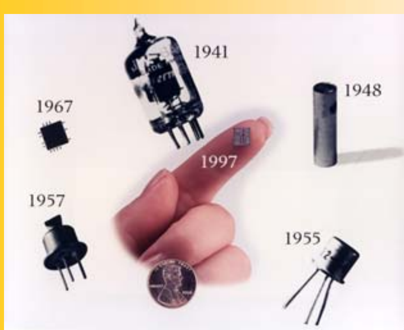
What is a Transistor?

A Transistor is an electronic device composed of layers of a semiconductor material which regulates current or voltage flow and acts as a switch or gate for electronic circuit.

History of the Transistor



P-N Junction

Russell Ohl 1939

First Transistor

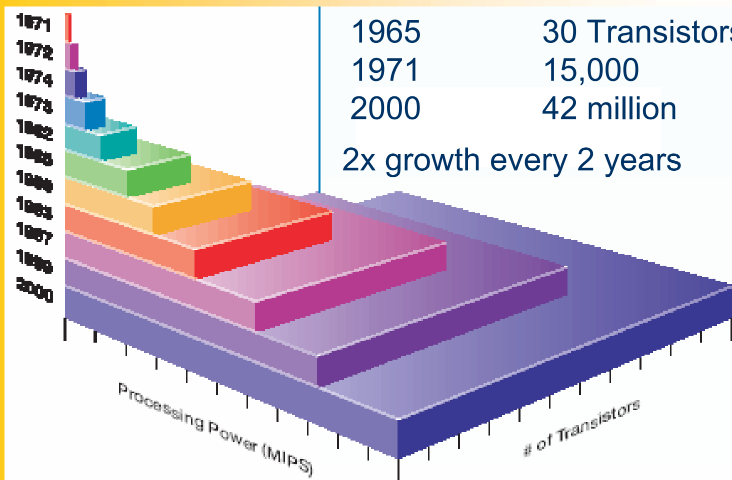
Bell Labs 1947

Shockley, Brattain, and Bardeen

First Solid State Transistor - 1951

History of the Transistor

Processor development followed Moore's Law



1965	30 Transistors
1971	15,000
2000	42 million

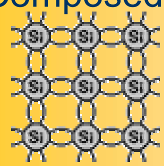
2x growth every 2 years

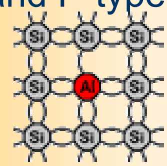
Applications

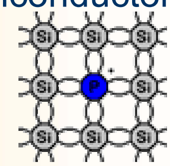
- Switching
- Amplification
- Oscillating Circuits
- Sensors

Transistor Physics

- Composed of N and P-type Semiconductors



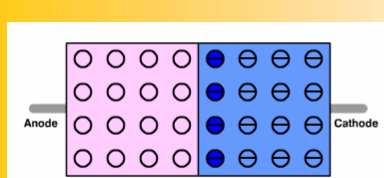




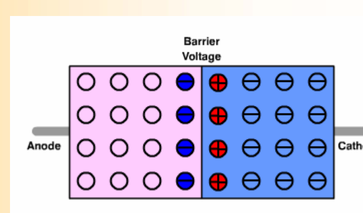
- N-type Semiconductor has an excess of electrons
  - Doped with impurity with more valence electrons than silicon
- P-type Semiconductor has a deficit of electrons (Holes)
  - Doped with impurity with less valence electrons than silicon

Transistor Physics

P-N Junction (Basic diode):
- Bringing P and N Semiconductors in contact
- Creation of a Depletion Zone

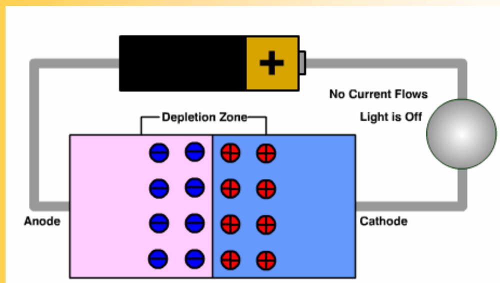


P-Type **N-Type**



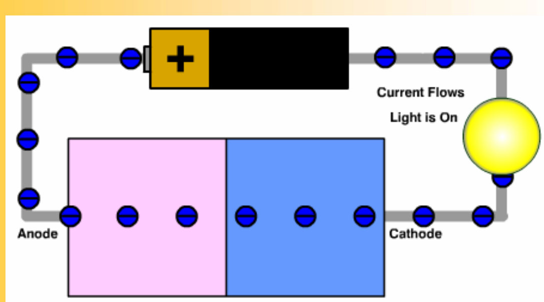
Transistor Physics

- P-N Junction
- Reverse Biased => No Current
- Applying –ve Voltage to Anode increases Barrier Voltage & Inhibits Current Flow



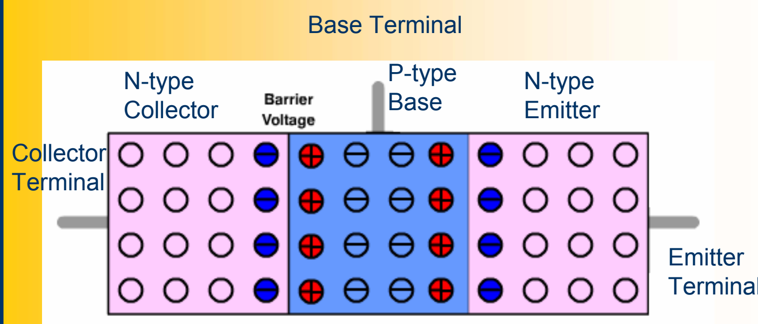
Transistor Physics

- P-N Junction
- Forward Biased => Current Flows
- Applying +ve Voltage > Barrier Voltage to Anode allows current flow



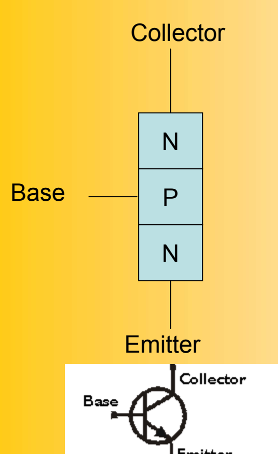
Transistor Physics

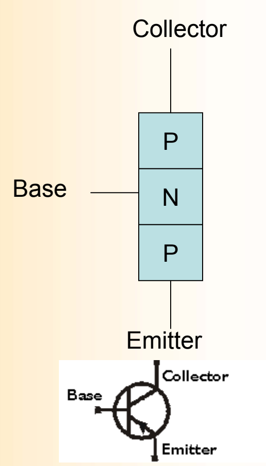
- Basic Transistor



Transistor Physics

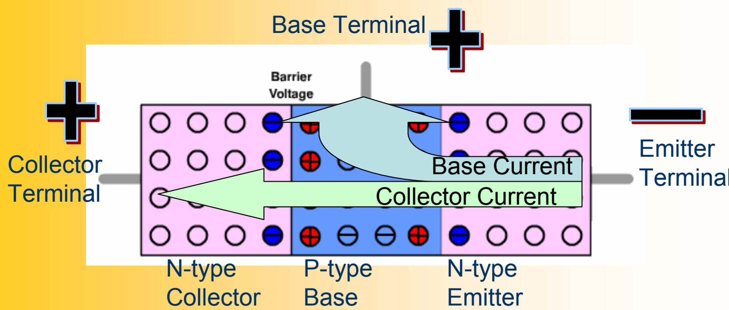
•Two Types - NPN and PNP



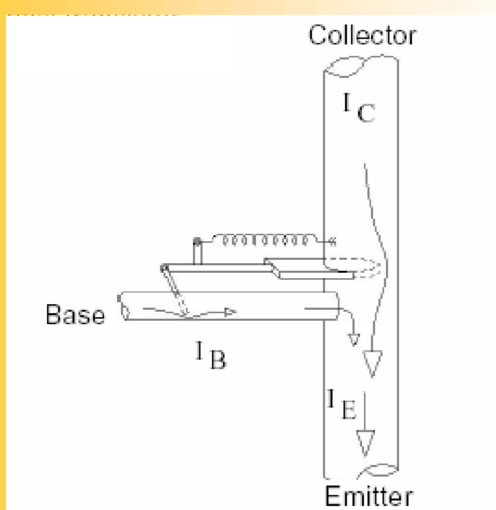


Transistor Physics

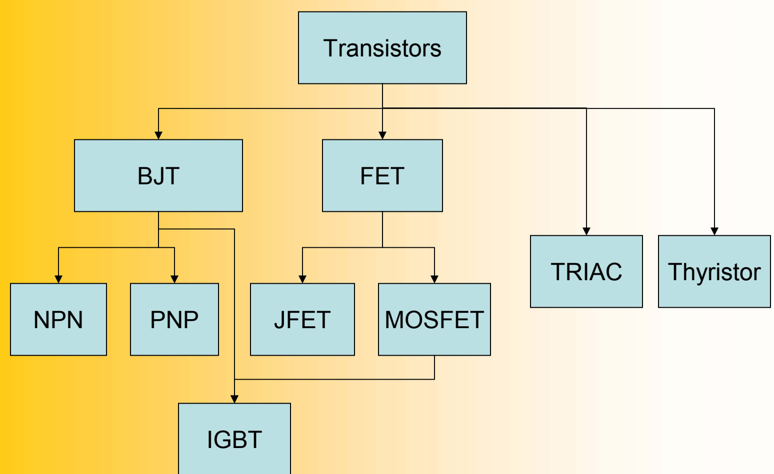
- Basic Transistor



Water pipe analogy

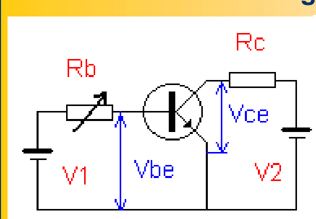


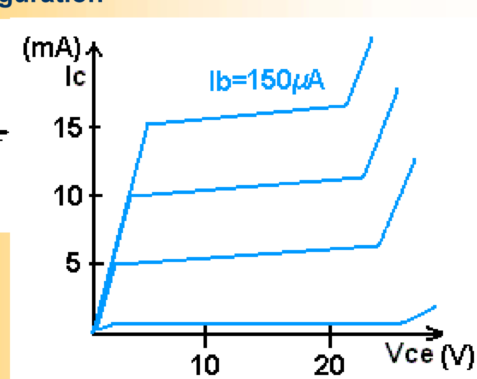
Types of Transistors



Properties of the BJT

Common emitter configuration





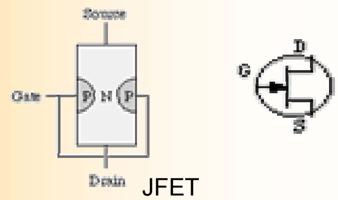
2 basic laws:

$I_e = I_b + I_c$

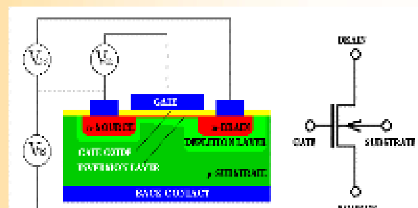
$I_c = \beta . I_b$ **(β=10 to 100)**

FET Basics

- Advantages
  - low power
  - high gate impedance
  - low S/D resistance
- Uses
  - amplifier
  - analog switch
- Design
  - gate==base
  - source==emitter
  - drain ==collector



JFET
http://encyclobeamia.solarbotics.net/articles/jfet.html


MOSFET
http://ece.colorado.edu/~bart/book/

FET Symbols

- Gate arrow --> n-type or p-type
- Gate/source separation --> MOSFET or JFET
- Broken source/drain line --> enhancement mode or depletion mode
- Gate line is offset towards the source


JFET
n-channel
depletion mode

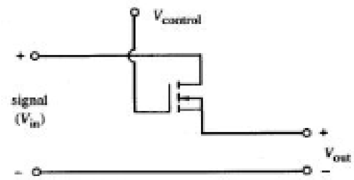

JFET
p-channel
depletion mode


MOSFET
n-channel
enhancement mode


MOSFET
p-channel
enhancement mode

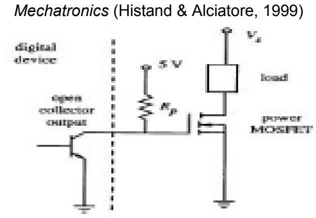
FET Applications

Analog Switch



Mechatronics (Histand & Alciatore, 1999)

Power Switch



Mechatronics (Histand & Alciatore, 1999)

Power Transistors

- Generally
  - Fabrication differences for dissipating more heat
  - Lower gain than signal transistors
- BJT
  - essentially the same as a signal level BJT
  - Power BJT cannot be driven directly by HC11
- MOSFET
  - base (flyback) diode
  - Large current requirements: use parallel MOSFETs

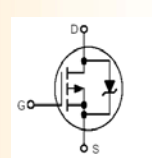
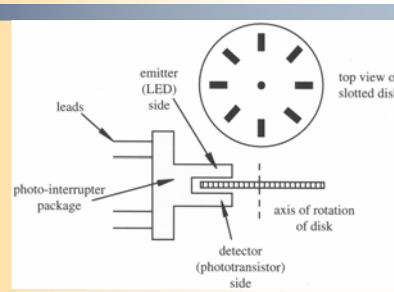
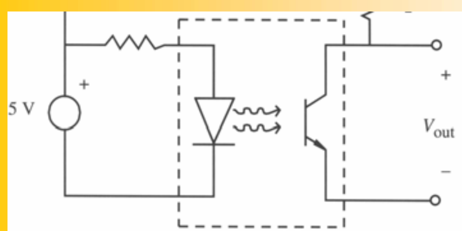


