Ballistic Transport in FETs with/without scattering

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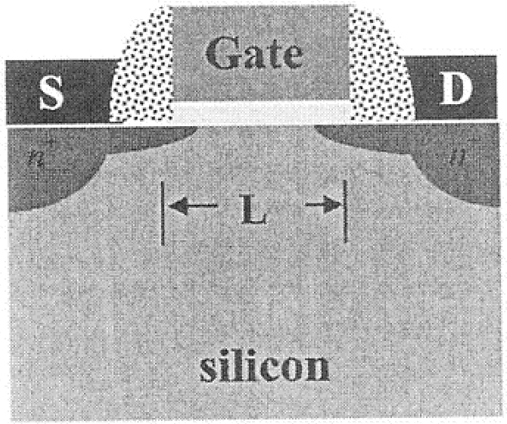
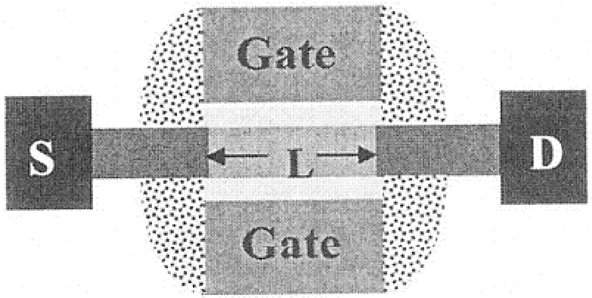
Nano-scale MOSFET Structure

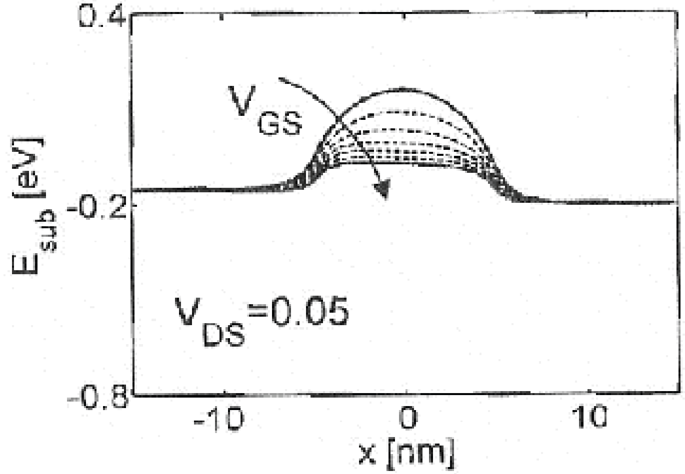


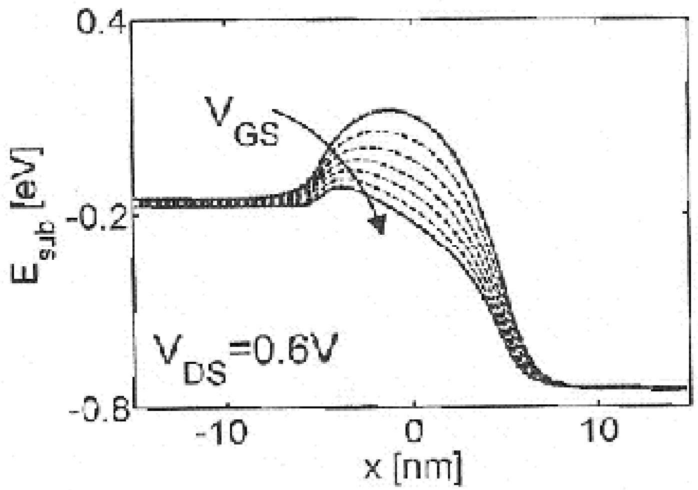
(a)



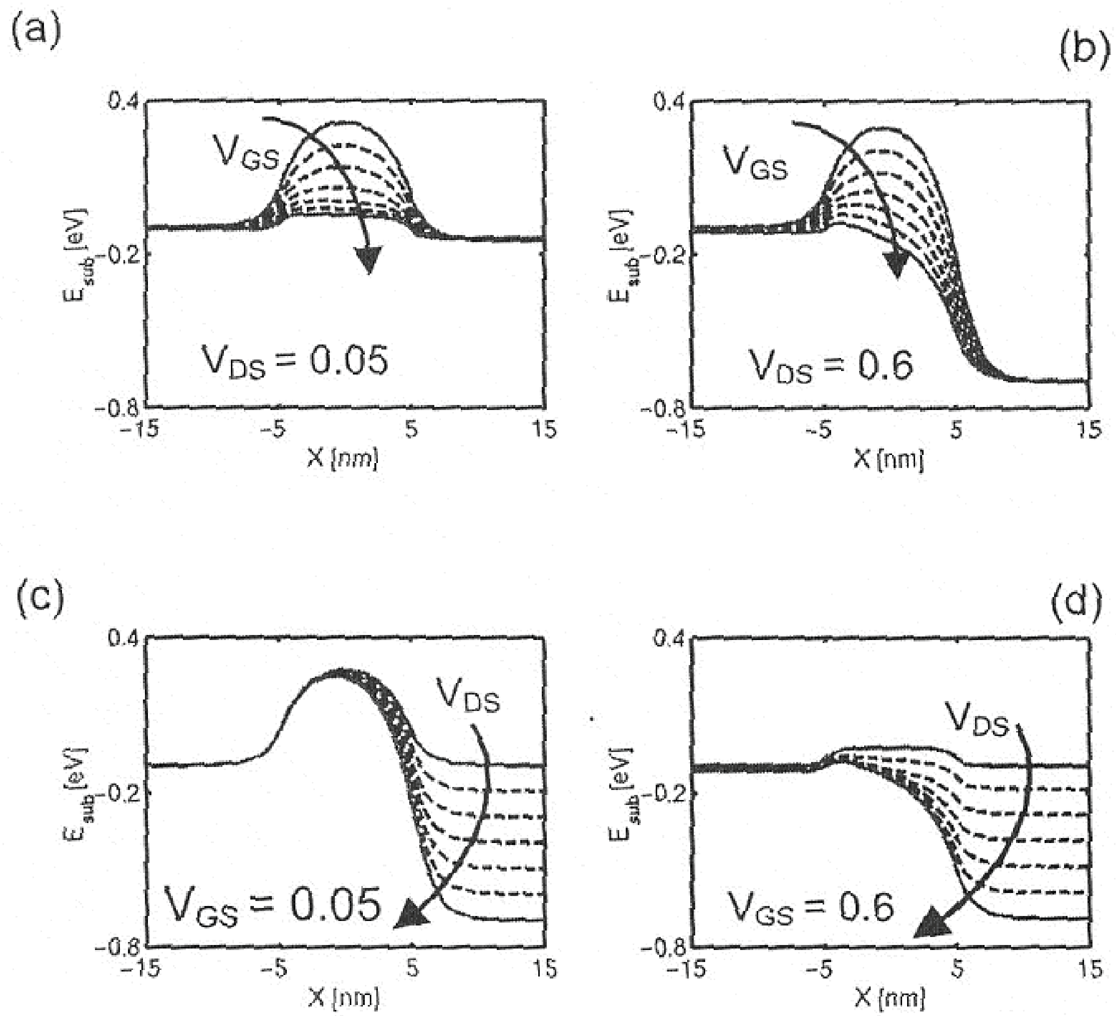
(b)

Cross sectional sketches of: a) a bulk, silicon MOSFET and b) a double-gate MOSFET. The third dimension, the width, W, of the MOSFET, is into the page.





