

NCN@Purdue - Intel Summer School: July 14-25, 2008

Physics of Nanoscale Transistors: Lecture 3A:

Theory of the Ballistic MOSFET

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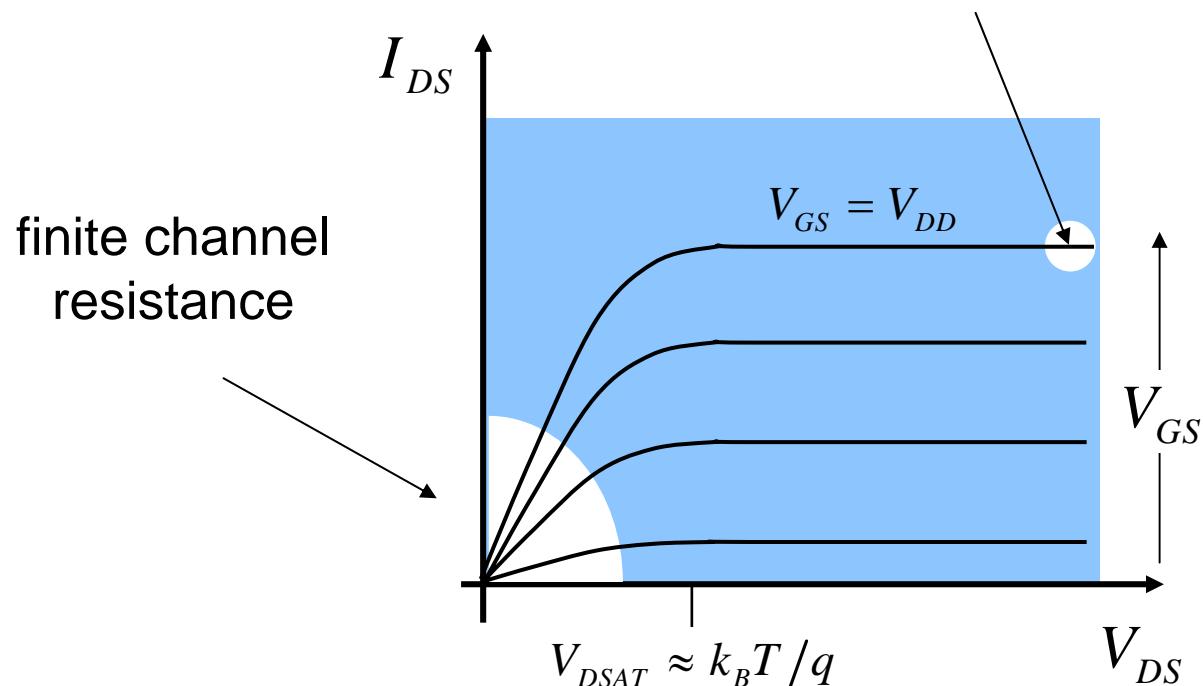
outline

- 1) **Introduction / Review**
- 2) Drain current
- 3) Filling states at the top of the barrier
- 4) I-V characteristic
- 5) Discussion
- 6) Summary

review: the ballistic MOSFET

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

(Boltzmann statistics)
“on-current”



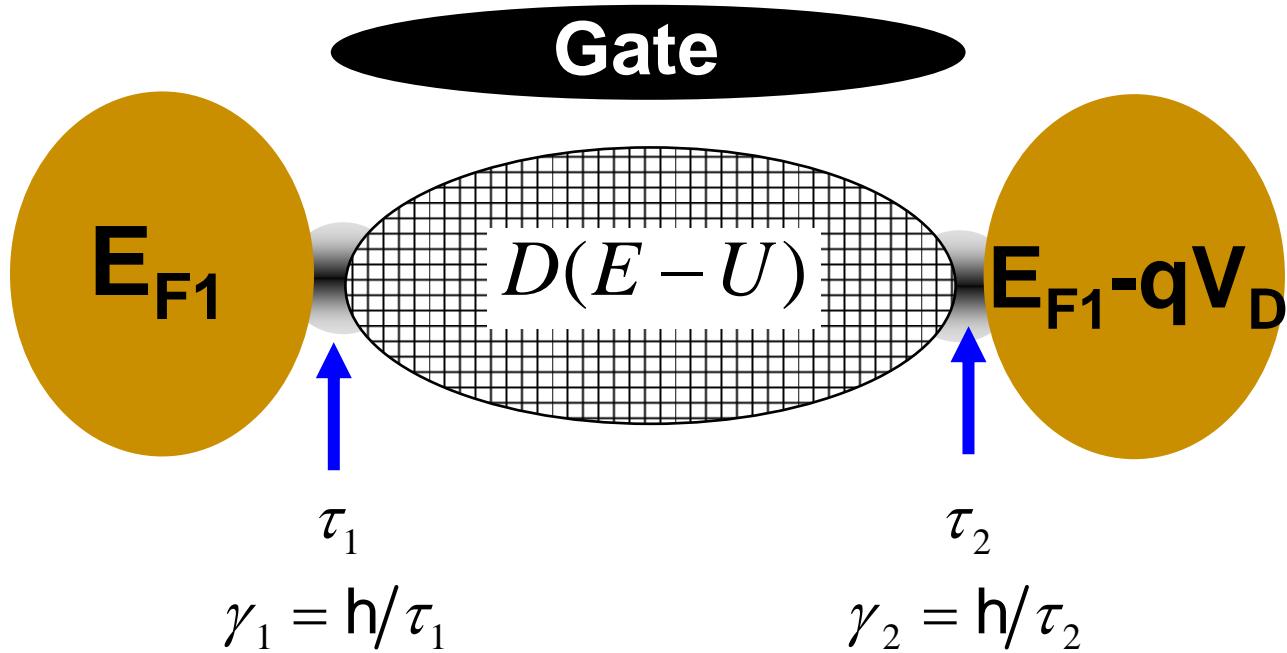
review: the ballistic MOSFET

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

Questions:

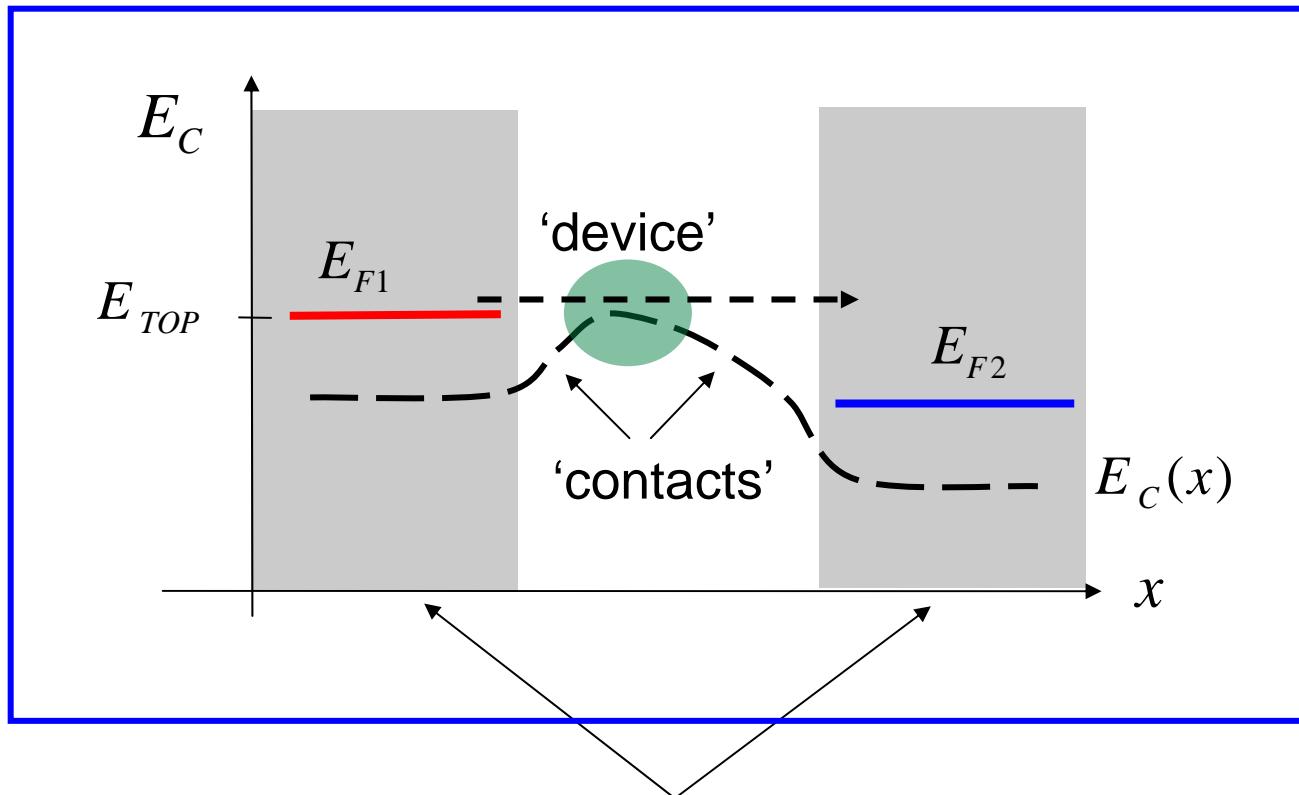
- 1) How do we generalize eqn. (1) for Fermi-Dirac statistics (essential above threshold)? **Part 1**
- 2) How do we properly treat MOS electrostatics? (subthreshold as well as above threshold and 2D in addition to 1D) **Part 2**

generic model of a nano-device



$$I = \frac{2q}{h} \int_{-\infty}^{\infty} \bar{T}(E) (f_1 - f_2) dE \quad \bar{T}(E) = \pi D(E - U) \frac{\gamma_1 \gamma_2}{\gamma_1 + \gamma_2}$$

the ballistic MOSFET and the generic model



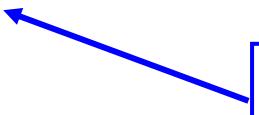
thermal equilibrium
reservoirs, **reflectionless**

