

information about the final exam

Final Exam:

Tuesday, Dec. 13, 8-10AM EE-115

Comprehensive

Open book (Lecture notes + Fund. Carrier Transport)

Part 1: short answer (50 points)

Part 2: (50 points) questions about a paper to be handed out Monday, Dec. 5. Will be due Tuesday, Dec. 13 at 8AM.

Please remember to complete your ECE-656 course evaluations by before 11pm Sunday, December 11.

no class on Wed. Dec. 9th

Instead view:

ECE 612 Lecture 10: The Ballistic MOSFET (Fall 2006)

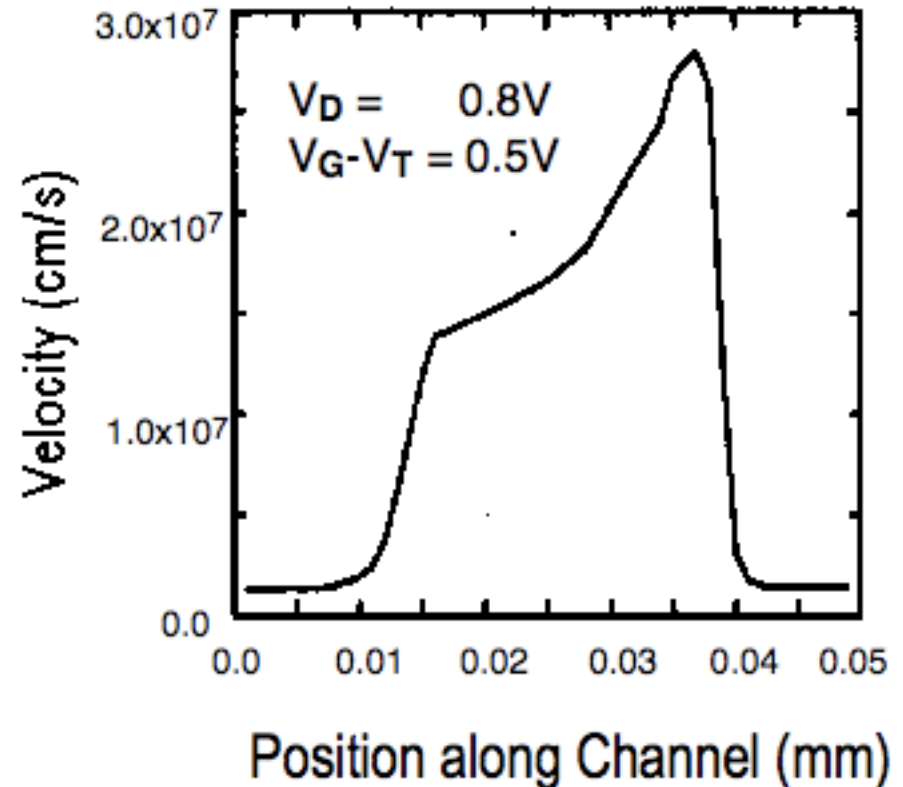
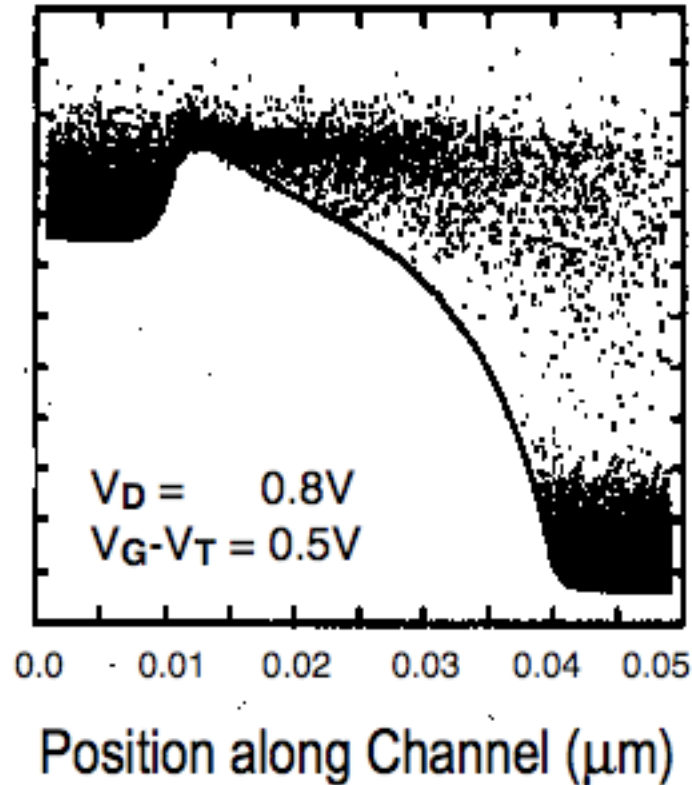
<http://nanohub.org/resources/1794>

ECE-656: Fall 2011

**Lecture 39:
Ballistic Transport
in Devices: I**

Mark Lundstrom
Purdue University
West Lafayette, IN USA

still “diffusive” transport



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

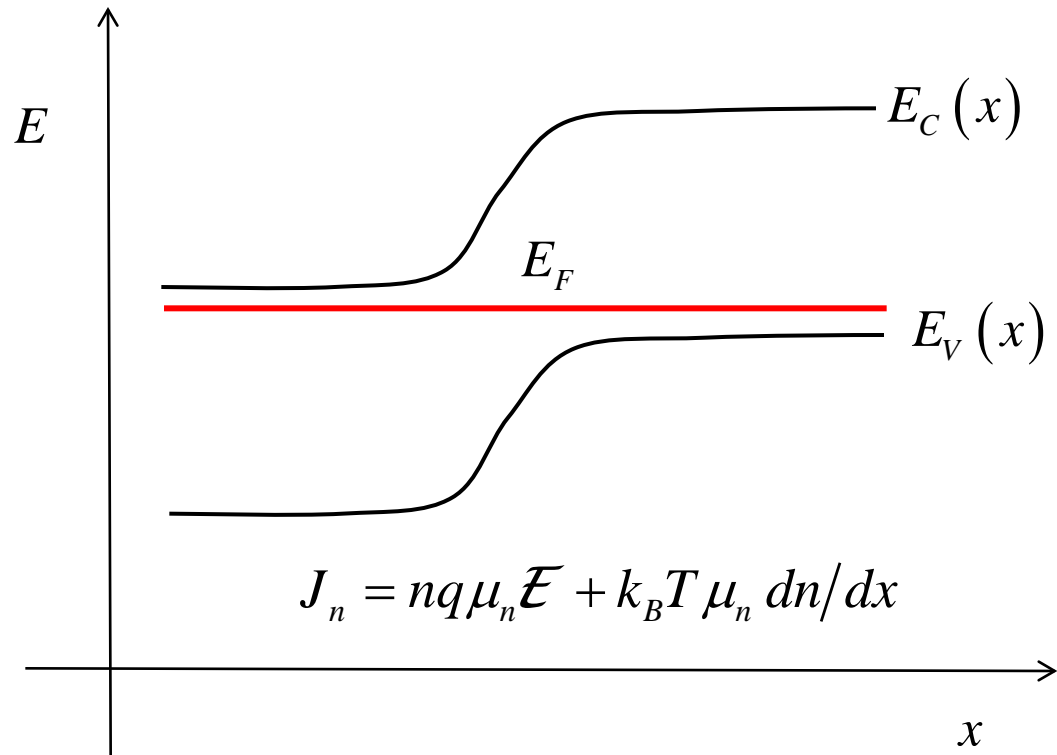
outline

- 1) **Transport across a barrier**
- 2) Transport across a thin base
- 3) High-field collectors
- 4) Questions?



