MEMS 201
Microsystems' Materials: Crystal Structures

Presented by
Southwest Center for
Microsystems Education
-SCME-
June 2012

SCME is a National Science Foundation Advanced Technological Education (ATE) Program at the University of New Mexico.

We offer professional development and educational materials to excite and engage high school, community college and university students in the field of Microsystems (MEMS) technology.

Support for this work was provided by the National Science Foundation's Advanced Technological Education (ATE) Program through Grants #DUE 0992411.

Our Presenters

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Southwest Center for Microsystems Education

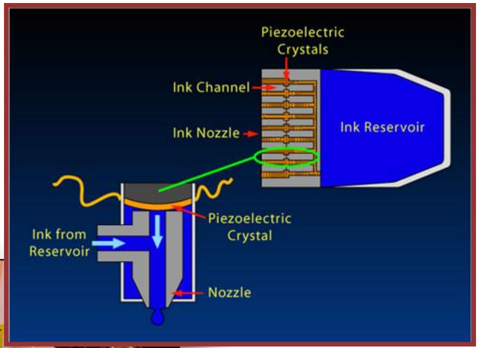
Objectives for Today

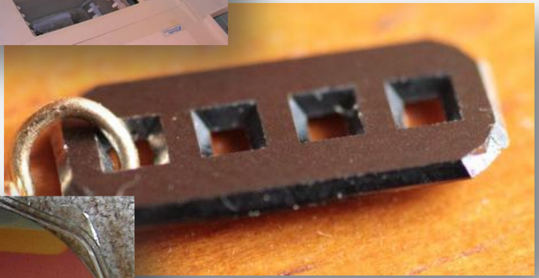
- Brief overview of what SCME can do for you
- Solid Structures
- Crystal Orientation – Miller Index
- Crystal Orientation and MEMS

Educational Materials

To date SCME offers

- 150 Shareable Content Objects (SCOs)
  - Informational Units / lessons
  - Supporting activities
  - Supporting assessments
- 37 Learning Modules in the areas of
  - Safety
  - Microsystems Introduction
  - Microsystems Applications
  - Bio MEMS
  - Microsystems Fabrication
- 11 Instructional Kits
- All are available @ scme-nm.org





SCME
Southwest Center for Microsystems Education

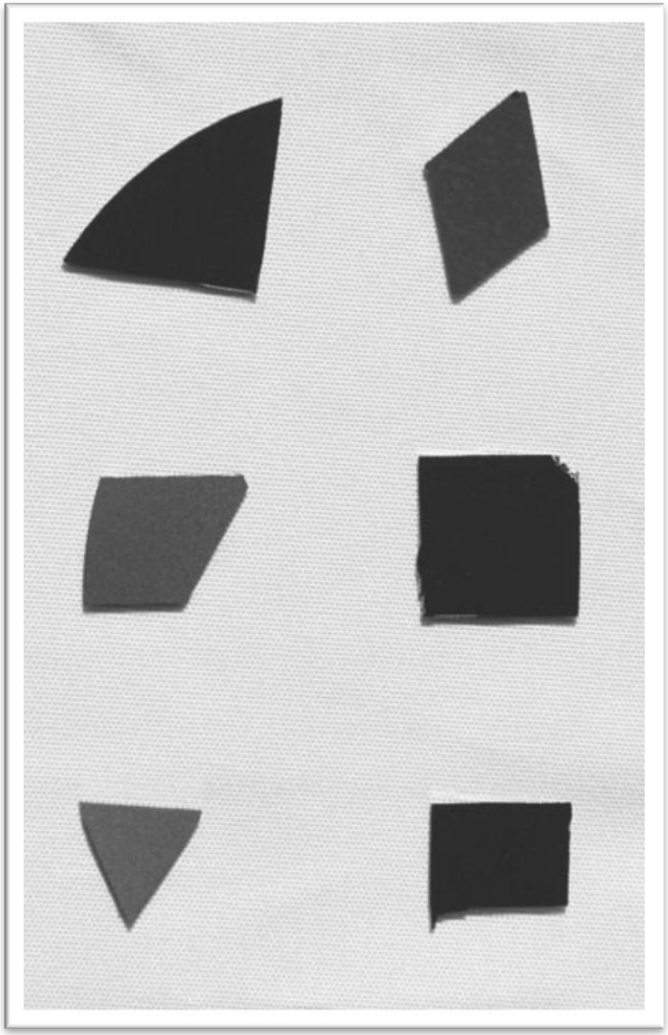
Professional Development

- 4 to 5-day workshops
- 2-day workshops
- 1-day workshop
- Conferences and conference workshops
- Create hubs at other colleges to teach our workshops
- Webinars

Let’s start with a question for you.

