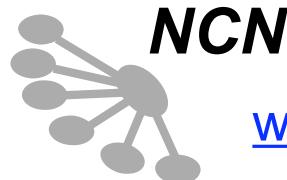


EE-612:

Lecture 11

The Quasi-ballistic MOSFET

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Fall 2006



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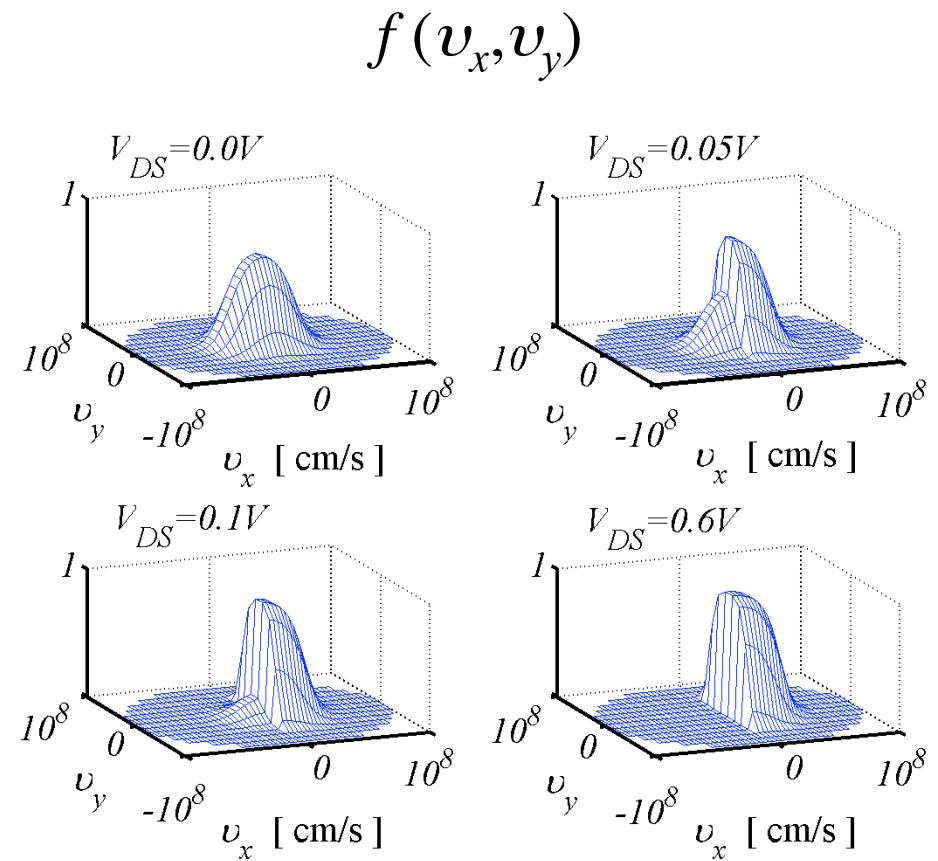
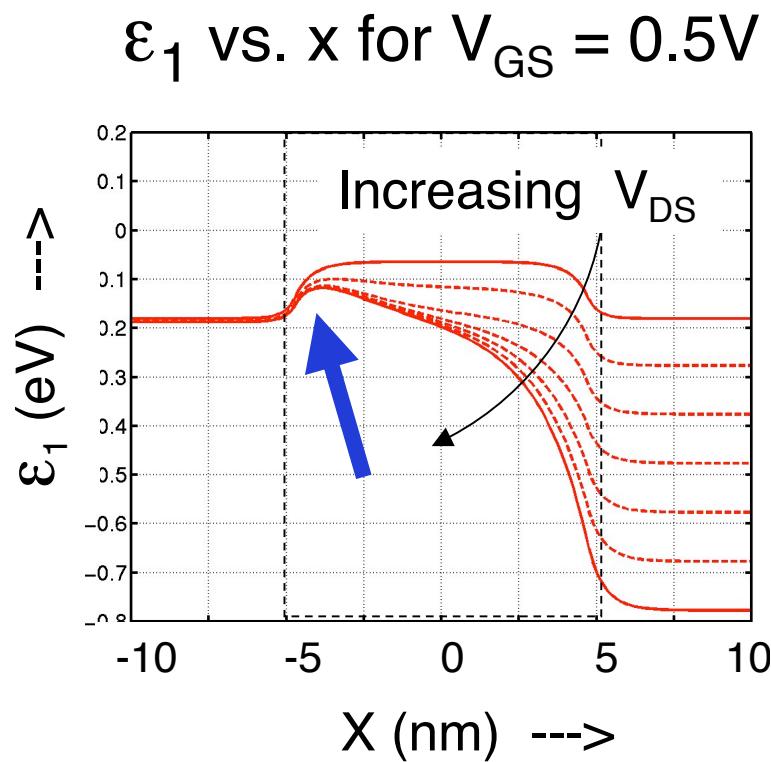
Lundstrom EE-612 F06

