2009 NCN@Purdue-Intel Summer School
Notes on Percolation and Reliability Theory

Lecture 7
On Reliability and Randomness in Electronic Devices

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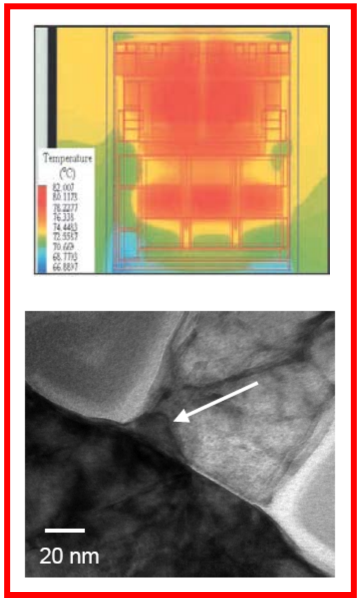
Outline of Lecture 7

1. Background information
2. Principles of reliability physics
3. Classification of Electronic Reliability
4. Structure Defects in Electronic Materials
5. Conclusions

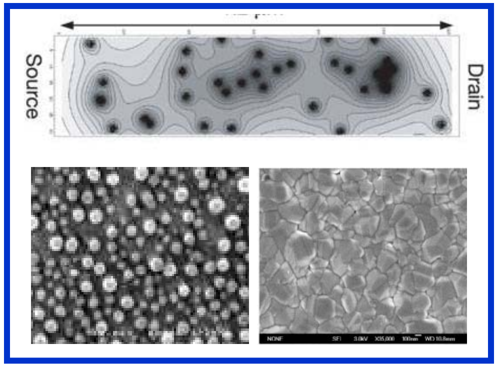
Process, Reliability, and Design

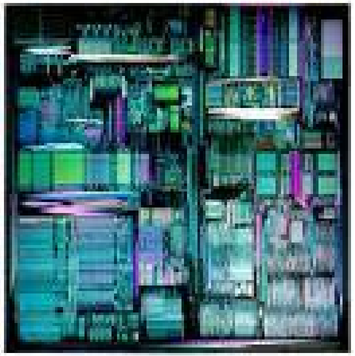
Reliability

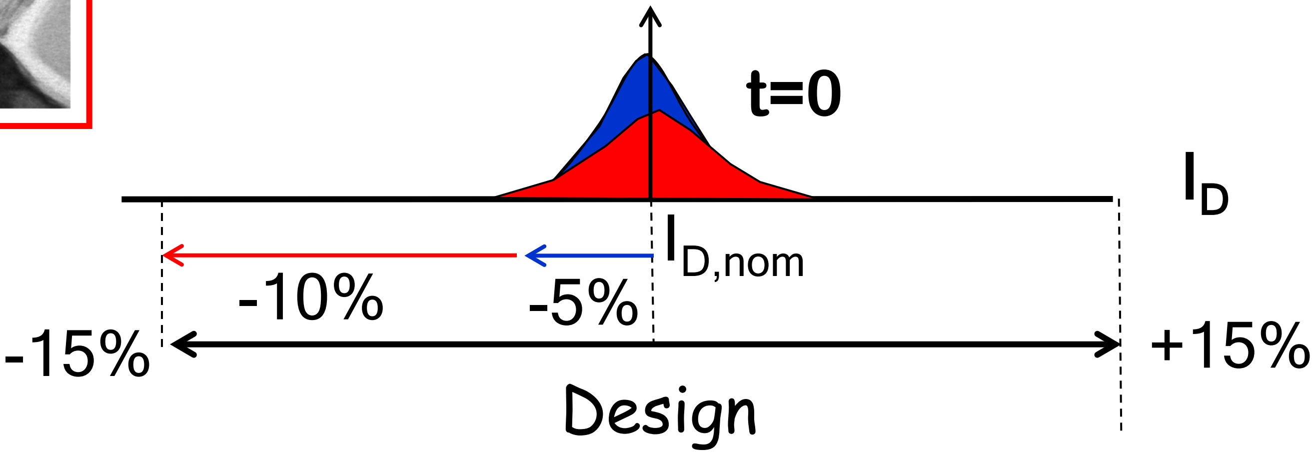


plus

Process



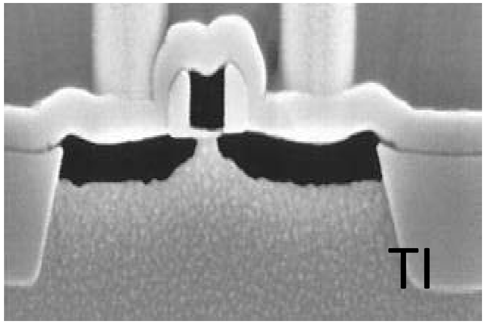




We do not have too much margin

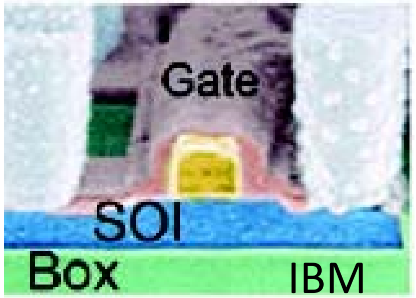
Complexity of the Reliability Problem

Mobility Improvement

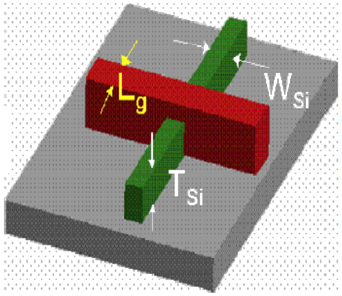


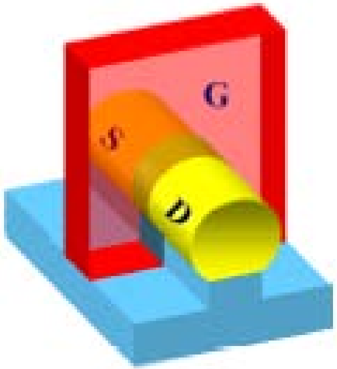
- Ge channel
- Strained silicon
  - uniaxial
  - bi-axial
- III-V materials

Improvement in Electrostatics



Berkeley
FINFET





- Silicon on insulator (SOI)
- Double-gated devices
- Tri-gate or FINFET devices
- Surround gate devices
  (VRG, Si-NW)

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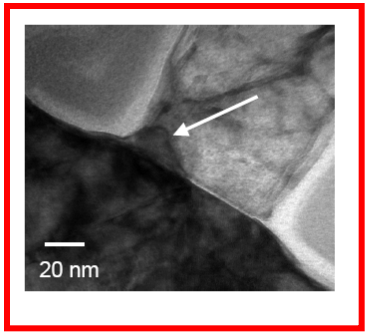
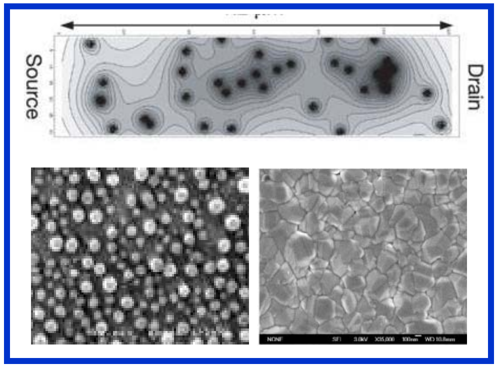
Equivalence between Spatial/Temporal Fluctuation

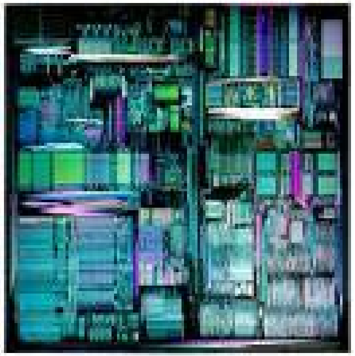
Reliability



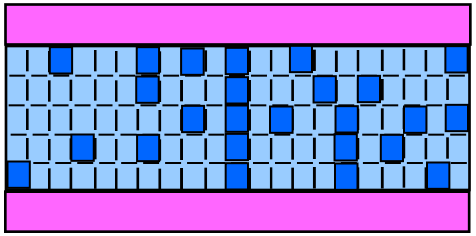
plus

Process

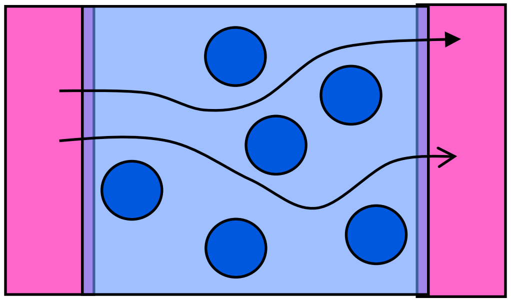




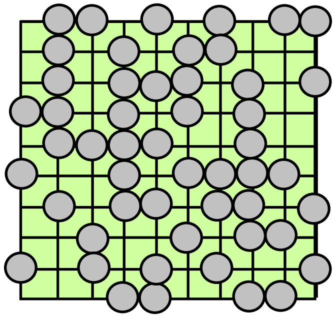
Side view (TDDB)



top view (RDF)



model



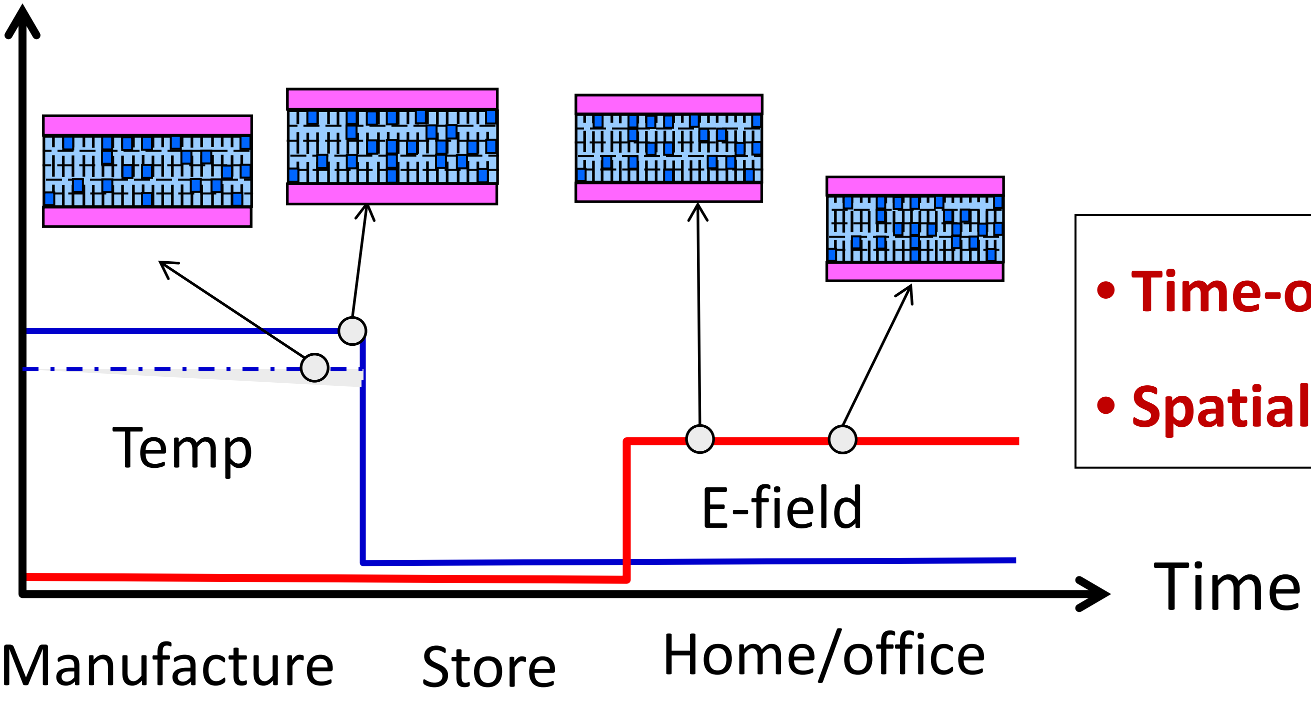
Spatial and temporal fluctuation should be considered with same framework …