Shown here are shards from different silicon wafers. Why are the shards different shapes?

a. The wafers were hit differently – at different angles creating these shapes.
b. Silicon is amorphous, thus it breaks randomly.
c. The wafers were cut from different ingots of different crystal orientations.
d. The right angle pieces are from a single-crystal wafer and the other pieces are from a polysilicon wafer.



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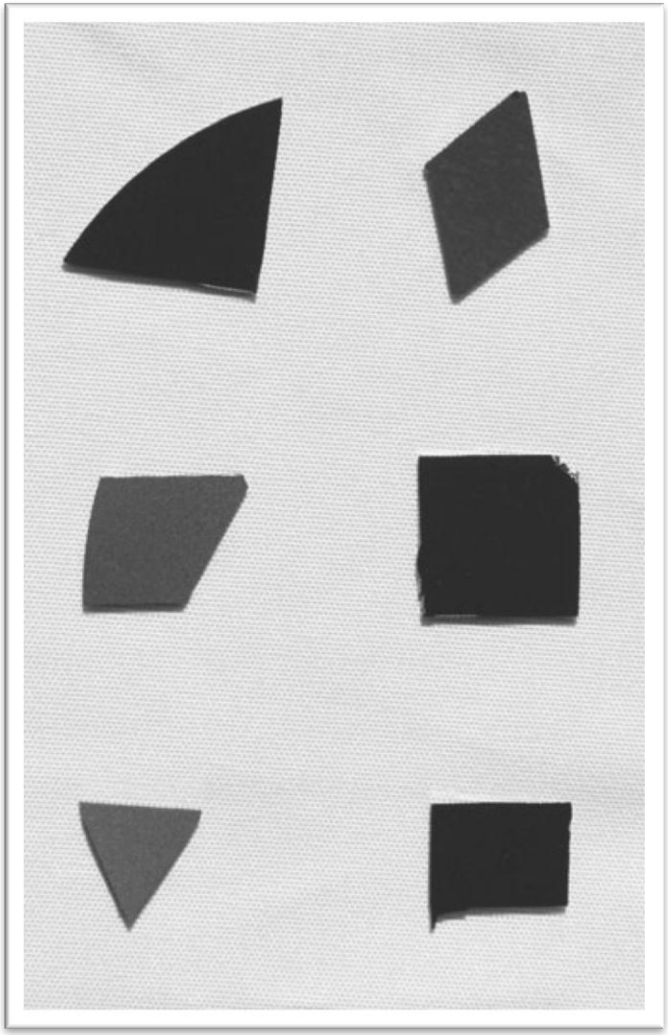


The State of Solids

All solid matter is either amorphous or crystalline.

Irregular arrangements are called amorphous or noncrystalline.

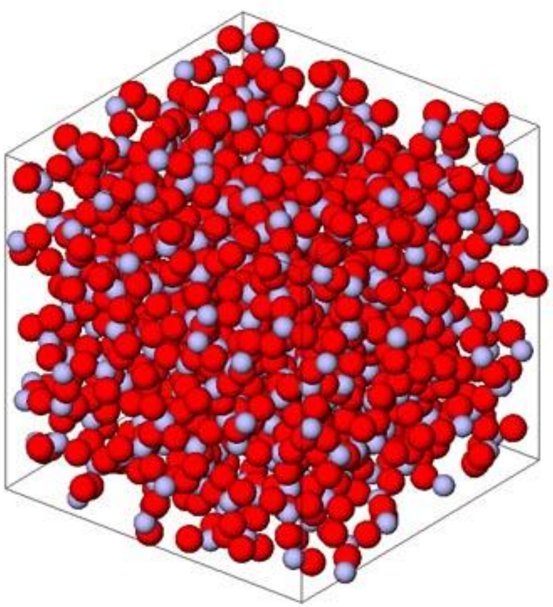
Amorphous: Moldavite, a natural glass formed by meteorite impact.
[Image courtesy of H. Raab – Wiki image]

Definitive patterns with a repeating structure are called crystalline structures.

Diamond
[Image courtesy Public Domain]

Amorphous Solids

When a solid's atoms are randomly "arranged" in a non-predictable order, the solid is referred to as amorphous.



Amorphous solids shatter or break into irregular patterns, much like peanut brittle.

Amorphous Characteristics

- No long range order exists at the atomic level. No predictability in the position of atoms, even over a short distance (i.e. a few nanometers).
- An amorphous solid cannot be cut (cleaved) like a crystal. It shatters rather than breaks along a plane.

