The role of Physics in technology Development

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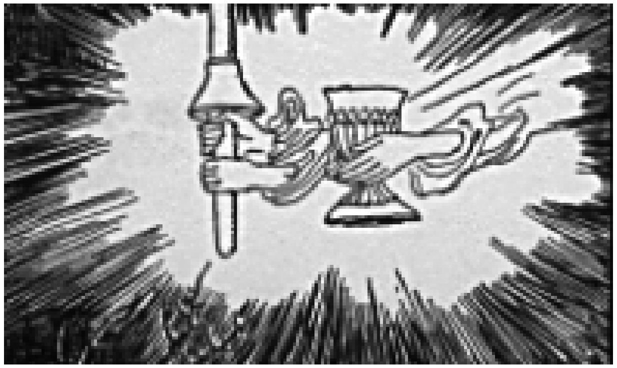
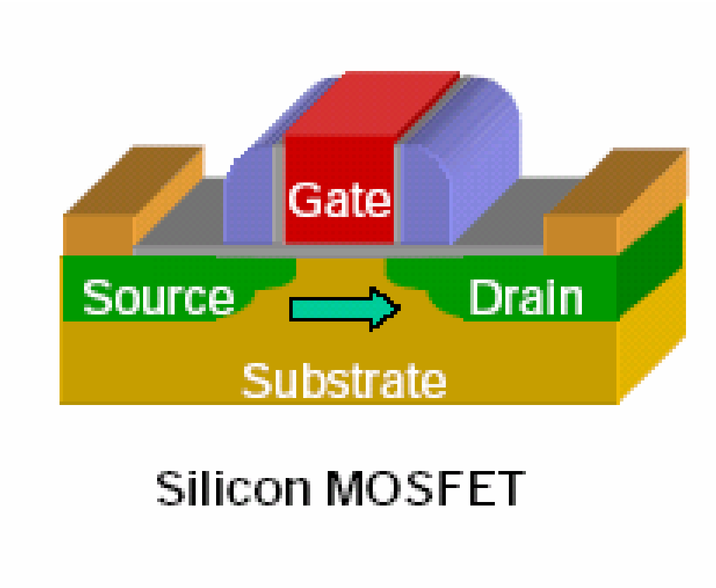
A physicist in the Semiconductor Industry

Field Effect Transistor



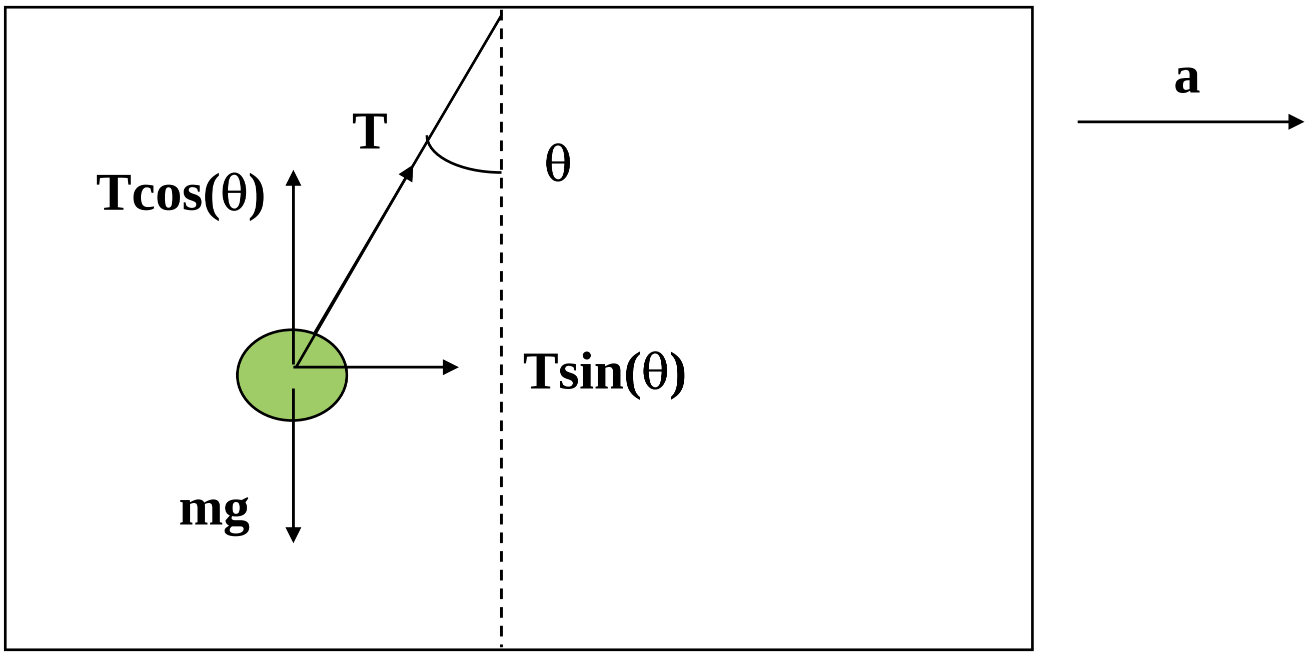


So pass I hostel, hall, and grange;
By bridge and ford, by park and pale,
All-arm'd I ride, whate'er betide,
Until I find the holy Grail.

ALFRED, LORD TENNYSON

Physics Saves Lives!!!

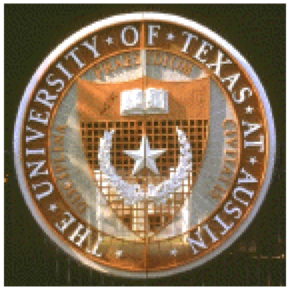
Physics: Second Newton's Law in action



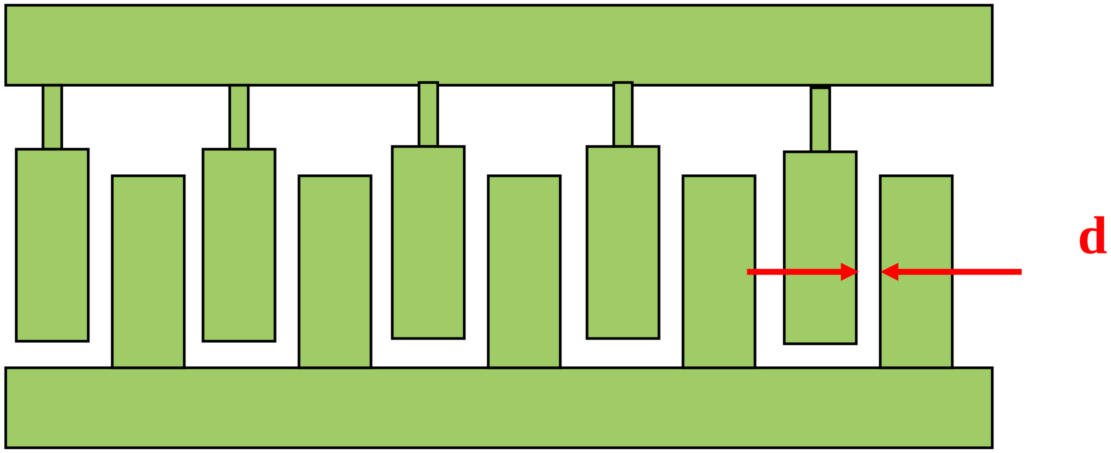
- **Vertically: $T\cos(\theta)-mg=ma_y=0$**
- **Horizontally: $T\sin(\theta)=ma_x$**

$g\tan(\theta)=a_x$

This is an accelerometer!

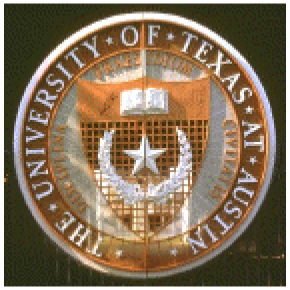


Practical design: Sensing



How can I measure this distance d (angle) accurately and inexpensively?

Well, it sort of looks like a capacitor….



Measurement:

