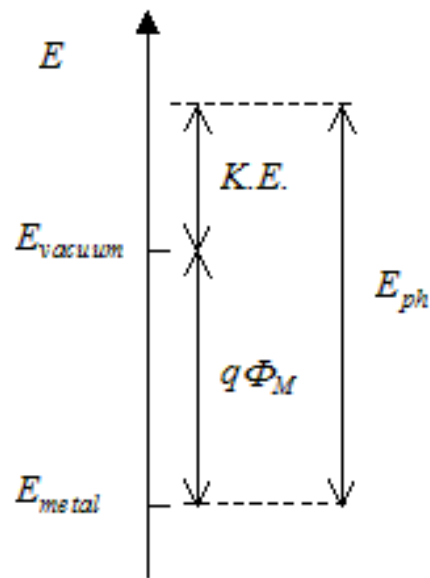
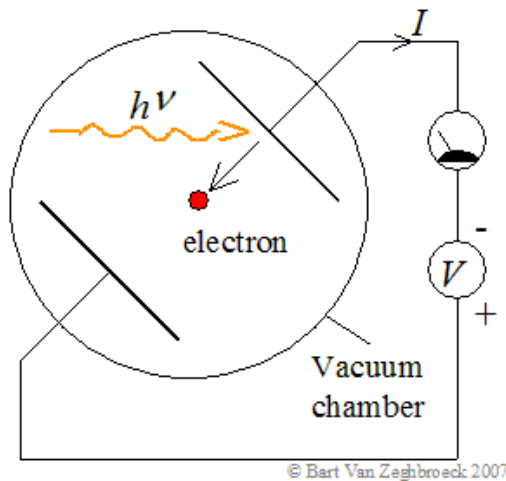


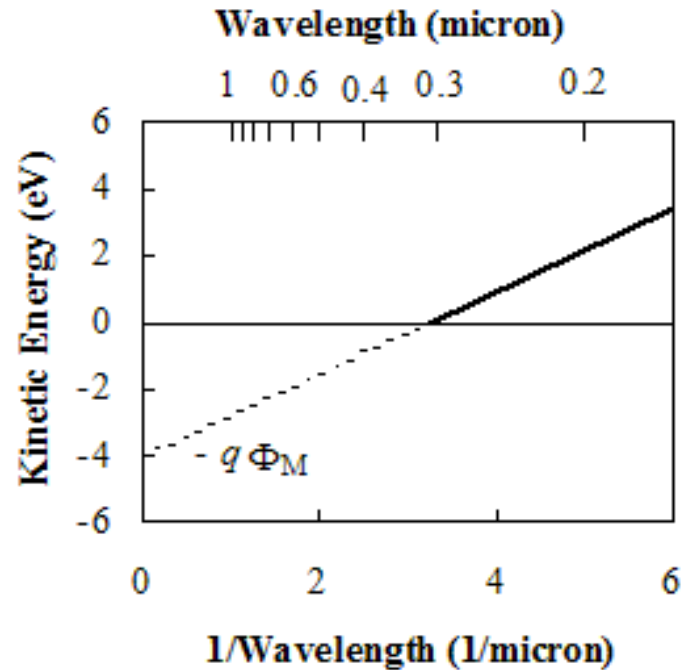
Physics 156: Applications of Solid State Physics

- Instructor: Sue Carter
- Office NSII 349
- Office Hours: Wednesdays 11:30 to 1 pm or by appointment
- Email: sacarter@ucsc.edu
- Book: <http://ece-www.colorado.edu/~bart/book/book/title.htm>
plus Additional Handouts provided in class
- Homework (30%), Exams (30%), Final Presentation (30%), Class Participation (10%)
- Applications:
Transistors (MOS, MOSFET, PN junction, Bipolar), Memory, LEDs/LASERS, Solid State Lighting, Displays, Solar Cells and Photodetectors, Magnetic Storage, MEMs, Other?