Amorphous: Moldavite, a natural glass formed by meteorite impact.
[Image courtesy of H. Raab – Wiki image]

A Poll Question

Which of the following is NOT an amorphous solid?

a. *Glass*
b. *Peanut Brittle*
c. *Styrofoam*
d. *Salt*
e. *Plastic*

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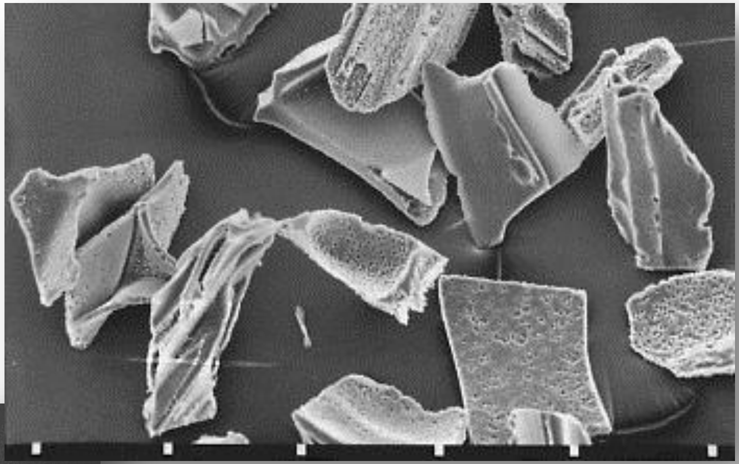
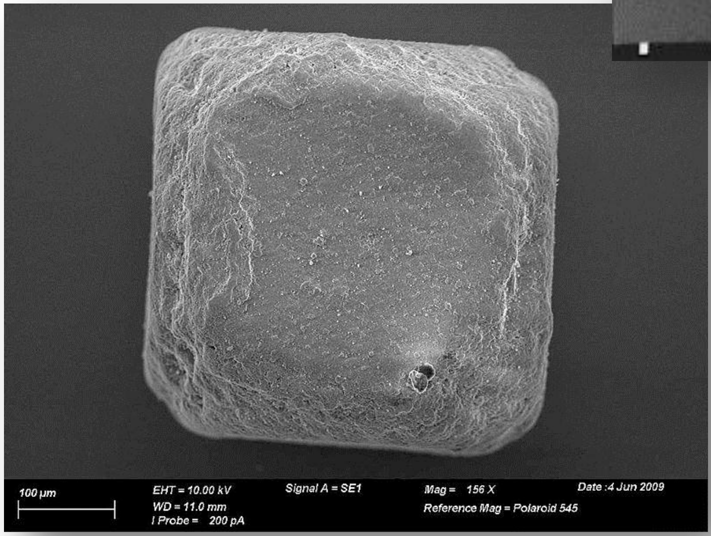




Scanning Electron Microscope images of glass shards (top) and table salt (left).

SEM image of glass provided by A.M. Sarna-Wojcicki

Crystalline Materials

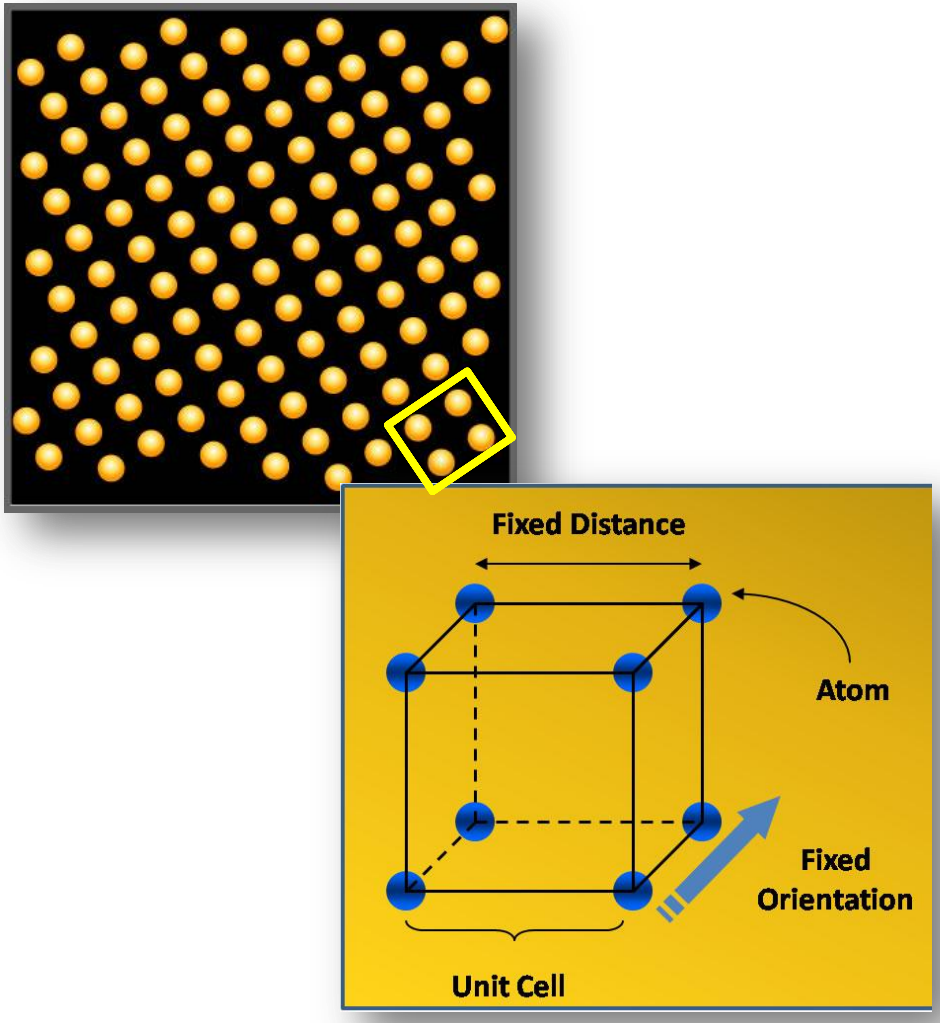
Crystalline materials fall under one of two categories:

Single or Mono Crystal

Polycrystalline

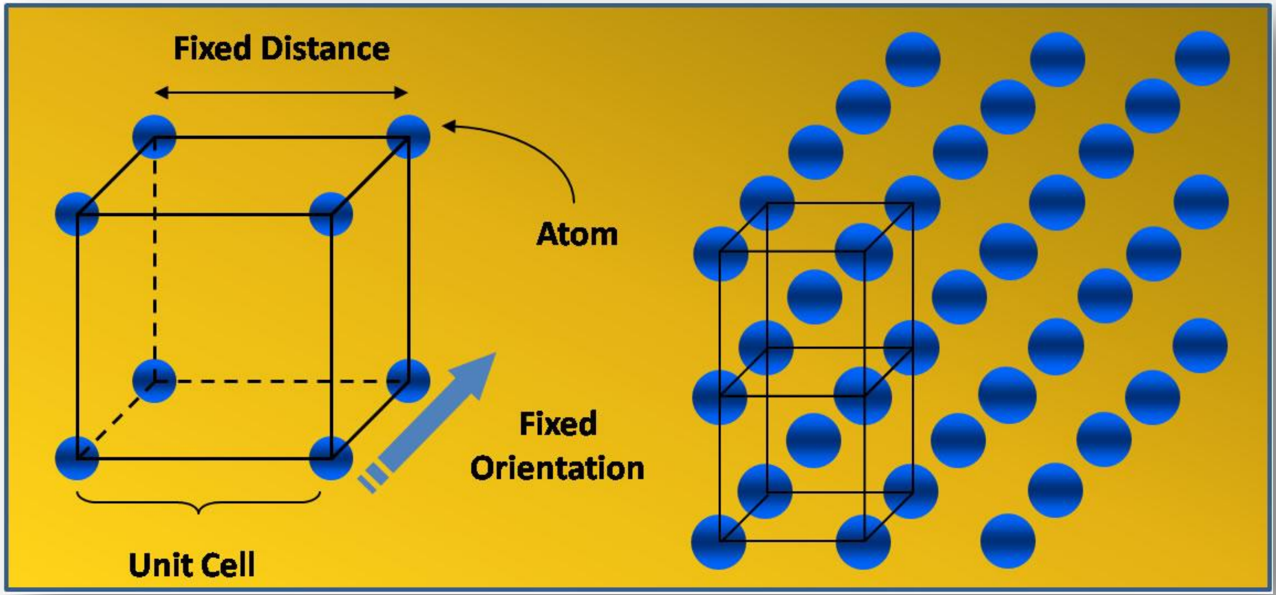
Single Crystalline Solids

- Matter composed of atoms arranged in a definitive pattern with a repeating structure is called a crystal.
- The repeating structure is called a unit cell.

