarrow qn\sqrt{k_B T/2m^*} = qn\upsilon_{th}$

$$D_n \frac{1}{n}\frac{dn}{dx} < \upsilon_{diff} < \upsilon_{th}$$

diffusion velocity vs. conc. gradient

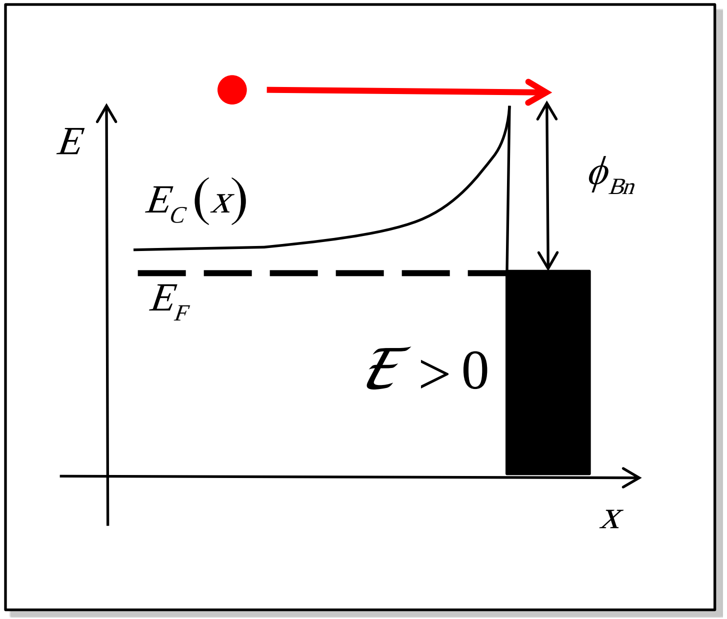


$$J_{nx} = qD_{eff}\frac{dn}{dx} = nq\left(D_{eff}\frac{1}{n}\frac{dn}{dx}\right)$$

D_{eff} must be reduced for high concentration gradients.

Schottky barriers

$$\left|\frac{dn}{dx}\right|$$ is very large.