Review of Modern Physics: Photoelectric Effect



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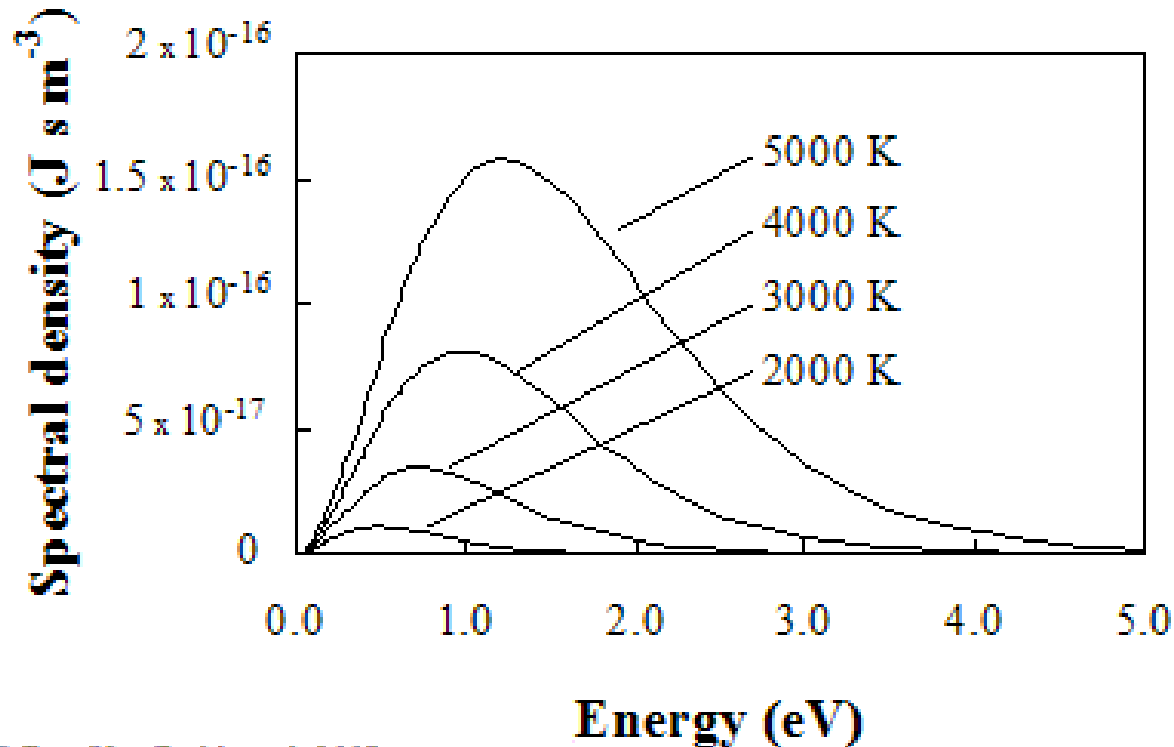


$$\text{K.E.} = E_{ph} - q\Phi_M$$

$$\text{where } E_{ph} = h\nu$$

$$\text{also } \lambda = h/p$$

Review of Modern Physics: Blackbody Radiation



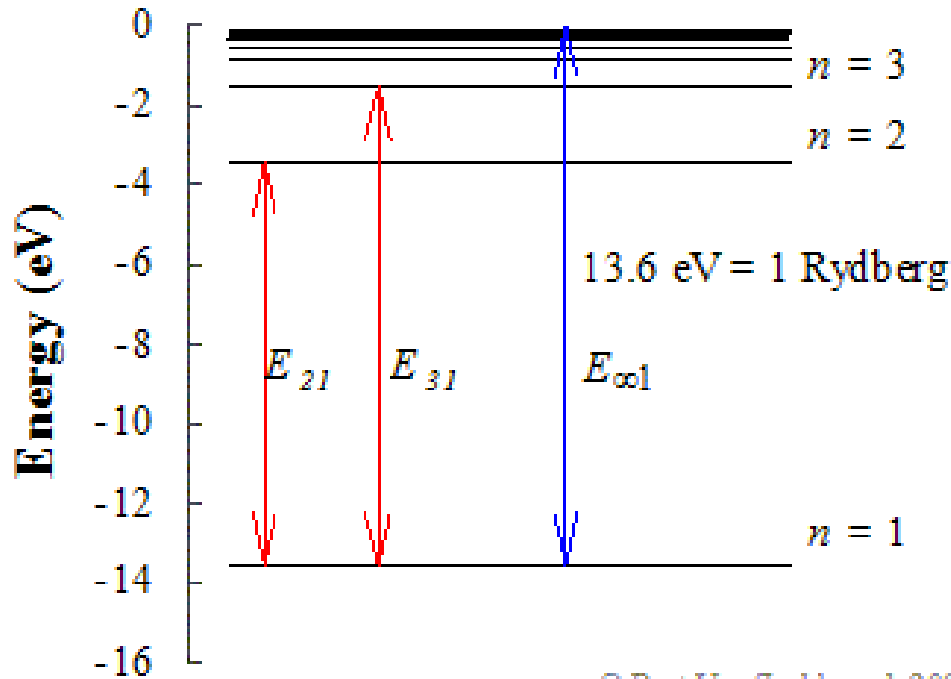
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Planck had to assume that $E_{\text{ph}} = h\nu$

