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ECE606: Solid State Devices
Lecture 38: Modern MOSFET

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Topic Map

	Equilibrium	**DC**	Small signal	Large Signal	Circuits
Diode					
Schottky					
BJT/HBT					
MOSFET					

Outline

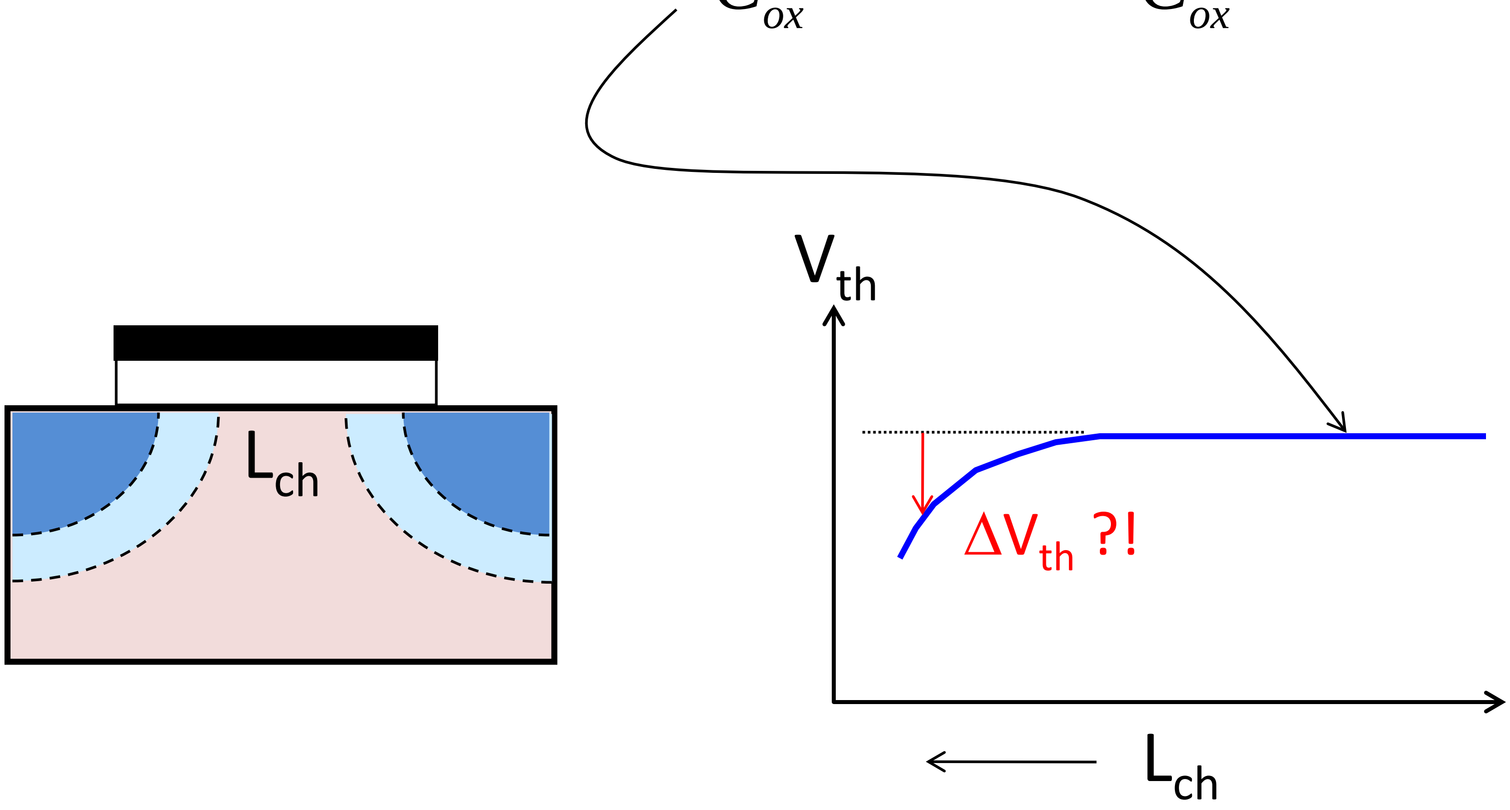
1. **Short channel effect**
2. Control of threshold voltage
3. Mobility enhancement
4. Conclusion

$$I_D = \frac{\mu C_{ox}}{L_{ch}} (V_G - V_{th}^*)^2$$

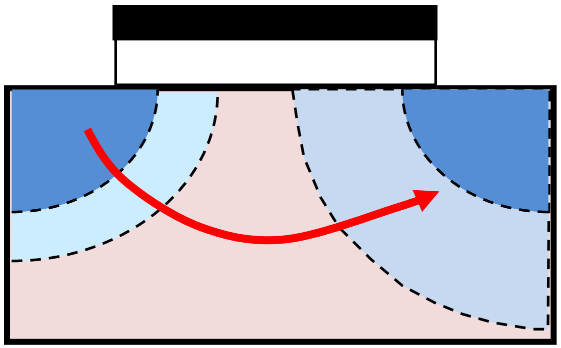
REF: Chapter 19, SDF

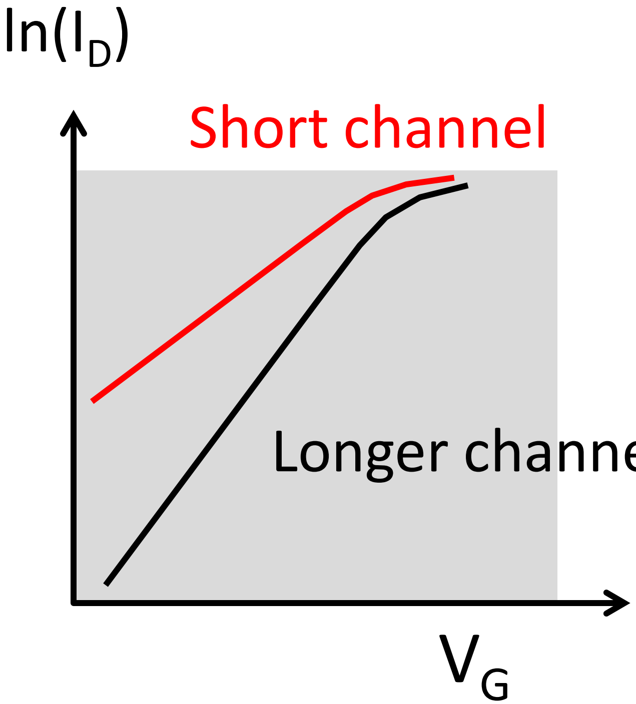
Short Channel Effect: V_{th} Roll-off

$$V_{th} = 2\phi_F - \frac{Q_B}{C_{ox}} = 2\phi_F + \frac{qN_A W_T}{C_{ox}}$$



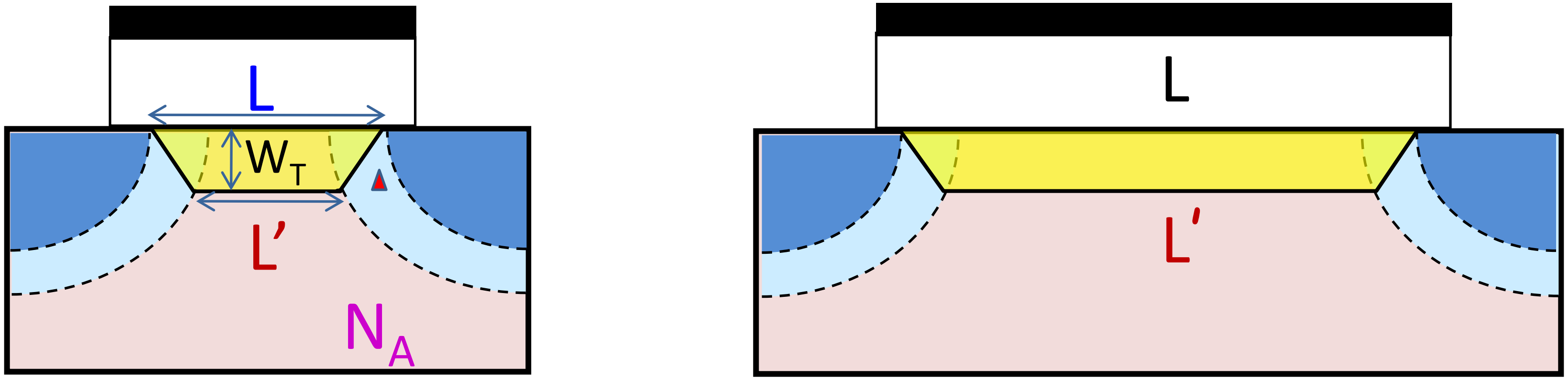
Short Channel Effect: Punch-through





Recall similar problem with bipolar transistor

Physics of Short Channel Effect



$$V_{th,Short} = 2\phi_F - \frac{Q_{B,Short}}{C_{ox}}$$

$$Q_{B,Short} = \frac{-qN_A \times Z \times W_T \left(\frac{L+L'}{2}\right)}{Z \times L}$$