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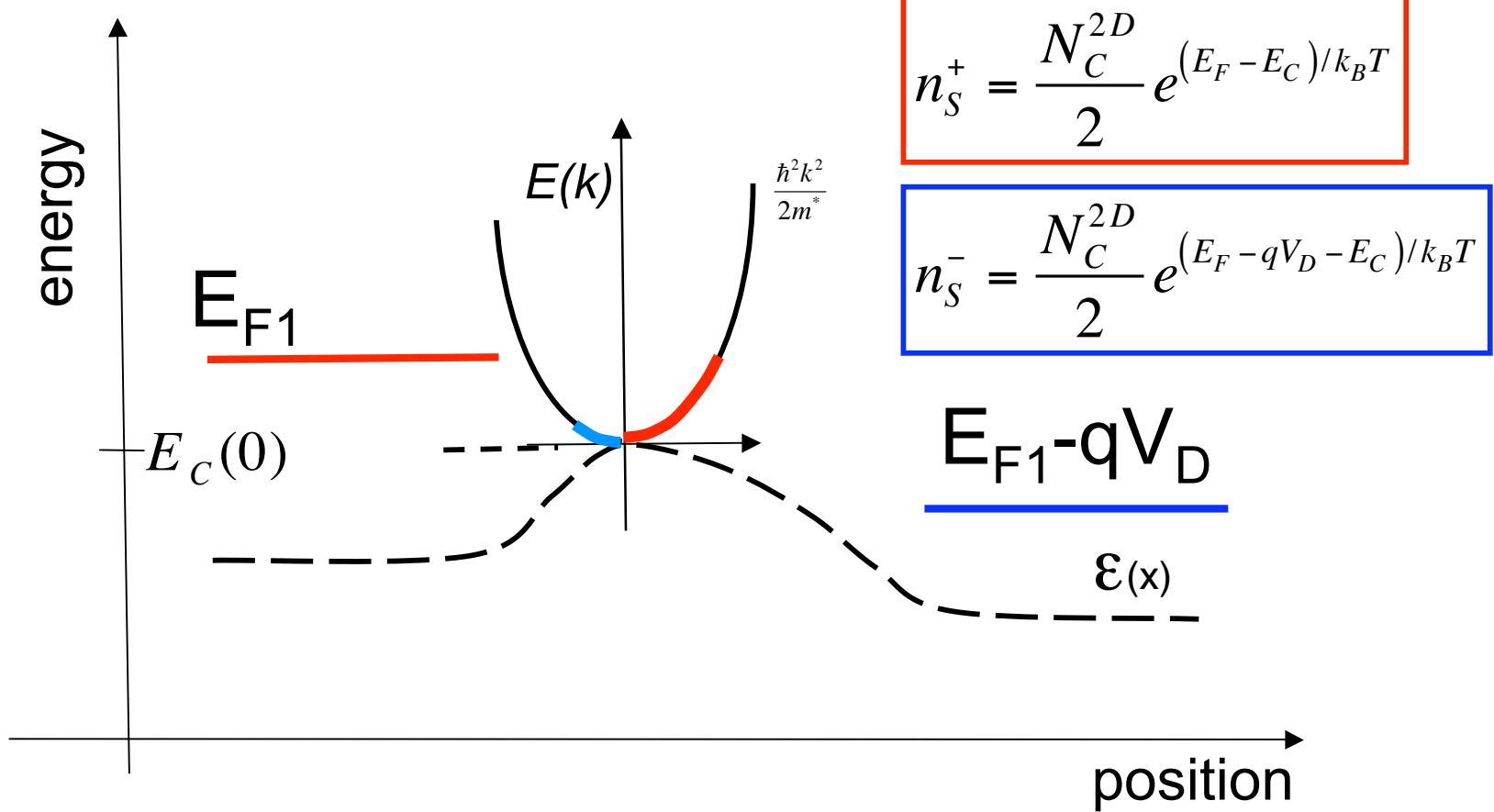
outline

- 1) Review of ballistic MOSFET
- 2) Fermi Dirac Statistics
- 3) The quasi-ballistic MOSFET

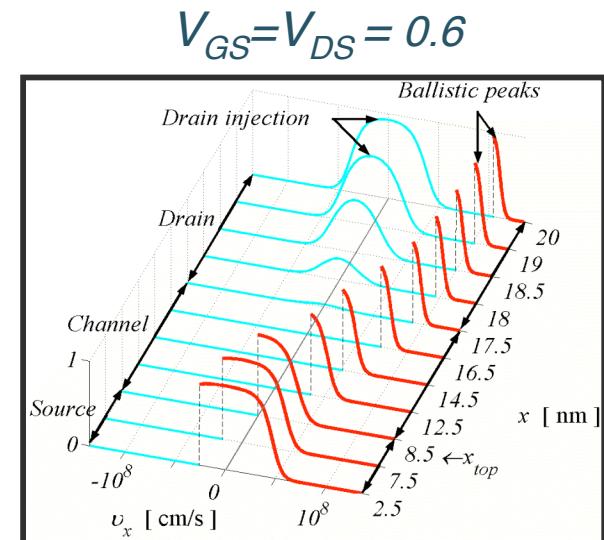
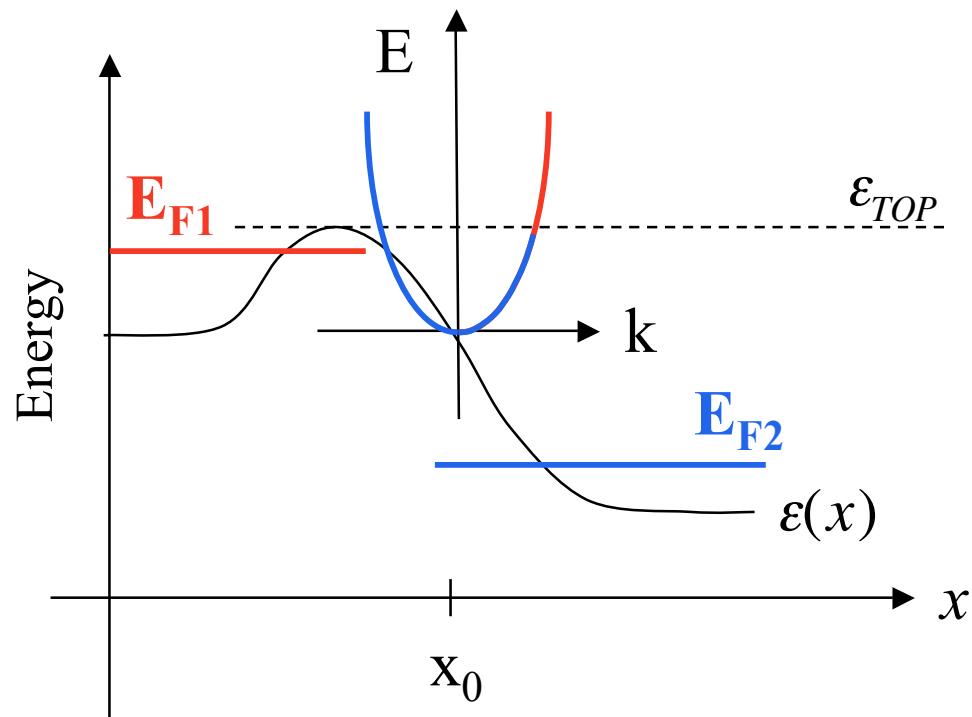
filling states at the top-of-the-barrier



filling states at the top-of-the-barrier (ii)

