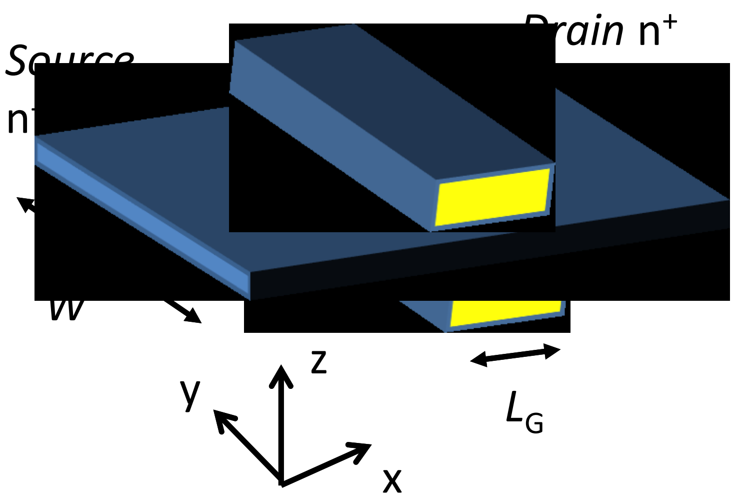
Lecture 3&4 –Ballistic 2D FETs

- 2D Ballistic FET (83-114)
- General Expression for currents
- 2D effects
- Bias self-consistency

2D Ballistic FET



Carriers are confined to the xy-plane

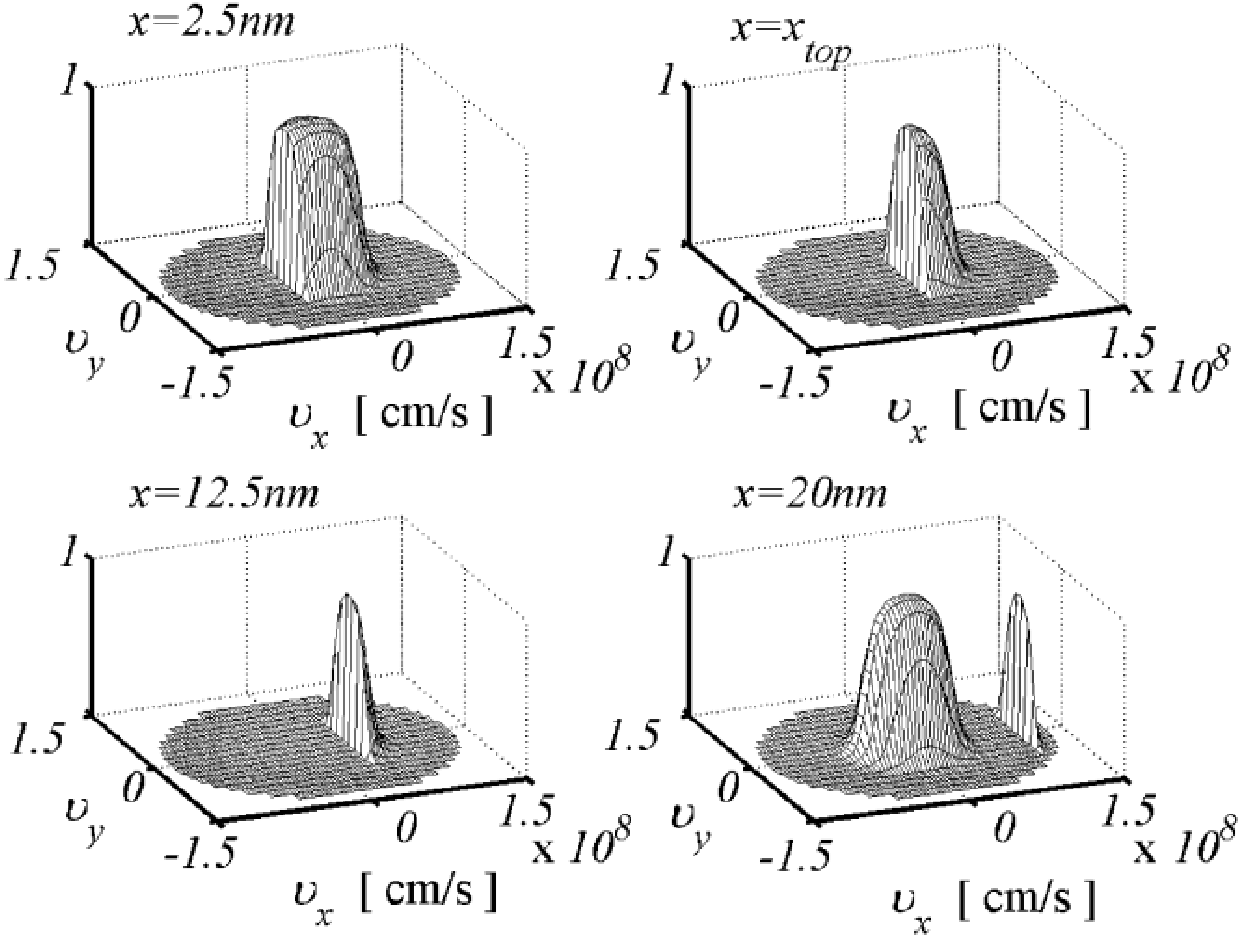
Electron velocities – distributed as v_x and v_y
v_x gives conduction current