$$C = \frac{8.85\times10^{-12} \times DC \times A}{D}$$

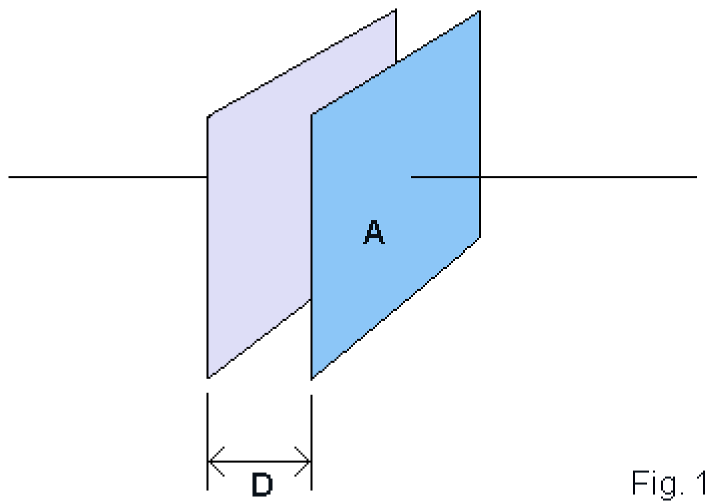


Fig. 1

The capacitance value of a two plate cap is calculated as follows:-

C=Q/V the amount of charge you can store at a given voltage

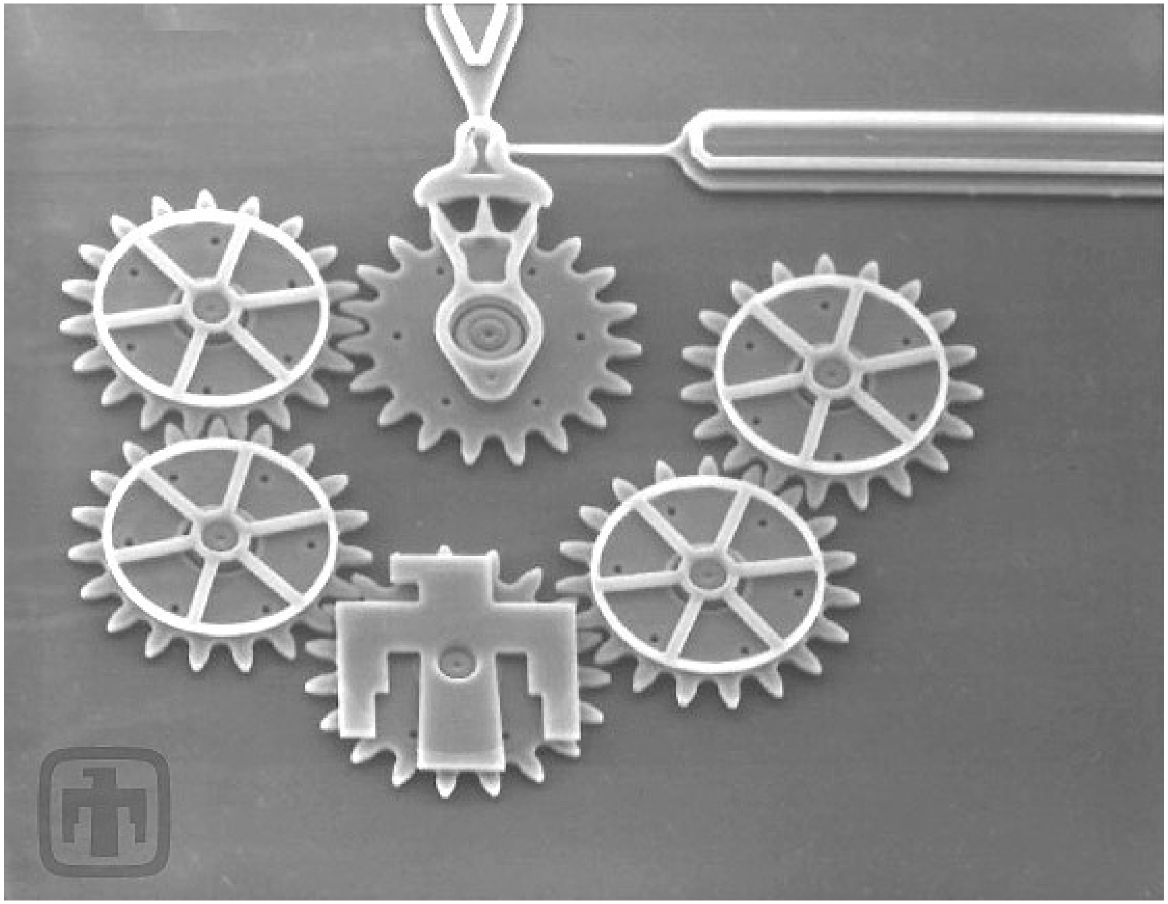
C = capacitance in Farads

DC = dielectric constant

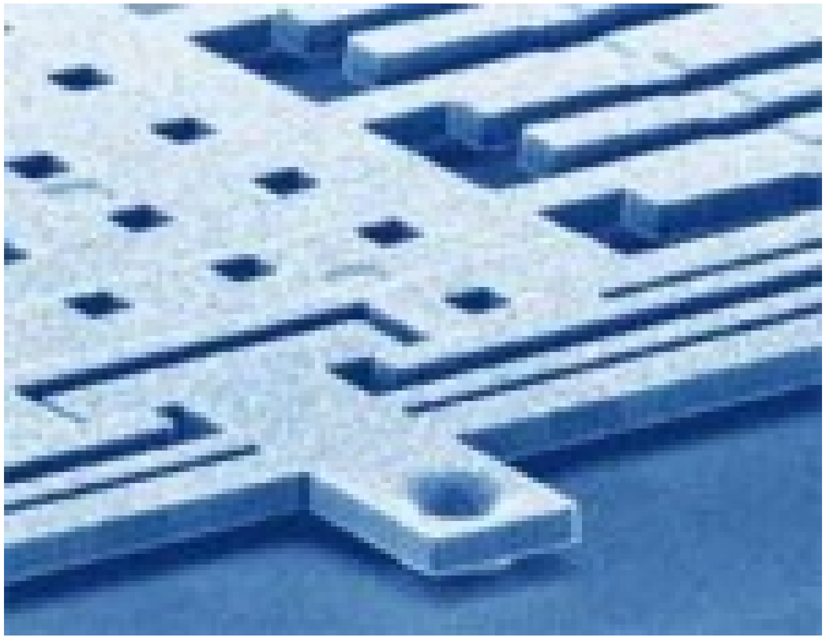
A = overlapping plate area in square meters

D = distance between plates in meters

Technology: MEMS (micro electromechanical system)



MEMS accelerometer

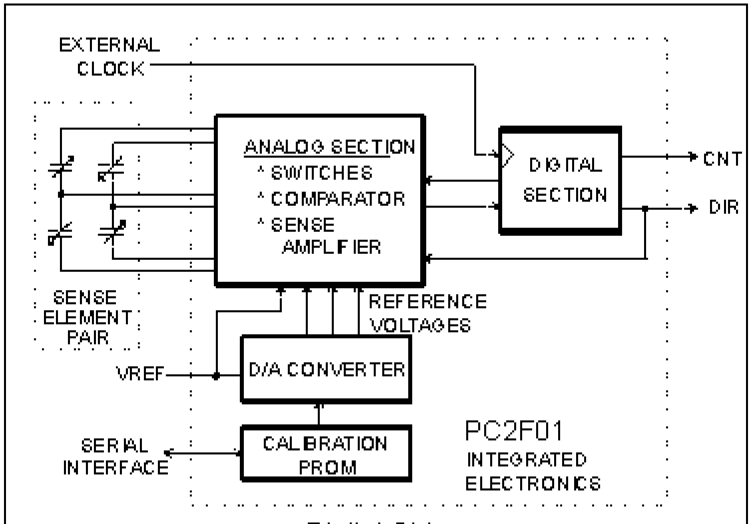


	characteristic	value		
beam:	proof mass	0.1	µg	
	length	280	µm	
	thickness	2	µm	
	suspension height	1.6	µm	
	resonant frequency	10-22	kHz	
plates:	length	38	µm	
	separation	1.3	µm	
	minimum detectable displacement	0.02	nm	
capacitance:	total	100	fF	per plate
	minimum detectable change	0.02	fF	per plate
	maximum change	10	fF	per plate
acceleration:	measurable range	±5	g	
	minimum detectable change	0.002	g	
	maximum shock	1000	g	

Source: Analog Devices

micrometer (µm)* 10^{-6} m
Also called the micron (µ)

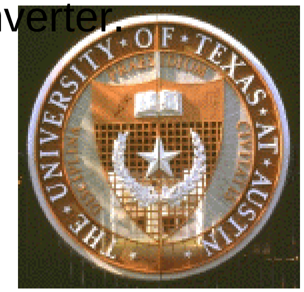
Communication: ASIC (application specific integrated circuit)



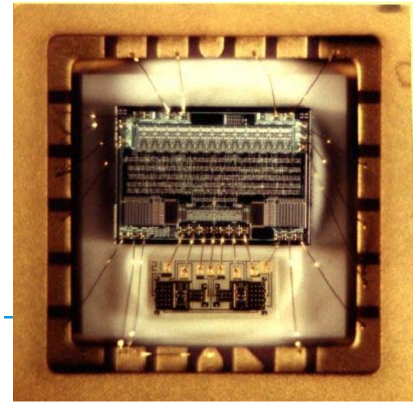
Digital Chip

Fabricated in a 2-micron **CMOS** process,
the digital ASIC functions as a sigma-delta type capacitance-to-frequency converter.

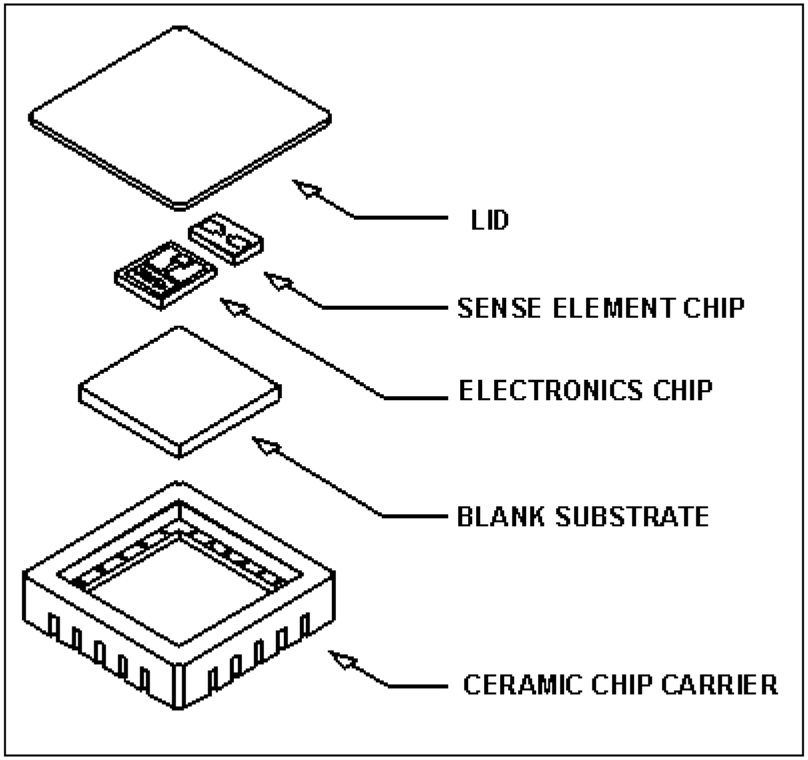
The ASIC modulates the capacitive sense element and monitors the effect of accelerations on the sense element via the sense amplifier.