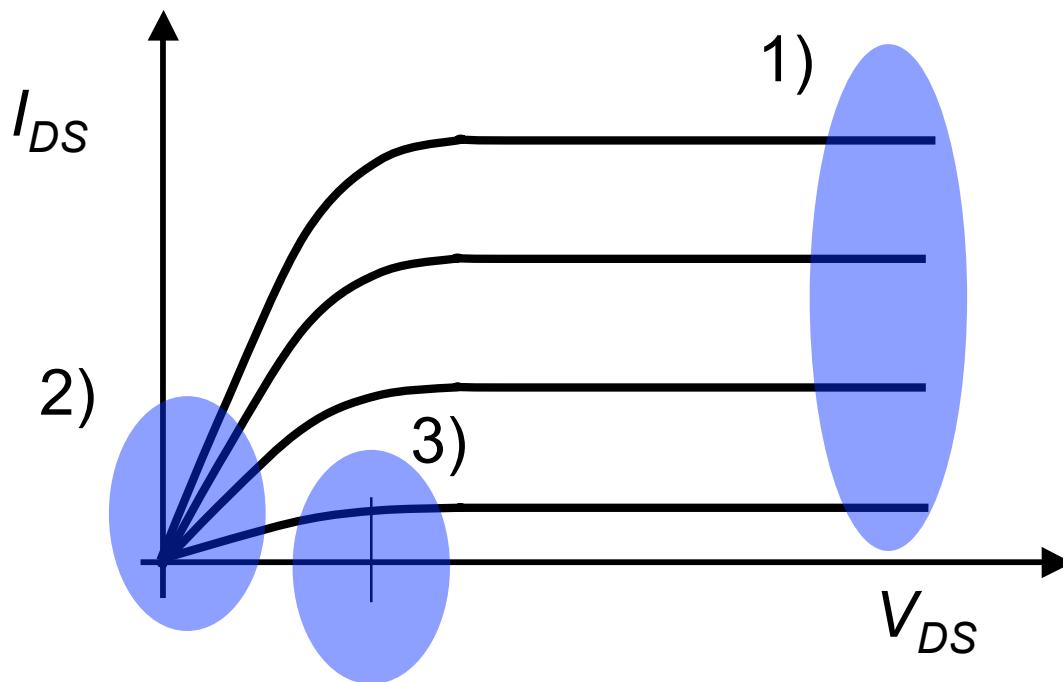


filling states in the channel



J-H Rhew, Z. Ren, and M.S. Lundstrom, *Solid-State Electron.* **46**, 1800, 2002

the ballistic MOSFET IV



$$I_D = WC_G v_T \left(V_{GS} - V_T \right) \frac{\left(1 - e^{-qV_{DS}/k_B T} \right)}{\left(1 + e^{-qV_{DS}/k_B T} \right)}$$