expression for current

$$I_D = \frac{2q}{h} \int_{-\infty}^{\infty} T(E)M(E)(f_1 - f_2)dE$$

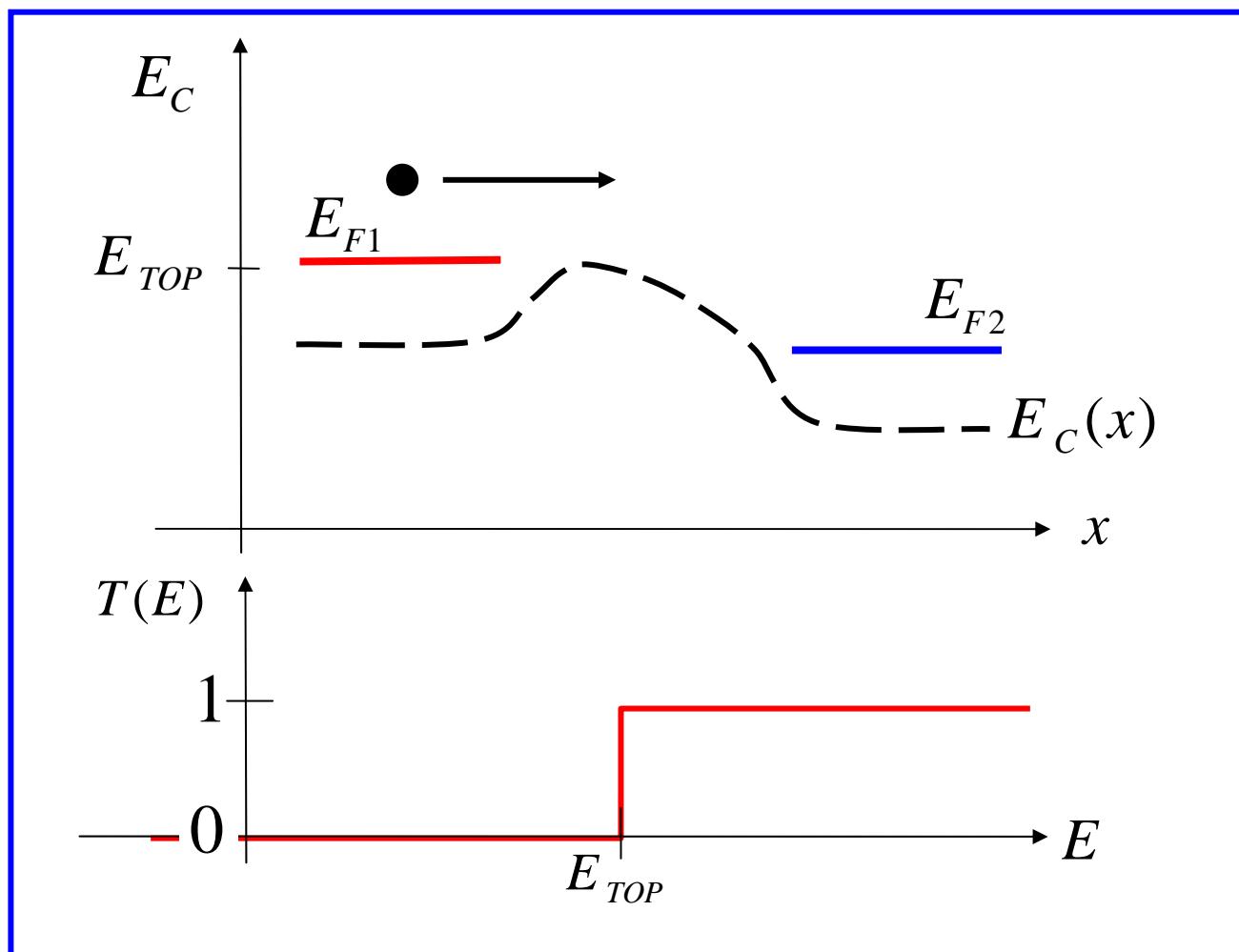


$\bar{T}(E) = T(E)M(E)$

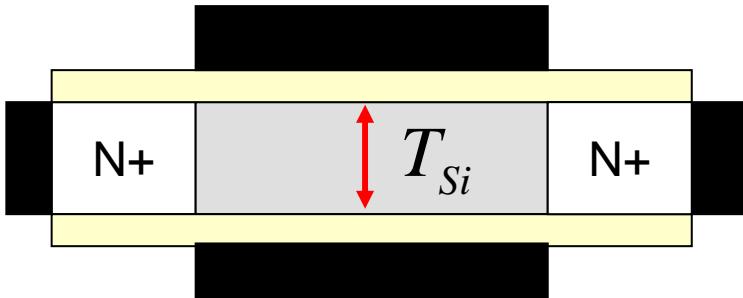


- 1) semiclassical treatment of $T(E)$
- 2) parabolic energy bands for $M(E)$

transmission in the ballistic MOSFET

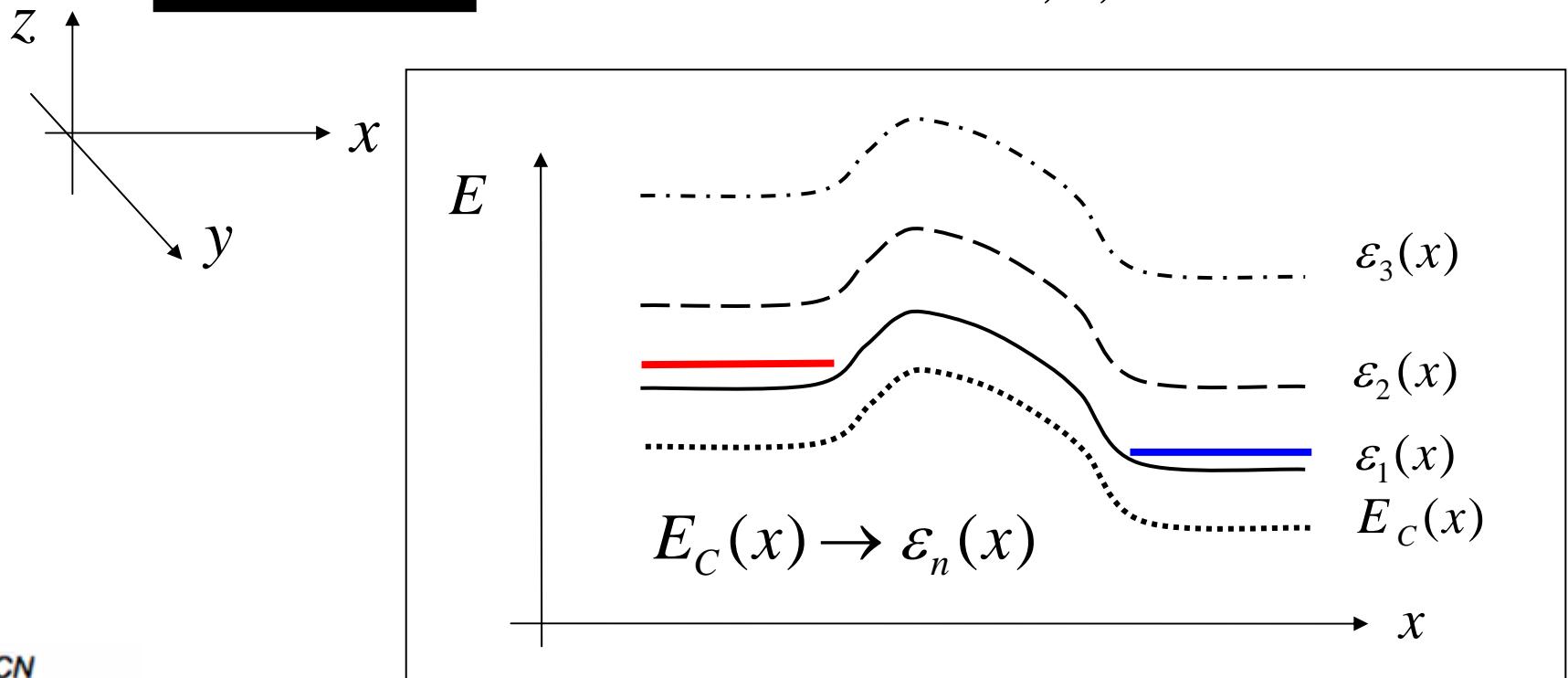


energy subbands in a MOSFET



$$\varepsilon_n = \frac{\hbar^2 n^2 \pi^2}{2m^* T_{Si}^2}$$

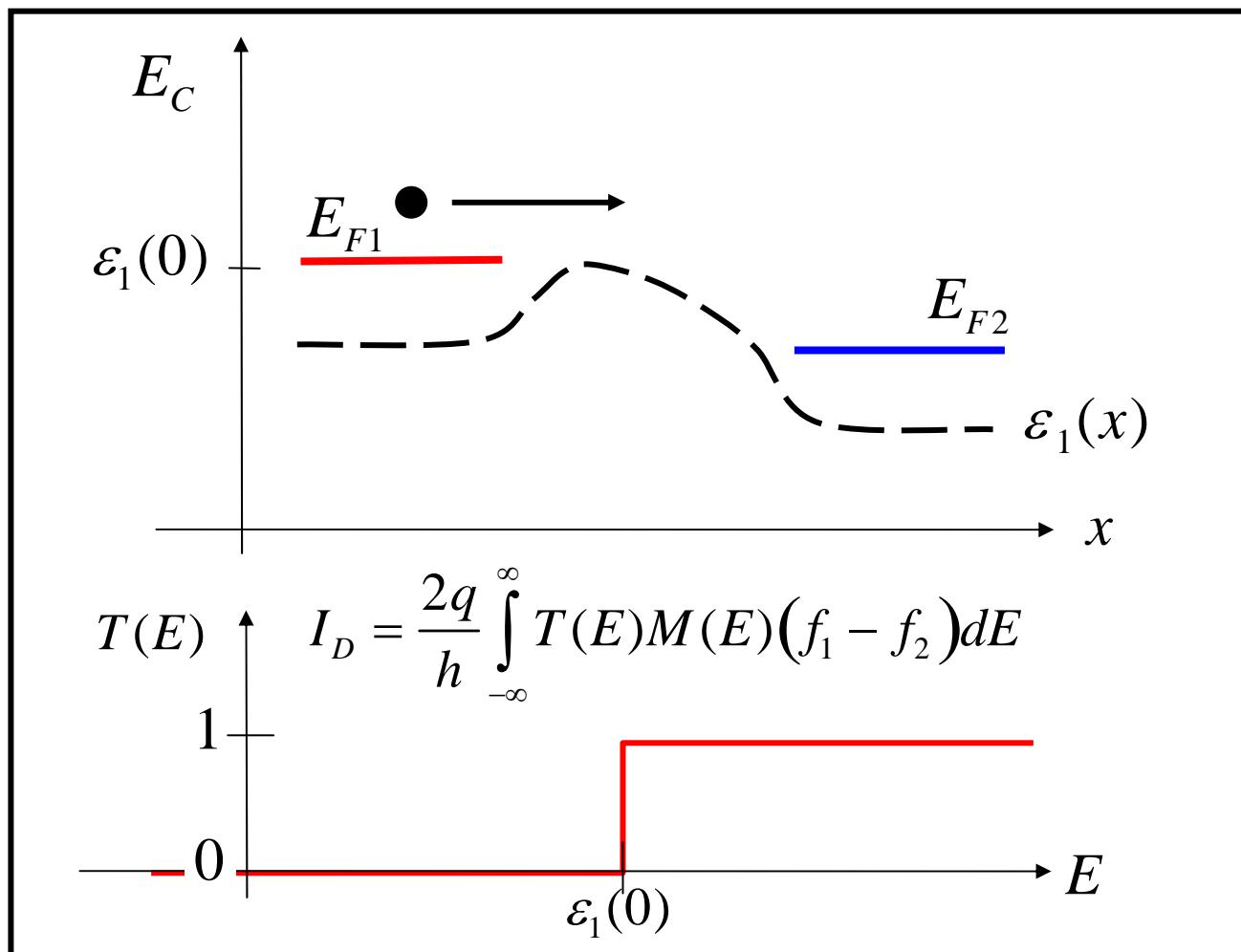
$$n = 1, 2, 3 \dots$$



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current in a ballistic MOSFET



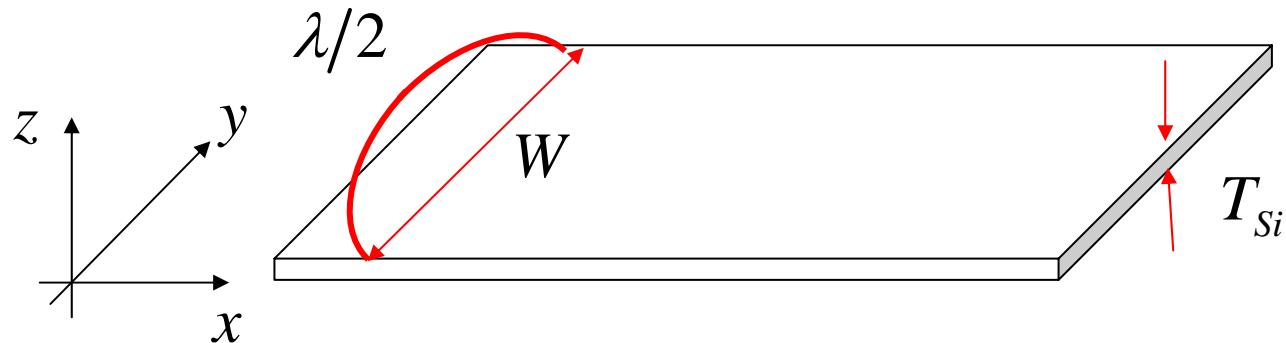
transverse conducting channels (modes)

$$I_D = \frac{2q}{h} \int_{-\infty}^{\infty} T(E)M(E)(f_1 - f_2)dE \quad I_D = \frac{2q}{h} \int_{\varepsilon_1(0)}^{\infty} M(E)(f_1 - f_2)dE$$