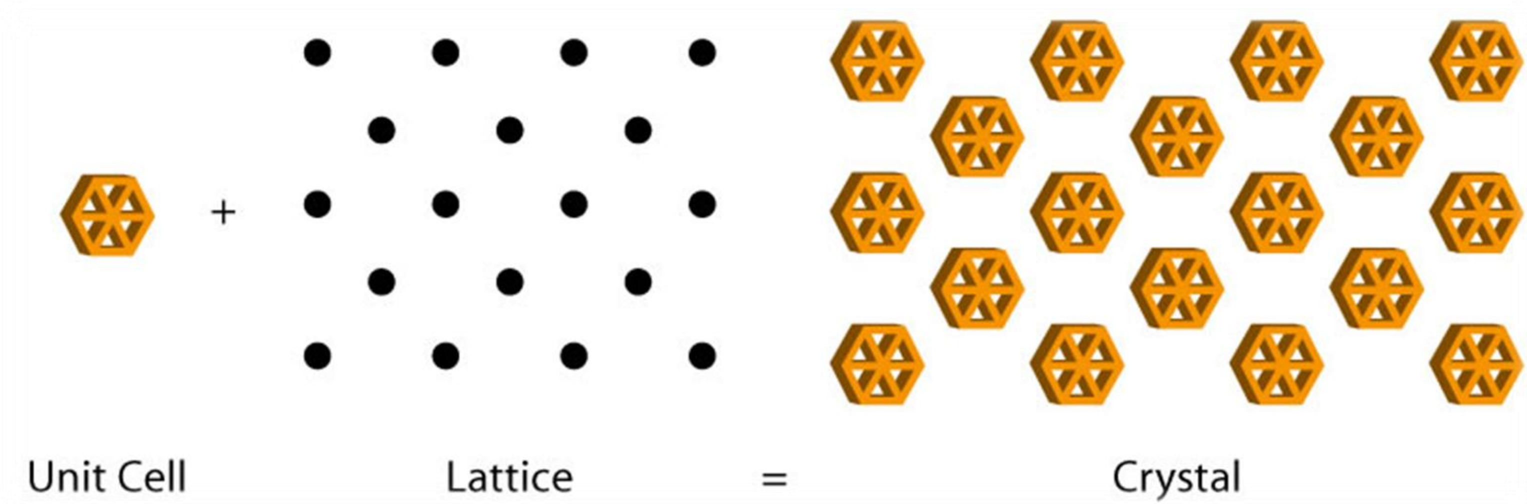


The Unit Cell

- The unit cell is the simplest repeating unit in a crystal.
- All unit cells are identical and are oriented the same way
- The opposite faces of a unit cell are parallel
- The edge of the unit cell connects equivalent points. The resulting structure is a lattice.



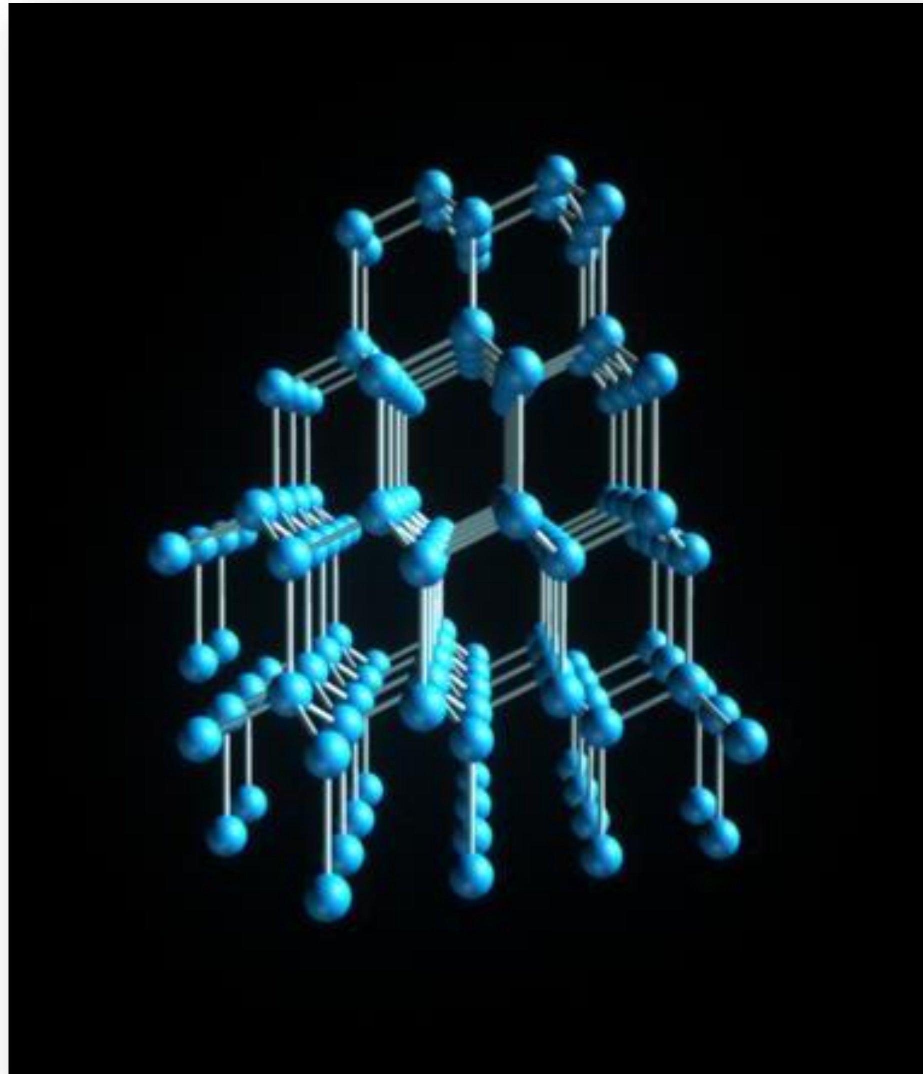
The Lattice Structure



- The pattern of a crystal is like the repeating pattern on wallpaper or tile.
- When viewed from different angles or planes one would see different geometries or patterns.