Photo Transistors

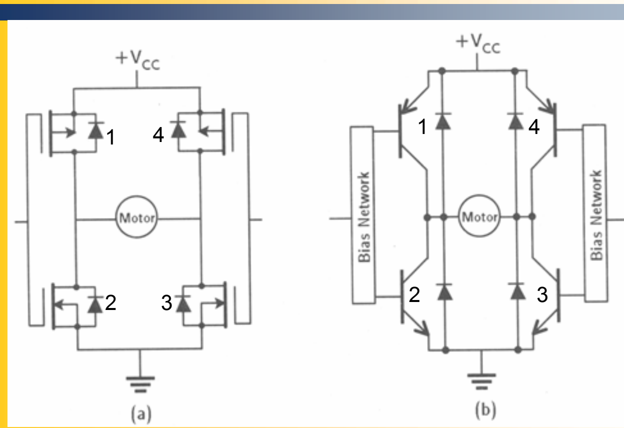
- Light acts as the base current





Opto-coupler

H-bridge example



Left side -5V, right side +5V → 1 & 3 on, 2 & 4 off

Left side +5V, right side -5V → 1 & 3 off, 2 & 4 on

PHY305F
Electronics Laboratory I

Section 7

The Discrete Building Block: Transistors and Transistor Amplifiers

Transistors

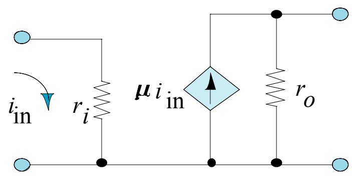
- Transistors are three-terminal semiconductor devices that can:
  - → *amplify* a signal by transferring energy to it from an external source
  - → *switch* a current or voltage across two terminals using a small control current or voltage applied at a third terminal
- There are two types of transistors:
  - → bipolar junction transistors (BJTs)
  - → field-effect transistors (FETs)
- Operation of transistors as linear amplifiers can be modelled using controlled sources:
  - → controlled voltage and current sources generate an output proportional to an input current or voltage
  - → constant of proportionality μ is the internal gain of the transistor

Transistors as Amplifiers

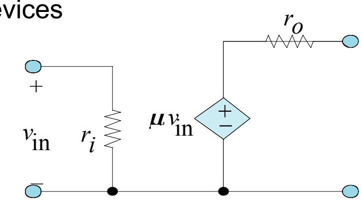
Controlled-source models of linear amplifier transistor operation:

→ BJTs act as current-controlled devices

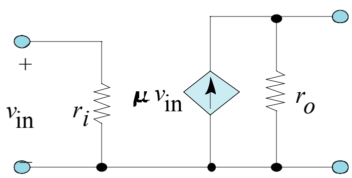
→ FETs act as voltage-controlled devices



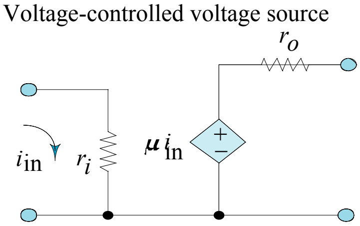
(a) Current-controlled current source



(b) Voltage-controlled voltage source



(c) Voltage-controlled current source



(d) Current-controlled voltage source

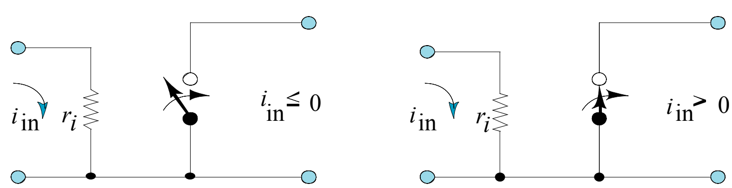
(from Rizzoni Figure 9.1)

Transistors as Switches

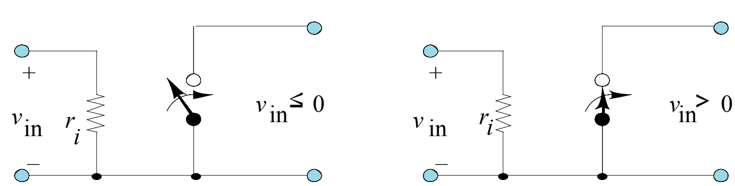
- Transistors can also act as switches in a nonlinear mode, with a small voltage or current used to control the current between two of the transistor terminals (on or off).

Model of ideal transistor switches:

- switch is closed (on) when control v or i is > 0
- switch is open (off) otherwise



Current-controlled switch



Voltage-controlled switch

(from Rizzoni Figure 9.2)

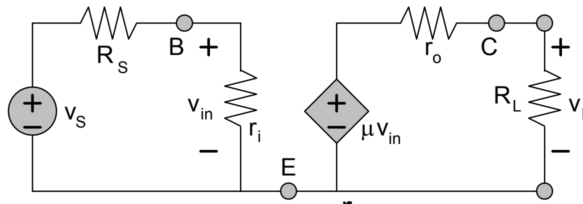
Example: Linear Amplifier Gain

Determine the voltage gain of the amplifier circuit model shown.

Known: amplifier internal input and output resistances r_i and r_o, amplifier internal gain μ, source and load resistances R_S and R_L.

Find: $A_V = v_L/v_S$

Solution:



Use voltage divider to get: $v_{in} = \dfrac{r_i}{r_i + R_S} v_S$

Output of controlled voltage source is: $\mu v_{in} = \mu \dfrac{r_i}{r_i + R_S} v_S$

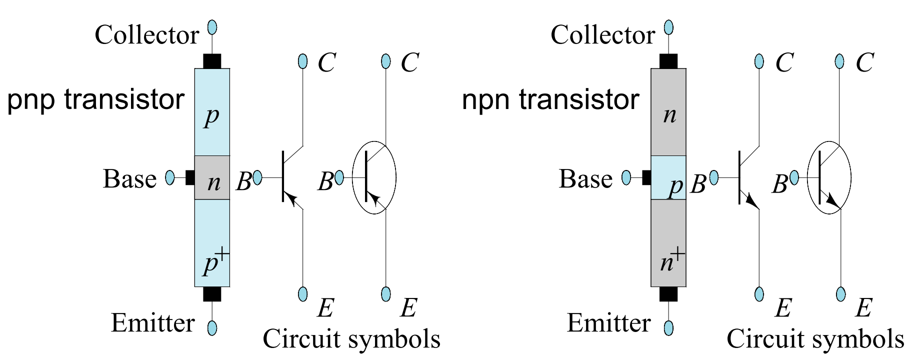
Use voltage divider to get output voltage: $v_L = \mu \dfrac{r_i}{r_i + R_S} v_S \times \dfrac{R_L}{r_o + R_L}$

Amplifier voltage gain is then: $A_V = \dfrac{v_L}{v_S} = \mu \dfrac{r_i}{r_i + R_S} \times \dfrac{R_L}{r_o + R_L}$

Note: A_V is always $< \mu$. $A_V \approx \mu$ if $r_i >> R_S$ and $r_o << R_L$.

Bipolar Junction Transistors (BJTs)

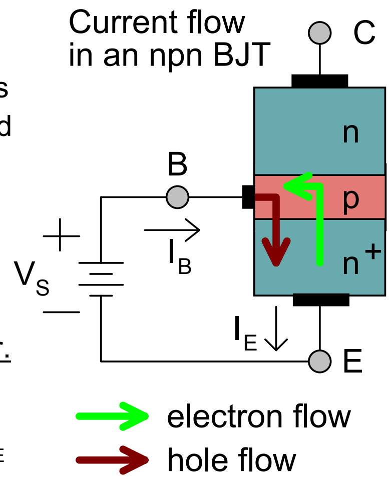
- A BJT is a three-terminal semiconductor device formed by joining three sections of semiconductor material, each with a different doping concentration.
- Two types of BJTs (superscript $^+$ means heavily doped material):
  - → pnp have a thin n region sandwiched between p^+ and p layers
  - → npn have a thin p region sandwiched between n^+ and n layers



(from Rizzoni Figure 9.4)

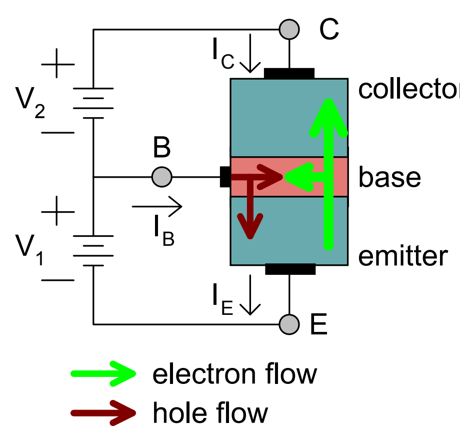
The npn BJT: Base-Emitter Junction

- The base-emitter (BE) pn junction acts like a forward-biased diode.
- When the collector is open, electrons and holes flow between the base and emitter as shown.
- Electron current > hole current because of heavier doping on the n side of the junction.
- Net current flow from base to emitter.
- With the collector open and the BE junction behaving like a diode: $I_B = I_E$
- Note that the base region is narrower than the emitter region.



The npn BJT: Base-Collector Junction

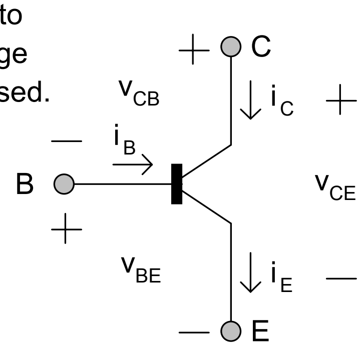
- If the base-collector (BC) pn junction is reverse-biased, then electrons emitted by the emitter, with the BE junction forward-biased, reach the base (where some are lost to recombination) and are collected by the collector.
- The reverse-biased BC junction thus sweeps electrons from emitter to collector (narrow base allows them to cross BC junction).



- Net current flow from collector to emitter (and from base to emitter).

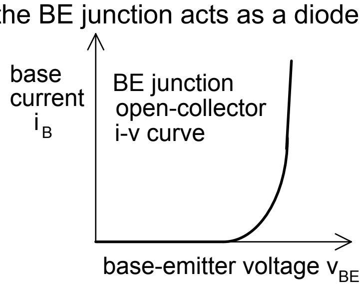
The npn BJT: Base-Collector Junction

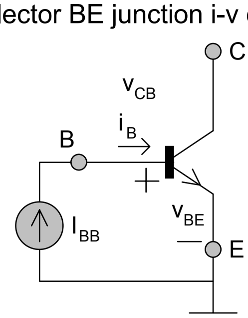
- Applying KCL: $I_E = I_B + I_C$
- The most important property of the BJT is that the small base current controls the amount of the much larger collector current:
  $I_C = \beta I_B$ where β is a current amplification factor that depends on the physical properties of the transistor (typically 20-200).
- Note: operation of a pnp BJT is similar to that of a npn BJT with the roles of charge carriers and signs of the currents reversed.
- Two voltages and two currents can be used to uniquely define the operation of a BJT.
- KCL: $i_E = i_B + i_C$
- KVL: $v_{CE} = v_{CB} + v_{BE}$



Characteristics of a BJT - 1

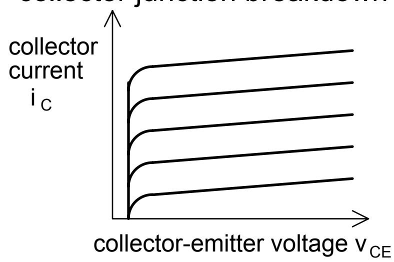
- Two i-v curves are needed to characterize a BJT (because it has three terminals):
  - → one relates the base current i_B to base-emitter voltage v_{BE}
  - → one relates the collector current i_C to collector-emitter voltage v_{CE}
- To determine the first, consider the BJT with the collector open:
  - → ideal current source I_{BB} injects a base current which forward biases the BE junction
  - → by varying I_{BB}, can determine open-collector BE junction i-v curve
  - → the BE junction acts as a diode

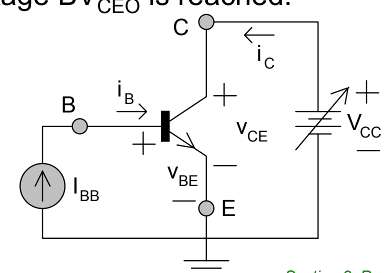




Characteristics of a BJT - 2

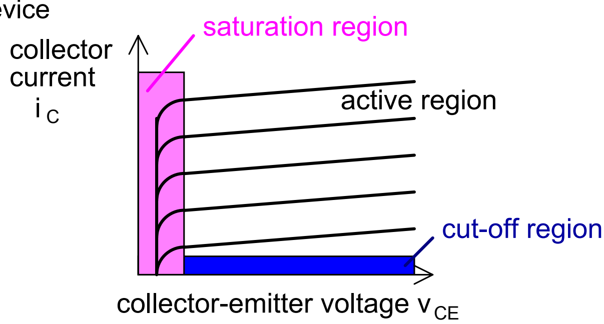
- To determine the second i-v curve, connect a voltage source to the collector circuit to vary collector-emitter voltage v_{CE} and hence collector current i_C (as well as base current i_B).
- Varying the base current and the collector-emitter voltage leads to a plot of the collector characteristic of the BJT.
- This consists of a family of i_C-v_{CE} curves, one for each value of i_B.
- For each i_B, as v_{CE} is increased, i_C increases rapidly until it reaches a nearly constant value, where it remains until the collector junction breakdown voltage BV_{CEO} is reached.





Characteristics of a BJT - 3

- The collector characteristic has four distinct regions:
  - → cut-off region where both junctions are reverse biased, the base current is very small, and essentially no collector current flows
  - → active linear region where the BE junction is forward biased and the CB junction is reverse biased (transistor can act as linear amplifier)
  - → saturation region where both junctions are forward biased
  - → breakdown region which determines the physical limits of operation of the device

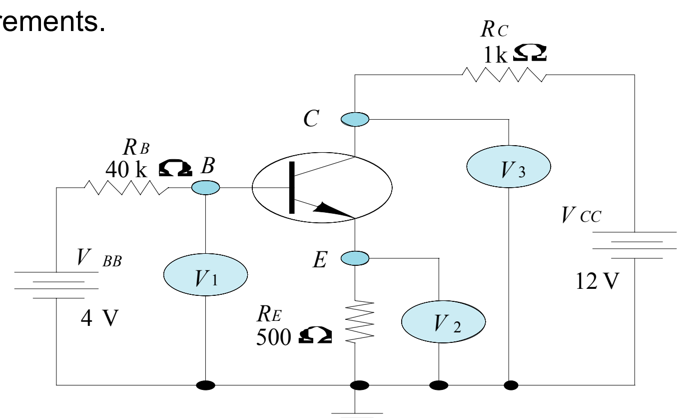


Finding the Operating Region of a BJT

- The state of a BJT (and its operating or active region) can be determined by measuring the collector, emitter, and base voltages.
- Consider this example, with V_B=V_1=2 V, V_E=V_2=1.3 V, V_C=V_3=8 V.
  - → first can calculate $V_{BE} = V_B - V_E = 0.7$ V, so know BE junction is forward biased
  - → then find base and collector currents:
    $$I_B = \frac{V_{BB} - V_B}{R_B} = \frac{4-2}{40{,}000} = 50\ \mu A \quad \text{and} \quad I_C = \frac{V_{CC} - V_C}{R_C} = \frac{12-8}{1{,}000} = 4\ mA$$
  - → so current amplification or gain factor for the BJT is: $I_C / I_B = \beta = 80$
  - → this value indicates that the BJT is in the linear active region because large current amplification is occuring (typically 20-200)
  - → can also find $V_{CE} = V_C - V_E = 6.7$ V
  - → currents I_B and I_C and voltage V_{CE} uniquely determine the state of the transistor in the I_C-V_{CE} and I_B-V_{BE} curves

Finding the Operating Region of a BJT

The following diagram shows the circuit used in the example of finding the operating region of the transistor using several voltage measurements.