Equivalence of Spatial/Temporal Fluctuations

Process → Device → Reliability →

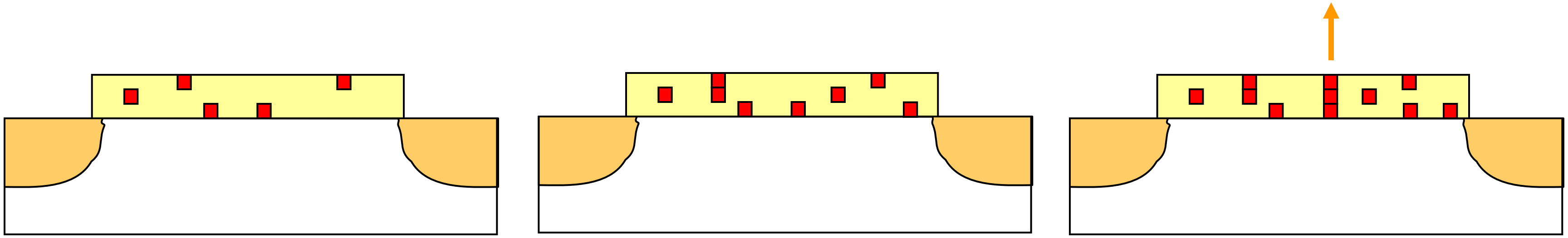
Process ⇄ Device

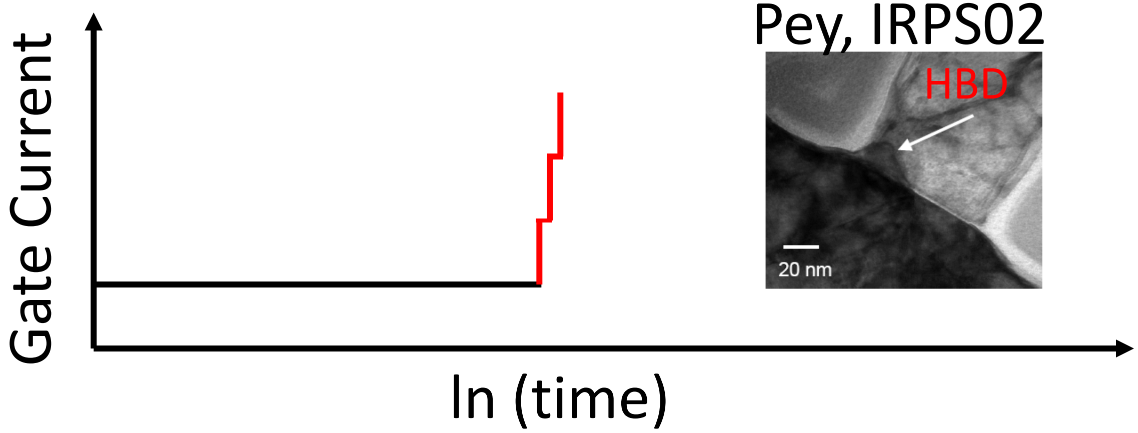
Same theoretical tools



- **Time-ordered (N~t)**
- **Spatial Correlation**

Reliability: Stochastic Process Terminated by a Threshold





Pey, IRPS02

Reliability: Physics of how Things Break

A child drops a glass

Bridges (Tacoma Narrows)

Shuttle (Challenger)

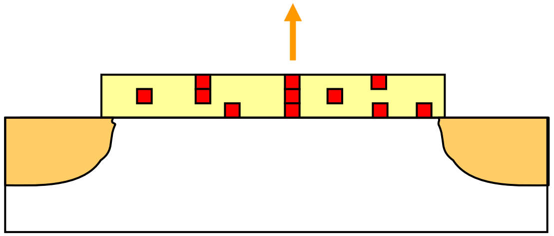
Lighting in a rain-soaked night

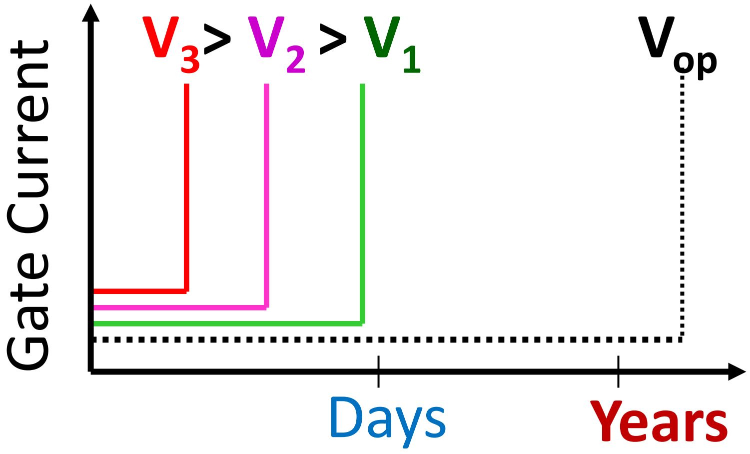
Volcano, landslides & forest fire

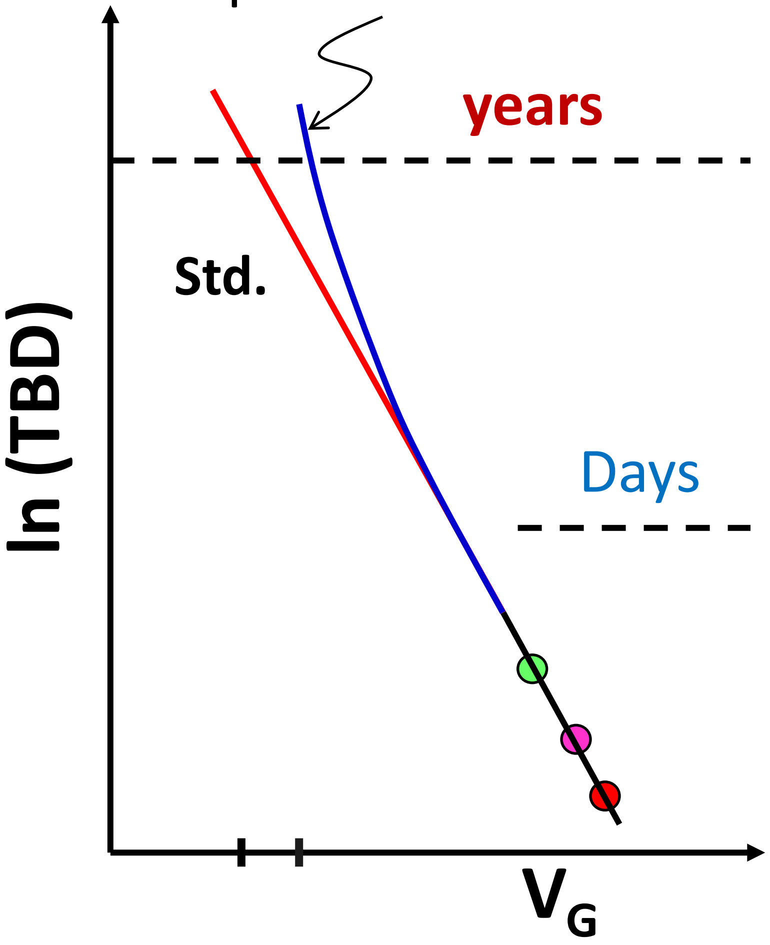
Check-out queues, scheduling

A stochastic process terminated by threshold

Theory of Accelerated Testing





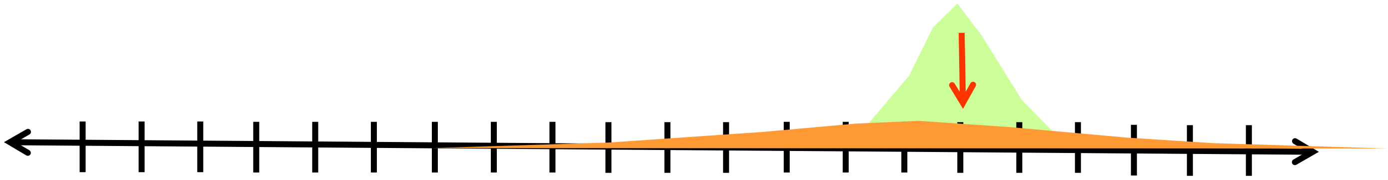


Nonlinear projection for processes with threshold

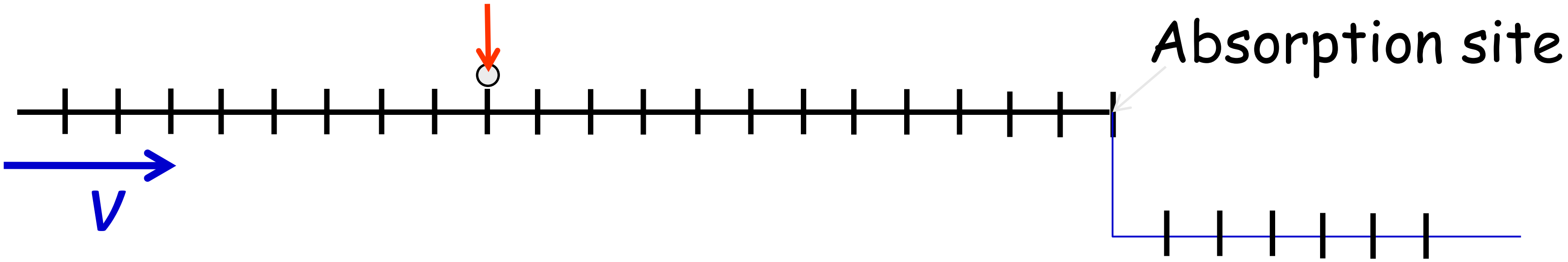
Empirical projection is very difficult, if not impossible …

Nonlinear Projection: an Illustrative Example

Stochastic Process

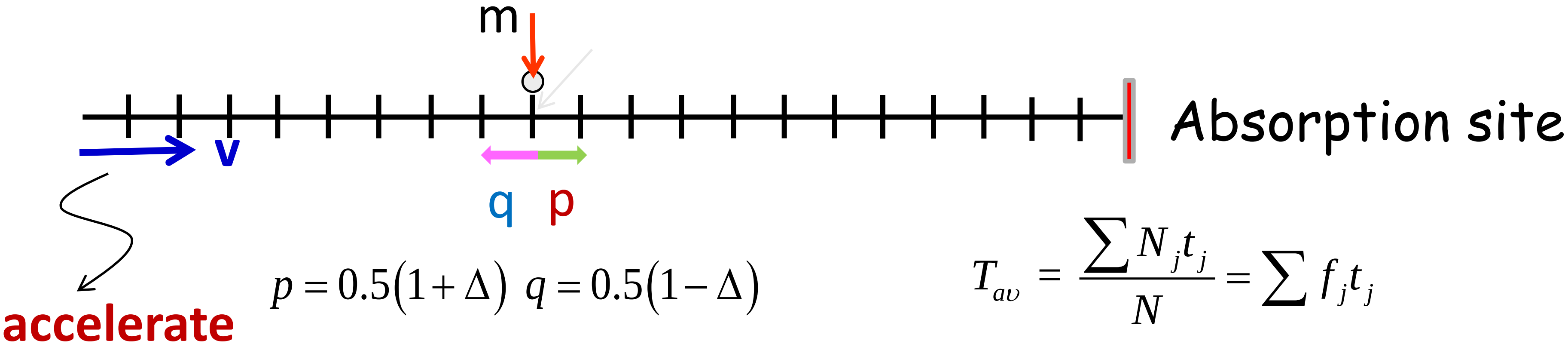


Stochastic Process with a threshold



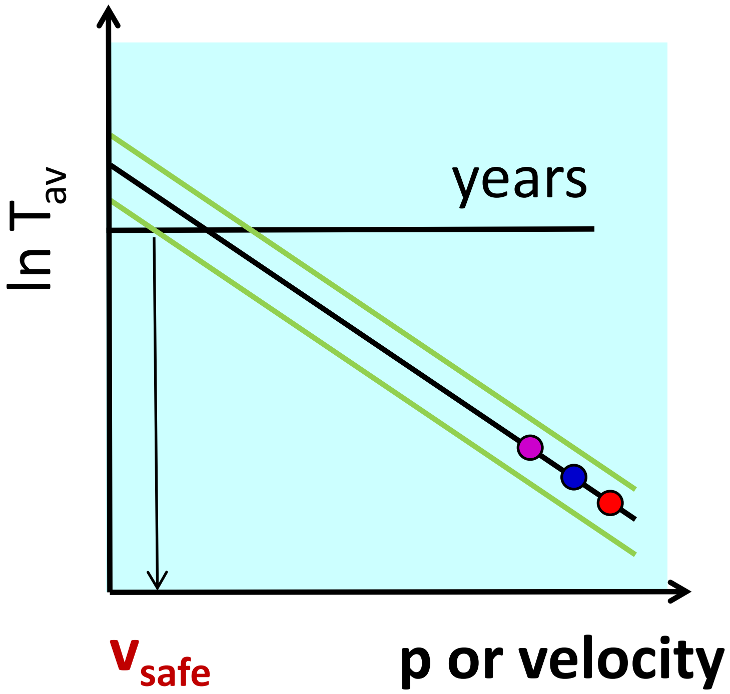
How far away from the trap-site do I need to inject the particles so that after TBD sec of diffusion no more than y percent of particles is lost?