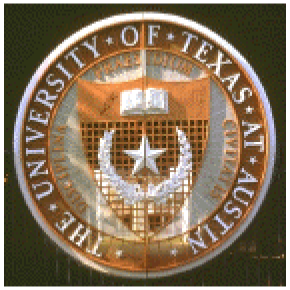


Product:



Accelerometer Packaging





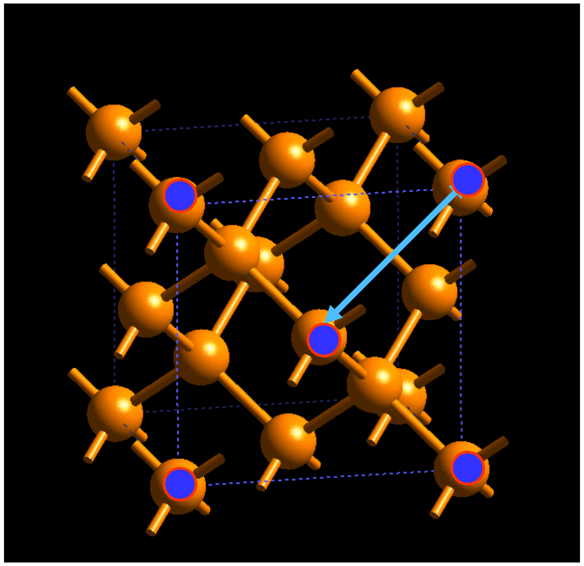
MEMS accelerometers are used ...

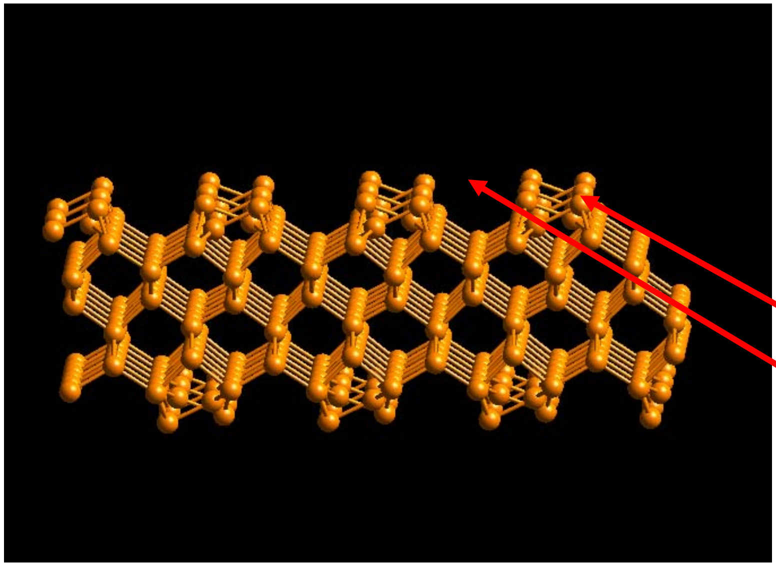
- to detect sudden automobile deceleration and then pretension seat belts or deploy air bags
- to determine velocity, position, and orientation for flight data recording systems
- to monitor vibrations in machines and detect unusual conditions or potential failure
- to detect forced entry and then activate an alarm (like a car alarm)
- to detect violent earthquakes and then shut off pipelines or water mains
- to measure inclination and warn of possible building collapse
- to analyze motion in professional and collegiate sports

The most important electronic material is Silicon

a_{Si}=5.43 Å

angstrom (Å)10^{-10} m

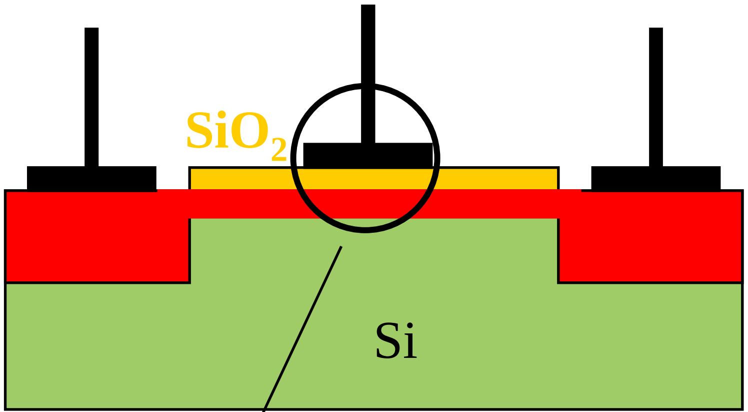




<u>Si (001) 2x1 reconstructed surface:</u>

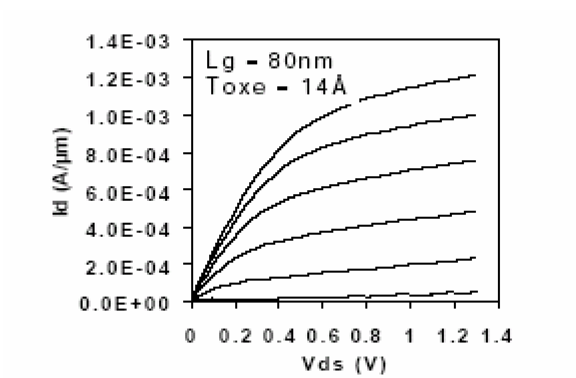
- **Dimer rows along (110)**
- **Troughs along (110)**
- **Surface energy 1710 erg/cm^2**

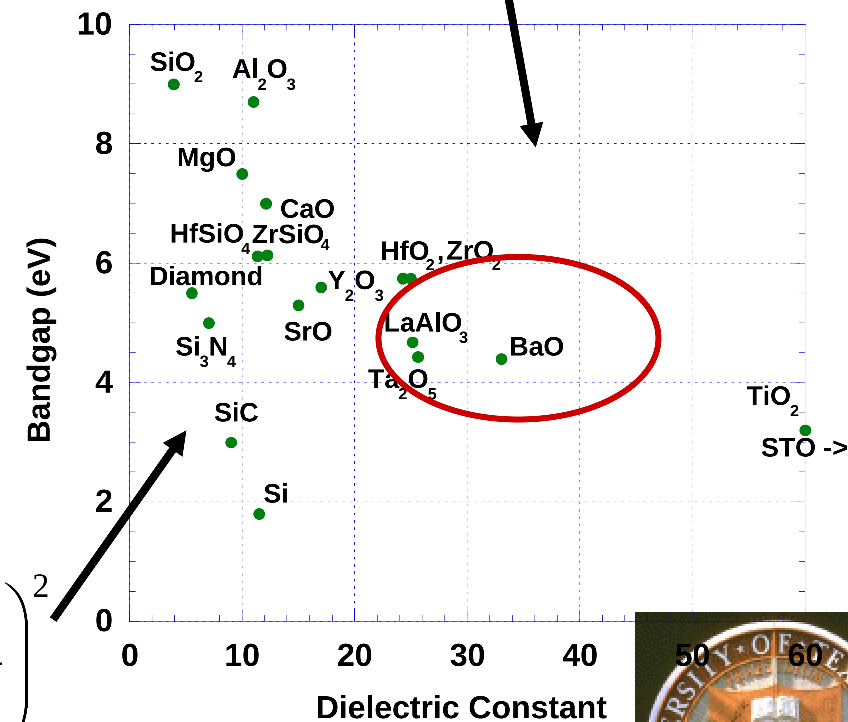
Complimentary Metal Oxide Semiconductor technology: FET



$$\alpha_{ij}(\omega) = \frac{1}{V}\sum_k (\omega_k^2 - \omega^2)^{-1} \times \left(\sum_l \frac{q_l \varpi_i^*(l,k)}{\sqrt{m_l}}\right)\left(\sum_{l'} \frac{q_{l'} \varpi_j^*(l',k)}{\sqrt{m_{l'}}}\right)$$