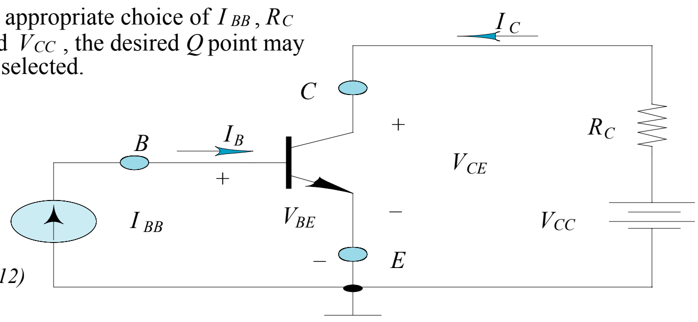


(from Rizzoni Figure 9.10)

The Operating Point for a BJT - 1

- The operating point or Q point of a BJT can be determined by selecting the base and collector currents (or v_{CE}).
- The Q point is defined using the quiescent or idle currents and voltages at the BJT terminals when connected to DC supplies.
- An ideal DC bias circuit (below) can be used to set the Q point of the BJT approximately in the centre of the collector characteristic.

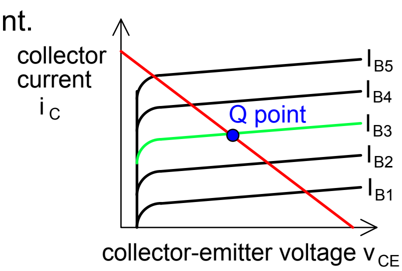
By appropriate choice of I_{BB}, R_C and V_{CC}, the desired Q point may be selected.



(from Rizzoni Figure 9.12)

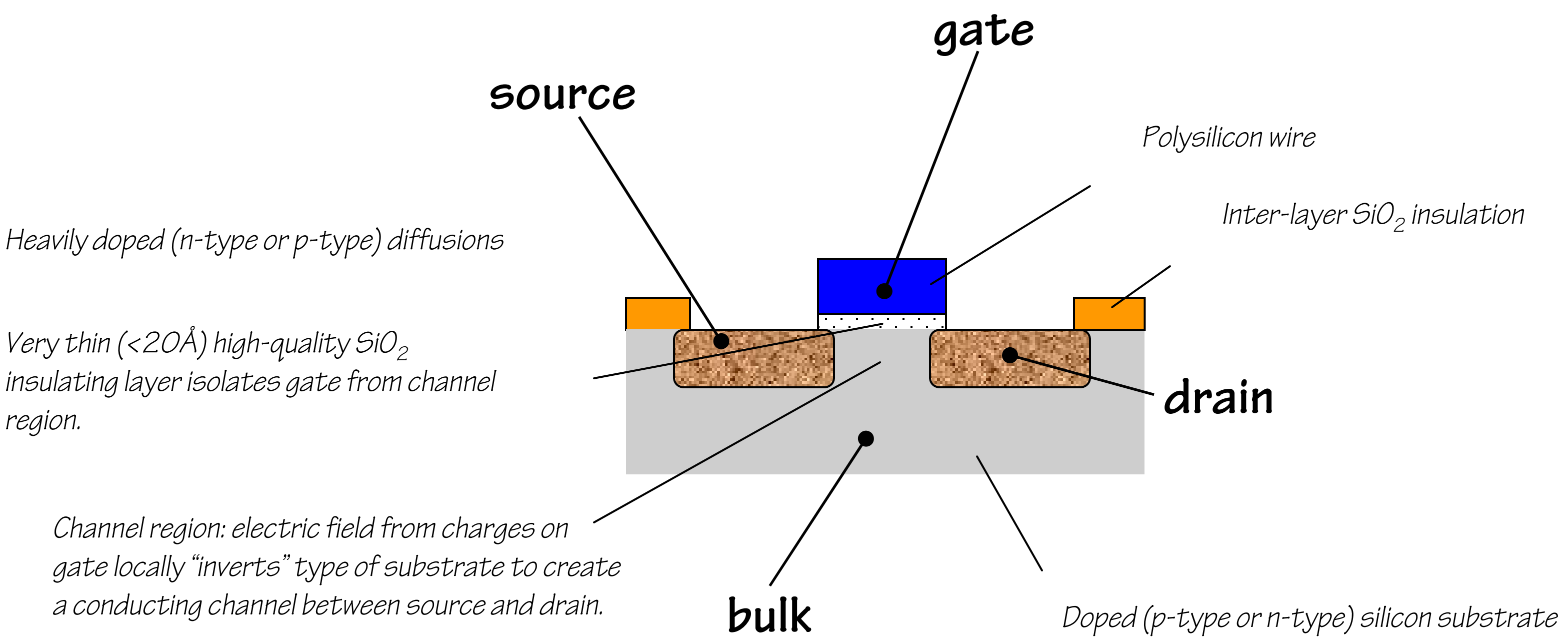
The Operating Point for a BJT - 2

- Apply KVL around the base-emitter circuit: $I_B = I_{BB}$
- Apply KVL around the collector circuit: $V_{CE} = V_{CC} - I_C R_C$
- Rewrite as: $I_C = \frac{V_{CC}}{R_C} - \frac{V_{CE}}{R_C}$
- This is a load-line curve, representing a line that intersects the I_C axis at V_{CC}/R_C and the V_{CE} axis at V_{CC}, with slope $-1/R_C$.
- This line intersects all of the collector characteristic curves.
- The point at which this line intersects the the curve for $I_B = I_{BB}$ is the Q point.



Load-line analysis of a simplified BJT amplifier

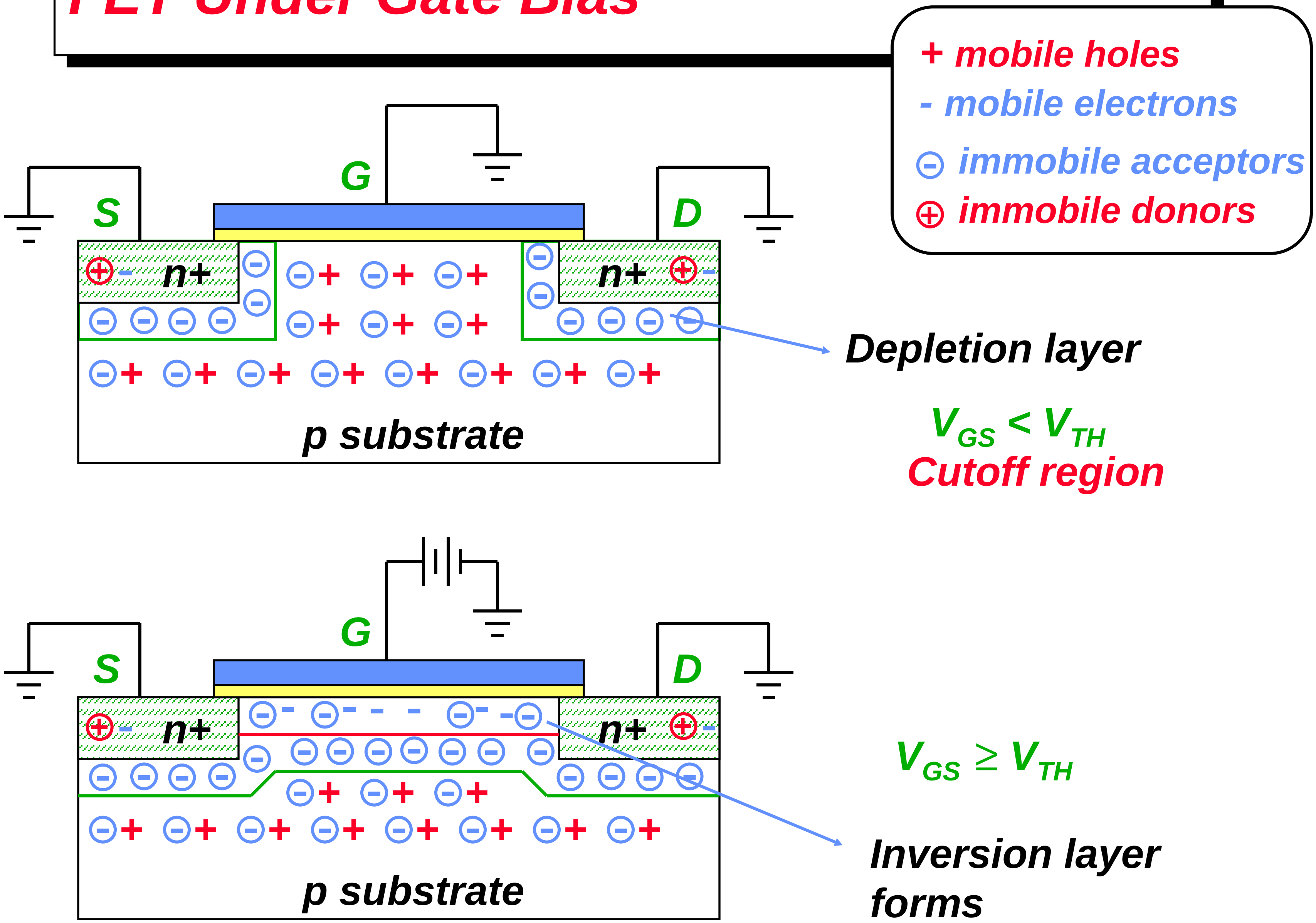
MOSFET



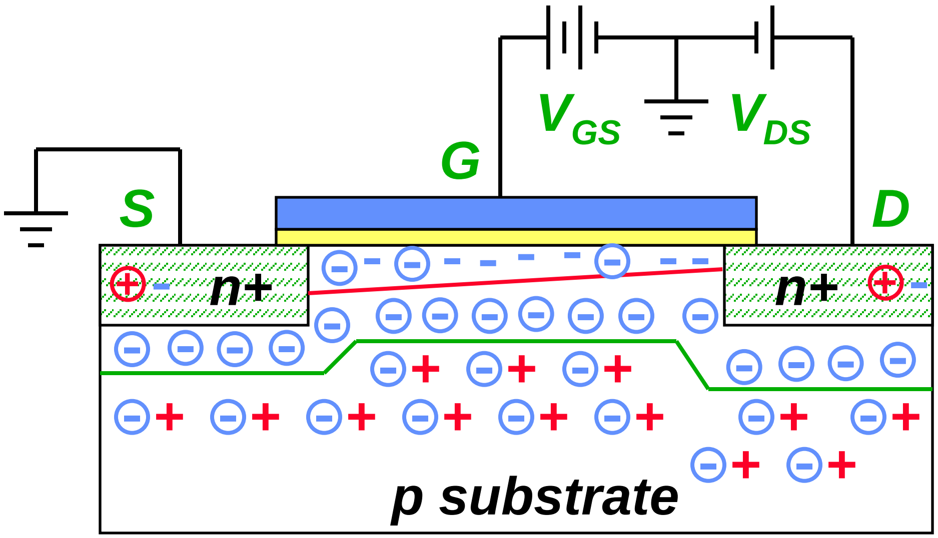
MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors) are four-terminal voltage-controlled switches.

Current flows between the diffusion terminals if the voltage on the gate terminal is large enough to create a conducting "channel", otherwise the diffusion terminals are not connected.