Subbands $E_1(x)$, $E_2(x)$

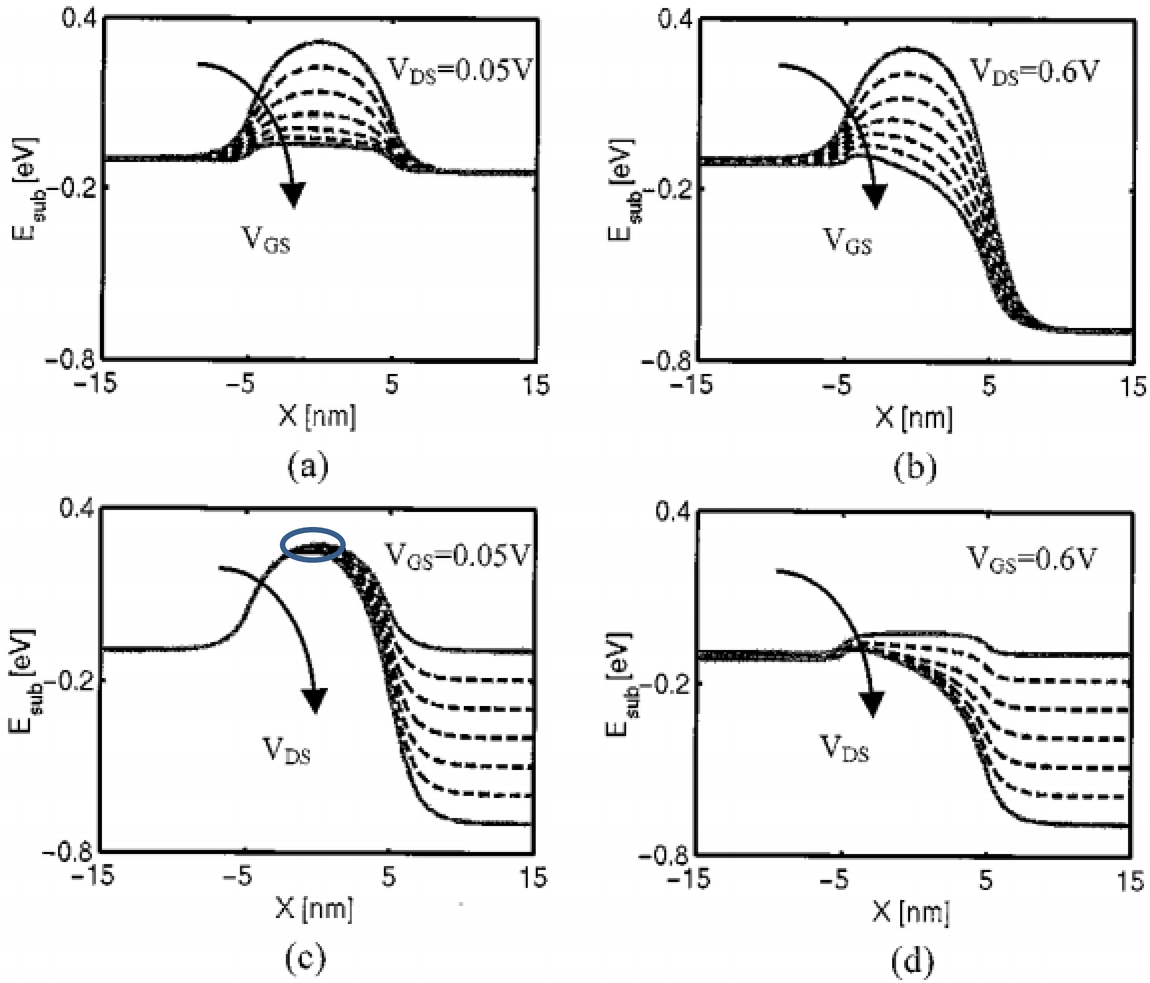
The device width W is assumed to be large – neglect quantization in y direction

Numerical 2D Ballistic Modeling

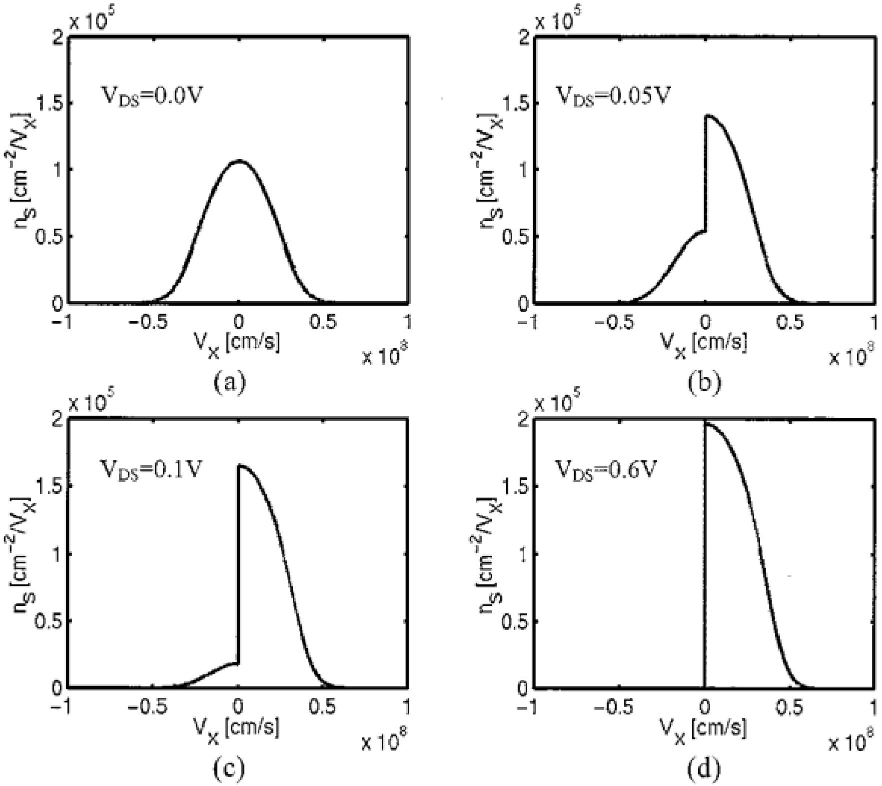
J.-H. Rhew et al. / Solid-State Electronics 46 (2002) 1899–1906