$M(E) = ?$

Assume that there is **one** subband associated with confinement in the z-direction. **Many** subbands associated with confinement in the y-direction

lowest mode

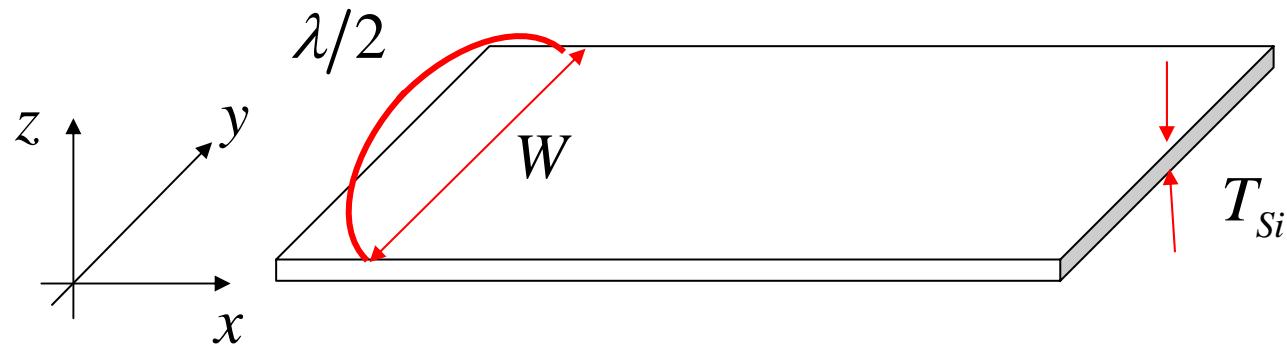


$M = \#$ of electron half wavelengths that fit into W .

transverse conducting channels below energy, E

$M = \# \text{ of electron half wavelengths that fit into } W.$

lowest mode



$$E - \varepsilon_1(0) = \frac{\hbar^2 k^2}{2m^*}$$

$$k = \frac{2\pi}{\lambda}$$

$$M(E) = \text{int} \frac{W}{(\lambda/2)}$$

$$\left. \right\}$$

$$M(E) = W \frac{\sqrt{2m^*[E - \varepsilon_1(0)]}}{\pi\hbar}$$

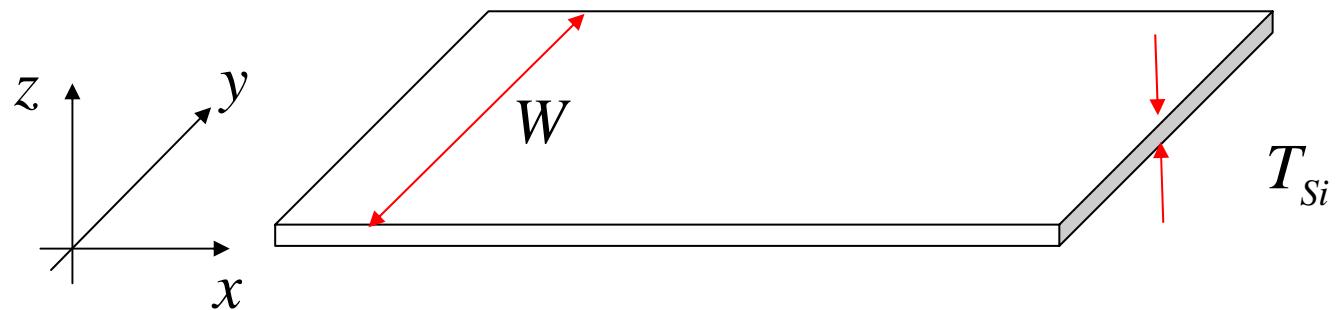
transverse modes below E (another approach)

$$g_{1D}(E) = \frac{1}{\pi h} \sqrt{\frac{m^*}{2[E - \varepsilon_1(0)]}} \text{ #/eV-cm}$$

(Divided by 2 to account for the fact the spin has already been included in the current formula.)

$$M(E) = W \int_{\varepsilon_1(0)}^E g_{1D}(E) dE = W \frac{\sqrt{2m^*[E - \varepsilon_1(0)]}}{\pi h}$$

$M(E)$ = number of transverse modes in the y-direction with energy cut-off less than E .



the drain current

$$I_D = \frac{2q}{h} \int_{\varepsilon_1(0)}^{\infty} M(E) (f_1 - f_2) dE \quad M(E) = W \sqrt{2m^* [E - \varepsilon_1(0)]} / \pi \hbar$$

$$I_D = I^+ - I^-$$

$$I^+ = \frac{2q}{h} \int_{\varepsilon_1(0)}^{\infty} M(E) f_1(E) dE \quad I^- = \frac{2q}{h} \int_{\varepsilon_1(0)}^{\infty} M(E) f_2(E) dE$$

$$I^+ = W \frac{2q}{h} \frac{1}{\pi \hbar} \int_{\varepsilon_1(0)}^{\infty} \frac{\sqrt{2m^* [E - \varepsilon_1(0)]}}{1 + e^{(E - E_F)/k_B T}} dE$$

the drain current: cont.

$$I^+ = W \frac{2q}{h} \frac{1}{\pi \hbar} \int_{\varepsilon_1(0)}^{\infty} \frac{\sqrt{2m^* [E - \varepsilon_1(0)]}}{1 + e^{(E - E_F)/k_B T}} dE$$

$$\left\{ \begin{array}{l} \eta \equiv [E - \varepsilon_1(0)]/k_B T \\ \eta_{F1} \equiv [E_{F1} - \varepsilon_1(0)]/k_B T \end{array} \right.$$

$$I^+ = W \frac{2q}{h} \frac{\sqrt{2m^*} (k_B T)^{3/2}}{\pi \hbar} \int_0^{\infty} \frac{\eta^{1/2}}{1 + e^{\eta - \eta_{F1}}} d\eta$$

$$\left\{ \begin{array}{l} \mathcal{F}_{1/2}(\eta_F) \equiv \frac{2}{\sqrt{\pi}} \int_0^{+\infty} \frac{\eta^{1/2} d\eta}{1 + e^{\eta - \eta_F}} \end{array} \right.$$

$$I^+ = Wq \left(\frac{m^* k_B T}{2\pi \hbar^2} \right) \sqrt{\frac{2k_B T}{\pi m^*}} \mathcal{F}_{1/2}(\eta_{F1}) = Wq \left(\frac{N_{2D}}{2} v_T \right) \mathcal{F}_{1/2}(\eta_{F1})$$

Fermi-Dirac integrals

$$\mathcal{F}_{1/2}(\eta_F) \equiv \frac{2}{\sqrt{\pi}} \int_0^{+\infty} \frac{\eta^{1/2} d\eta}{1 + e^{\eta - \eta_F}}$$

Fermi-Dirac integral of **order 1/2**

the drain current: cont.

$$I^+ = Wq \left(\frac{N_{2D}}{2} v_T \right) \mathcal{F}_{1/2}(\eta_{F1}) \quad \eta_{F1} \equiv [E_{F1} - \varepsilon_1(0)]/k_B T$$

$$I^- = Wq \left(\frac{N_{2D}}{2} v_T \right) \mathcal{F}_{1/2}(\eta_{F2}) \quad \begin{aligned} \eta_{F2} &\equiv [E_{F2} - \varepsilon_1(0)]/k_B T \\ &= [E_{F1} - qV_{DS} - \varepsilon_1(0)]/k_B T \\ &= \eta_{F1} - qV_{DS}/k_B T \end{aligned}$$

$$I_D = I^+ - I^-$$

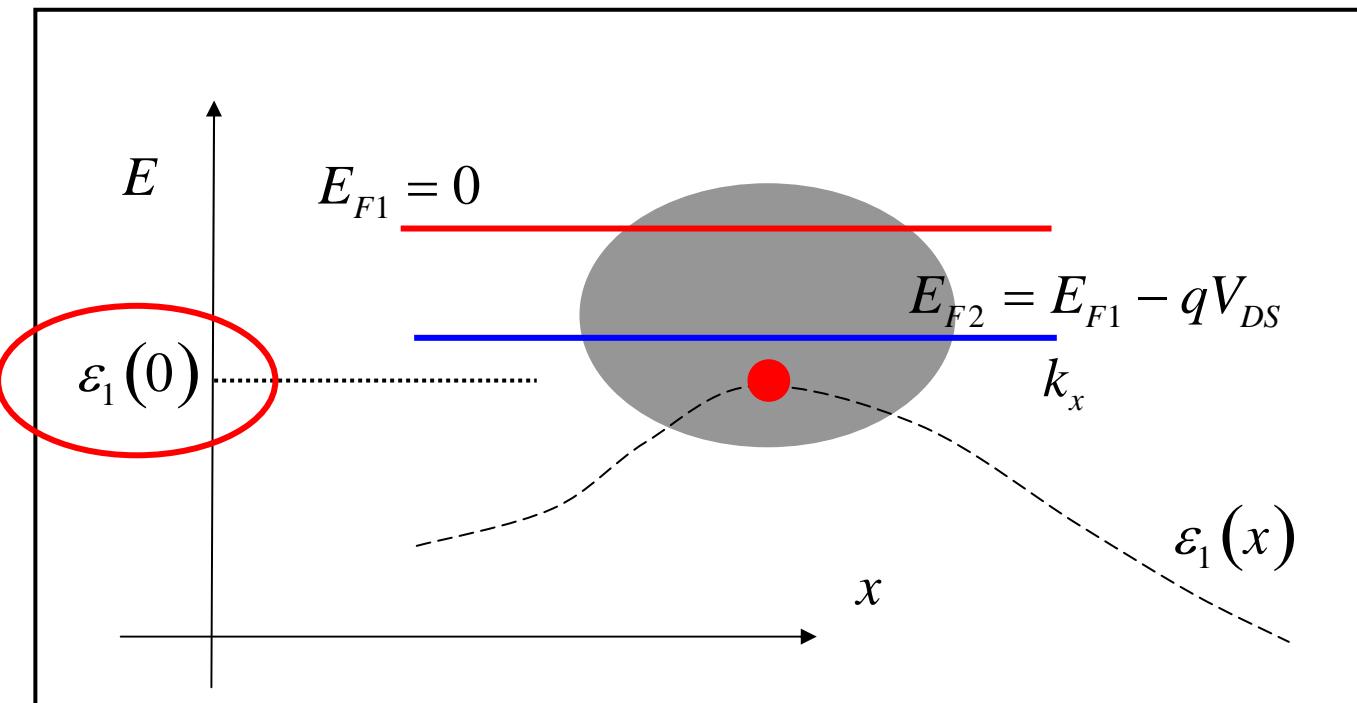
$$I_D = Wq \left(\frac{N_{2D}}{2} v_T \right) [\mathcal{F}_{1/2}(\eta_{F1}) - \mathcal{F}_{1/2}(\eta_{F2})]$$

the drain current: cont.

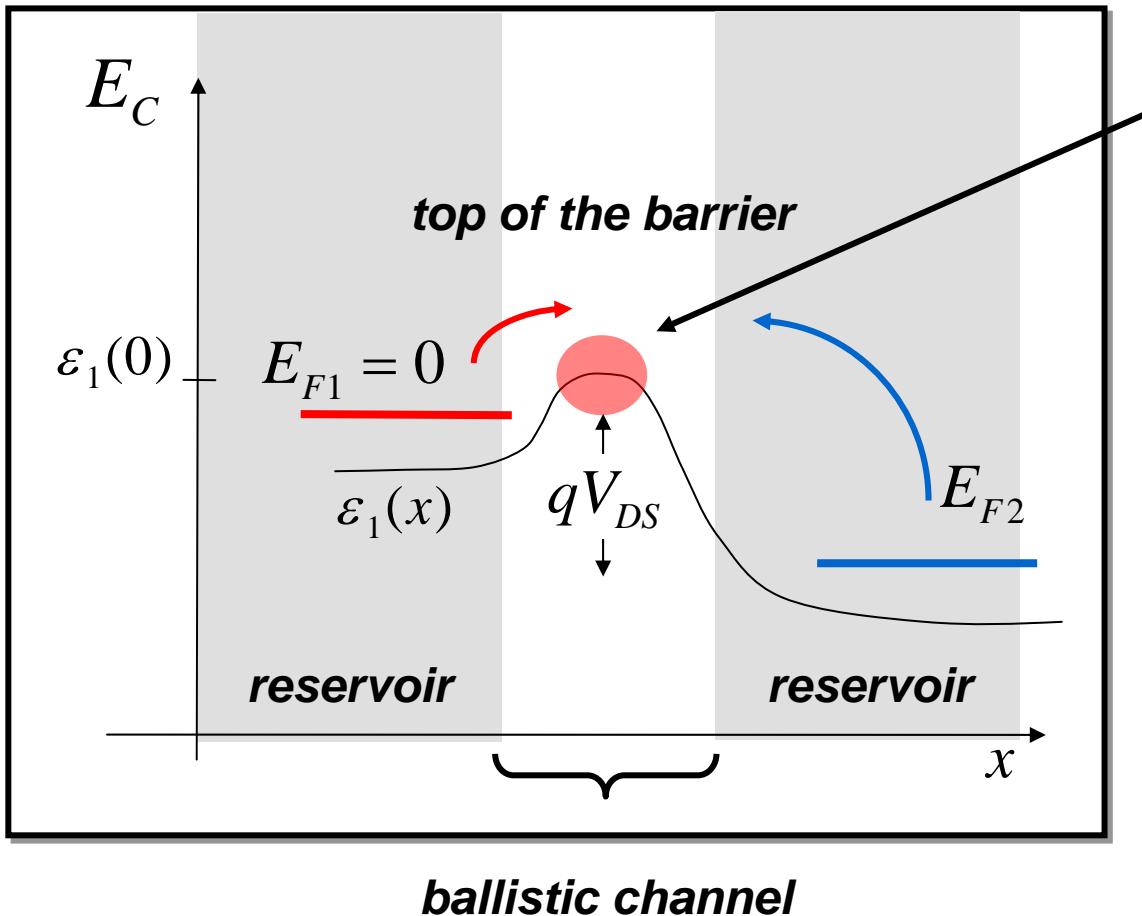
$$I_D = Wq \left(\frac{N_{2D}}{2} v_T \right) [\mathcal{F}_{1/2}(\eta_{F1}) - \mathcal{F}_{1/2}(\eta_{F2})]$$

