High performance CMOS: gate-stack engineering

LECTURE 22

- the effect of C_{ox} on leakage and ON currents
- high-k dielectrics
- tunneling through the oxide
- the importance of electron affinity
- metal gates

The C_{ox} dilemma: 1

ON current:

$$I_{Dsat} = ZC_{ox}(V_{GS}-V_T)\cdot v_{\mathrm{sat}}\frac{\sqrt{1+2\mu_{\mathrm{eff}}(V_{GS}-V_T)/(m\,v_{\mathrm{sat}}L)}-1}{\sqrt{1+2\mu_{\mathrm{eff}}(V_{GS}-V_T)/(m\,v_{\mathrm{sat}}L)}+1}$$

Break this down into charge and velocity.

A high C_{ox} is needed to get more charge in the channel.

OFF Current:

A high C_{ox} is needed to get a steeper inverse sub-threshold slope

$$S = \left(\frac{\partial \log_{10} I_D}{\partial V_{GS}}\right)^{-1} \equiv 2.303 m\, V_{\mathtt{th}}$$

$$m(0) = 1 + \frac{\gamma}{2\sqrt{2\phi_B + V_{SB}}} \equiv 1 + \frac{C_b(0)}{C_{ox}}$$

Relation between m and $C_b(0)$

10.3

From (10.43) $m = 1 + \frac{\gamma}{2\sqrt{2\phi_B + V_{SB}}}$ where $\gamma = \frac{\sqrt{2q\varepsilon_s N_A}}{C_{ox}}$

$$C_b = \frac{\varepsilon_s}{W} = \frac{\varepsilon_s}{\sqrt{\frac{2\varepsilon_s}{q}\, 2\phi_B \frac{1}{N_A}}} \quad @\ \psi_s = 2\phi_B \rightarrow C_b = \frac{1}{\sqrt{2}} \sqrt{\frac{\varepsilon_s q N_A}{2\phi_B}}$$

$$= \frac{1}{2} \sqrt{\frac{2\varepsilon_s q N_A}{2\phi_B}}$$

$$\therefore \gamma C_{ox} = 2 C_b \sqrt{2\phi_B}$$

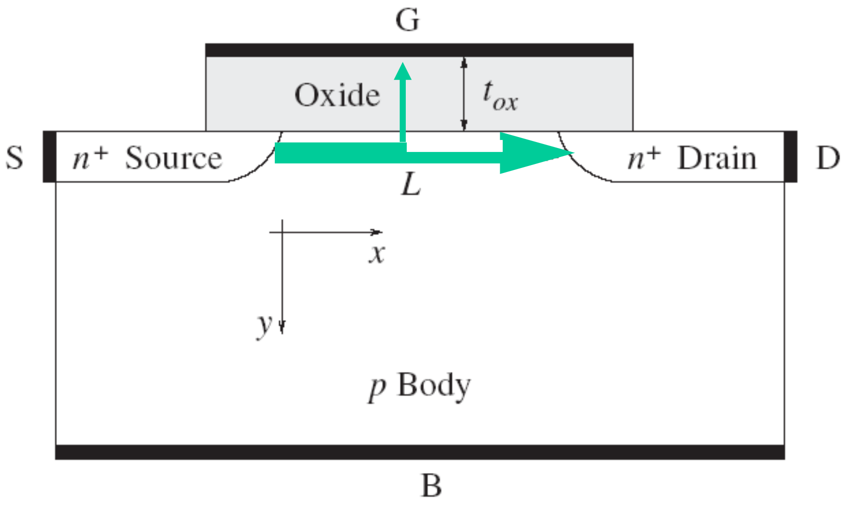
and $m = 1 + \frac{C_b}{C_{ox}}$ as per (10.36), provided $\psi_s = 2\phi_B$, as would be the case in strong inversion at the source and when $V_{SB} = 0$.

The C_{ox} dilemma: 2

Leakage current:

