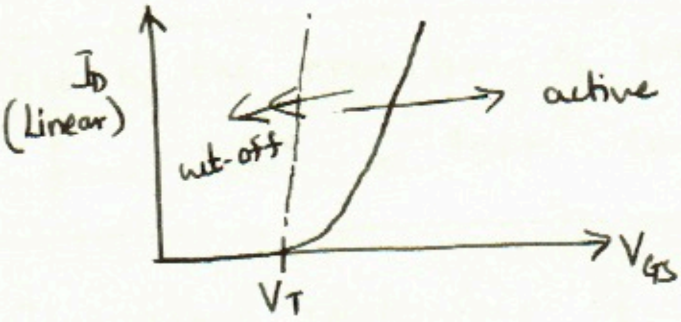
Subthreshold Conduction ⇒ also called subthreshold leakage.

If we look at the $I_D - V_{GS}$ plot on a linear scale, it appears as

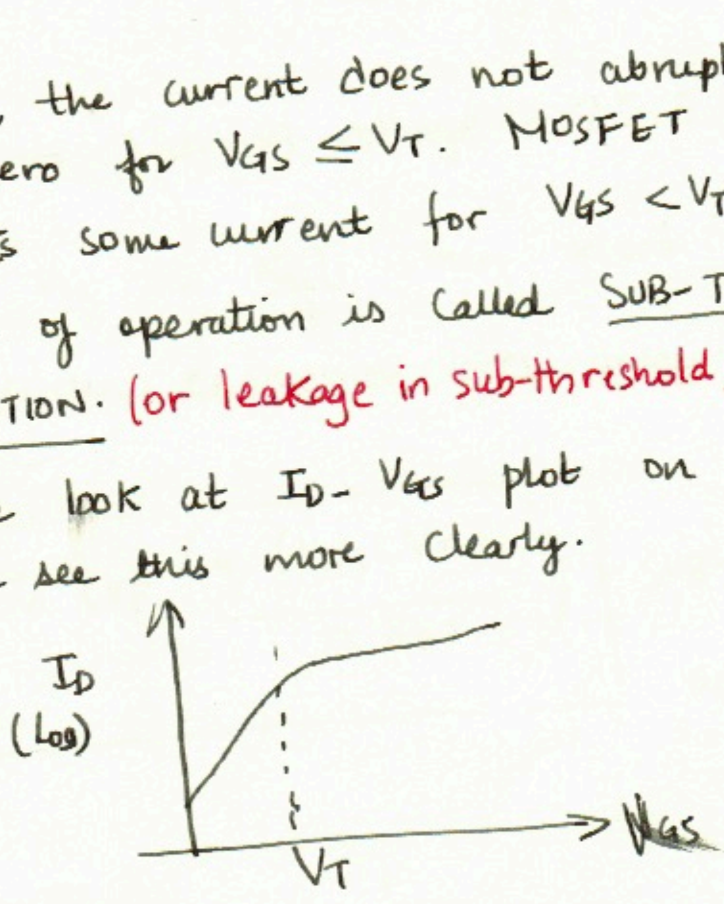


cut-off = OFF
active = ON

The region $V_{GS} < V_T$ is called the cut-off region, while $V_{GS} > V_T$ is called the active region.

However, the current does not abruptly drop to zero for $V_{GS} \leq V_T$. MOSFET still conducts some current for $V_{GS} < V_T$. This regime of operation is called <u>SUB-THRESHOLD CONDUCTION</u>. (or leakage in sub-threshold / off state leakage)

If we look at $I_D - V_{GS}$ plot on a log-scale, we can see this more clearly.



On the Log scale, it is clear that current varies exponentially with V_{GS} in the sub-threshold region.

$\boxed{\text{That is, the transition of MOSFET operation from "ON" to "OFF" conditions is \underline{NOT ABRUPT}.}}$

The actual relationship of $I_D - V_{GS}$ for sub threshold is given as :-

$$I_D = I_0 \exp\left(\frac{q(V_{GS} - V_T)}{n K_B T}\right)\left(1 - \exp\left(-\frac{qV_{ds}}{K_B T}\right)\right)$$

$\frac{K_B T}{q}$ = Thermal voltage = 25.8 mV at 300K

When $V_{ds} \gg \frac{K_B T}{q}$ then second term in the current expression goes away. And we get :-

$$\boxed{I_D = I_0 \exp\left(\frac{q(V_{GS} - V_T)}{n K_B T}\right)}$$

SUB-THRESHOLD CURRENT FOR $V_{ds} \gg \frac{K_B T}{q}$

What is n ?