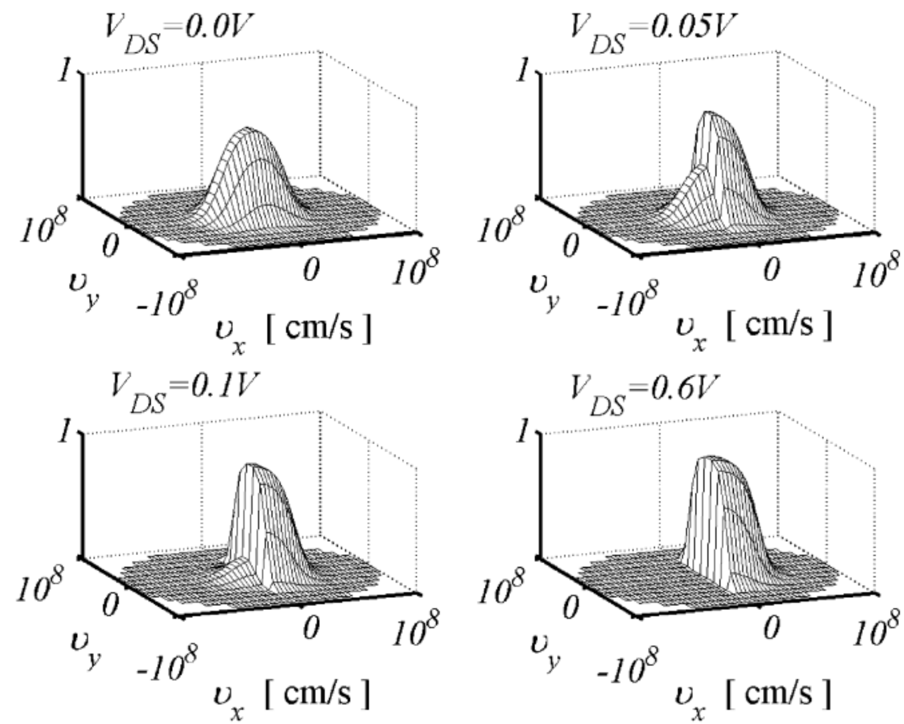


Numerical 2D Ballistic Modeling

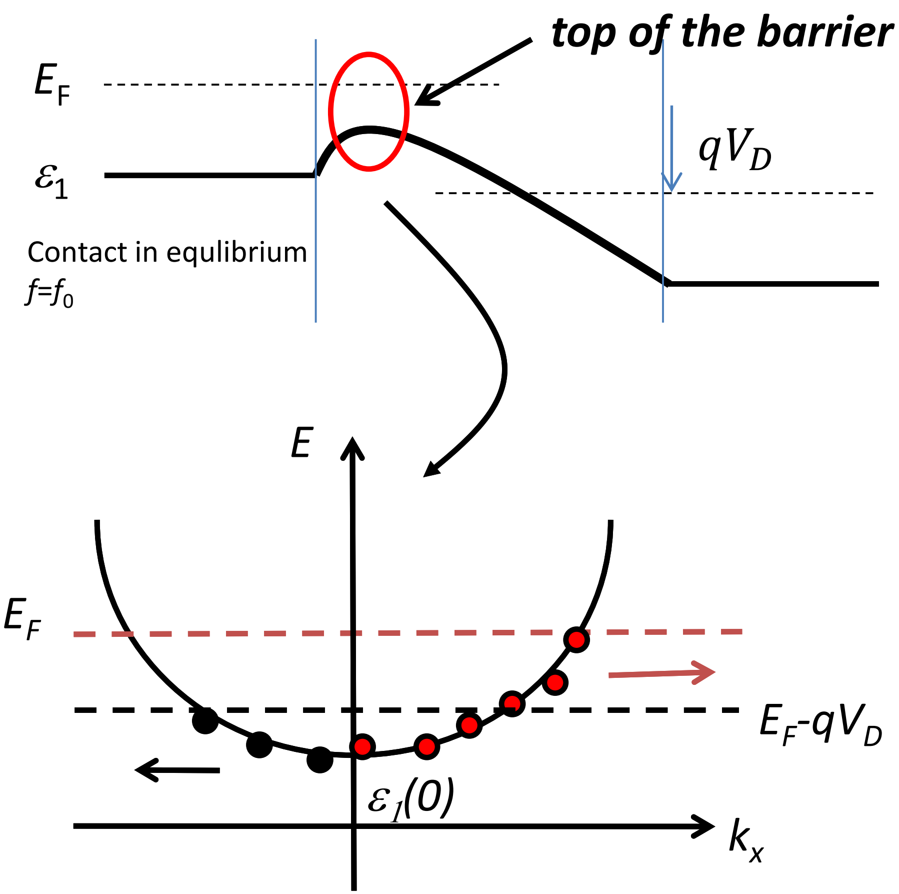


Current Saturation





2D Ballistic MOSFET Currents / Charges



$$n_S^+(0) = \frac{1}{A}\sum_{\boldsymbol{k_x,k_y>0}} f_0(E_F)$$

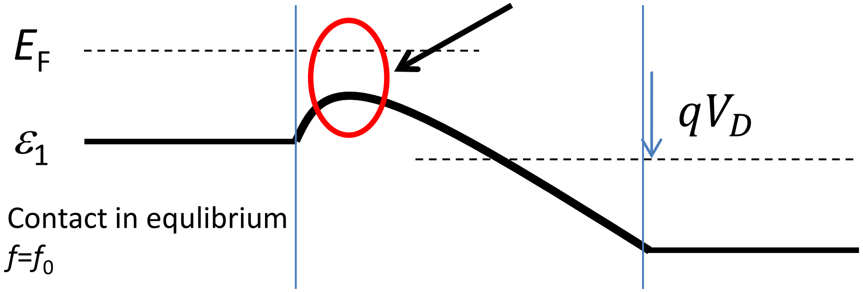
$$J^+ = \frac{1}{A}\sum_{k_x,k_y>0} q v_x f_0(E_F)$$

$$n_S^-(0) = \frac{1}{A}\sum_{\boldsymbol{k_x,k_y<0}} f_0(E_F - qV_D)$$

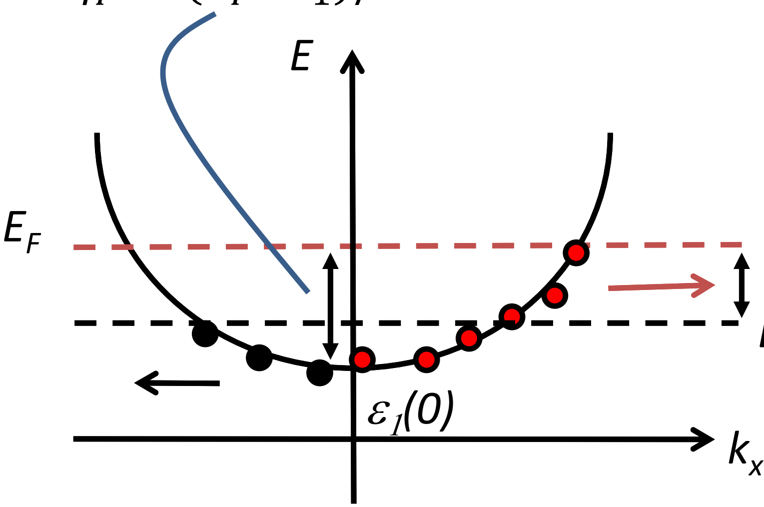
$$J^- = \frac{1}{A}\sum_{k_x,k_y<0} q v_x f_0(E_F - qV_D)$$

$$\sum_{\boldsymbol{k}} g(\boldsymbol{k}) \rightarrow \frac{A}{(2\pi)^2}\int_{\boldsymbol{k}} g(\boldsymbol{k})\, d\boldsymbol{k}$$