$$= -qN_A W_T \left(\frac{L+L'}{2L}\right)$$

$$V_{th,L} = 2\phi_F - \frac{Q_{B,Long}}{C_{ox}}$$

$$Q_{B,long} \rightarrow -qN_A W_T \quad (L \cong L')$$

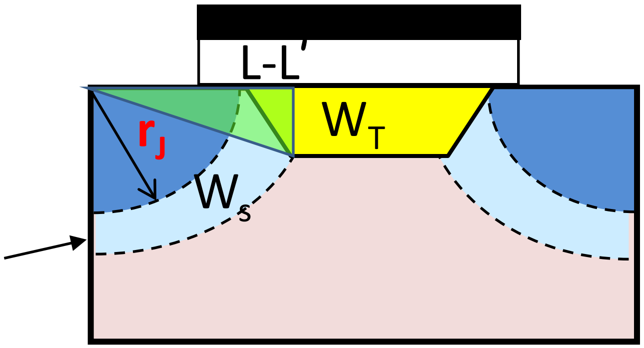
$$\Delta V_{th} = -\frac{Q_{B,Long}}{C_{ox}} + \frac{Q_{B,short}}{C_{ox}}$$

$$= \frac{-qN_A W_T}{C_{ox}}\left[1 - \frac{L'+L}{2L}\right]$$

Short Channel Effect

$$(r_J + W_S)^2 = W_T^2 + \left(r_J + \frac{L - L'}{2} \right)^2$$

$$L' = L - 2r_J \left(\sqrt{1 + \frac{2W_T}{r_J}} - 1 \right)$$



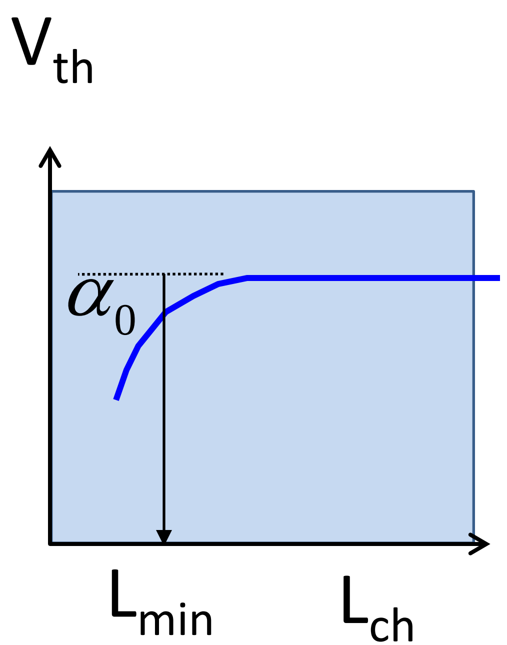
$$\Delta V_{th} = \frac{-qN_A W_T}{C_{ox}} \left[1 - \frac{L' + L}{2L} \right]$$

$$= \frac{-qN_A W_T}{C_{ox}} \frac{r_J}{L} \left(\sqrt{1 + \frac{2W_T}{r_J}} - 1 \right) = \alpha_0$$ Minimum acceptable …

How to reduce V_{th} roll-off ...

Shallow junction/geometry of transistors
laser annealing of junctions, FINFETs

Reduced substrate doping N_A
consider WT and junction breakdown



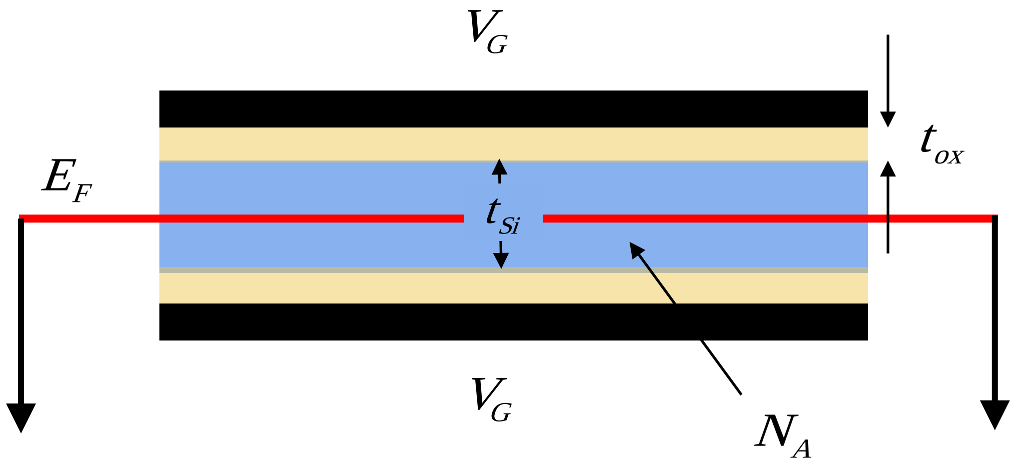
$$L_{min} = \frac{qN_A W_T}{C_{ox}} \frac{r_J}{\alpha_0}\left(\sqrt{1+\frac{2W_T}{r_J}}-1\right)$$

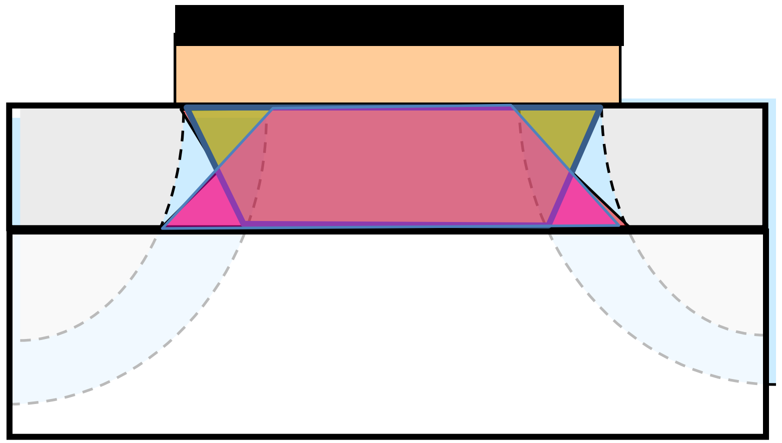
Thinner gate oxides
Consider tunneling current
Higher gate dielectric
Consider bulk traps

Outline

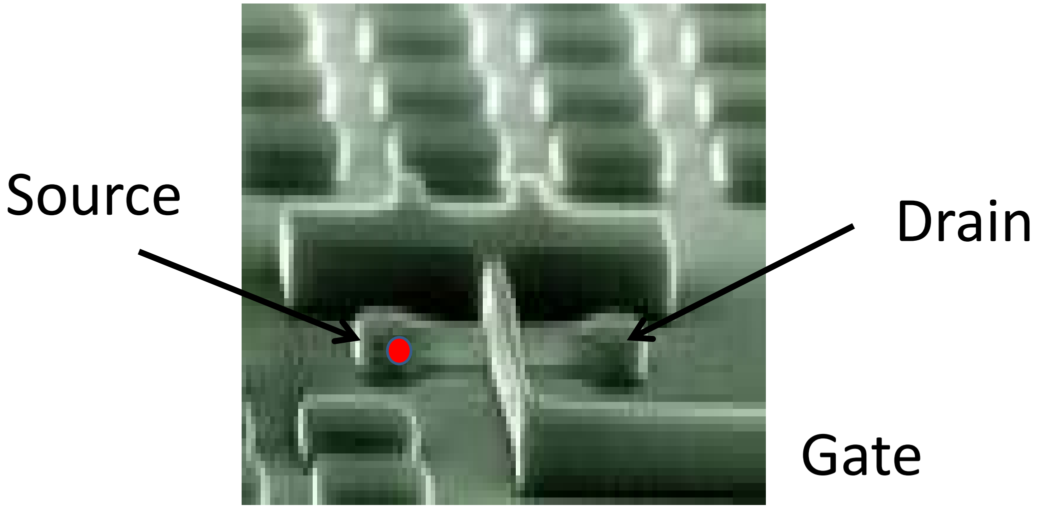
1. Short channel effect
2. **Control of threshold voltage**
3. Mobility enhancement
4. Conclusion