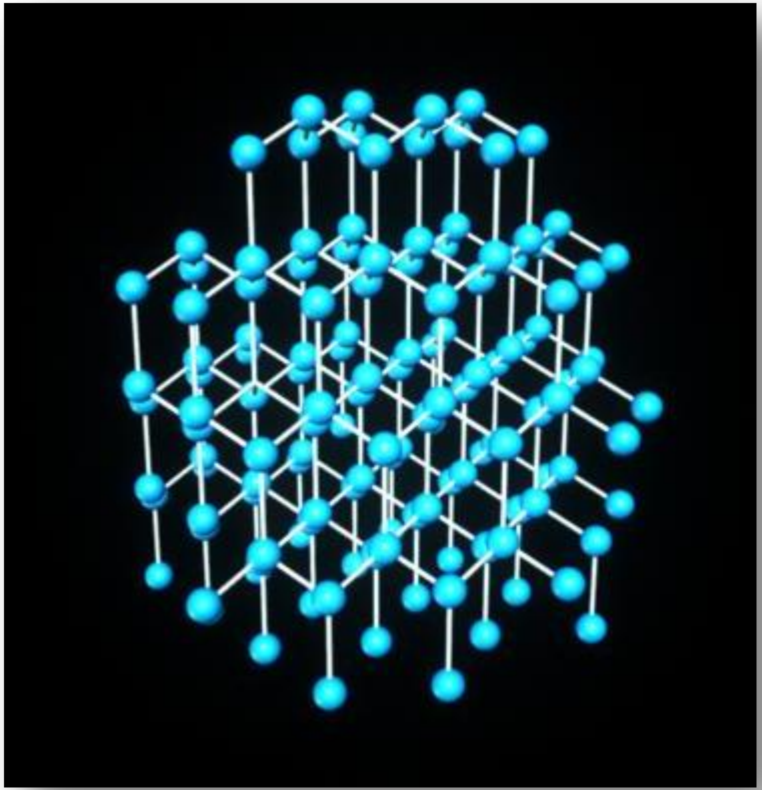
Single Crystals

- Single crystals are defined by a regular, well-ordered atomic lattice structure.
- Crystals have strong electrical attractions between the atoms
- Crystals are typically very strong



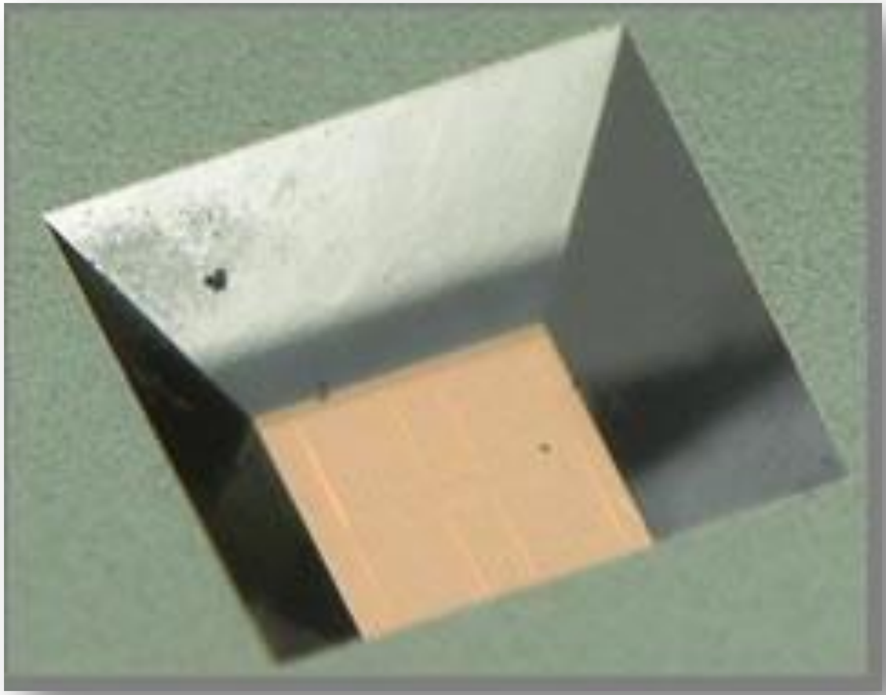
Diamond Crystal

- Diamonds are single crystals.
- High quality diamonds are colorless with none to few impurities or structural defects in the crystal lattice.
- Pure silicon, germanium, and man-made diamonds are used in MEMS and semi-conductor fabrication
- Other crystal solids include gemstones, salt, sugar, some metals



