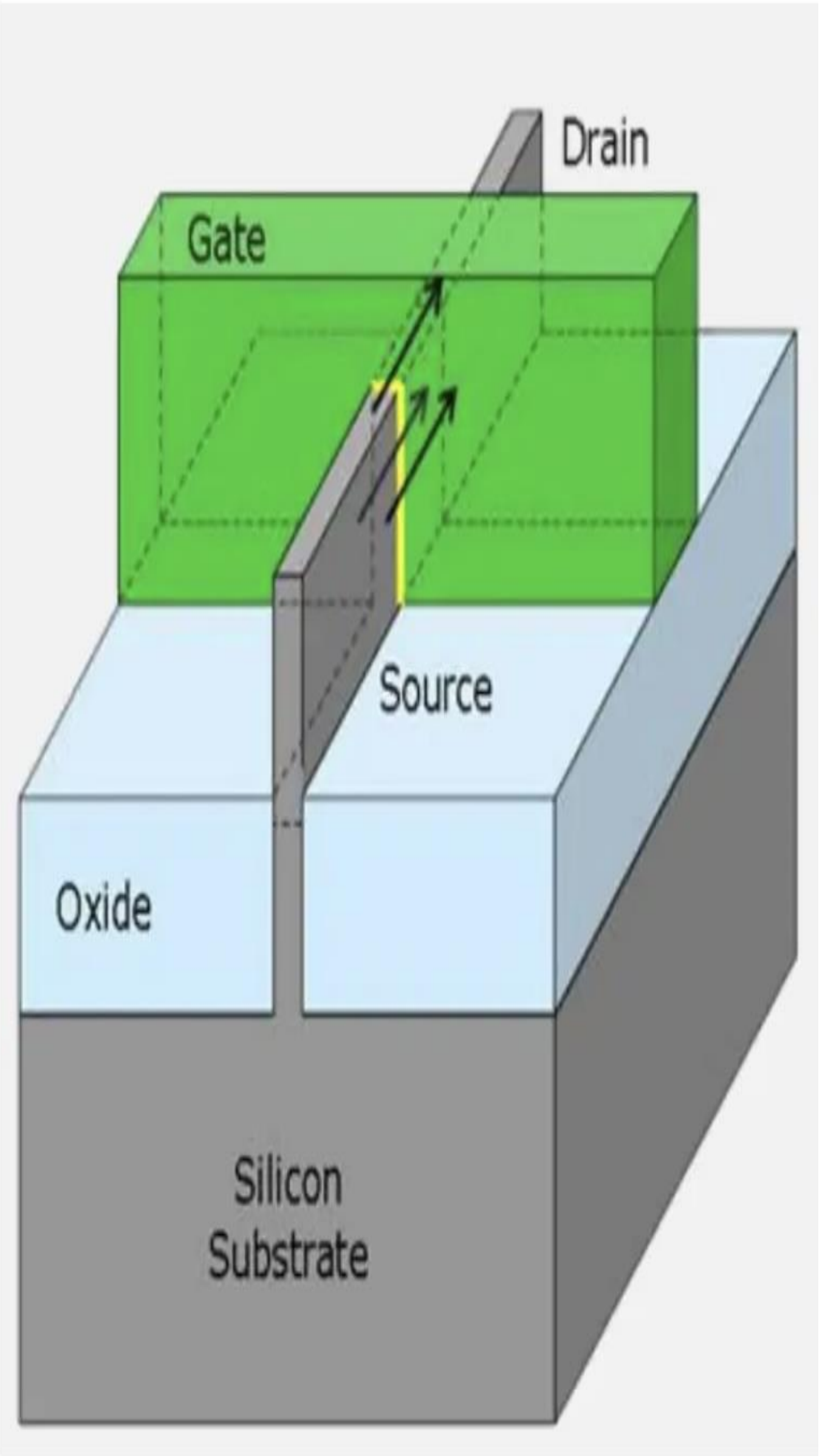
Electrostatic and quantum size effects in short channel MOSFETs