MOS capacitor: C=Aε/d



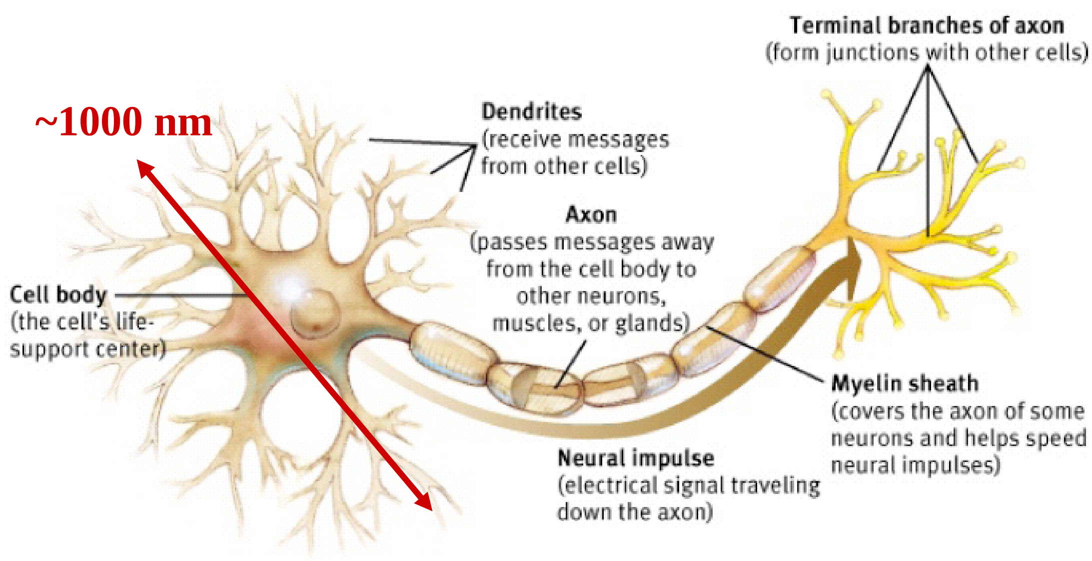


$$\varepsilon = 1 + \left(\frac{\hbar\omega_p}{E_{PG}}\right)^2$$

$I_{Dsat}=(Z\mu C/2L)(V_G-V_T)^2$

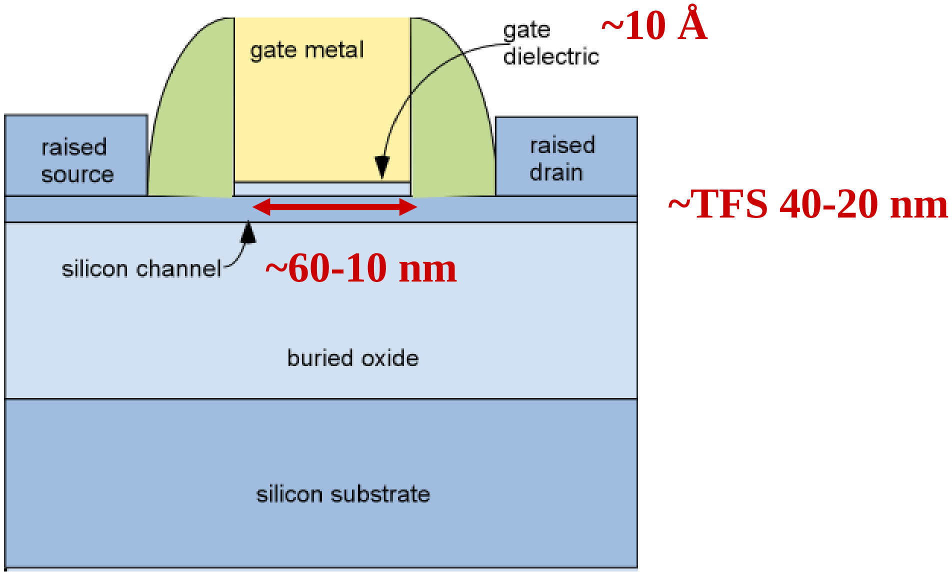
A.A. Demkov, *phys. stat. sol. (b)* 226, 57 (2001).

Advanced CMOS



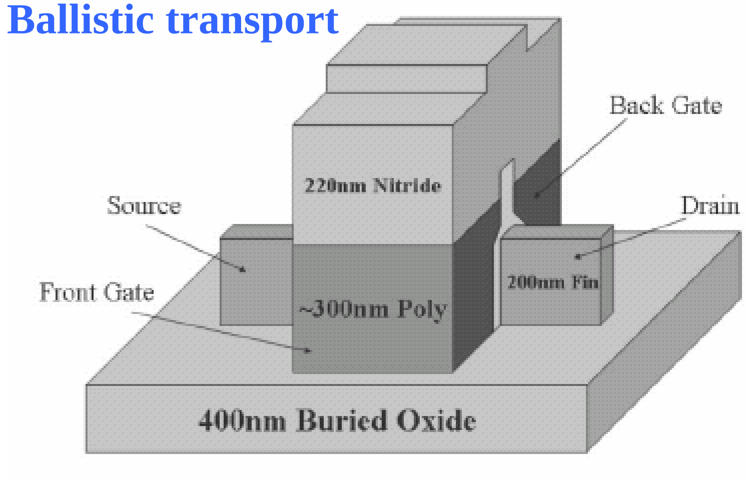
SOI

- Thin film Si (TFS)
- Novel gate dielectrics
- New channel orientation
- Novel gate metals
- Novel contact metals
- Novel S/D materials, strain
- New interfaces, diffusion, *etc.*

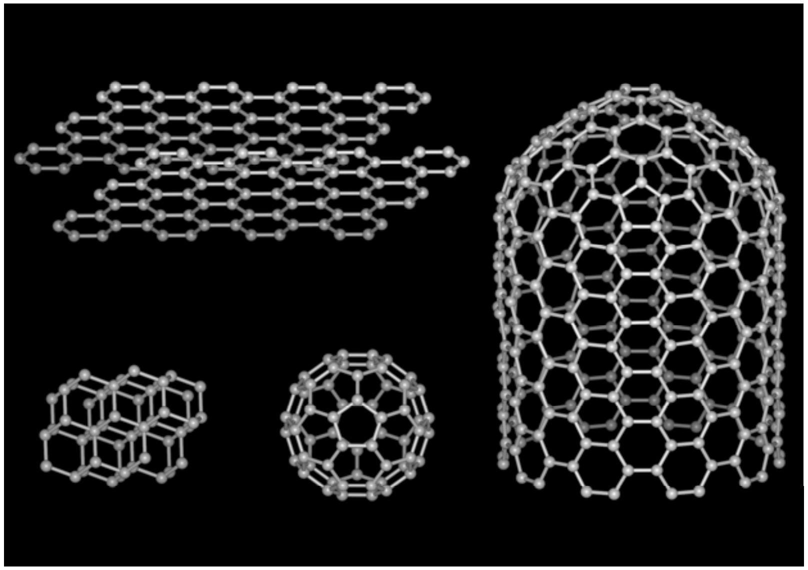


FinFET

- New channel orientation
- New Si-SiO_2 interface
- Ballistic transport



First principles DFT-LDA calculations



Starting atomic positions {R_i} and atomic numbers {Z_i}

Construct the Kohn-Sham effective Hamiltonian:

$$\left(\frac{p^2}{2m} + U_{eff}(\rho, R_i)\right)\varphi_i = \varepsilon_i \varphi_i$$

$$\rho = \sum_i \left|\phi_i^2\right|$$

$$\frac{\delta E}{\delta \rho} = 0$$

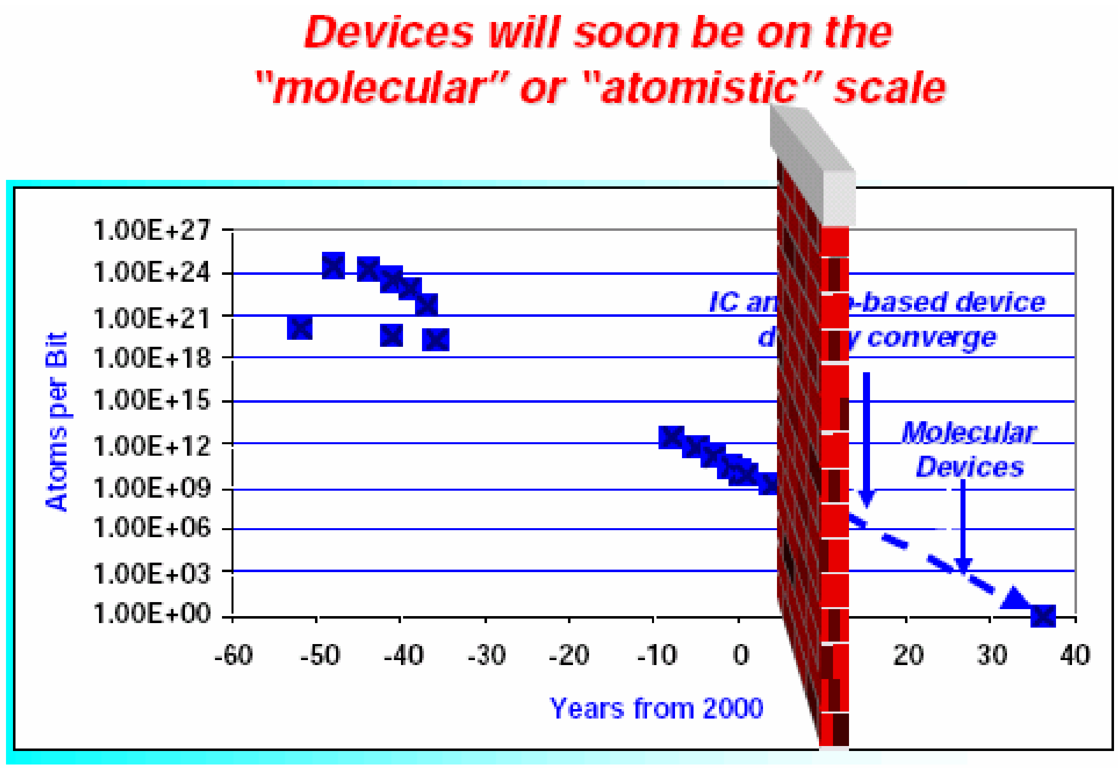
Find the self-consistent solution and get the total energy E(ρ) . From the total energy one can find forces acting on the atoms and optimize the structure; dynamical matrix can be calculated to find the phonon spectrum; etc.

$$F_i = -\frac{\partial E}{\partial R_i} \longrightarrow F_i = m_i \ddot{x}_i$$

Very often the Kohn-Sham electronic spectrum ε is used to analyze the electronic structure of the system. Though strictly speaking wrong, this is a very instructive exercise.