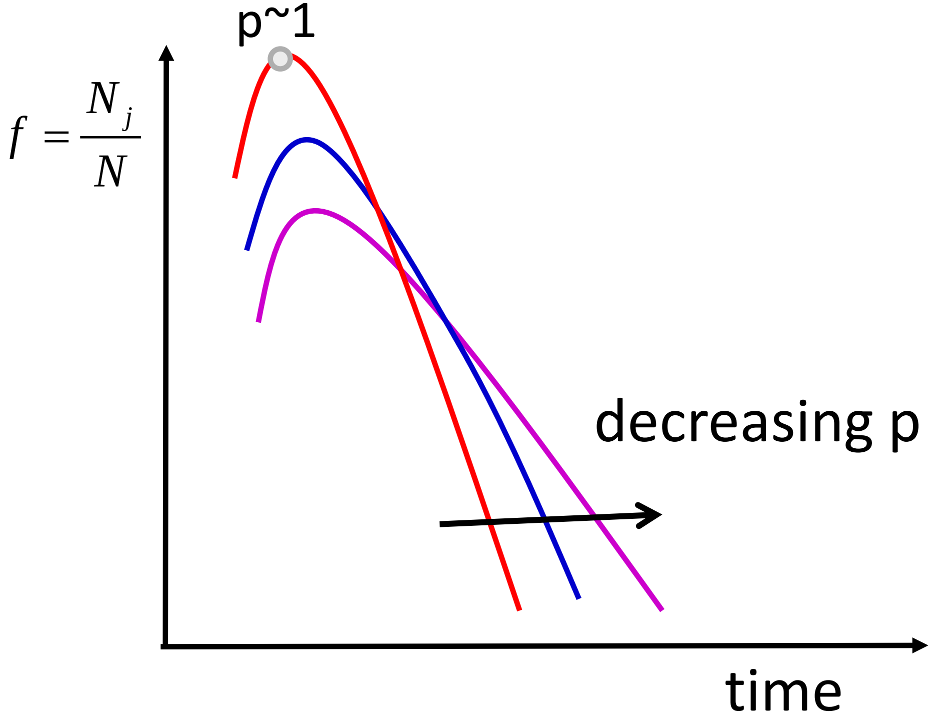
Accelerated Testing: Empirical Approach



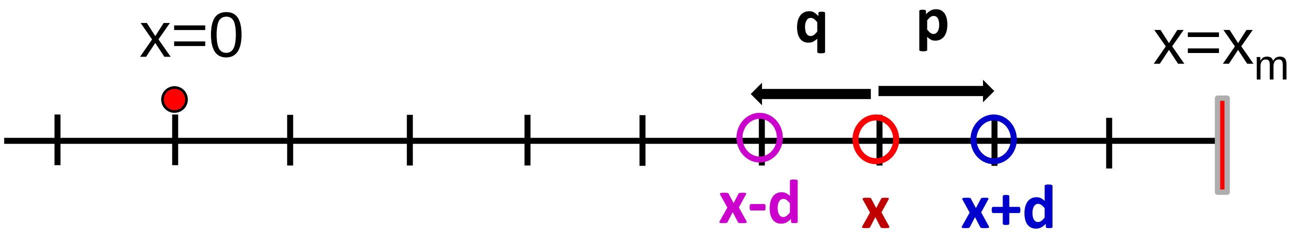
$$p = 0.5(1+\Delta) \quad q = 0.5(1-\Delta)$$

$$T_{av} = \frac{\sum N_j t_j}{N} = \sum f_j t_j$$





Average Arrival Time Distribution



$$T(x) = \tau + \left[q \times T(x-\delta)\right] + \left[p \times T(x+\delta)\right]$$

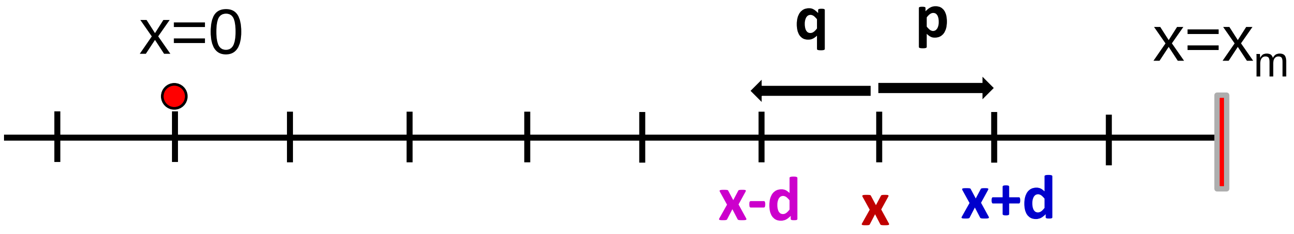
Time to absorption after being injected at x ….

$$\frac{T(x) - \frac{1}{2}\left(T(x+\delta) + T(x-\delta)\right)}{\delta^2} - \frac{\Delta}{2}\frac{\left(T(x+\delta) - T(x-\delta)\right)}{\delta^2} - \frac{\tau}{\delta^2} = 0$$

$$\boxed{\frac{d^2T}{dx^2} + \frac{2}{v}\frac{dT}{dx} + \frac{2}{D} = 0}$$

$$v \equiv {}^{\delta}\!/_{2\Delta} \qquad D \equiv {}^{\delta^2}\!/_{\tau}$$

Average Arrival Time Distribution



$$\frac{d^2T}{dx^2}+\frac{2}{v}\frac{dT}{dx}+\frac{2}{D}=0$$

$$T(x=x_m)=0,\ \ C_1=C_2x_m$$

$$T(x)=C_1-C_2x$$

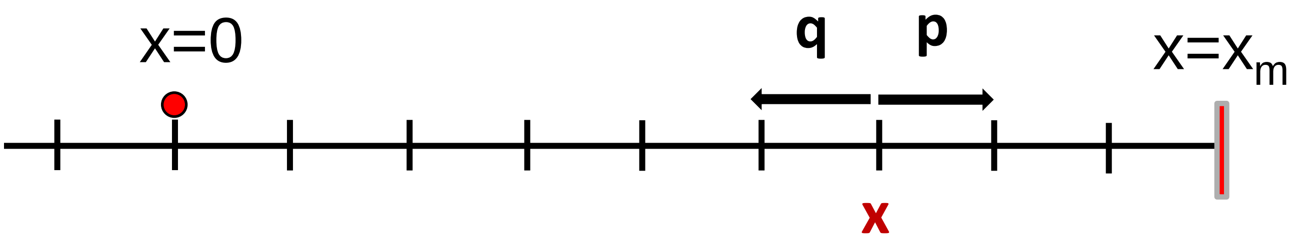
$$-\frac{2\Delta}{\delta}C_2+\frac{2\tau}{\delta^2}=0$$

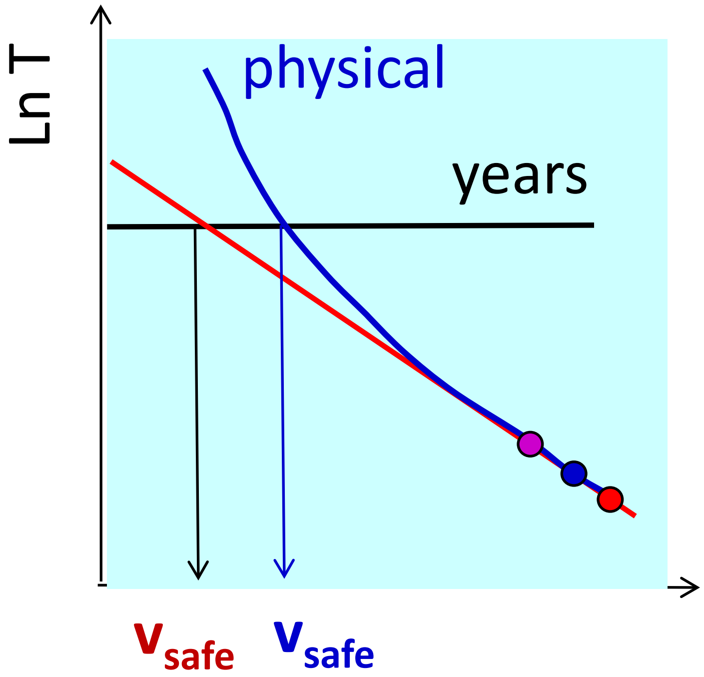
$$\therefore C_2=\frac{\tau}{\delta\Delta}$$

$$T(x)=\frac{\tau}{\delta\Delta}\left(x_m-x\right)=\frac{\tau}{\delta}\frac{\left(x_m-x\right)}{2\left(p-\tfrac{1}{2}\right)}$$

Average lifetime diverges at small velocity, v or p -> 0

Physical vs. Empirical Projection





$$T(x) = \frac{\tau}{2\delta}\left[\frac{x_m - x}{p(\upsilon) - 0.5}\right]$$

- Empirical meas. & comp. simulation would not do
- Prediction is possible because t=0- is smooth

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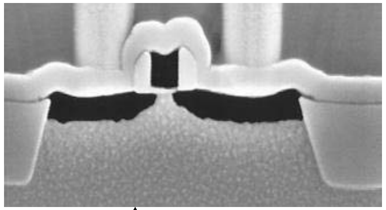
Front and Backend Reliability

Transistor Reliability Issues

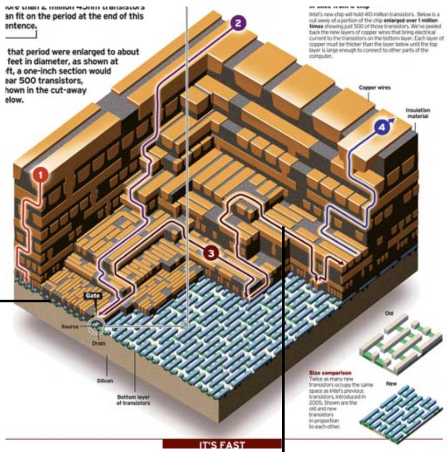
- Gate Dielectric Breakdown
- Negative Bias Temperature Instability
- Hot Carrier Degradation
- Radiation Induced damage