With spectral density

$$u_{\omega} = \frac{\hbar}{\pi^2 c^3} \frac{\omega^3}{\exp\left(\frac{\hbar\omega}{kT}\right) - 1}$$

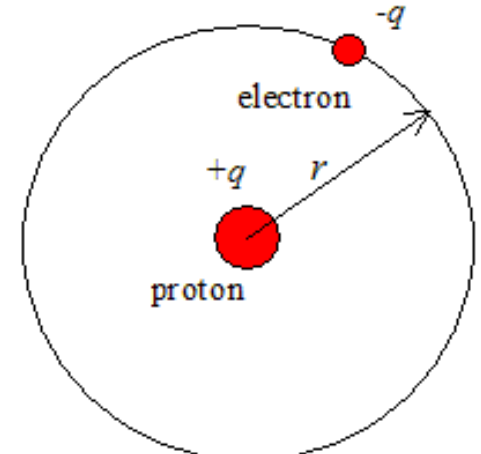
Review of Modern Physics: Bohr's Model



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$$E_n = -\frac{13.6 \text{ eV}}{n^2}, \text{ with } n=1, 2, \dots$$

$$E_{ph} = 13.6 \text{ eV} \left(\frac{1}{j^2} - \frac{1}{i^2} \right), \text{ with } i > j$$