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

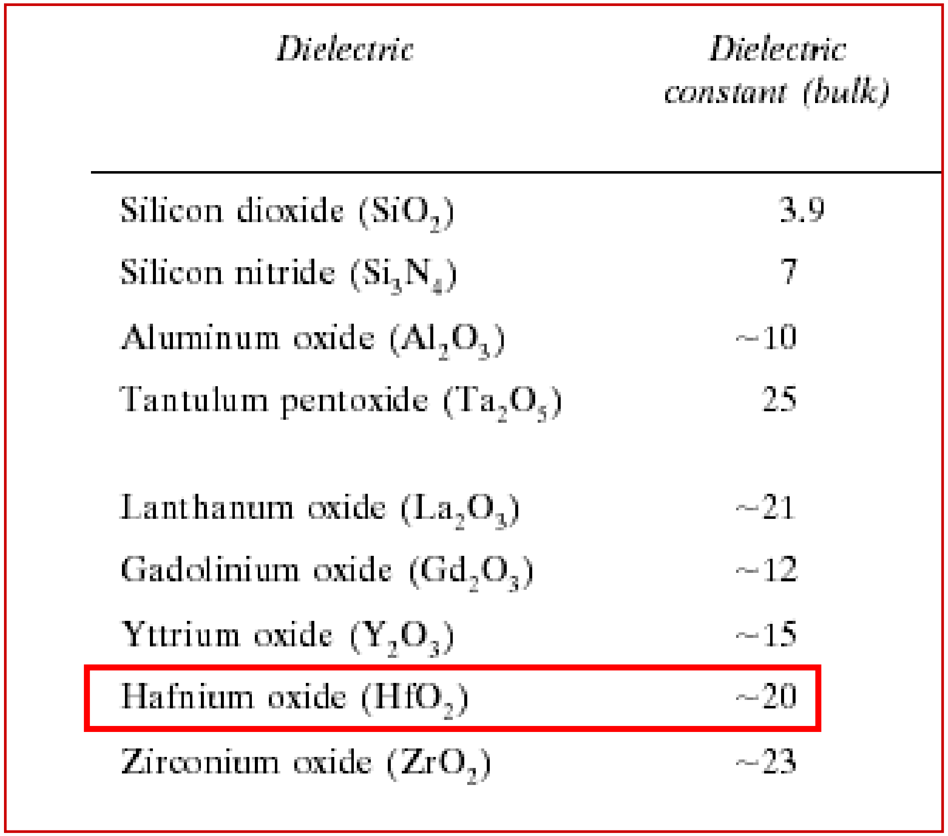
There's a limit to how far t_{ox} can be reduced before channel-gate leakage occurs



High-k dielectrics

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

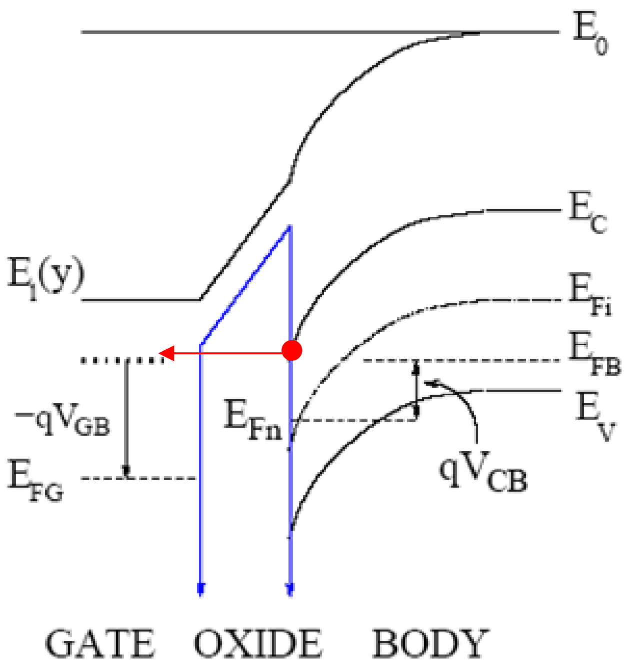
- High C_{OX} needed for I_D and S
- High t_{OX} needed to reduce gate leakage
- Resolve conflict by increasing ε



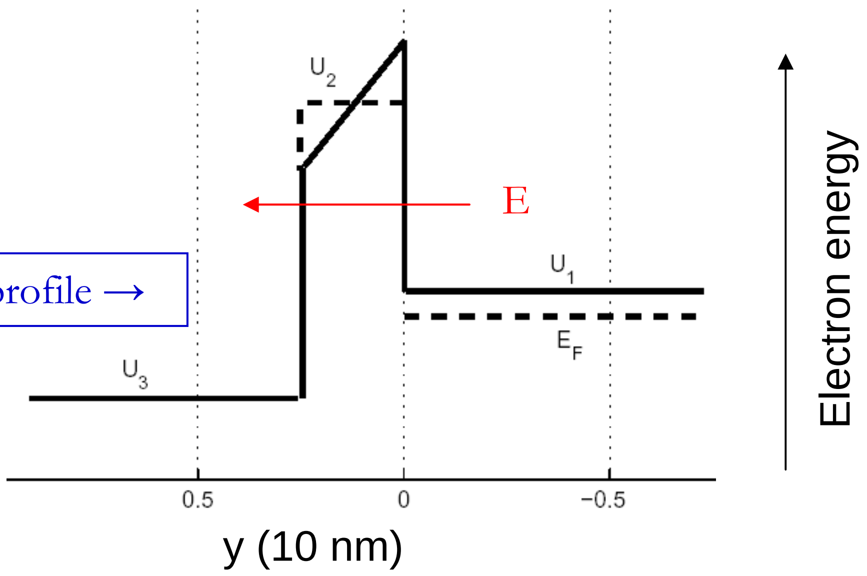
Dielectric	*Dielectric constant (bulk)*
Silicon dioxide (SiO_2)	3.9
Silicon nitride (Si_3N_4)	7
Aluminum oxide (Al_2O_3)	~10
Tantulum pentoxide (Ta_2O_5)	25
Lanthanum oxide (La_2O_3)	~21
Gadolinium oxide (Gd_2O_3)	~12
Yttrium oxide (Y_2O_3)	~15
Hafnium oxide (HfO_2)	~20
Zirconium oxide (ZrO_2)	~23