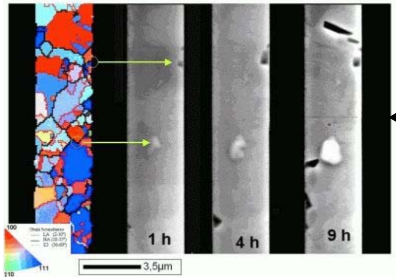
Interconnect Reliability Issues

- Electro-migration/Stress-migration.
- Inter-level dielectric breakdown

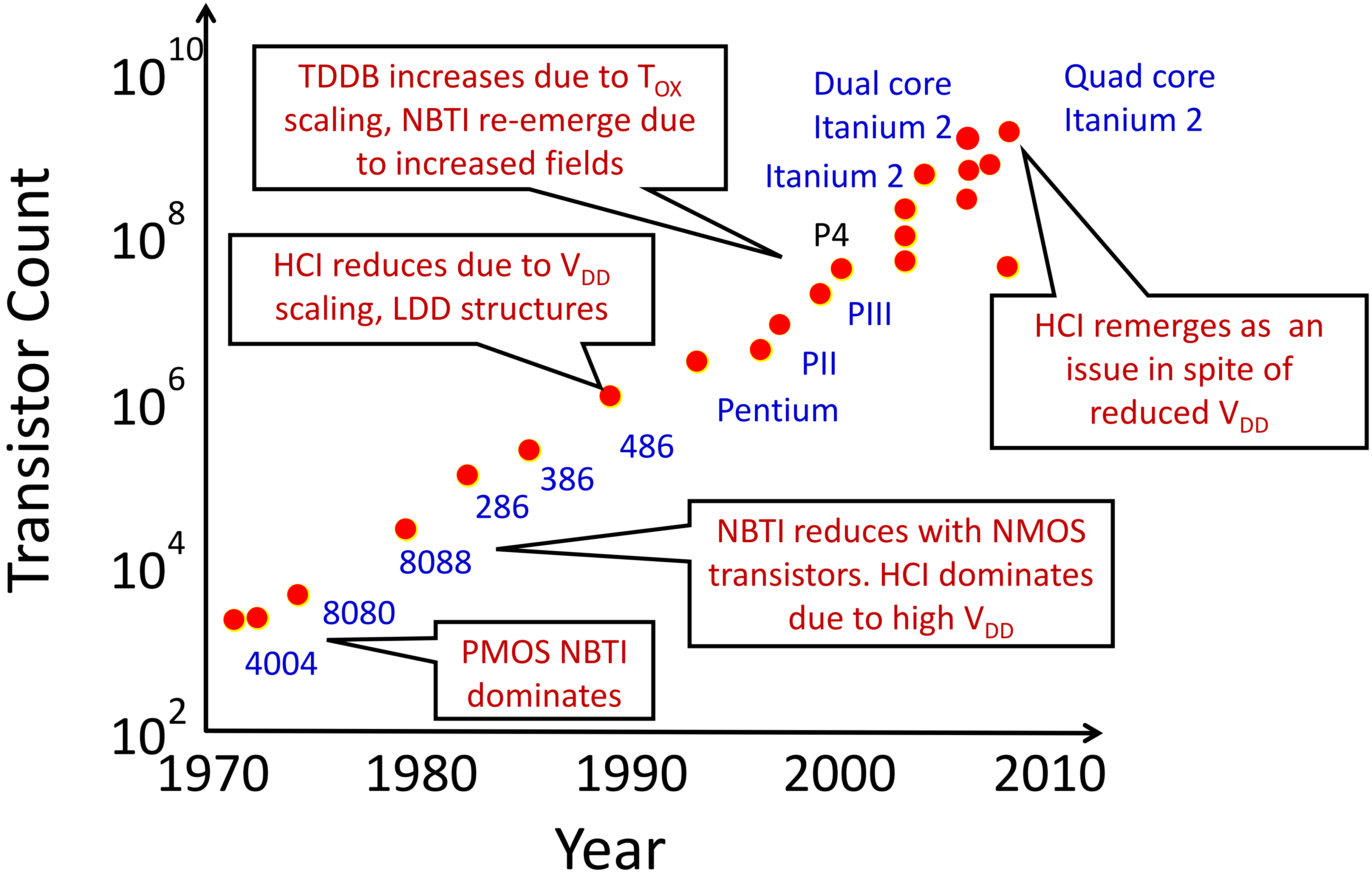


The Oregonian, 2008





Scaling and Reliability: A Short History



TDDB increases due to T_{OX} scaling, NBTI re-emerge due to increased fields

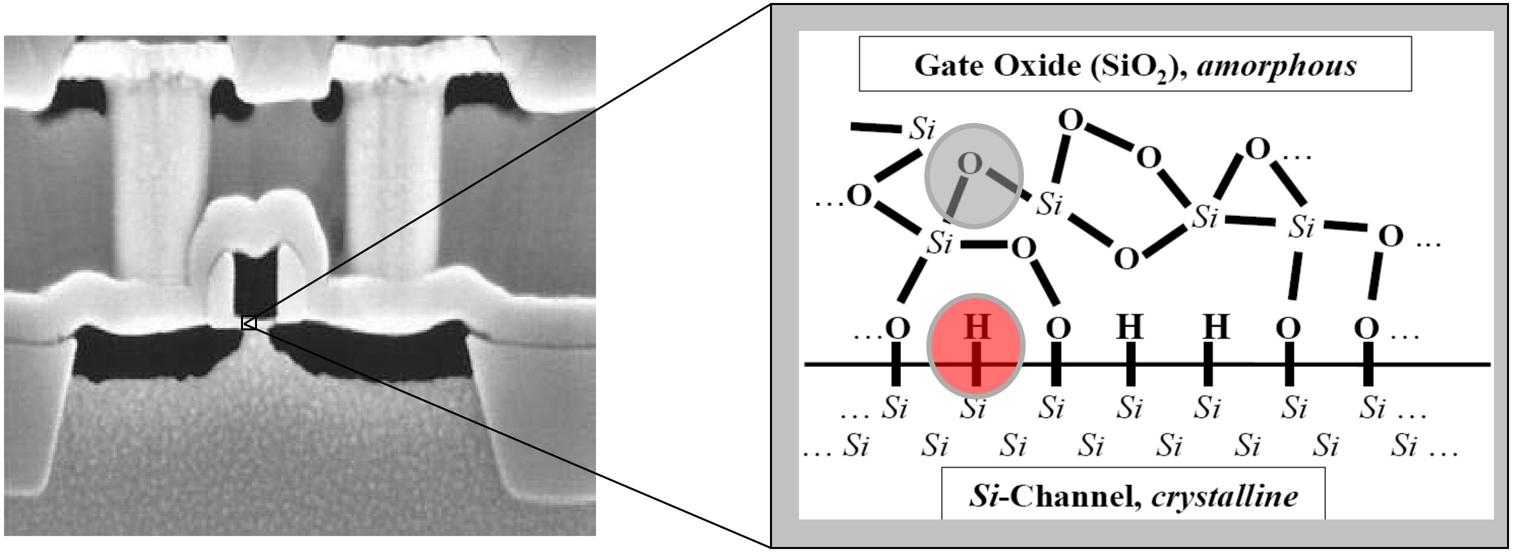
HCI reduces due to V_{DD} scaling, LDD structures

HCI remerges as an issue in spite of reduced V_{DD}

NBTI reduces with NMOS transistors. HCI dominates due to high V_{DD}

PMOS NBTI dominates

SiO and SiH Bonds



Broken Si-H bonds

Negative Bias Temperature Instability (NBTI)
Hot carrier degradation (HCI)

Broken Si-O bonds

Gate dielectric Breakdown (TDDB)
Electrostatic Discharge (ESD)
Radiation induced Gate Rupture (RBD)

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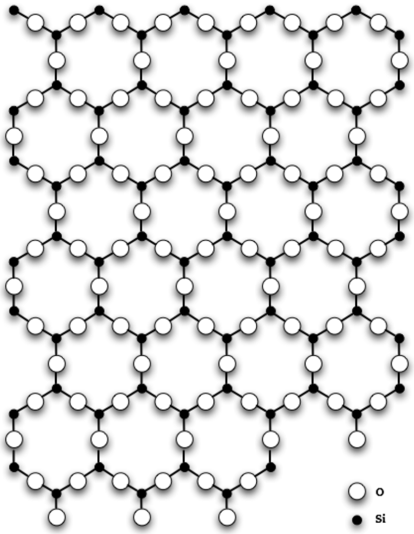
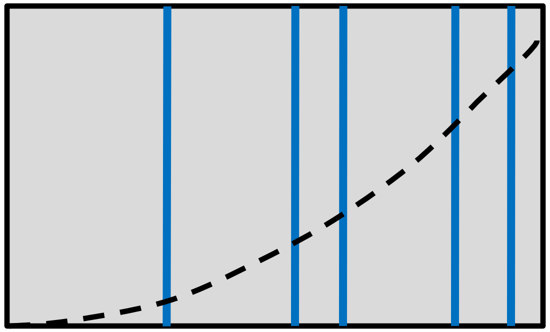
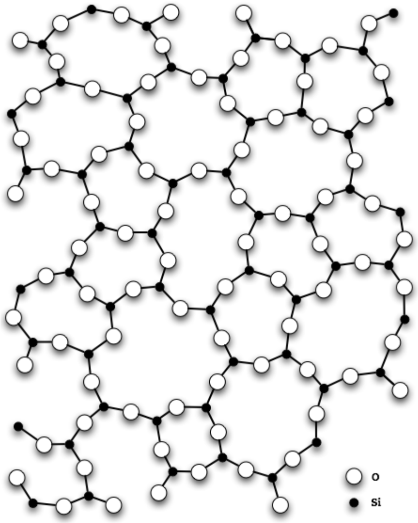
Crystalline, Amorphous, and Random Materials

