VLSI Devices
Lecture 23

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Coverage

- Two YouTube lectures reserved for advanced topics
  - L14: ~~Substrate bias~~, ~~channel mobility~~
  - L15: ~~3.2.1~~
  - L16: ~~3.2.1 (Continued)~~
  - L17: ~~Velocity saturation (3.2.2)~~
  - L18: ~~Channel length modulation and so on (3.2.3, 3.2.4, 3.2.5)~~
  - L19: MOSFET scaling
  - L20: MOSFET scaling (Continued)
  - L21: Quantum effect (4.2.4)
  - L22: Double-gate MOSFETs (10.3)
  - L23: FinFETs
  - L24: CFETs

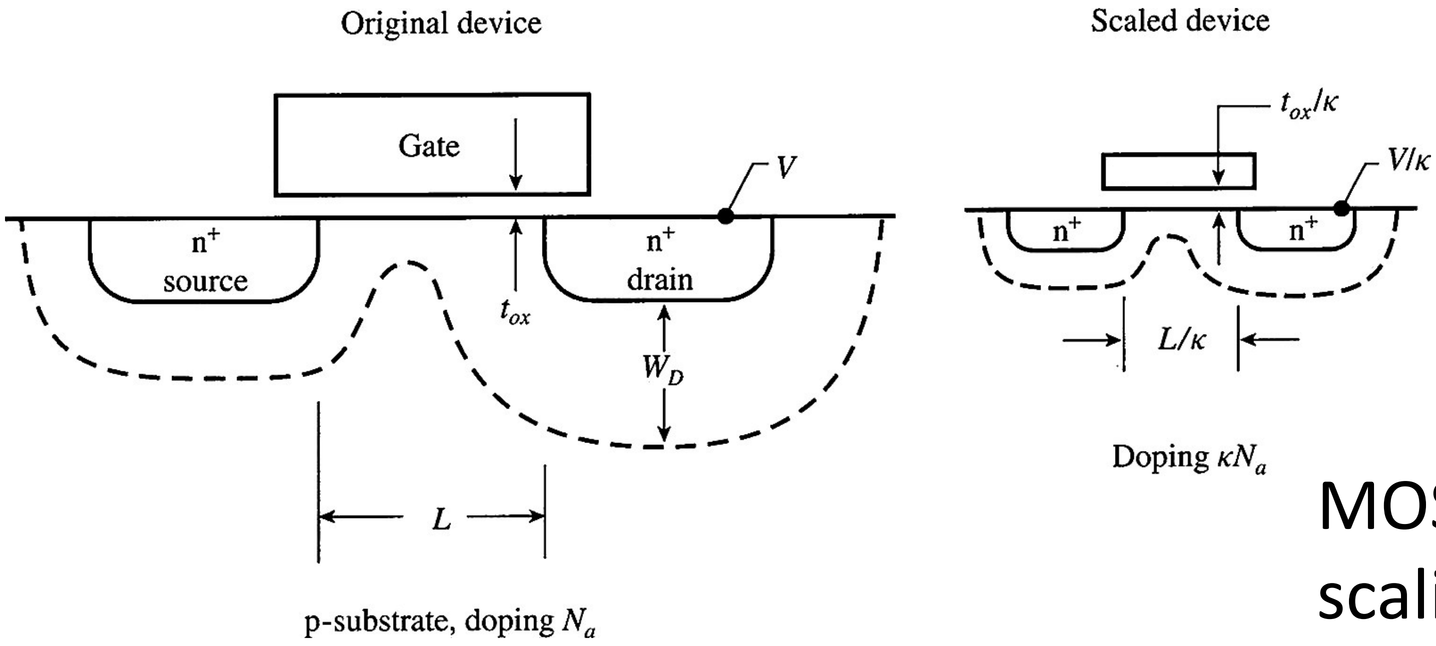
Basic assumptions

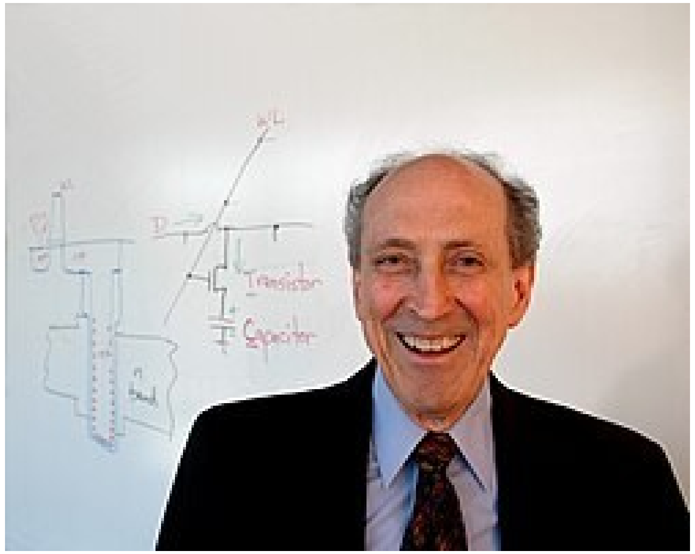
- High-resolution lithographic techniques (Minimum L)
- Technological advancement in ion implantation (Shallow junction)

An architect and a construction worker (Image generated by ChatGPT)

Constant-field scaling (Dennard scaling)

- Keep short-channel effects under control,
  - By scaling down the vertical dimensions along with the horizontal dimensions.
  - Decrease the applied voltage.
  - Increase the substrate doping concentration.





R. H. Dennard
(Inventor of DRAM)

MOSFET constant-electric-field scaling (Taur, Fig. 4.1)

Rules for constant-field scaling (1)

- Scaling assumption (κ>1)
  - Device dimensions (t_{ox}, L, W, and x_j): $1/\kappa$
  - Doping concentration (N_a and N_d): κ
  - Voltage (V): $1/\kappa$
- Maximum drain depletion width

$$W_D = \sqrt{\frac{2\epsilon_{si}(\phi_{bi} + V_{dd})}{qN_a}} \rightarrow \sqrt{\frac{2\epsilon_{si}\left(\phi_{bi} + \frac{1}{\kappa}V_{dd}\right)}{q\kappa N_a}}$$

Taur, Eq. (4.1)

$$\approx \frac{1}{\kappa}\sqrt{\frac{2\epsilon_{si}(\phi_{bi} + V_{dd})}{qN_a}} = \frac{1}{\kappa}W_D$$

Rules for constant-field scaling (2)

- Capacitances
  - They scale down by κ.
- Charge per device ($\sim C \times V$)
  - It scaled down by κ^2.
- Drain current
  - The original one

$$I_d = \mu_n C_{ox} \frac{W}{L}\left[\left(V_{gs} - V_t\right)V_{ds} - \frac{1}{2}V_{ds}^2\right]$$

$$\mu_n \kappa C_{ox} \frac{\frac{1}{\kappa}W}{\frac{1}{\kappa}L}\left[\left(\frac{1}{\kappa}V_{gs} - \boldsymbol{V_{t,scaled}}\right)\frac{1}{\kappa}V_{ds} - \frac{1}{2}\frac{1}{\kappa^2}V_{ds}^2\right] \approx \frac{1}{\kappa}I_d$$