Sec. 5.7.2

Tunneling through the oxide



Simplify the U profile →



Solve SWE in each region:

write as:

$$
\begin{aligned}
k_1 &= \frac{1}{\hbar}\sqrt{2m_1^*(E-U_1)} \\
k_2 &= \frac{1}{\hbar}\sqrt{2m_2^*(E-U_2)} \equiv ik_2' \\
k_2' &= \frac{1}{\hbar}\sqrt{2m_2^*(U_2-E)} \\
k_3 &= \frac{1}{\hbar}\sqrt{2m_3^*(E-U_3)}\,.
\end{aligned}
$$

Sec. 5.7.2

Solutions for ψ ψ*

$$\begin{aligned}
\psi_1 &= Ae^{ik_1y} + Be^{-ik_1y} \\
\psi_2 &= Ce^{k_2'y} + De^{-k_2'y} \\
\psi_3 &= Fe^{ik_3y}\ ,
\end{aligned}$$

Physically what is the “C-wave" ?

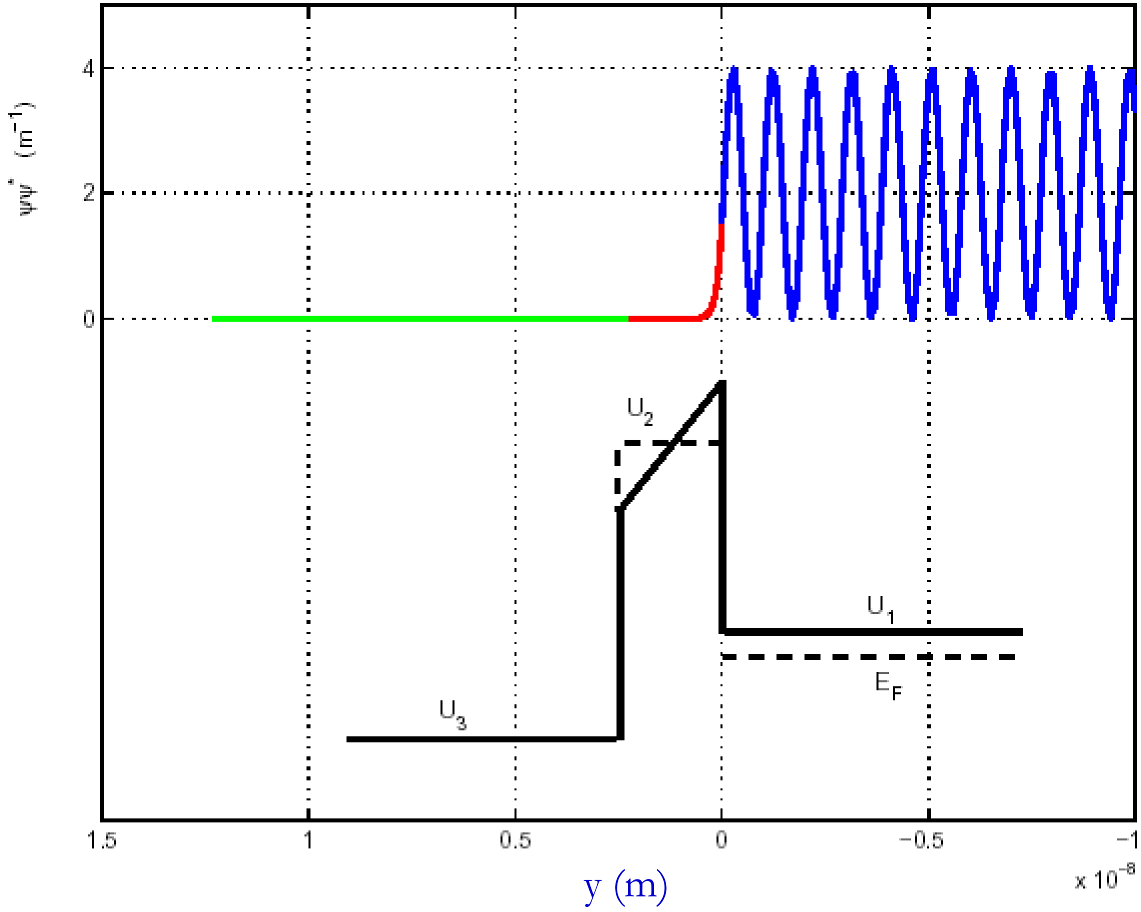
What is ψ ψ* ?