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$$2\pi r = n\lambda$$

$$m \frac{v^2}{r} = \frac{q^2}{4\pi\epsilon_0 r^2}$$

$$a_0 = \frac{\epsilon_0 h^2 n^2}{\pi m_0 q^2}$$

$$E_n = -\frac{m_0 q^4}{8\epsilon_0^2 h^2 n^2}, \text{ with } n=1, 2, \dots$$

Review of Modern Physics: Schrodinger's equation

$$E = K.E. + V = \frac{p^2}{2m} + V(x)$$

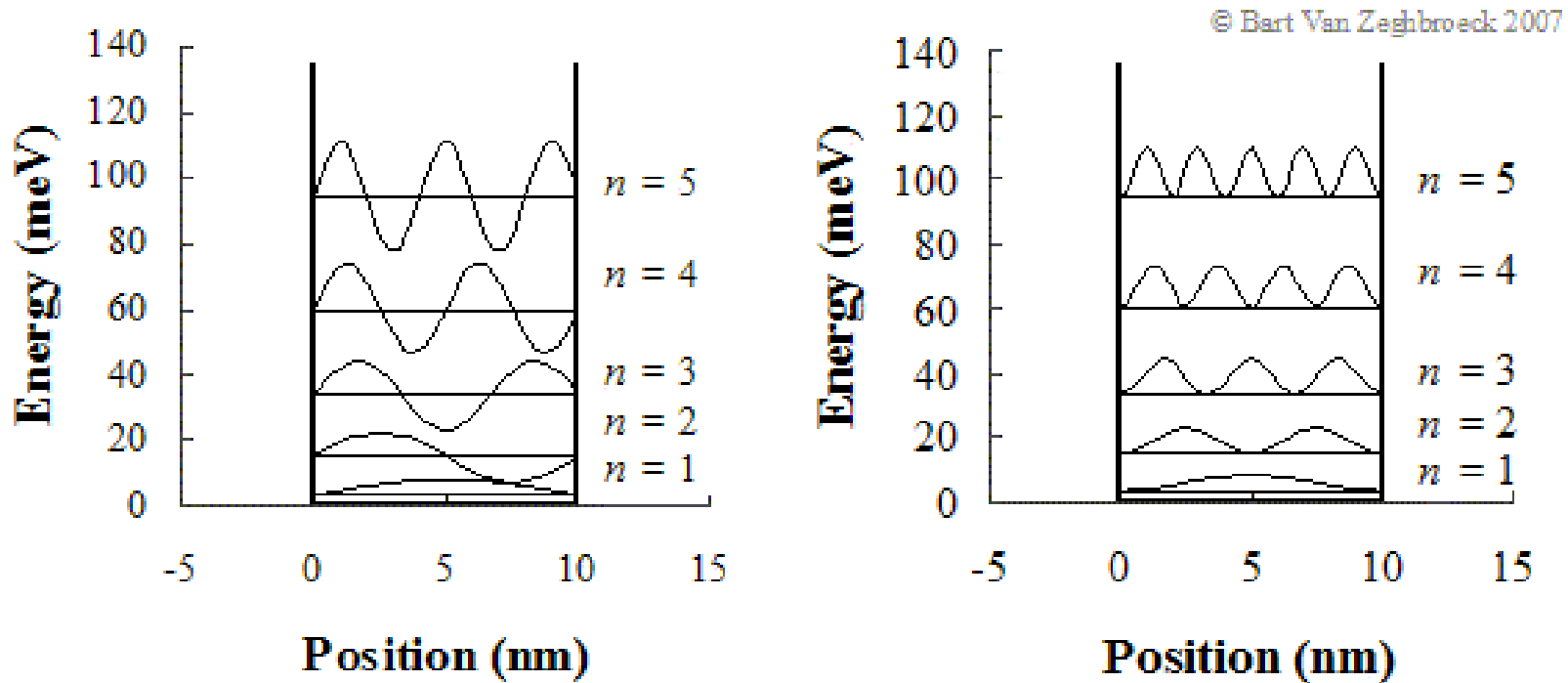
$$E\Psi = \frac{p^2}{2m}\Psi + V(x)\Psi$$

$$-\hbar^2 \frac{\partial^2 \Psi}{\partial x^2} = \hbar^2 k^2 \Psi = p^2 \Psi, \text{ for } \Psi = e^{i(kx - \omega t)}$$

where $k = 2\pi/\lambda$

$$-\frac{\hbar^2}{2m} \frac{d^2 \Psi(x)}{dx^2} + V(x)\Psi(x) = E\Psi(x)$$

Review of Modern Physics: Schrodinger's equation



(a) Energy levels, wavefunctions and (b) probability density functions in an infinite quantum well. The figure is calculated for a 10 nm wide well containing an electron with mass m . The wavefunctions and the probability density functions have an arbitrary magnitude (i.e. they are not normalized) and are shifted by the corresponding electron energy.

Review of Modern Physics: Hydrogen atom

$$V(\vec{r}) = -\frac{q^2}{4\pi\epsilon_0|\vec{r}|}$$

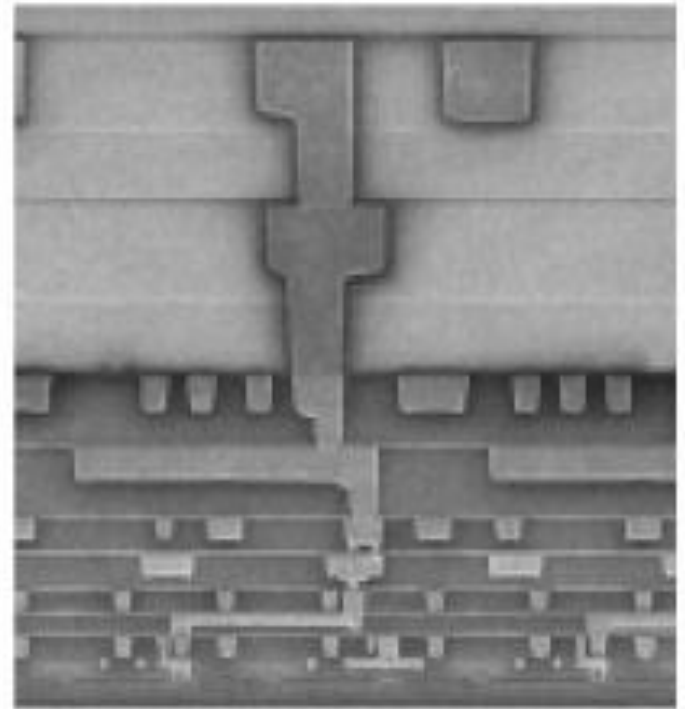
$$-\frac{\hbar^2}{2m}\nabla^2\Psi(x,y,z) + V(x,y,z)\Psi(x,y,z) = E\Psi(x,y,z)$$