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a familiar problem with strong gradients



Should we use a field-dependent mobility?

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

pn junction: energy balance

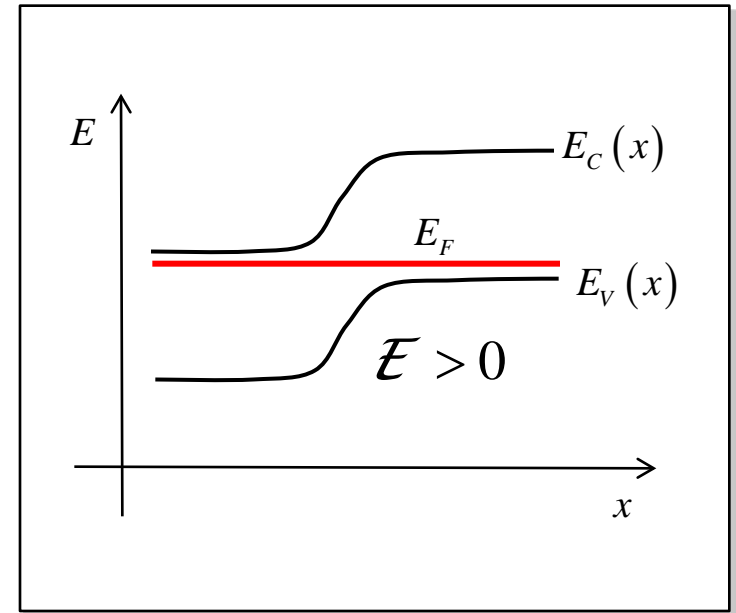
$$J_n \mathcal{E} \approx \frac{3 n k_B (T_e - T_L)}{2 \langle \tau_E \rangle} \quad (\text{ignores diffusion})$$

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

1) equilibrium:

$$J_n = 0 \quad \mathcal{E}_C \rightarrow \infty$$

$$T_e \rightarrow T_L \quad \mu_n \rightarrow \mu_n^0$$



pn junction: under bias

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

2) forward bias:

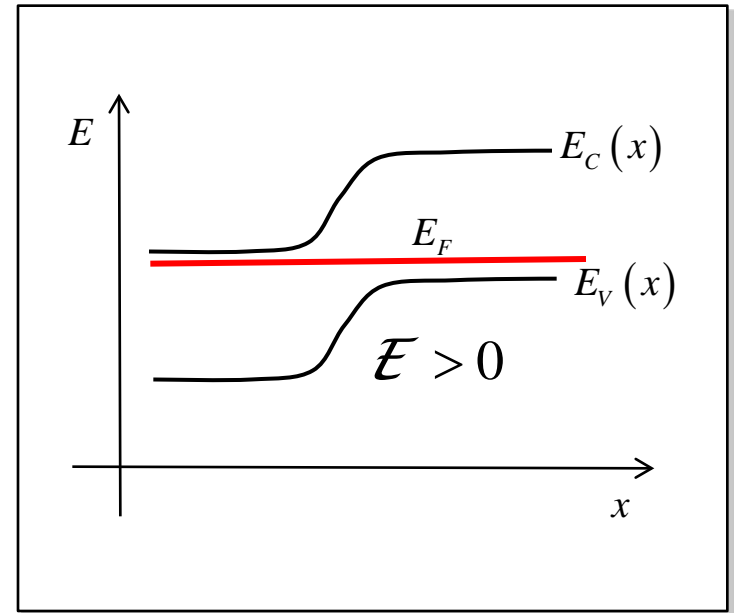
$$J_n < 0 \quad \mathcal{E}_c^2 < 0$$

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

3) reverse bias:

$$J_n > 0 \quad \mathcal{E}_c^2 > 0$$

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



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

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

pn junction: summary

1) Zero bias:

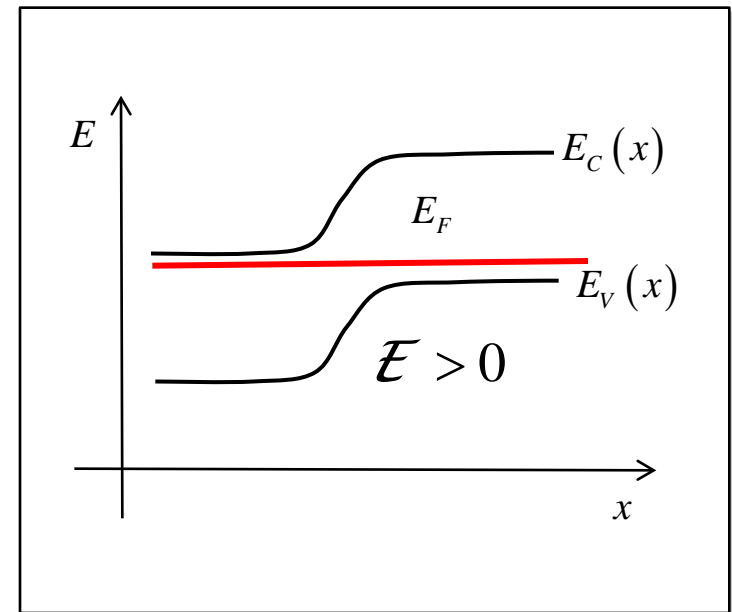
$$\mu_n = \mu_n^o$$

2) Forward bias:

$$\mu_n > \mu_n^o$$

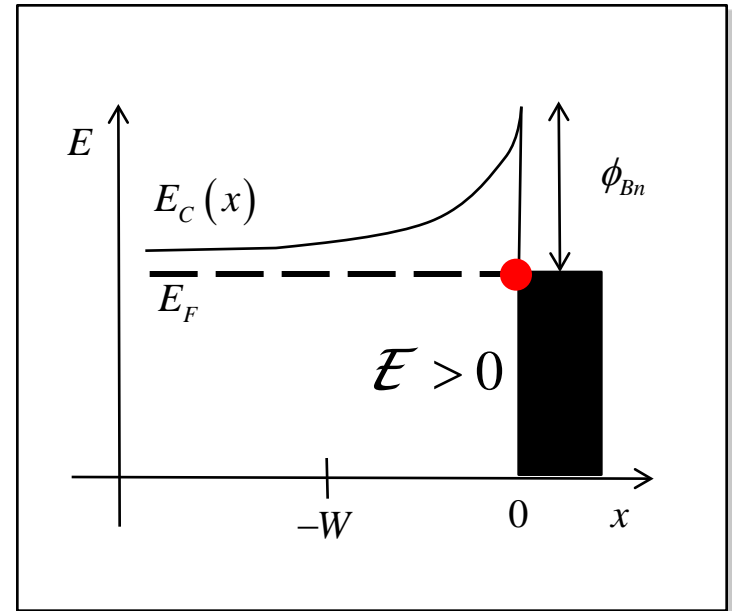
3) Reverse bias:

$$\mu_n < \mu_n^o$$



Schottky barriers

Here the problem is clearer
(and more important)
because there is **only** a
junction.



Schottky barriers: diffusion theory

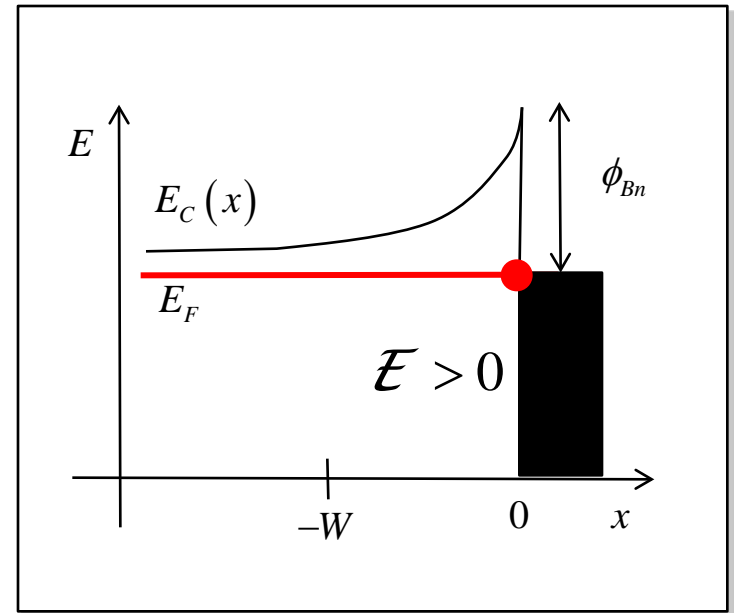
solve:

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

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

result:

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



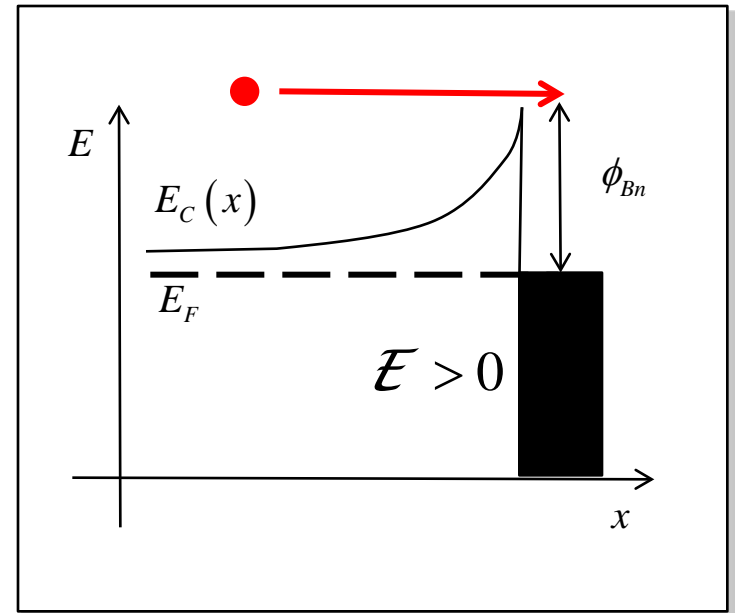
Schottky barriers: TE theory

assume:

ballistic transport

result:

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



Which of these two results is correct?

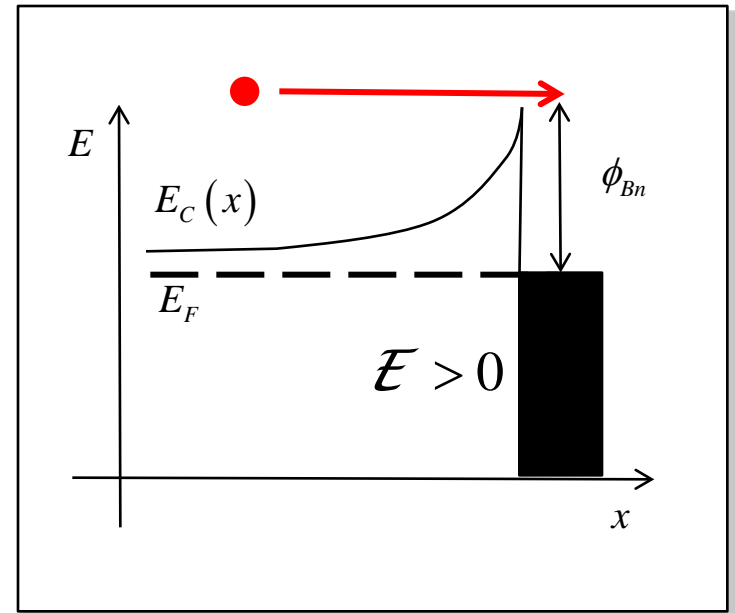
Schottky barriers: discussion

diffusion theory:

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

ballistic (TE) theory:

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



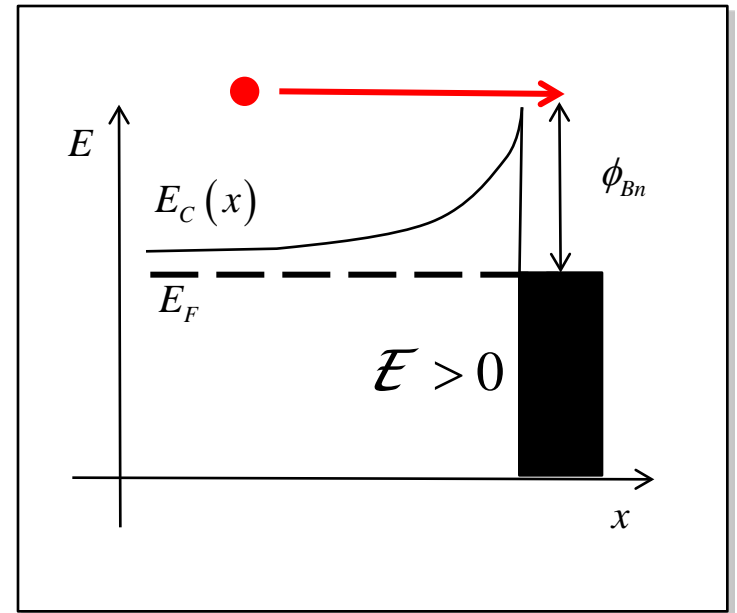
DD fails when: $\mu_n\mathcal{E}(0) > \frac{v_T}{2}$

but why, what went wrong?