$$\eta_{F1} \equiv [E_{F1} - \varepsilon_1(0)]/k_B T$$

$$\eta_{F2} = \eta_{F1} - qV_{DS}/k_B T$$



the Landauer picture of a nano-MOSFET



The gate voltage controls the top of the barrier, and, therefore, $\varepsilon_1(0)$.

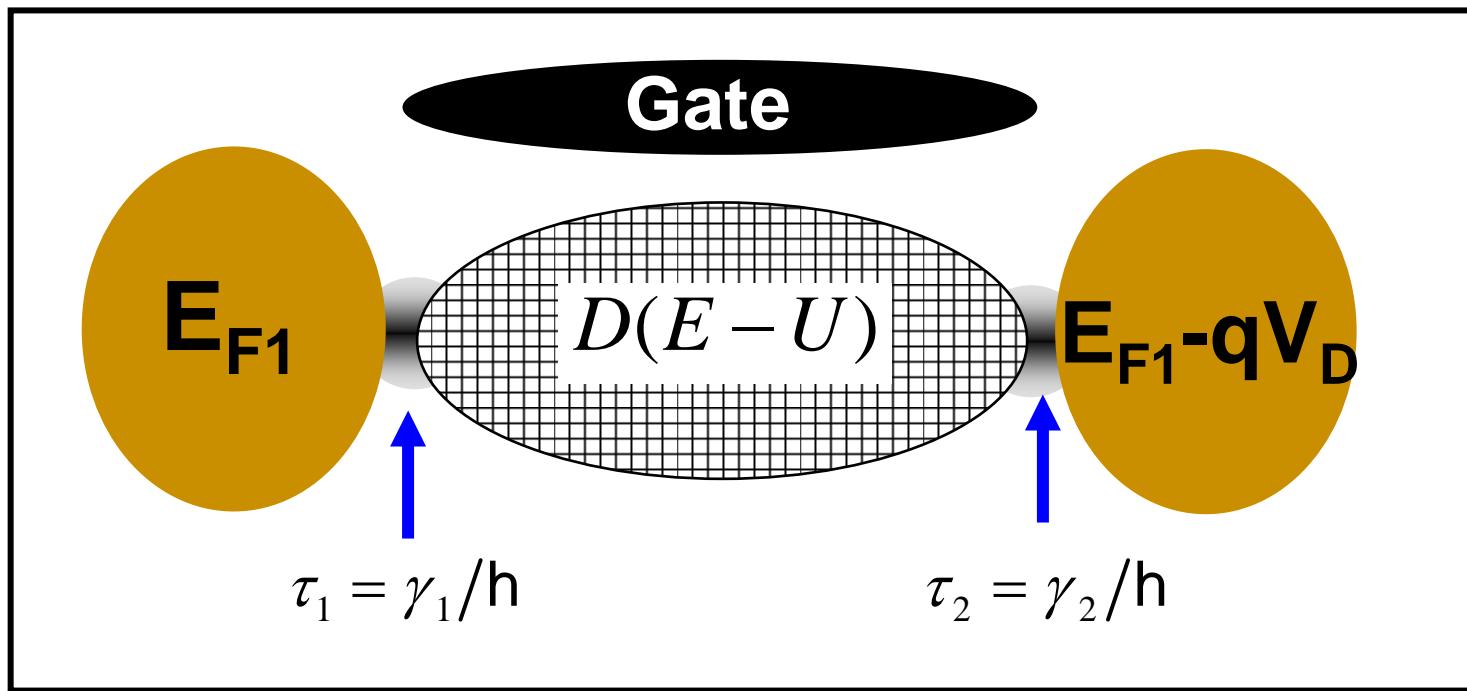
If we know $\varepsilon_1(0)$, then we know η_{F1} and η_{F2} .

If we know η_{F1} and η_{F2} , then we know I_D .

outline

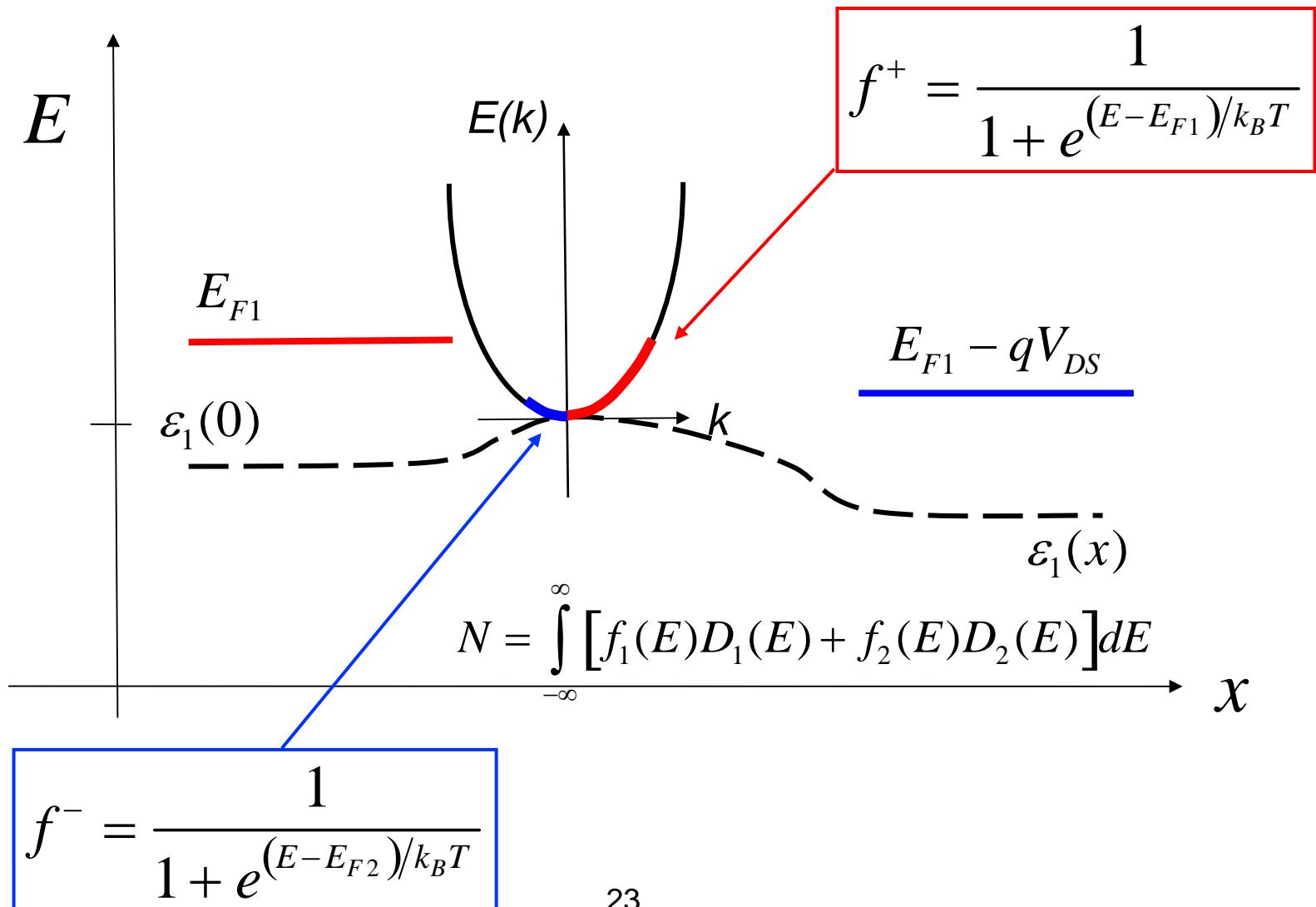
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the generic model

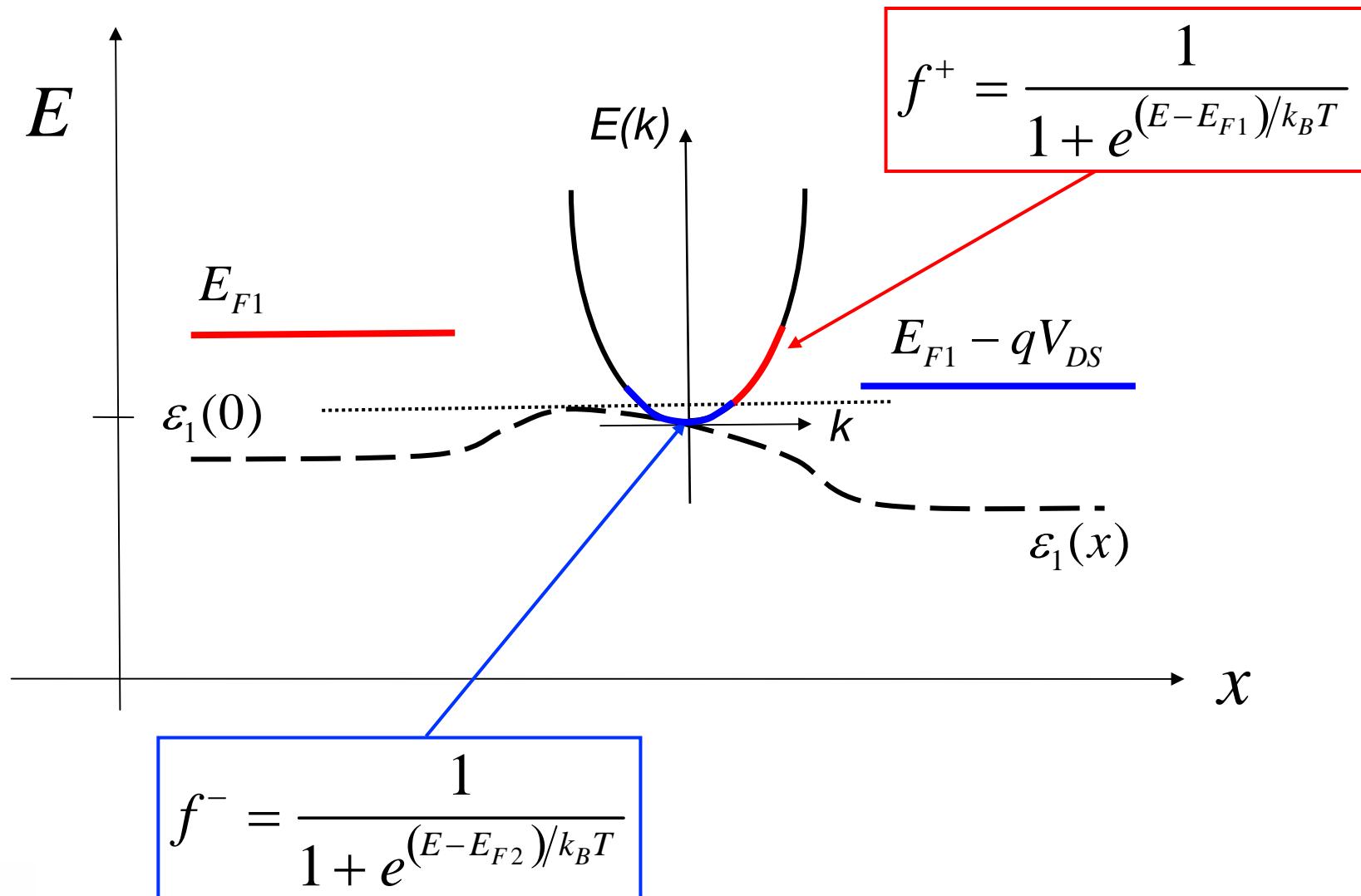


$$N = \int_{-\infty}^{\infty} [f_1(E)D_1(E) + f_2(E)D_2(E)]dE$$

filling states in a ballistic MOSFET (k-space approach)



filling states in a ballistic MOSFET (k-space approach)