Solution: Ultra-thin Body SOI

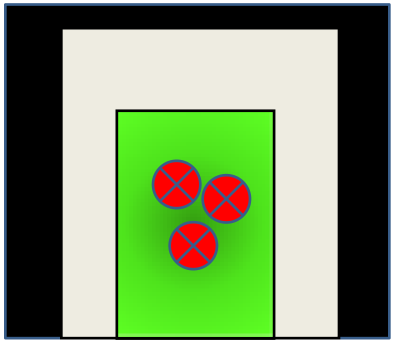




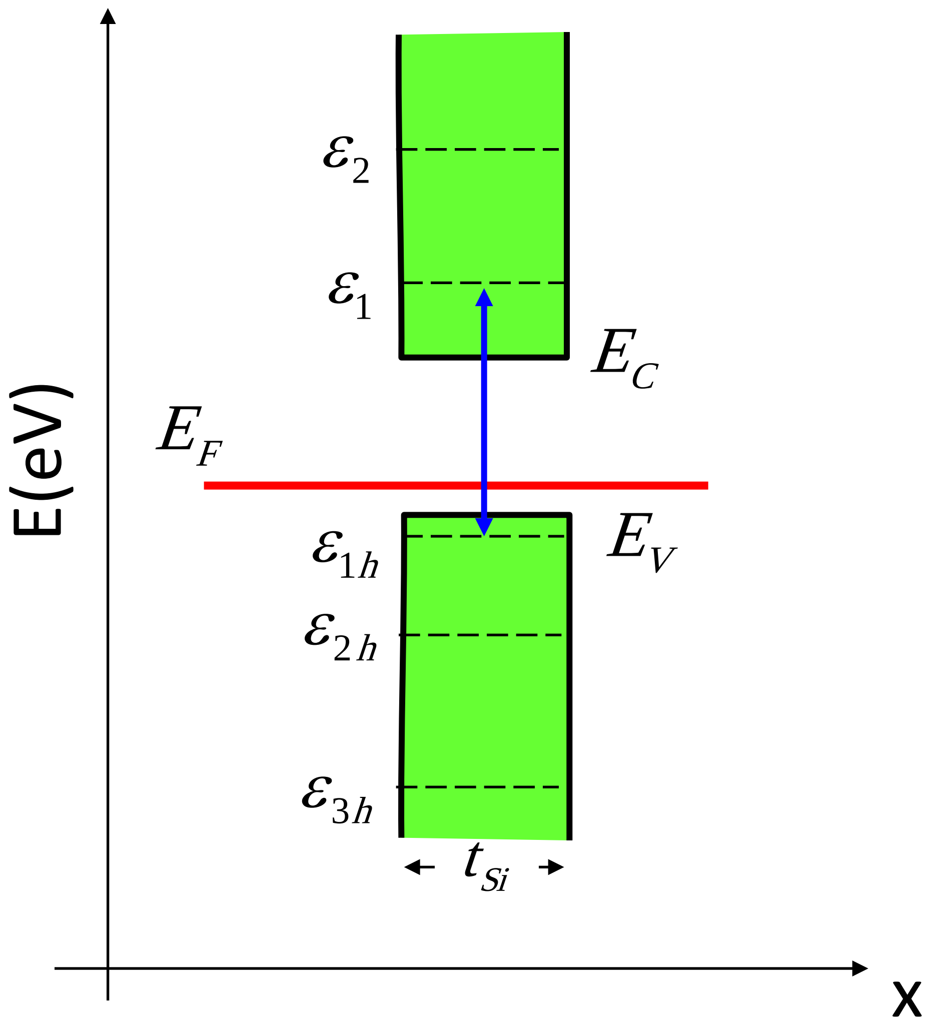
Example: FINFET, OmegaFET, X-FET



Cross-section



Quantization and Control of Fin-width



$$\varepsilon_n = \frac{h^2 n^2 \pi^2}{2 m^* t_{Si}^2}$$

$$E'_G = E_G + \varepsilon_1 + \varepsilon_{1h}$$

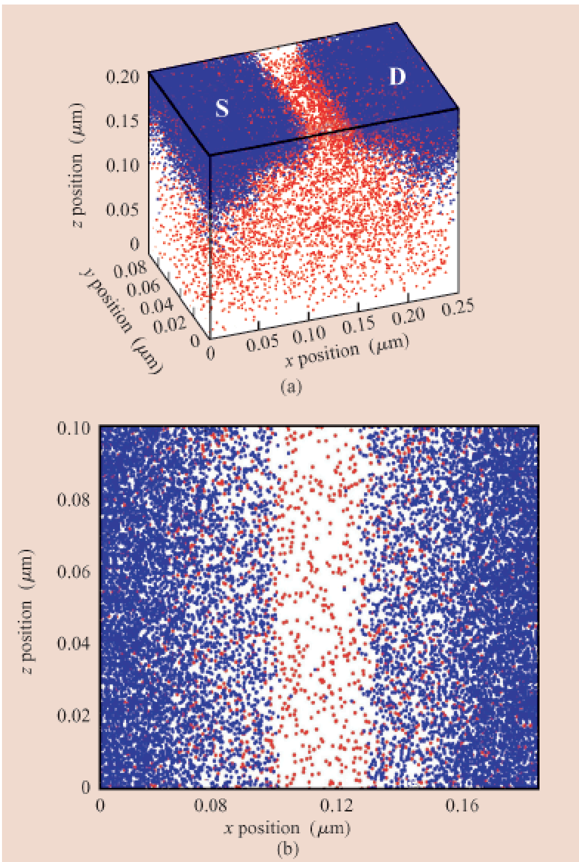
Band-gap widening

Fluctuation in thickness

Variability in Vth at Low Doping

$$V_{th} = 2\phi_F - \frac{Q_B}{C_{ox}} = 2\phi_F - \frac{qN_D W_T}{C_{ox}}$$

$$\sigma_{V_T} = 3.19 \times 10^{-8} \left(\frac{t_{ox} N_A^{0.4}}{\sqrt{L_{eff} W_{eff}}} [V] \right),$$