Effect of scaling on circuit parameters

- Important colcusion of constant-field scaling:
  - Once the device dimensions and the power-supply voltage are scaled down, the circuit speeds up by the same factor.

$$\tau \sim \frac{\overset{\frac{1}{\kappa^2}}{C}\,\overset{\frac{1}{\kappa}}{V}}{\underset{\frac{1}{\kappa}}{I}}$$

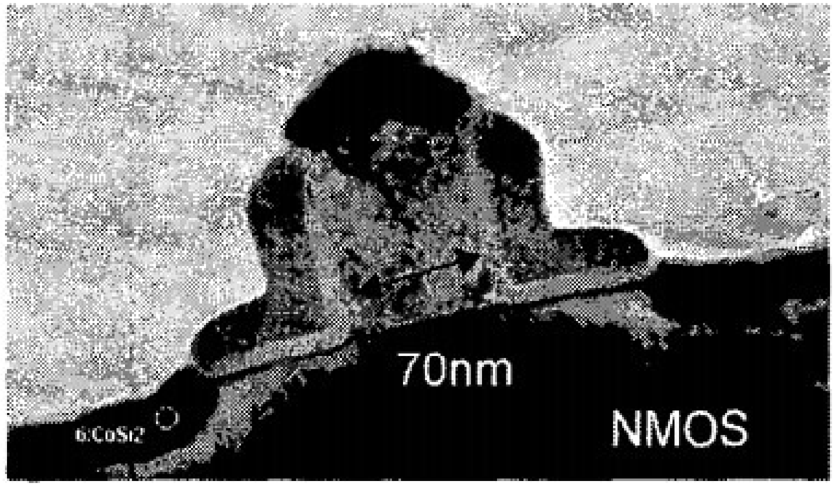
  - Moreover, power dissipation per circuit, which is proportional to VI, is reduced by κ^2.

Chronicles

- Intel and TSMC. IEDM and VLSI papers
  - 130nm: 2000 (Intel, IEDM)
  - 90nm: 2003 (Intel, IEDM)
  - 65nm: 2004 (Intel, IEDM)
  - 45nm: 2007 (Intel, IEDM)
  - 32nm: 2008 (Intel, IEDM)
  - 22nm: 2012 (Intel, VLSI)
  - 16nm: 2013 (TSMC, IEDM), 14nm: 2014 (Intel, IEDM)
  - 10nm: 2016 (TSMC, IEDM)
  - 7nm: 2016 (TSMC, IEDM)
  - 5nm: 2019 (TSMC, IEDM)
  - 3nm: 2022 (TSMC, IEDM)
  - 2nm: 2024 (TSMC, IEDM)

Prehistoric(?) MOSFET

- 130-nm MOSFET
  - Major issue: Cu interconnection (Previously, Al)
  - Operation voltage: 1.3 V
  - Oxide thickness: 1.5 nm
  - Poly-silicon gate



SUMMARY OF TRANSISTOR CHARACTERISTICS

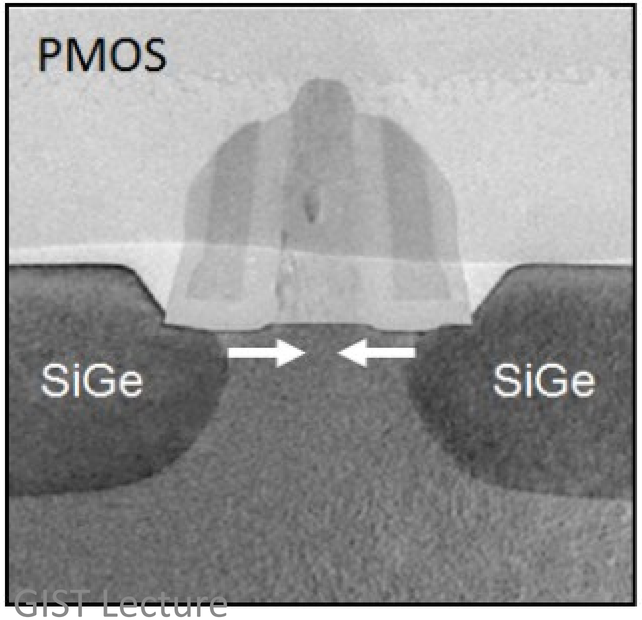
Parameter		180 nm Generation [1]	This Work
V_{DD}	[V]	1.5	1.3
L_{GATE}	[nm]	130	70
T_{OX}	[nm]	2.0	1.5
I_{OFF}	[nA/μm]	3	10
I_{DSAT}(n)	[mA/μm]	1.04	1.02
I_{DSAT} (p)	[mA/μm]	0.46	0.5
Low Vt I_{OFF}	[nA/μm]	-	100
Low Vt I_{DSAT}(n)	[mA/μm]	-	1.17
Low Vt I_{DSAT} (p)	[mA/μm]	-	0.6

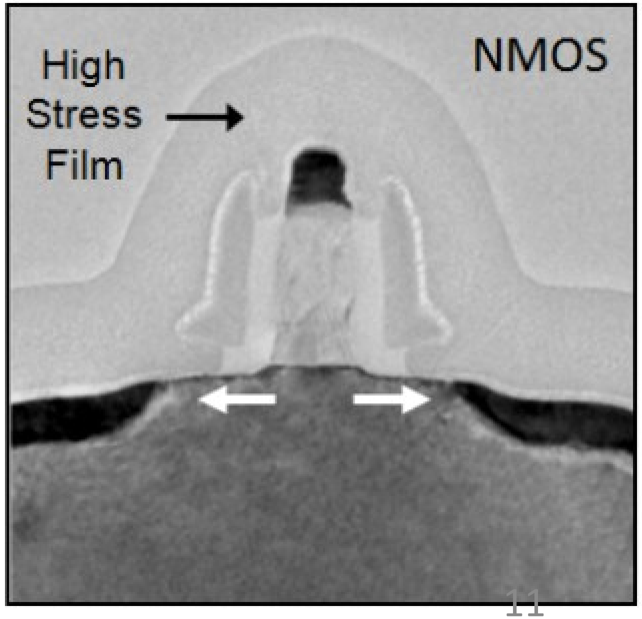
Running out of steam

- In the early 2000s. Why?
  - Due to leakage limitations!
  - The SiO_2 gate oxide had scaled to ~1.2 nm at the 90 nm generation. ➔ The gate oxide leakage was increasing exponentially and had become a noticeable percentage of total chip power.
  - Deceasing supply voltage ➔ decreasing threshold voltage ➔ ever-higher subthreshold leakage current
- Increasing transistor leakage
  - Was against the market preferences.
  - The 1980s and 1990s were the era of the home PC.
  - The 2000s was the "mobile" era.