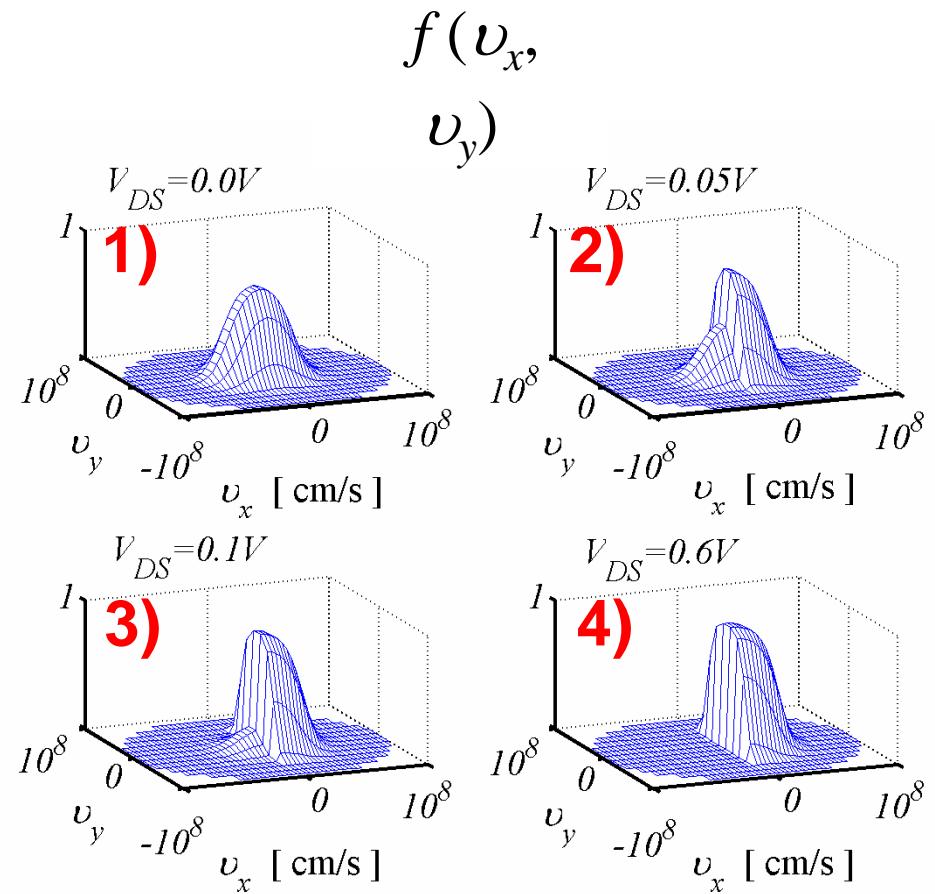
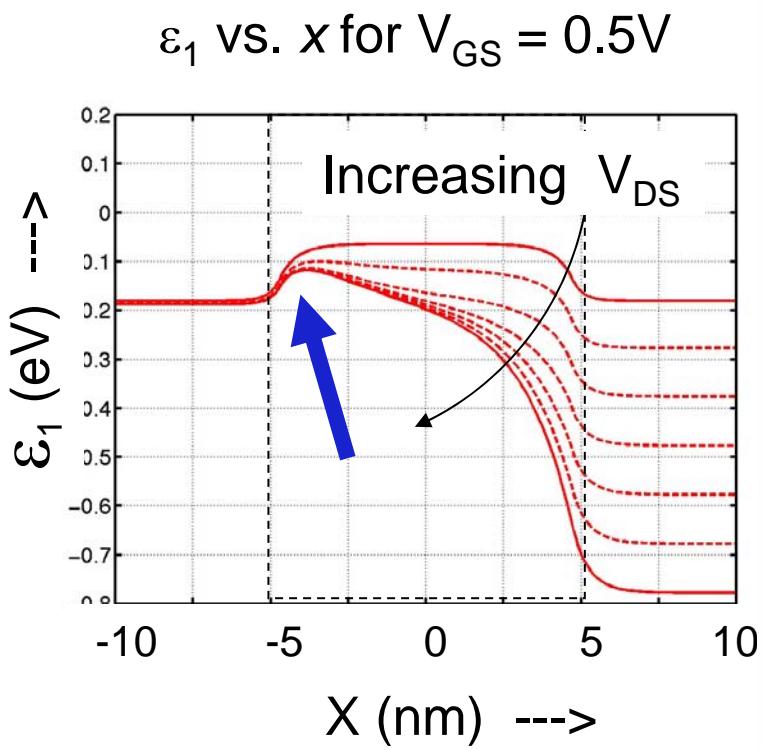
filling states: summary

$$N = \int_{-\infty}^{\infty} [f_1(E)D_1(E) + f_2(E)D_2(E)]dE$$

- 1) In a ballistic device with contacts in equilibrium and identical connections to the contacts, each state inside the device is in **equilibrium** - with *one* of the two contacts.

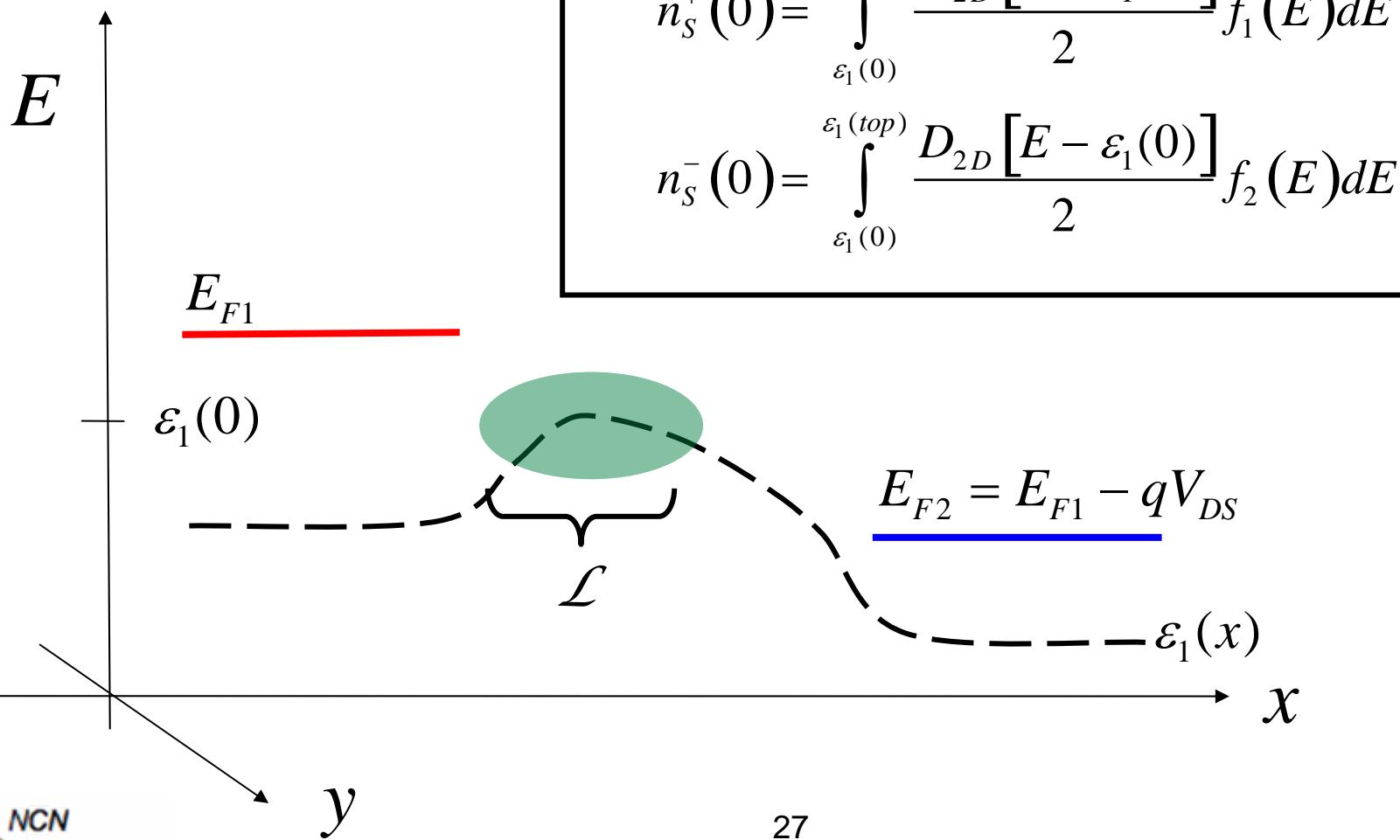
- 2) Things are especially simple at the top of the barrier: + velocity states are filled by the source, and - velocity states are filled by the drain.

filling states in a planar MOSFET



(Numerical simulations of an $L = 10$ nm double gate Si MOSFET from J.-H. Rhew and M.S.Lundstrom, *Solid-State Electron.*, **46**, 1899, 2002)

mathematics of filling states (energy space)



integration in energy space

$$n_S^+(0) = \int_{\varepsilon_1(0)}^{\varepsilon_1(\text{top})} \frac{D_{2D} [E - \varepsilon_1(0)]}{2} f_1(E) dE \quad D_{2D}(E) = \frac{m^*}{\pi \hbar^2}$$

$$n_S^+(0) = \frac{m^*}{2\pi \hbar^2} \int_{\varepsilon_1(0)}^{\infty} \frac{dE}{1 + e^{(E - E_{F1})/k_B T}}$$

$$\left\{ \begin{array}{l} \eta \equiv [E - \varepsilon_1(0)]/k_B T \\ \eta_{F1} \equiv [E_{F1} - \varepsilon_1(0)]/k_B T \end{array} \right.$$

$$n_S^+(0) = \frac{m^* k_B T}{2\pi \hbar^2} \int_0^{\infty} \frac{d\eta}{1 + e^{\eta - \eta_{F1}}} = \frac{N_{2D}}{2} \ln(1 + e^{\eta_{F1}}) = \frac{N_{2D}}{2} \mathcal{F}_0(\eta_{F1})$$