Aidan Szabo, Robert Troy, A Varonides, Physics & Engineering Dept

[1]University of Scranton,

Abstract

Two-dimensional electrostatics and quantum size effects have become important features of modern short channel MOSFET device design where the surface potential becomes spatially dependent affecting the threshold voltage. Several nanometer channel lengths between Source and Drain cause quantum effects that need to be addressed in modern MOSFET design. We present a model of electron transport in the 2-D inversion layer, where (a) electrostatic and (b) quantum size effects are pointed out.



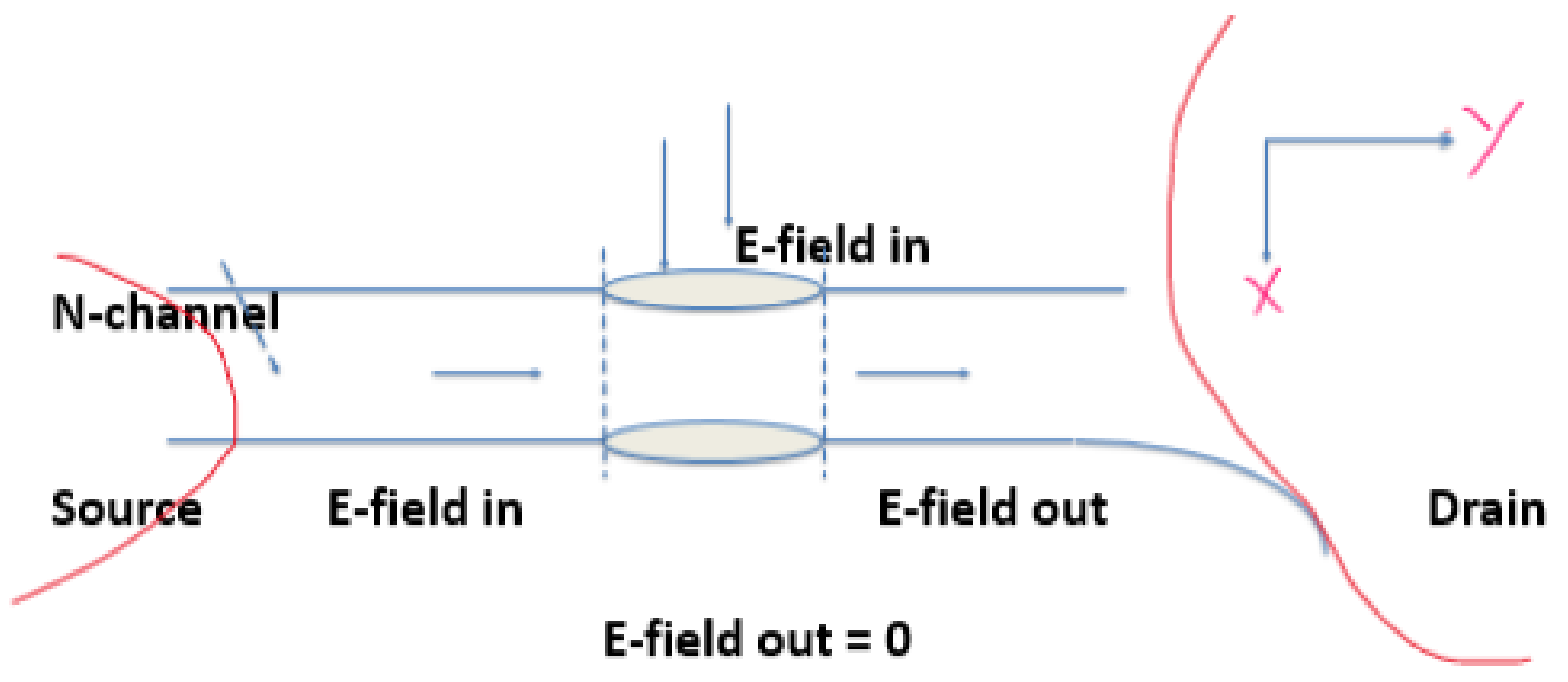
We solve Poisson’s equation in the inversion layer (channel) surrounded by the gate-oxide above and the p-Si substrate below. The solution of Poisson’s equation describes the surface potential variation in the horizontal space between source and drain. The horizontal spread of the potential is described by the *natural length* l which depends on (i) gate-oxide and the silicon depletion layer thickness and (ii) on silicon and oxide dielectric constants. As surface potential boundary conditions, we take the built-in voltage at the source and the voltage V_{ds} at the drain (distance L from the source). We discuss the conditions for short channel based on the explicit solution for the surface potential.