2D Ballistic MOSFET Currents / Charges



$$\eta_F = (E_F - \varepsilon_1)/kT$$



$$U_D = \frac{qV_D}{kT}$$

$$n_S^+(0) = \frac{N_{2D}}{2} F_0(\eta_F)$$

$$n_S^-(0) = \frac{N_{2D}}{2} F_0(\eta_F - qV_D)$$

$$J^+ = \frac{qN_{2D}}{2} v_T \left[F_{1/2}(\eta_{F1})\right]$$

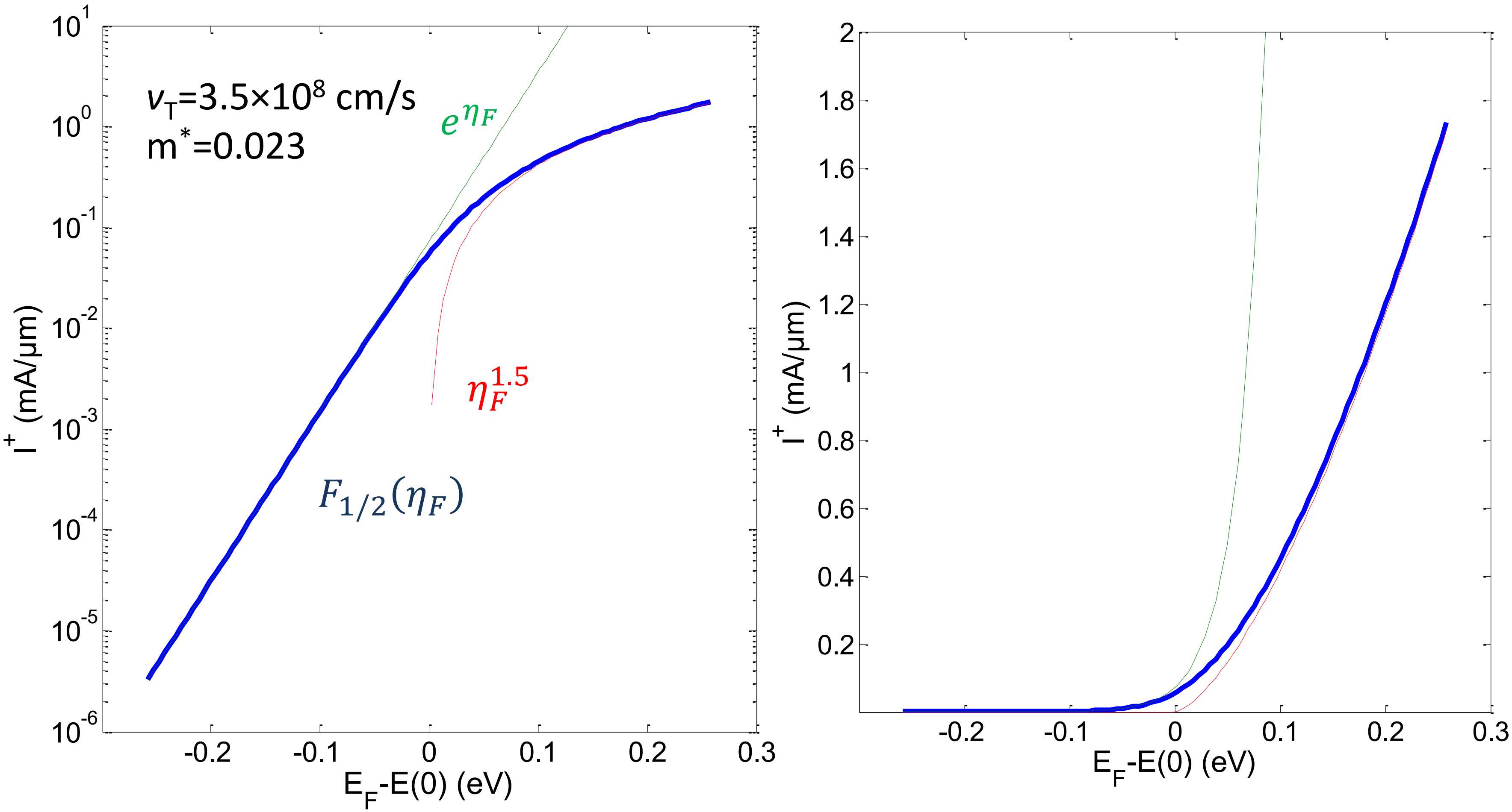
$$J^- = \frac{qN_{2D}}{2} v_T \left[F_{1/2}(\eta_{F1} - U_D)\right]$$

$$J^+ = qn_S^+ v^+$$

$$v^+ = v_T \frac{F_{1/2}(\eta_F)}{F_0(\eta_F)}; v_T = \sqrt{\frac{2kT}{\pi m^*}}$$