Barrier Controlled by Gate and Drain



Electron Distribution and Velocity in Channel

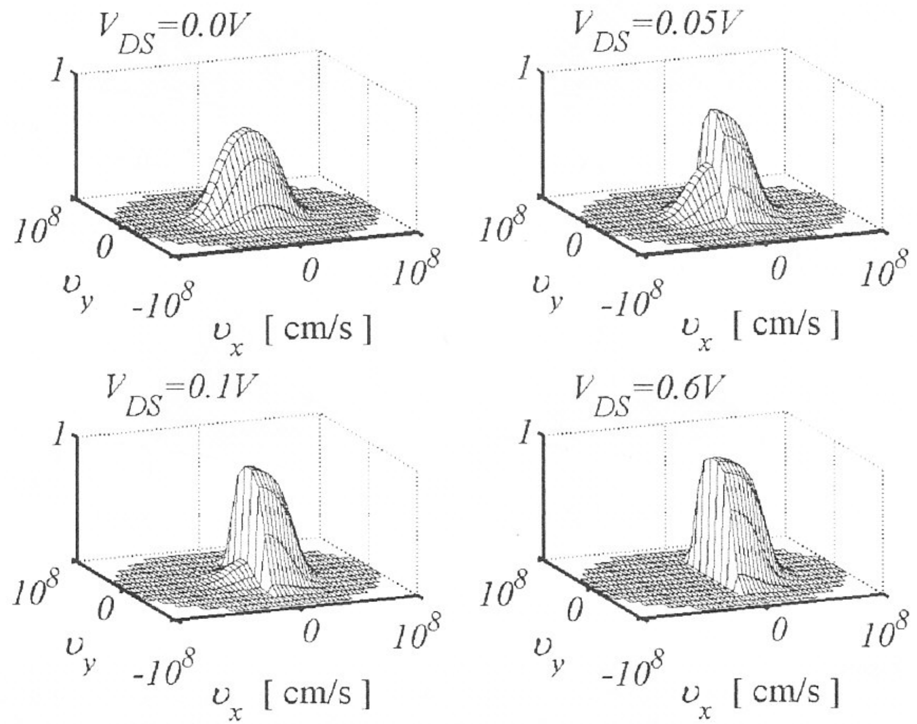
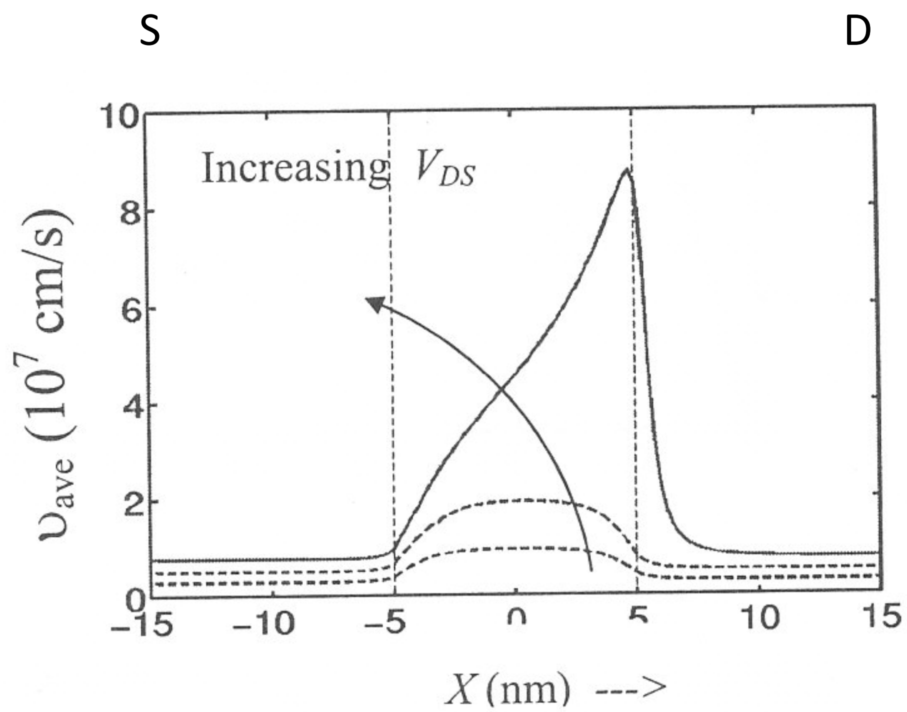


Figure 3.5. Electron distribution function at the top of the source-channel barrier for a ballistic n-MOSFET as computed under high gate and four different drain biases. (Reproduced with permission from [3.9])



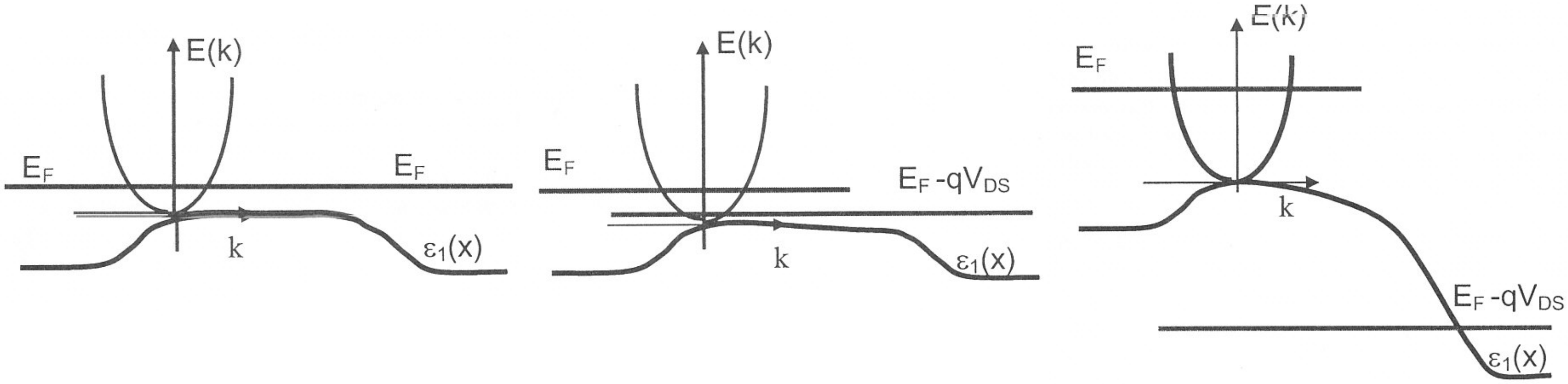
Average velocity vs position for the ballistic, double-gate MOSFET