90-nm node

- Oxide thickness: 1.2nm ($\times$ 0.8 scaling, not $\times$ 0.7)
  - SiGe was selectively deposited in PMOS source-drain regions to provide compressive channel strain.
  - A tensile SiN cap layer was deposited over NMOS transistors to provide tensile channel strain.

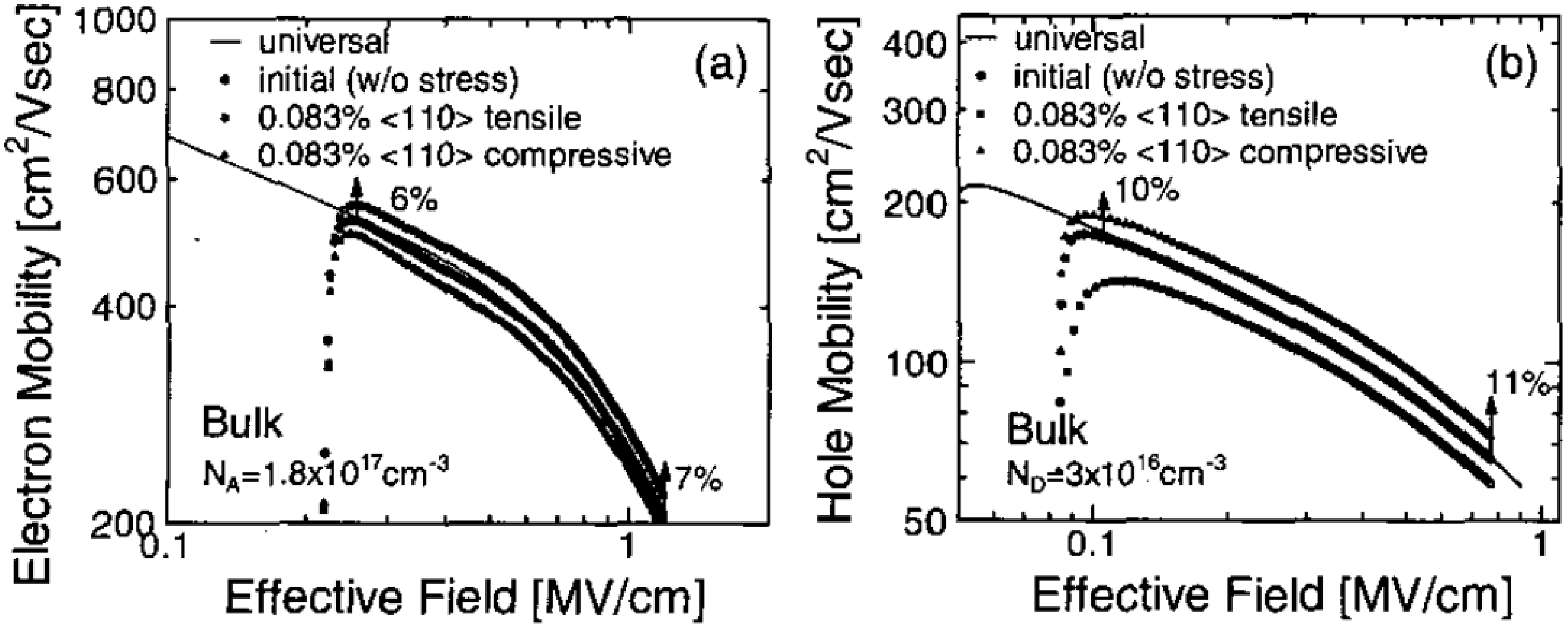




90nm uniaxial strained silicon transistors

Impact of stress engineering

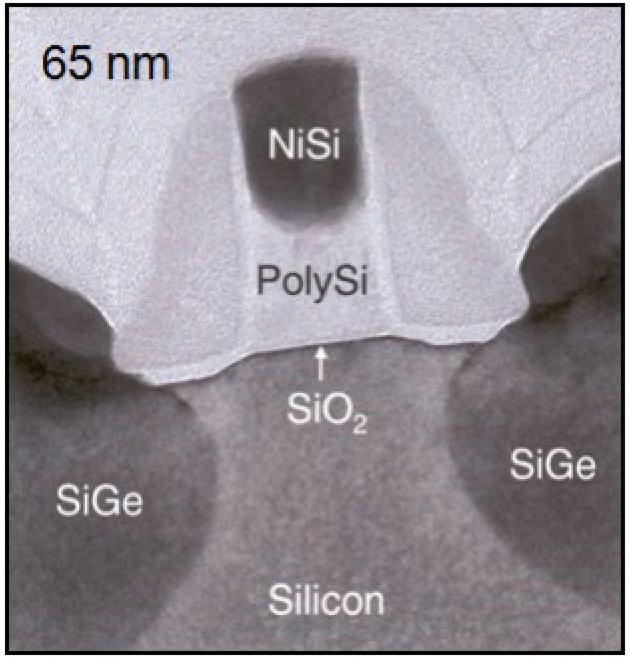
- Mobility enhancement
  - For electrons, tensile strain. For holes, compressive strain



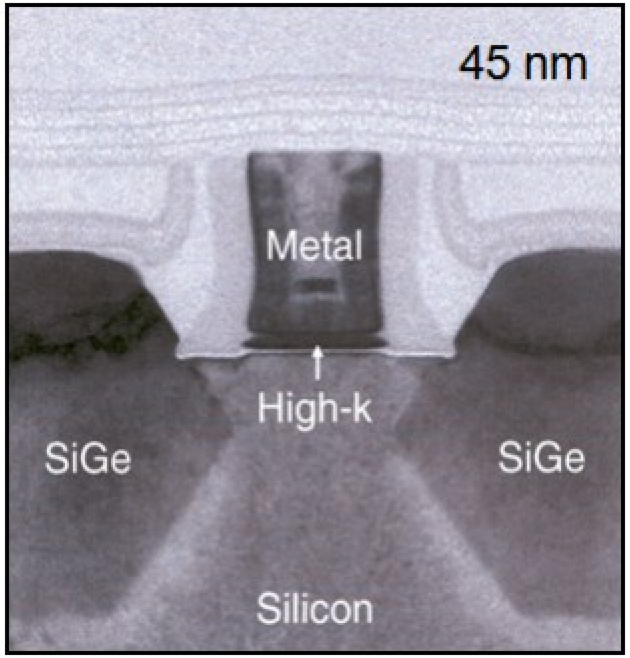
Mobility characteristics under <110> uniaxial strain (K. Uchida, IEDM 2004)

“High-k + metal” gate

- We need to scale the “effective” oxide thickness.
  - Keeping the physical thickness & increasing the oxide capacitance
- Poly depletion effect is now removed.