filling states in a planar MOSFET

$$n_S^+(0) = \frac{N_{2D}}{2} \mathcal{F}_0(\eta_{F1})$$

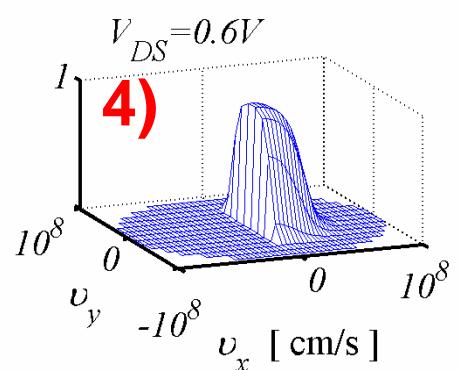
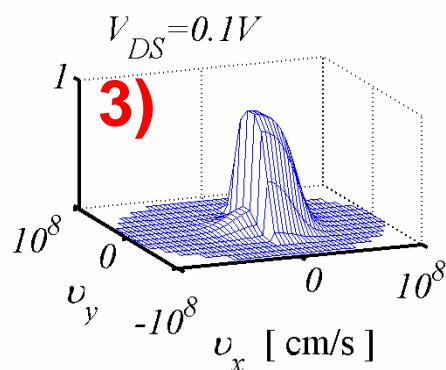
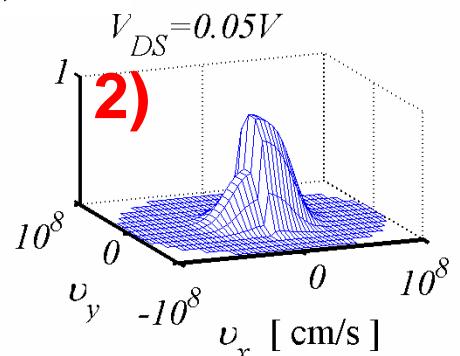
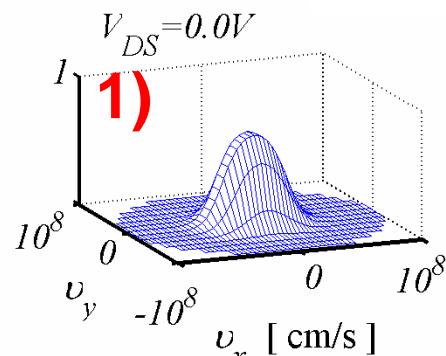
$$n_S^-(0) = \frac{N_{2D}}{2} \mathcal{F}_0(\eta_{F2})$$

$$N_{2D} = \frac{m^* k_B T}{\pi \hbar^2} \text{#/cm}^2$$

$$\eta_{F1} \equiv (E_{F1} - \varepsilon_1(0)) / k_B T$$

$$\eta_{F2} \equiv \eta_{F1} - qV_{DS}/k_B T$$

$$f(v_x, v_y)$$



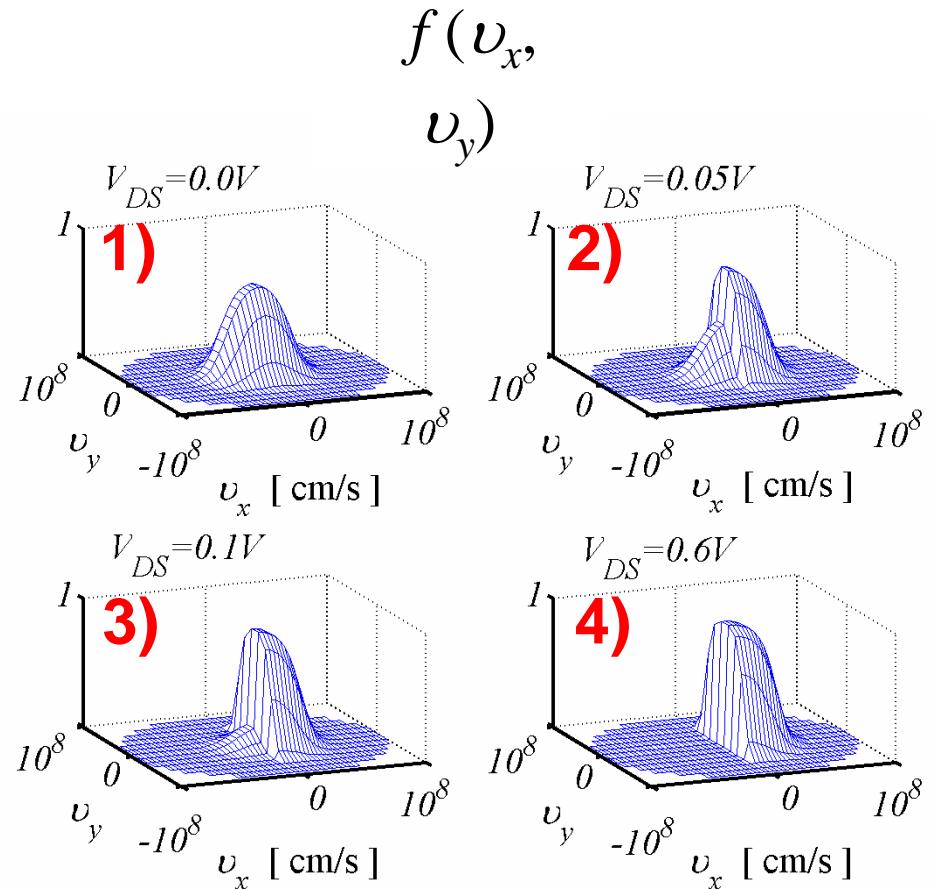
filling states in a planar MOSFET

Note that the positive half in case 4) ($V_{DS} \gg k_B T/q$) is larger than the positive half in case 1) ($V_{DS} = 0$). Why?

Answer: Because the total number of carriers is fixed at:

$$n_s(0) = \frac{C_{ox}}{q} (V_{GS} - V_T)$$

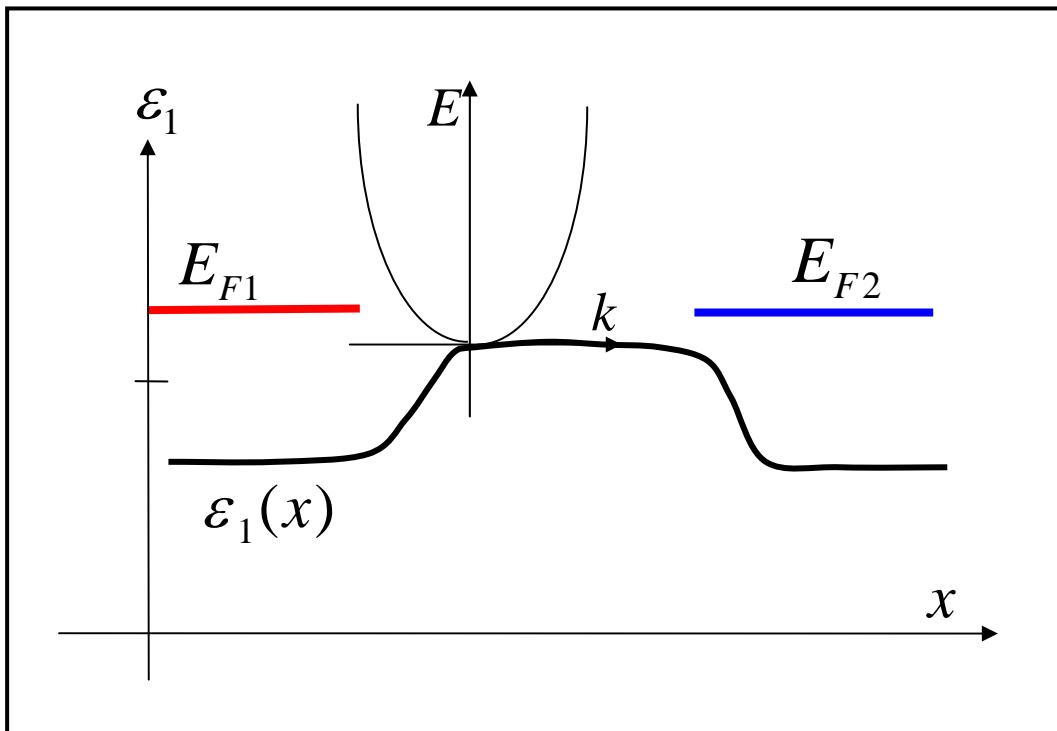
How does this happen?



low V_{DS}

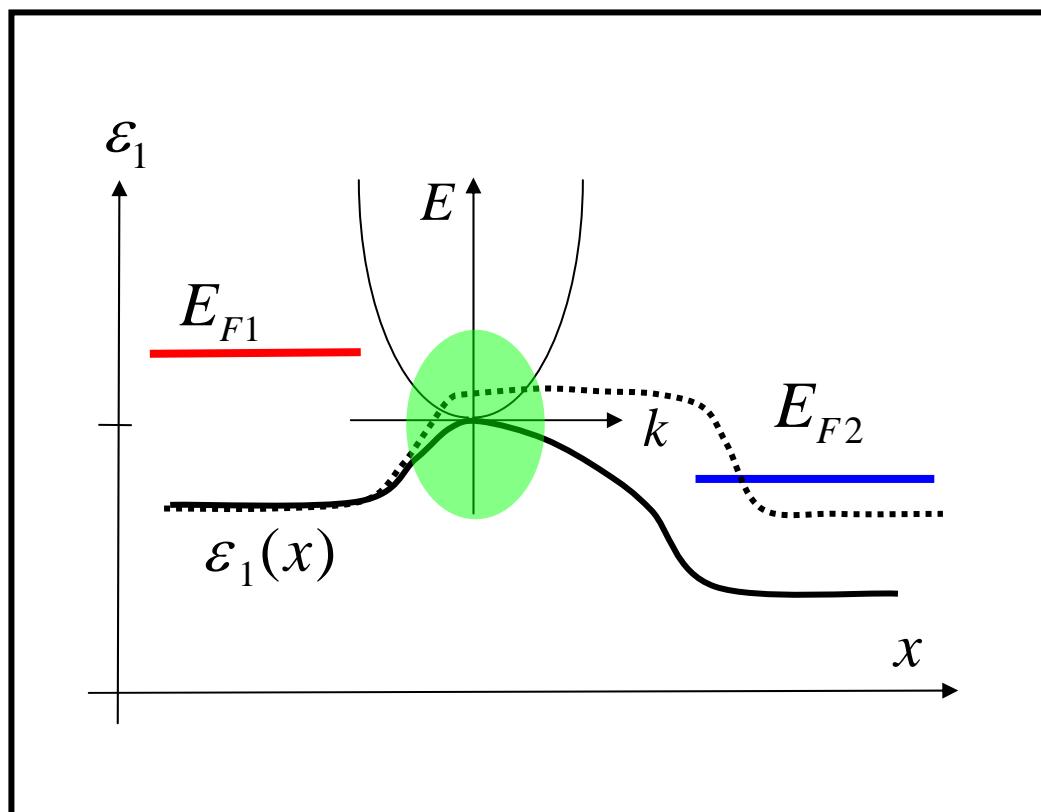
$$n_s(0) = n_s^+(0) + n_s^-(0)$$

$$n_s^+(0) \approx n_s^-(0)$$



high V_{DS}

$$n_s(0) \approx n_s^+(0)$$



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re-cap

$$I_D = Wq \left(\frac{N_{2D}}{2} v_T \right) [\mathcal{F}_{1/2}(\eta_{F1}) - \mathcal{F}_{1/2}(\eta_{F2})] \quad (1)$$

$$n_s(0) = \frac{N_{2D}}{2} [\mathcal{F}_0(\eta_{F1}) + \mathcal{F}_0(\eta_{F2})] \quad (2)$$

Solve (2) for N_{2D} , then insert in (1):

I-V characteristic

$$I_D = Wqn_s(0)v_T \left[\frac{\mathcal{F}_{1/2}(\eta_{F1}) - \mathcal{F}_{1/2}(\eta_{F2})}{\mathcal{F}_0(\eta_{F1}) + \mathcal{F}_0(\eta_{F2})} \right]$$

$$I_D = Wqn_s(0) \left\{ v_T \frac{\mathcal{F}_{1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} \right\} \left[\frac{1 - \mathcal{F}_{1/2}(\eta_{F2})/\mathcal{F}_{1/2}(\eta_{F1})}{1 + \mathcal{F}_0(\eta_{F2})/\mathcal{F}_0(\eta_{F1})} \right]$$

$qn_s(0) \approx C_{ox}(V_{GS} - V_T)$ (simple, 1D MOS electrostatics
 $V_{GS} > V_T$)

final result

$$I_D = WC_{ox} (V_{GS} - V_T) \wp \left[\frac{1 - \mathcal{F}_{1/2}(\eta_{F2}) / \mathcal{F}_{1/2}(\eta_{F1})}{1 + \mathcal{F}_0(\eta_{F2}) / \mathcal{F}_{10}(\eta_{F1})} \right]$$

$$\wp \equiv \sqrt{\frac{2k_B T}{\pi m^*}} \frac{\mathcal{F}_{1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} = v_T \frac{\mathcal{F}_{1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})}$$

using the final result

$$I_D = WC_{ox} (V_{GS} - V_T) \wp \left[\frac{1 - \mathcal{F}_{1/2}(\eta_{F2}) / \mathcal{F}_{1/2}(\eta_{F1})}{1 + \mathcal{F}_0(\eta_{F2}) / \mathcal{F}_{10}(\eta_{F1})} \right] \quad (1)$$

$$\wp \equiv \sqrt{\frac{2k_B T}{\pi m^*}} \frac{\mathcal{F}_{1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} = v_T \frac{\mathcal{F}_{1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} \quad (2)$$

$$C_{ox} (V_{GS} - V_T) = q \frac{N_{2D}}{2} [\mathcal{F}_0(\eta_{F1}) + \mathcal{F}_0(\eta_{F2})] \quad (3)$$

$$\eta_{F2} = \eta_{F1} - qV_{DS}/k_B T \quad (4)$$

Given, V_{GS} and V_{DS} , solve (3) for η_{F1}
then solve (2) for the ‘ballistic injection velocity.’