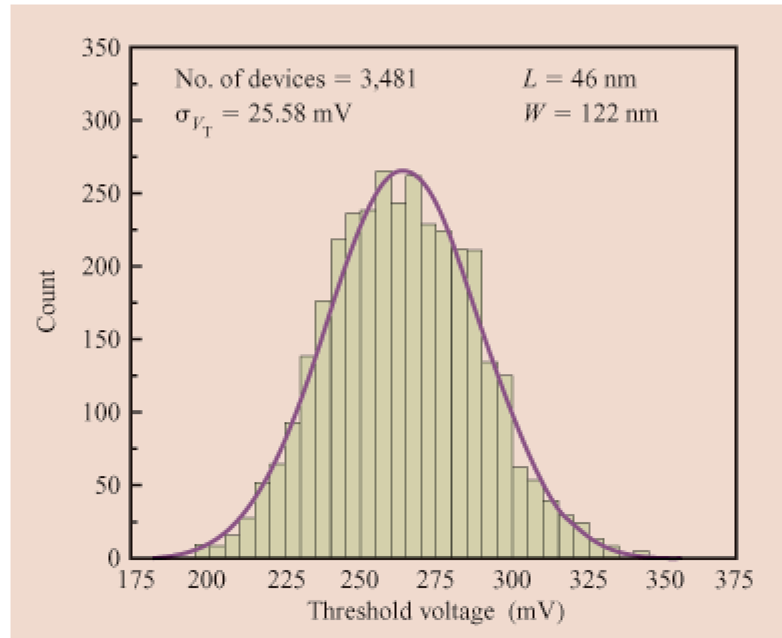


Figure 2

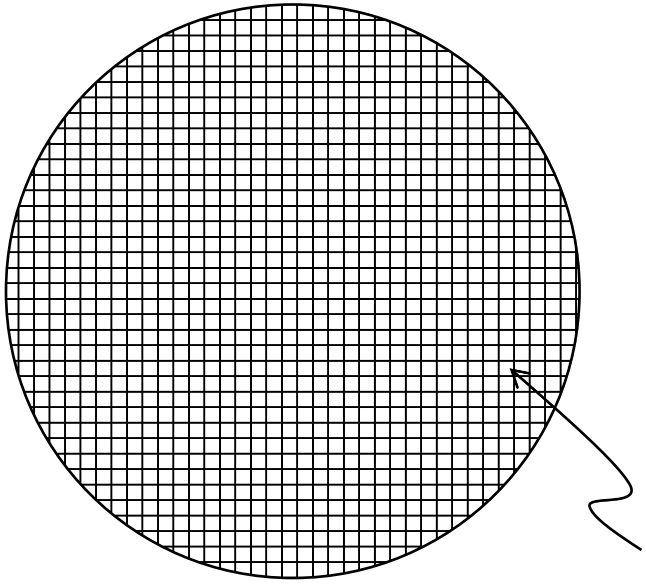
Threshold voltage histogram for FETs in the 90-nm-technology node.

IBM Journal of Res. And Tech. 2003.

Variability in Threshold Voltage

$$V_{th} = 2\phi_F - \frac{Q_B}{C_{ox}} = 2\phi_F - \frac{qN_A W_T}{C_{ox}}$$

$$\sigma_{V_T} = 3.19 \times 10^{-8} \left(\frac{t_{ox} N_A^{0.4}}{\sqrt{L_{eff} W_{eff}}} [V] \right),$$

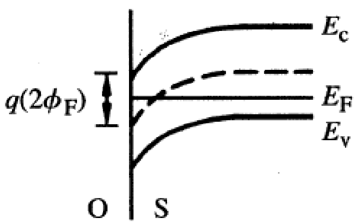


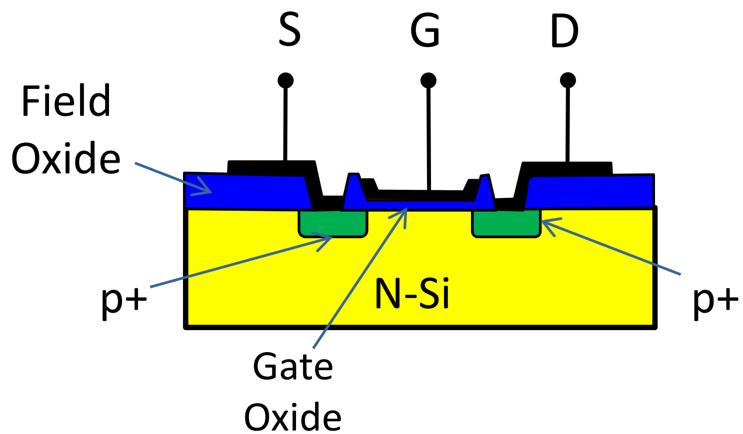
$$I_D = \frac{\mu C_{ox}}{L_{ch}} (V_G - V_{th}^{\ *})^2$$

If every transistor has different V_{th} and therefore different current, circuit design becomes difficult

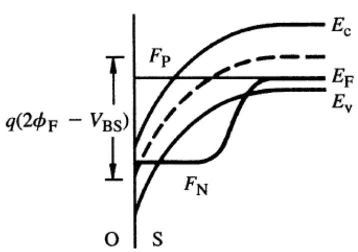
V_{th} control by Substrate Bias

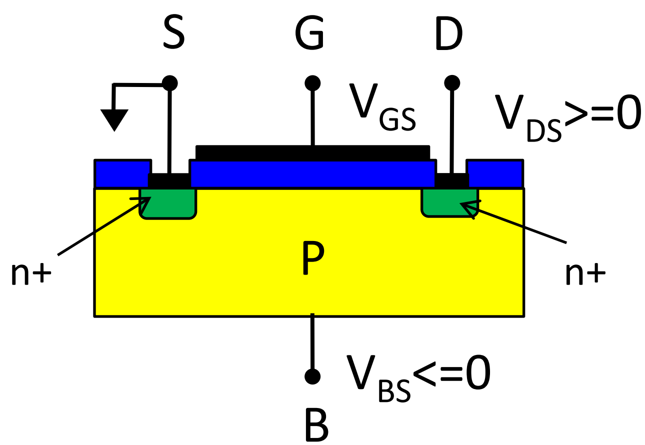
$$V_{th} = \psi_s - \frac{Q_B}{C_{ox}} = \psi_s + B\sqrt{\psi_s}$$