$$D_{eff} < D^o$$

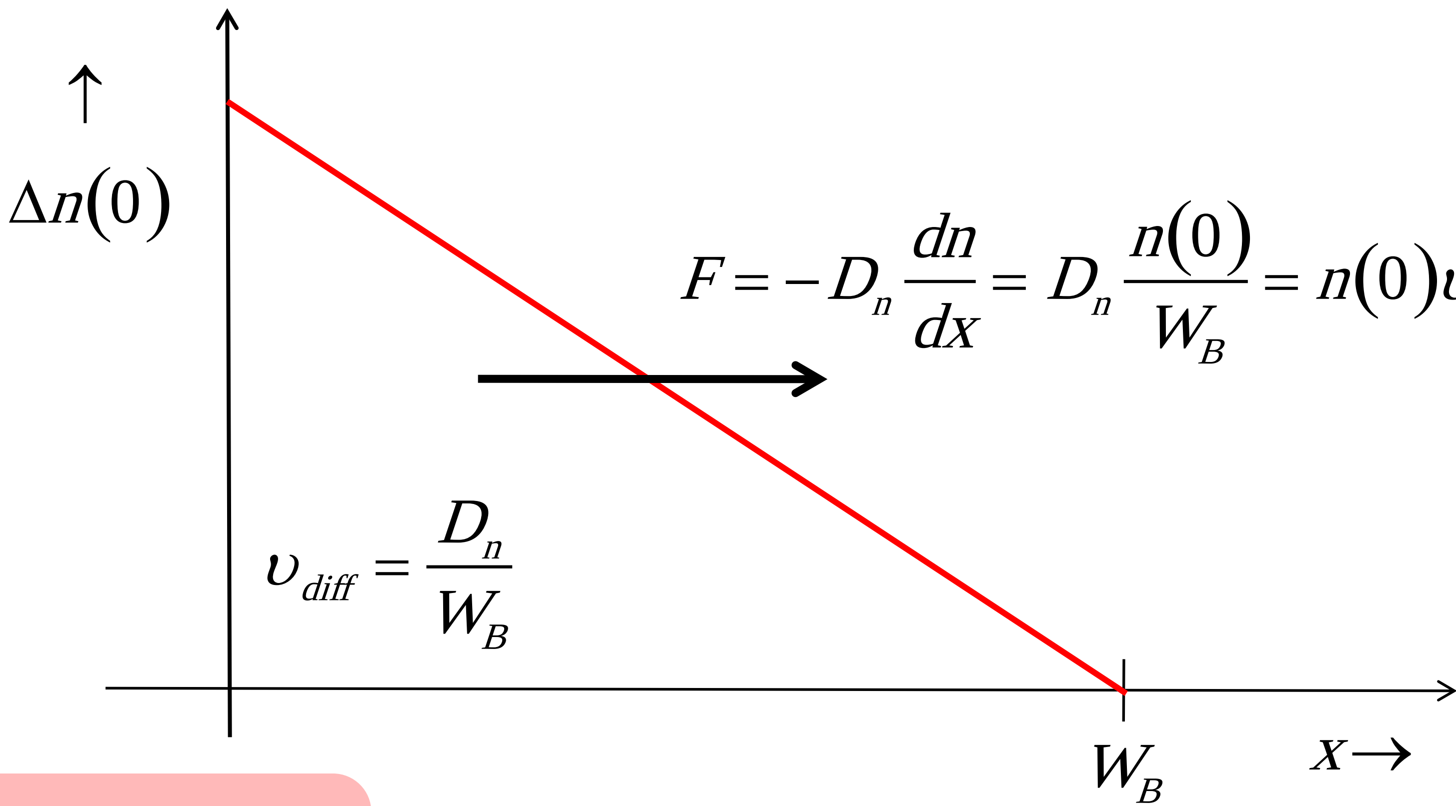
$$\mu_{eff} = \frac{D_{eff}}{k_B T/q} < \mu^o$$

The mobility, μ, ***should*** be reduced in a forward-biased PN junction even though the carrier are not heated.

DD fails when: $\mu_n \mathcal{E}(0) > \frac{\upsilon_T}{2}$

$$\mu_n \mathcal{E}(0) \rightarrow \upsilon_{th}$$

is Fick's Law wrong?