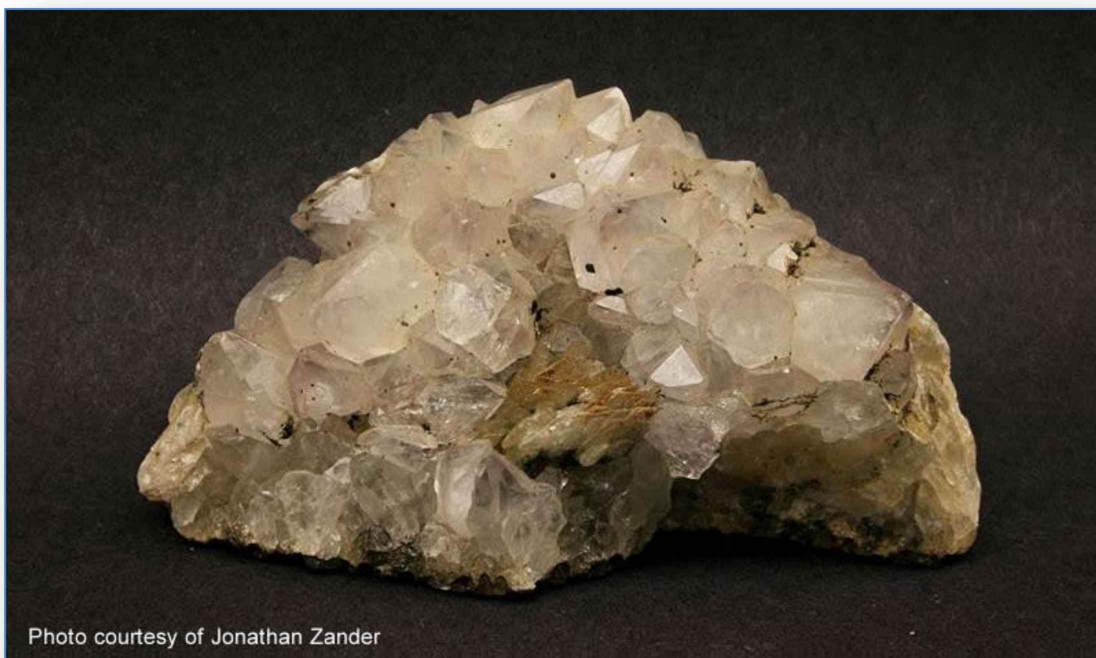
Single Crystal Characteristics

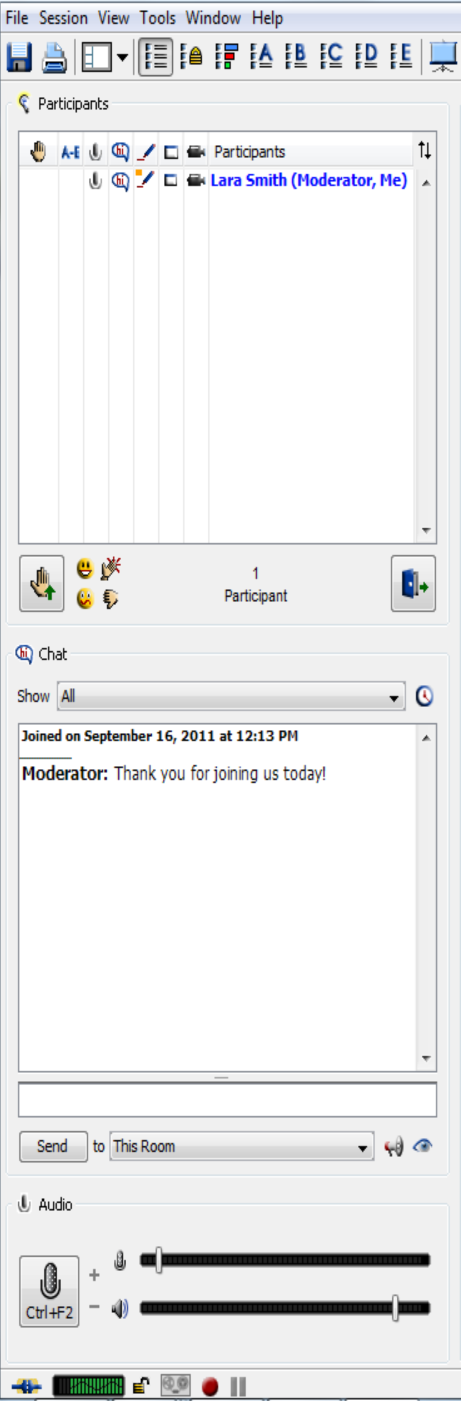
- Extreme long term order and predictability exists with very few defects.
- The environment is always the same throughout the crystal solid.
- Crystals can be cut along flat planes called *cleavage faces*. Cutting a crystal is essentially separating one lattice plane from its adjacent plane.
- This produces a nearly perfect flat surface.