Schottky barriers: aside

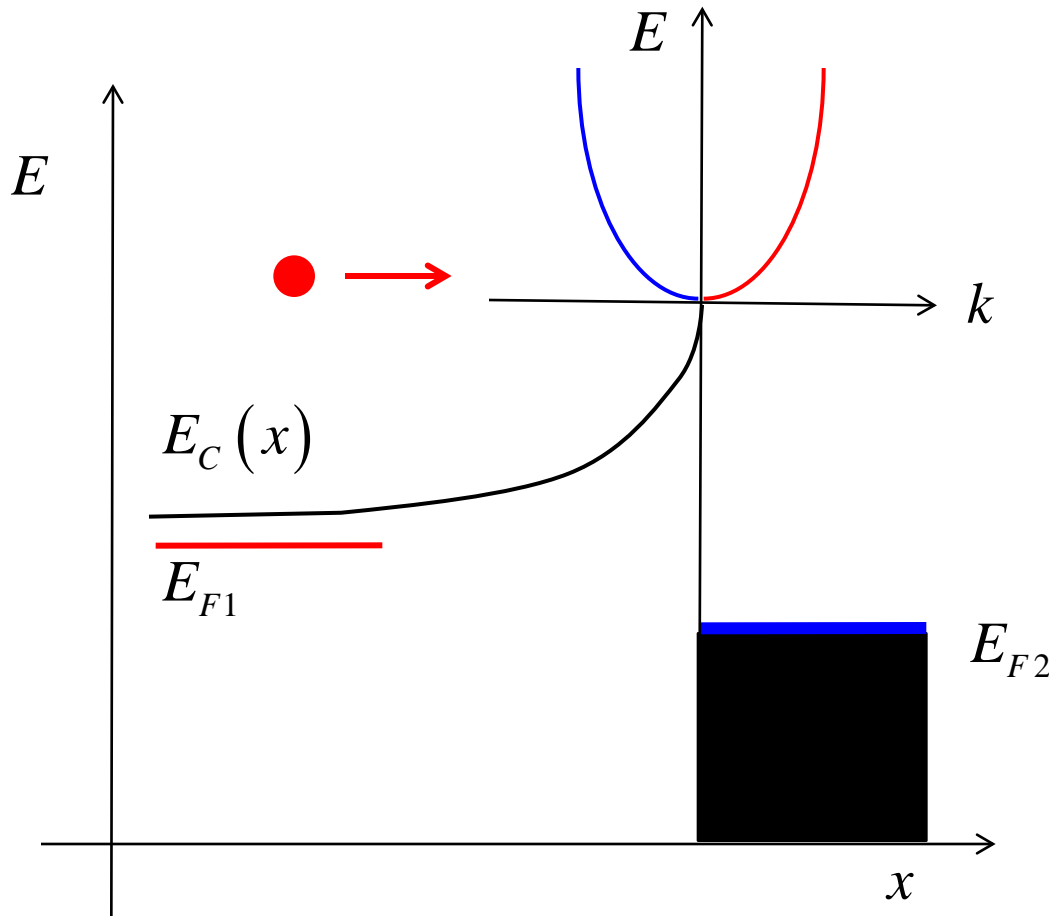
TE result:

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



This result can be easily obtained by solving the ballistic BTE.
See Lecture 29.

Schottky barriers: ballistic BTE



$$J = \frac{1}{\Omega} \sum_{k>0} qv_x f_1(k) - \frac{1}{\Omega} \sum_{k<0} qv_x f_2(k)$$

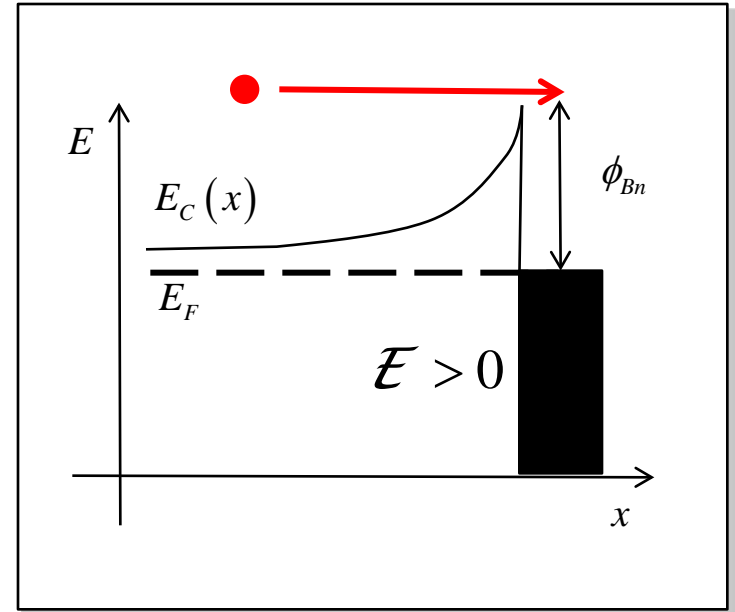
Schottky barriers: discussion

diffusion theory:

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

ballistic (TE) theory:

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



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

but why, what went wrong?