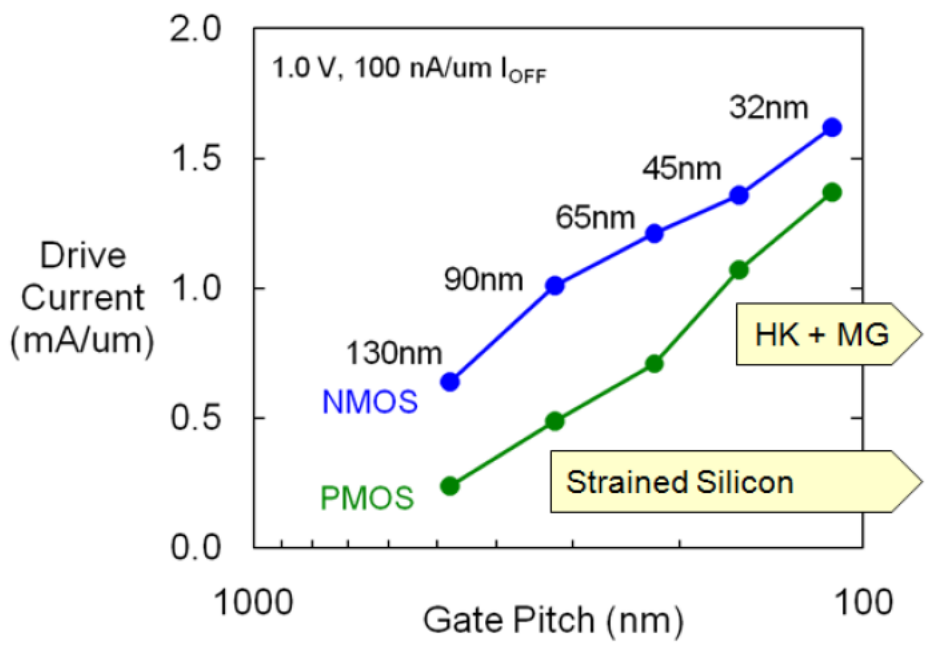
65nm

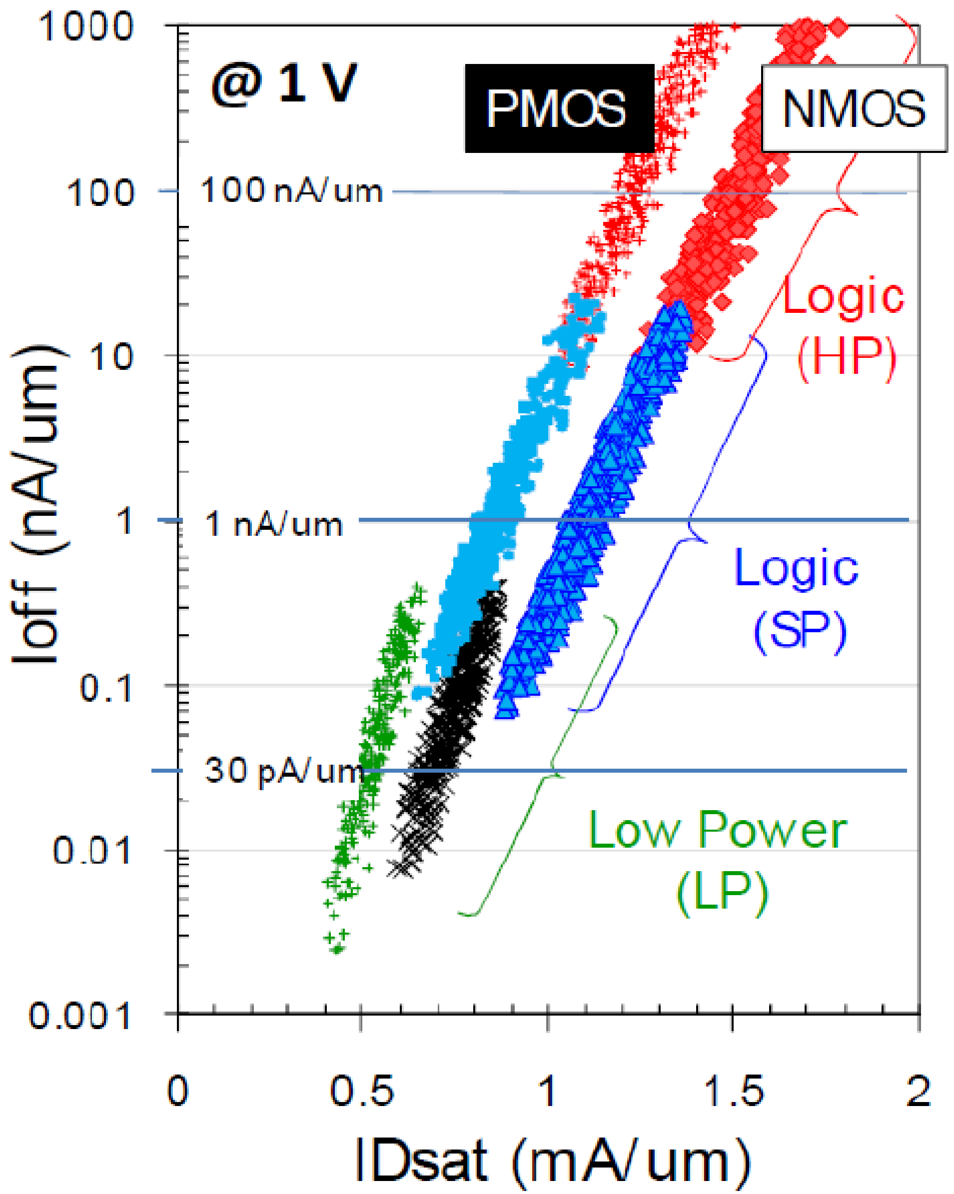


45nm (high-k metal gate)

