- For ***inversion channel*** to exist at the ***D end***, ***V_{GD} must be > V_{TN}***
  - ***V_{DS} must be < V_{GT}***
- When ***$V_{DS} = V_{GT}$***, the ***channel*** is said to be ***pinched-off*** at the ***D end***, and ***I_D does not increase any more***
- This value of V_{DS} is known as the ***drain-to-source saturation voltage*** $V_{DS,sat}$
  - $V_{DS,sat} = V_{GT}$

- For $V_{DS} > V_{DS,sat}$, the ***mode of operation*** is known as ***saturation***
- ***Drain current in saturation***:

$$I_D = \frac{k_N}{2} V_{GT}^2$$

  - ***Obtained from the non-saturation I_D expression by substituting $V_{DS} = V_{GT}$***
  - ***Note that I_D is independent of V_{DS}***
- ***Above equations are valid for $V_{GT} > 3V_T$***

(~ ***80 mV at room temperature***)

The Complete LEVEL 0 Model

$$I_D = k_N\left(V_{GT}V_{DS} - V_{DS}^2/2\right)$$

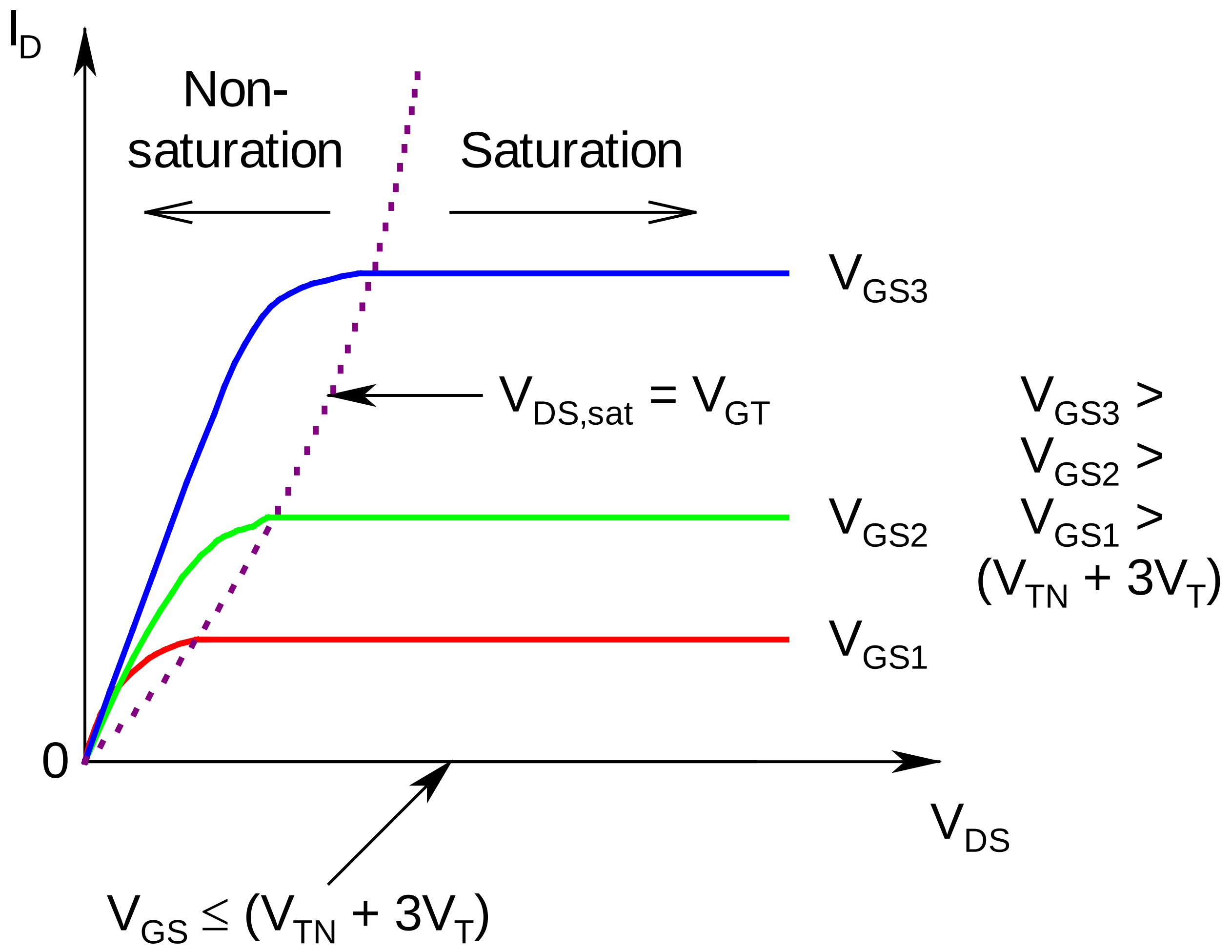
$$\left(\textbf{\textit{linear region}}\ \textbf{-}\ V_{GT} > 3V_T, V_{DS} < V_{GT}\right)$$