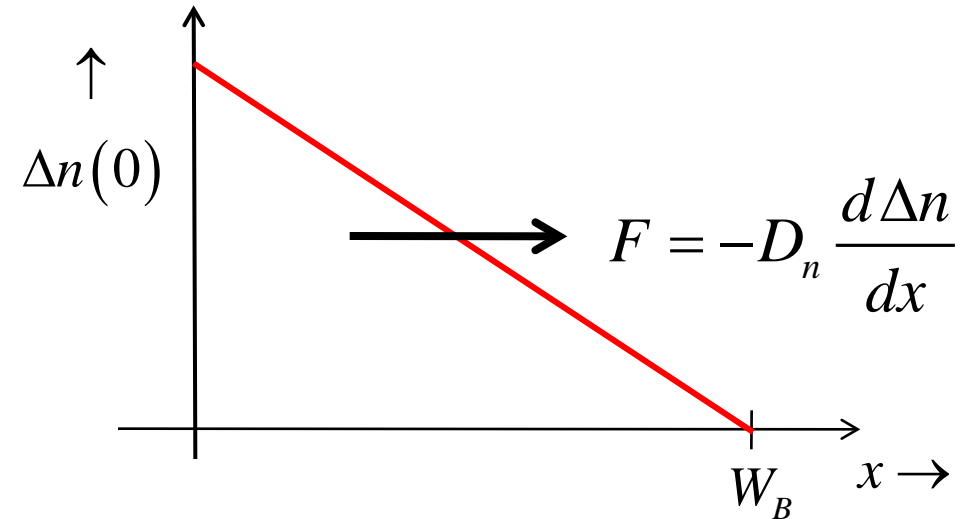
outline

- 1) Transport across a barrier
- 2) Transport across a thin base**
- 3) High-field collectors
- 4) Questions?



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diffusion across a thin base



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

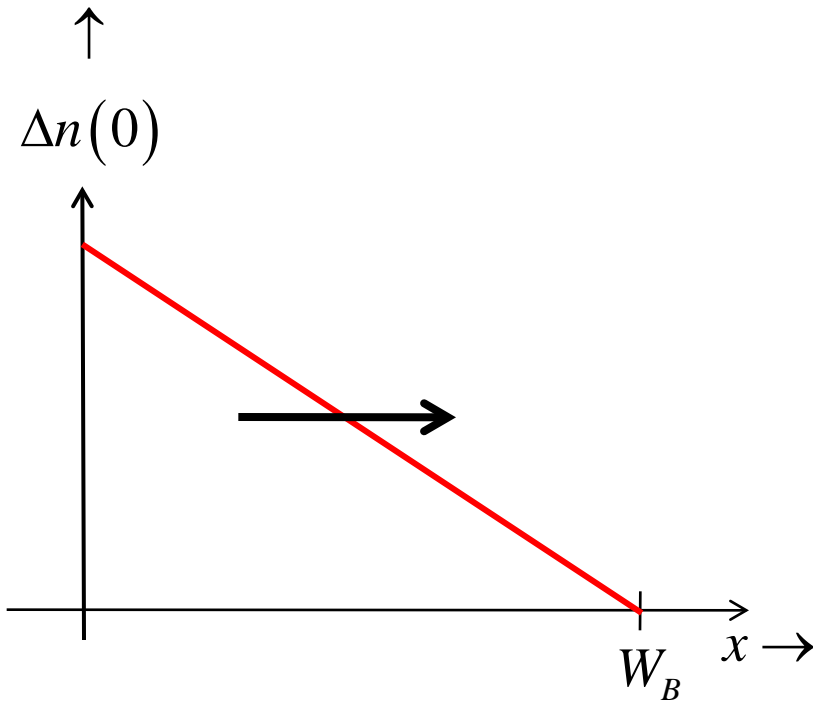
$$v_{diff} = \frac{D_n}{W_B} \ll v_T$$

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

$$W_B \gg \lambda_0$$

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

why does DD fail?



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

$$u_{xx} = \frac{k_B T_L}{2} + \frac{1}{2} m^* v_{dx}^2 \quad J_{nx} = -qn v_{dx}$$

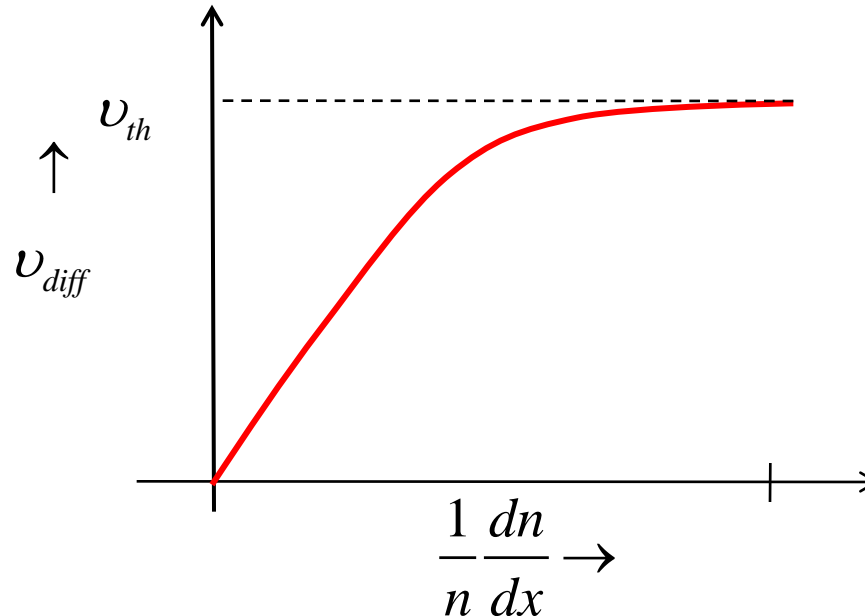
$$J_{nx}^2 + \frac{n^2 q^2}{2\mu_n m^* (dn/dx)} J_{nx} - \frac{n^2 q^3 D_n}{2\mu_n m^*} = 0$$

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

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

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

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

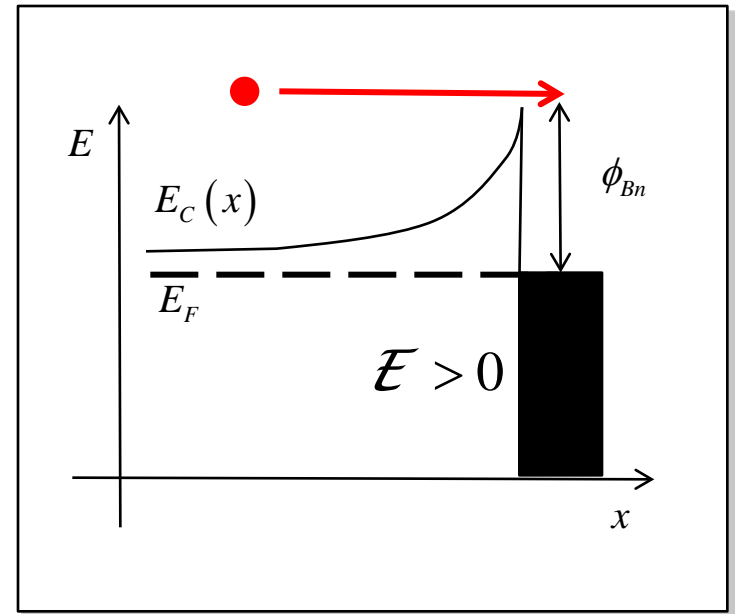
$\left| \frac{dn}{dx} \right|$ is very large.