$$E_n = -\frac{m_r q^4}{8\epsilon_0^2 h^2 n^2}, \text{ with } n = 1, 2, \dots$$

$$\frac{1}{m_r} = \frac{1}{m_{\text{electron}}} + \frac{1}{m_{\text{proton}}}$$

Classification of Solids

- Order / disorder
- Resistivity
- Importance of metals for chips



High Performance 65 nm SOI Technology with Enhanced Transistor Strain and Advanced-Low-K BEOL, W-H. Lee et al, Proceedings of IEDM, 2005.

Crystal Structure

- Crystalline vs. amorphous
 - Diamond
 - graphite



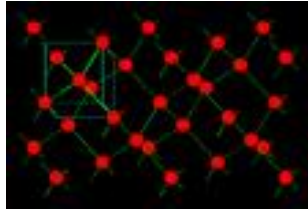
soot



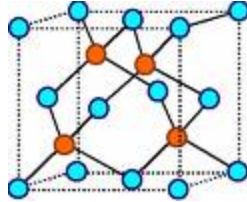
- Binding
 - Covalent/metallic bonds (metals)
 - Ionic bonds (insulators)
- Crystal structure determines properties
 - Binding, atomic density, scattering
 - **Symmetry controls properties of solids**

Purity

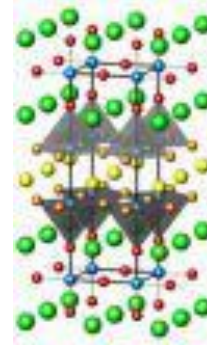
- Binary, ternary crystals



Diamond



GaAs



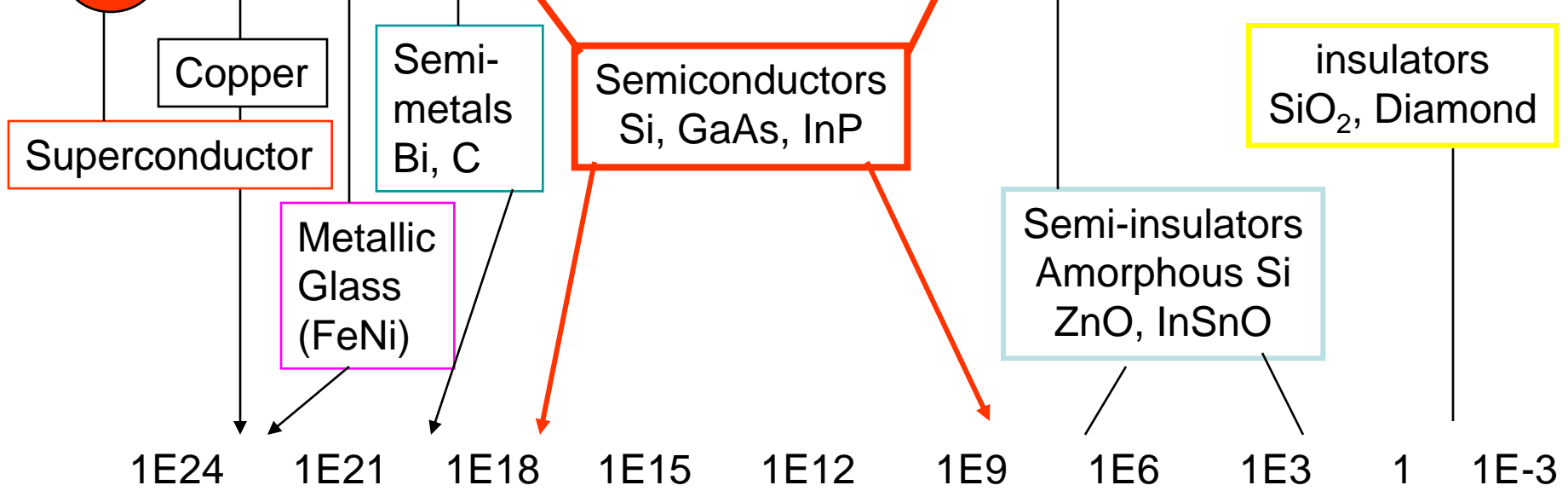
YBaCuO

- Impurities
 - Interstitial = between atoms (C in Iron)
 - Substitution = replaces atoms (B in Silicon)
- Impurities modify properties of material