$$= \left(k_N/2\right)V_{GT}^2$$

$$(\textbf{\textit{saturation region}}\ \textbf{-}\ V_{GT} > 3V_T, V_{DS} \geq V_{GT})$$

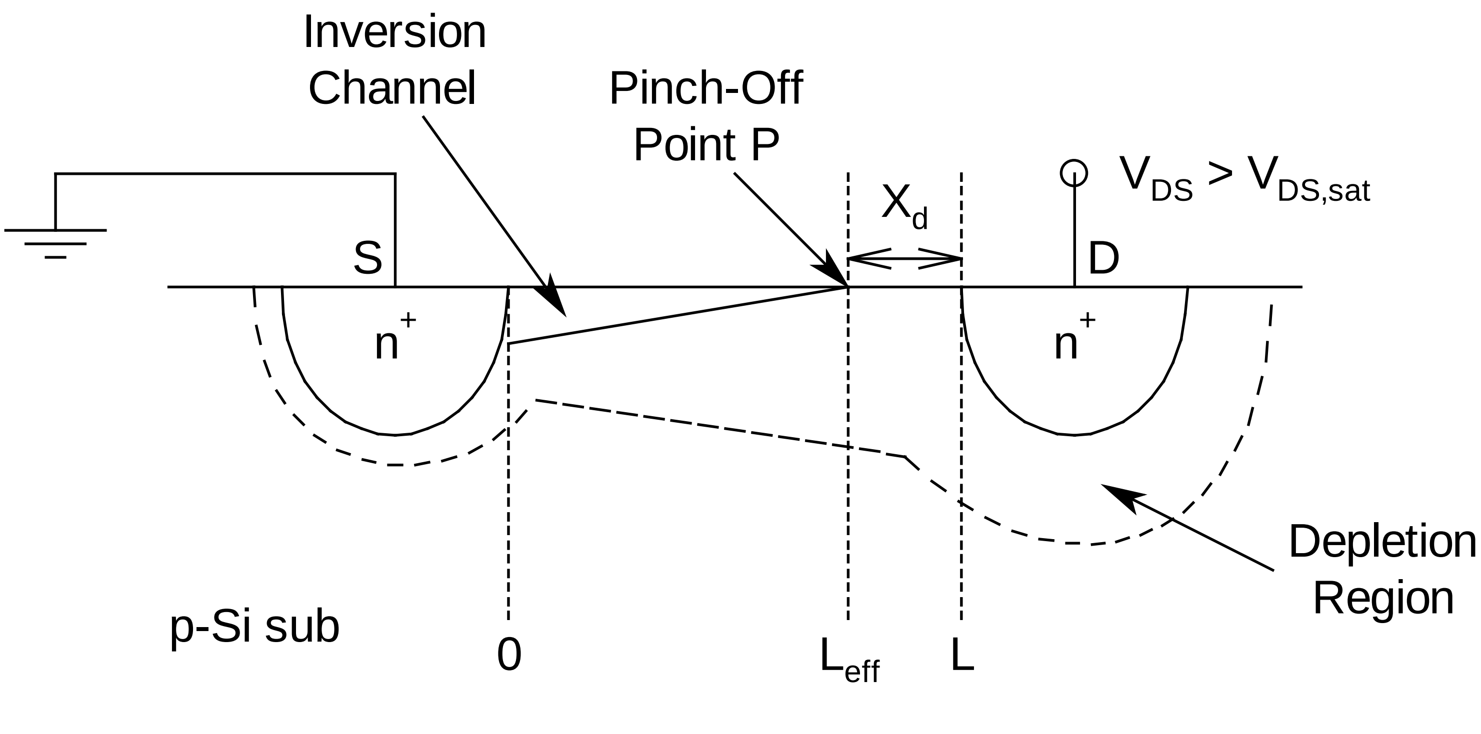
$$= 0$$

$$(\textbf{\textit{cutoff region}}\ \textbf{-}\ V_{GT} \leq 3V_T,\ \textbf{\textit{any}}\ \boldsymbol{V_{DS}})$$