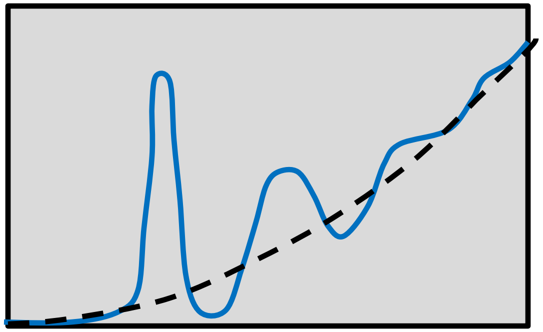
Crystalline



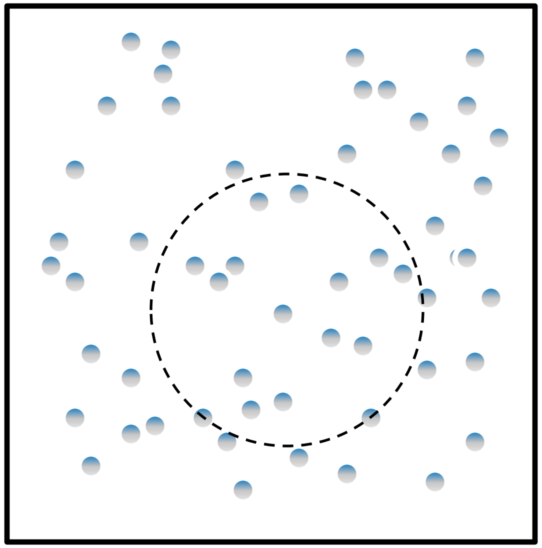


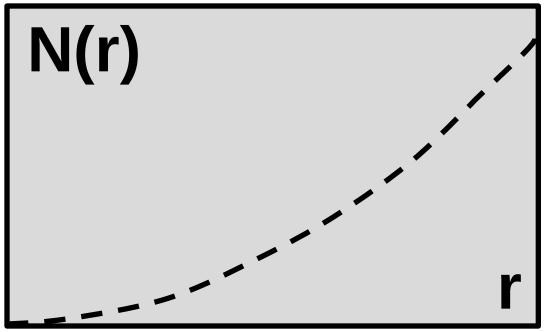
Amorphous





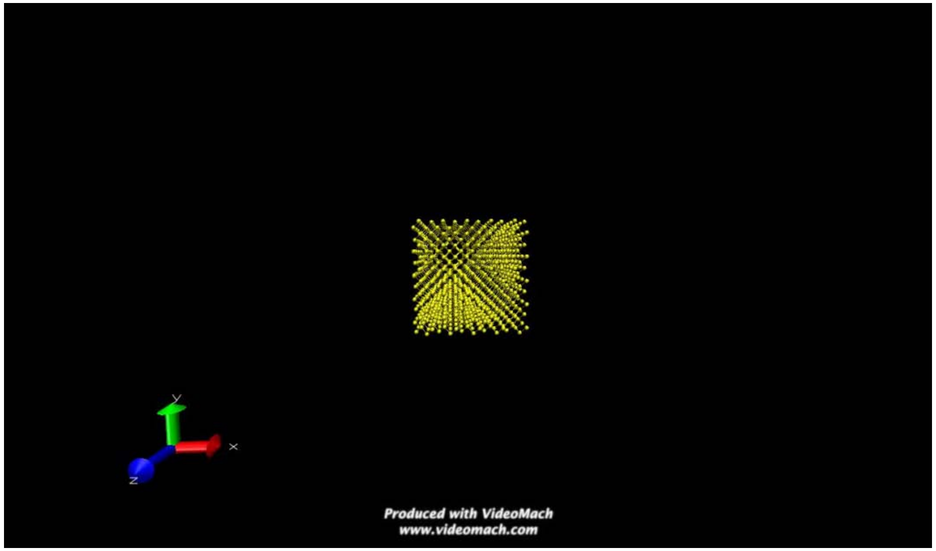
Random



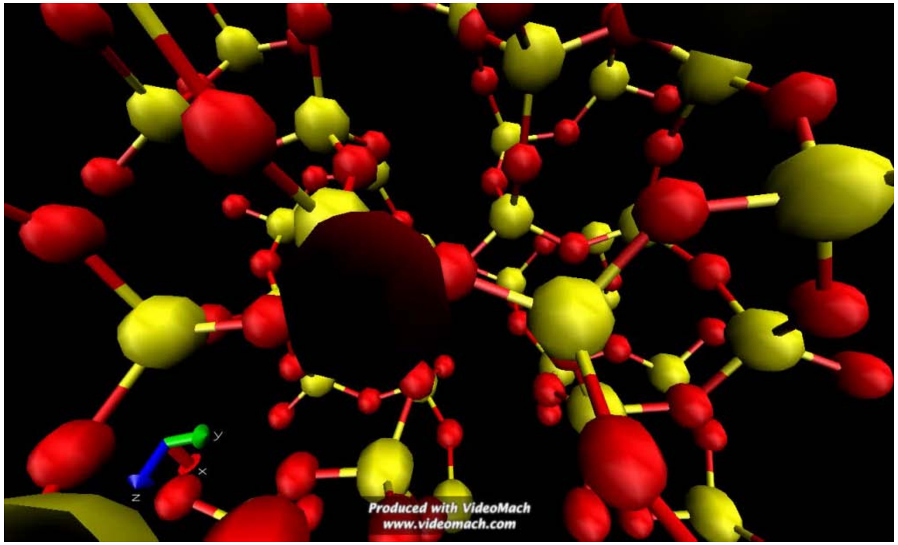


Crystalline Si and SiO2

crystalline Si

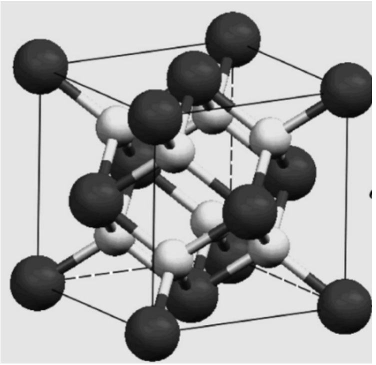


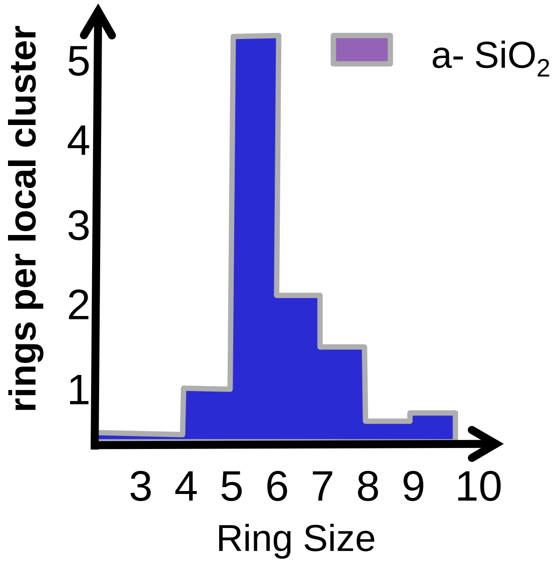
amorphous SiO2

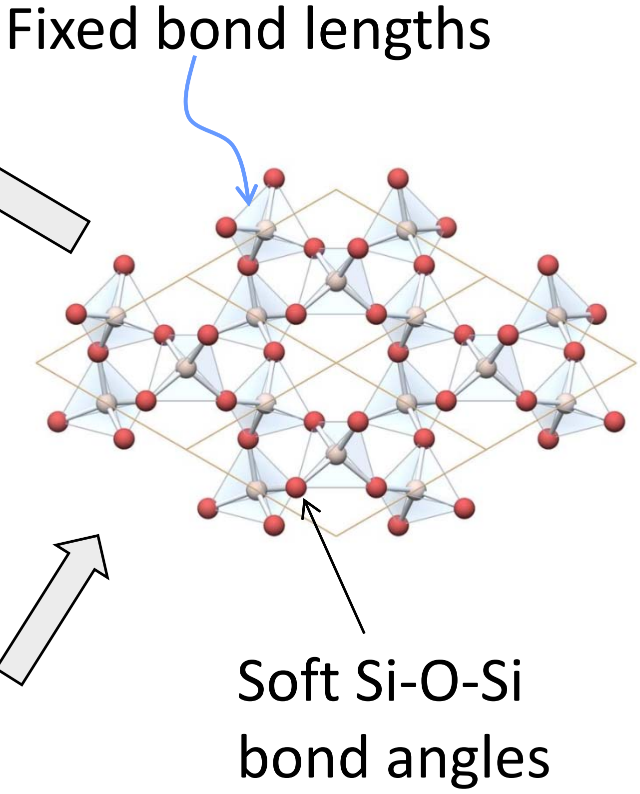


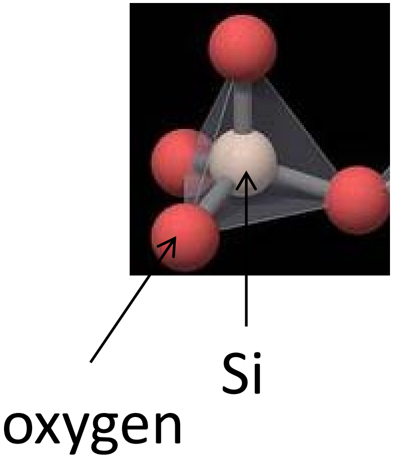
For a dynamic view of SiO2 see,
http://cst-www.nrl.navy.mil/lattice/struk.jmol/coesite.html

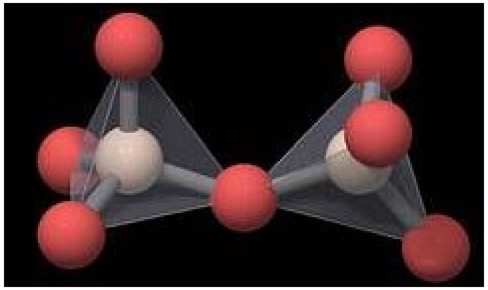
Crystalline vs. Amorphous SiO_2









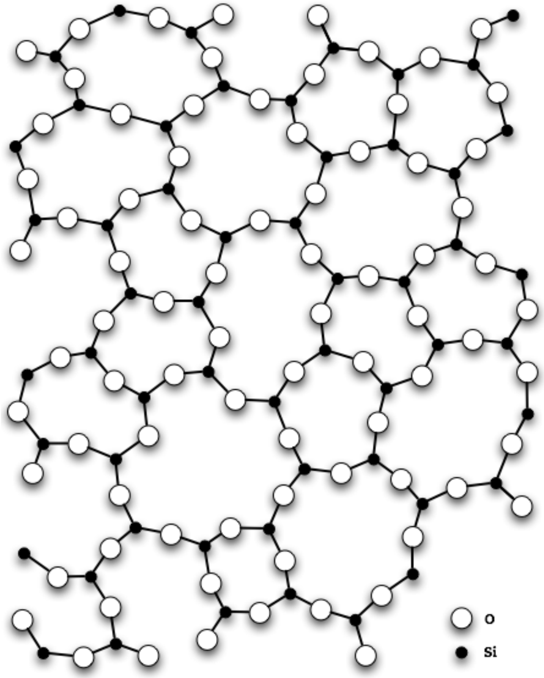


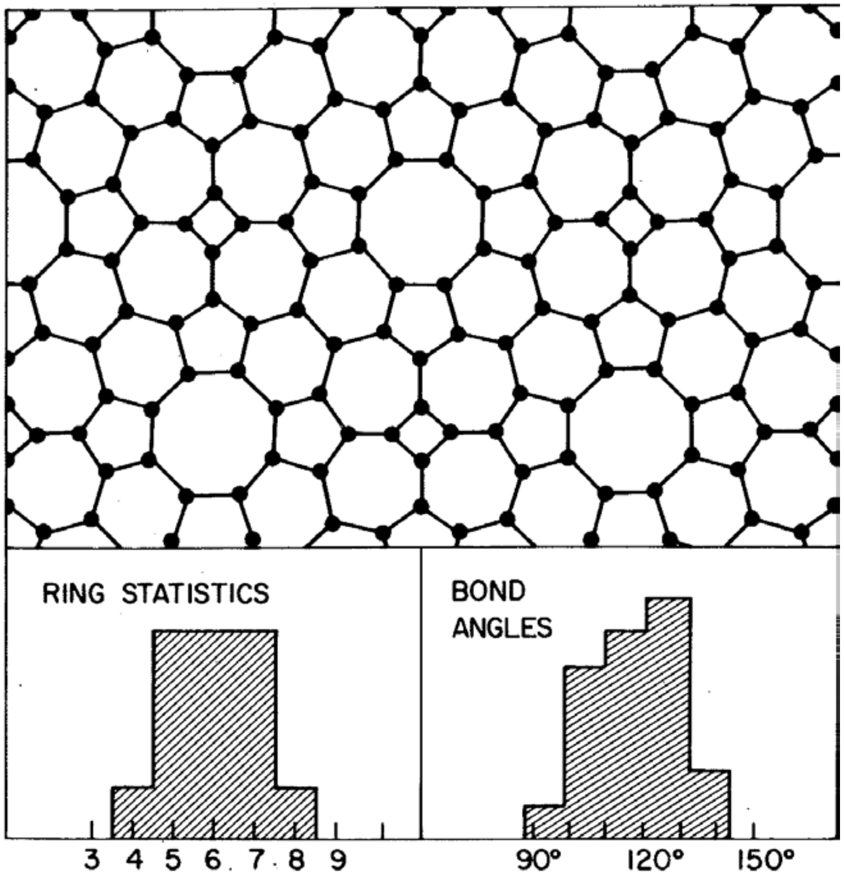
$$z_{Si} = 8 - N_{Si} = 4$$

$$z_O = 8 - N_o = 2$$

Amorphous is neither completely random, nor it is defective

Amorphous





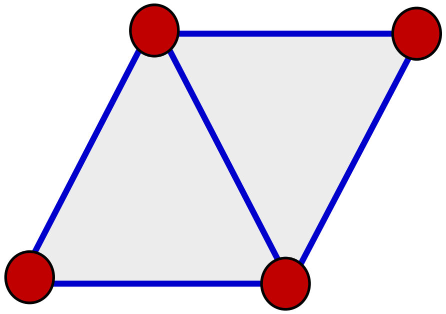
small scatter in ring distribution …

Geometry defines ring statistics

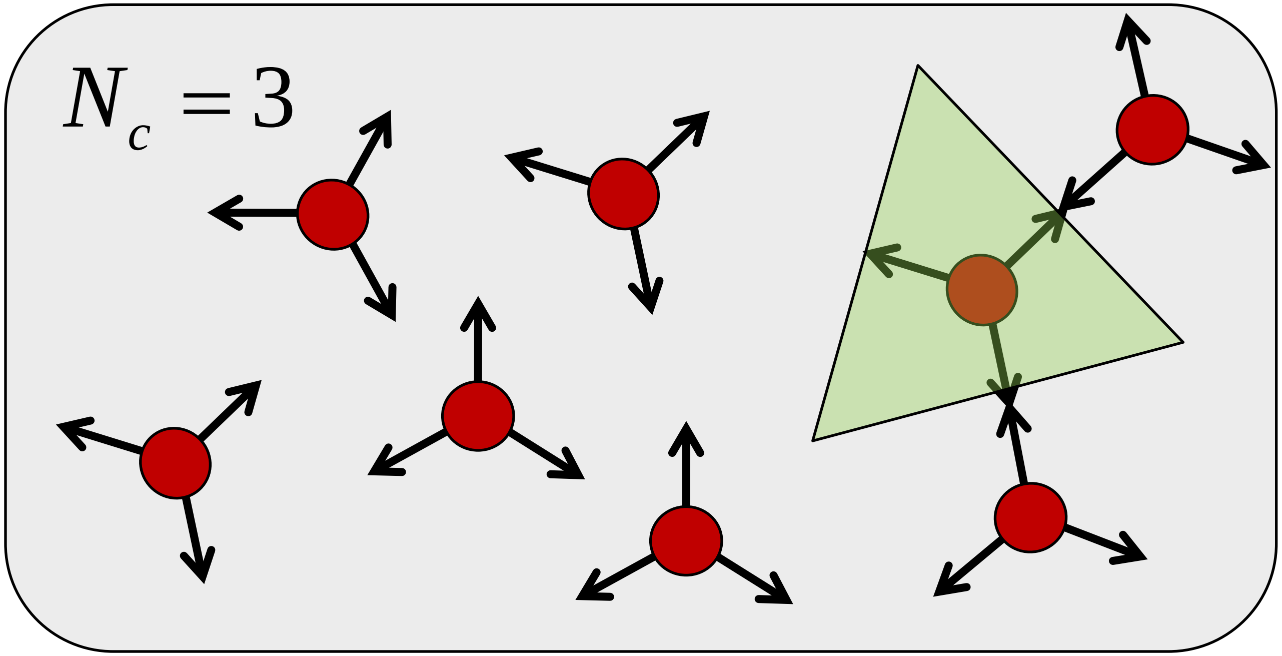
Euler Relationship in 2D

$$V - E + N = 1$$

vertices edges cell number

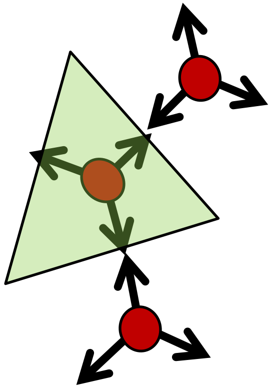


$$\left.\begin{array}{l} V = 4 \\ E = 5 \\ N = 2 \end{array}\right] \Rightarrow 1$$



$$N_c = 3$$

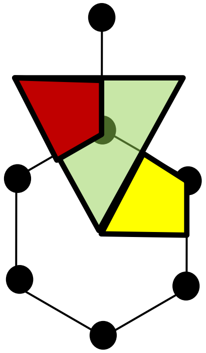
Geometry defines ring statistics



$$\left.\begin{aligned} V &= 1 \\ E &= \frac{3}{2} \end{aligned}\right\} 2E = 3V = N_p N$$