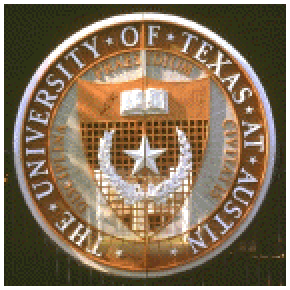
 A.A. Demkov, J. Ortega, M.P. Grumbach, and O.F. Sankey, Phys. Rev. B 52, 1618 (1995).

One man's brick wall is another man's …



Number of atoms a state of the art density functional theory code can deal with:

1985	**1990**	**1995**	**2000**	**2005+**
2	**>10**	**>50**	**1000**	**10,000**



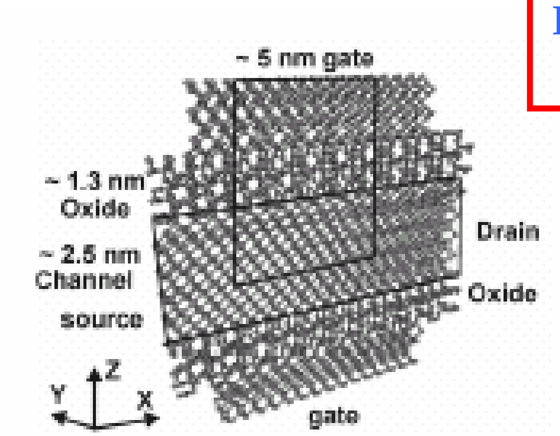
Traditional Device Modeling Flow

Process simulation
(diffusion, implantation, *etc.*)

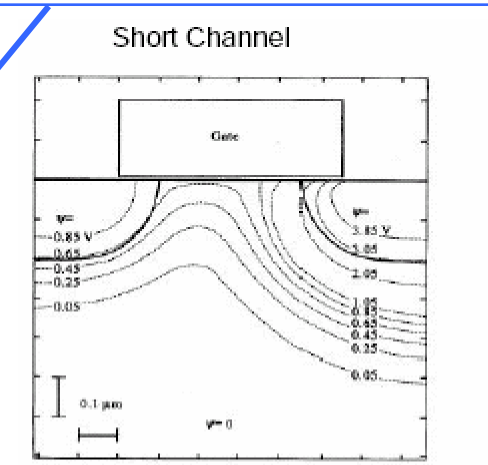
Windl et al.
Delarubia et al.
Beardmore et al. …

Si data (TEM, SIMS, EELS, IR/Raman, SE, etc.)

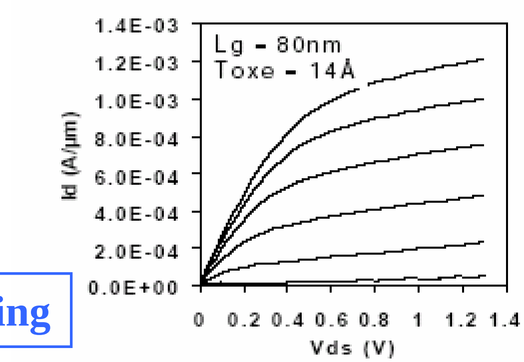
Tersoff et al.
Pantelides et al.
Dong et al.
Müller et al…



Device Structure
(drawn)



Device Performance
(I-V, C-V)



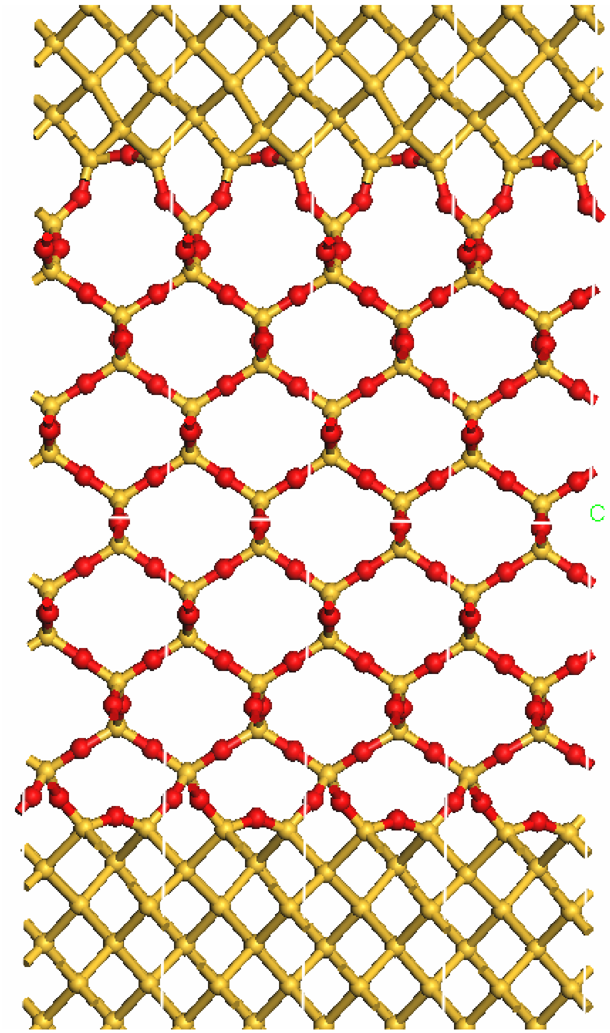
Lake et al.
Stockbro et al.
Staedle et al.
Datta et al..
…