Natori's Ballistic MOSFET Model

- Above threshold, the total carrier density is appox. independent of V_{DS}
- Equation for Fermi level

$$n_S^+(E_F) + n_S^-(E_F - qV_{DS}) = Q(0)/(-q) \approx C_{ox}(V_{GS} - V_T)/(-q)$$

- Current flow direction



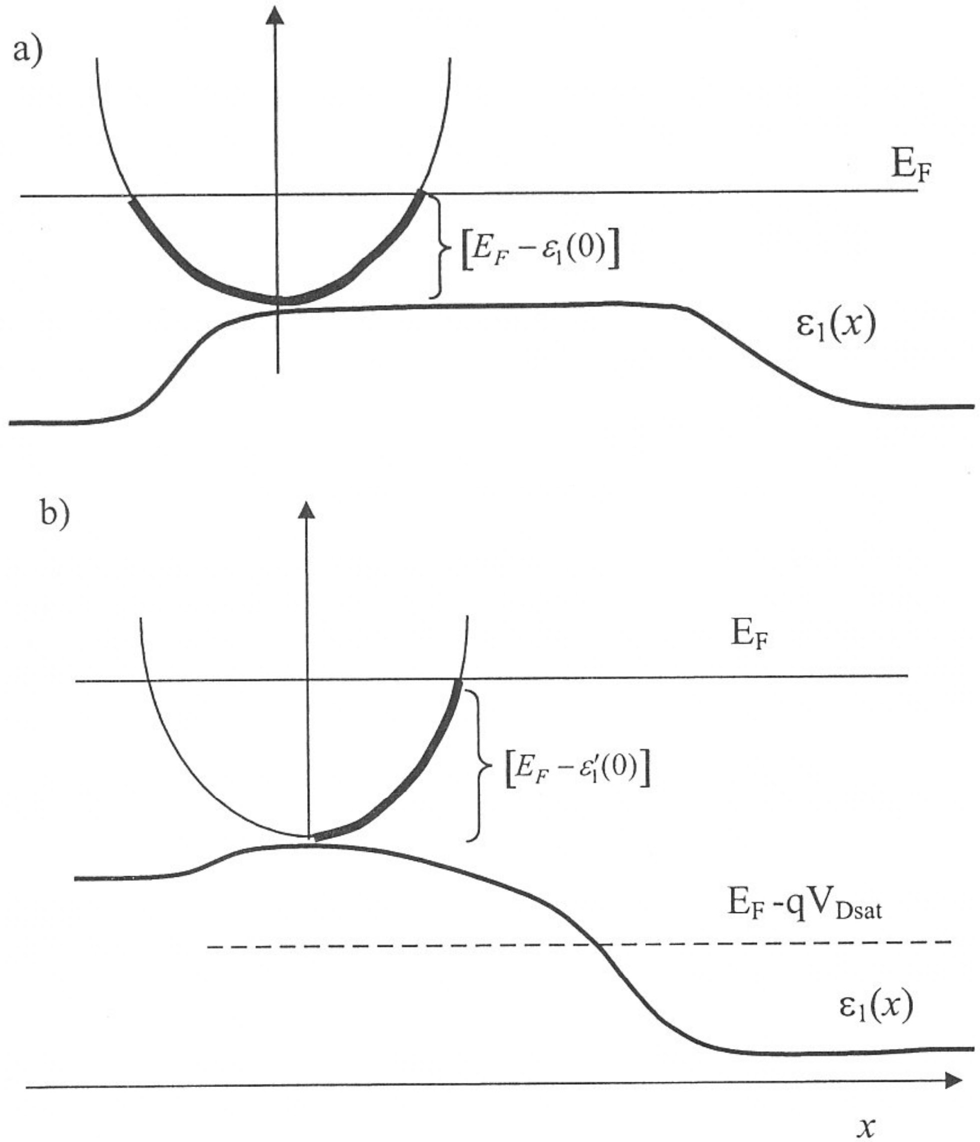
At High Drain Bias

- At equilibrium

  Equal amount of electrons move in both direction

- At high drain bias

  Most electrons move in the positive direction



I-V Characteristic of Ballistic MOSFET

$$n_s^+(0) = \frac{N_{2D}}{2}\log\left(1+e^{(E_F-\varepsilon_1)/k_BT_L}\right) = \frac{N_{2D}}{2}F_0(\eta_F)$$

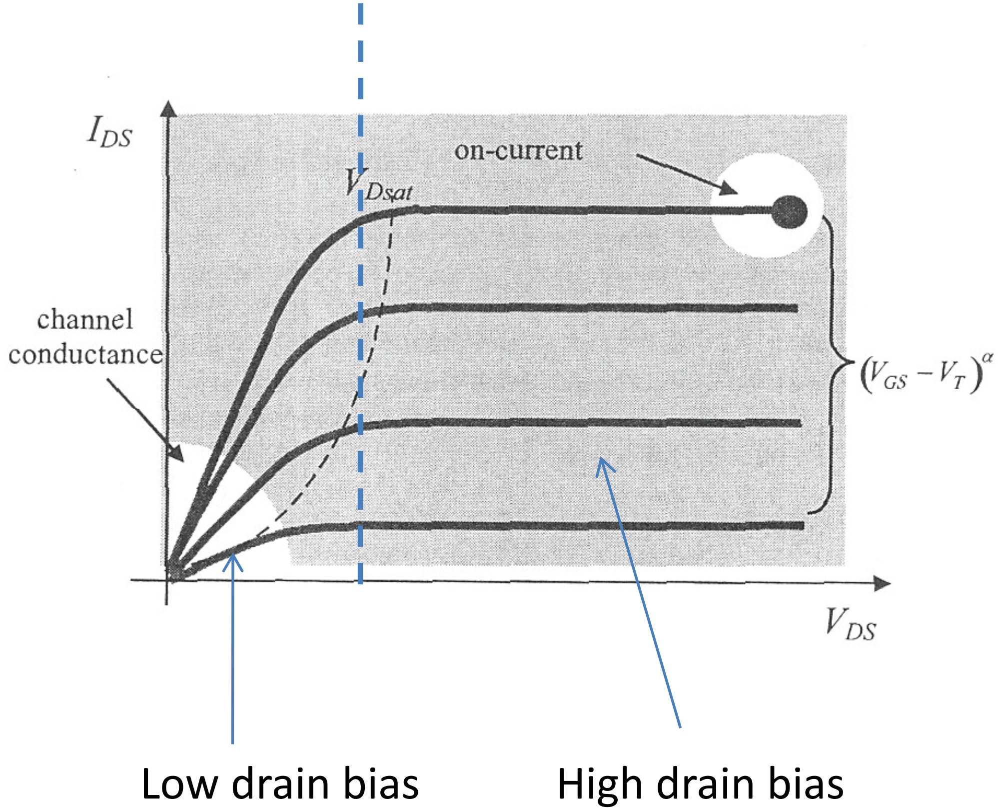
$$n_s^-(0) = \frac{N_{2D}}{2}\log\left(1+e^{(E_F-qV_D-\varepsilon_1)/k_BT_L}\right) = \frac{N_{2D}}{2}F_0(\eta_F-U_D)$$