Jamil Kawa, R&D Group
Director, Synopsys, Inc

We solve Schrodinger’s equation to count for source-to-drain tunneling for 5nm channel lengths. Electric field fluxes out from the drain to the channel and the depletion region underneath in the p-Si substrate. At 5nm, the electronic motion of the electrons in the channel becomes 2D. Electrons traversing the channel must **either surmount such barriers or *tunnel* through it**. **We propose a tunneling model** for such electrons and relate to device properties such as threshold voltage V_T

Modeling Method

2-D Electrostatics



E-field in

N-channel

Source

E-field in

E-field out

Drain

E-field out = 0

- **Solve Poisson’s equation in the “pill-box”:**
- **Express oxide capacitance and oxide voltage in terms of gate-source, flat band and surface potential , and oxide thickness**
- **$\varepsilon_s E_x(0,y)$ = surface charge density = $C_{ox} V_{ox}$**
- **the surface potential satisfies the following differential equation:**

$$\frac{d^2\Phi_s(y)}{dy^2} - \frac{\Phi_s(y)}{\lambda^2} = 0$$

- **The parameter λ is the natural length of the MOSFET**

$$\lambda = \sqrt{\frac{\varepsilon_s\, t_{ox}\, x_d}{G_{ox}}}$$

- **Electric field fluxes out of the cylindrical box is a Gaussian surface**
- **Surface potential spatially depends on V_T**
- **MOS in Full depletion**
- **The solution is:**

$$\phi_s(y) = A\sinh\left(\frac{y}{\lambda}\right) + B\cosh\left(\frac{y}{\lambda}\right)$$