Performance

- Drive current improvement
  - Strain engineering
  - High-k + metal gate

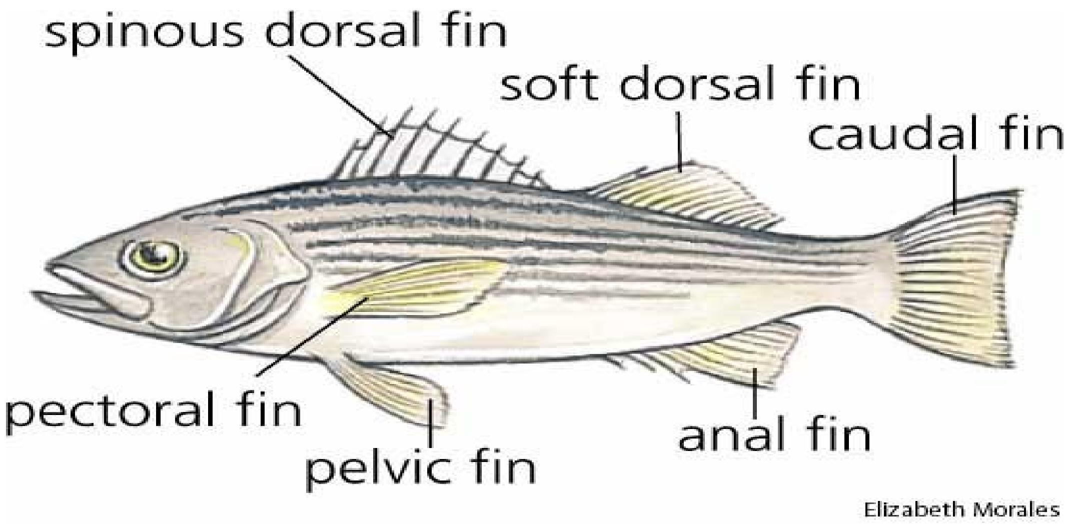




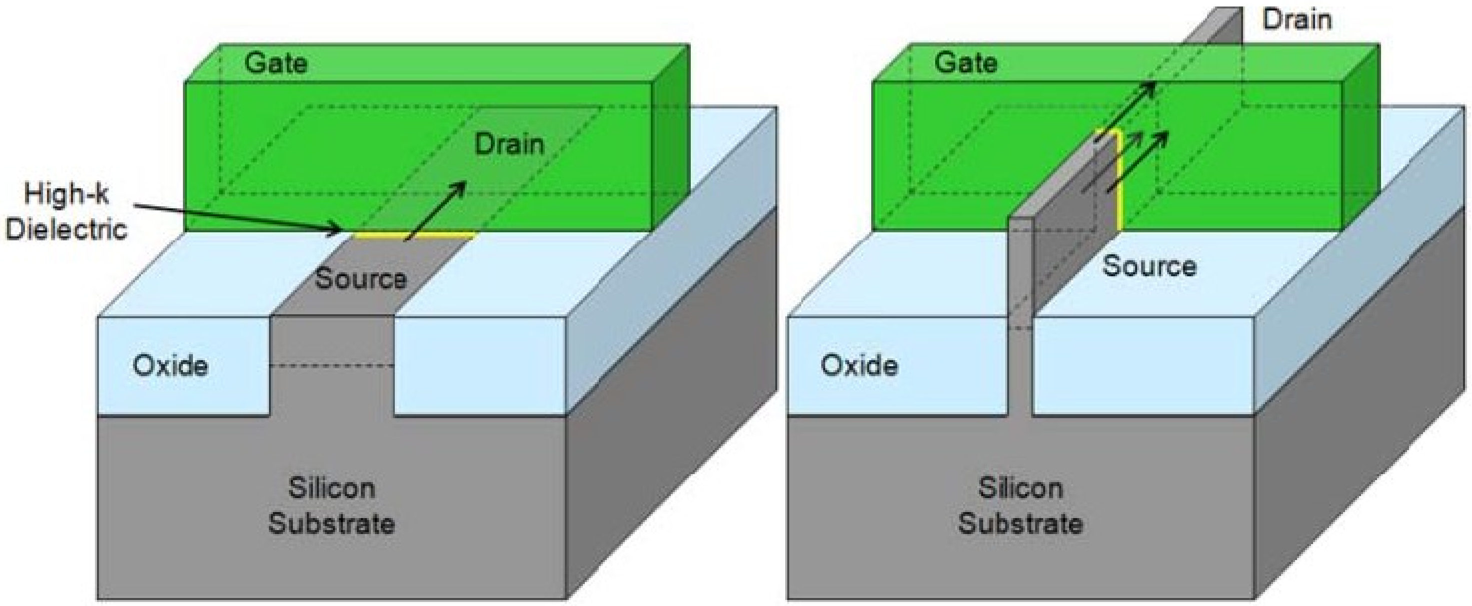
32nm transistor performance and leakage options

FinFET

- FinFET
  - Following its shape
  - Initially proposed as a SOI FinFET
  - Later, a bulk FinFET



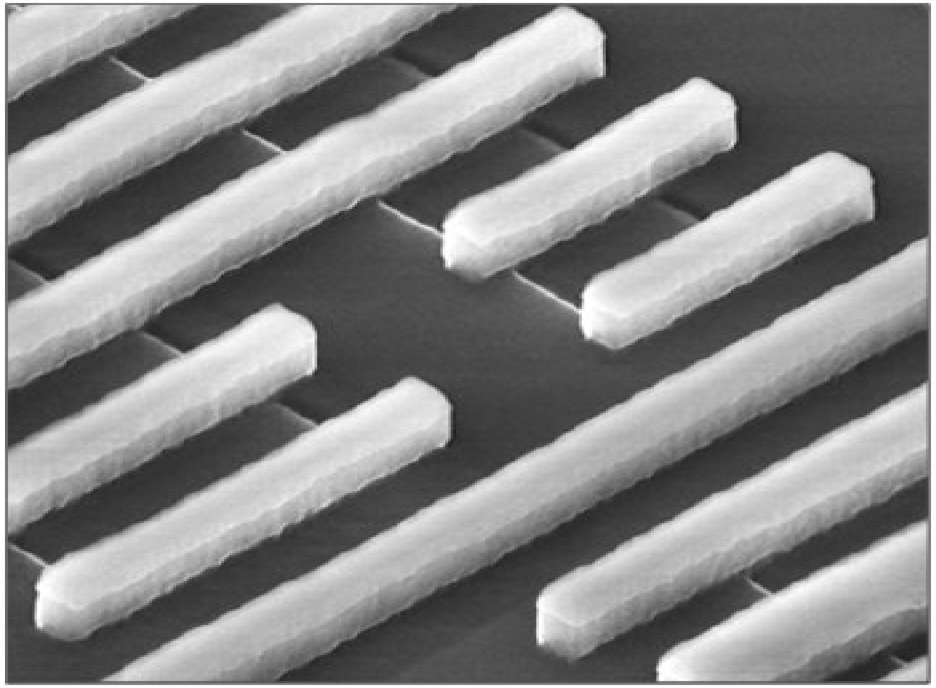
Fins (Google images)