Finally, solve (1) for I_D .

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key results

$$I_D = WC_{ox} (V_{GS} - V_T) \wp \left[\frac{1 - \mathcal{F}_{1/2}(\eta_{F2})/\mathcal{F}_{1/2}(\eta_{F1})}{1 + \mathcal{F}_0(\eta_{F2})/\mathcal{F}_0(\eta_{F1})} \right]$$

$$\wp \equiv \sqrt{\frac{2k_B T}{\pi m^*}} \frac{\mathcal{F}_{1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} = v_T \frac{\mathcal{F}_{1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})}$$

See: “Notes on Fermi-Dirac Integrals, 2nd Edition”
by Raseong Kim and Mark Lundstrom

Boltzmann limit: $[E_F - \varepsilon_1(0)]/k_B T \ll 0$ $\eta \ll 0$ $\mathcal{F}_j(\eta) \rightarrow e^\eta$

Boltzmann limit

$$I_D = WC_{ox} (V_{GS} - V_T) \mathcal{B}_P \left[\frac{1 - \mathcal{F}_{1/2}(\eta_{F2}) / \mathcal{F}_{1/2}(\eta_{F1})}{1 + \mathcal{F}_0(\eta_{F2}) / \mathcal{F}_0(\eta_{F1})} \right]$$

$$\mathcal{B}_P \equiv \sqrt{\frac{2k_B T}{\pi m^*}} \frac{\mathcal{F}_{1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} = v_T \frac{\mathcal{F}_{1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})}$$

$$\tilde{v}_T \rightarrow v_T = \sqrt{\frac{2k_B T}{\pi m^*}} \quad I_D \rightarrow WC_{ox} (V_{GS} - V_T) v_T \left[\frac{1 - e^{-qV_{DS}/k_B T}}{1 + e^{-qV_{DS}/k_B T}} \right]$$

examine result

$$I_D = WC_{ox} (V_{GS} - V_T) \vartheta_T \left[\frac{1 - \mathcal{F}_{1/2}(\eta_{F2}) / \mathcal{F}_{1/2}(\eta_{F1})}{1 + \mathcal{F}_0(\eta_{F2}) / \mathcal{F}_0(\eta_{F1})} \right] \quad \vartheta_T = v_T \frac{\mathcal{F}_{1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})}$$

- 1) Ballistic injection velocity (now gate voltage dependent)
- 2) High drain bias (on-current)
- 3) Low drain bias (ballistic channel conductance)
- 4) Ballistic mobility
- 5) Drain saturation voltage (was $\sim k_B T/q$)

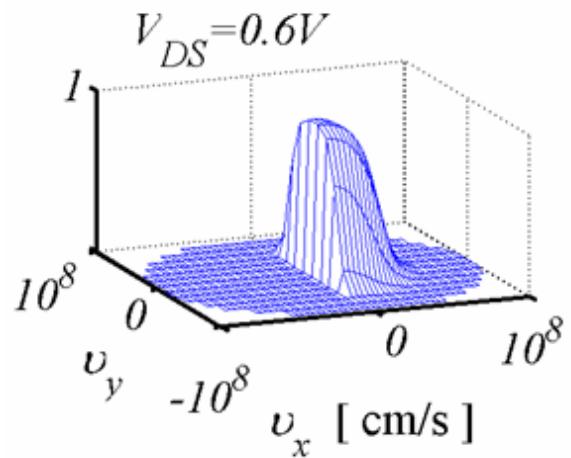
injection velocity

$$\beta_p \equiv \sqrt{\frac{2k_B T}{\pi m^*}} \frac{\mathcal{F}_{1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} = v_T \frac{\mathcal{F}_{1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})}$$

most convenient to plot vs. $n_S(0)$.

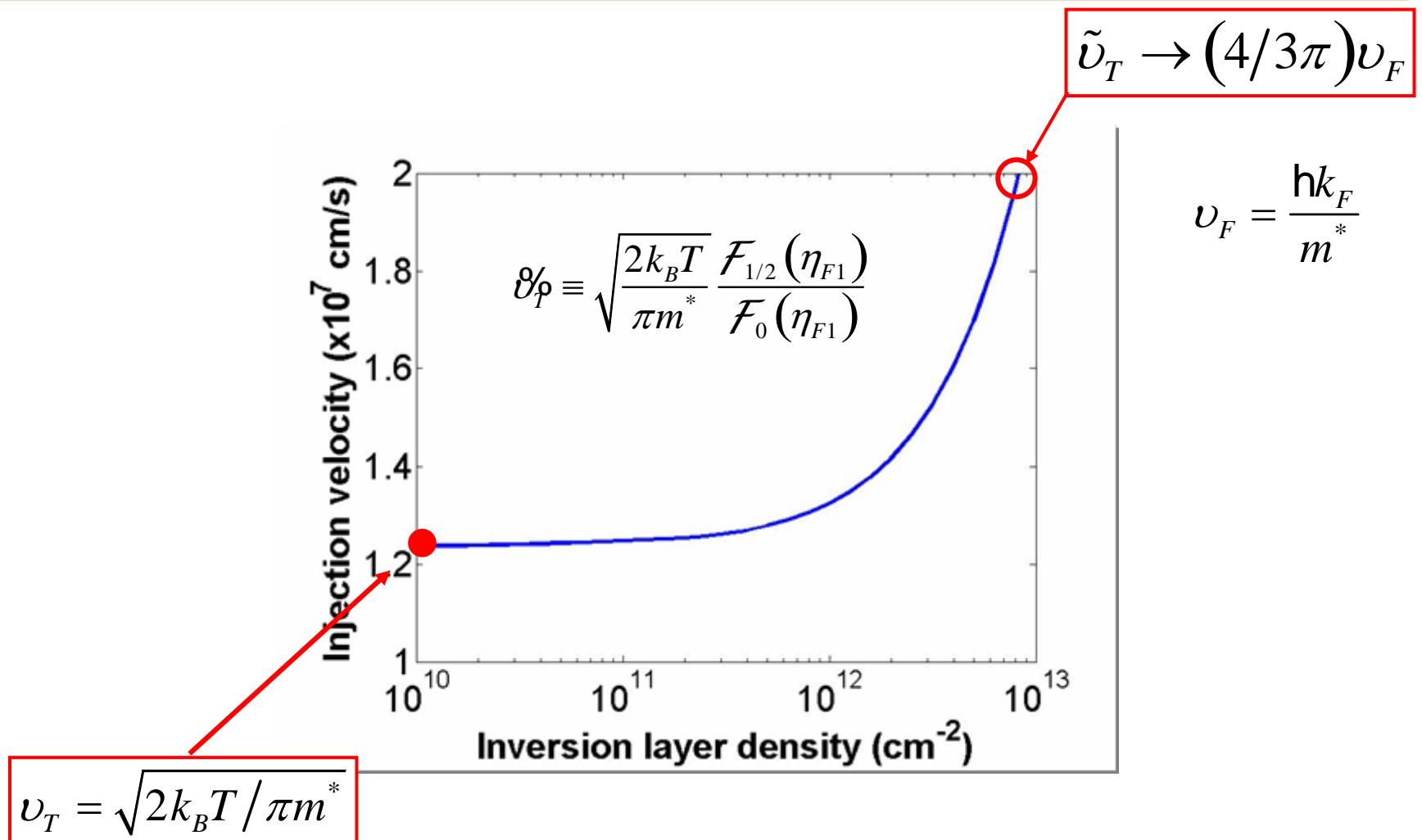
Assume:

- 1) Si (100)
- 2) 1 subband occupied
- 3) parabolic energy bands



$\langle v(0) \rangle$ for high drain bias.

injection velocity vs. $n_S(0)$



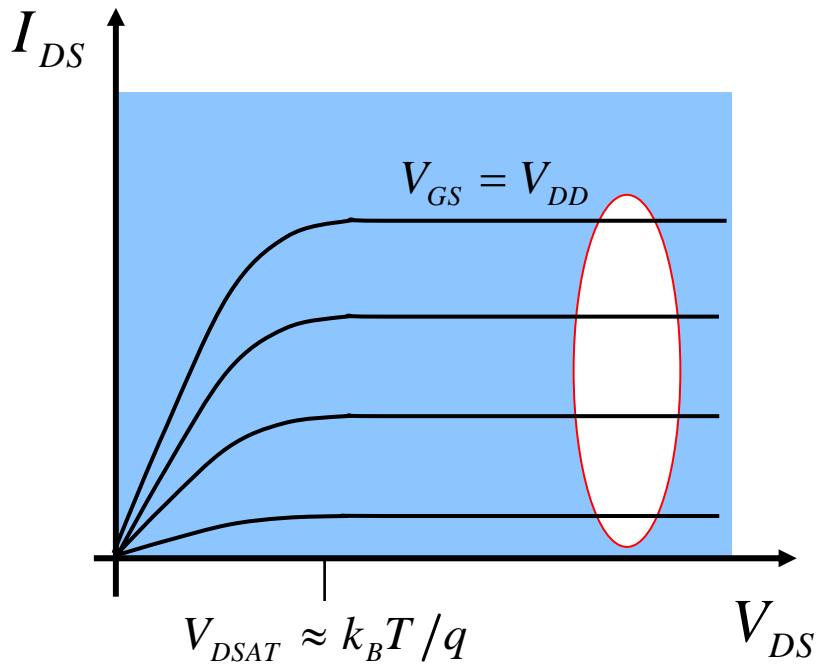
high drain bias

$$I_D = WC_{ox} \vartheta_T (V_{GS} - V_T) \left[\frac{1 - \mathcal{F}_{1/2}(\eta_{F2}) / \mathcal{F}_{1/2}(\eta_{F1})}{1 + \mathcal{F}_0(\eta_{F2}) / \mathcal{F}_{10}(\eta_{F1})} \right]$$

$$\eta_{F2} = \eta_{F1} - qV_{DS}/k_B T = [E_{F1} - qV_{DS} - \varepsilon_1(0)]/k_B T \ll 0$$

$$\mathcal{F}_{1/2}(\eta_{F2}), \mathcal{F}_0(\eta_{F2}) \rightarrow e^{\eta_{F2}} \rightarrow 0$$

$$I_D \rightarrow WC_{ox} \vartheta_T (V_{GS} - V_T)$$



high gate and drain bias

$$I_D = WC_{ox} \vartheta_F (V_{GS} - V_T)$$

$$\tilde{v}_T \rightarrow v_T \frac{4}{3\sqrt{\pi}} \eta_{F1}^{1/2} \sim (V_{GS} - V_T)^{1/2}$$