FET Under Gate Bias



"Linear" Operating Region



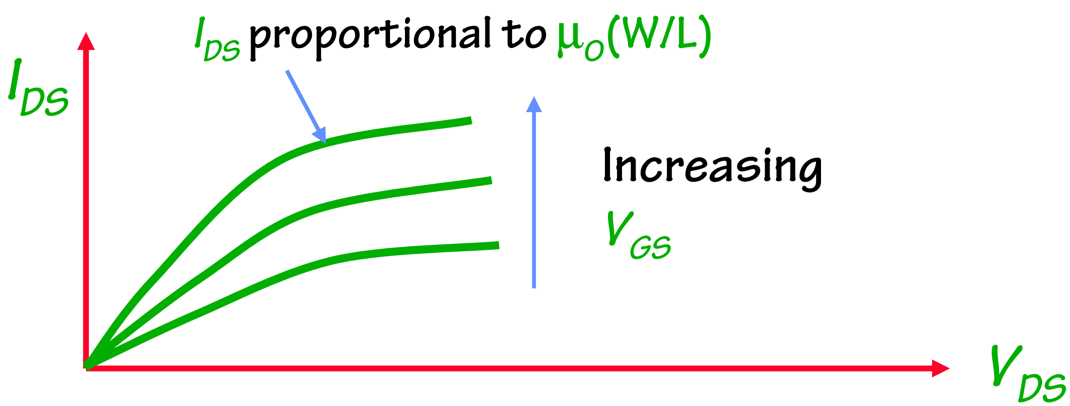
$V_{GS} \geq V_{TH}$

$V_{GS} - V_{TH} > V_{DS}$

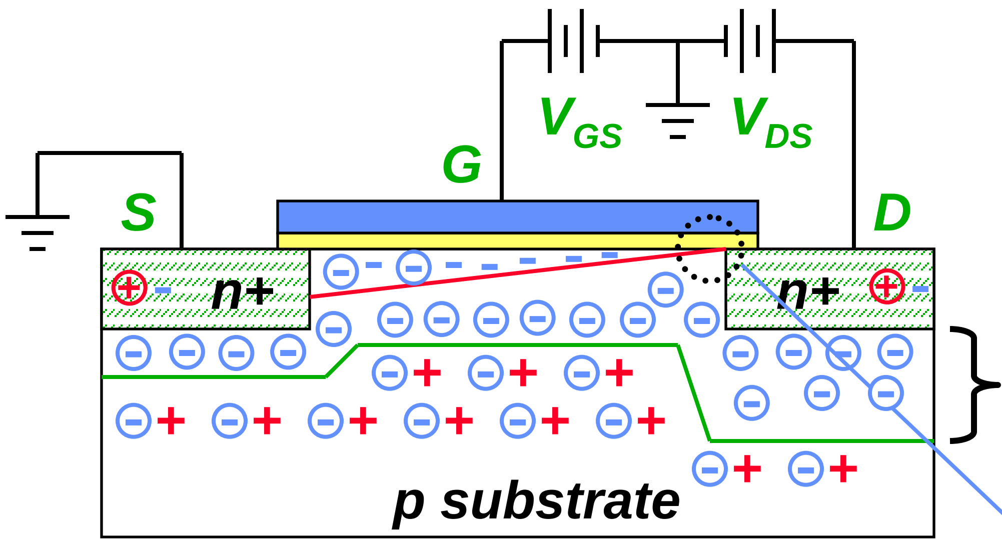
Current flows from drain to source

Larger V_{DS} increases I_{DS}

Larger V_{GS} creates deeper channel which increases I_{DS}



Saturated Operating Region



$V_{GS} \geq V_{TH}$

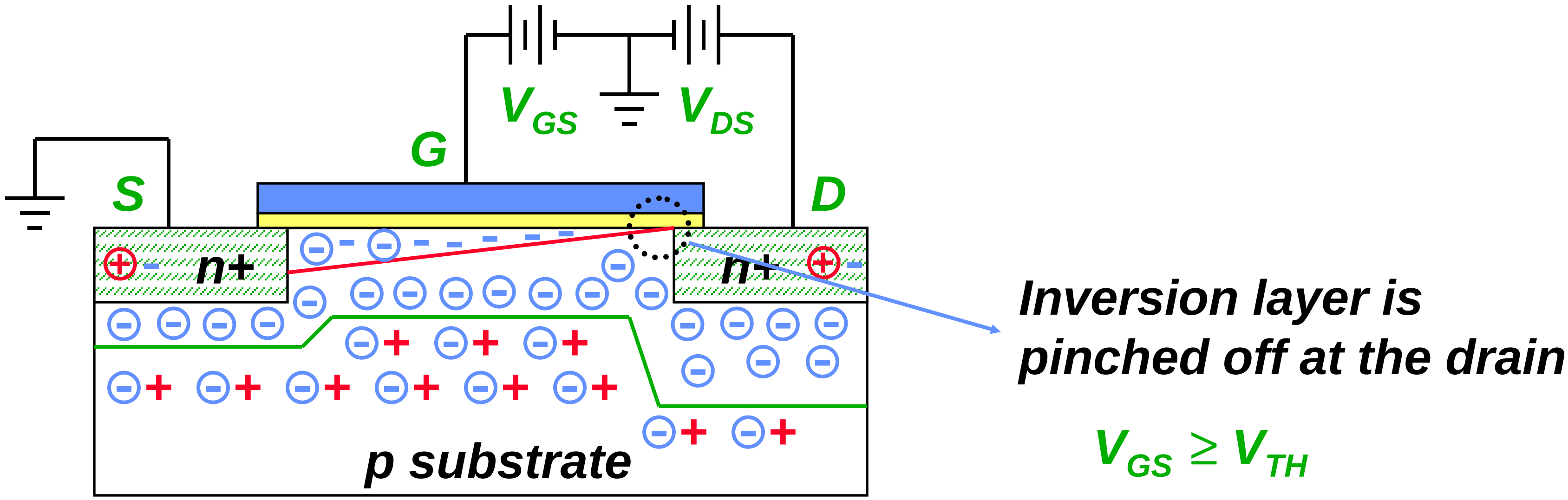
$V_{GS} - V_{TH} = V_{DS}$

Why is the depletion layer deeper near the drain?

Inversion layer is pinched off near the drain

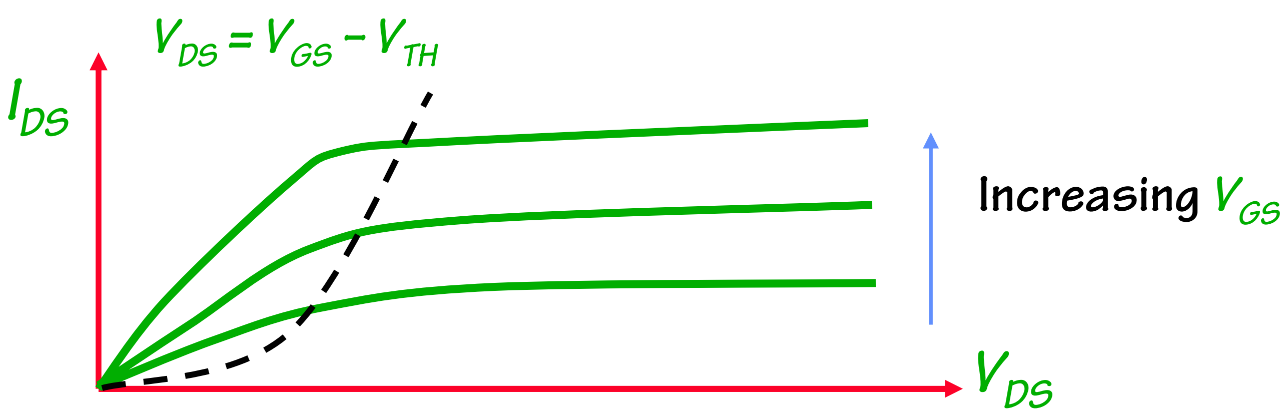
Voltage difference across the channel remains $V_{GS} - V_{TH}$ even with increased V_{DS}

Saturated Operating Region - 2

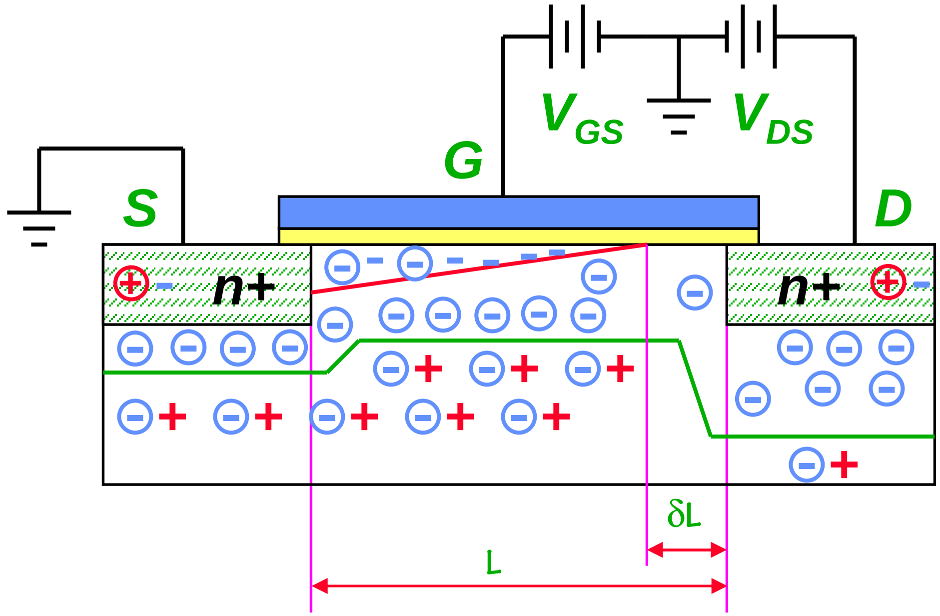


$V_{GS} \geq V_{TH}$

To the first order, once $V_{DS} \geq V_{GS} - V_{TH}$, I_{DS} does not increase



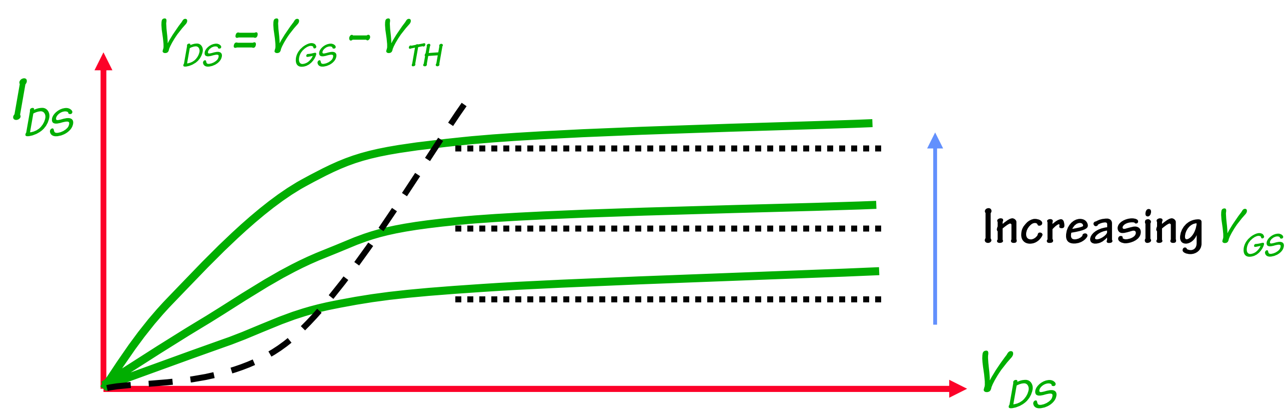
Channel Length Modulation Effect



$V_{GS} \geq V_{TH}$

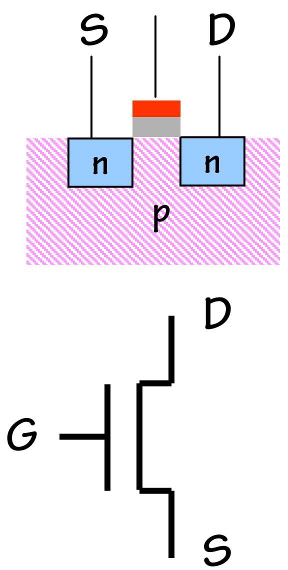
$V_{DS} \geq V_{GS} - V_{TH}$

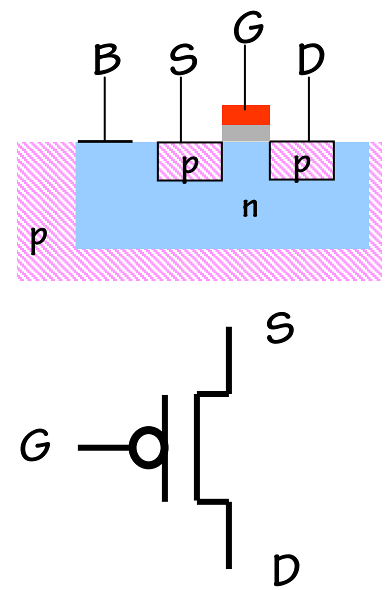
Increased V_{DS} results in effective channel length decreasing, i.e., δL getting larger, which increases I_{DS}



FETs come in two flavors

By embedding p-type source and drain in a n-type substrate, we can fabricate a complement to the N-FET:

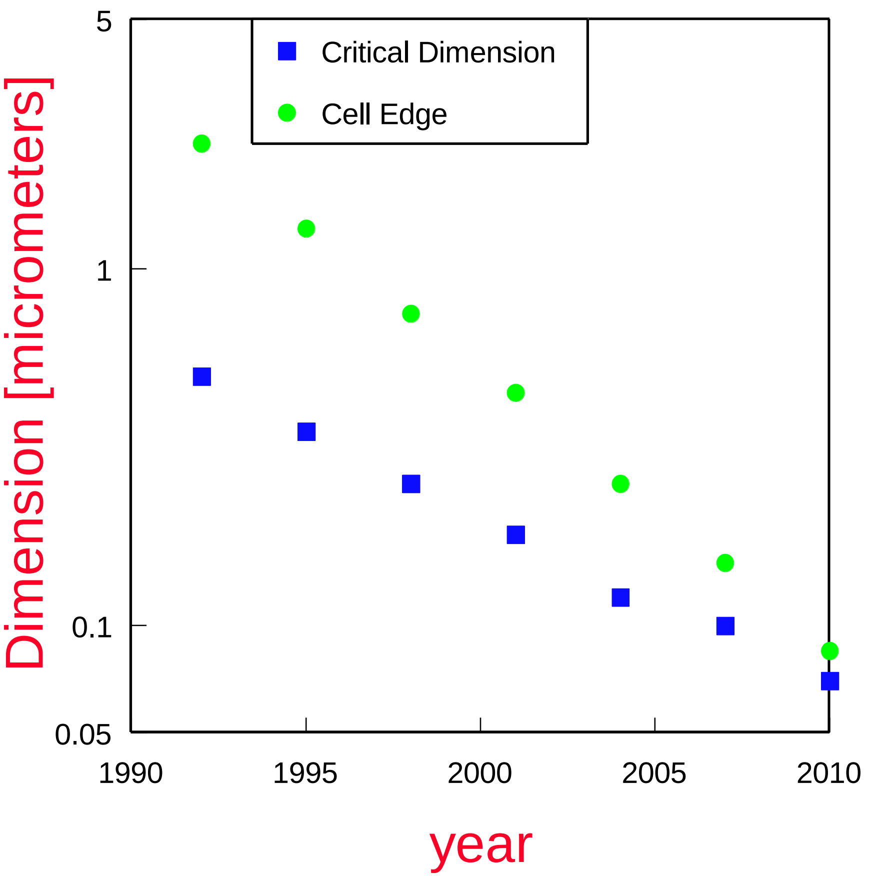




The use of both NFETs and PFETs – complementary transistor types – is a key to CMOS (complementary MOS) logic families.