Conductivity

Resistivity (ohm-cm)

0 1E-6 1E-3 1E0 1E3 1E6 1E9 1E12 1E15 1E18



1E24 1E21 1E18 1E15 1E12 1E9 1E6 1E3 1 1E-3



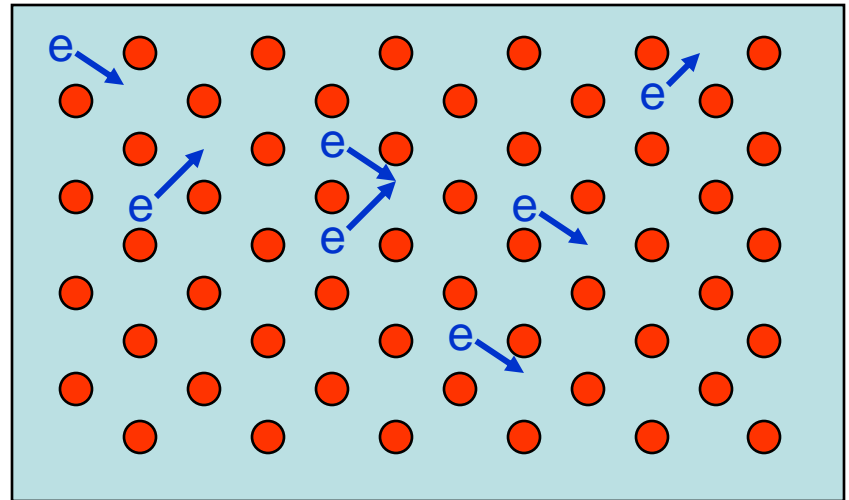
Electron density (e/cm³)



Transparency

Drude Model

- **Electron Sea**
 - Atomic Lattice
 - Electron density = $Z * n_a$
 - n_a = atomic density
 - Z = valence
- **Electrical Resistance**
 - Electron density
 - Scattering of electrons
 - Electron-electron scattering?
 - Electron-ion scattering?
 - Electron-surface scattering?
 - Other??



Limitations to Free Electron Model

- Number of conduction electrons?
 - Resistance should scale with Z – it does not

H																	He
1																	2
Li	Be											B	C	N	O	F	Ne
2,1	2,2											2,3	2,4	2,5	2,6	2,7	2,8
Na	Mg											Al	Si	P	S	Cl	Ar
2,8,1	2,8,2											2,8,3	2,8,4	2,8,5	2,8,6	2,8,7	2,8,8
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
2,8,8,1	2,8,8,2	2,8,9,2	2,8,10,2	2,8,11,2	2,8,13,1	2,8,13,2	2,8,14,2	2,8,15,2	2,8,16,1	2,8,18,1	2,8,18,2	2,8,18,3	2,8,18,4	2,8,18,5	2,8,18,6	2,8,18,7	2,8,18,8
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18
8,1	8,2	9,2	10,2	12,1	13,1	14,1	15,1	16,1	18,0	18,1	18,2	18,3	18,4	18,5	18,6	18,7	18,8
Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
2,8,18	2,8,18		2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18	2,8,18
18,8,1	18,8,2		32,10,2	32,11,2	32,12,2	32,13,2	32,14,2	32,15,2	32,17,1	32,18,1	32,18,2	32,18,3	32,18,4	32,18,5	32,18,6	32,18,7	32,18,8
Fr	Ra	**	Rf	Db	Sg	Bh	Hs	Mt	Uuu	Uuu	Uub						
2,8,18,32	2,8,18,32		2,8,18,32	2,8,18,32	2,8,18,32	2,8,18,32	2,8,18,32	2,8,18,32	2,8,18,32	2,8,18,32	2,8,18,32						
18,8,1	18,8,2		32,10,2	32,11,2	32,12,2	32,13,2	32,14,2	32,15,2	32,17,1	32,18,1	32,18,2						

Zn has more valence electrons than Cu
Zn has higher resistivity than Cu ??