Why is it :

-oscillatory in the channel ?

- damped in the oxide ?

- constant in the gate ?



Sec. 5.7.2

Emphasizing the reduction in ψ ψ*

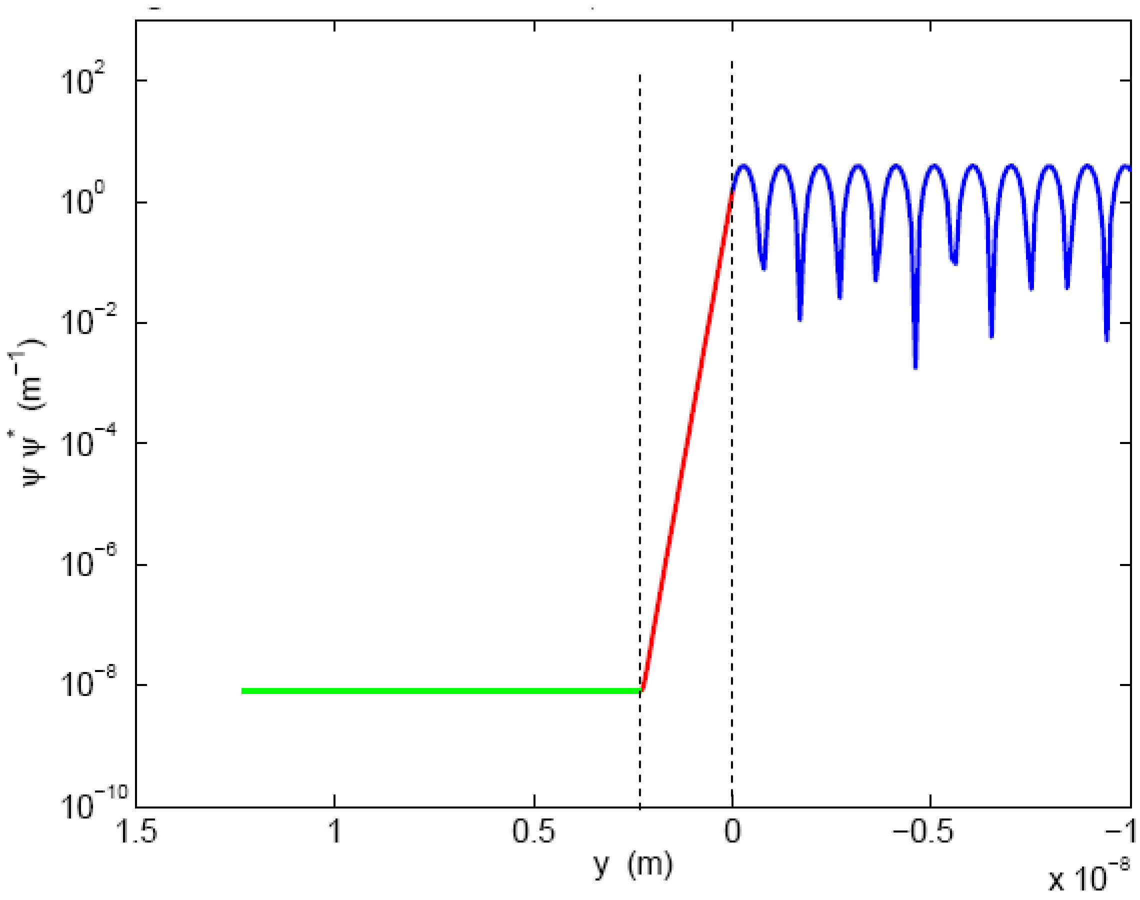


Figure 5.9 Redrawing of the probability density from Fig. 5.8 The logarithimic scale emphasizes the small ($\approx 10^{-8}\,\mathrm{m}^{-1}$) probability density of electrons tunneling from region 1.