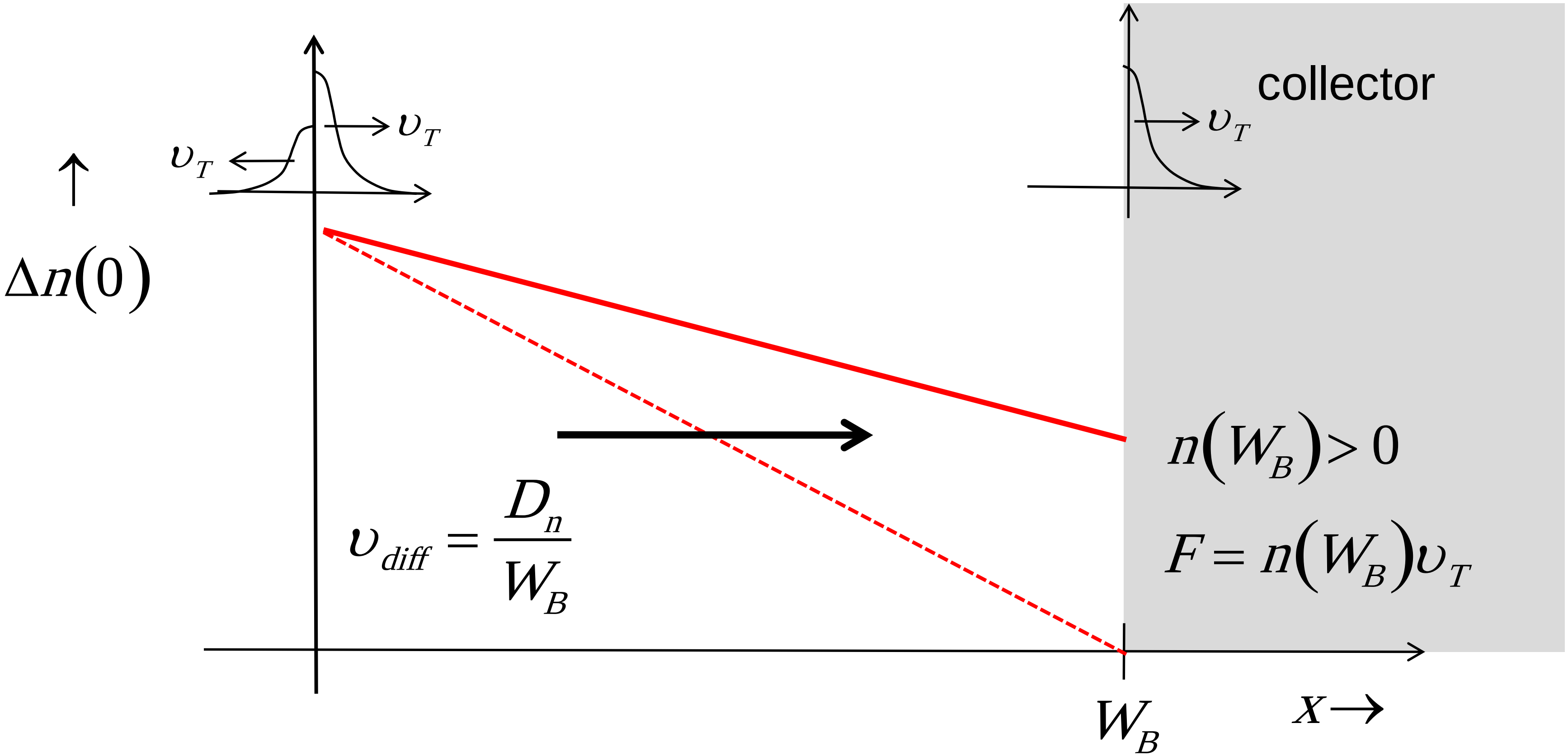
$$F = -D_n \frac{dn}{dx} = D_n \frac{n(0)}{W_B} = n(0)\upsilon_{diff}$$

$$\upsilon_{diff} = \frac{D_n}{W_B}$$

$$\upsilon_{diff} = \frac{D_n}{W_B} << \upsilon_T$$

We just showed that we can get around this problem by reducing *D_n*, but….