'n' is called the non-ideality factor.

The best-case or ideal value for n is unity.

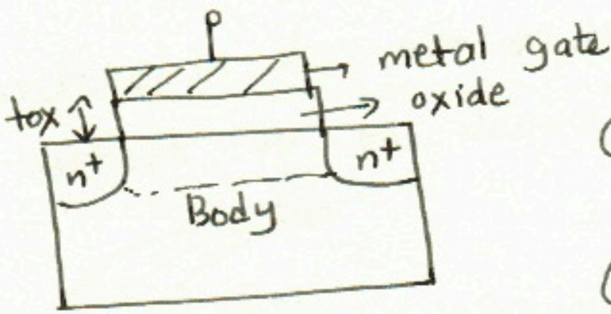
However, in real transistors, 'n' usually varies between 1.0 and 1.5.

The physical definition of n is given as

$$n = \left(1 + \frac{C_{dep}}{C_{ox}}\right)$$

C_{dep} = Depletion capacitance

C_{ox} = oxide capacitance.

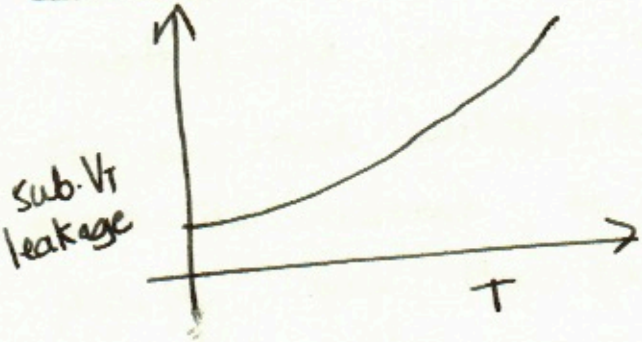


$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$$

C_{dep} = Depletion capacitance in the body at inversion

Depends on doping and surface potential at inversion.

Effect of temperature on sub-threshold leakage

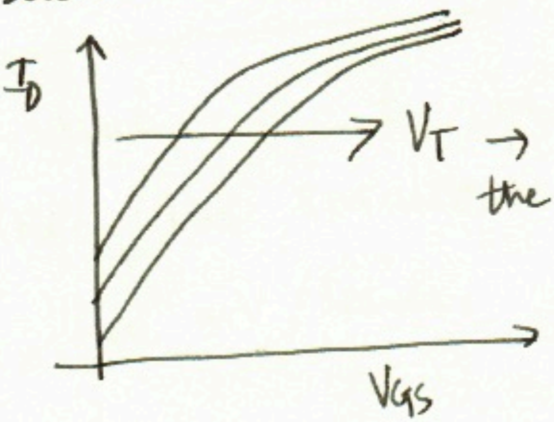


Effect of V_T on sub-threshold leakage

$$I_D = I_0 \exp\left(\frac{q(V_{GS} - V_T)}{n K_B T}\right)$$

As $V_T \uparrow \rightarrow I_D \downarrow \longrightarrow$ good for sub-threshold leakage.

However, increase in V_T also reduces the ON state current of the device.



$V_T \rightarrow$ increases then the current reduces.

In digital applications, the presence of subthreshold current is undesirable.

For an ideal switch-like behavior, we want the current to drop as fast as possible once the gate-source voltage falls below V_T.

The "goodness" of the mosfet switch is quantified by the parameter sub-threshold slope, S.

$$S = n\left(\frac{k_B T}{q}\right) \underbrace{\log_e(10)}_{2.3}$$

$$\boxed{S = 2.3\, n\left(\frac{k_B T}{q}\right)} \longrightarrow \left\{ \overset{\text{unit:-}}{mV/\text{decade}} \right\}$$

We want 'S' to be as small as possible. The smallest value of S possible is 60 mV/decade.

'S' tells us how much of gate-source voltage drop is needed to reduce I_D by one decade in sub-threshold.

'S' tells us how much ΔV_{GS} we need so that ΔI_D changes by one order of magnitude.

Since $n = 1$, best case value of $S = 2.3 \left(\frac{k_B T}{q}\right)$

$\Downarrow$

26 mV

$= \underline{\underline{60 mV/decade}}$.