$$\psi_s = 2\phi_F$$

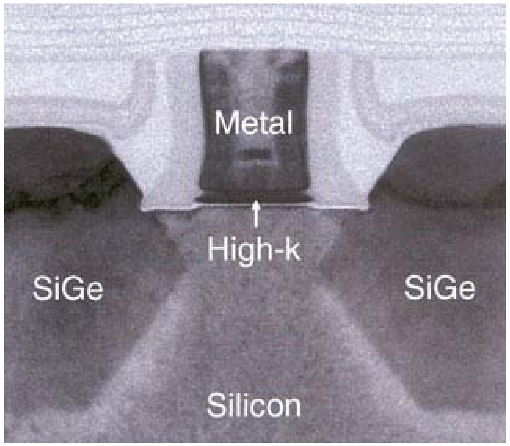




$$\psi_s = 2\phi_F - V_{BS}$$

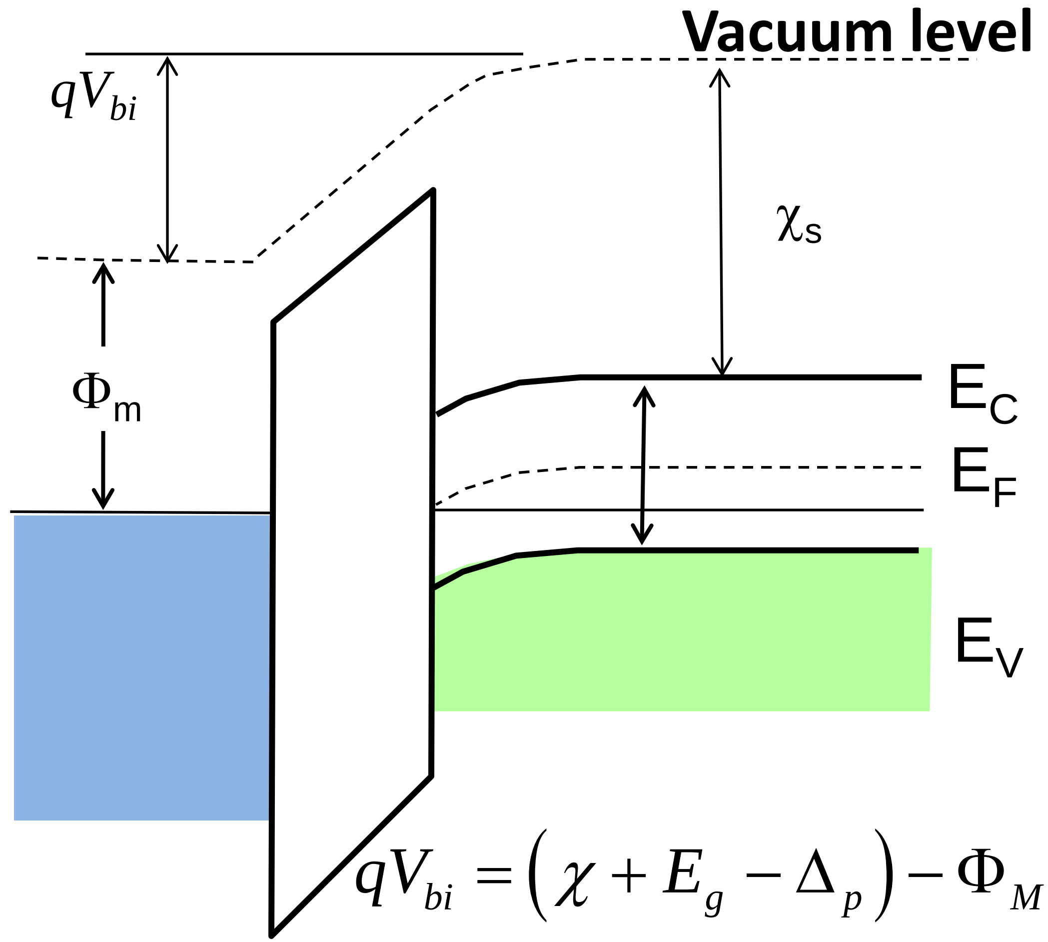
V_{th} control by Metal Work-function

High-k/metal gate MOSFET



$$Q_i = C_{ox}(V_G - V_{th})$$

$$V_{th} = -V_{FB} + \psi_s - \frac{Q_B}{C_{ox}}$$



$$qV_{bi} = \left(\chi + E_g - \Delta_p\right) - \Phi_M$$

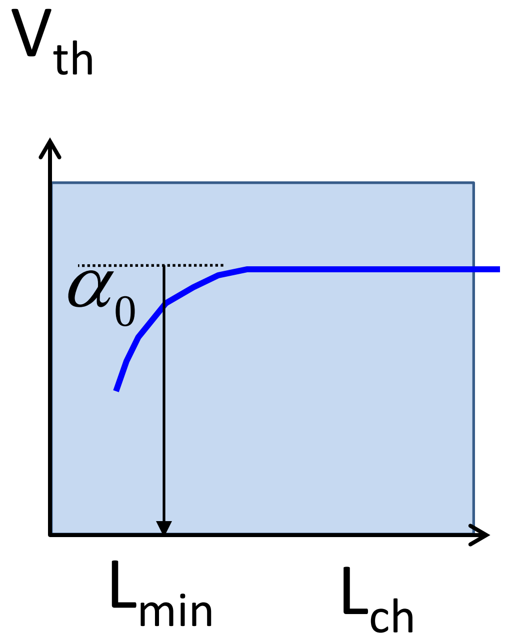
$$= qV_{FB}$$

How to reduce V_{th} roll-off …

Shallow junction/geometry of transistors
laser annealing of junctions, FINFETs

Reduced substrate doping NA
consider WT and junction breakdown

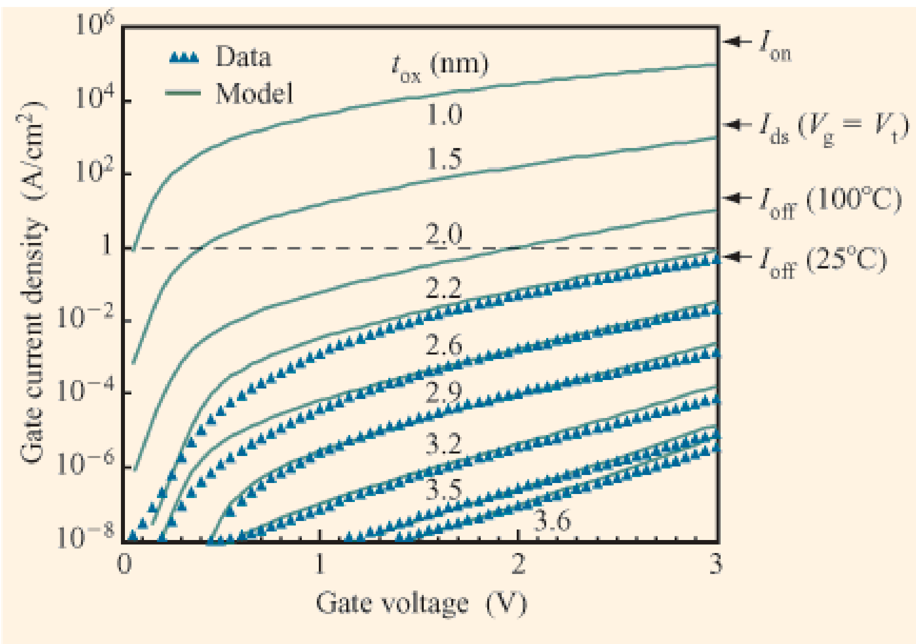
$$L_{\min} = \frac{qN_A W_T}{C_{ox}} \frac{r_J}{\alpha_0}\left(\sqrt{1+\frac{2W_T}{r_J}}-1\right)$$

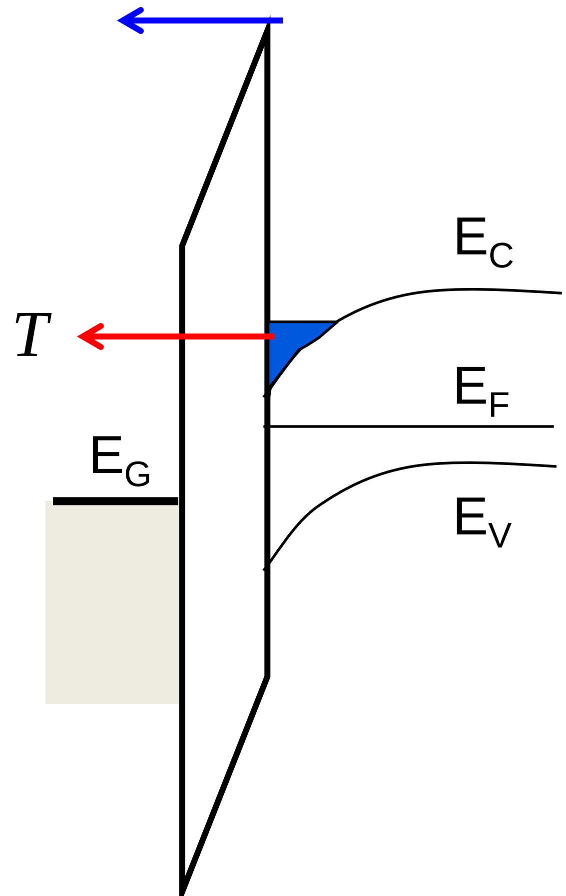


Thinner gate oxides
Consider tunneling current
Higher gate dielectric
Consider bulk traps

Tunneling Current

$$J_T = \left[Q_i(V_G) - \frac{n_i^2}{N_A} e^{-qV_G\beta} \right] \upsilon_{th} \langle T(E) \rangle$$

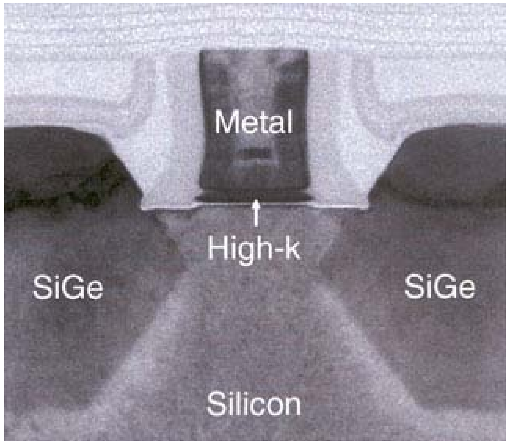




How to make Vth Roll-off small …

$$L_{\min} = \frac{qN_A W_T}{\frac{\kappa_{ox}\varepsilon_0}{x_0}} \frac{r_J}{\alpha}\left(\sqrt{1+\frac{2W_T}{r_J}}-1\right)$$

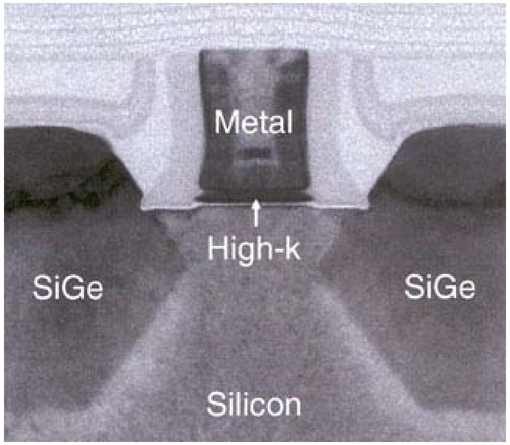
High-k/metal gate MOSFET

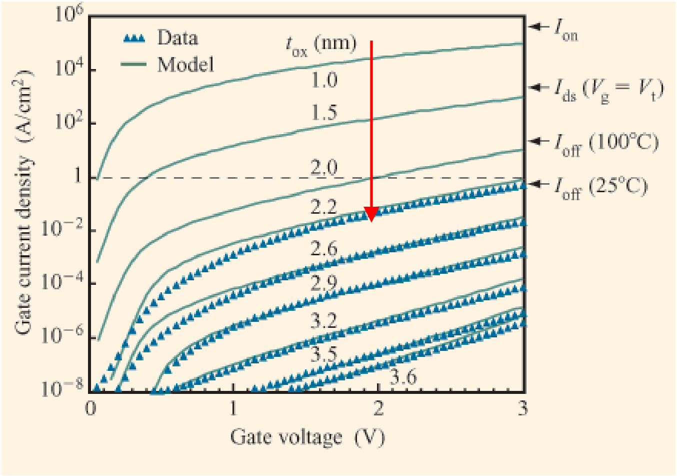


- Shallow junction and geometry of transistors
  laser annealing of junctions, FINFET
- Substrate doping NA
  consider WT and junction breakdown
- Thinner gate oxides
  consider tunneling current
- Higher gate dielectric
  consider bulk traps