$$\upsilon^+ = \upsilon_T\frac{F_{1/2}(\eta_F)}{F_0(\eta_F)}$$

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

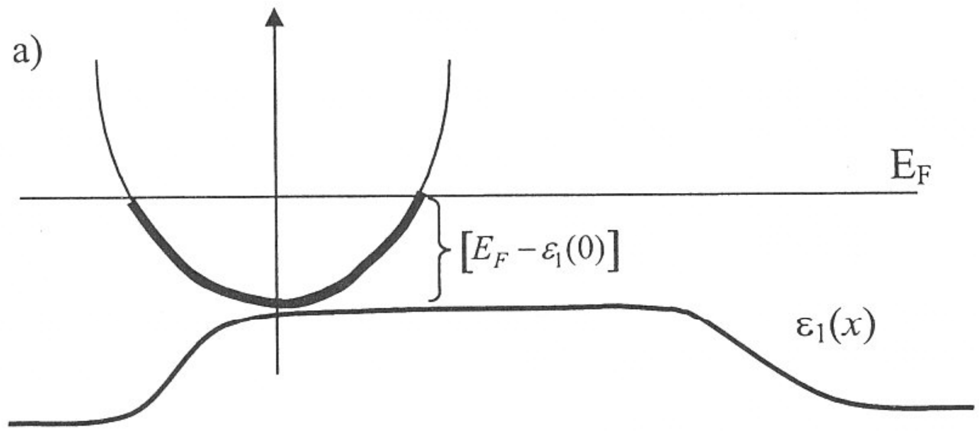
$$I^+ = q\,W\,n_S^+\,\upsilon^+.$$

$$I^- = q\,W\,n_S^-\,\upsilon^-,$$



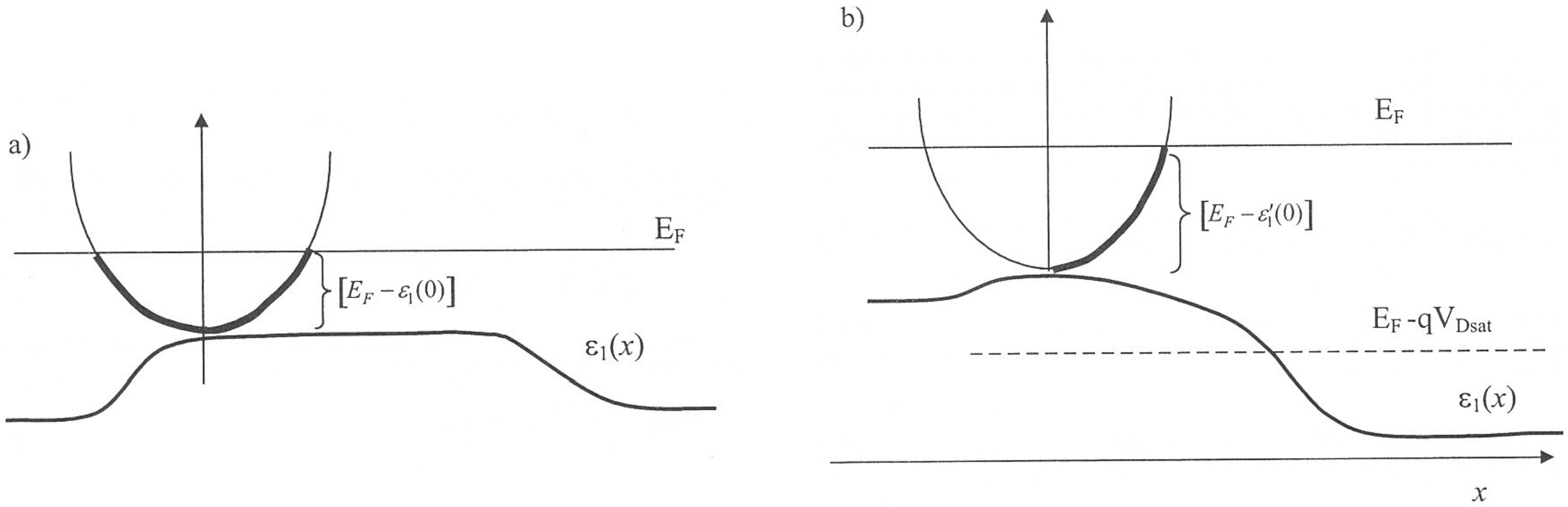
Fact 1 for Ballistic MOSFET

- Carrier distribution function at the barrier top consists of two thermal equilibrium halves, from Source and from Drain



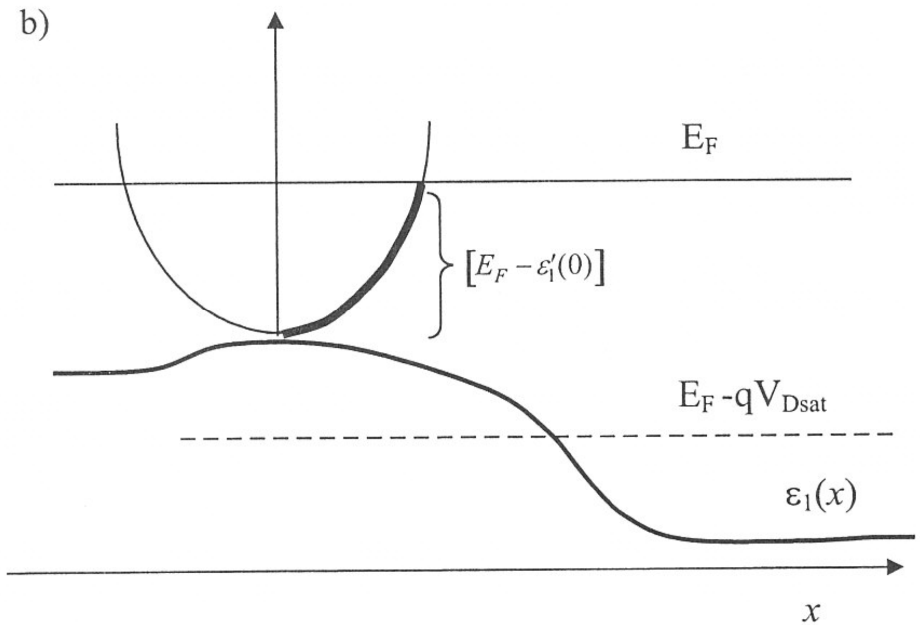
Fact 2 for Ballistic MOSFET

- The total carrier density at the barrier top is about a constant (for an electrostatically well-designed MOSFET)