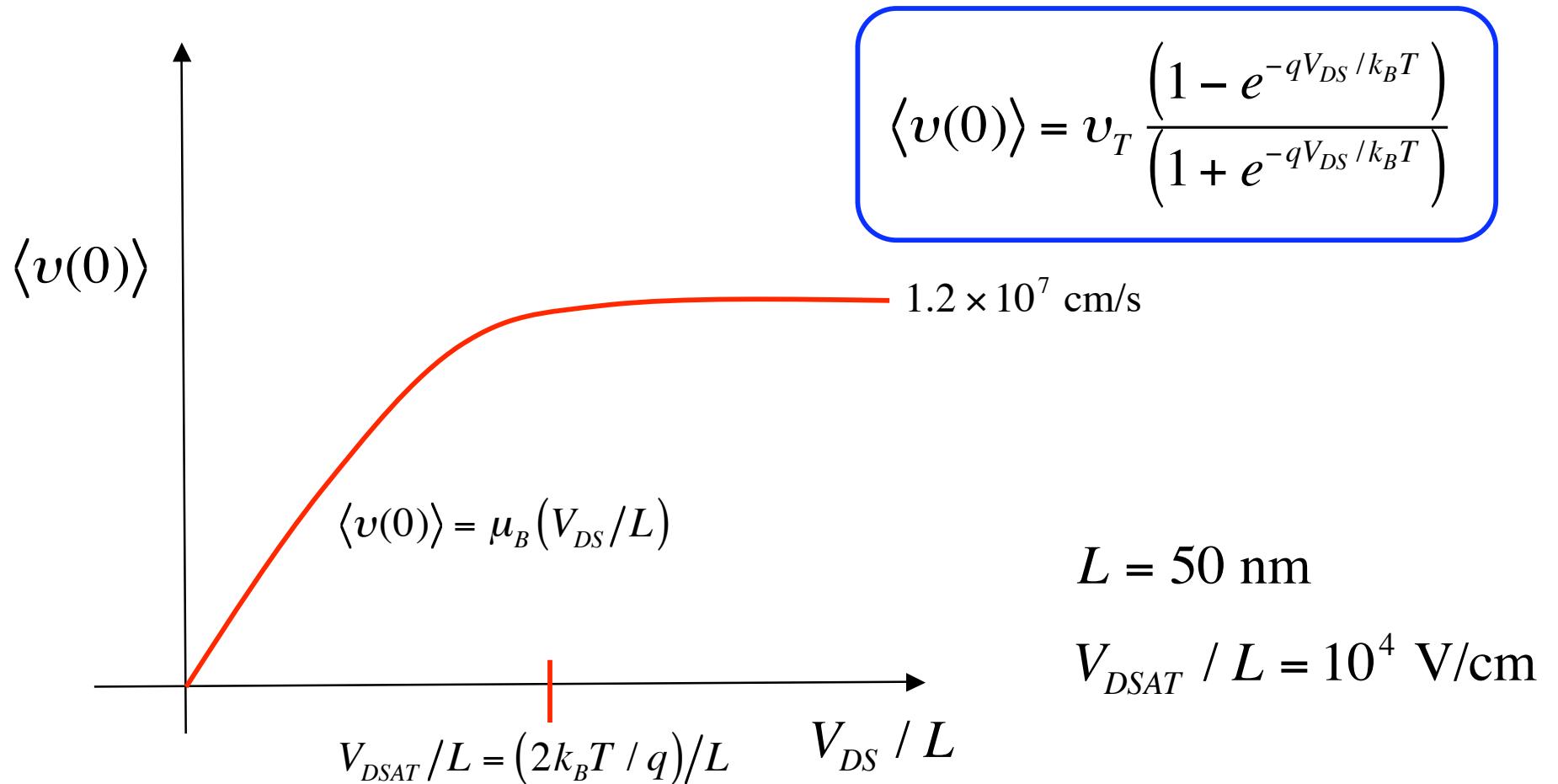
key features

$$1) \quad I_{ON} = WC_G v_T (V_{GS} - V_T) \quad V_{DS} \gg k_B T / q$$

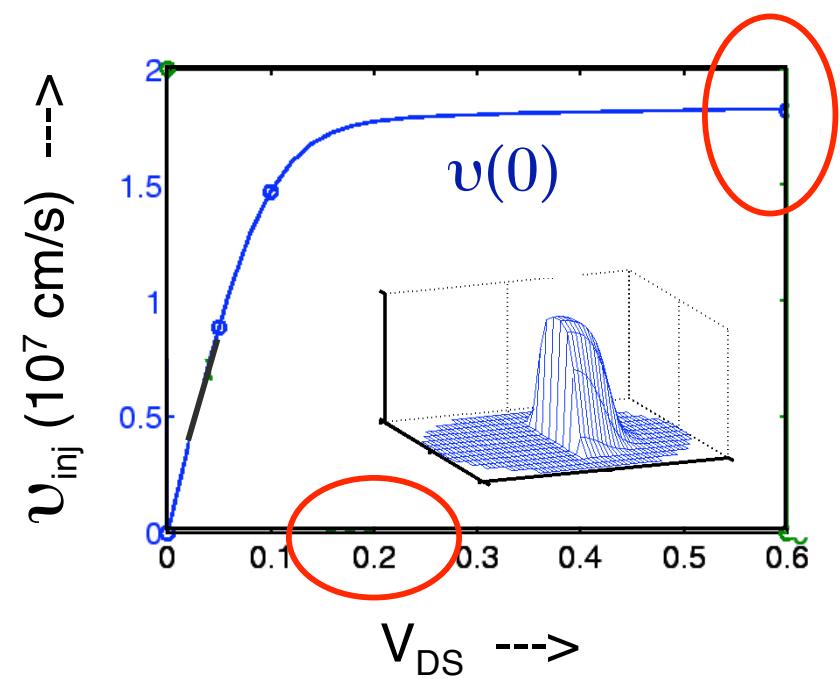
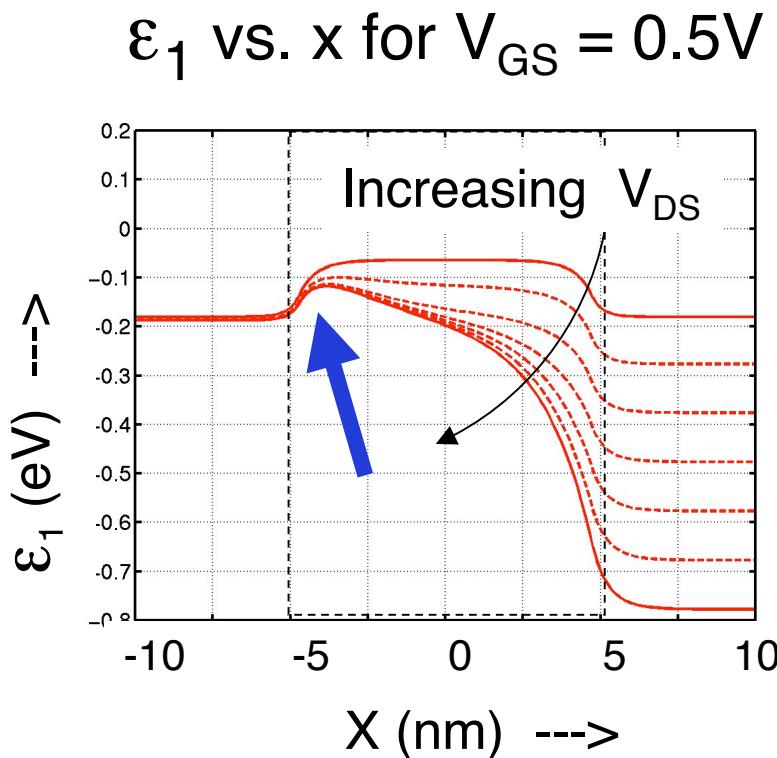
$$2) \quad I_D = WC_G \frac{v_T}{2k_B T / q} (V_{GS} - V_T) V_{DS} \quad V_{DS} \ll k_B T / q$$

$$3) \quad I_D = W Q_i(0) \langle v(0) \rangle$$
$$\langle v(0) \rangle = v_T \frac{\left(1 - e^{-qV_{DS}/k_B T}\right)}{\left(1 + e^{-qV_{DS}/k_B T}\right)} \quad V_{DSAT} \approx 2k_B T / q$$