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

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

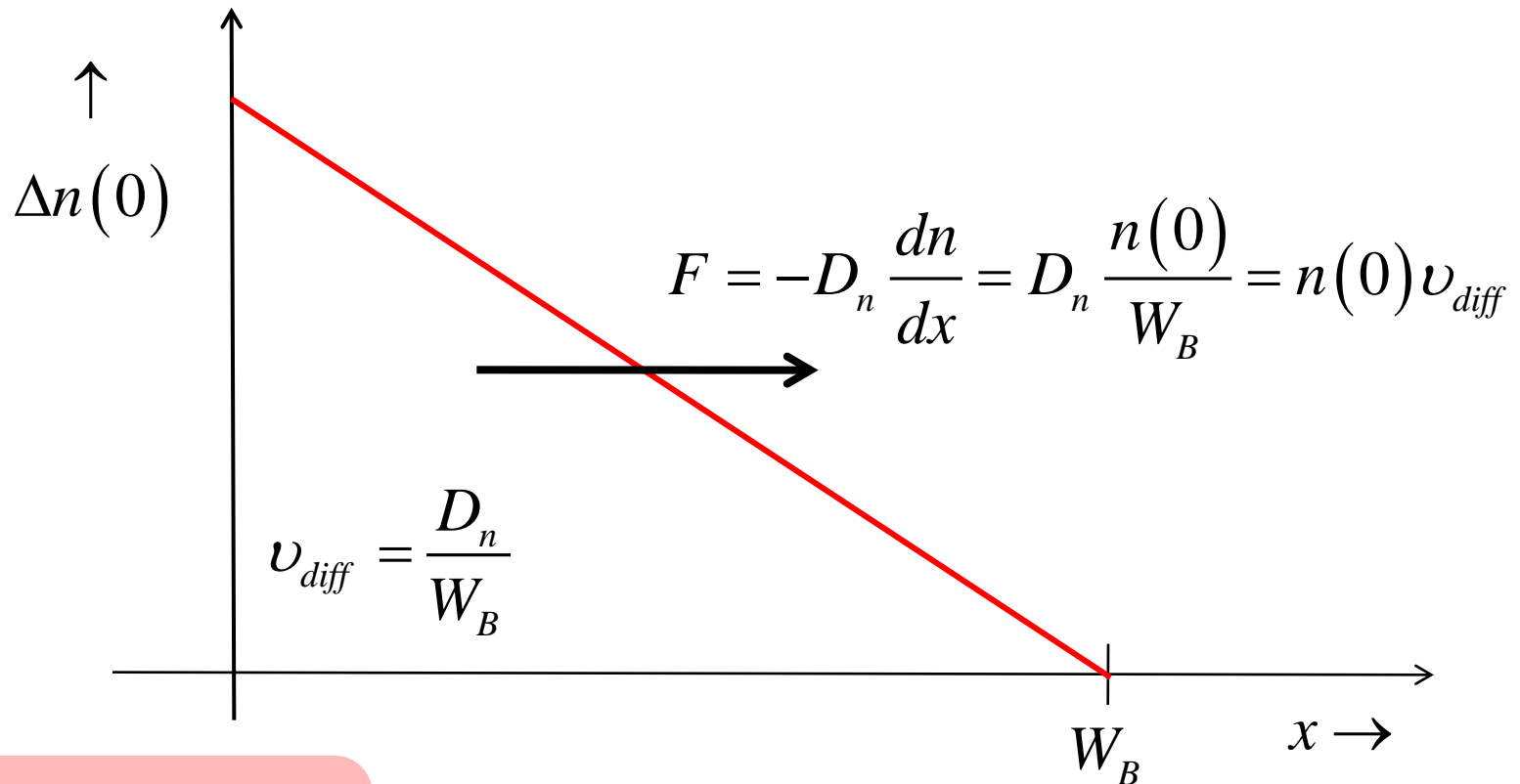
The mobility, μ , **should** be reduced in a forward-biased PN junction - even though the carrier are not heated.

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



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

is Fick's Law wrong?