Advantages of High-k Dielectric …

High-k/metal gate MOSFET





$$L_c = \frac{qN_A W_T}{\frac{\kappa_{ox}\varepsilon_0}{x_0}} \frac{r_J}{\alpha}\left(\sqrt{1+\frac{2W_T}{r_J}}-1\right)$$

$$I_D = \frac{\mu C_{ox}}{L_{ch}}(V_G - V_{th}^{*})^2$$

Thicker oxide (x_0) for same capacitance …

… ensures the drive-current is not reduced

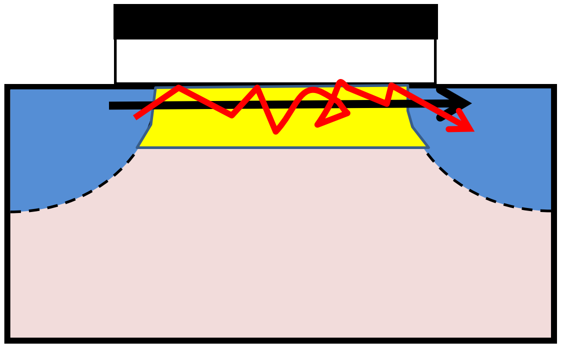
, but tunneling current is suppressed.

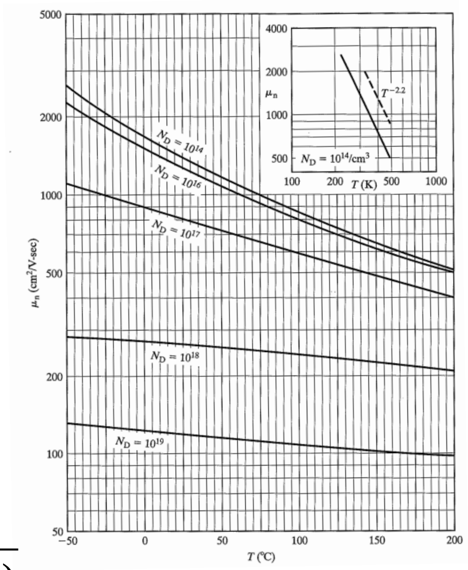
Outline

1. Short channel effect
2. Control of threshold voltage
3. **Mobility enhancement**
4. Conclusion

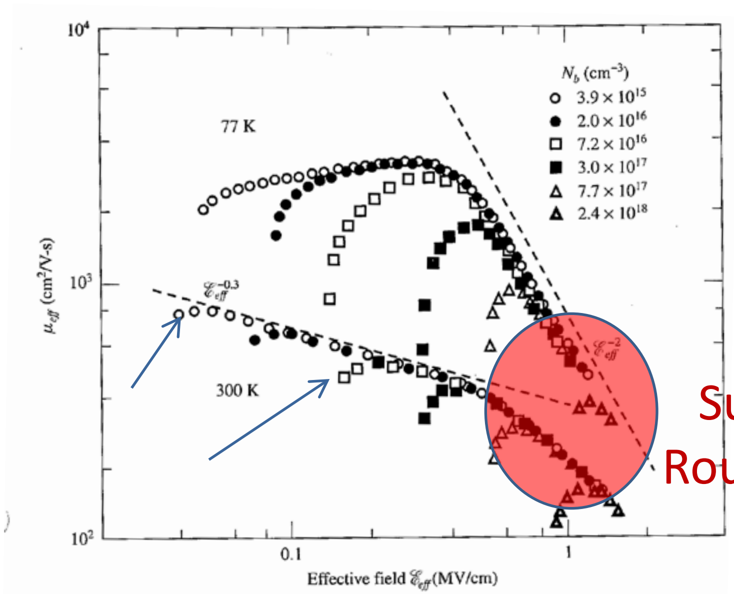
$$I_D = \frac{\mu C_{ox}}{L_{ch}}(V_G - V_{th}^{*})^2$$

Few words about universal Mobility ….

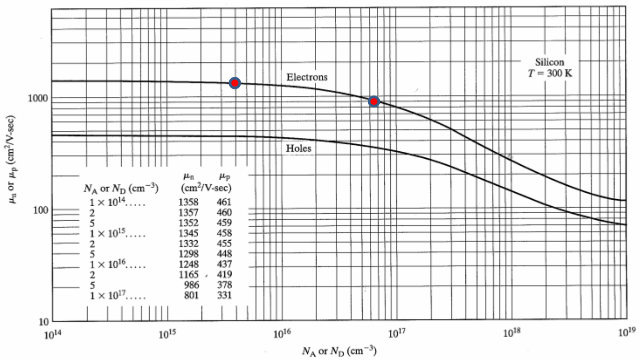




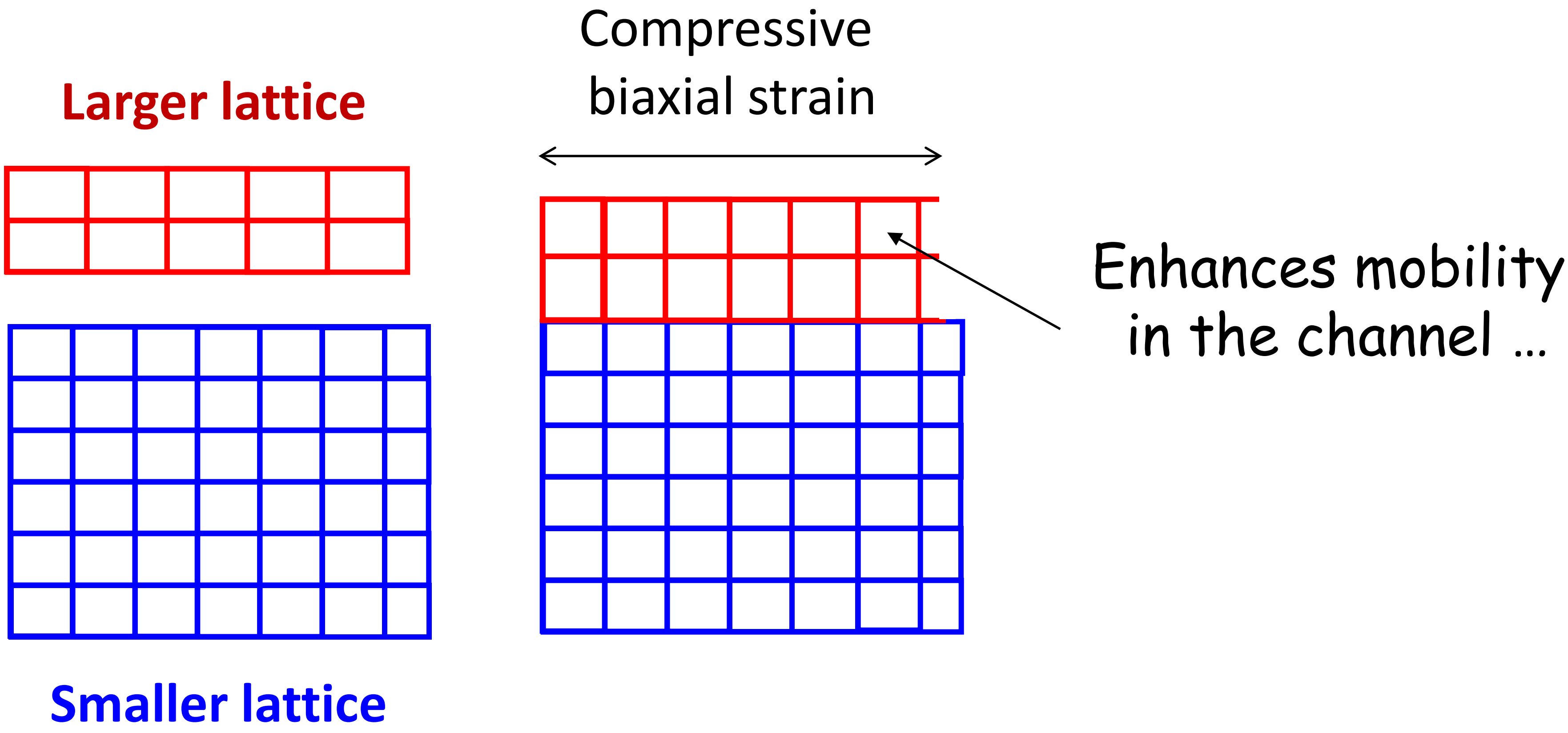
$$\mu_{eff} = \frac{\mu_0}{1+\theta(V_G - V_{th})}$$