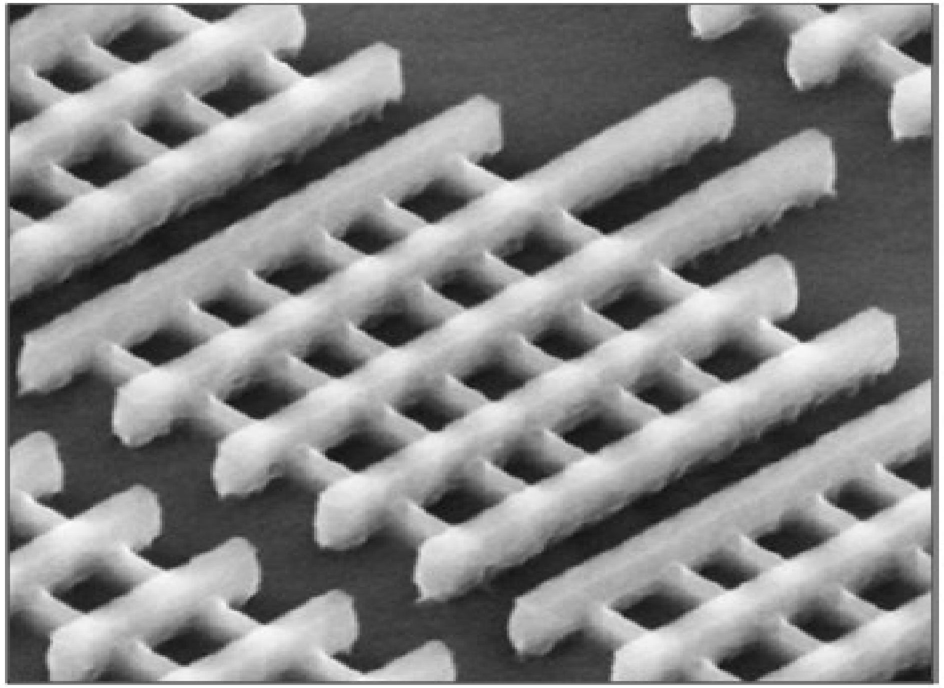


Planar transistor structure (left) and FinFET structure (right)

SEM image

- FinFET
  - Improved electrostatic control of the channel region

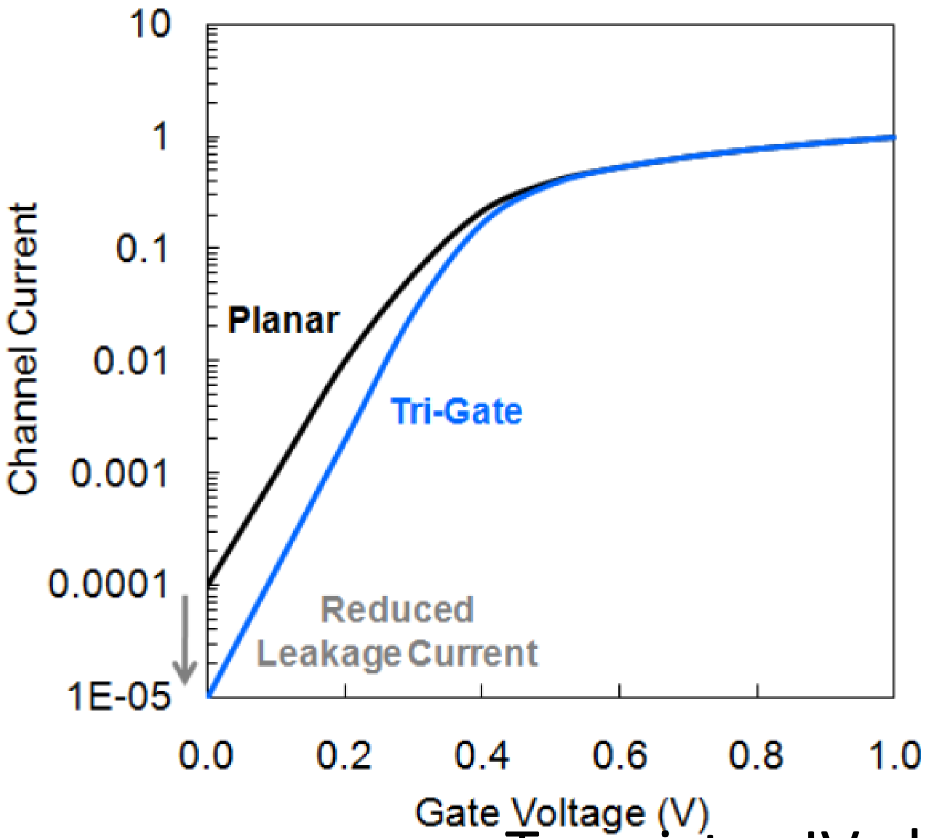


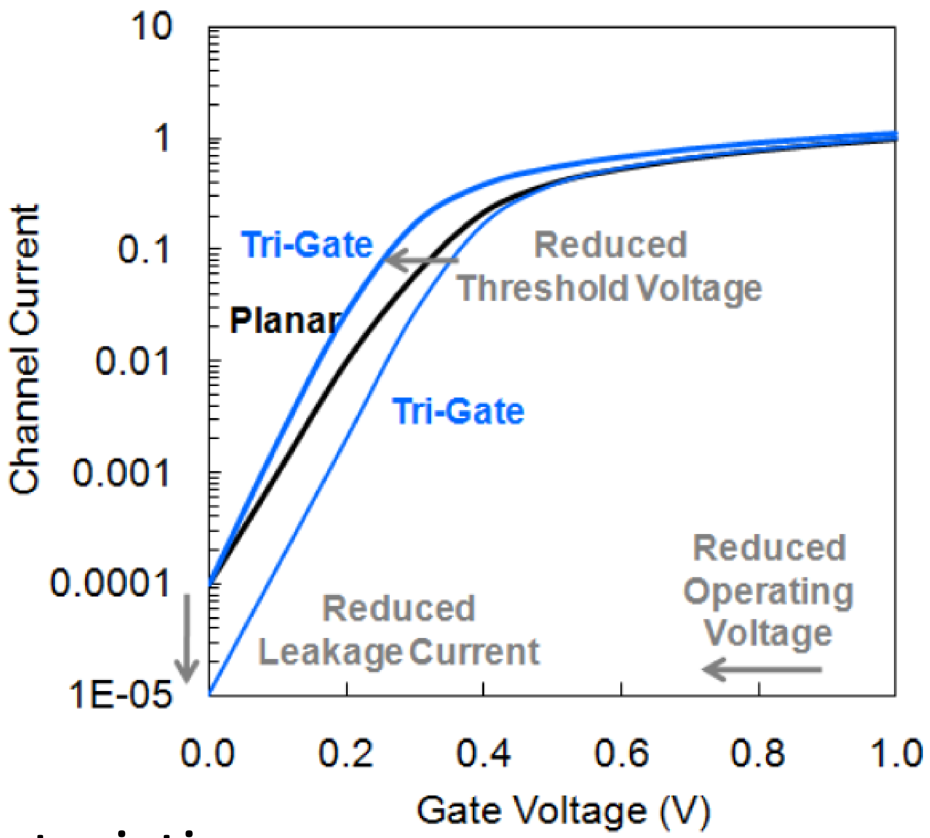


32nm planar transistors (left) and 22nm FinFETs (right)