velocity vs. “field” for a ballistic MOSFET



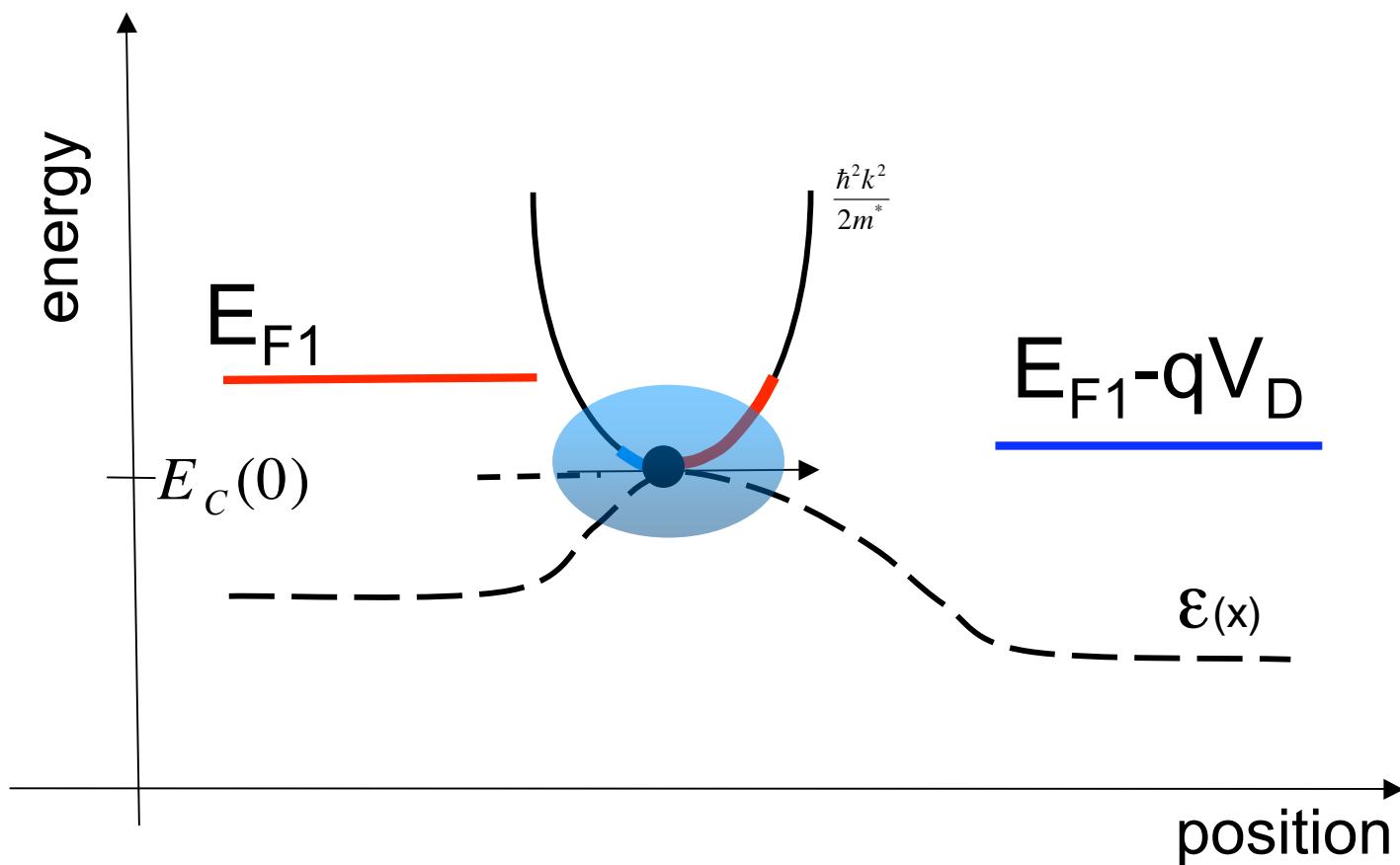
comparison to simulation



outline

- 1) Review of the ballistic MOSFET
- 2) Fermi-Dirac statistics**
- 3) The quasi-ballistic MOSFET

need degenerate carrier statistics



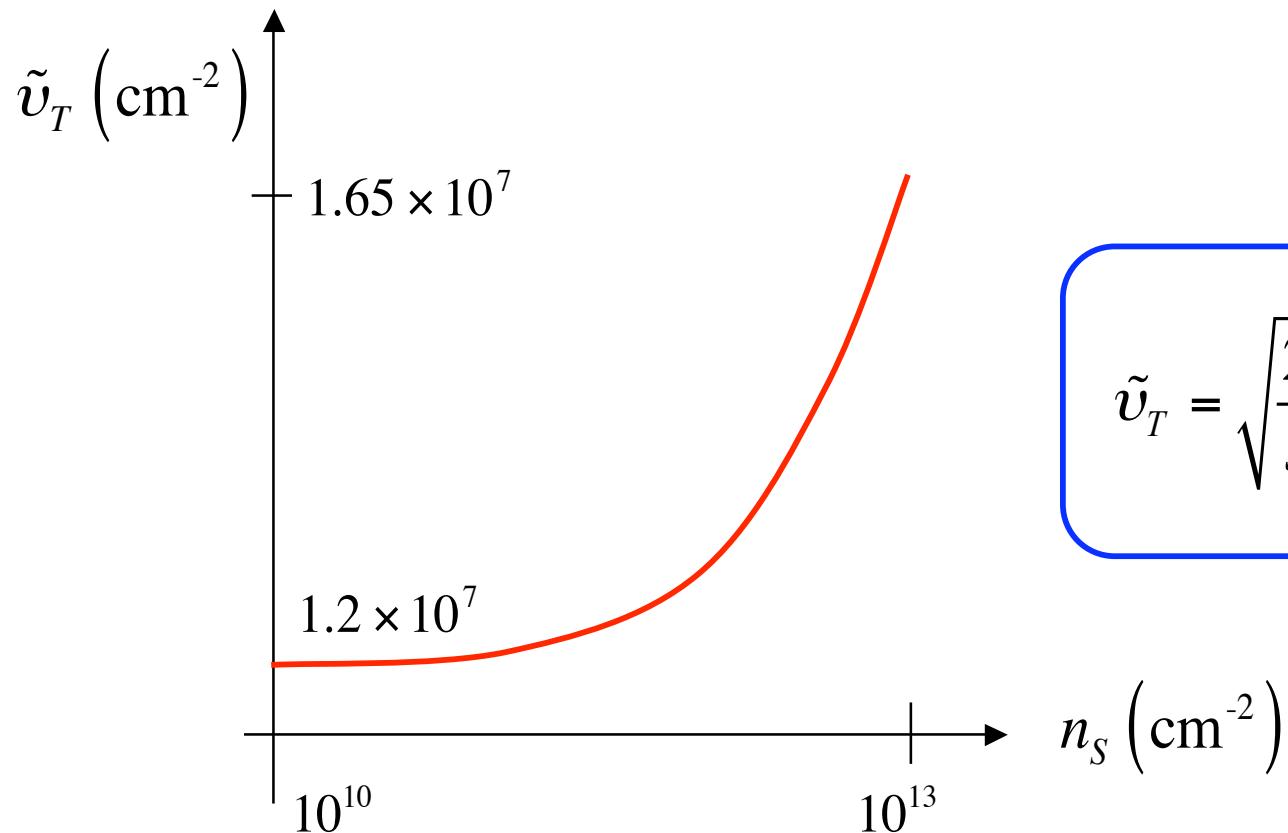
degenerate carrier statistics

$$n_S^+ = \frac{N_C^{2D}}{2} e^{\eta_{F1}} \rightarrow \frac{N_C^{2D}}{2} \mathcal{F}_0(\eta_{F1}) \quad \eta_{F1} = (E_F - E_C)/k_B T$$