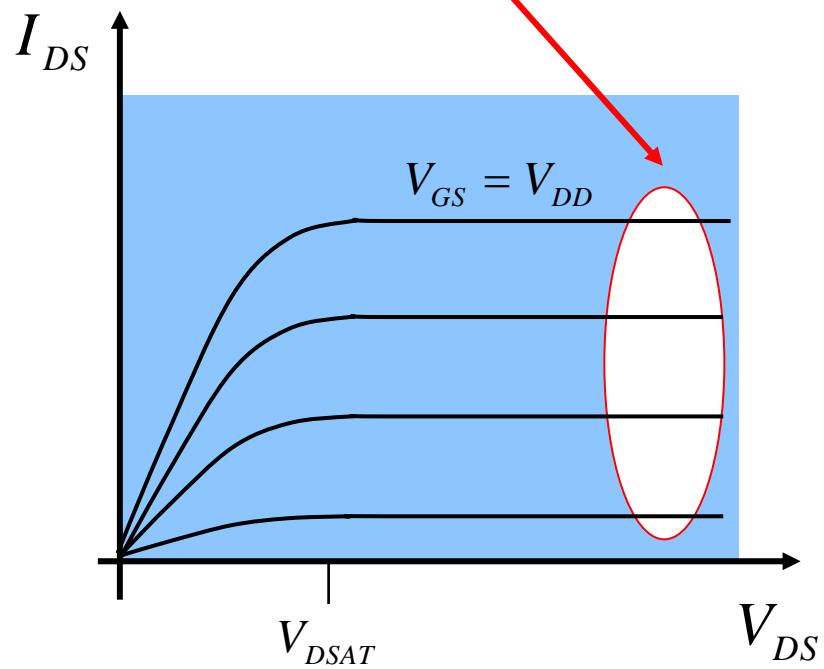
$$I_D \propto (V_{GS} - V_T)^{3/2}$$

Recall, in the non-degenerate case,

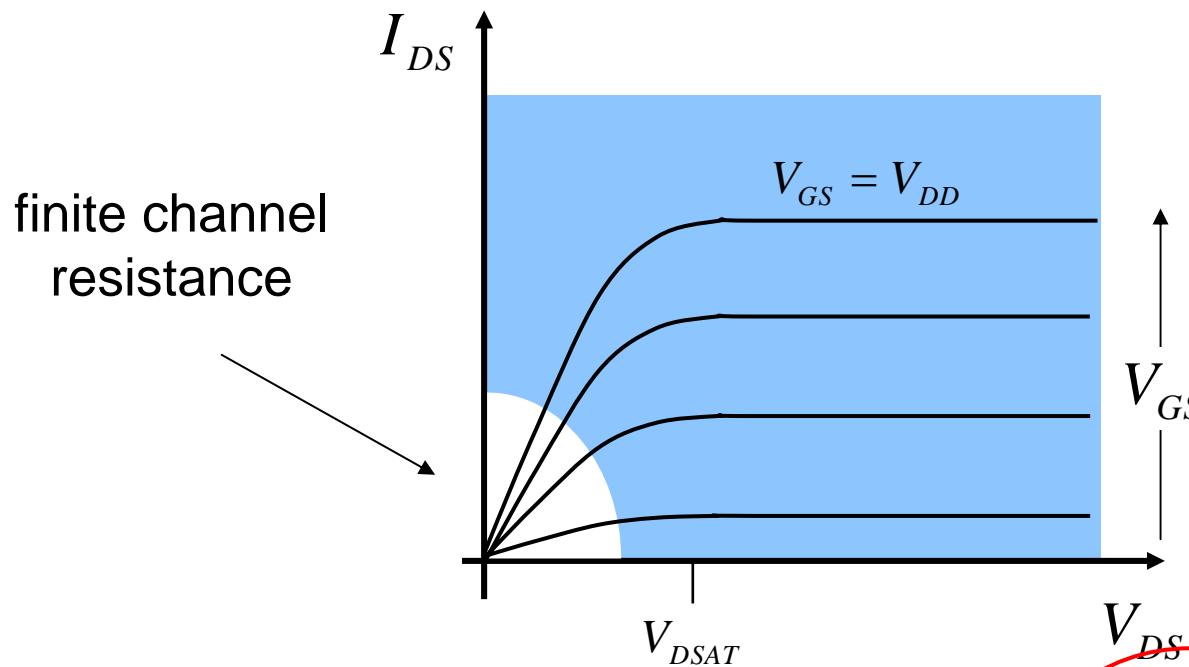
$$I_D \propto (V_{GS} - V_T)^1$$

$$I_D \propto (V_{GS} - V_T)^\alpha$$

$$1 \leq \alpha \leq 1.5$$



low drain bias



$$G_{CH} = \left(WC_{ox} (V_{GS} - V_T) \frac{v_T}{(2k_B T / q)} \right) \left[\frac{\mathcal{F}_{-1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} \right]$$

Fermi-Dirac correction

typical numbers

$$G_{CH} = \left(W q n_s(0) \frac{v_T}{(2k_B T/q)} \right) \left[\frac{\mathcal{F}_{-1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} \right]$$

assume Si (100), single subband, $T = 300\text{K}$, $n_s(0) \sim 10^{13} \text{ cm}^{-2}$

$$G_{CH}/W \Big|_{\text{Boltz}} = \left(q n_s(0) \frac{v_T}{(2k_B T/q)} \right) \approx 0.038 \text{ mhos}/\mu\text{m}$$

$$\left[\mathcal{F}_{-1/2}(\eta_{F1})/\mathcal{F}_0(\eta_{F1}) \right]; 0.5$$

$$R_{CH} W = \left(G_{CH}/W \right)^{-1} \approx 52 \Omega - \mu\text{m}$$

channel resistance:

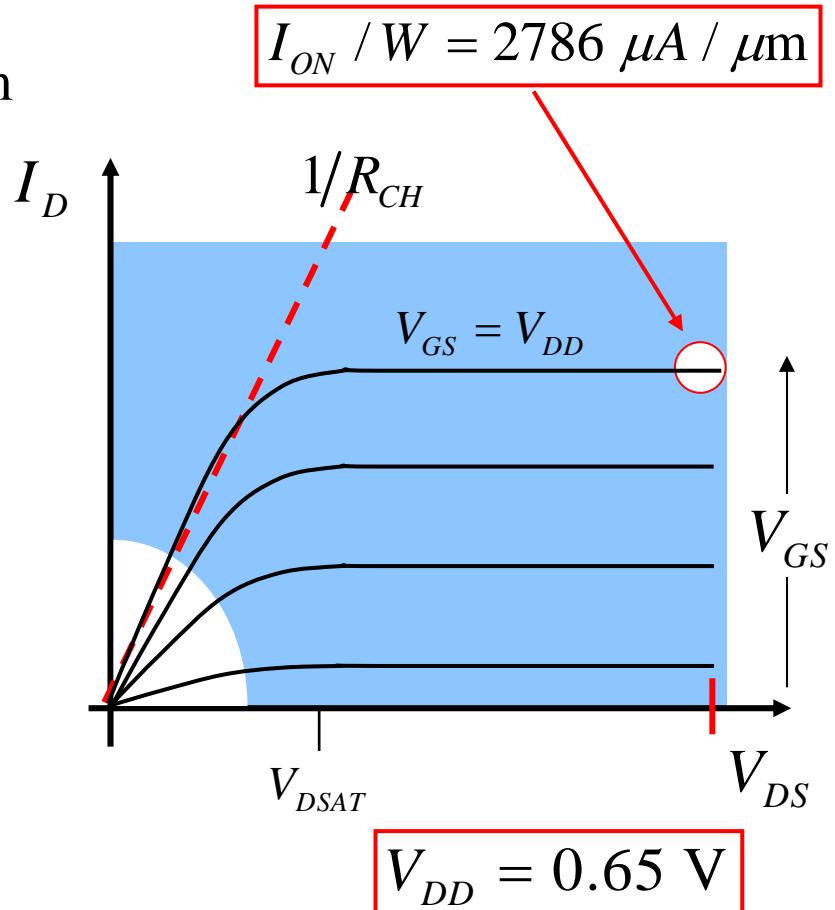
$$R_{CH}W < V_{DD}/(I_{ON}/W) \approx 230 \Omega - \mu\text{m}$$

series resistance:

$$R_{SD}W < 135 \Omega - \mu\text{m}$$

ballistic resistance:

$$R_{CH}W|_{ballistic} \approx 52 \Omega - \mu\text{m}$$



ballistic mobility

ballistic:

$$I_D = \left(WC_{ox} (V_{GS} - V_T) \frac{v_T}{(2k_B T / q)} \right) \left[\frac{\mathcal{F}_{-1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} \right] V_{DS}$$

diffusive:

$$I_D = \frac{W}{L} \mu_{eff} C_{ox} (V_{GS} - V_T) V_{DS}$$

at $n_S \approx 10^{13} \text{ cm}^{-2}$

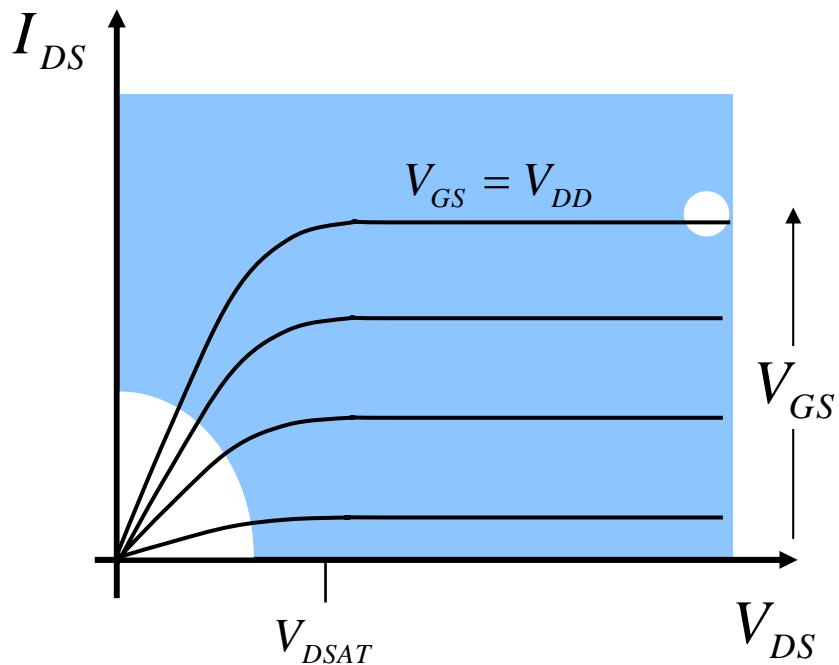
$$\mathcal{F}_{-1/2}(\eta_{F1})/\mathcal{F}_0(\eta_{F1}) \approx 0.5$$

ballistic mobility:

$$\mu_B \equiv \frac{v_T L}{(2k_B T / q)} \left[\frac{\mathcal{F}_{-1/2}(\eta_{F1})}{\mathcal{F}_0(\eta_{F1})} \right]$$

$$\mu_B \approx 12 \times L(\text{nm}) \text{ cm}^2/\text{V-s}$$

drain saturation voltage



$$V_{DSAT} \approx (k_B T / q) \ln \left[\exp \left(\frac{2C_{ox} (V_{GS} - V_T)}{qN_{2D}} \right) - 1 \right] \approx \beta (V_{GS} - V_T)$$

$$\beta = \frac{2C_{ox} (k_B T / q)}{qN_{2D}}$$

drain saturation voltage

traditional:

$$V_{DSAT} = (V_{GS} - V_T) \quad \text{0.97 V}$$

ballistic (Boltzmann statistics):

$$V_{DSAT} \approx (k_B T / q) \quad \text{0.026 V}$$

ballistic (Fermi-Dirac statistics):

$$V_{DSAT} \approx \left[\frac{2C_{ox}(k_B T / q)}{qN_{2D}} \right] (V_{GS} - V_T) \quad \text{0.12 V}$$

Ex.: 100nm NMOS

$$V_{GS} = V_{DD} = 1.2 \text{ V}$$

$$V_T = 0.23 \text{ V}$$

$$C_{ox} = 1.5 \times 10^{-6} \text{ F/cm}^2$$

$$N_{2D} = 4.1 \times 10^{12} \text{ cm}^{-2}$$

$$V_{DSAT} \approx 0.35 \text{ V}$$

outline

- 1) Introduction / Review
- 2) Drain current
- 3) Filling states at the top of the barrier
- 4) I-V Characteristics
- 5) Discussion
- 6) Summary**

summary

1) We have generalized

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

to include Fermi-Dirac statistics.

$$I_D = WC_{ox} (V_{GS} - V_T) v_F \left[\frac{1 - \mathcal{F}_{1/2}(\eta_{F2})/\mathcal{F}_{1/2}(\eta_{F1})}{1 + \mathcal{F}_0(\eta_{F2})/\mathcal{F}_0(\eta_{F1})} \right]$$

summary

2) We discussed key device parameters for ballistic MOSFETs:

- ballistic injection velocity
- ballistic on-current
- ballistic channel resistance
- ballistic mobility
- drain saturation voltage

questions

- 1) How do we treat more realistic band structures (e.g. conduction band of Si?)
- 2) How do we treat subthreshold conduction and 2D electrostatics?

These questions are addressed in Part 2