Performance

- Steeper sub-threshold slope
  - $\times$ 10 off-state leakage reduction

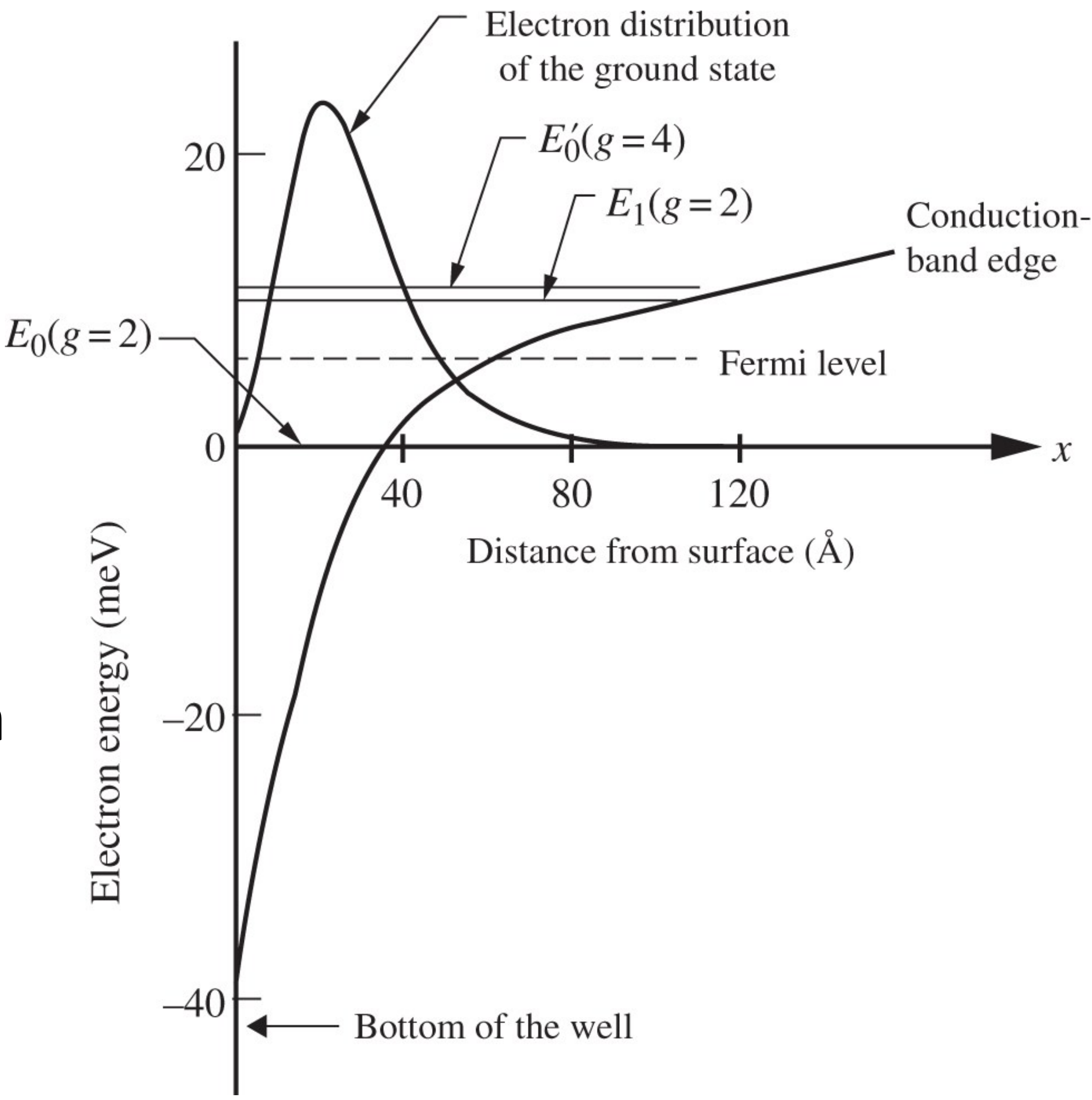




Transistor IV characteristics

Quantum effect

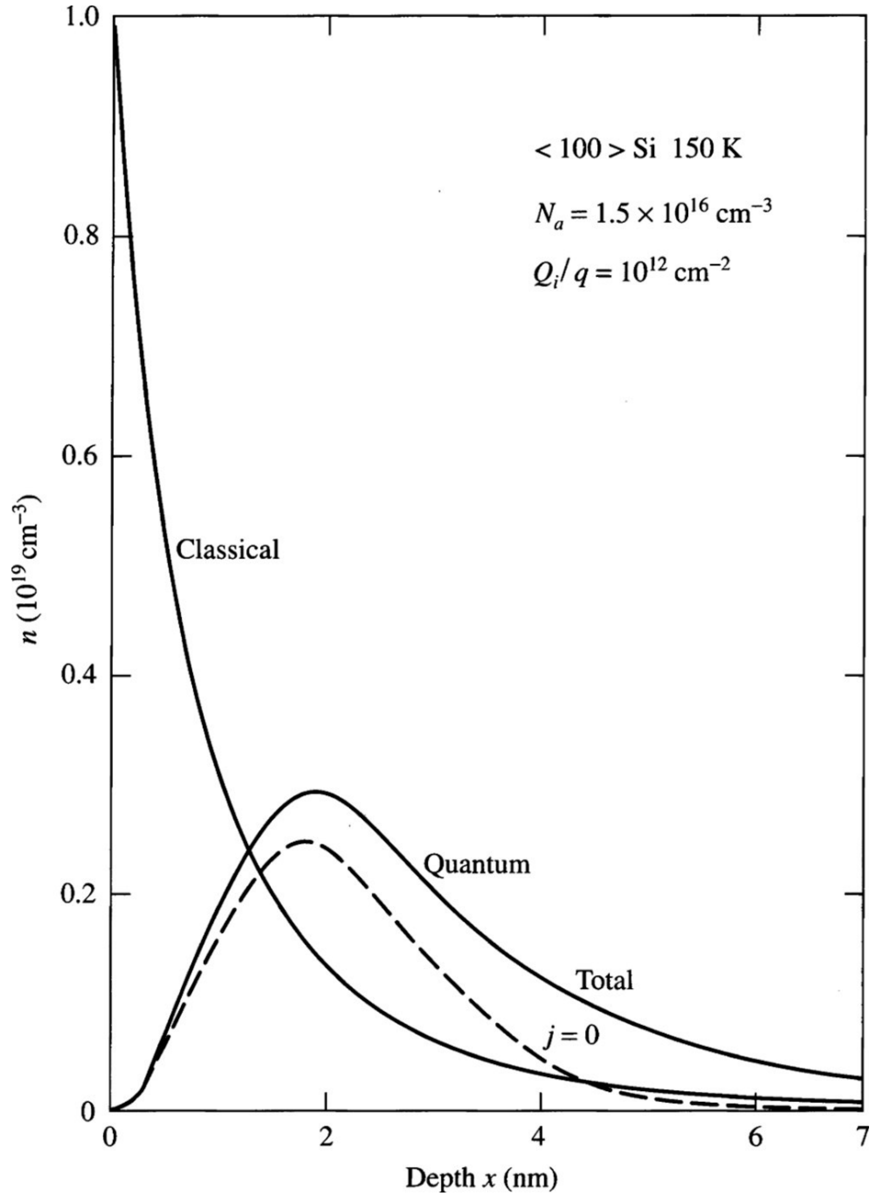
- Potential well formed by
  - The oxide barrier
  - The silicon conduction band
- Subbands
  - Quantized levels
  - Solutions of the Schrödinger equation
- Nearly zero n at the interface



Energy levels of inversion-layer electrons (Taur, Fig. 4.18)

Electron profile

- Classical vs. quantum-mechanical
  - Maximum n at the interface
- Quantum mechanical effects
  - At high fields, V_t becomes higher.
  - Effective gate oxide thickness is larger.