$$n_S^- = \frac{N_C^{2D}}{2} e^{\eta_{F2}} \rightarrow \frac{N_C^{2D}}{2} \mathcal{F}_0(\eta_{F2}) \quad \eta_{F2} = (E_F - qV_{DS} - E_C)/k_B T$$

$$v_{inj} \rightarrow \tilde{v}_T = \sqrt{\frac{2k_B T}{\pi m^*}} \left(\frac{\mathcal{F}_{1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} \right)$$

degenerate injection velocity



$$\tilde{v}_T = \sqrt{\frac{2k_B T}{\pi m^*}} \left(\frac{\mathcal{F}_{1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} \right)$$

degenerate I-V

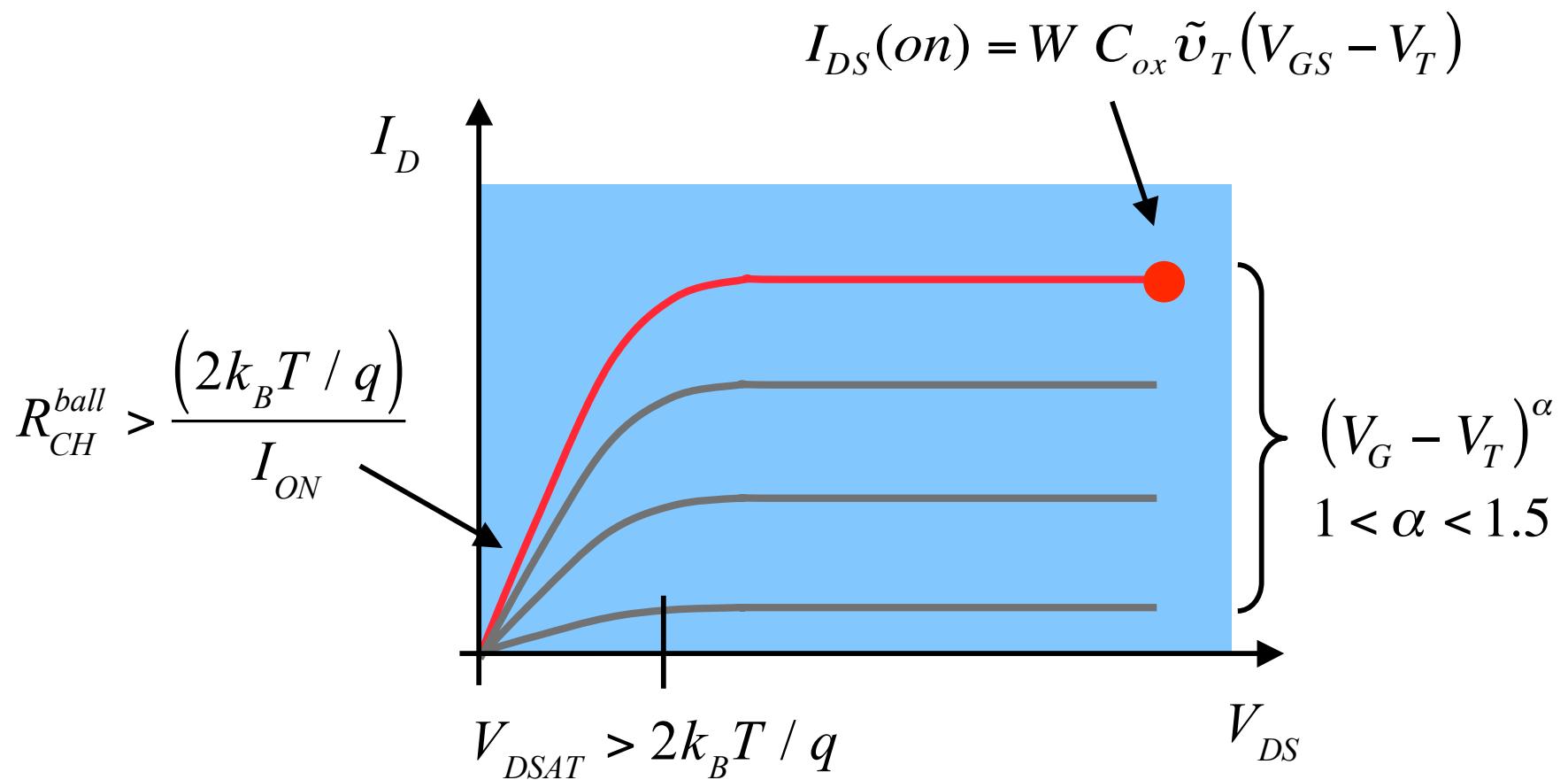
$$I_D = WC_G \tilde{v}_T (V_{GS} - V_T) \frac{\left[1 - \mathcal{F}_{1/2}(\eta_{F1} - qV_{DS}/k_B T) / \mathcal{F}_{1/2}(\eta_{F1}) \right]}{\left[1 + \mathcal{F}_0(\eta_{F1} - qV_{DS}/k_B T) / \mathcal{F}_0(\eta_{F1}) \right]} \quad (1)$$

$$\tilde{v}_T = \sqrt{\frac{2k_B T}{\pi m^*}} \left(\frac{\mathcal{F}_{1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} \right) \quad (2)$$

$$C_G (V_{GS} - V_T) = \frac{N_C^{2D}}{2} \left[\mathcal{F}_0(\eta_{F1}) + \mathcal{F}_0(\eta_{F1} - qV_{DS}/k_B T) \right] \quad (3)$$