$$v^- = v_T \frac{F_{1/2}(\eta_F - U_D)}{F_0(\eta_F - U_D)}$$

I^+: T=300K



Quantum Capacitance / Bias self consistency

$$V_G' = \psi_s + Q/C_{ox}$$

$$V_G' = -\frac{\varepsilon_1(0)}{q} + \frac{qn_s(\varepsilon_1)}{C_{ox}}$$

$$n_s = \frac{N_{2D}}{2}\{F_0(\eta_F) + F_0(\eta_F - U_D)\}$$

Solve for η_F

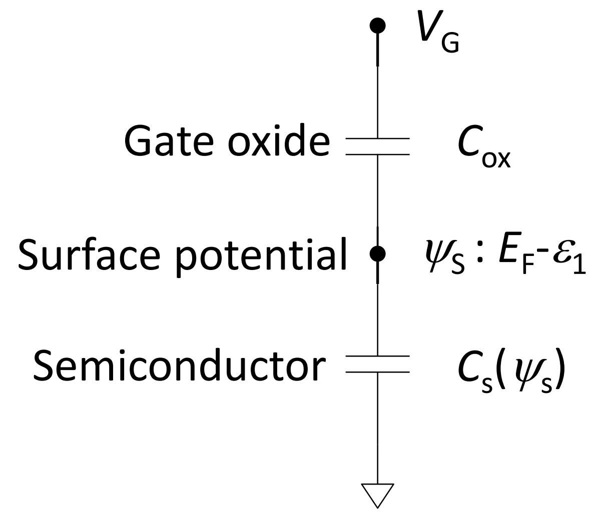
Calculate I^+-I^-

$$J^+ = \frac{qN_{2D}}{2} v_T\left[F_{1/2}(\eta_F)\right]$$

$$J^- = \frac{qN_{2D}}{2} v_T\left[F_{1/2}(\eta_F - U_D)\right]$$

MOS-limit: $C_{ox} << C_S$: n_s constant

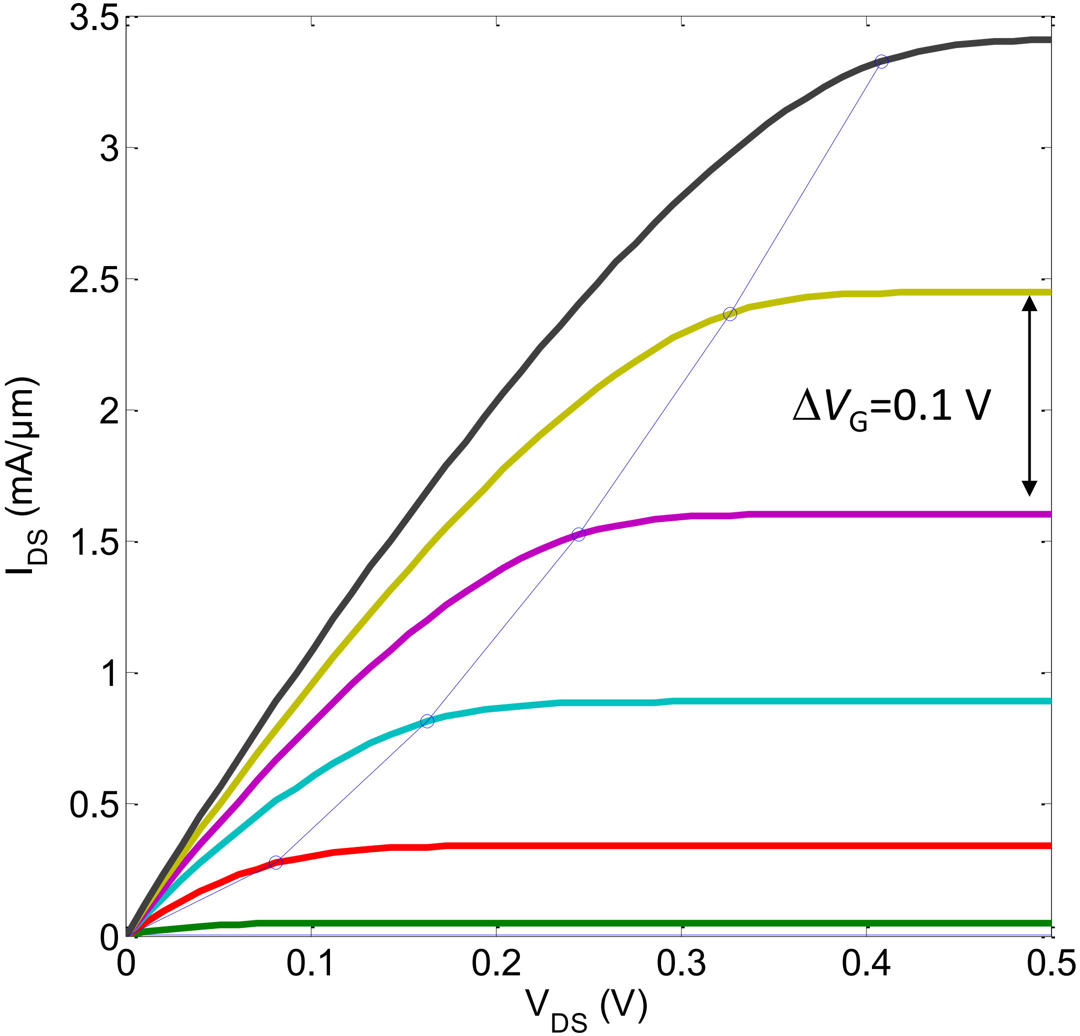
Bipolar limit: $C_{ox} \rightarrow \infty$ $\delta\varepsilon_1 = -q\delta V_G$