Classical and quantum-mechanical electron density (Taur, Fig. 4.19)5

Poisson-Schrödinger solver

- General way to calculate the subband structure
  - It requires numerical analysis…
  - Interested? Watch my YouTube videos. (They are recorded in Korean.)

Triangular potential approximation

- Parabolic potential profile
  - However, it is further approximated as a linear potential. ➔ Triangular potential well
  - Then, the Schrödinger equation reads

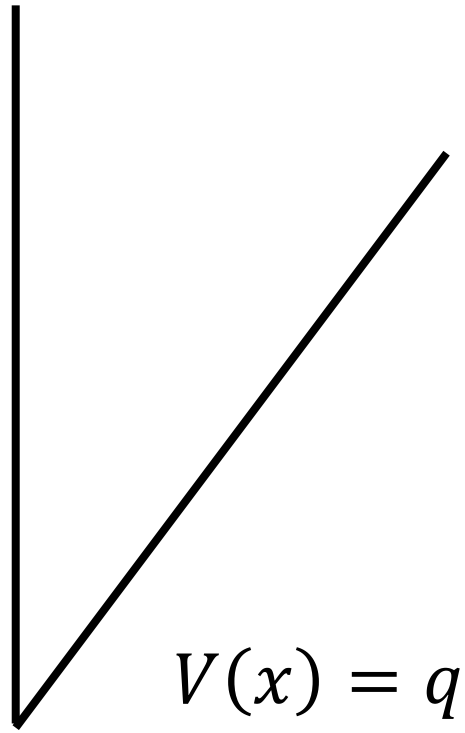
$$\left[-\frac{\hbar^2}{2m_{xx}}\frac{d^2}{dx^2}+q\mathcal{E}_s x\right]\psi(x)=E\psi(x)$$

  - Airy function

$$Ai(x)=\frac{1}{\pi}\int_0^\infty \cos\left(\frac{t^3}{3}+xt\right)dt$$

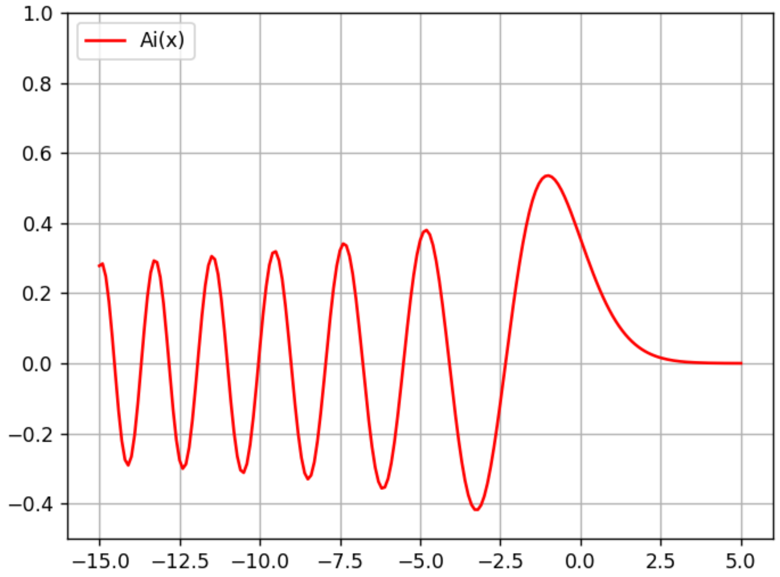
  - Its seond derivative is

$$\frac{d^2}{dx^2}Ai(x)=$$



$V(x)=q\mathcal{E}_s x$

Its solution



- Airy function

$$Ai(x) = \frac{1}{\pi}\int_0^\infty \cos\left(\frac{t^3}{3} + xt\right) dt$$

- Its seond derivative is

$$\frac{d^2}{dx^2}Ai(x) = -\frac{1}{\pi}\int_0^\infty t^2 \cos\left(\frac{t^3}{3} + xt\right) dt$$

- Note that $\frac{d}{dt}\sin\left(\frac{t^3}{3} + xt\right) = (t^2 + x)\cos\left(\frac{t^3}{3} + xt\right)$.
- Therefore,

$$-xAi(x) + \frac{d^2}{dx^2}Ai(x) = -\frac{1}{\pi}\int_0^{\infty} \frac{d}{dt}\sin\left(\frac{t^3}{3} + xt\right) dt = 0$$

Simple manipulation

$$\frac{2m_{xx}}{\hbar^2}q\mathcal{E}_s$$

- The Schrödinger equation is written as

$$\left[\frac{d^2}{dx^2}-\frac{2m_{xx}}{\hbar^2}(q\mathcal{E}_s x-E)\right]\psi=\left[\frac{d^2}{dx^2}-\alpha^3\left(x-\frac{1}{q\mathcal{E}_s}E\right)\right]\psi=0$$

  - With a new variable, $\xi=\alpha\left(x-\frac{1}{q\mathcal{E}_s}E\right)$, it becomes

$$\left[\frac{d^2}{d\xi^2}-\xi\right]\psi=0$$

  - The solution is $\psi(x)\sim Ai(\xi)=Ai\left(\alpha\left(x-\frac{1}{q\mathcal{E}_s}E\right)\right)$.
  - At $x=0$, the wavefunction must vanish:

$$-\alpha\frac{1}{q\mathcal{E}_s}E_j=a_j$$

Zeros of the Airy function

$$a_0\approx-2.3381$$
$$a_1\approx-4.0879$$

Eigenenergy

- Zeros are well approximated as $a_j \approx -\left[\frac{3\pi}{2}\left(j+\frac{3}{4}\right)\right]^{2/3}$.
  - Then, the eigenenergy becomes
$$E_j = \frac{q\mathcal{E}_s}{\alpha}\left[\frac{3\pi}{2}\left(j+\frac{3}{4}\right)\right]^{2/3} = \left[\frac{3hq\mathcal{E}_s}{4\sqrt{2m_{xx}}}\left(j+\frac{3}{4}\right)\right]^{2/3}$$
Taur, Eq. (4.46)
  - There are two different m_{xx} values: $0.91m_0$ (degeneracy of 2) and $0.19m_0$ (degeneracy of 4)

Thank you!