thin base transport again



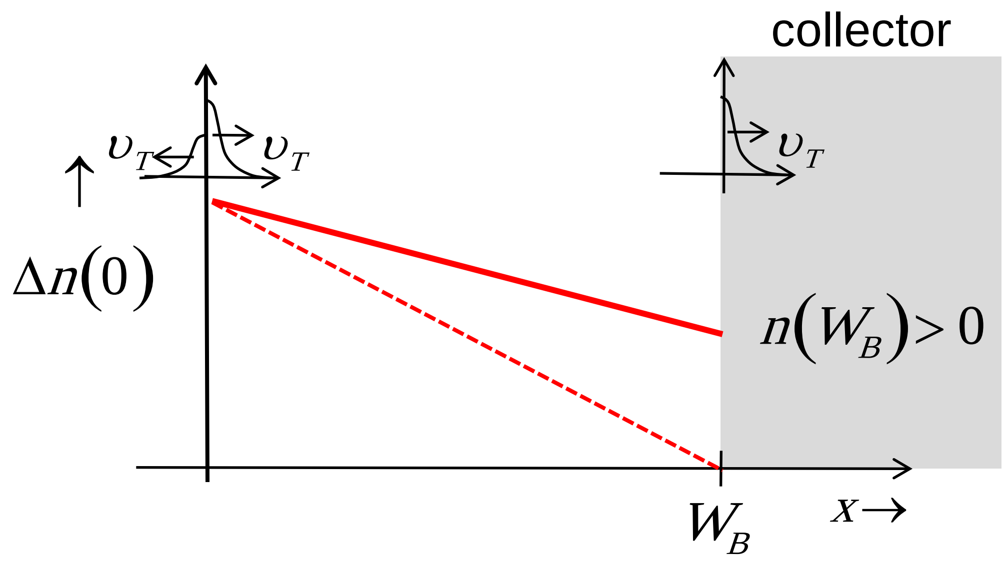
Fick's Law in a thin base

$$F = D_n \frac{n(0) - n(W_B)}{W_B}$$

$$F = n(W_B)\upsilon_T$$

$$n(W_B) = \frac{n(0)}{1 + \upsilon_T / (D_n / W_B)}$$

$$F = n(0)\frac{D_n}{W_B} \times \frac{1}{1 + \frac{(D_n / W_B)}{\upsilon_T}}$$

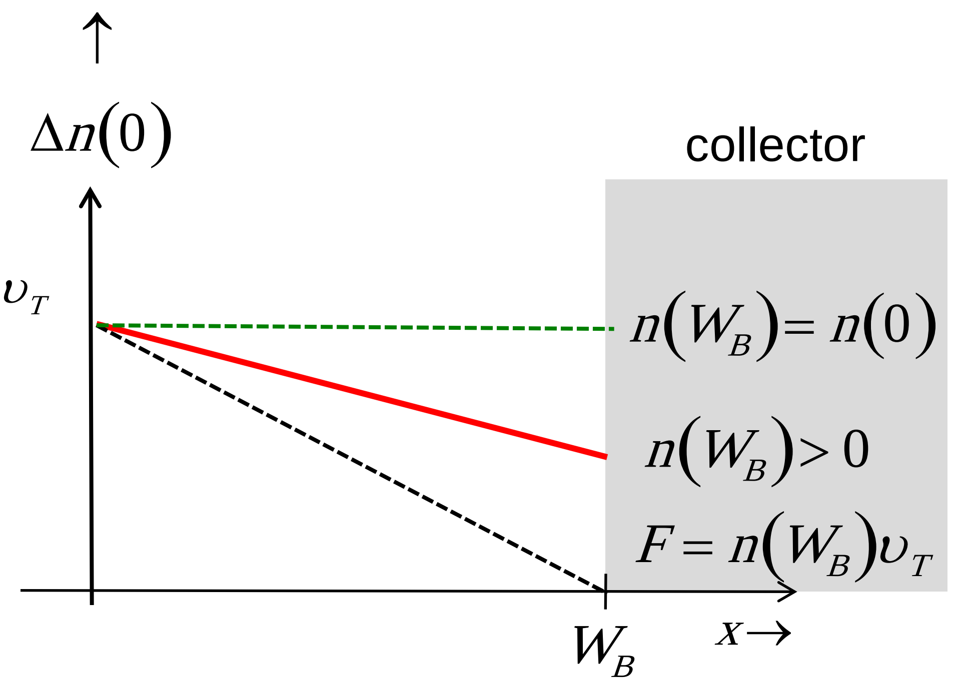


Fick's Law

$$F = n(0)\frac{D_n}{W_B} \times \frac{1}{1 + \frac{(D_n/W_B)}{\upsilon_T}}$$

$$\frac{D_n}{W_B} << \upsilon_T \quad F \to n(0)\frac{D_n}{W_B}$$

$$\frac{D_n}{W_B} >> \upsilon_T \quad F \to n(0)\upsilon_T$$



No need to reduce *D* because *dn*/*dx* → 0 when $W_B << \lambda$

Fick's Law always holds – no matter how small the base!