$$B.C.\text{'s}\ :$$

$$\phi_s(\Delta) = \phi_{bi} = V_{bi}$$

$$\phi_s(L) = \text{ Drain End } = V_{bi} + V_{ds}$$

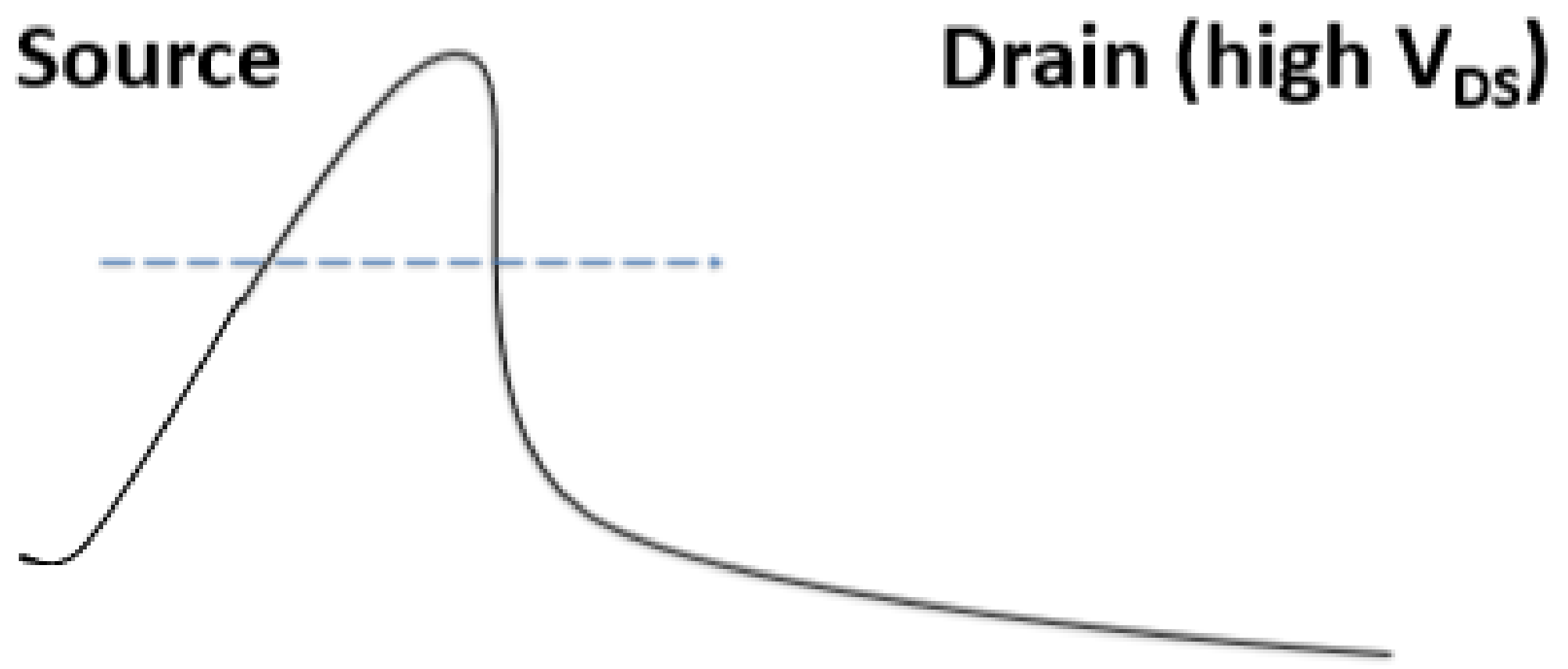
- **$\Phi_s(y)$ is the surface potential**
- **$\Phi_s(L)$ is surface potential for long/bulk MOSFET**
- **Φ_s (y = 0) = V_{bi} , at the source junction**
- **Φ_s (y = L) = V_{bi} +V_{DS}, DS is drain-source voltage**
- **A and B appropriate constants based on the BC’s**
- **Surface Potential Solution in the channel is:**
- **L is the channel length along the Y direction**
- **V_{bi} is the potential at the source**
- **V_{ds} is the drain source potential difference**

$$\Phi_s = \Phi_o + V_{bi}\left(1 - \frac{\tanh\left(\frac{y}{\lambda}\right)}{\tanh\left(\frac{L}{\lambda}\right)}\right)\cosh\left(\frac{y}{\lambda}\right)$$