I_D-V_{DS} Characteristics

Channel-Length Modulation (CLM)



$X_d \rightarrow$ length of the pinched-off region

- For $V_{DS} = V_{DS,sat}$, ***pinch-off point P at D end***
- For $V_{DS} > V_{DS,sat}$, ***P moves towards source***
- ***Effective channel length reduces*** from L to $L_{eff} = L - X_d$
  - X_d = ***pinch-off region/drain region/saturation region length***
- ***Excess voltage*** $(V_{DS} - V_{DS,sat})$ ***drops across*** $\boldsymbol{X_d}$

- ***Reduction of effective channel length causes an increase in current***
  - ***Channel length modulation***
- With $V_{DS}\uparrow$, $X_d\uparrow$, $L_{eff}\downarrow$, and $I_D\uparrow$
  - ***No real current saturation***
- Thus, ***saturated drain current***:

$$I_{D,sat} = \left(k'_N/2\right)\left(W/L_{eff}\right)V_{GT}^2$$

$$= \left(k_N/2\right)V_{GT}^2\left(1+\lambda V_{DS}\right)$$

- λ = ***Channel length modulation parameter***

$$= \frac{1}{L}\frac{dX_d}{dV_{DS}}$$

  - ***Function of L and N_A***
  - ***Higher L and N_A*** => ***Lower λ***
  - ***Typical values of λ*** may range from ***close to 0*** to ***as high as 0.1-0.3*** V^{-1}
  - ***Very similar to V_A inverse for BJTs***

- This gives ***LEVEL 1 model*** (also known as ***Shichman-Hodges model***) for MOSFETs:

$$I_D = k_N\left[V_{GT}V_{DS} - V_{DS}^2/2\right]\left(1+\lambda V_{DS}\right)$$

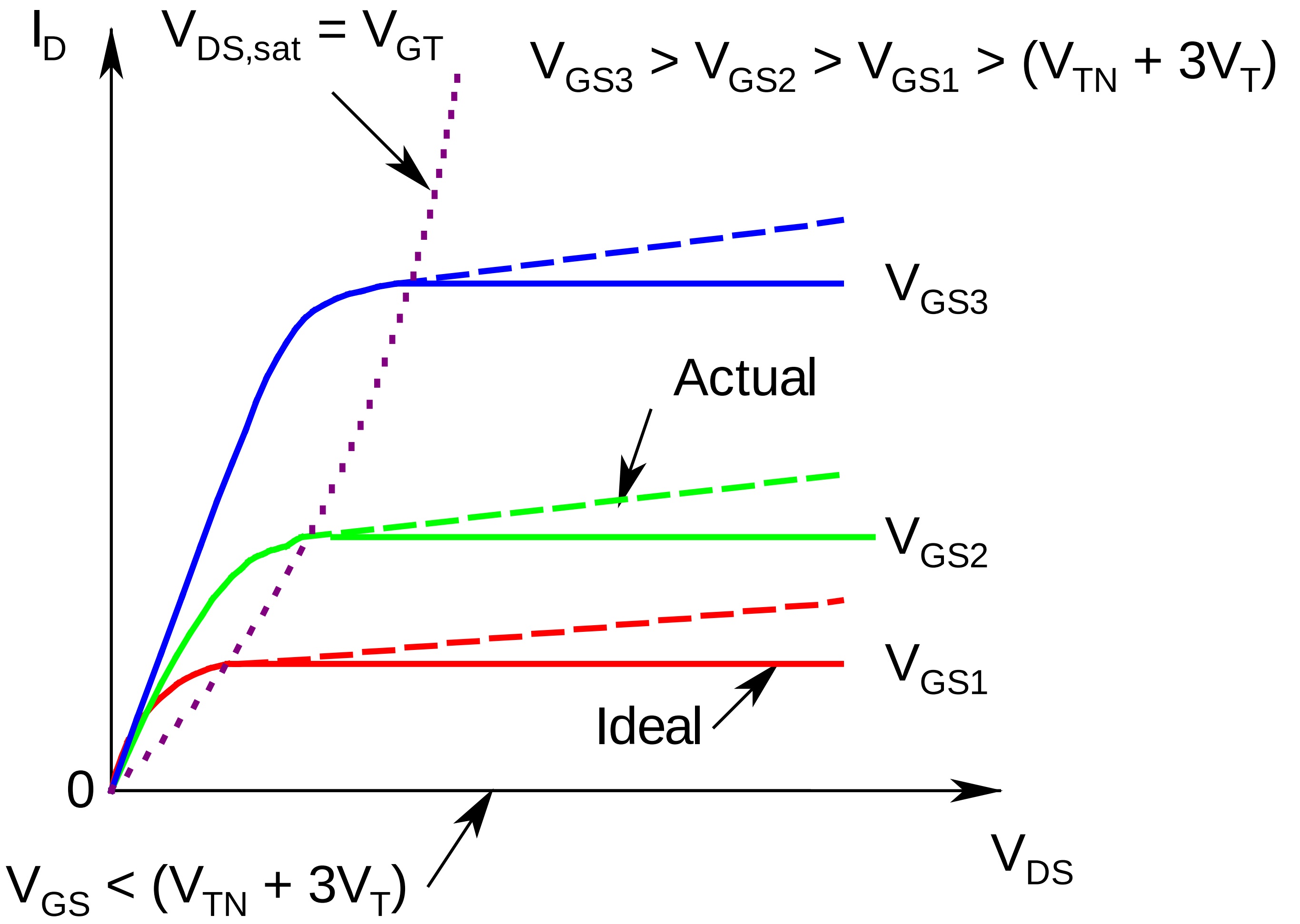
(***linear region*** - $V_{GT} > 3V_T,\ V_{DS} < V_{GT}$)

$$= \left(k_N/2\right)V_{GT}^2\left(1+\lambda V_{DS}\right)$$

(***saturation region*** - $V_{GT} > 3V_T,\ V_{DS} \geq V_{GT}$)

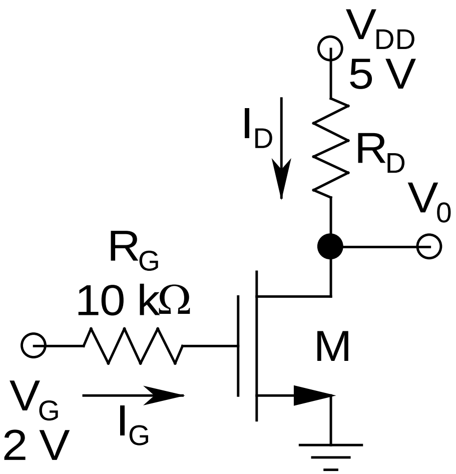
$$= 0$$

(***cutoff region*** - $V_{GT} \leq 3V_T,\ \text{any } V_{DS}$)



I_D-V_{DS} Characteristics in presence of CLM

DC Bias Point Calculation



- ***To find R_D for BB***
  - $V_{TN0} = 1$ V, $k'_N = 40\ \mu A/V^2$, $W/L = 10$
- ***Body terminal not shown***
  - ***Implies that it is connected to the most negative potential available in the circuit*** (***ground in this case***)

    $\Rightarrow V_{SB} = 0 \Rightarrow V_{TN} = V_{TN0}$
- $I_G = 0 \Rightarrow V_{GS} = V_G = 2$ V

- $V_{GT} = V_{GS} - V_{TN} = 1$ V
- ***Assuming saturation mode of operation and neglecting CLM***:

$$I_D = (k_N/2)V_{GT}^2 = 200\ \mu A$$

- ***For BB***, $V_{DS} = V_{DD}/2 = 2.5$ V (***2-element output branch***):

$$R_D = (V_{DD} - V_{DS})/I_D = 12.5\ k\Omega$$

- $V_{DS} > V_{GT} \Rightarrow$ ***Assumption of saturation mode of operation validated***
- $P_D = V_{DS} \times I_D = 0.5$ mW