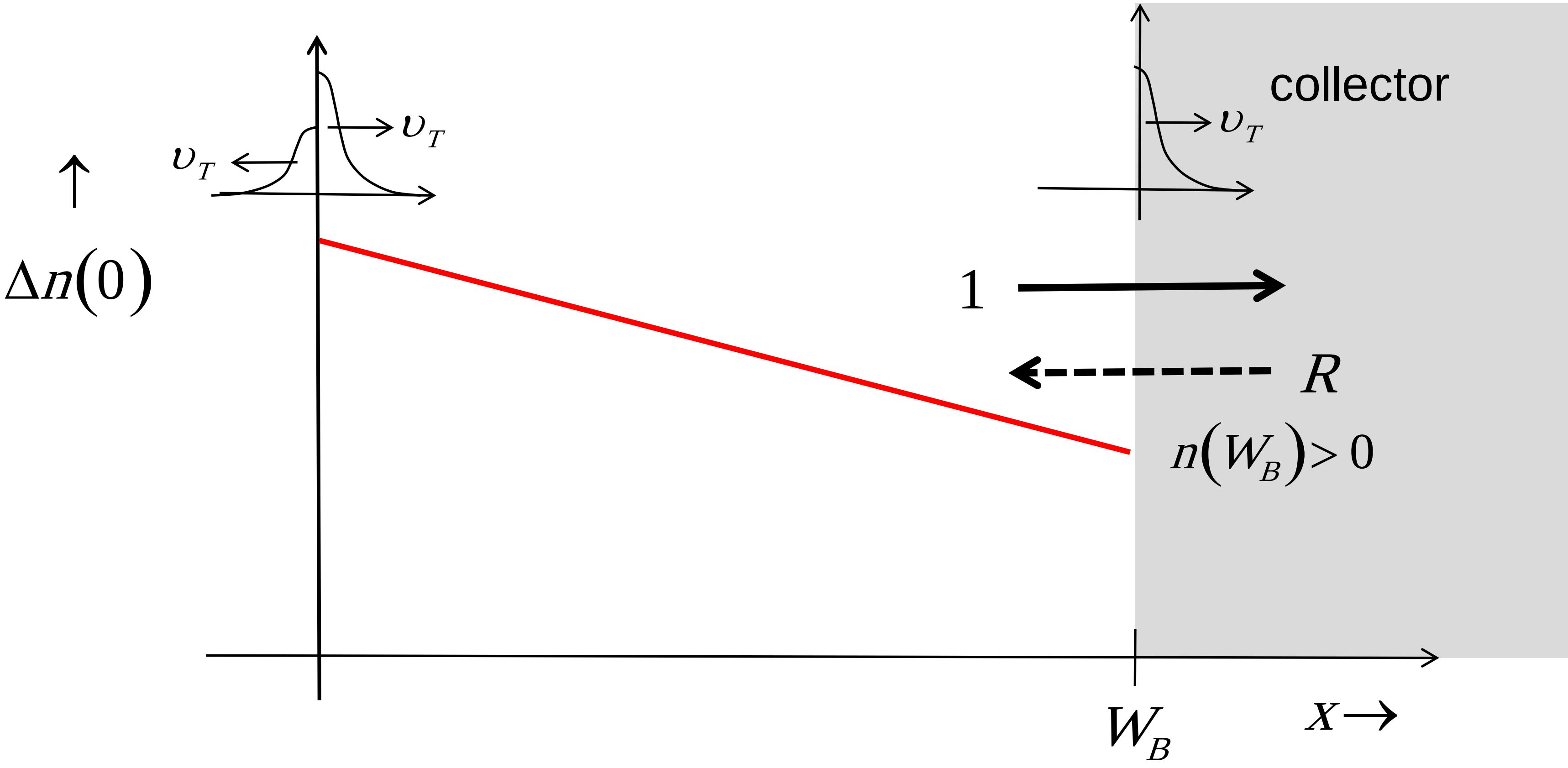
outline

1) Schottky barriers

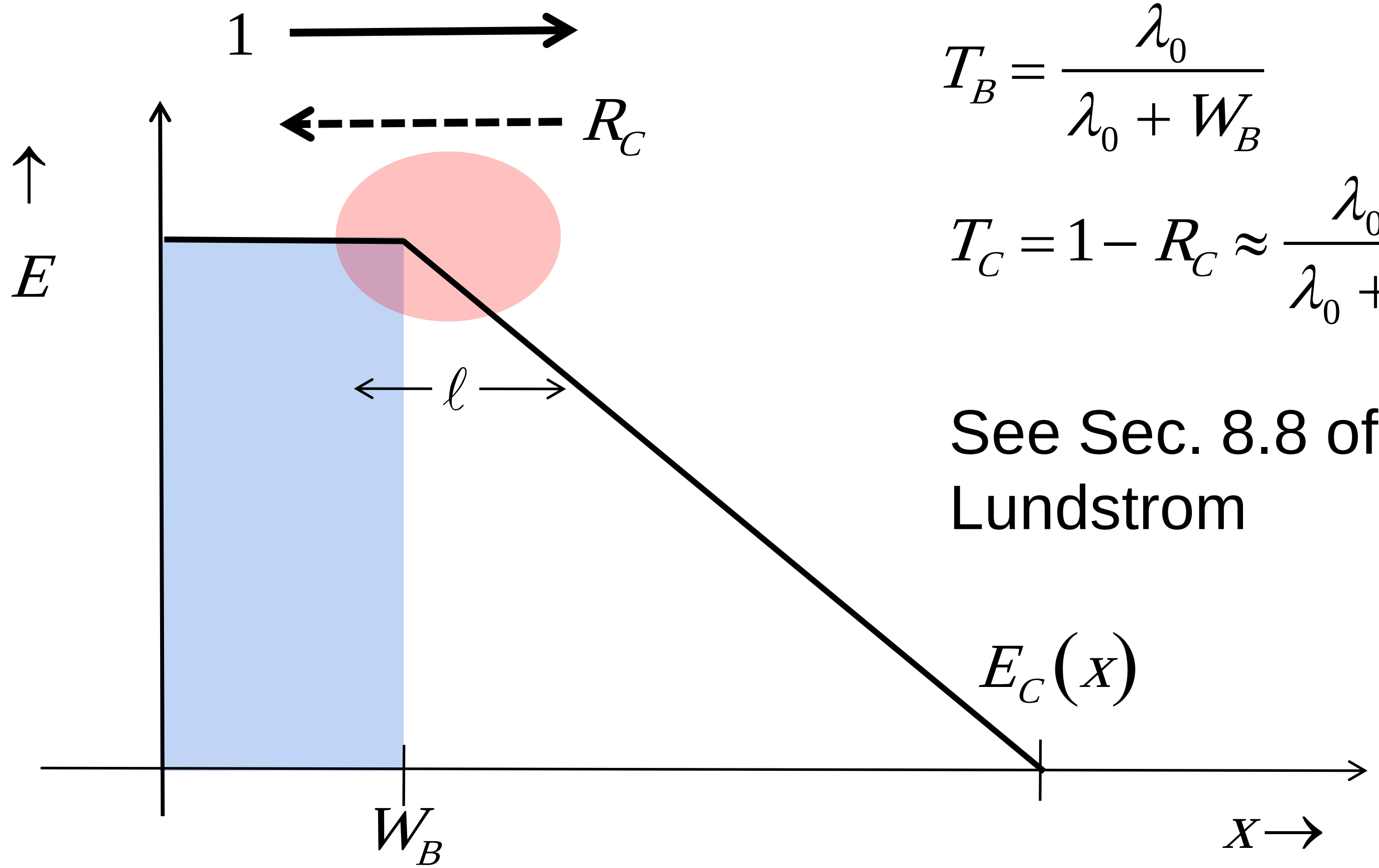
2) Transport across a thin base

3) High-field collectors

how good is the collector?



backscattering from the collector



$$T_B = \frac{\lambda_0}{\lambda_0 + W_B}$$

$$T_C = 1 - R_C \approx \frac{\lambda_0}{\lambda_0 + l}$$

See Sec. 8.8 of Lundstrom

questions

1) Schottky barriers
2) Transport across a thin base
3) High-field collectors

Question & Answer 1