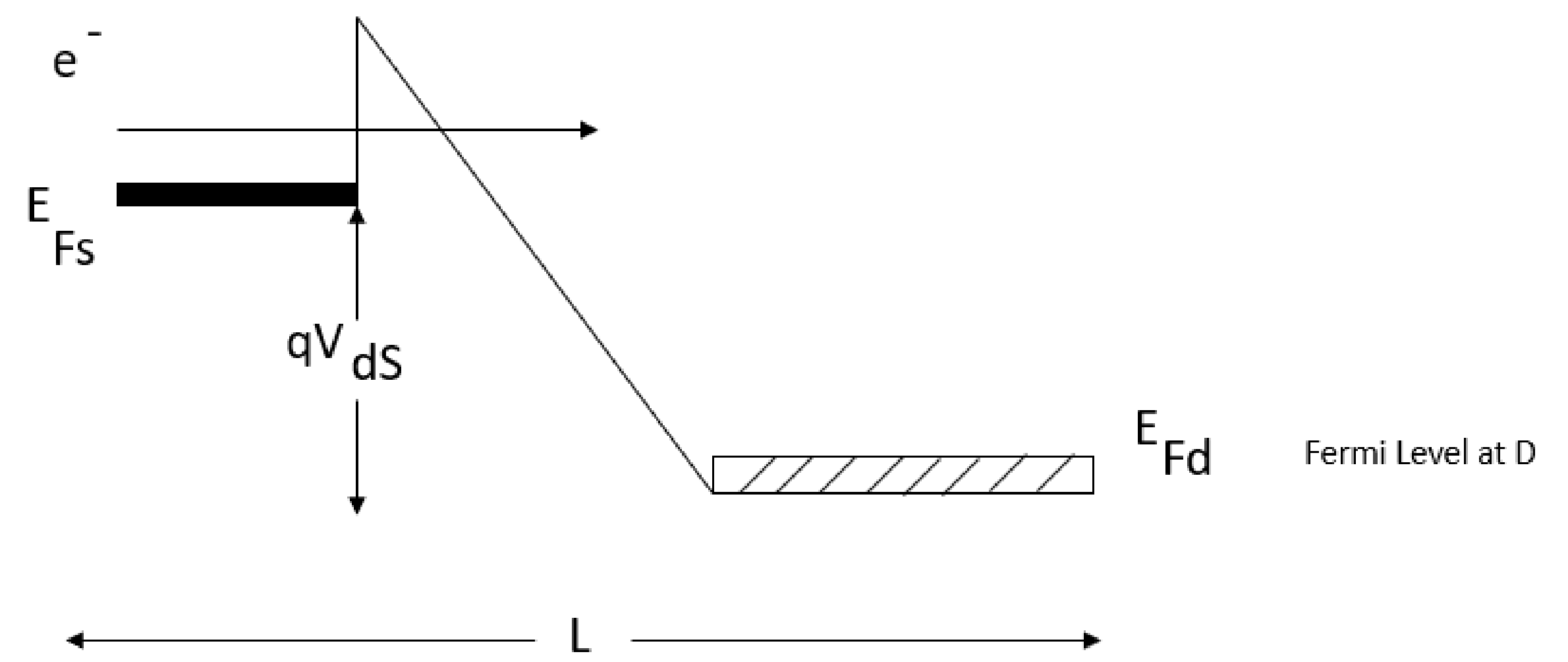
$$\Phi_o = \frac{V_{bi} + V_{ds}}{\sinh\left(\frac{L}{\lambda}\right)}$$

Quantum effects

- **Electrons are free to move in the y-z direction**
- **They are confined in the x direction**
- **Under high V_{DS} bias, the energy bands of the short channel are deformed as shown below:**



- **Energy Diagram of the Short Channel MOSFET**



- **Electron tunneling through the barrier. We solve for the tunneling current from S to D that affects threshold voltage**
- **Equation below:**

$$J(Tu) = AT^2 e^{\left(-\frac{2}{3}\Delta^{\frac{3}{2}}\frac{\sqrt{(V_{bi} - V_{ds})}}{E_{OD}}\right)} * e^{\left(-\frac{q\phi_b}{KT}\right)} * e^{\left(\frac{V_{ds}}{V_t} - 1\right)}$$

Conclusion

- **We have outlined the case for electrostatic and quantum size effects in modern short-channel MOSFETs.**
- **We have shown channel dependence on characteristic length of the device and presented a method of calculating source drain currents and high drain-source voltages and short channel.**
- **At high V(DS) voltage, the conduction energy band of the channel region is deformed with the formation of a potential barrier, through which electron need to tunnel in order to reach the drain region.**
- **We have derived and presented the tunneling current equations.**

Arggyrios,varonides@scranton.edu

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