B and Al, Same column
Insulator → metal ??

Bi ~ 100x higher ρ

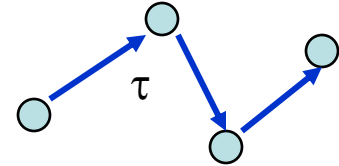
Scattering Mechanisms

- Scattering

- Electron average velocity = $\frac{-eE\tau}{m}$

- Electron flux = $j = -n_e ev$

- Conductivity: $j = \sigma * E \gg \sigma = \frac{ne^2\tau}{m}$



- Typical bulk resistivity for metals: 10 – 1 $\mu\Omega$ –cm

- **Typical scattering times: 0.1 - 1 E-14 s**

- **Frequency = 10 – 100 E14 Hz**

Mean free path

- Electron energy
 - Classical Boltzmann distribution $\frac{1}{2} mv^2 \sim k_B T = 0.023\text{eV}$ at RT
 - $v \sim 1 \text{ E}5 \text{ m/s}$
 - Mean free path $\lambda \sim 1 - 10 \text{ E-}10 \text{ m} = 10 - 100\text{nm}$ (close to true)
- Copper:
 - Electron density = $8.5 \text{ E}22 / \text{cm}^3$
 - Electron-electron distance = 0.14nm
 - Atomic distance = 0.36nm
- Scattering length greater than electron – electron / ion distance
- How can electron move past >100 lattice spacings without scattering?