$$\delta\varepsilon_1 = -\frac{q\delta V_G}{1 + \frac{C_S}{C_{ox}}}$$

If we also include the charge centriod capacitance: $C_{ox} \rightarrow C_{ox}||C_C$

Modeled 2D I-V



m^*=0.023/m_0
t_{ox}=5 nm
ε_r=20

Degenerate expressions with Quantum Capacitance

$$I^{+} \approx \frac{qW2\sqrt{2m^*}}{3\pi^2\hbar^2}\left(\frac{qC_{ox}}{C_{ox}+C_s}\right)^{\frac{3}{2}}(V_{GS}-V_T)^{\frac{3}{2}} \qquad C_s = \frac{C_q}{2} = \frac{m^*}{2\pi\hbar^2}$$

$$V_{ds,sat} \approx \frac{V_{GS}-V_T}{1+\frac{C_q}{2C_{ox}}}$$

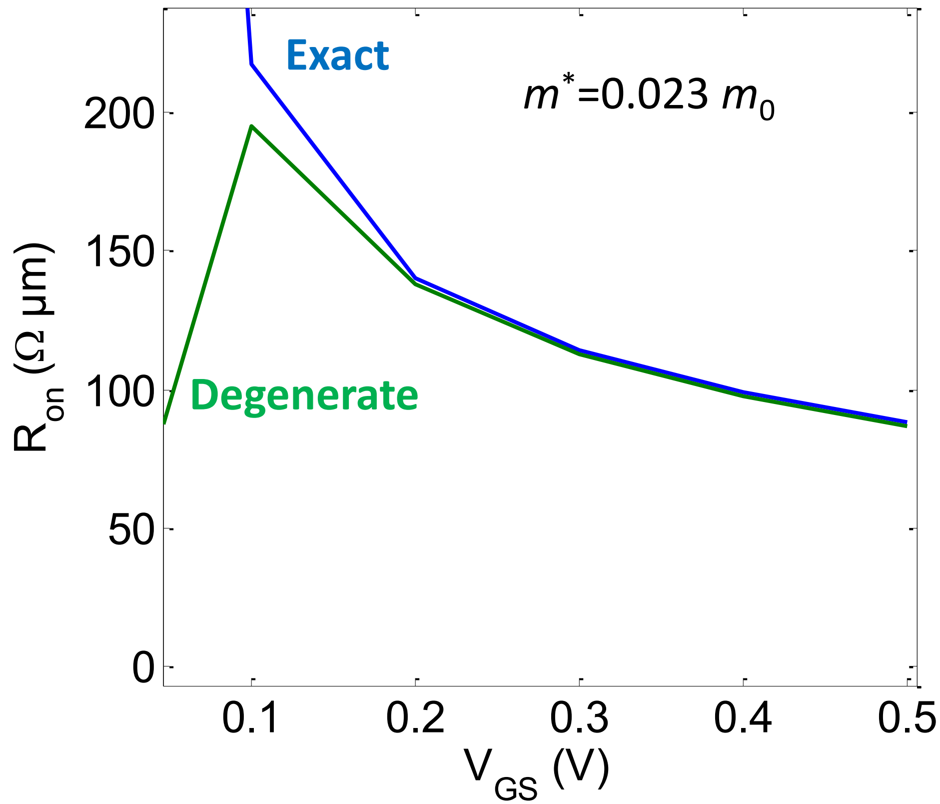
$$G_{CH} = \frac{q^2W\sqrt{2m^*}}{\pi^2\hbar^2}\sqrt{q\frac{C_{ox}}{C_{ox}+C_q}(V_G-V_T)}$$