Sec. 5.7.1

Probability Density Current

$$\begin{aligned}\frac{dP}{dt} &= \Psi^*\frac{\partial\Psi}{\partial t} + \Psi\frac{\partial\Psi^*}{\partial t}\\ &= \frac{1}{i\hbar}\left[\Psi^*(i\hbar\frac{\partial\Psi}{\partial t}) + \Psi(i\hbar\frac{\partial\Psi^*}{\partial t})\right]\end{aligned}$$

What does the flow of P mean ?

The time-dependent Schrödinger Wave Equation is

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m^*}\nabla^2\Psi + U\Psi$$

$$\begin{aligned}\frac{dP}{dt} &= -\frac{i\hbar}{2m^*}\nabla\cdot[\Psi\nabla\Psi^* - \Psi^*\nabla\Psi]\\ &\equiv -\nabla\cdot\vec{J}_P\end{aligned}$$

Do you recognize this as a Continuity Equation ?

Sec. 5.7.2

Transmission Probability: Definition

$$\frac{dP}{dt} = -\frac{i\hbar}{2m^*}\nabla \cdot [\Psi\nabla\Psi^* - \Psi^*\nabla\Psi]$$
$$\equiv -\nabla \cdot \vec{J}_P$$

1. For the channel:

$$\psi_1 = Ae^{ik_1 y} + Be^{-ik_1 y}$$

2. Do the derivatives and the conjugates:

$$J_{P,A} = \frac{\hbar k_1}{m_1^*}|A|^2$$
$$J_{P,F} = \frac{\hbar k_3}{m_3^*}|F|^2$$

What do these mean ?

3. Define the Transmission Probability:

$$T(E) = \frac{k_3}{k_1}\frac{m_1^*}{m_3^*}\frac{|F|^2}{|A|^2}$$
$$\equiv \frac{v_{k,3}}{v_{k,1}}\frac{|F|^2}{|A|^2},$$

What is the interpretation of this ?

Sec. 5.7.2

Transmission Probability: Evaluation

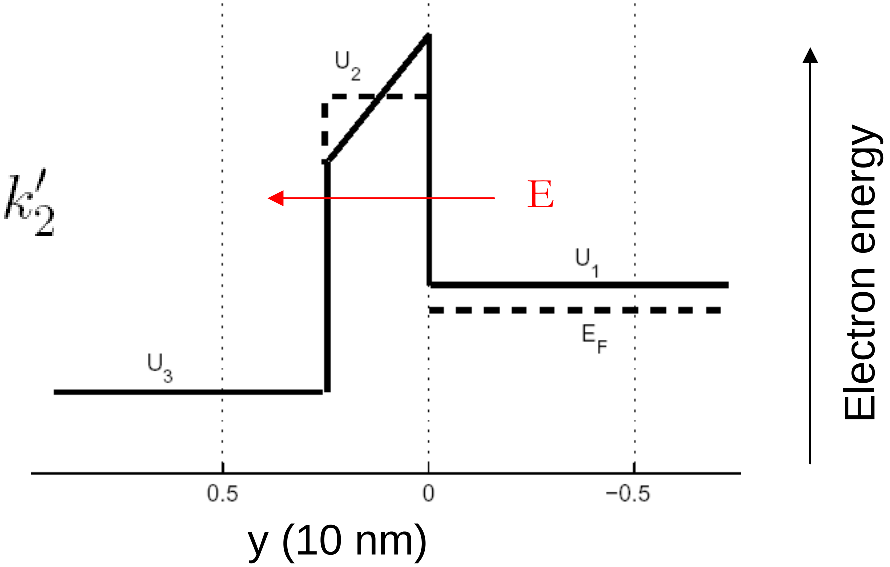
Solve for F and A:

$$T = \frac{4m_1k_3/m_3k_1}{(1+k_3m_1/k_1m_3)^2\cosh^2(k_2'd) + (k_2'm_1/k_1m_2 - k_3m_2/k_2'm_3)^2\sinh^2(k_2'd)}\,.$$