Copper Resistivity and Finite Size

- Resistance of copper line vs. temperature and size

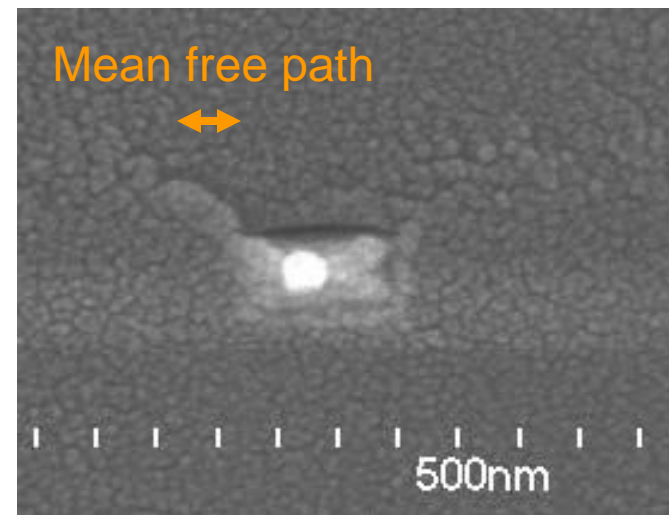
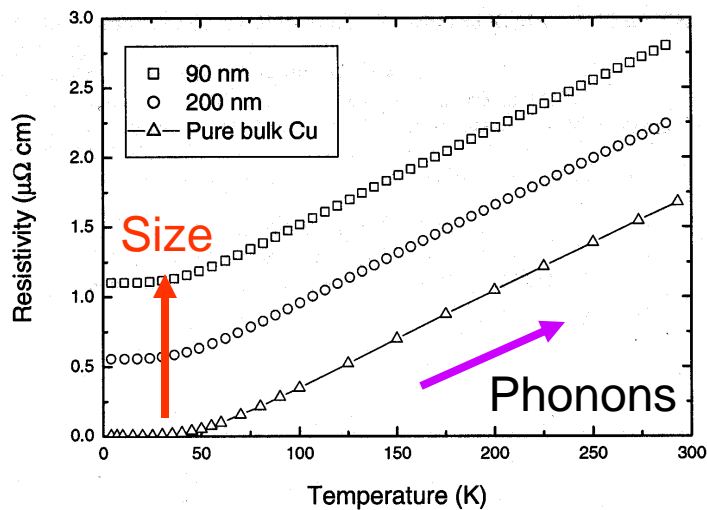
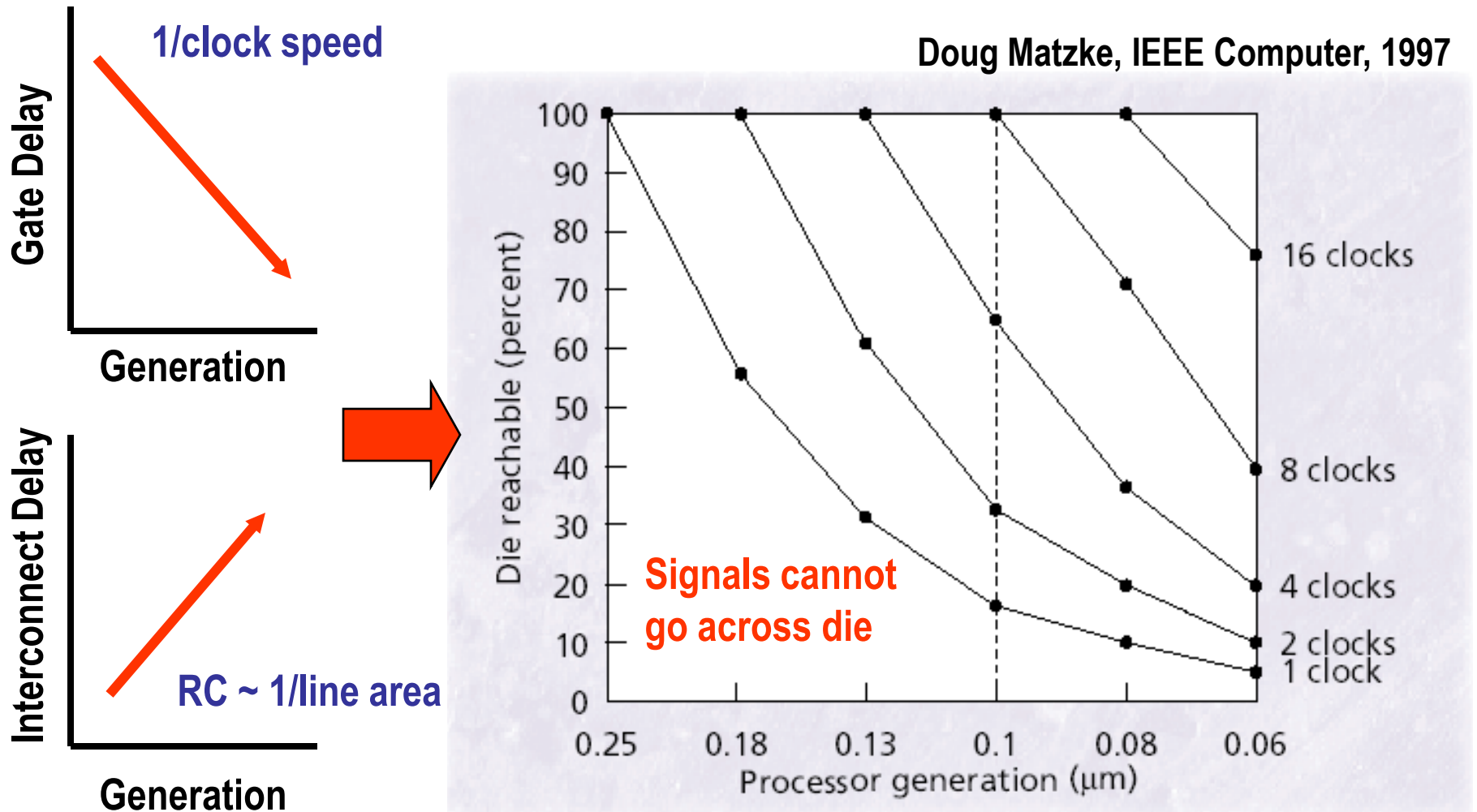


Figure 4. Resistivity of 90 nm and 200nm lines and fitting with size effect and grain boundary scattering. Values for bulk Cu are taken from [6].

As line size is reduced, metallic resistivity increases

Interconnect Delay is Key Performance Limiter



- Implications: (1) Multi-core designs to minimize cross-die delays
(2) More emphasis on scaling interconnects than transistors

Intel Multi Core Processors