$$v_{diff} = \frac{D_n}{W_B} \ll v_T$$

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

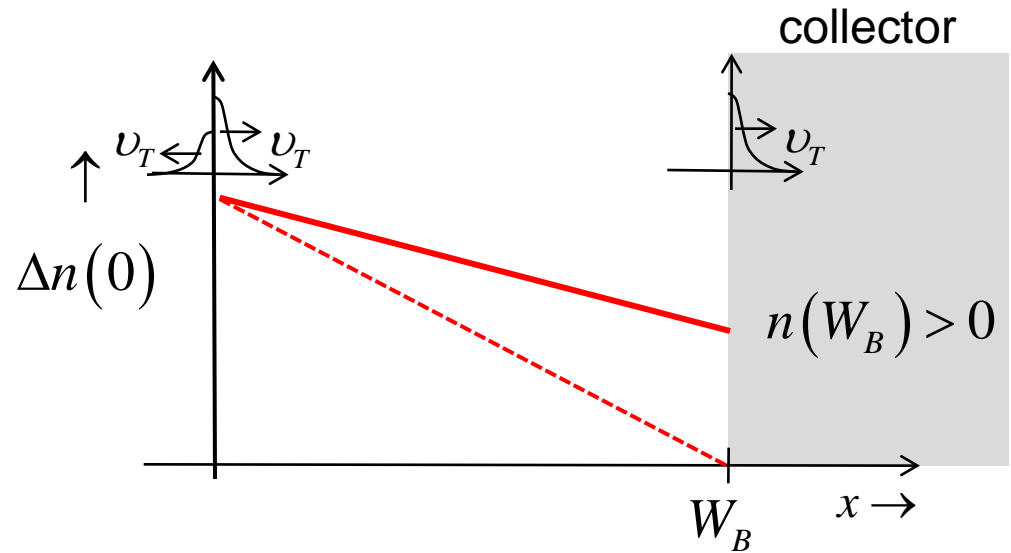
Fick's Law in a thin base

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

$$F = n(W_B) v_T$$

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

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

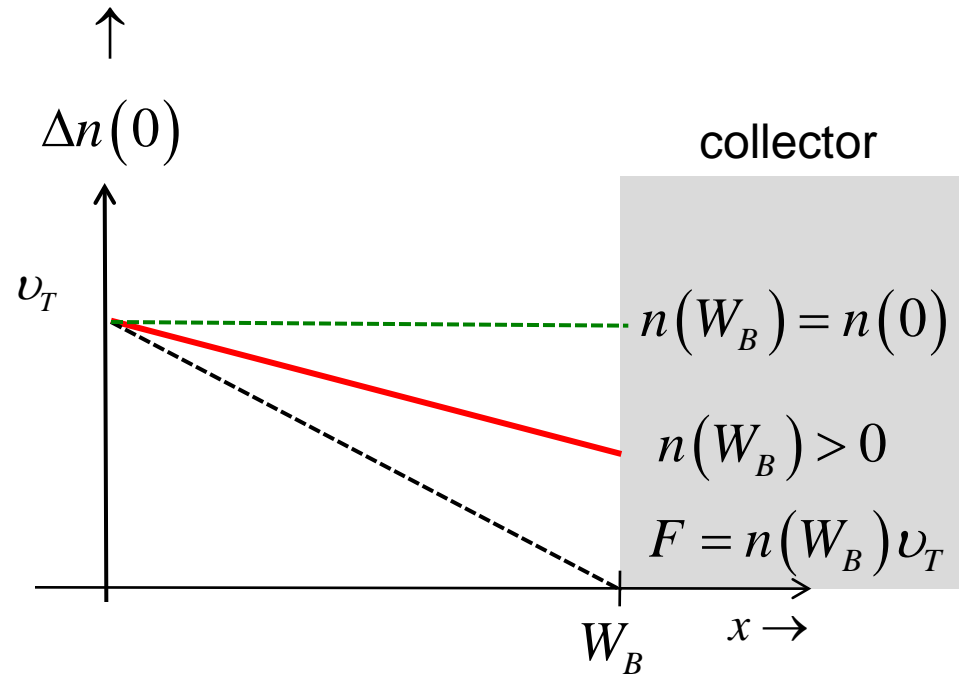


Fick's Law

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

$$\frac{D_n}{W_B} \ll v_T \quad F \rightarrow n(0) \frac{D_n}{W_B}$$

$$\frac{D_n}{W_B} \gg v_T \quad F \rightarrow n(0) v_T$$

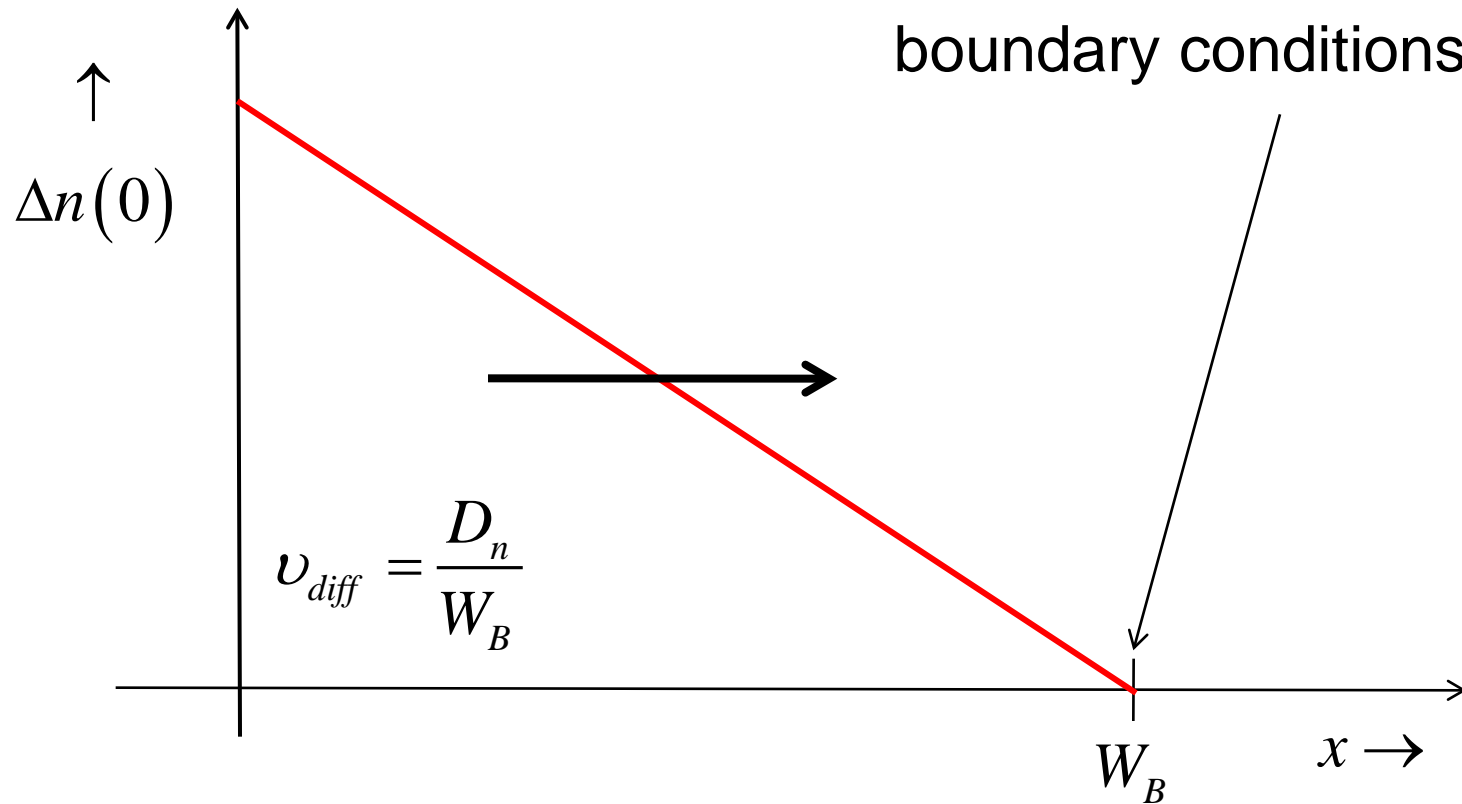


No need to reduce D because $dn/dx \rightarrow 0$ when $W_B \ll \lambda$

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

is Fick's Law wrong?

No – not if we use the right boundary conditions.