Minimum on-resistance: $\mathrm{R_{on}} = \frac{1}{G_{CH}}$

R_{on} - resistance

A ballistic FET/conductor has a minimum on-resistance!

This is important when trying to extract R_c from measured data.



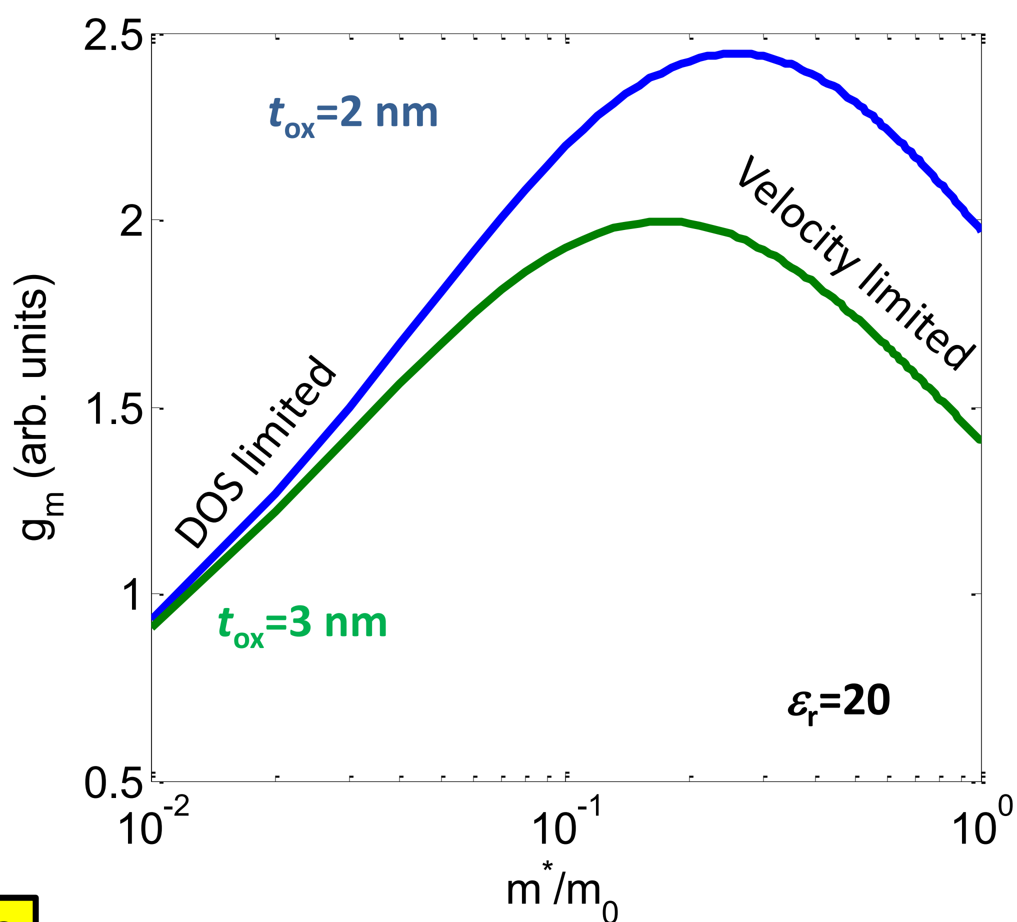
Density of states bottle neck

Optimal mass when:

$$\frac{C_q}{4} = C_{ox}$$

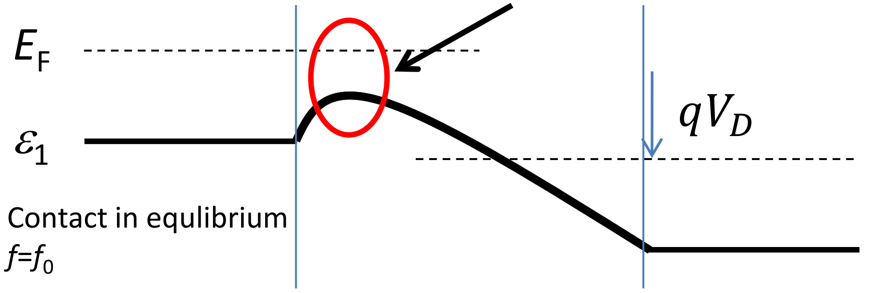
$$m^*_{opt} = \frac{4C_{ox}\pi\hbar^2}{q^2}$$

$$I^+ \propto \sqrt{m^*}\left(\frac{1}{1+\frac{m^*}{2\pi\hbar^2 C_{ox}}}\right)^{\frac{3}{2}}$$