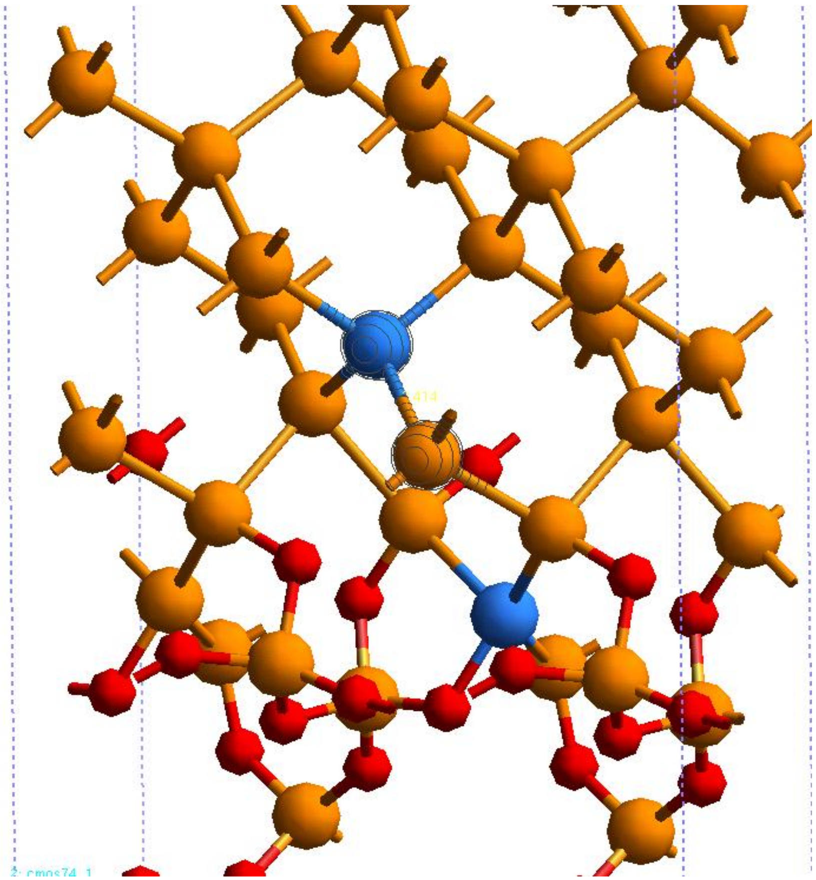
Circuit Level Modeling

System Level Modeling

Computational Materials

Si-SiO_2 interface

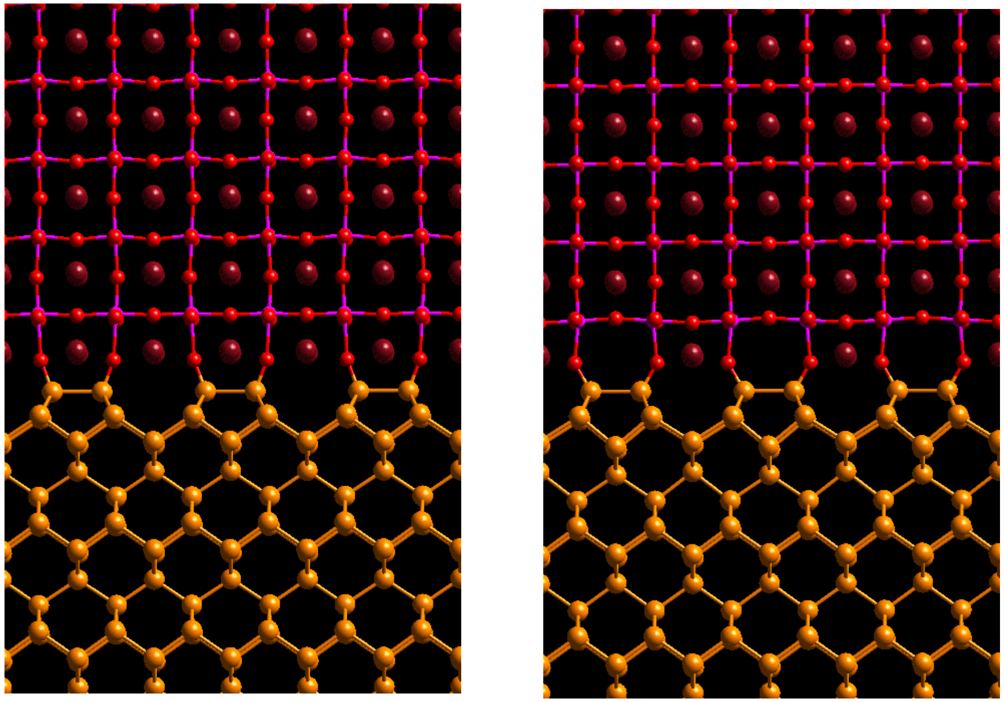




A.A. Demkov and O.F. Sankey, Phys. Rev. Lett. 83, 2038 (1999).

Si-$SrTiO_3$ Interface structure

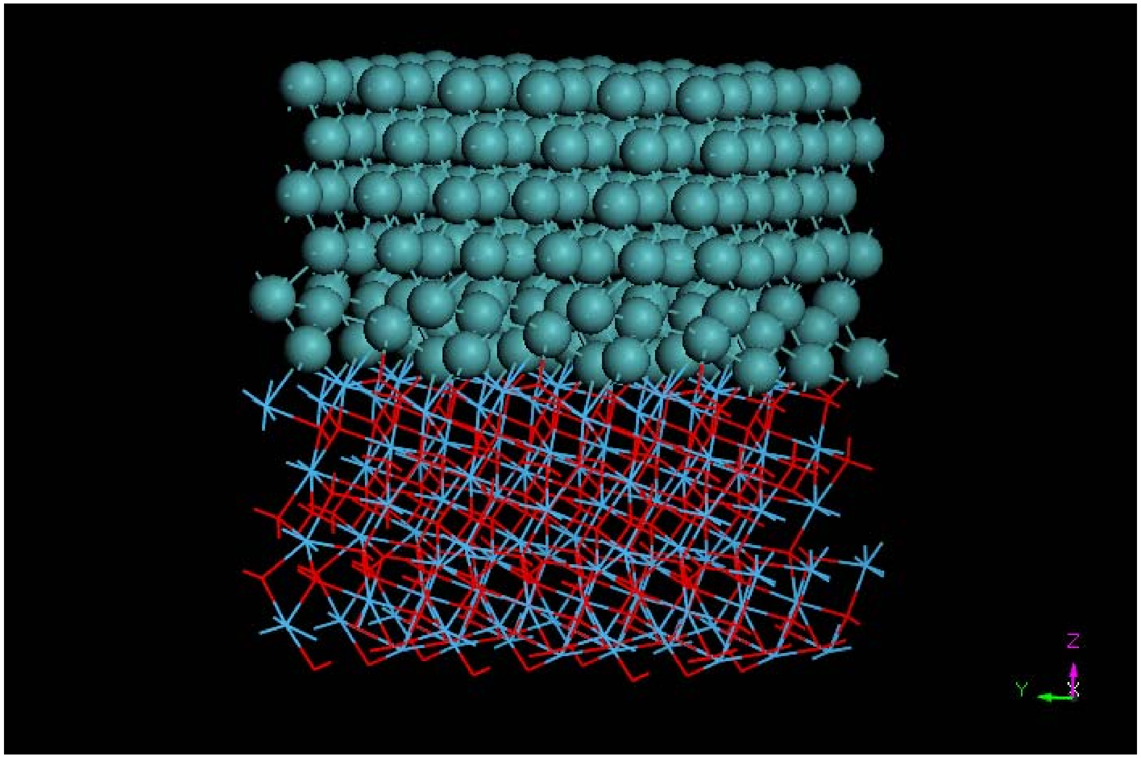
(a) (b)

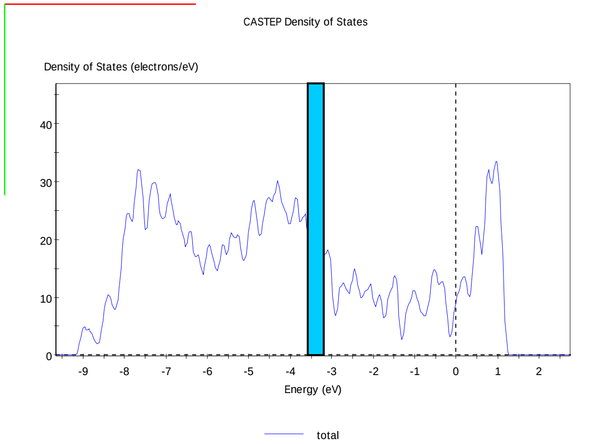


Both structures have 2x1 symmetry. Structure (a) has a full ML of Sr at the interface (1ML), structure (b) has a half ML of Sr at the interface (1/2 ML)

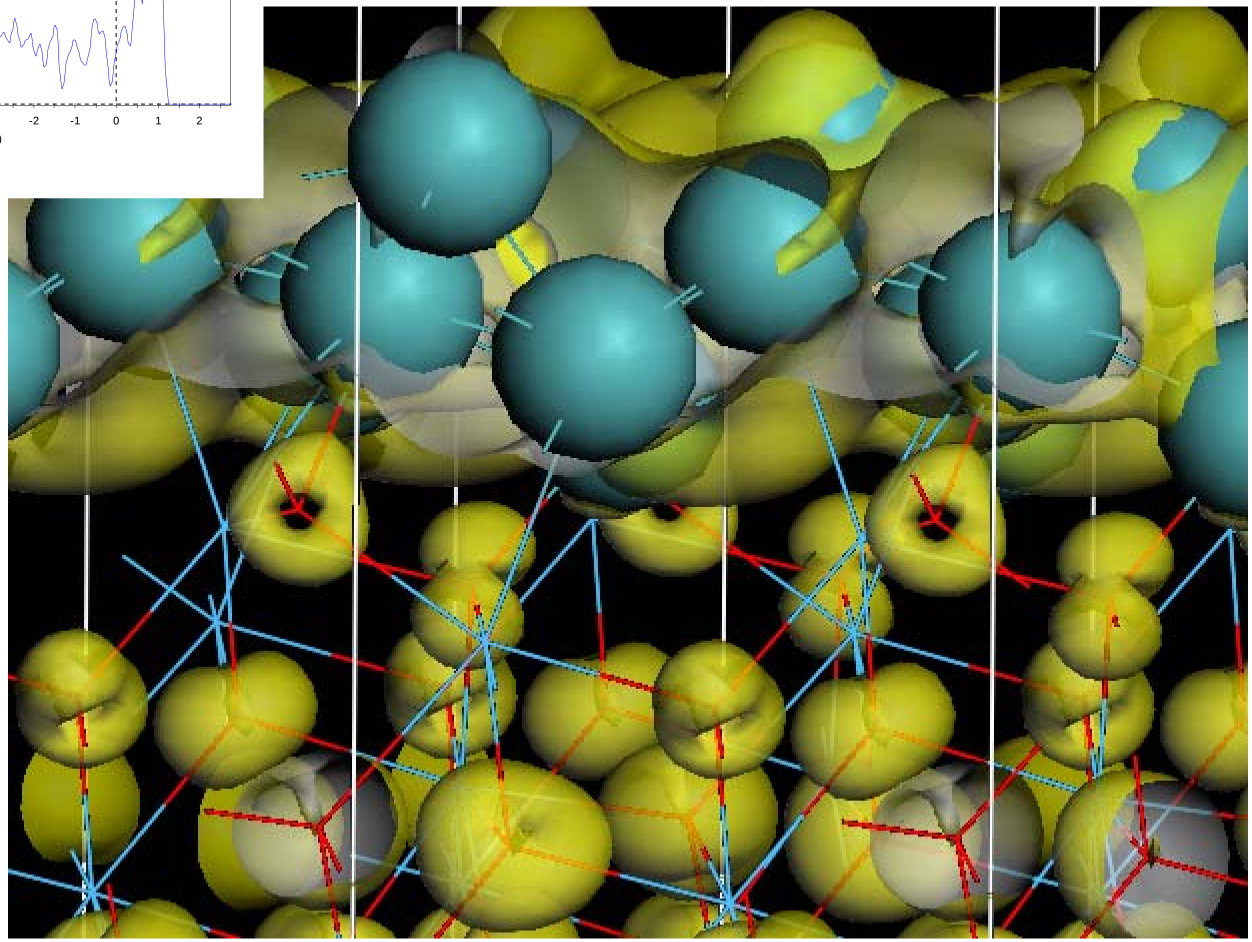
X. Zhang, A.A. Demkov, H. Li, X. Hu, Y. Wei, and J. Kulik, Phys. Rev. B 68, 125323 (2003).