1. Introduction

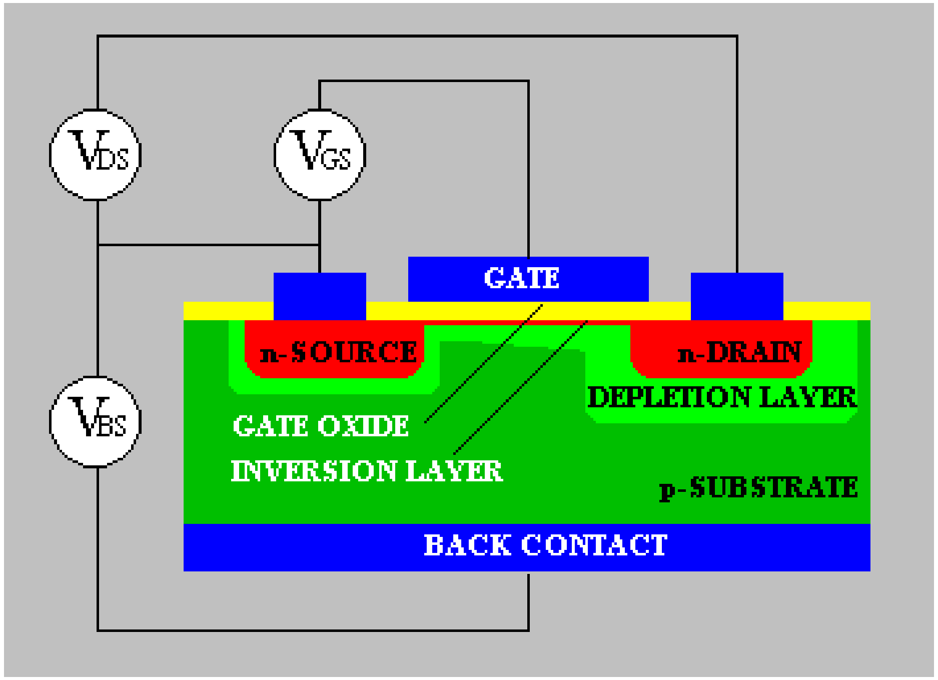
- First proposal for a MOSFET device was given by *Lilienfeld* and *Heil* in 1930.
- First operational device was made in 1947 at Bell Labs.
- Since then, the MOSFET dimensions have been continuously scaled to achieve more functions on a chip.



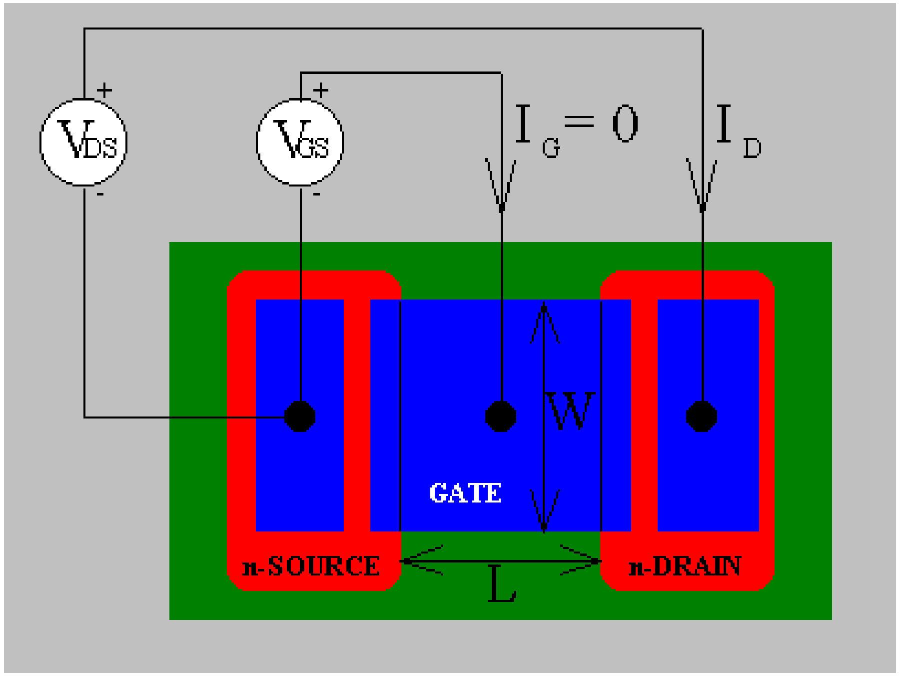
From SIA roadmap for semiconductors (1997)

• MOSFET is a four-terminal device. Basic device configuration is illustrated on the figures below.

Side-view of the device



Top-view of the device

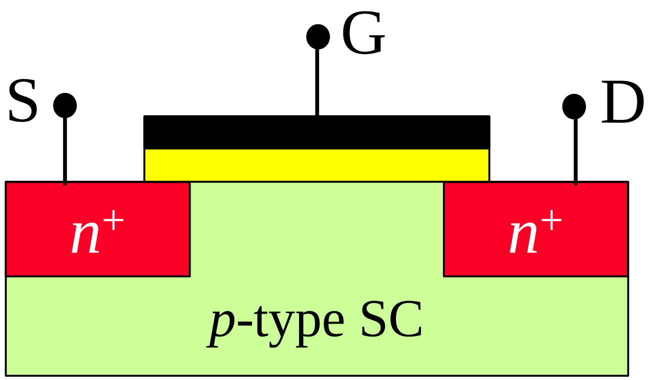


Basic device parameters:

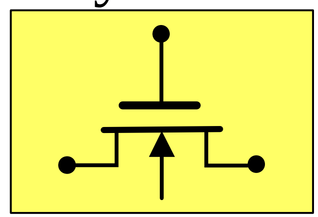
channel length L
channel width W
oxide thickness d_{ox}
junction depth r_j
substrate doping N

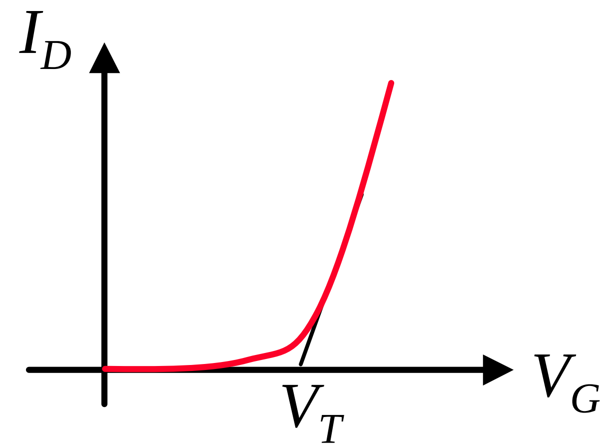
- There are basically four types of MOSFETs:

(a) *n*-cnannel, enhancement mode device

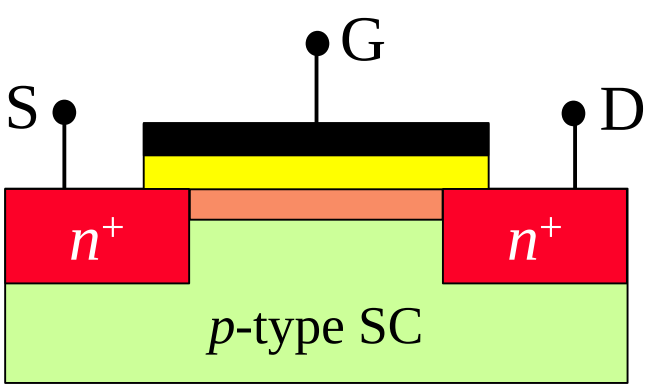


symbol

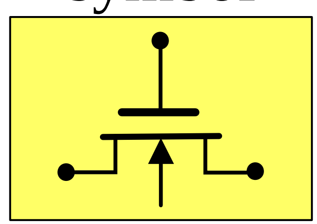


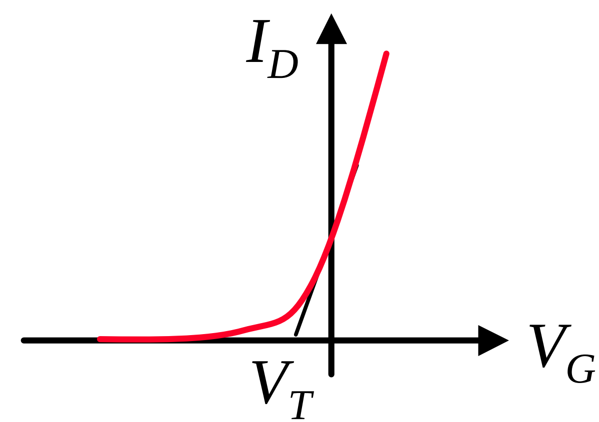


(b) *n*-cnannel, depletion mode device

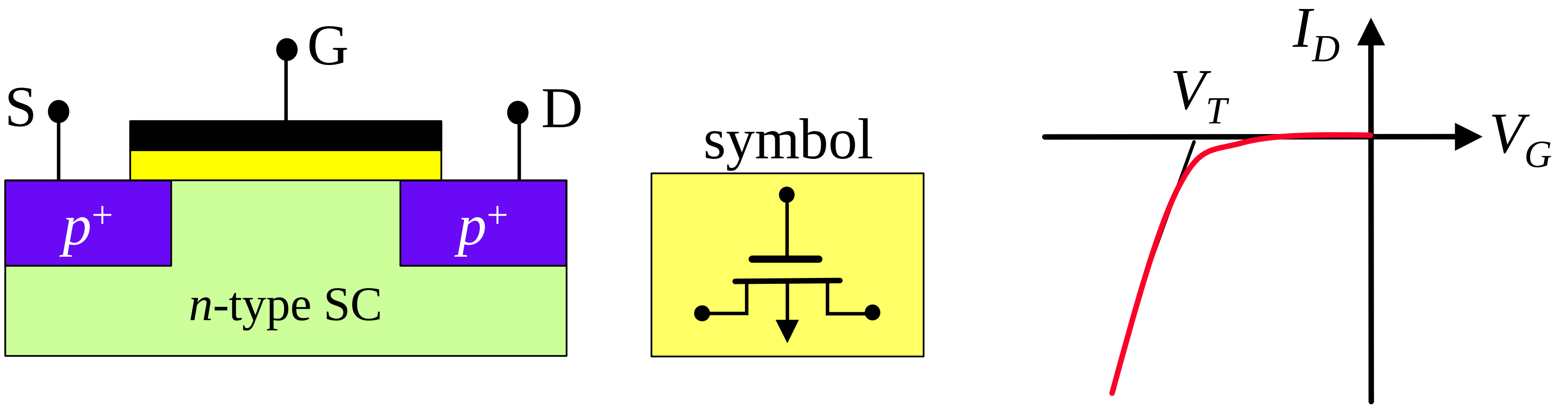


symbol

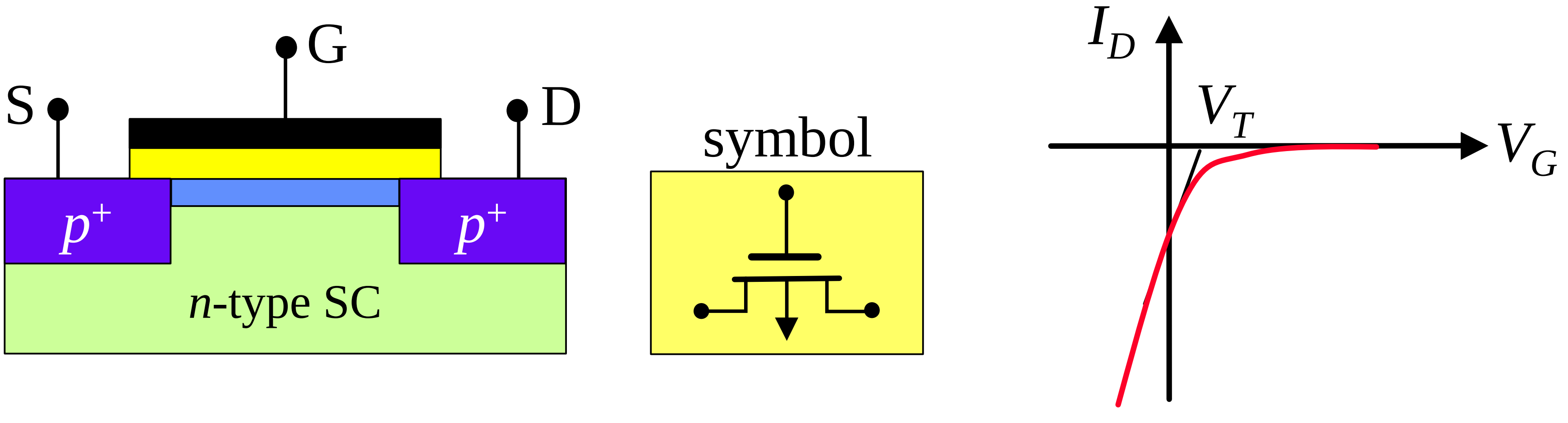




(c) *p*-cnannel, enhancement mode device

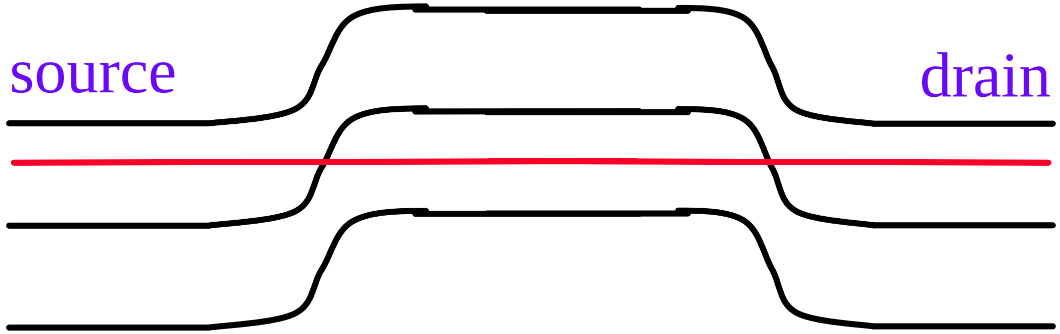


(b) *p*-cnannel, depletion mode device

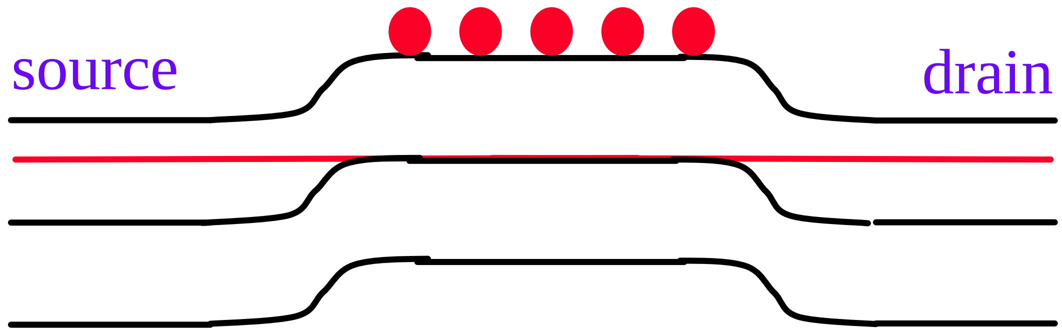


- The role of the Gate electrode for *n*-channel MOSFET:

$V_G = 0$



$V_G > V_T$



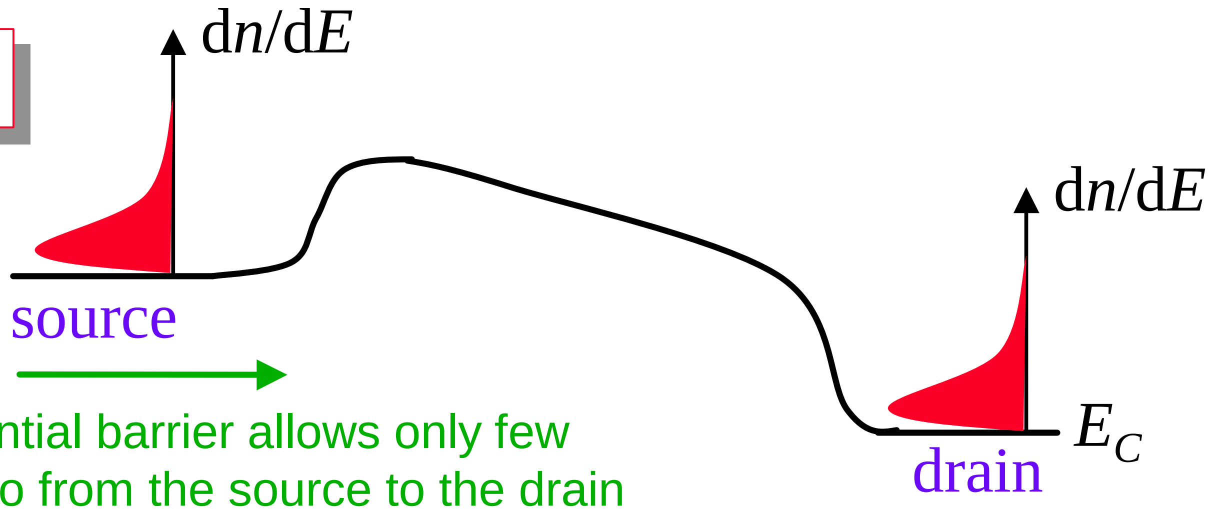
Positive gate voltage does two things:

(1) Reduces the potential energy barrier seen by the electrons from the source and the drain regions.