(assumes 1 subband occupied and parabolic bands)

degenerate I-V

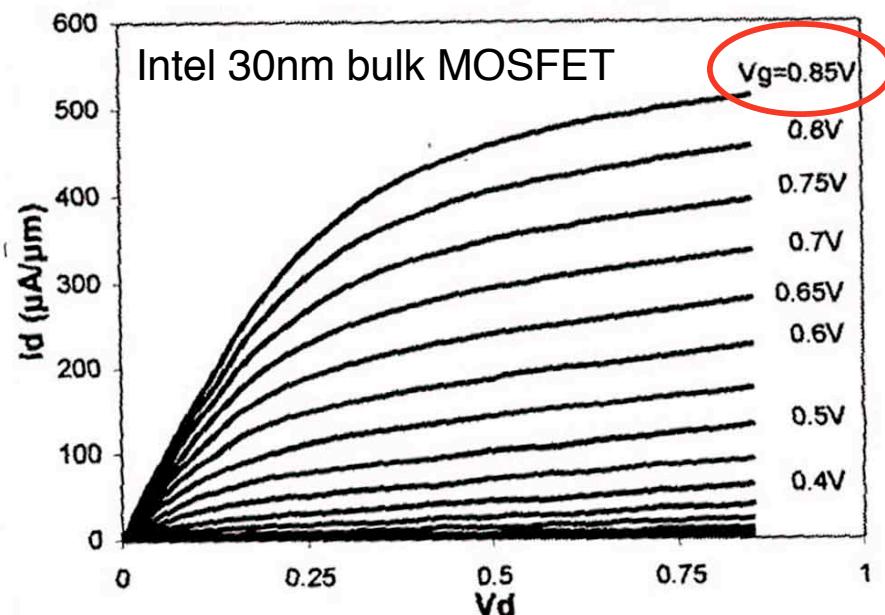


outline

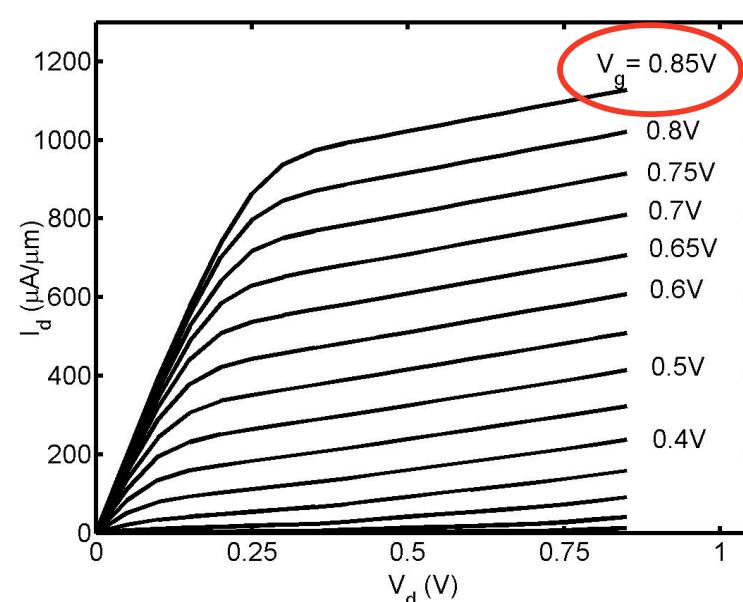
- 1) Review of the ballistic MOSFET
- 2) Fermi-Dirac statistics
- 3) The quasi-ballistic MOSFET**

comparison with experiment

measured



ballistic



Chau et al, IEDM Technical Digest,
2000, pp 45 -48

MOSFETs operate at $\approx 50\%$ of their ballistic limit

between ballistic and diffusive

$$I_D = WC_G (V_{GS} - V_T) \langle v(0) \rangle$$

1) ballistic

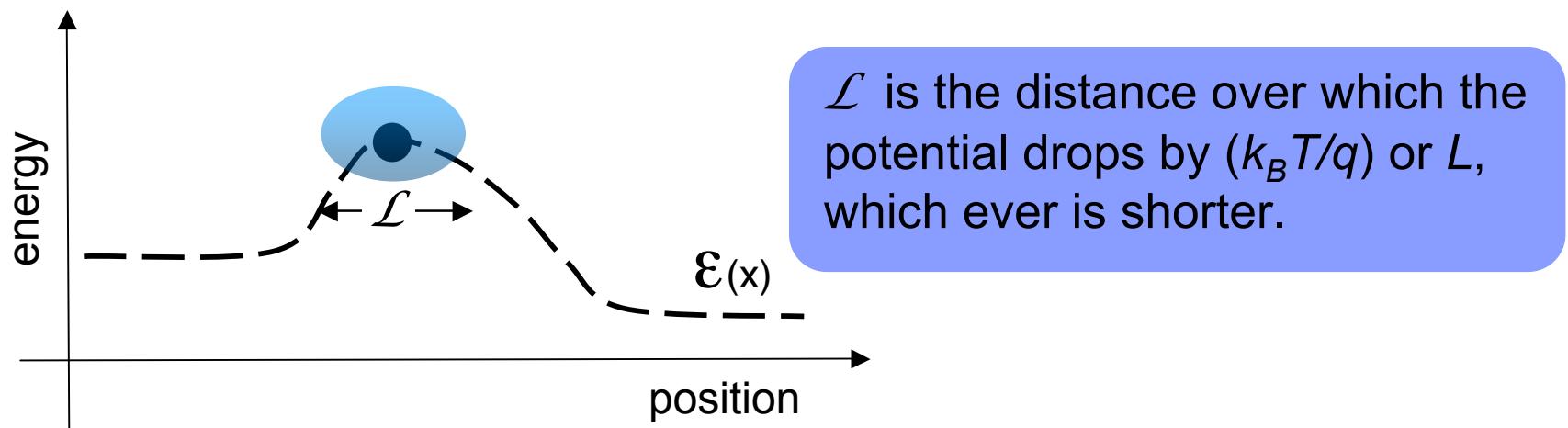
$$\langle v(0) \rangle = v_T \frac{\left(1 - e^{-qV_{DS}/k_B T}\right)}{\left(1 + e^{-qV_{DS}/k_B T}\right)}$$

2) diffusive

$$\langle v(0) \rangle = \left(D_{eff}/\mathcal{L}\right) \frac{\left(1 - e^{-qV_{DS}/k_B T}\right)}{\left(1 + e^{-qV_{DS}/k_B T}\right)}$$