3 bonds/atoms to honeycomb lattice

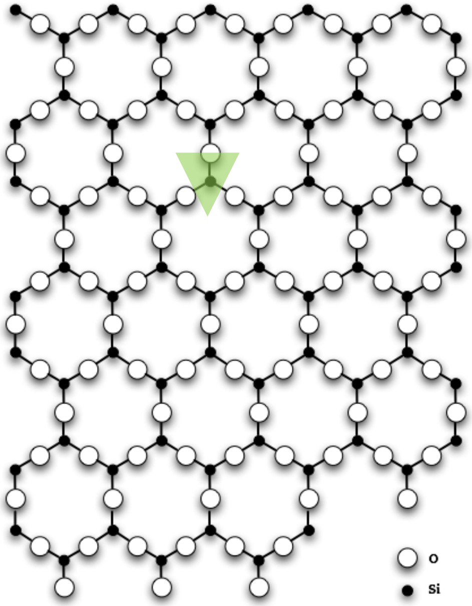
$$V - E + N = 1$$



$$\frac{N_p N}{3} - \frac{N_p N}{2} + N \sim 0$$

$N_p \cong 6 \longleftarrow$ edges/cell

$$6N = 3V \Rightarrow N = \frac{1}{2}$$

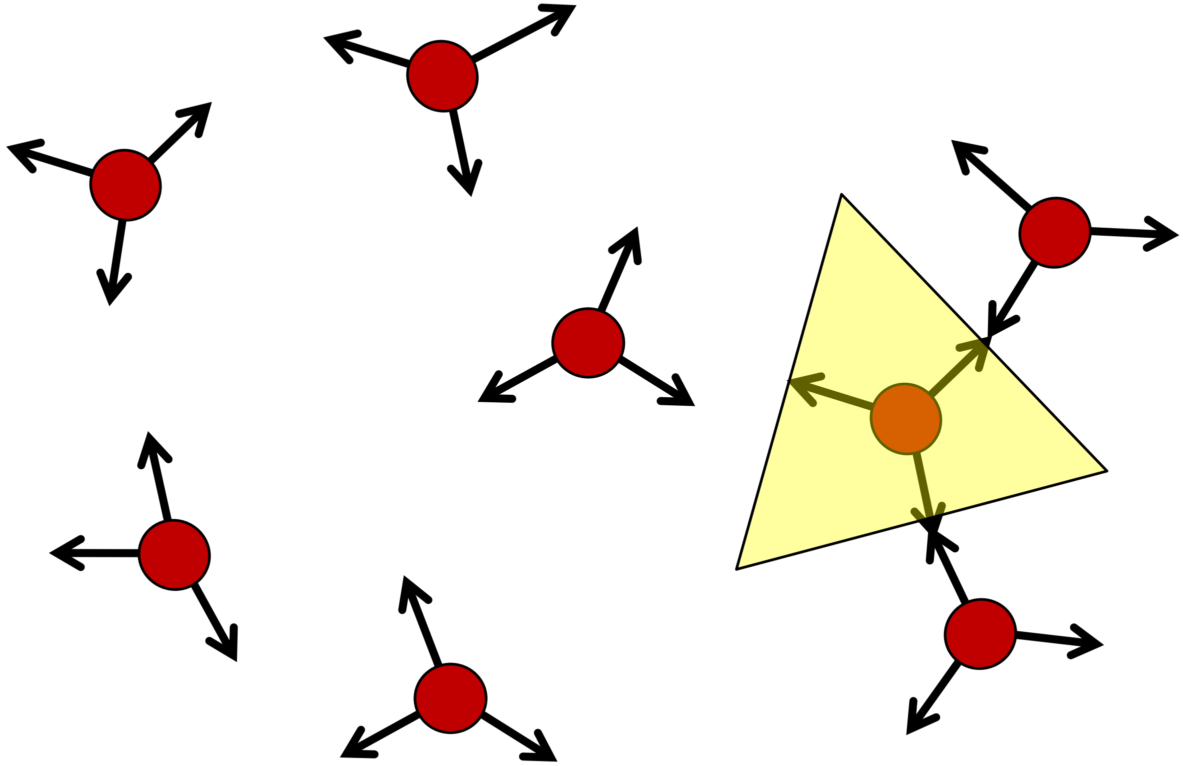


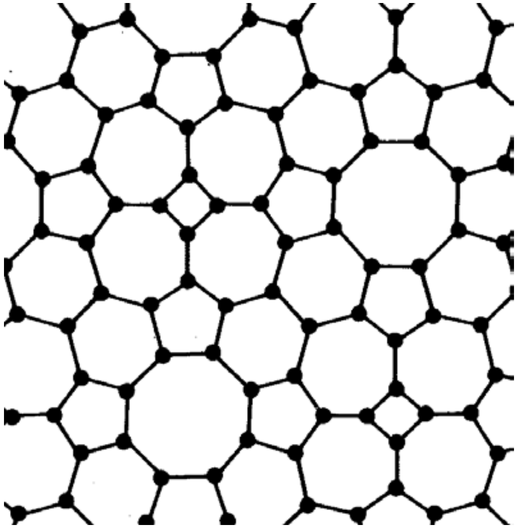
HW: 6 bonds/atoms triangular lattice

1/2 of a cell; therefore each cell must have 6-sides!

Rings with Hard vs. Soft Bonds

$$N_c = 3$$





Ring Statistics in Random Structure

Euler Relationship

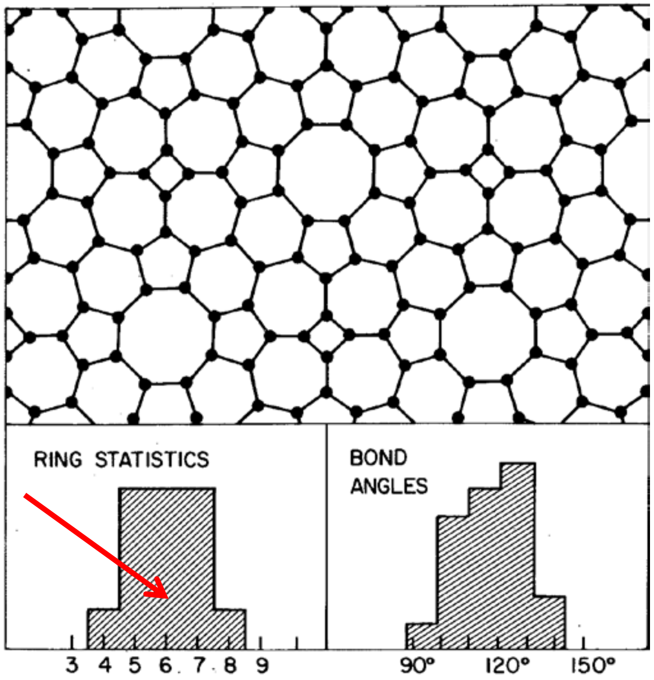
$$V - E + N = 1$$

$$2E = 3V = \langle N_p \rangle N$$

Prob. of
k-sided ring

$$\langle N_p \rangle = 6 \quad = \sum_k k \times P_k$$

$$6 = 9P_9 + 8P_8 + 7P_7 + 6P_6 + 5P_5 + 4P_4 + 3P_3$$



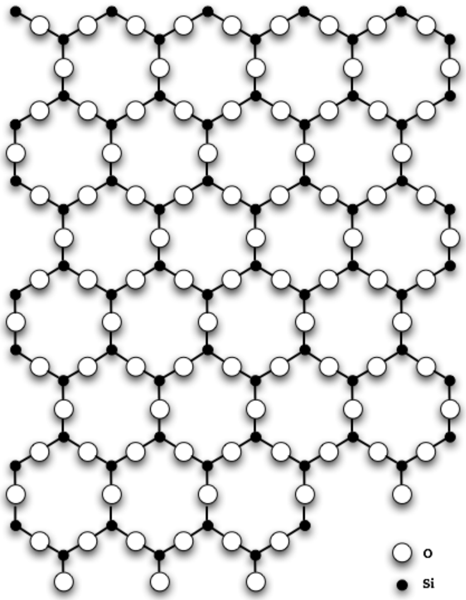
Ex. $P_9 = P_8 = P_4 = P_3 \equiv P$

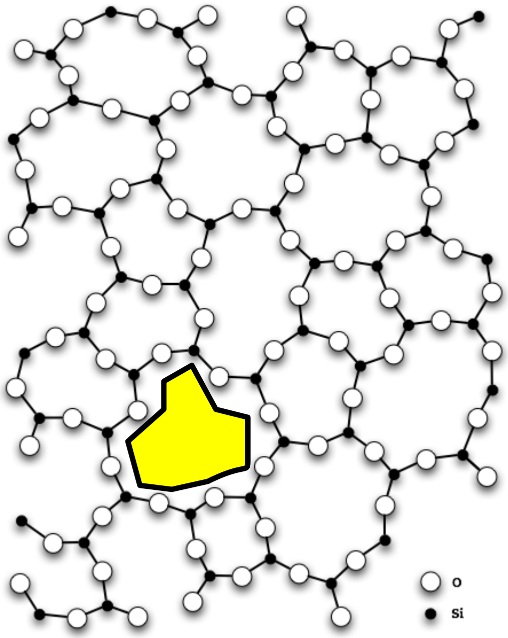
$P_7 = P_6 = P_5 \equiv 3P$

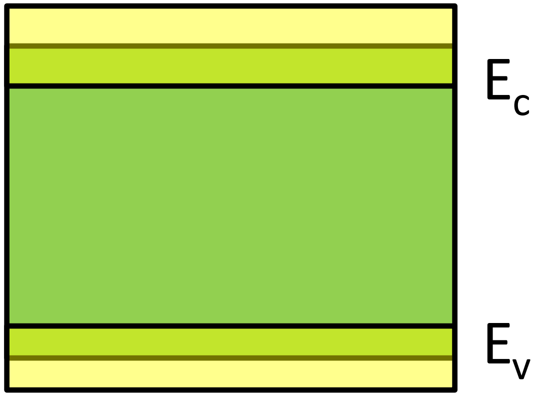
$$78P \approx 6 \;\Rightarrow P \sim 1/12$$

Large rings pay steric penalty and are therefore rare …

Amorphous Material and Bandtail states

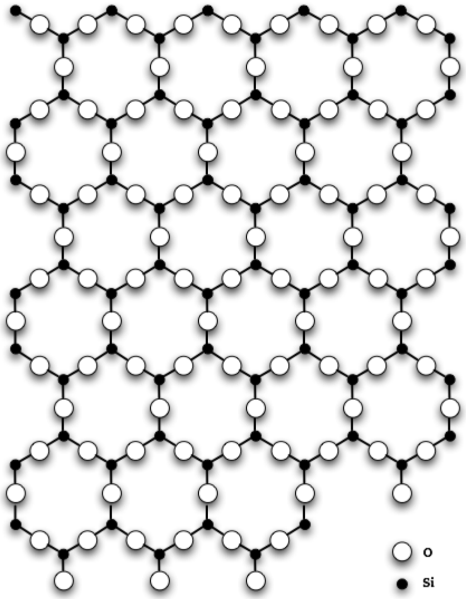


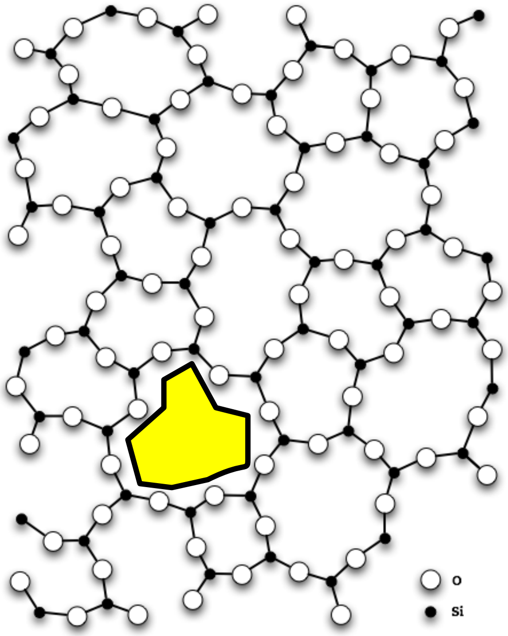


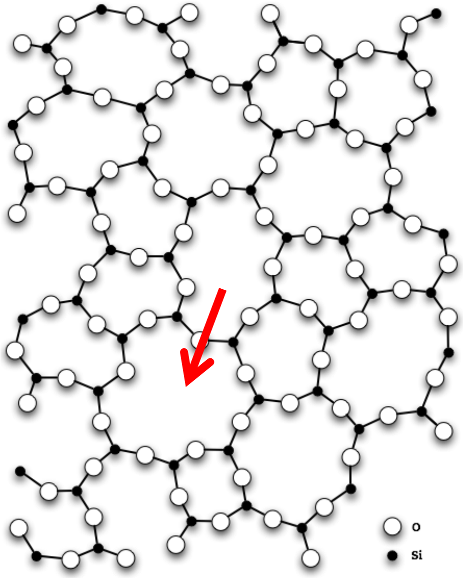


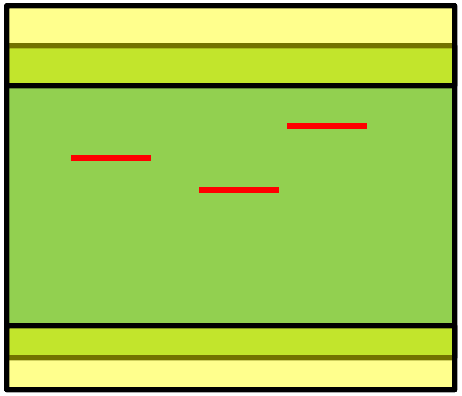
Resolves the puzzle why glass is transparent ….