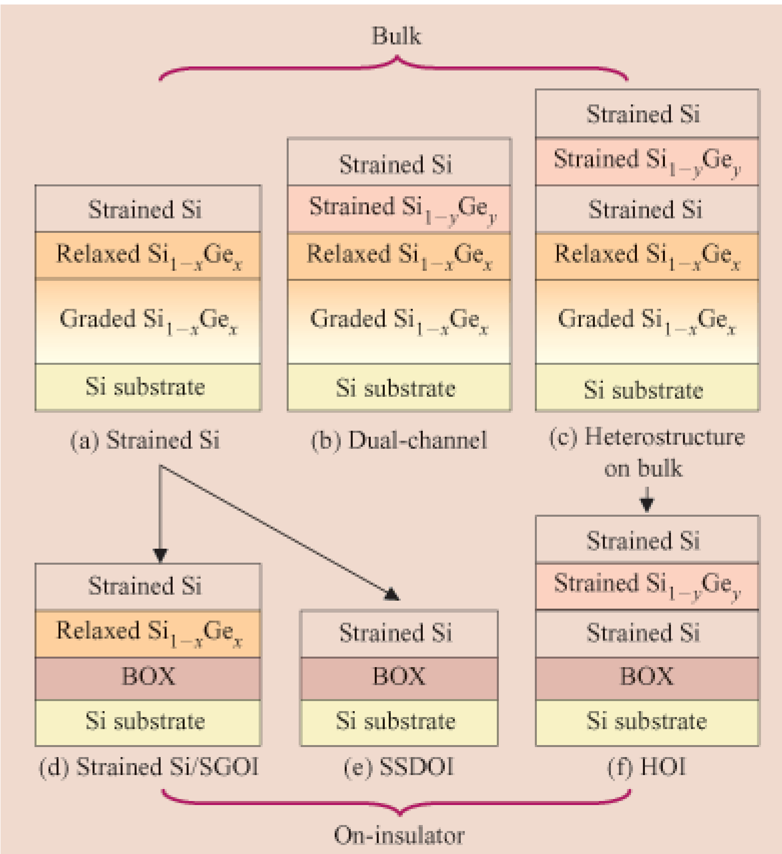
Surface Roughness

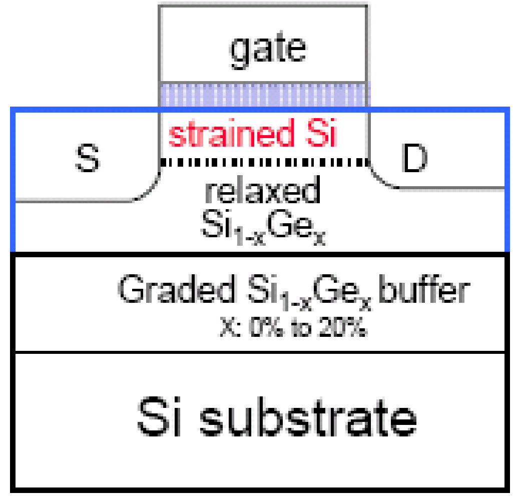


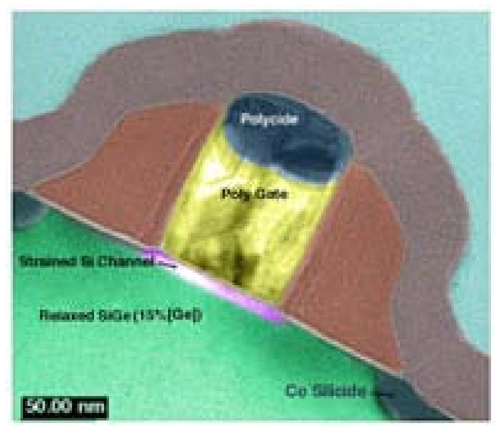
Basics of Strain ..