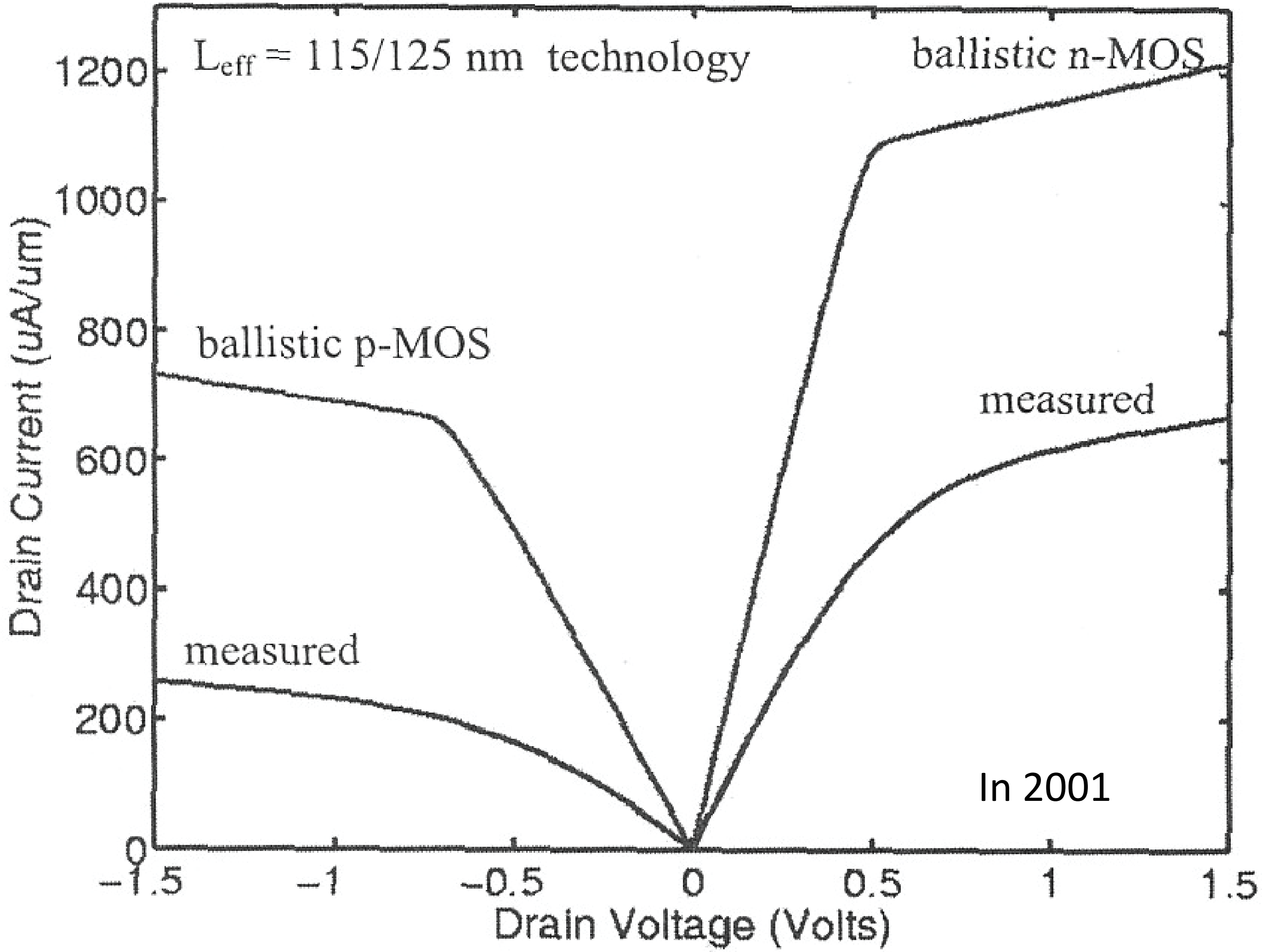


Fact 3 for Ballistic MOSFET

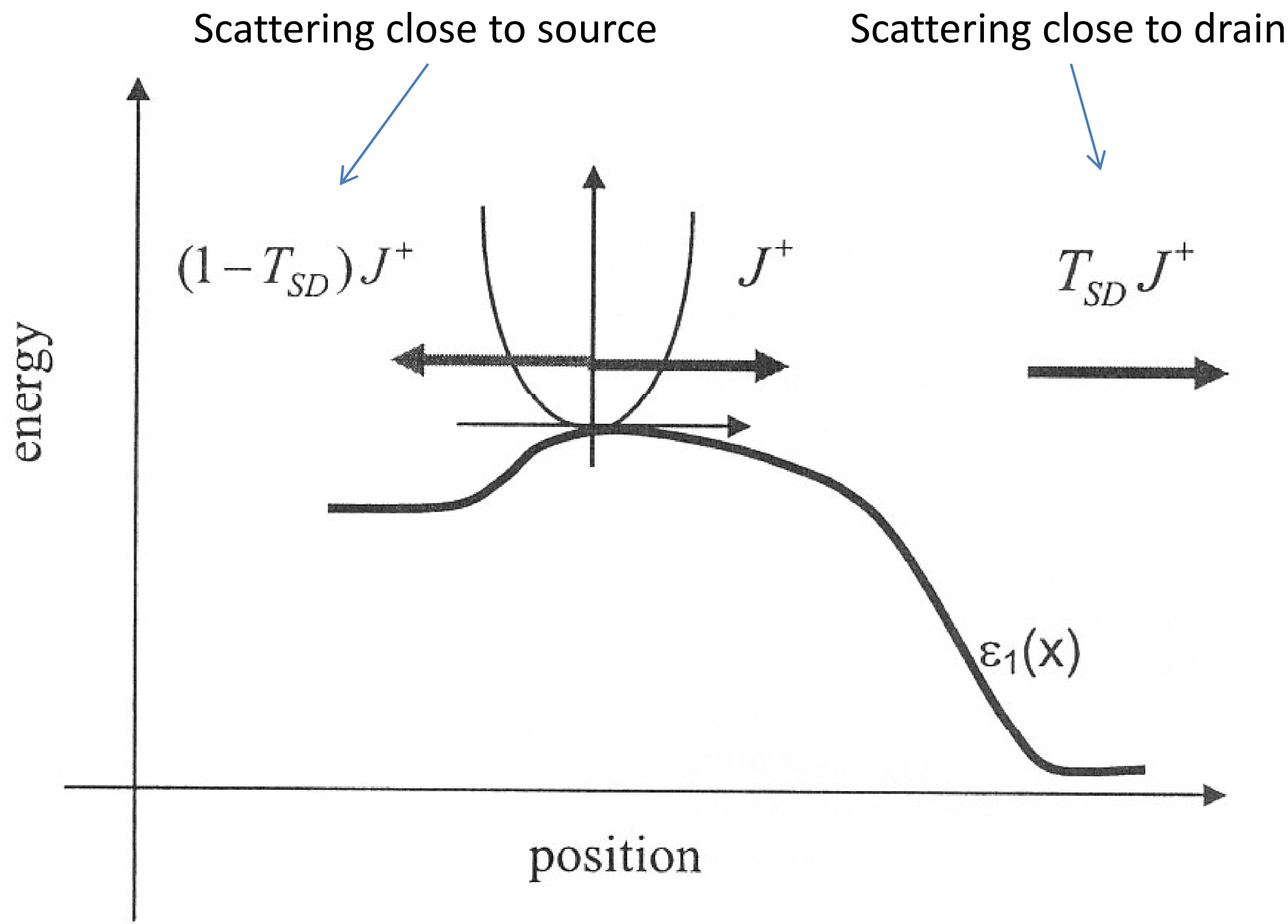
- The average velocity at the barrier top increases with V_{DS} and then saturates at a limit, which is the average velocity of a thermal equilibrium hemi-Fermi-Dirac distribution.
- The magnitude of saturated velocity increases with gate voltage.