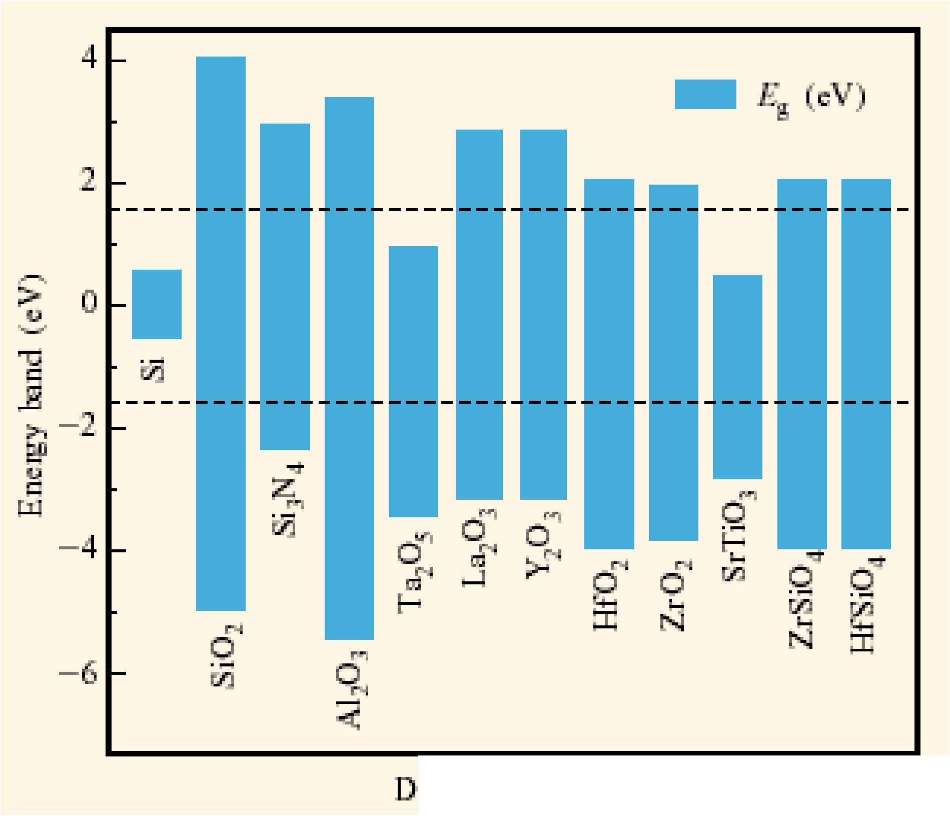
Identify the symbols with features on the band diagram. For example:

$$k_2 = \frac{1}{\hbar}\sqrt{2m_2^*(E-U_2)} \equiv ik_2'$$

What is important besides t_{ox} ?



Silica vs. Hafnia: properties



	ϵ_r	t_{ox} (nm)	χ (eV)	m^* (m_0)
Silica	3.9	2.3	0.9	0.3
Hafnia	$5\epsilon_{r,\text{silica}}$	$t_{ox}\epsilon_{r,\text{hafnia}}/\epsilon_{r,\text{silica}}$	2.9	0.1
Silicon	-	-	4.1	0.91