Meaning of an oxide/nitride defect

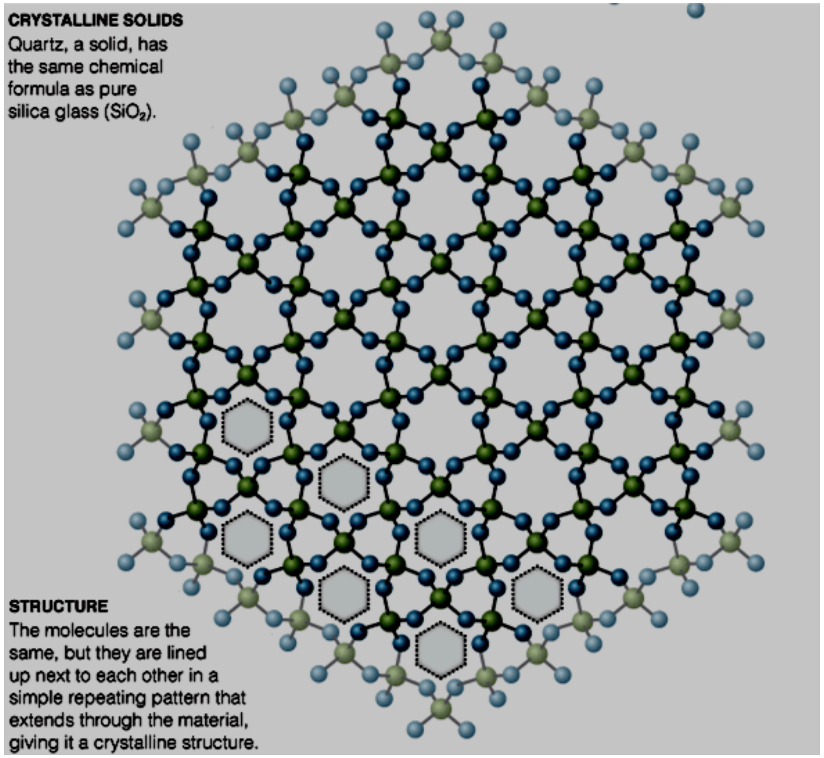








Crystalline vs. Amorphous Oxides

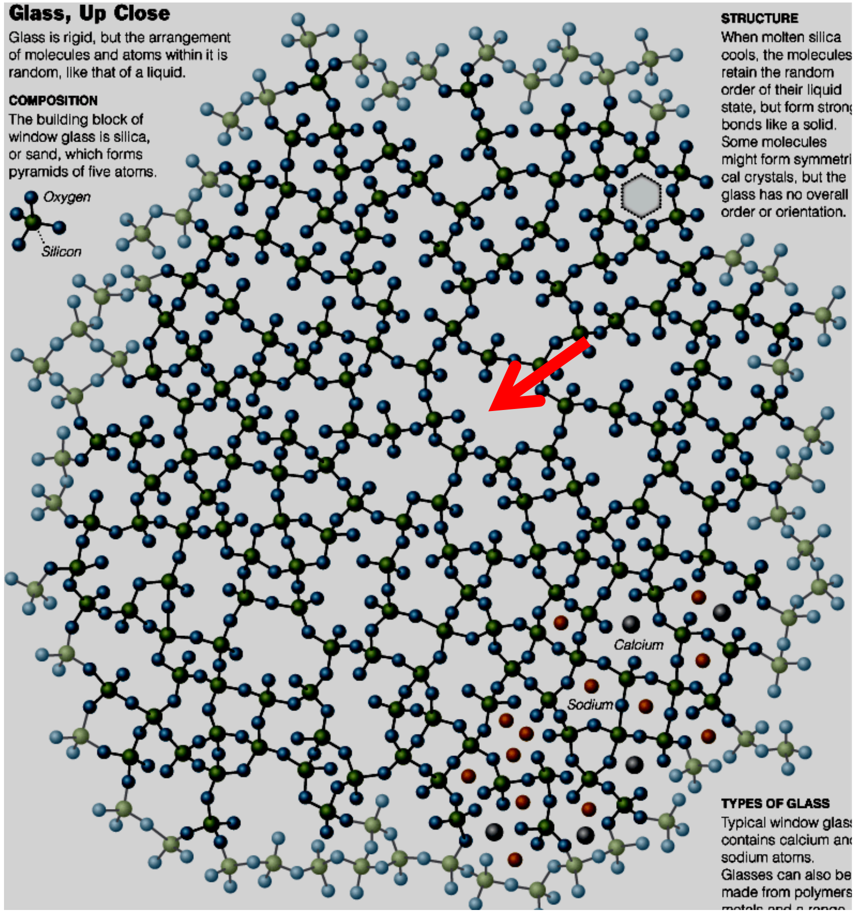


CRYSTALLINE SOLIDS

Quartz, a solid, has the same chemical formula as pure silica glass (SiO_2).

STRUCTURE

The molecules are the same, but they are lined up next to each other in a simple repeating pattern that extends through the material, giving it a crystalline structure.



Glass, Up Close

Glass is rigid, but the arrangement of molecules and atoms within it is random, like that of a liquid.

COMPOSITION

The building block of window glass is silica, or sand, which forms pyramids of five atoms.

STRUCTURE

When molten silica cools, the molecules retain the random order of their liquid state, but form stron
bonds like a solid. Some molecules might form symmetri
cal crystals, but the glass has no overall order or orientation.

TYPES OF GLASS

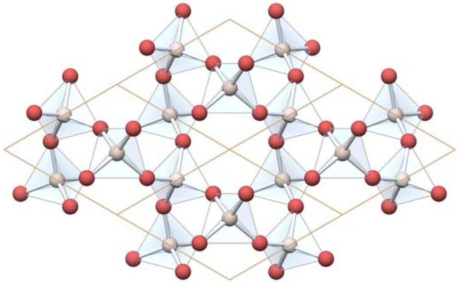
Typical window glas
contains calcium an
sodium atoms. Glasses can also be made from polymers

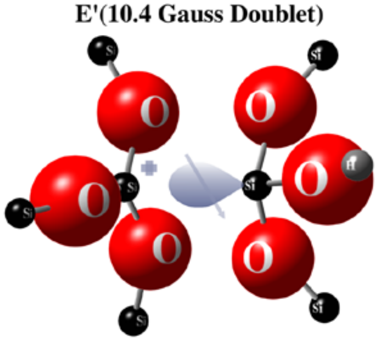
‘Glass up Close’,

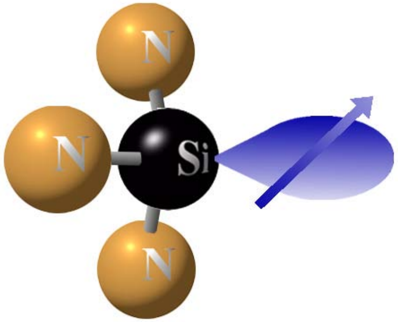
NY Times, July 29, 2008.

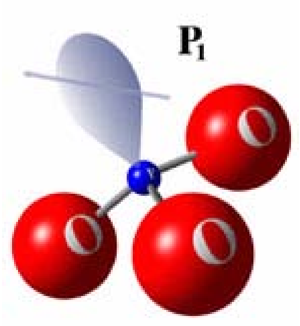
Bulk defects of missing oxygen: E’, K, and P defects