Scattering is proportional to DOS
Low m* → less scattering

MOS statistics – MOS Limit



$$C_{ox} \ll C_S, C_q$$

$$n_s = n_S^+(E_F) + n_S^-(E_F, V_D\ ) = C_{ox}(V_{GS} - V_T)/q$$

Allows us easily to solve for η_F
And to relate n_s to V_{GS}

Charge at the top of the barrier is constant, independent of V_D

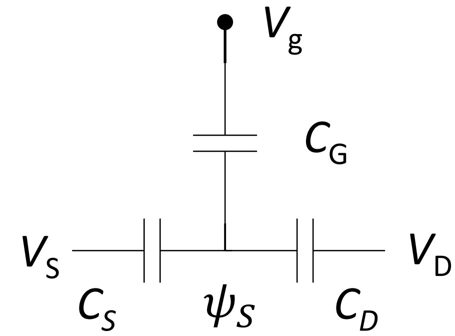
This is correct if $C_{ox} << C_s$ and above V_T

E_F-ε_1 needs to increase as V_D increases

1) No 2D effects
2) Large DOS, thick C_{ox}

2D Electrostatics – ballistic FETs

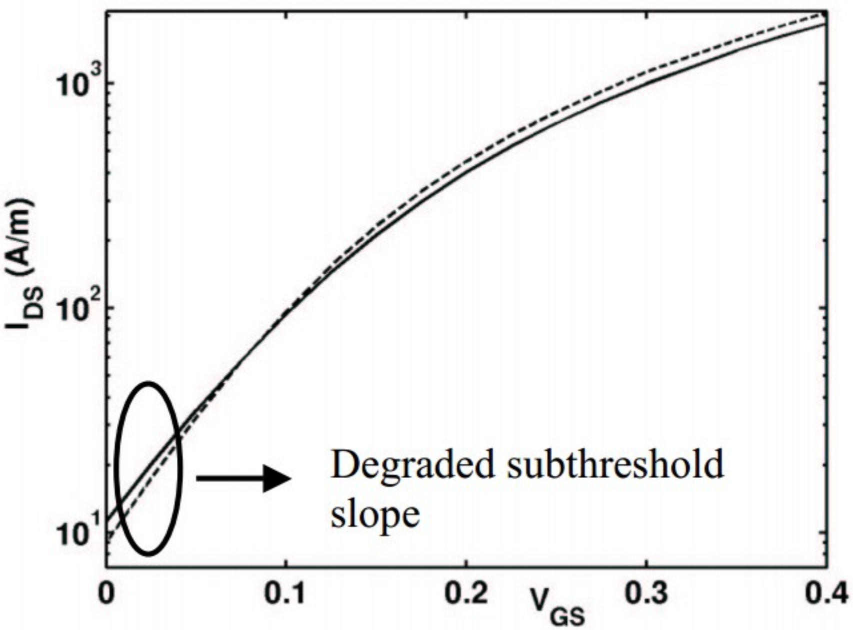
$$V_G' = -\frac{\varepsilon_1(0)}{q} + \frac{q n_s(\varepsilon_1(0))}{C_{ox}}$$ 1D

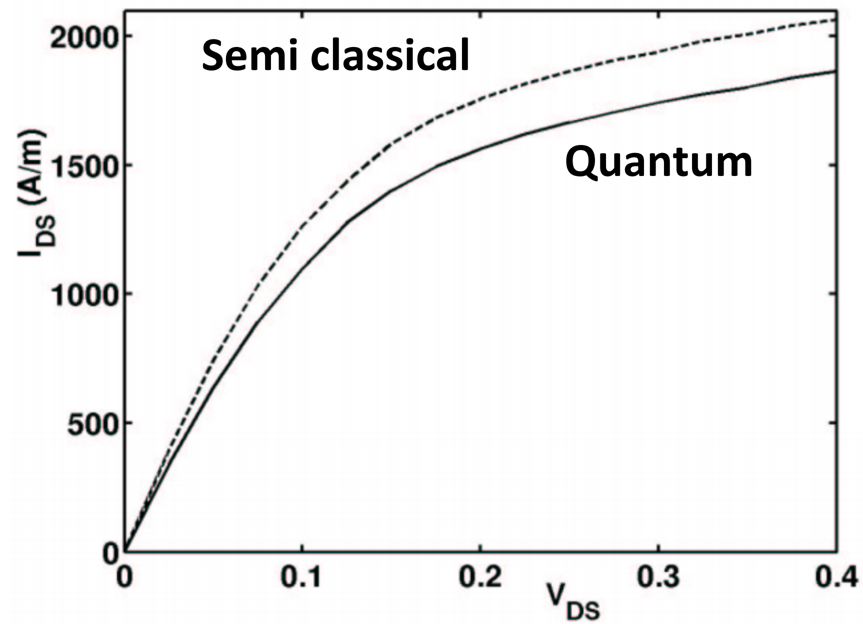


$$\begin{cases} \varepsilon_1(0) = U_L + U_P \\ U_L = \alpha_G V_G + \alpha_D V_D + \alpha_S V_S & \text{Laplace Eq.} \\ U_P = \dfrac{q^2}{C_\Sigma} n_s(\varepsilon_1(0)) = U_C n_s & \text{Mobile Charge/Possion Eq.} \end{cases}$$

α_G : subthreshold slope, g_m
α_D: DIBL/g_d
E_F: correct off-current

Quantum / Semiclassical





$$I^+ = \frac{2q}{h}\int_0^\infty M(E)T(E)f_0(E,E_F)dE$$

Semi-classical: We assume T(E) step function

Quantum: T(E)<1 above E(0) due to reflections
T(E)>0 below E(0) due to tunneling

*Quantum effects are **small** for L_g=10 nm (Si) devices!*