Sec. 13.1.6

The importance of electron affinity

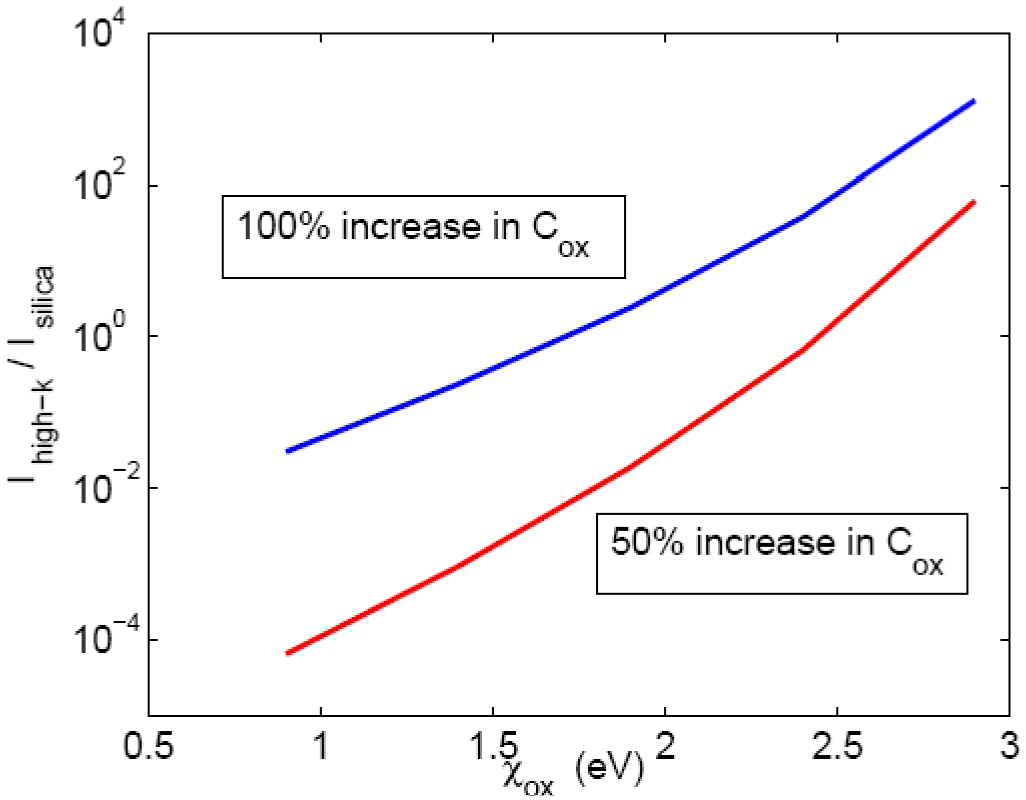


Figure 13.8: Ratio of tunnel current in a high-k dielectric to that in silica as a function of the electron affinity of the high-k dielectric. The high-k dielectric is taken to have a relative permittivity that is 4 times that of silica. The top curve is for an improvement in C_{ox} of 100%, and the bottom curve is for an improvement of 50%. The parameter values are as given in the caption to Fig. 5.9, unless otherwise stated. $(E_{C,Si} - E_F)$ was taken to be 50 meV.

Is it possible to reduce I_{leak} and improve I_{ON} ?

Sec. 13.1.5

The new gate stack

45nm High-k + Metal Gate Strain-Enhanced CMOS Transistors

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Logic Technology Development, Intel Corp., Hillsboro, OR, U.S.A.

Guess what Intel is doing

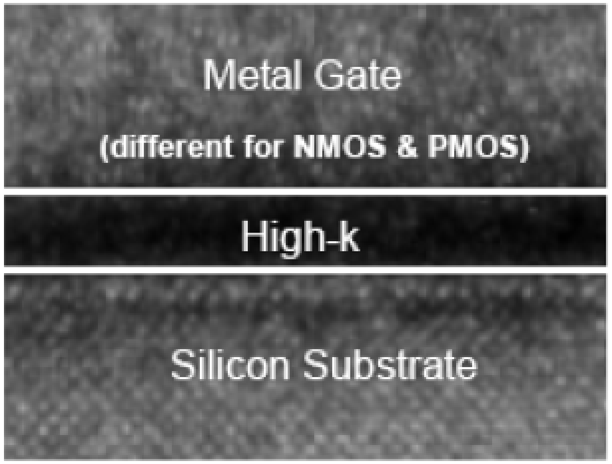


Figure 3: TEM of High-k/Metal gate stack

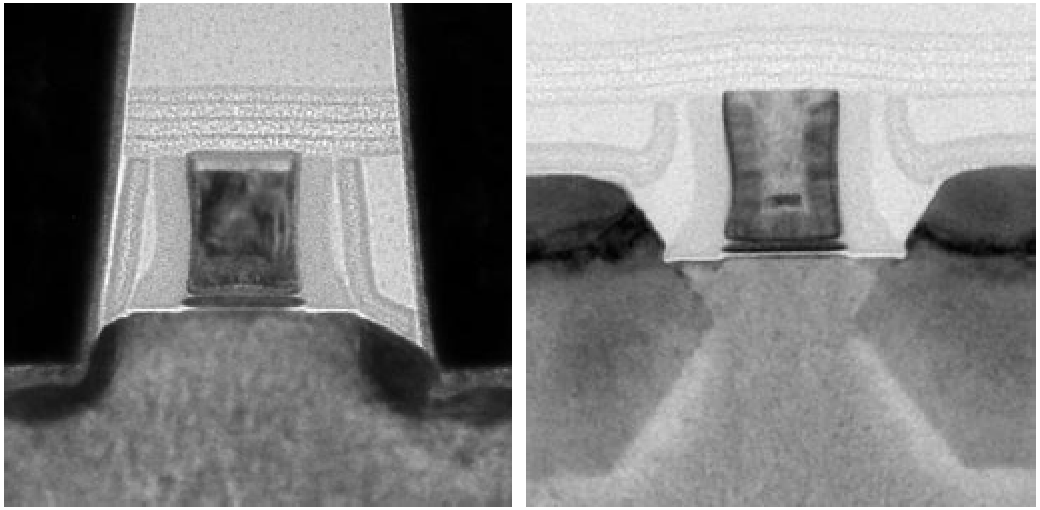
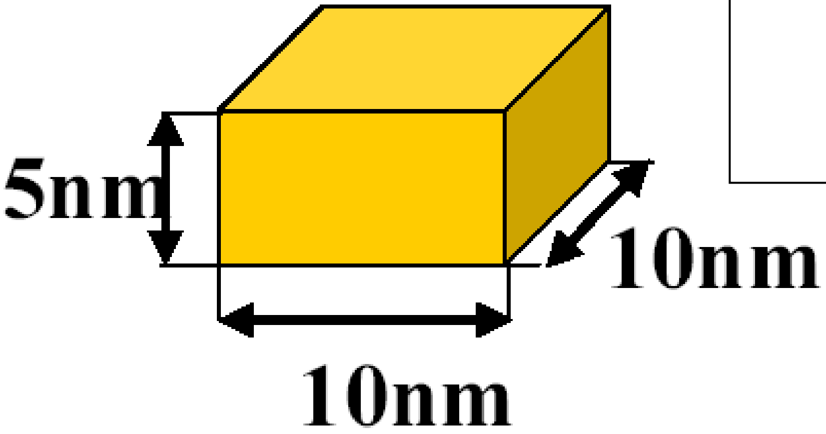