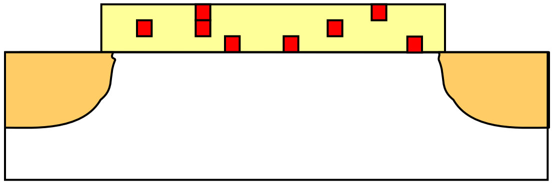
Courtesy:
Prof. Lenahan

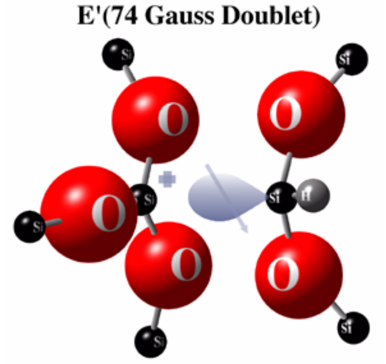


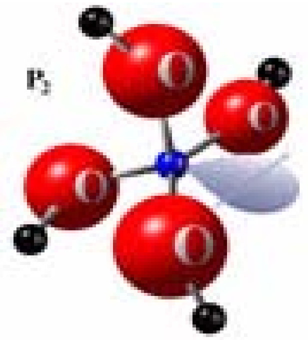


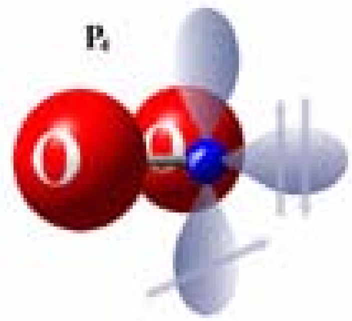






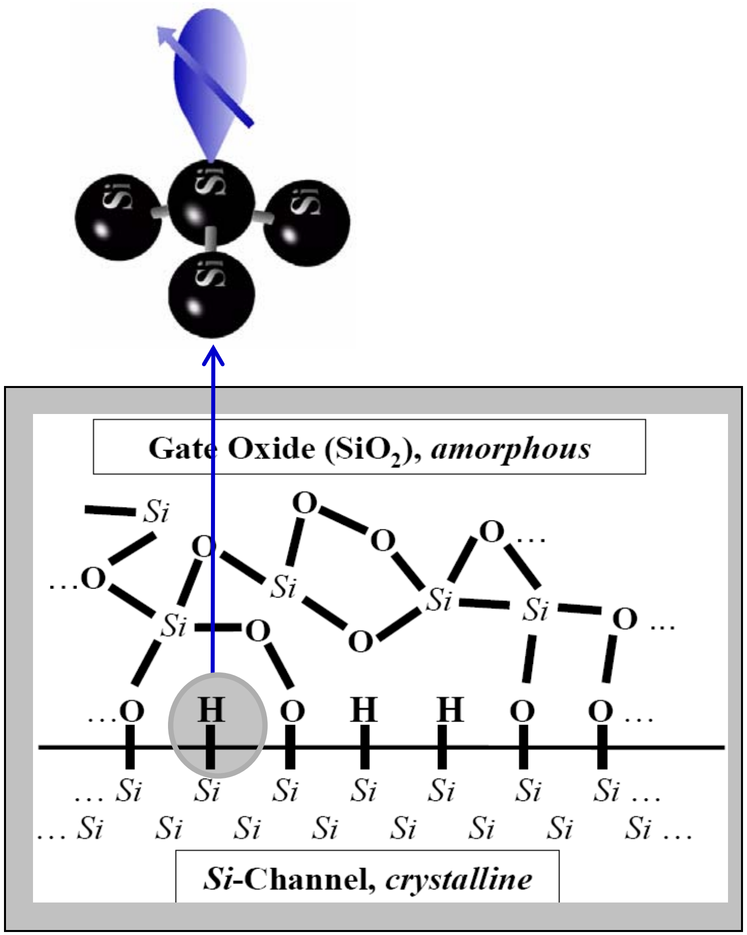


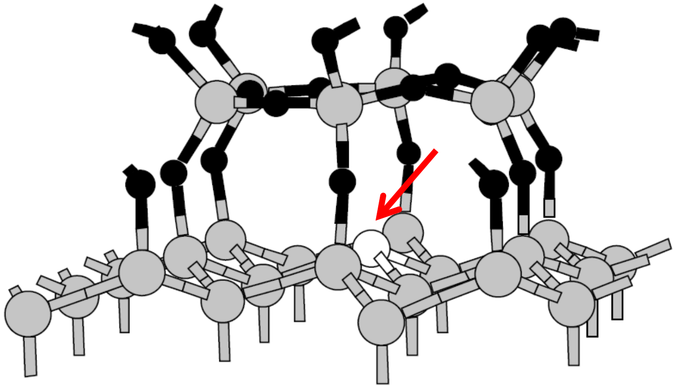




Responsible for gate dielectric breakdown
Will discuss in lectures 8 and 9

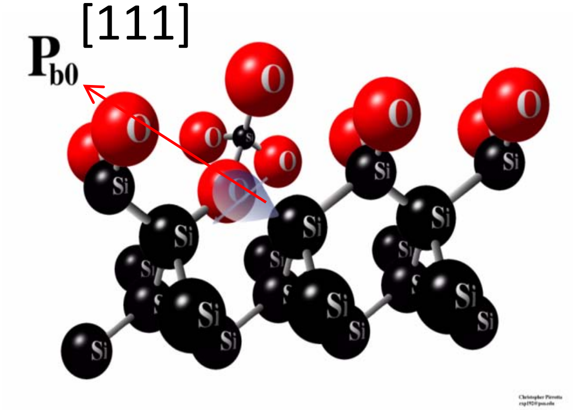
Pb centers – Interface Traps



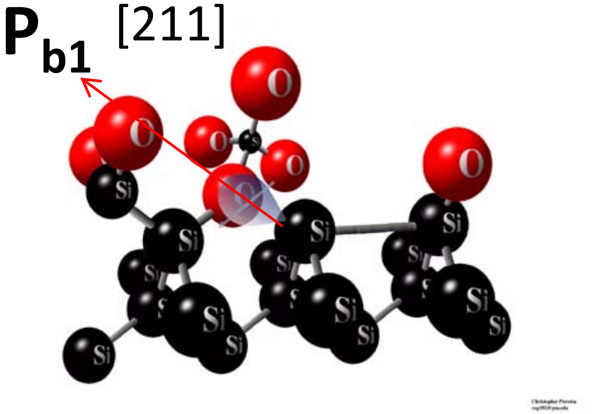


[111] surface
P_b along [111]

Stirling, PRL, 2000.



[100] surface
Pb_0 along [111]



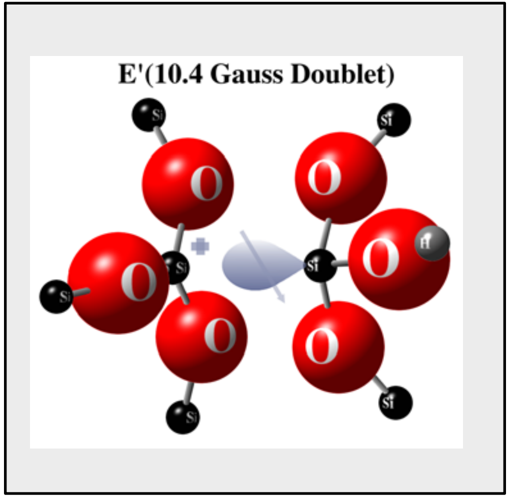
[100] surface
Pb_1 along [211]

Of Pa, Pb, Pc -- only Pb survives
Related to NBTI degradation
(Lecture 10)

Electron Spin Resonance: a ‘microscope’ for defects

10 GHz Microwave

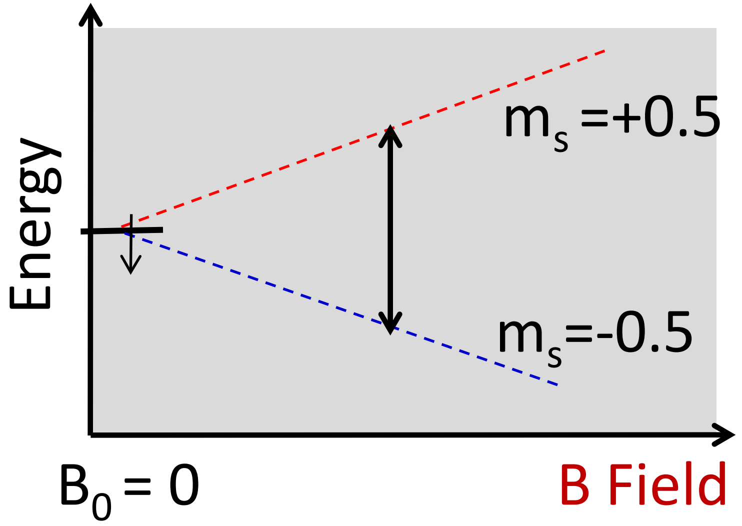
Variable B-field



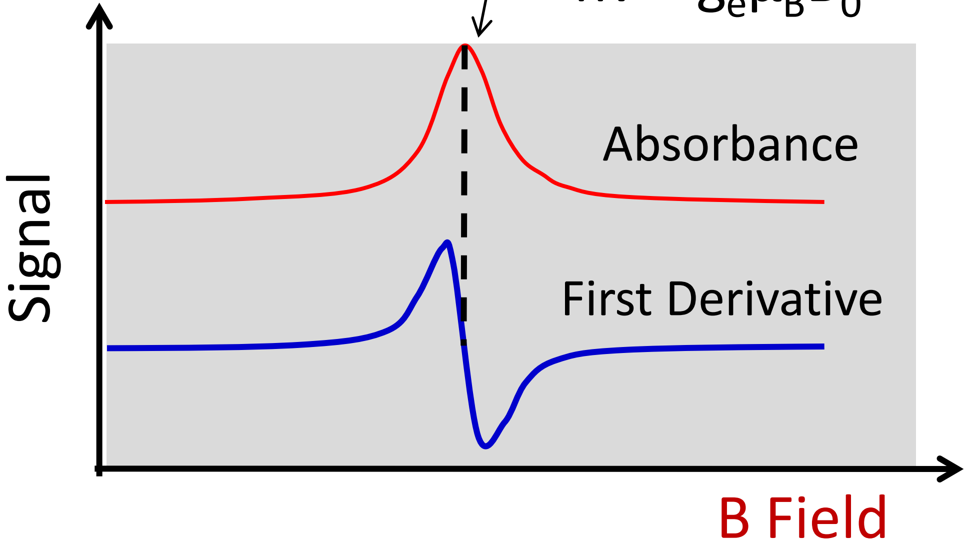
Absorption Spectra

B-value suggests local environment

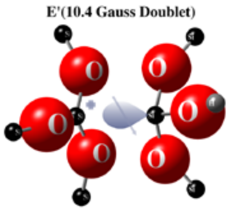
$\Delta E = g_e \mu_B B_0$



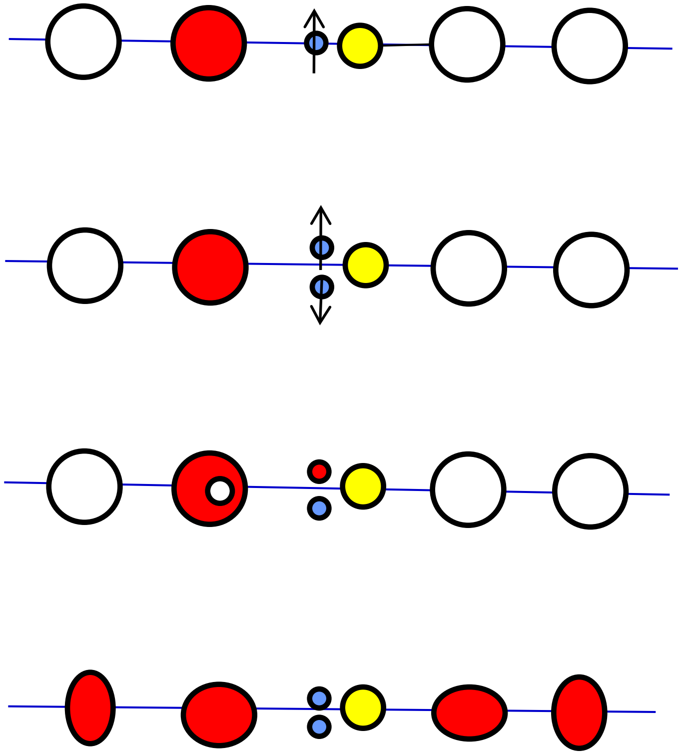
$h\nu = g_e \mu_B B_0$



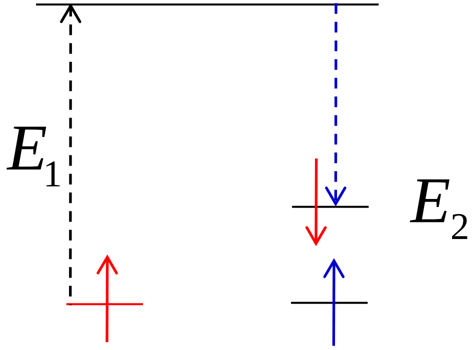
ESR Invisible Defects



Paramagnetic materials may appear diamagnetic



$$D_0 + E_1 = D^+ \qquad D_0 - E_2 = D^-$$



$$2D_0 + (E_1 - E_2) = D^+ + D^-$$

$$2D_0 + (E_1 - E_2) - U_{e-h} = D^+ + D^-$$

Like superconductivity with phonon assisted e-e attraction

Conclusions

- Reliability is a very important technology problem. The success or failure of any technology depends on its intrinsic reliability (e.g. Stone vs. Cu age)

- Historically reliability has been an empirical science; it has changed dramatically since WWII (Military applications, AT&T trans-Atlantic cable, IBM mainframe, Introduction of CMOS).

- Reliability as a ‘Stochastic process with a threshold’ provides the physical basis for wide range of phenomena.

- There are many reliability concerns for electronic devices – an analysis of these problems beings with the analysis of the nature of defects. We will related bulk oxide E’ centers to TDDB and depassivation of SiH bonds at the interface to NBTI.

Ring Statistics in Random Structure

Euler Relationship

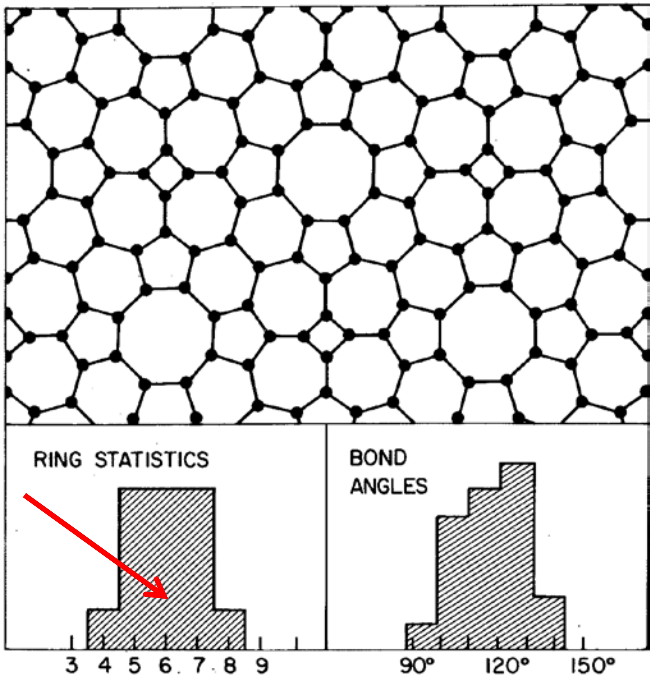
$$V - E + N = 1$$

$$2E = 3V = \langle N_p \rangle N$$

$$\langle N_p \rangle = 6 \quad = \sum_k k \times P_k$$

Prob. of
k-sided ring

$$6 = 9P_9 + 8P_8 + 7P_7 + 6P_6 + 5P_5 + 4P_4 + 3P_3$$



Ex. $P_9 = P_8 = P_4 = P_3 \equiv P$

$P_7 = P_6 = P_5 \equiv 3P$

$$78P \approx 6 \;\Rightarrow P \sim 1/12$$

Large rings pay steric penalty and are therefore rare …