(2) Inverts the surface, and increases the conductivity of the channel.

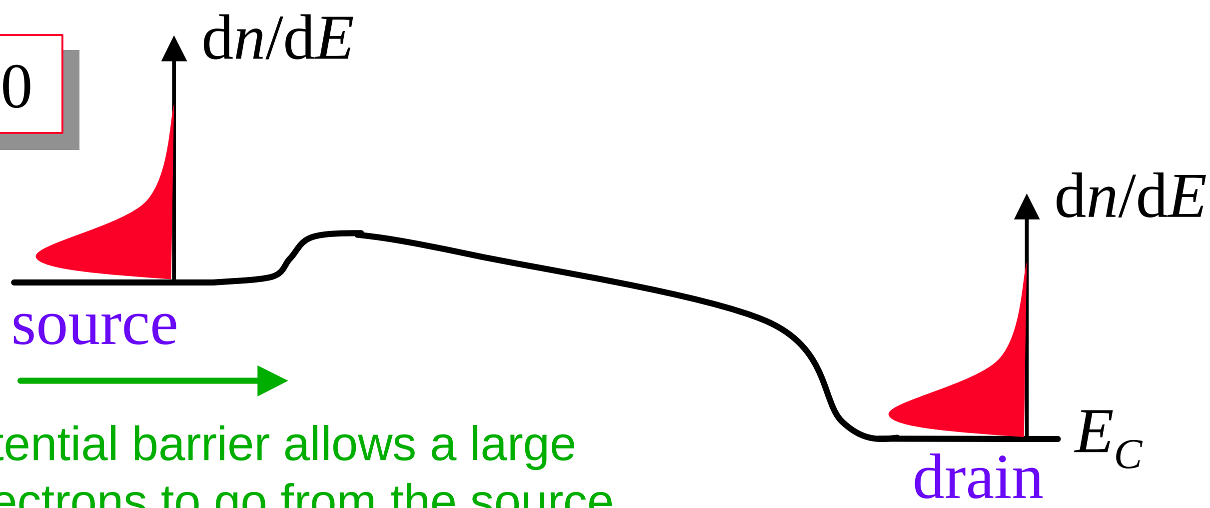
- The role of the Drain electrode for *n*-channel MOSFET:

$V_G = 0,\ V_D > 0$



Large potential barrier allows only few electrons to go from the source to the drain (subthreshold conduction)

$V_G > V_T,\ V_D > 0$



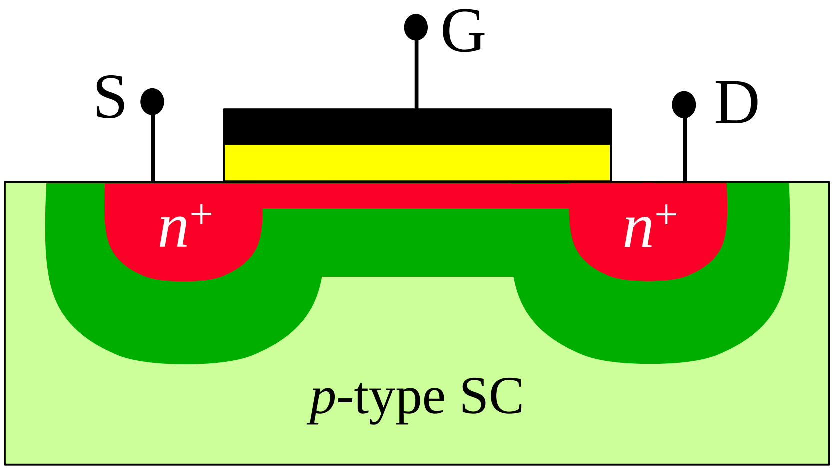
Smaller potential barrier allows a large number of electrons to go from the source to the drain

- Qualitative description of MOSFET operation:

(a) $V_G > V_T$, $V_D > 0$ (small)

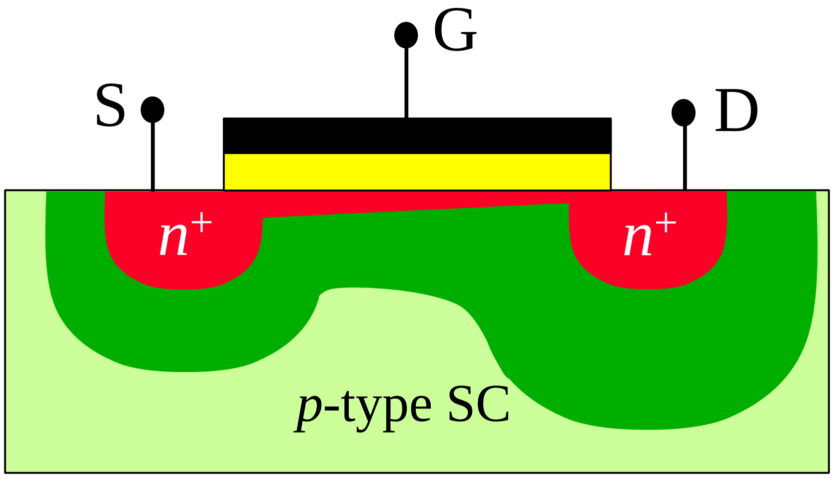
Variation of electron density along the channel is small:

$$I_D \propto V_D$$

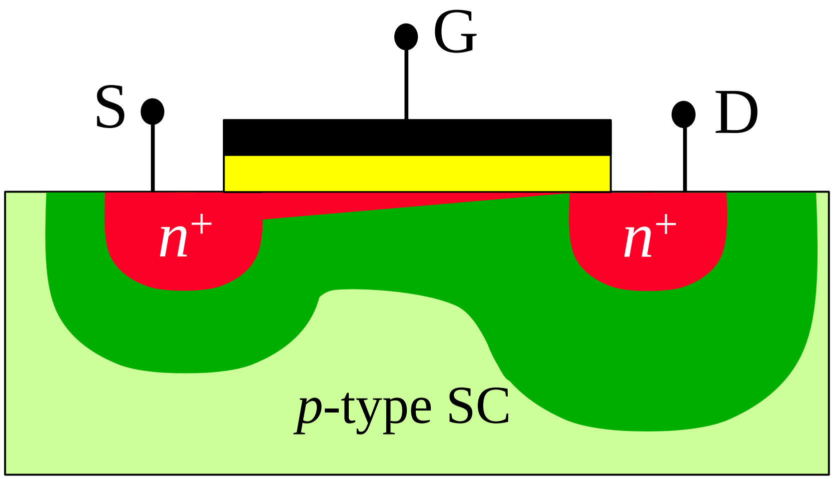


(b) $V_G > V_T$, $V_D > 0$ (larger)

Increase in the drain current reduces due to the reduced conductivity of the channel at the drain end.

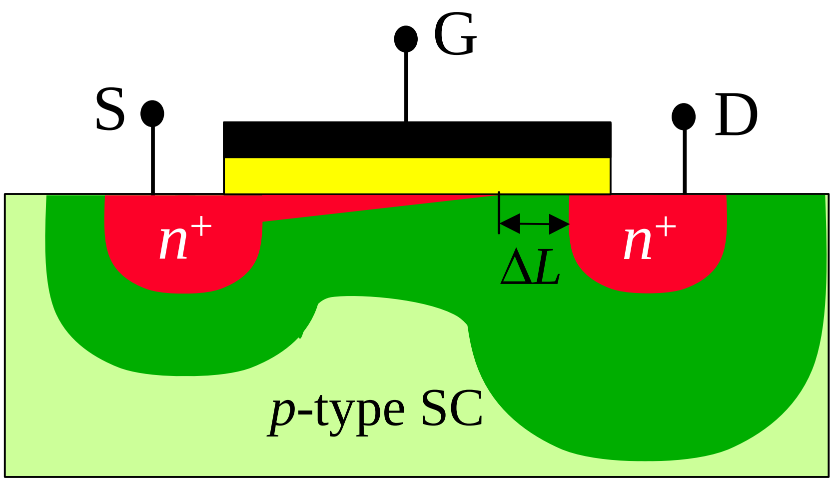


(c) $V_G > V_T$, $\mathrm{V_D} = V_G - V_T$



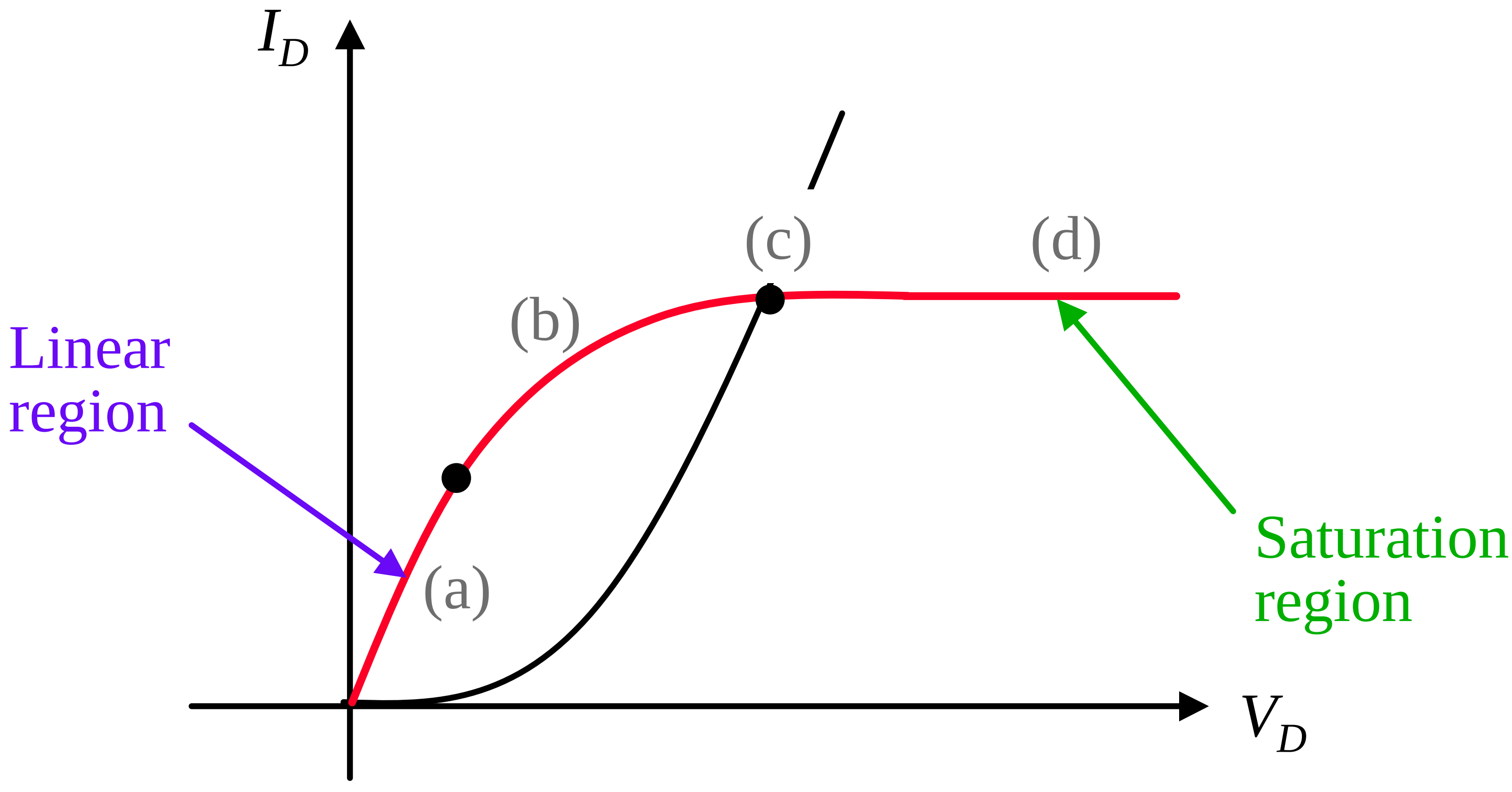
Pinch-off point. Electron density at the drain-end of the channel is identically zero.