A practical example: Mo (110) on t-HfO_2 (111)

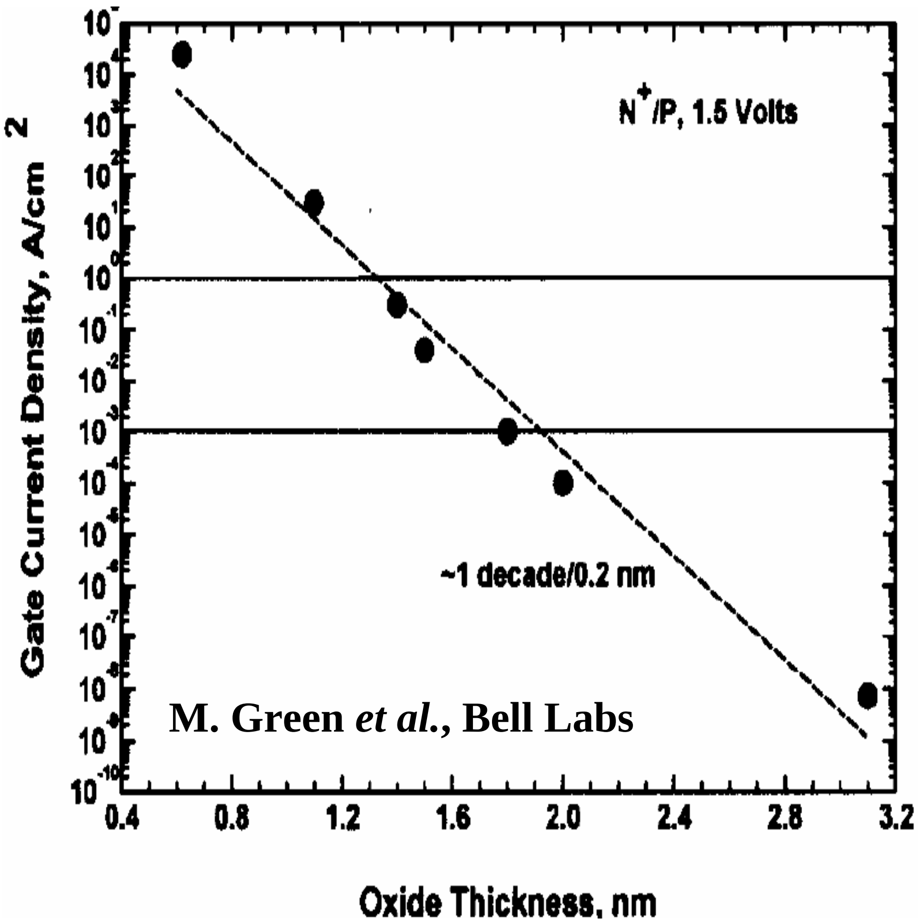




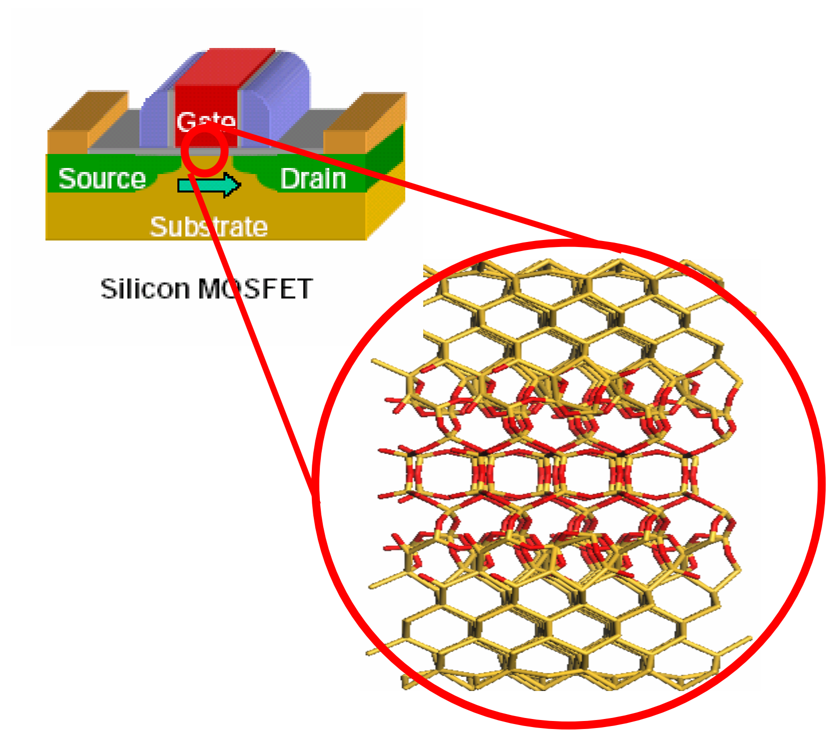
Where are all these electrons?



Example: modeling the gate leakage current:

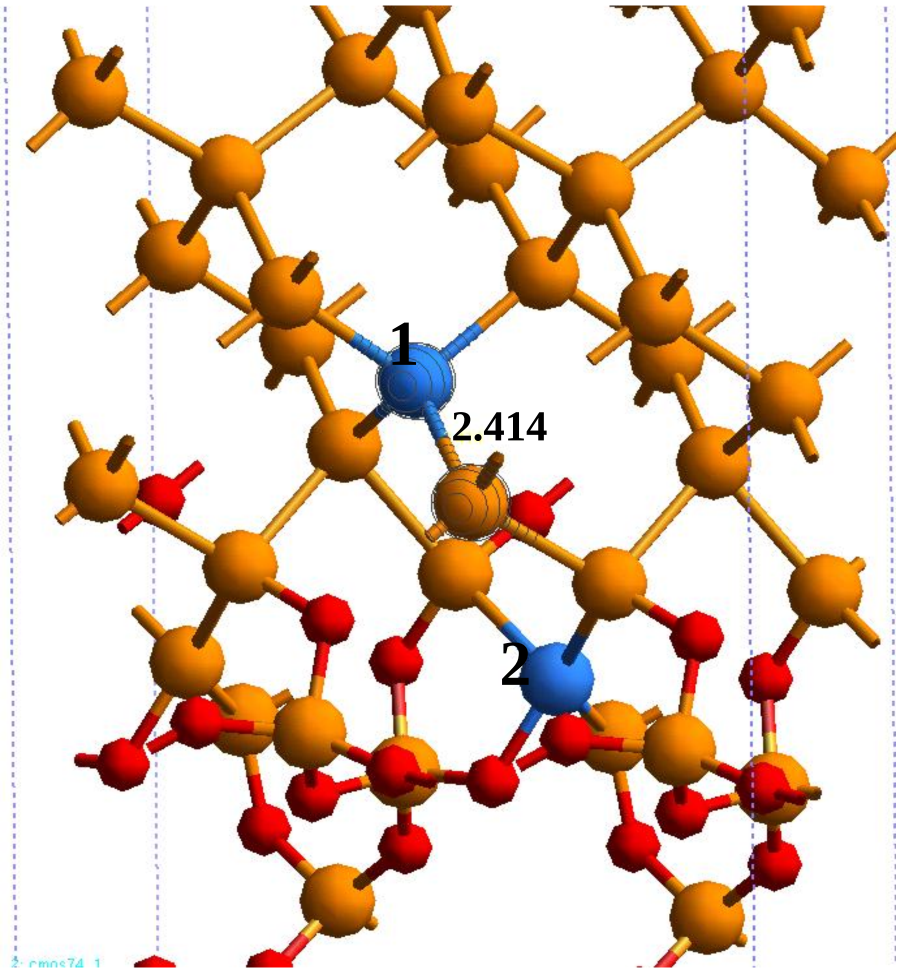


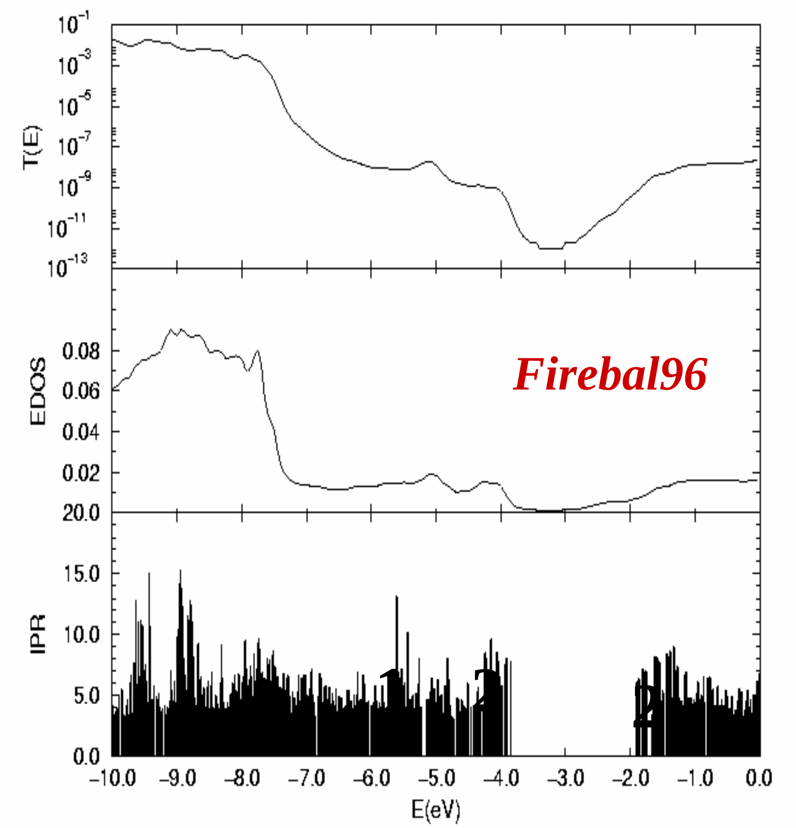
$$T \propto \exp(-2\sqrt{m^* E_g}\, L / \hbar)$$



For a nm-size capacitor, what are the effective mass, barrier height and thickness?