Classic vs. Ballistic MOSFET



Scattering is the Reason



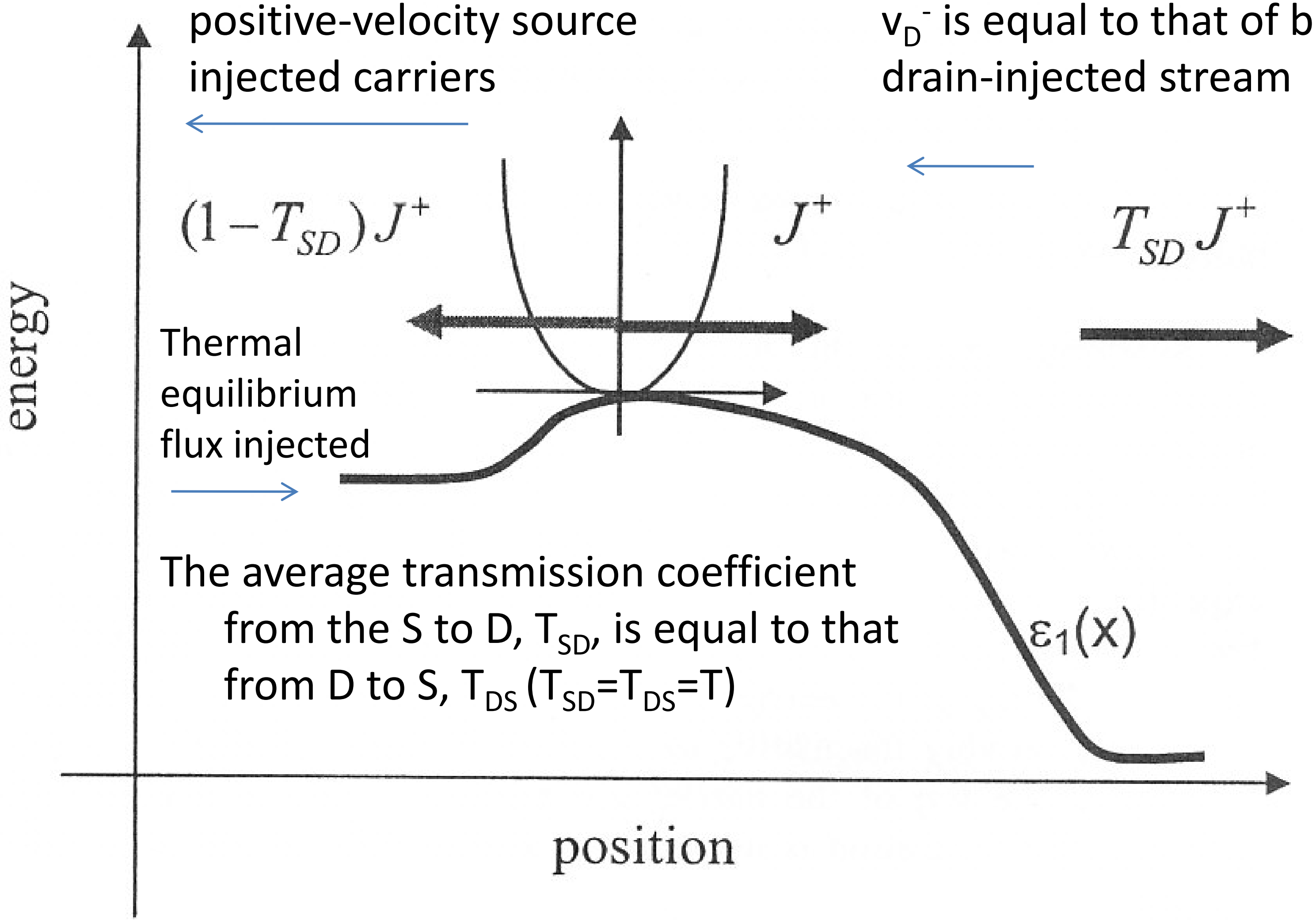
Assumptions

v_S^- is equal to that of the positive-velocity source injected carriers

v_D^- is equal to that of ballistic drain-injected stream

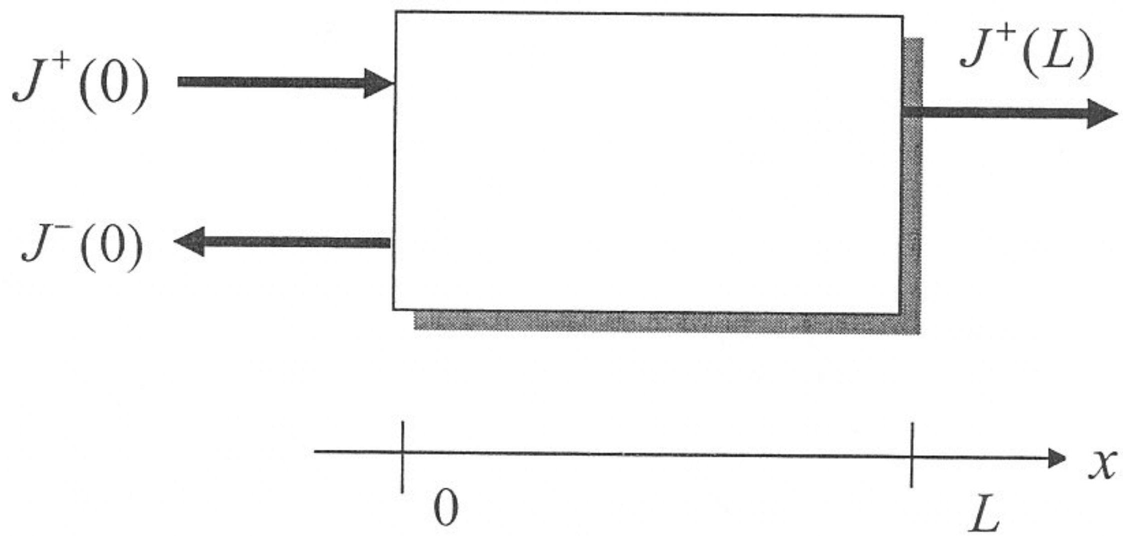
Thermal equilibrium flux injected

The average transmission coefficient from the S to D, T_{SD}, is equal to that from D to S, T_{DS} ($T_{SD}=T_{DS}=T$)