Figure 5: TEMs of High-k + Metal Gate NMOS (left) and PMOS (right) transistors

Threshold voltage

$$V_T \equiv V_{GS}^T = V_{fb} + 2\psi_B + \frac{1}{C_{ox}}\sqrt{2\epsilon_S q N_A (2\psi_B + V_{SB})}$$

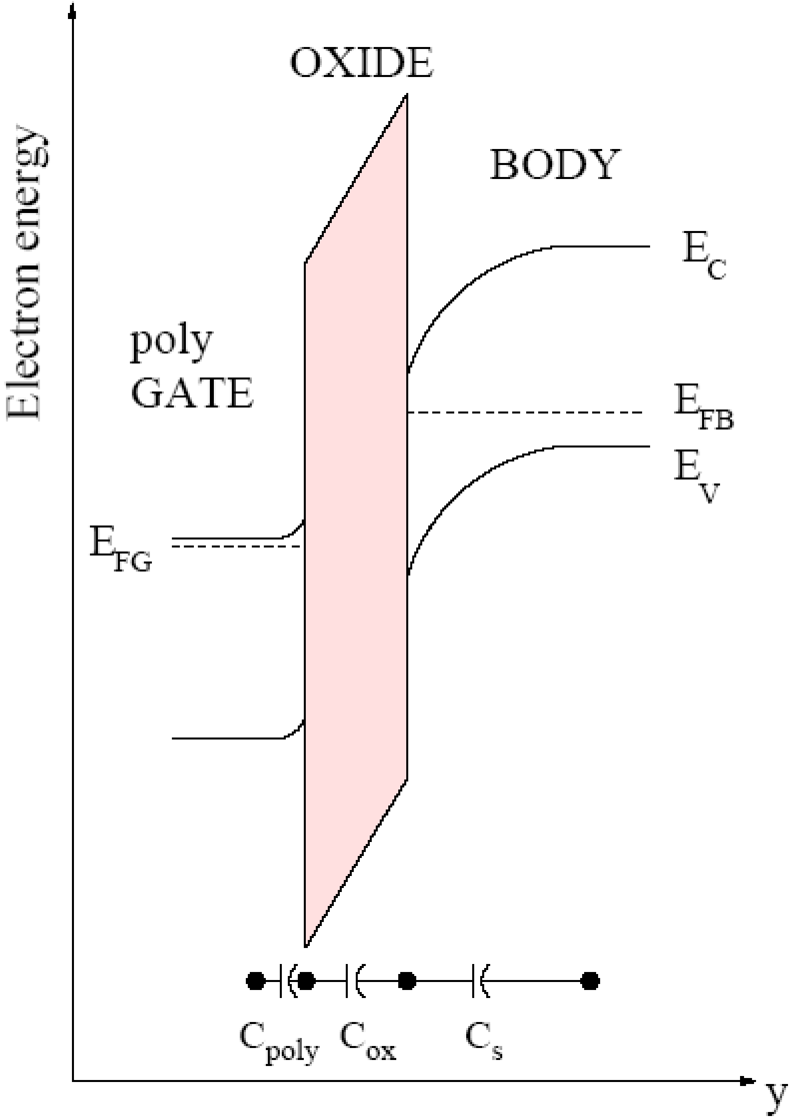
What if N_A were greatly reduced?



- If V_T controlled by metal, perhaps can use undoped Si substrate.
- This would remove the problem of dopant fluctuations.
- But what about self-alignment?

Sec. 13.1.6

Another reason for metal gates



The finite conductivity of the poly-gate results in band bending in the gate.

$$V_{GB} - V_{fb} = \psi_{\text{poly}} + \psi_{ox} + \psi_s$$

How does this affect V_T ?