(d) $V_G > V_T$, $\mathrm{V_D} > V_G - V_T$



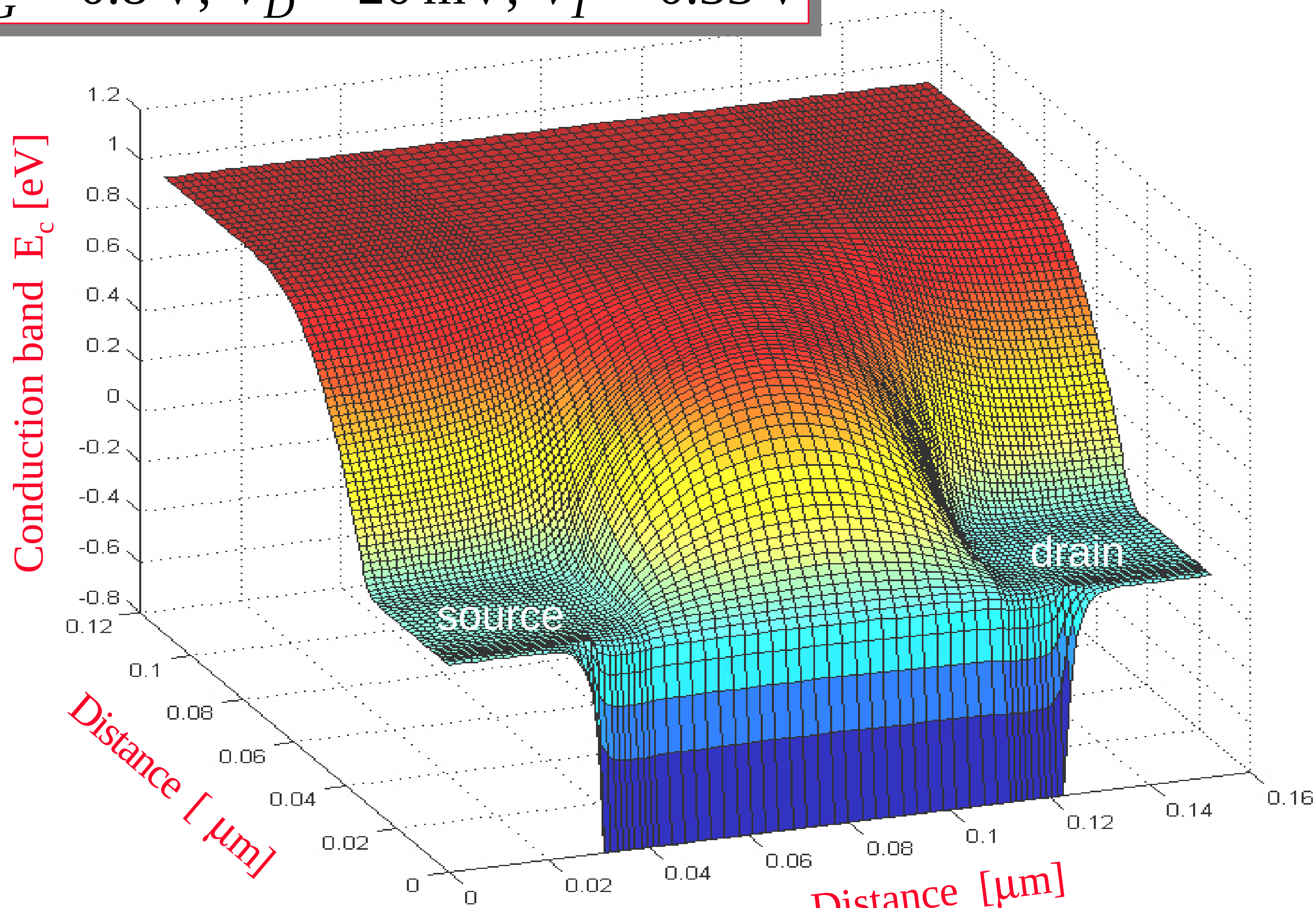
Post pinch-off characteristic. The excess drain voltage is dropped across the highly resistive pinch-off region denoted by ΔL.

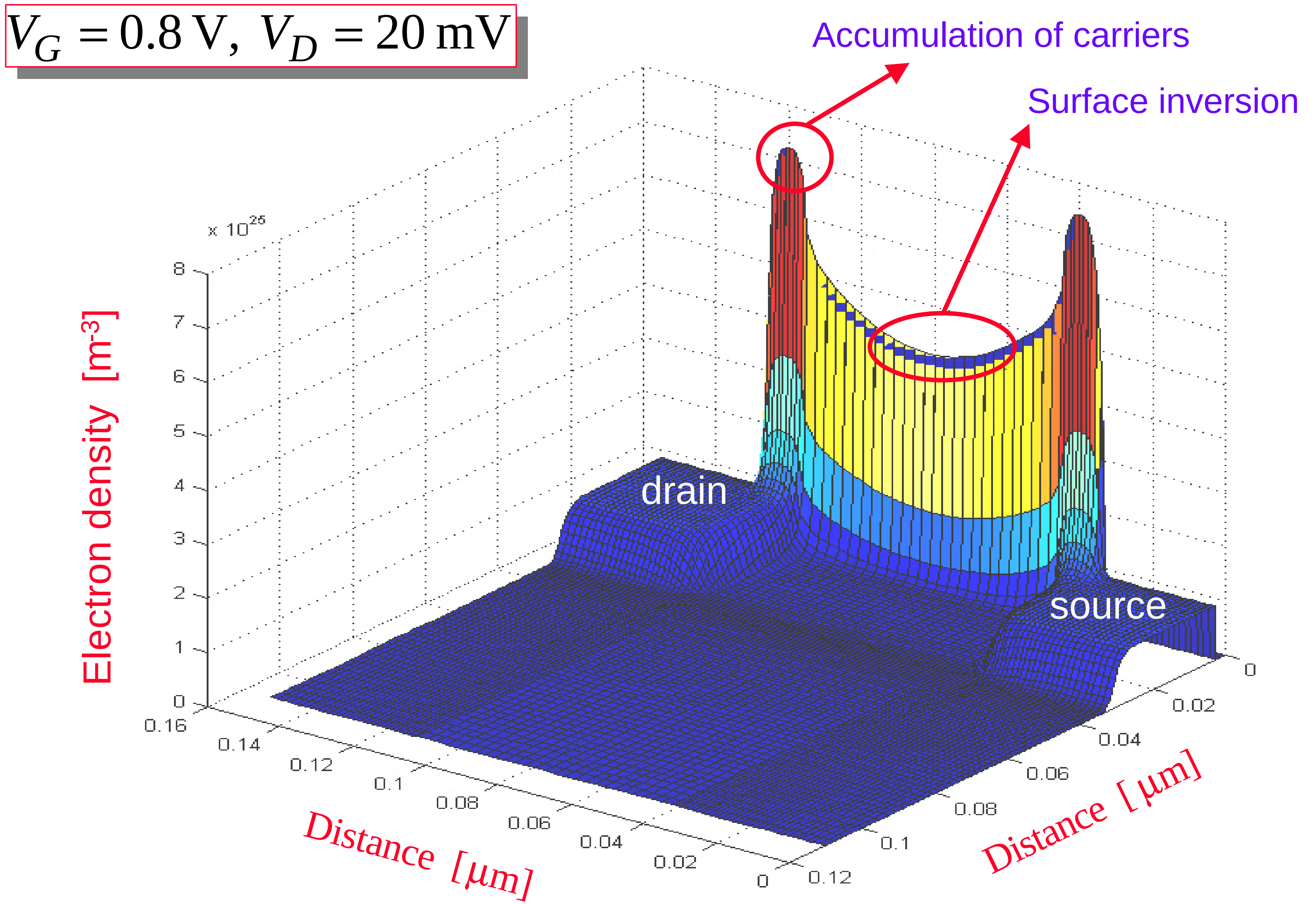
- *IV*-characteristics (long-channel devices):



$N_A = 8 \times 10^{17}\, cm^{-3},\ d_{ox} = 3\, nm$

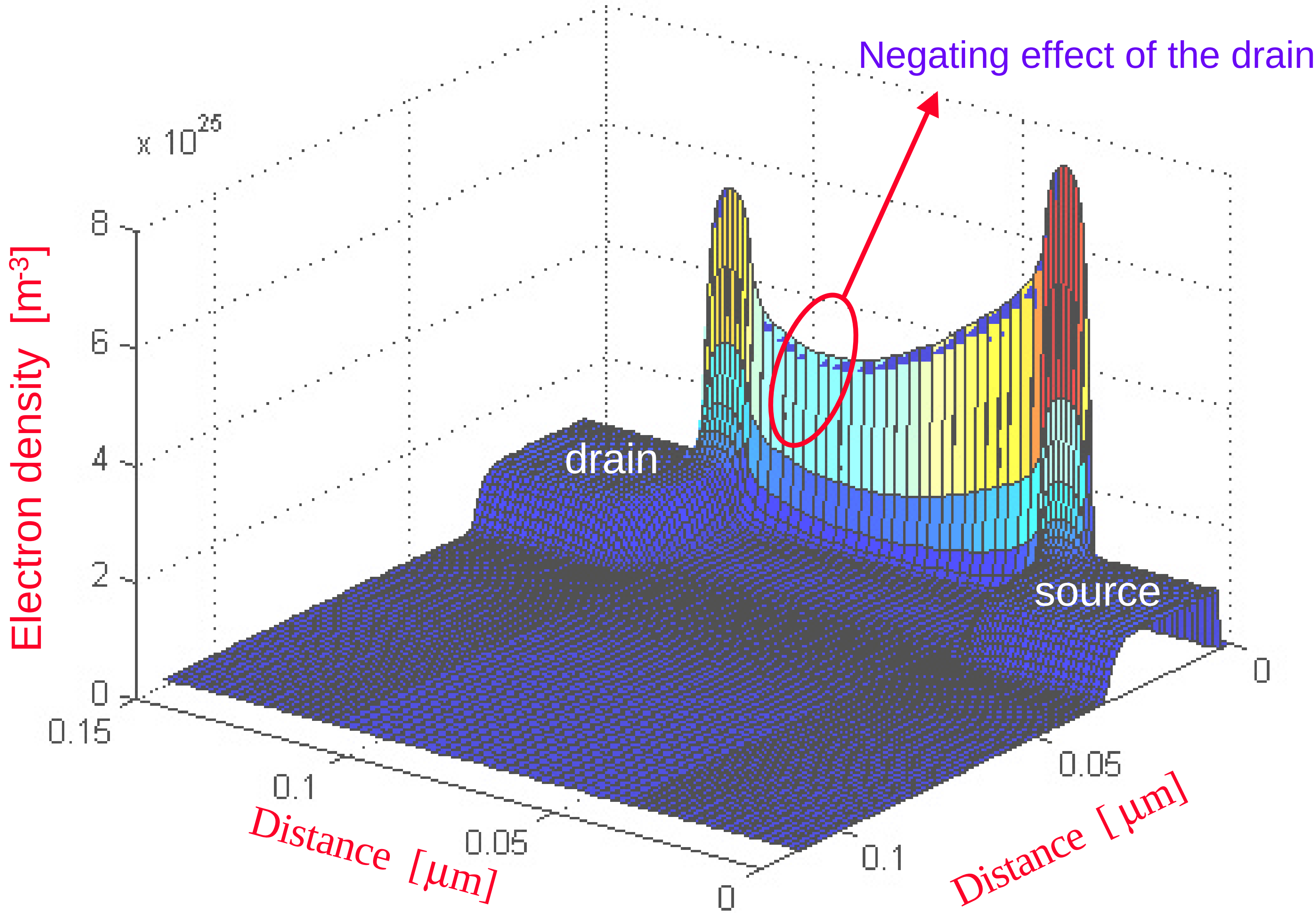
$V_G = 0.8\,\mathrm{V},\ V_D = 20\,\mathrm{mV},\ V_T = 0.33\,\mathrm{V}$



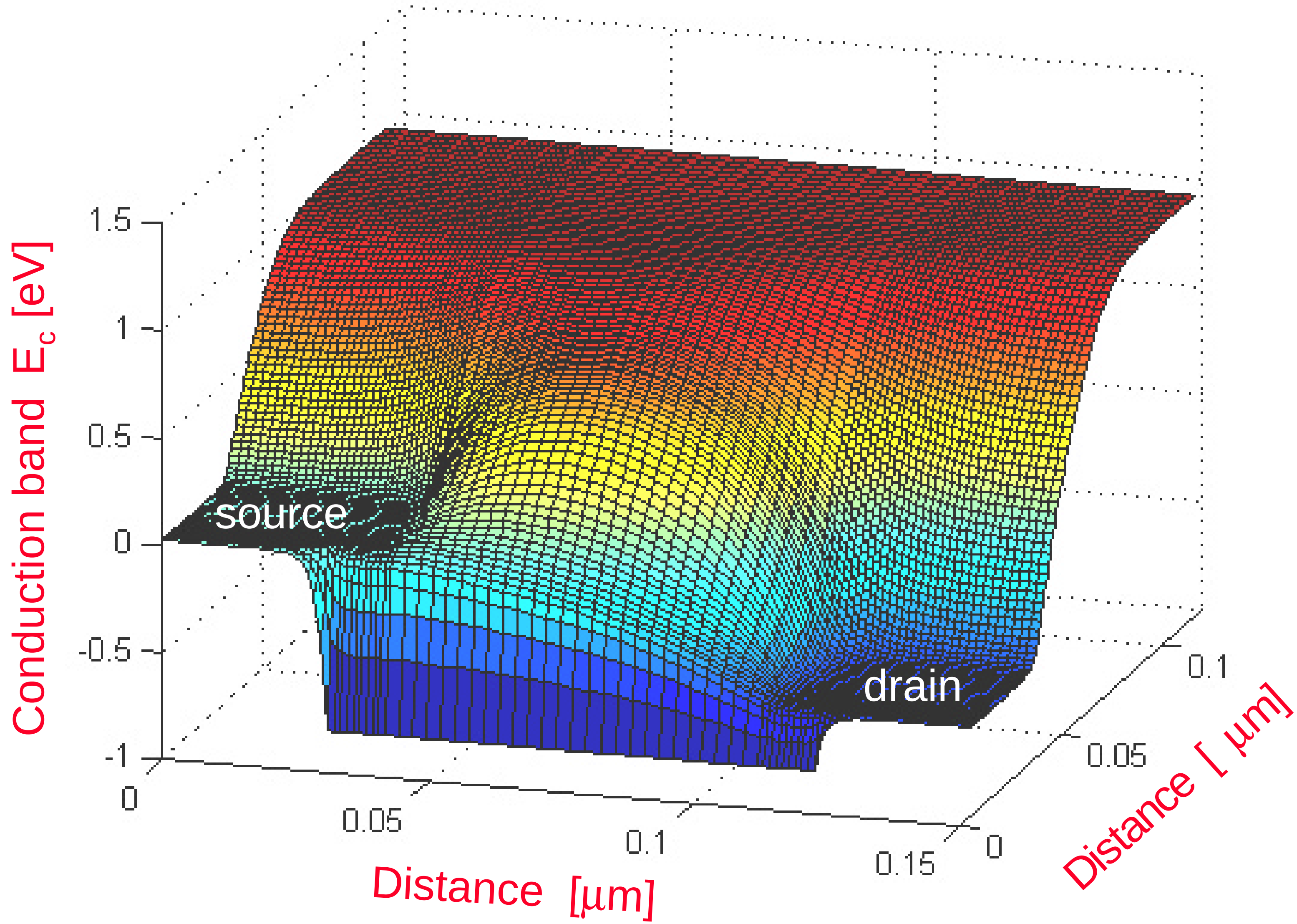


$V_G = 0.8\,\mathrm{V},\ V_D = 20\,\mathrm{mV}$
Accumulation of carriers
Surface inversion
x 10^25
Electron density [m^-3]
drain
source
Distance [μm]
Distance [μm]