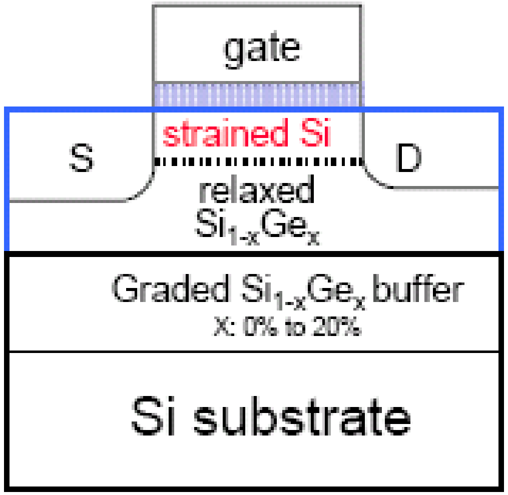
Biaxial Strain to Enhance Mobility

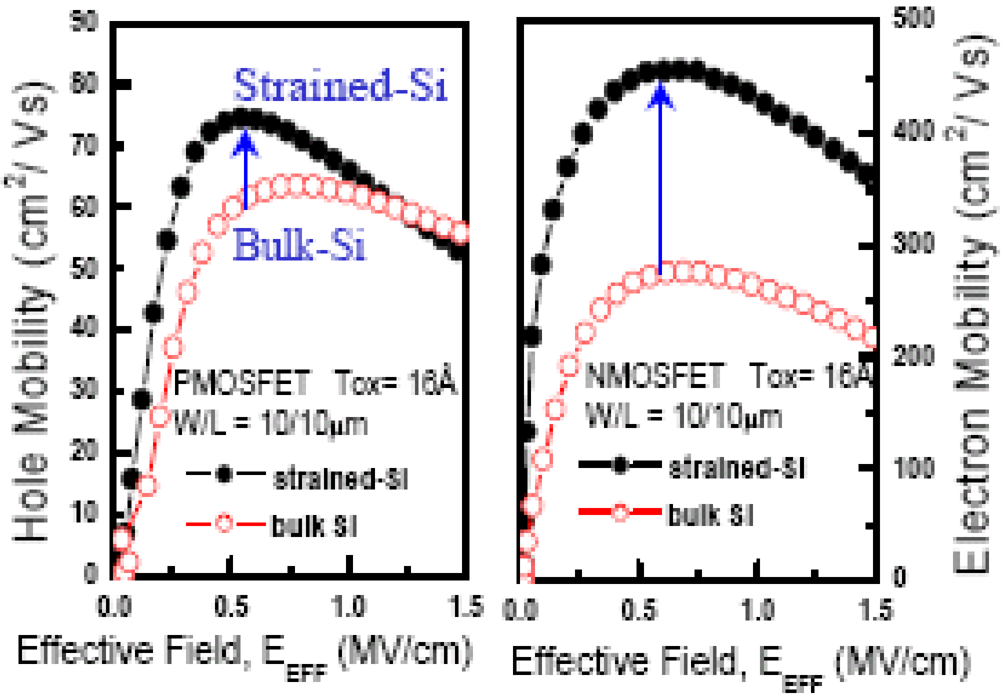






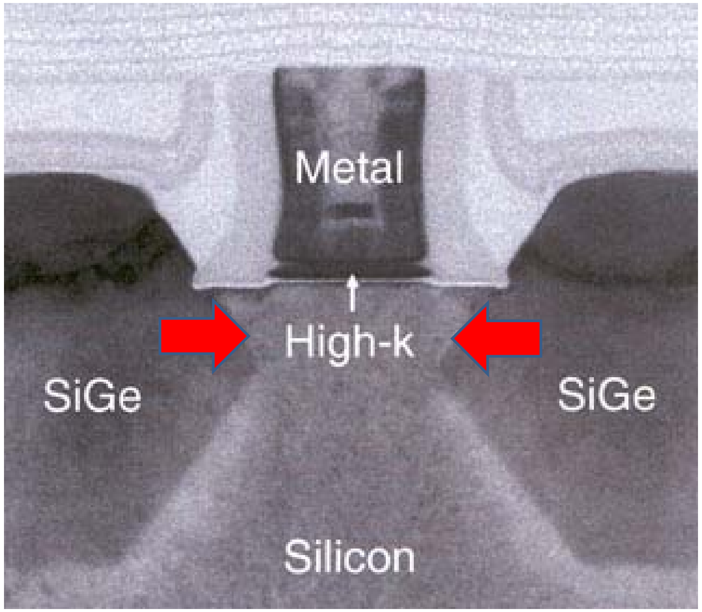
Biaxial Strain to Enhance Mobility



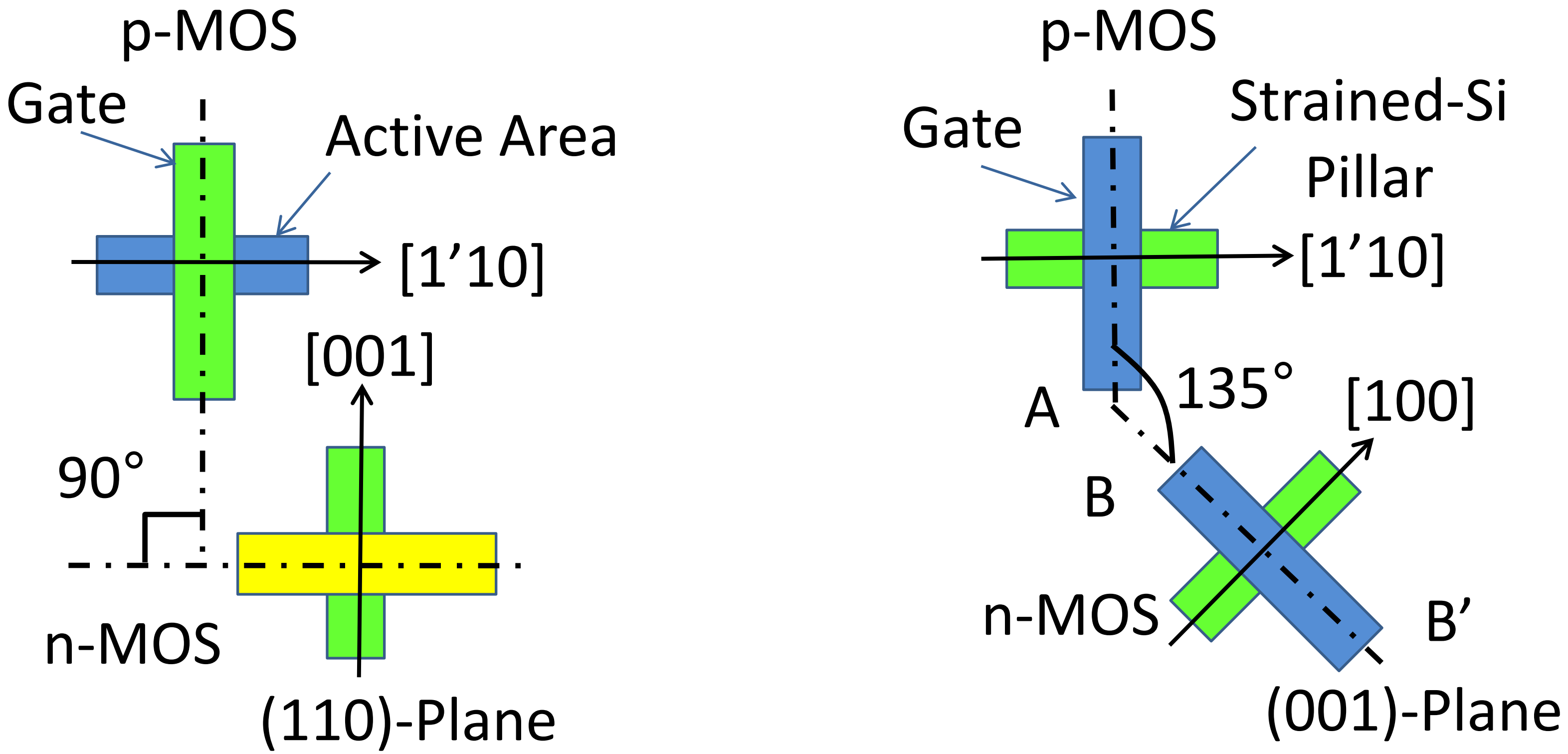


Adapted from Chang et. al, IEDM 2005.

Uniaxial Compressive Strain to Enhance Mobility



Orientation Dependent Mobility

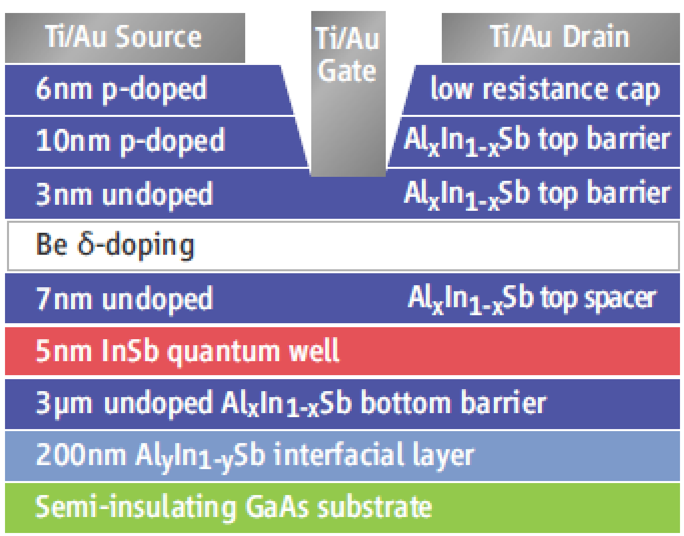


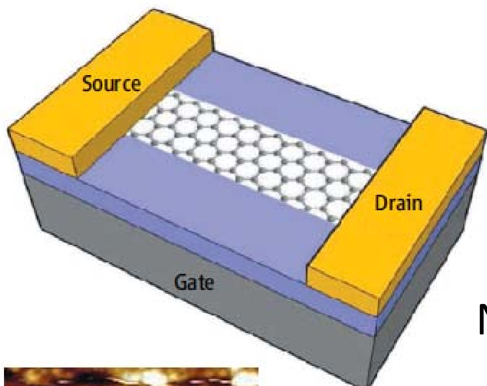
Takagi, TED 52, p.367, 2005

New Channel Materials for improved Mobility

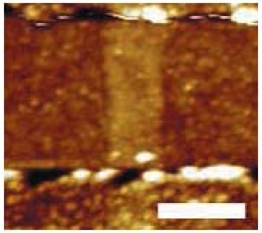
	Speed of Charges in Different Materials ($cm^2/V \cdot s$)					
Charges	Si	GaAs	$In_{0.53}Ga_{0.47}As$	InAs	InSb	Ge
Electrons*	300	7000	10,000	15,000	30,000	*
Holes*	450	400	200	460	1250	1900

*Electron carrier mobilities measured in transistor channels with electron concentration of $1 \times 10^{12}\ cm^{-2}$. Hole mobilities in bulk.





Nature, 2009



New kid. Transistors made from graphene nanoribbons could be blinding fast. But can they perform on an industrial scale?

Ge in PNP transistors, bandgap too small, but now coming back for PMOS

Summary

1) Short channel effect is a serious concern for MOSFET scaling.

2) Many novel solutions at the material, device, circuit level have been proposed to reduce short channel effect.

3) The success of these efforts are now reflected in effective MOSFET channel lengths of 30 nm.