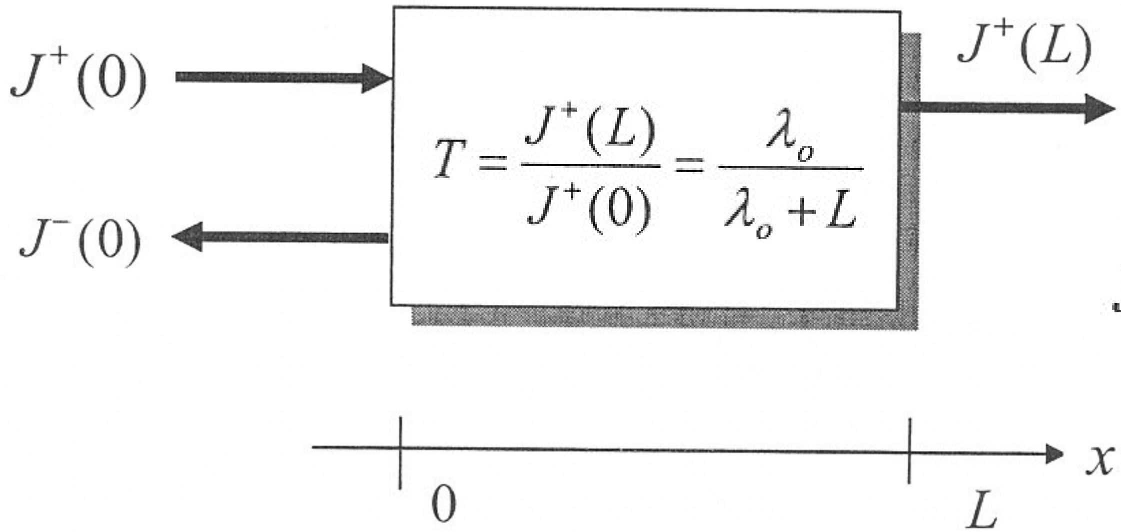


Low Drain Bias

- Channel length is the region length carriers diffuse. The potential drop across the channel is less than $K_B T_L/q$ ~ 26 mV at RT



Near-Equilibrium Mean-free-path



Fick's law

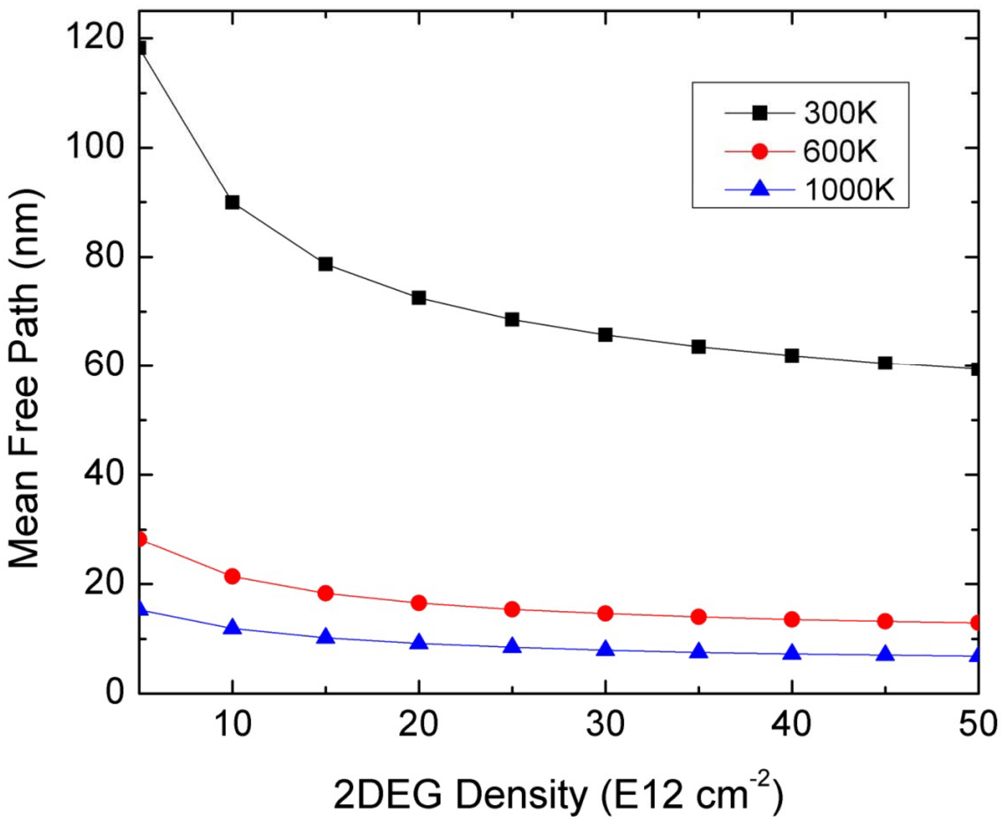
$$J = -\left(\frac{\lambda_o \upsilon_T}{2}\right)\frac{dn}{dx} = -D\frac{dn}{dx}$$

Apply Einstein relation

$$D \equiv \lambda_o \upsilon_T / 2 = \left(k_B T_L / q\right)\mu_{eff}$$

$$I_D = \left(\frac{W}{L + \lambda_o}\right)\mu_{eff}\, C_{ox}\left(V_G - V_T\right)\, V_D$$

Preliminary Calculation for GaN

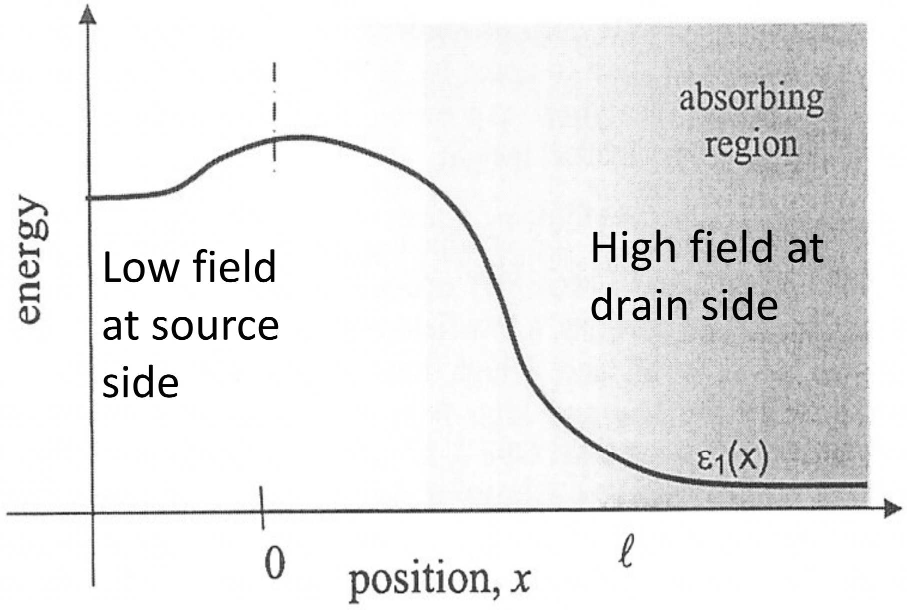


$$v_t = \sqrt{\frac{2k_B T_L}{\pi m^*}}$$

$$D \equiv \lambda_o \upsilon_T / 2 = (k_B T_L / q)\mu_{eff}$$

POP and AP scattering considered

High Drain Bias



$$T = \frac{\lambda_o}{\lambda_o + \ell}$$

l=L for low drain bias

But only a portion of L for high drain bias (distance over which the first $K_B T_L/q$ of potential drops)