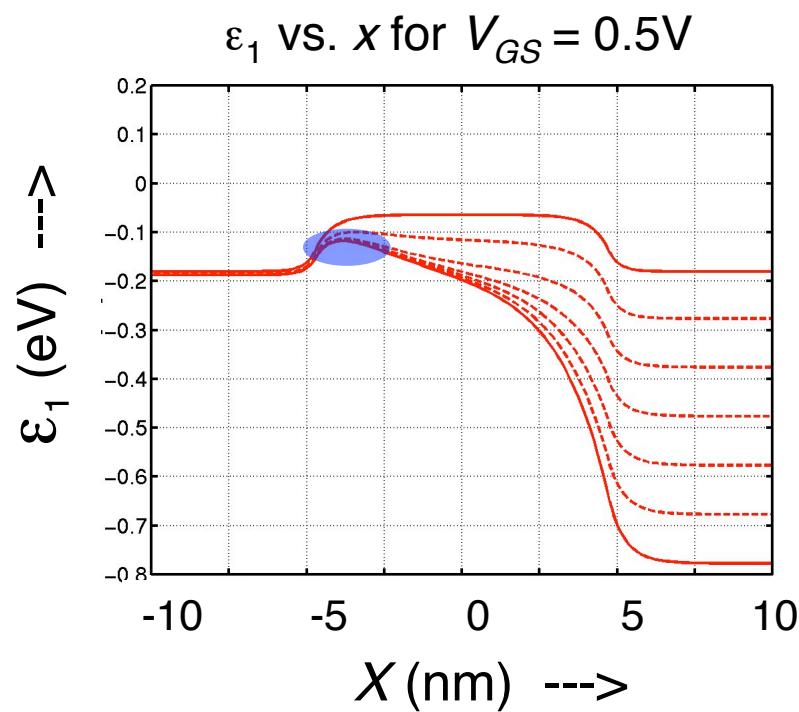
between ballistic and diffusive

$$\langle v(0) \rangle = \left[\frac{1}{\left(1/v_{inj} \right) + 1 / \left(D_{eff} / \mathcal{L} \right)} \right] \frac{\left(1 - e^{-qV_{DS}/k_B T} \right)}{\left(1 + e^{-qV_{DS}/k_B T} \right)}$$



(Note: $k_B T / q$ is replaced by $(E_F - E_C) / q$ for degenerate carriers.)

scattering in a MOSFET



$$\mathcal{L} \ll L$$

between ballistic and diffusive (low V_{DS})

1) ballistic:

$$I_D = \frac{W}{L} C_G \mu_B (V_{GS} - V_T) V_{DS}$$

2) quasi-ballistic:

$$\mu_B \rightarrow \frac{1}{1/\mu_B + 1/\mu_{eff}}$$

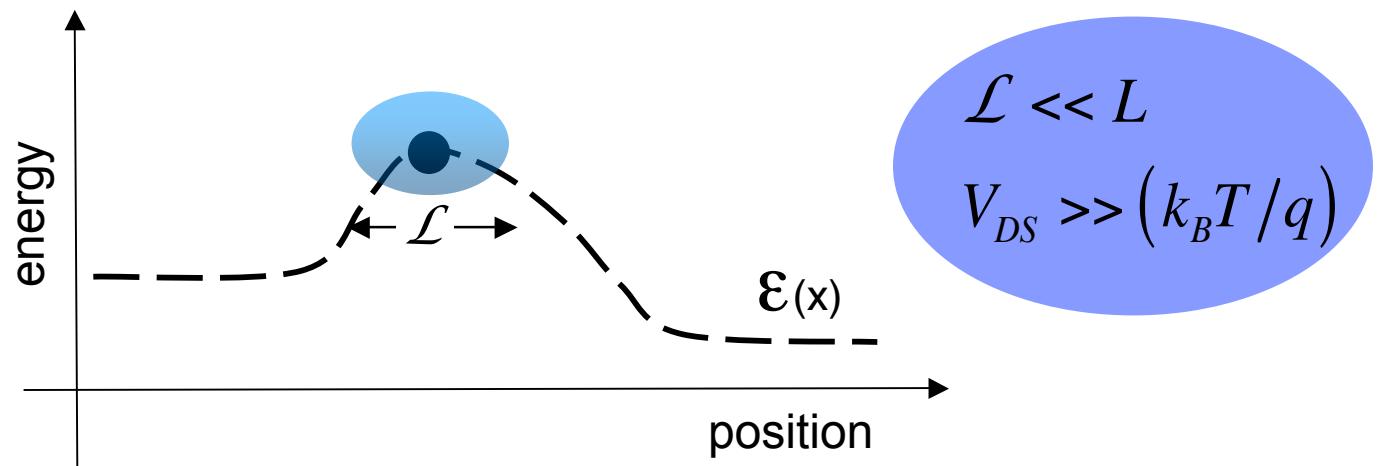
3) diffusive:

$$\mu_B \rightarrow \mu_{eff}$$

between ballistic and diffusive (high V_{DS})

$$I_D = WC_G \left(V_{GS} - V_T \right) \langle v(0) \rangle$$

$$\frac{1}{\langle v(0) \rangle} = \frac{1}{v_{inj}} + \frac{1}{(k_B T / q) \mu_{eff} / \mathcal{L}}$$



diffusive limit (high V_{DS})

$$I_D = WC_G (V_{GS} - V_T) \langle v(0) \rangle$$

$$\langle v(0) \rangle \rightarrow (k_B T / q) \mu_{eff} / \mathcal{L}$$

$$I_D = WC_G (V_{GS} - V_T) \mu_{eff} \frac{k_B T / q}{\mathcal{L}} = WC_G (V_{GS} - V_T) \mu_{eff} E_y(0)$$

$$E_y(0) = (V_{GS} - V_T) / 2L \quad (\text{long channel theory})$$

$$I_D = \frac{W}{2L} C_G \mu_{eff} (V_{GS} - V_T)^2 \quad (\text{long channel result})$$

what is missing?

$$I_D = WC_G(V_{GS} - V_T) \langle v(0) \rangle$$

$$\langle v(0) \rangle = \left[\frac{1}{\left(1/v_{inj} \right) + 1 / \left(D_{eff} / \mathcal{L} \right)} \right] \frac{\left(1 - e^{-qV_{DS}/k_B T} \right)}{\left(1 + e^{-qV_{DS}/k_B T} \right)}$$

need: $\mathcal{L}(V_{GS}, V_{DS})$

references

Lundstrom and Guo, *Nanoscale Transistors*, Springer, 2006

Lundstrom, “Notes on the Ballistic Transistor,”
EE612 handout

summary

- 1) Easy to calculate I - V assuming drift transport
- 2) Easy to calculate I - V assuming ballistic transport
- 3) Easy to understand the physics of transport between ballistic and diffusive regimes (the quasi-ballistic region)
- 4) Hard to calculate the I - V characteristic in the quasi-ballistic regime (where MOSFETs operate today).