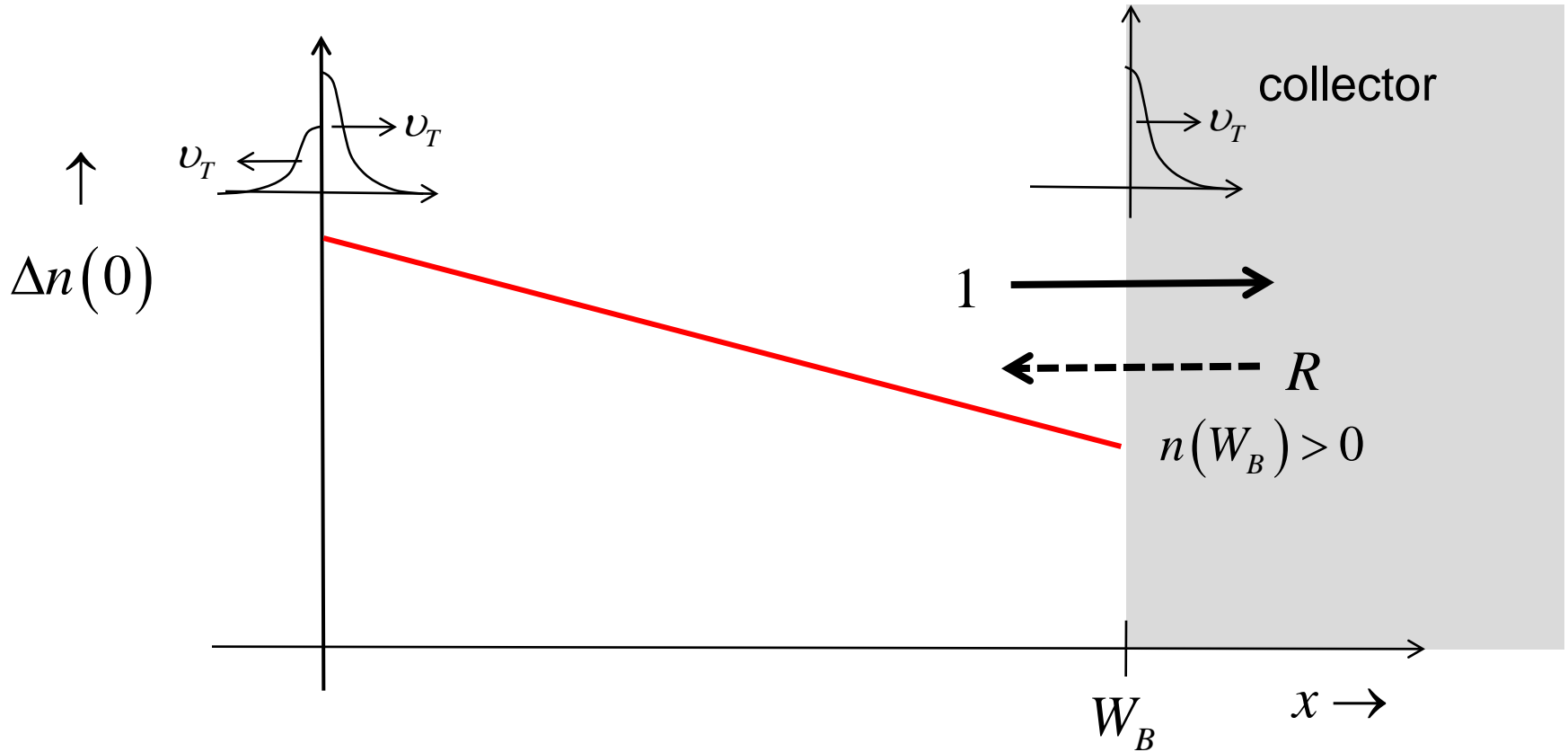
outline

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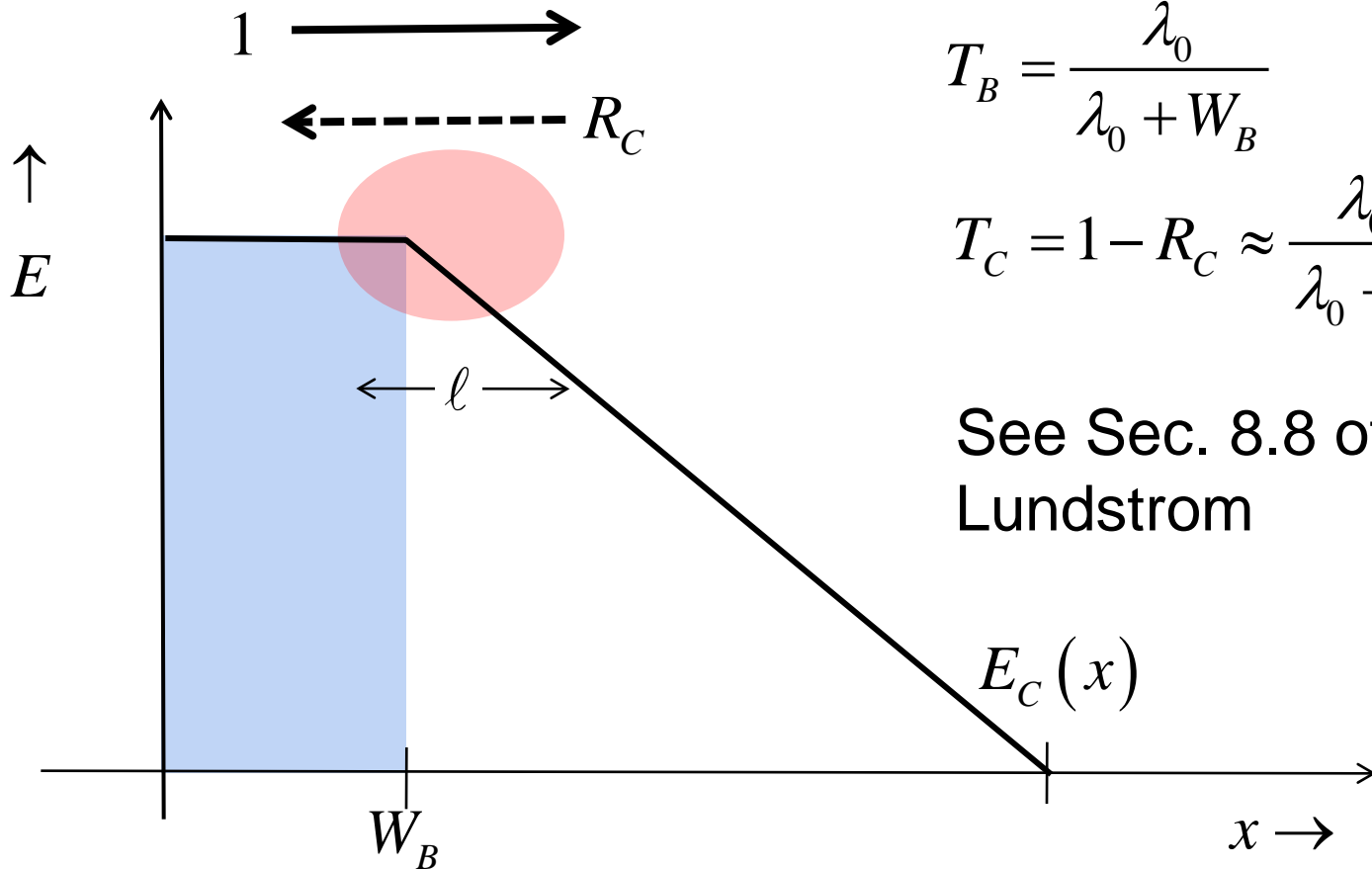


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how good is the collector?



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?

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