Defects and Transport properties



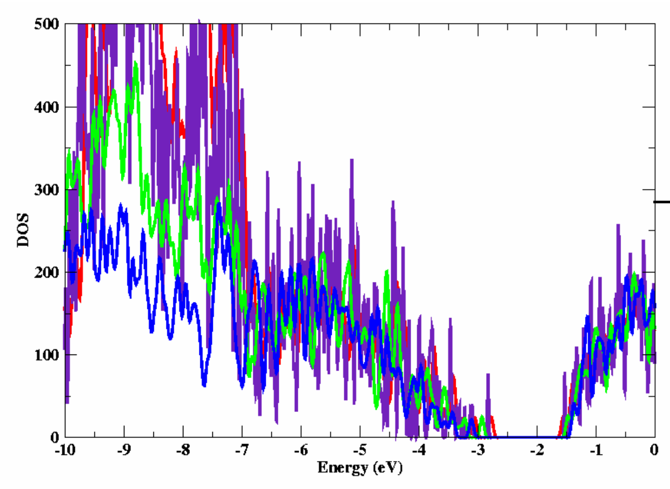


1: Strained Si

2: Sub-oxide

A.A. Demkov, X. Zhang and D.A. Drabold, . Rev. B 64, 125306-1 (2001)

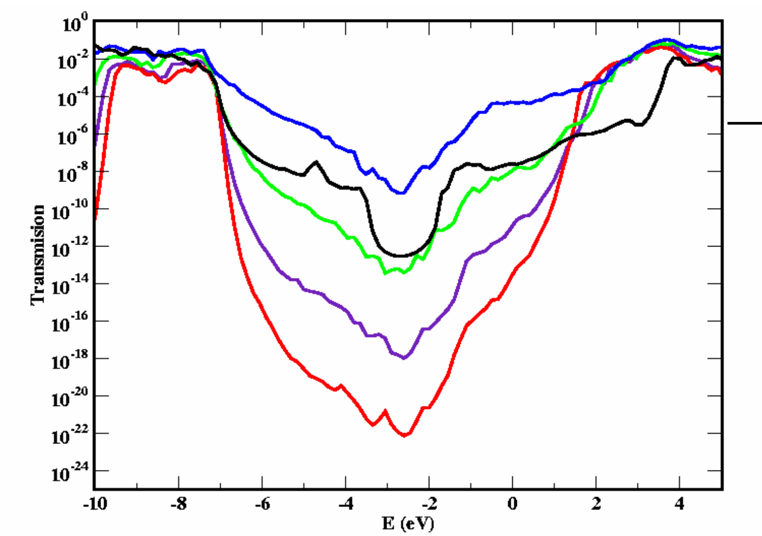
Leakage current

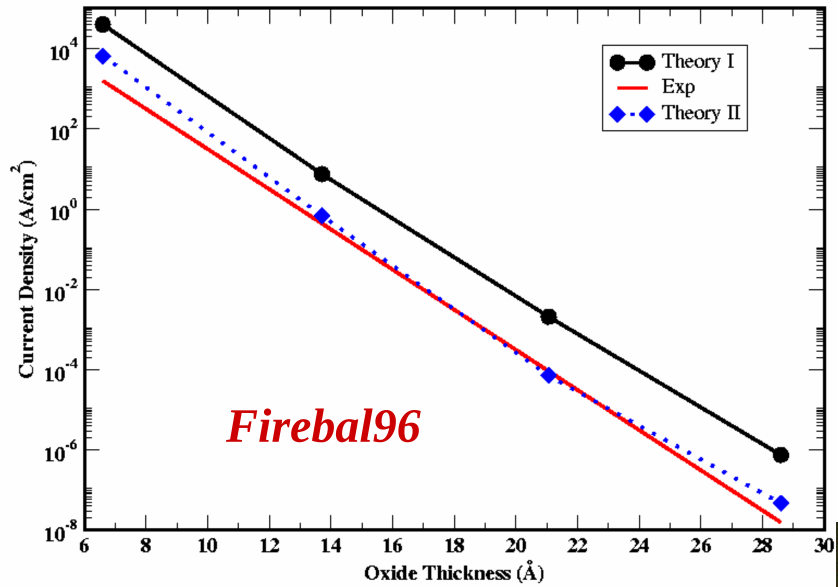


Fermi Level

Transmission

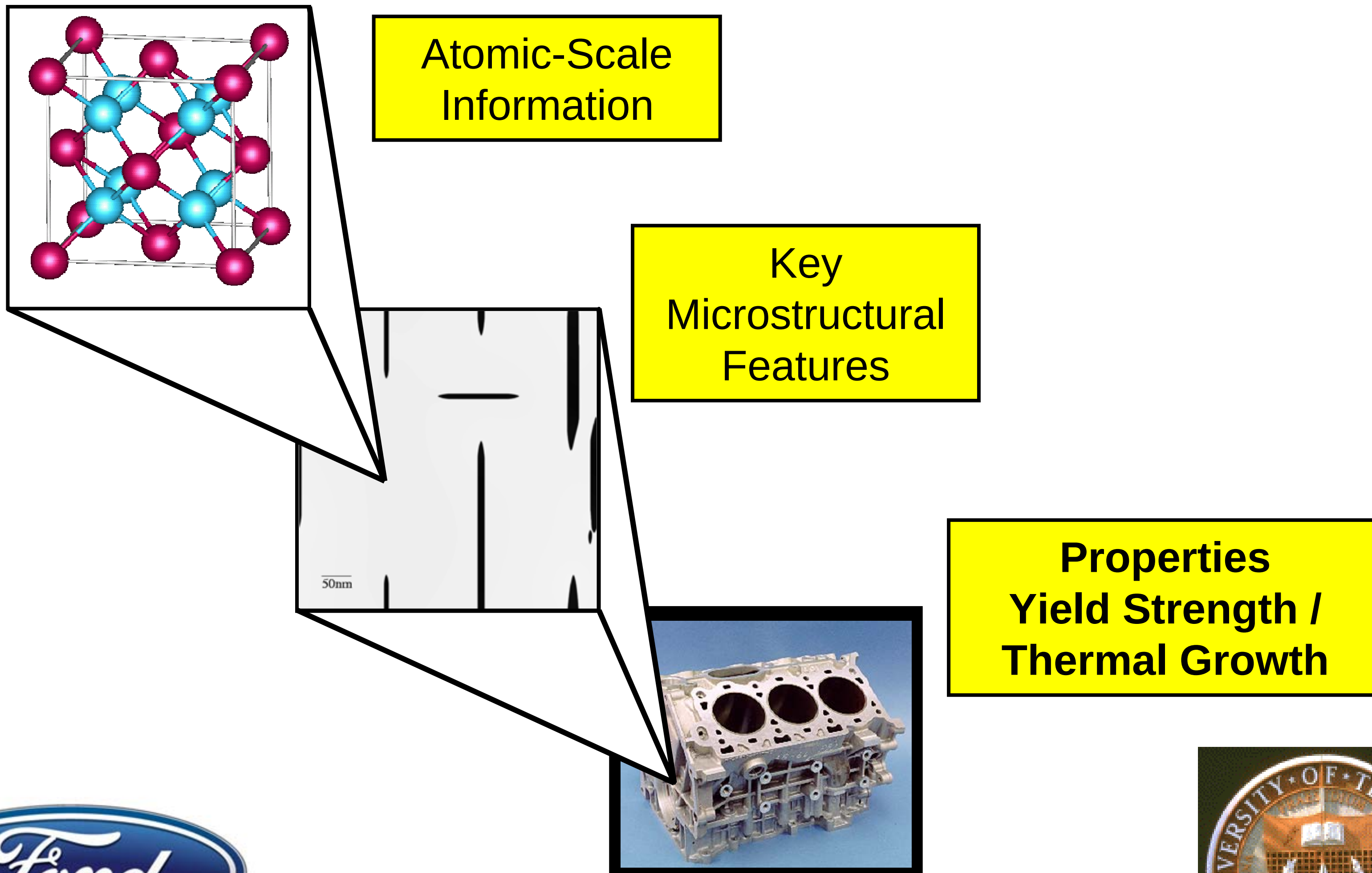
$$I = \int_{E_f - \eta V}^{E_f + (1-\eta)V} T(E)\,dE$$





X. Zhang, L. Fonseca, and A.A. Demkov, *phys. stat. sol. (b)* 233, 70 (2002).

"Atoms to Engines"
Modeling at all length scales helps Ford produce better engine blocks



Provided by Dr. Chris Wolverton, a UT Physics Graduate!!!