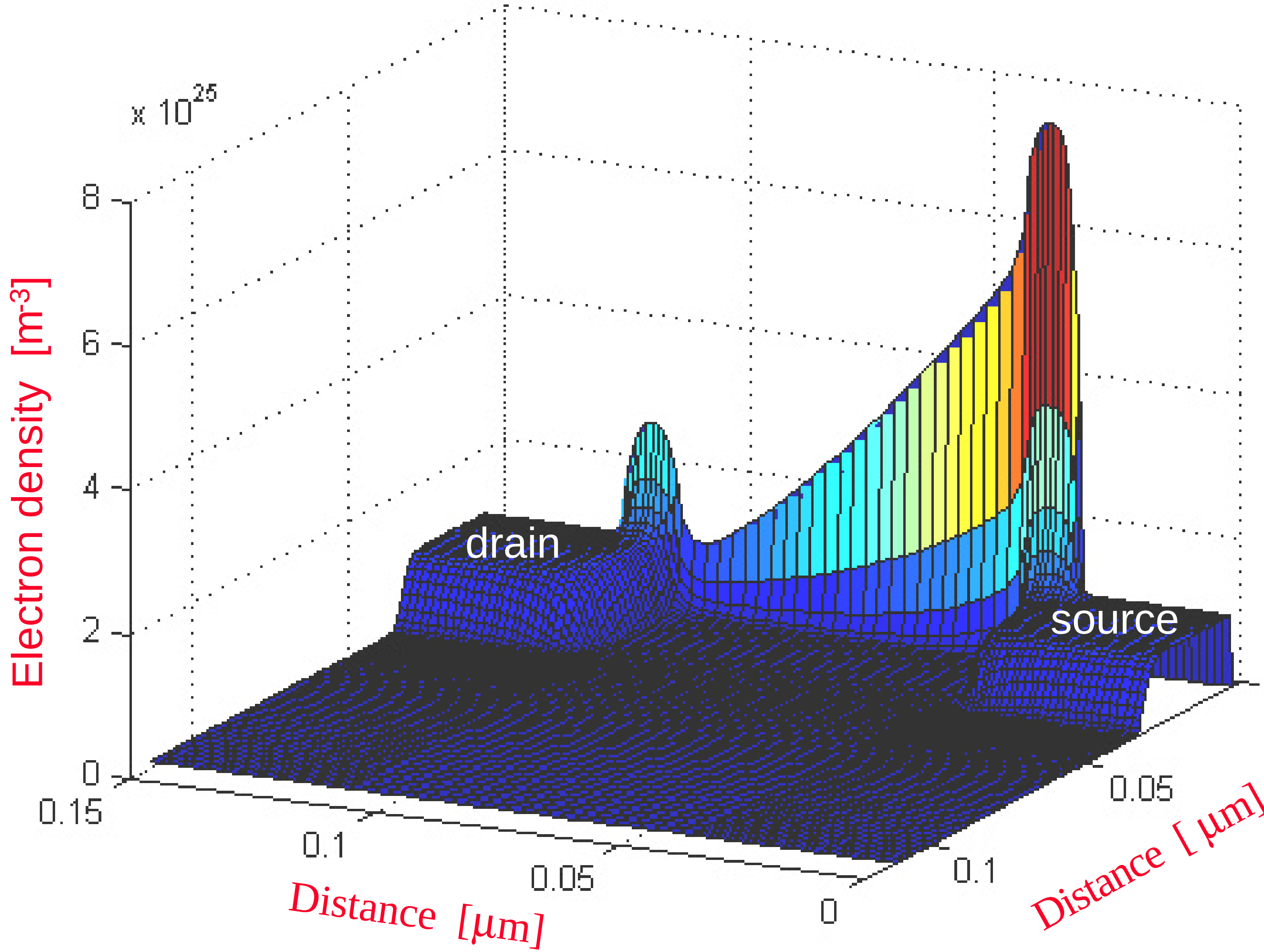
$V_G = 0.8\,\mathrm{V},\ V_D = 0.2\,\mathrm{V},\ V_T = 0.33\,\mathrm{V}$



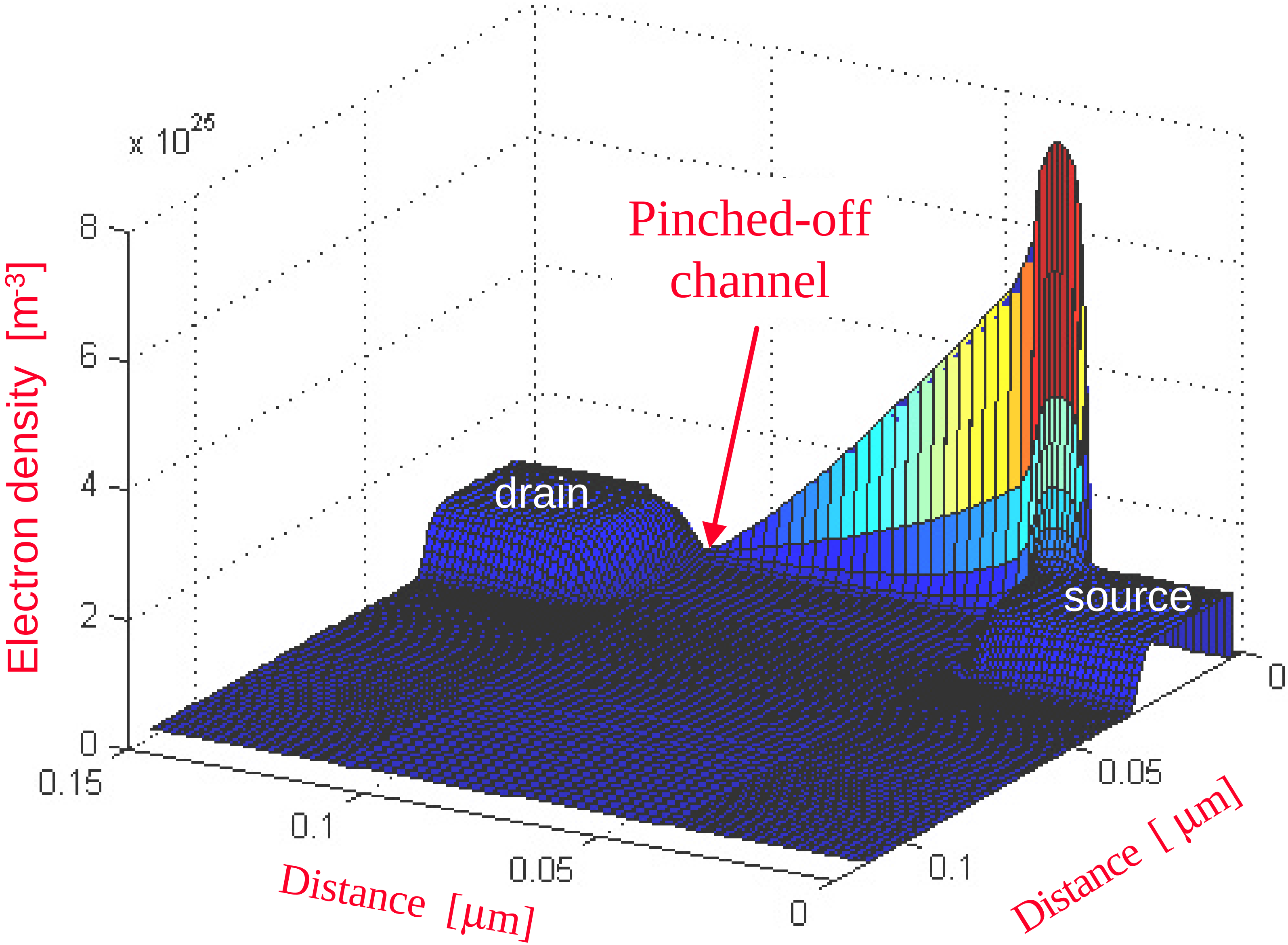
$$V_G = 0.8\,\mathrm{V},\ V_D = 0.56\,\mathrm{V},\ V_T = 0.33\,\mathrm{V}$$



$V_G = 0.8\,\mathrm{V},\; V_D = 0.56\,\mathrm{V},\; V_T = 0.33\,\mathrm{V}$

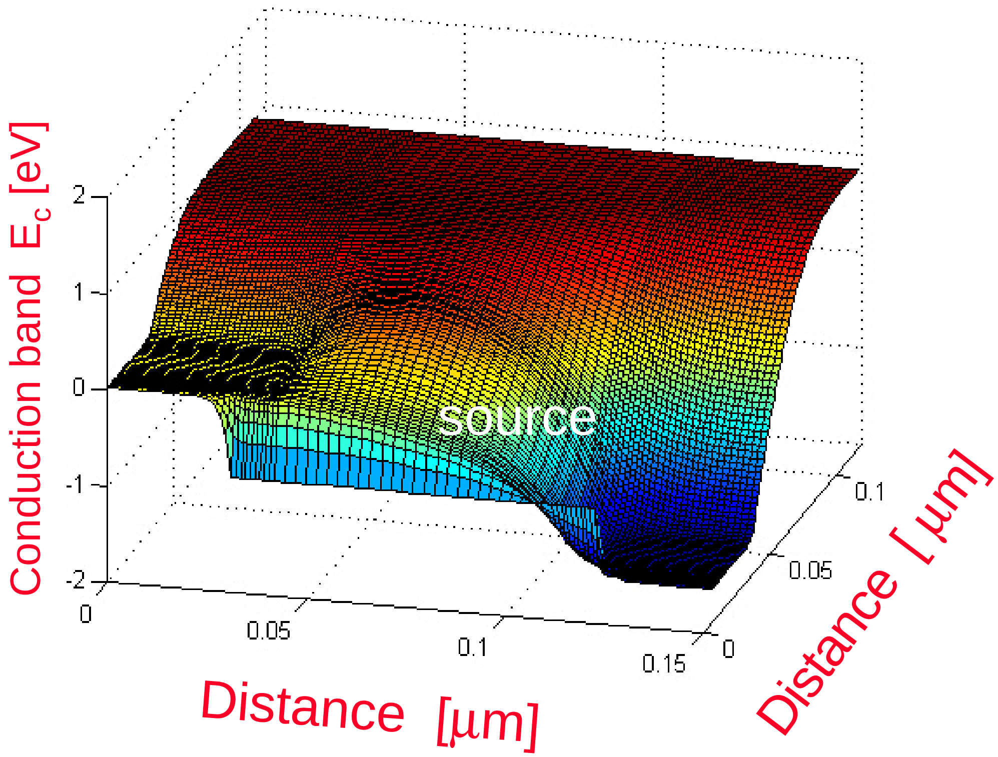


$V_G = 0.8\,\mathrm{V},\ V_D = 0.9\,\mathrm{V},\ V_T = 0.33\,\mathrm{V}$

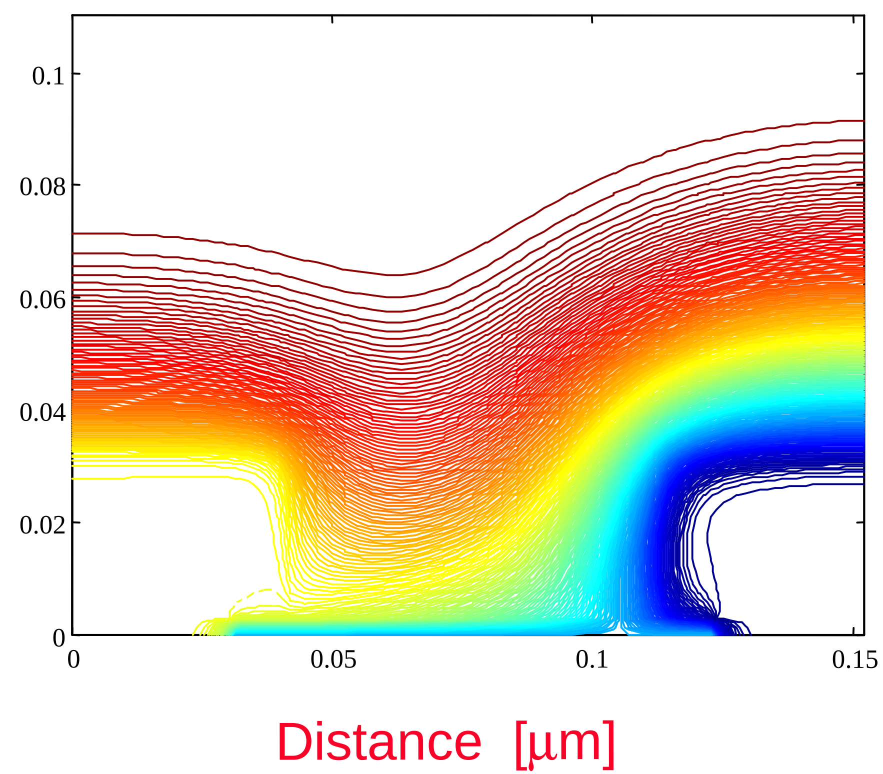


$$V_G = 0.8\,\mathrm{V},\ V_D = 1.56\,\mathrm{V},\ V_T = 0.33\,\mathrm{V}$$

3D View



Contour plot



$$V_G = 0.8\,\mathrm{V},\ V_D = 1.56\,\mathrm{V},\ V_T = 0.33\,\mathrm{V}$$