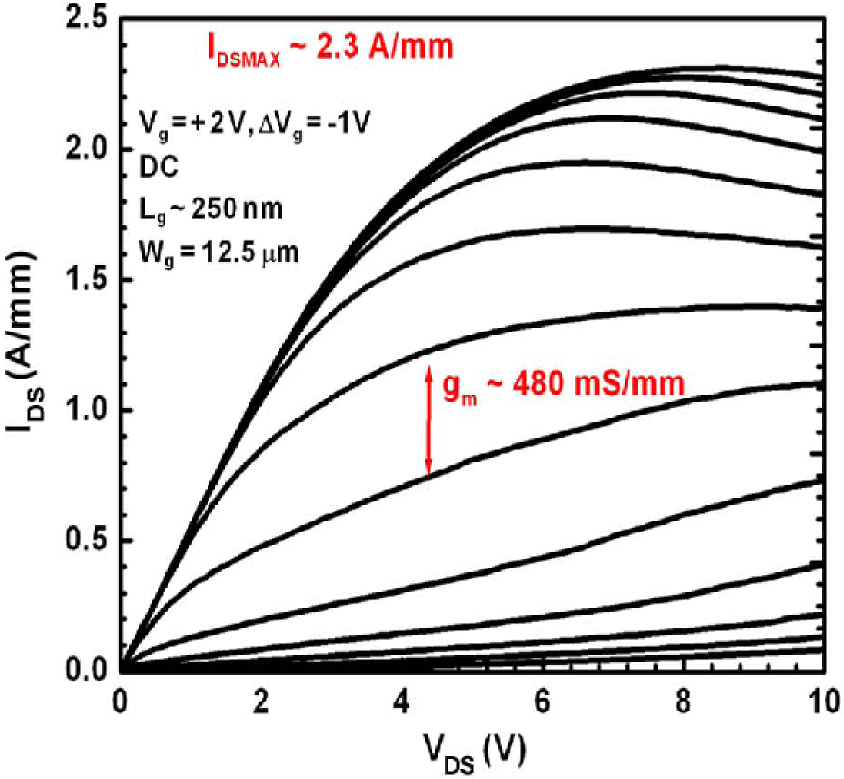
Beyond l, the carrier will be unlikely to return to the source after scattering

How Far Away from Ballistic

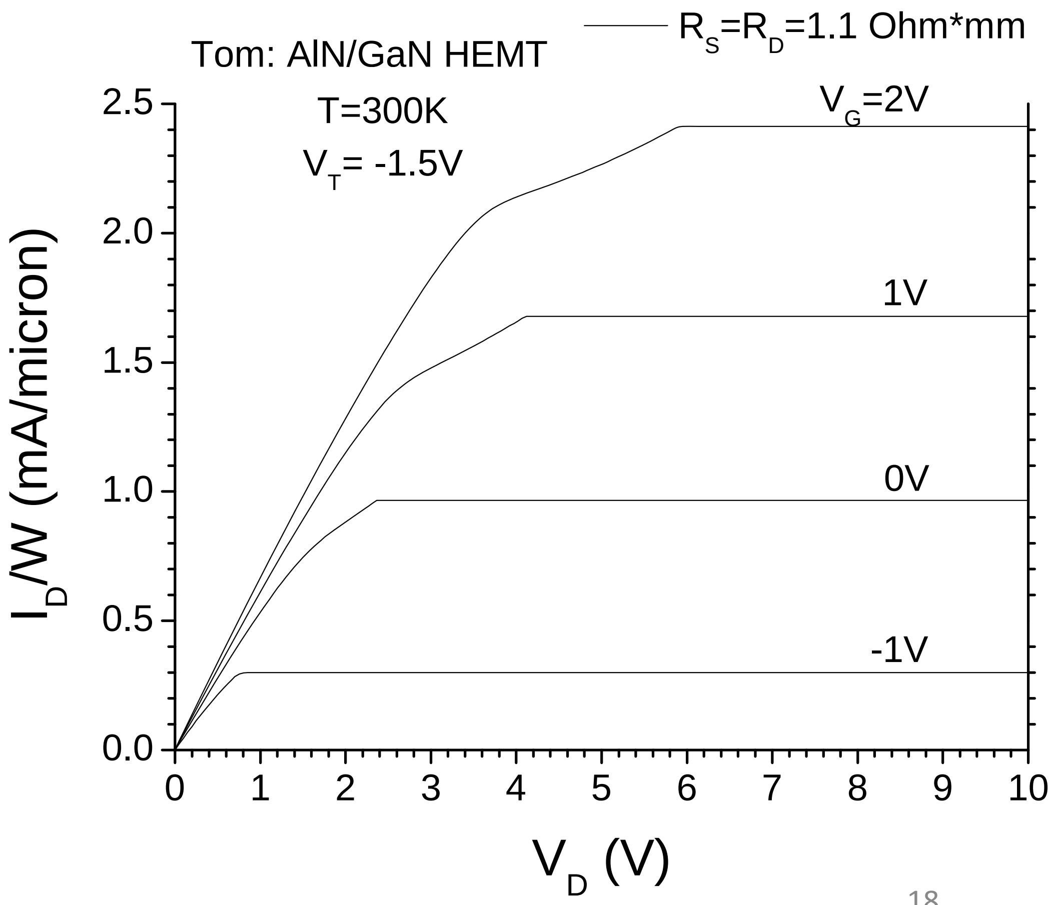
$$B = \frac{I_D(\text{on})}{I_D(\text{on}-\text{ballistic})} = \frac{T}{2-T} = \frac{\lambda_o}{2\ell + \lambda_o}$$

$$\lambda_o >> 2\ell \longrightarrow B \rightarrow 1$$

This shows devices can operate relatively close to the ballistic limit even though they are several mean-free-path longer.



Device measured by Tom



Ballistic Model calculated by Guowang

Future Work

- Apply the model to GaN based HEMTs
- Include phonon scattering in GaN channel in the ballistic model
- Plot I-V for GaN based HEMT under ballistic or close to ballistic limit

THANK YOU!