Polycrystalline Solids

- Polycrystalline solids consist of small single crystals called **grains**.
- The grains randomly arrange to form the final structure.





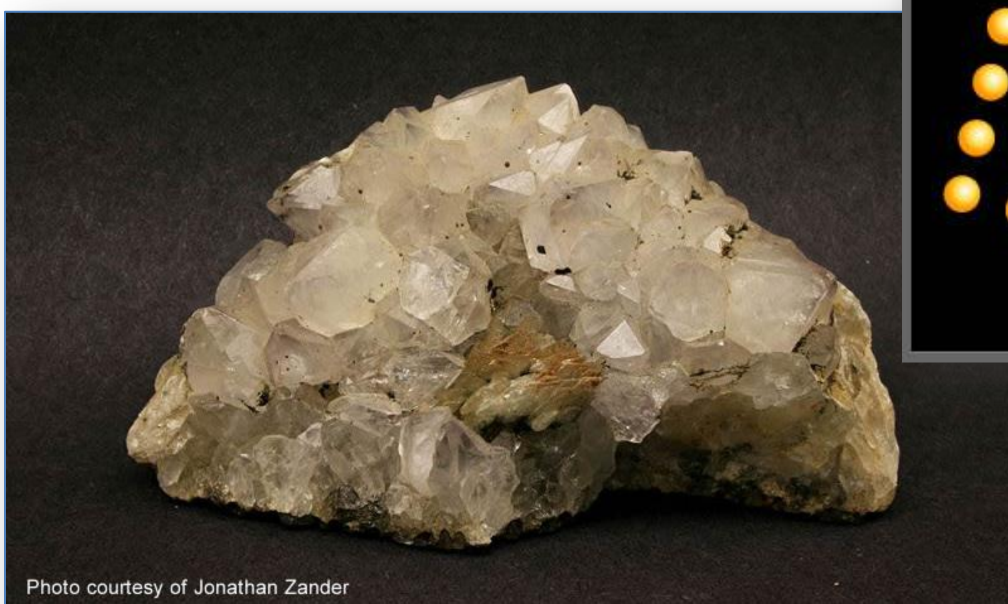
QUESTION:

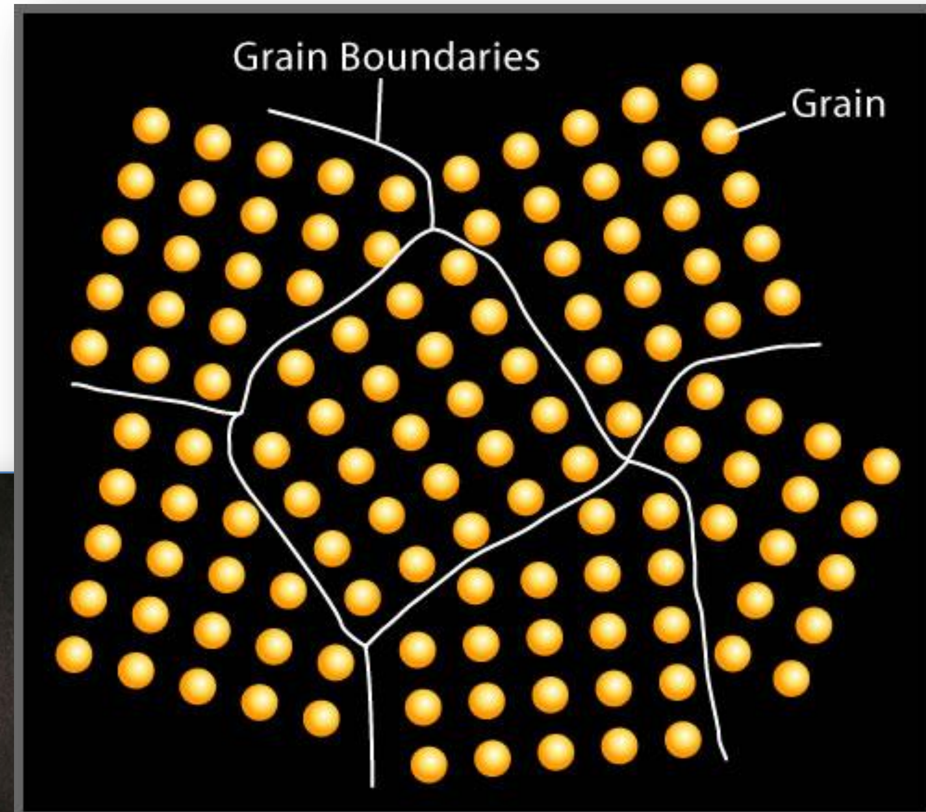
How do you think polycrystalline material would break?

Type answers into the chat box

Grain Boundaries

If you said where the single crystals join together, you are correct!

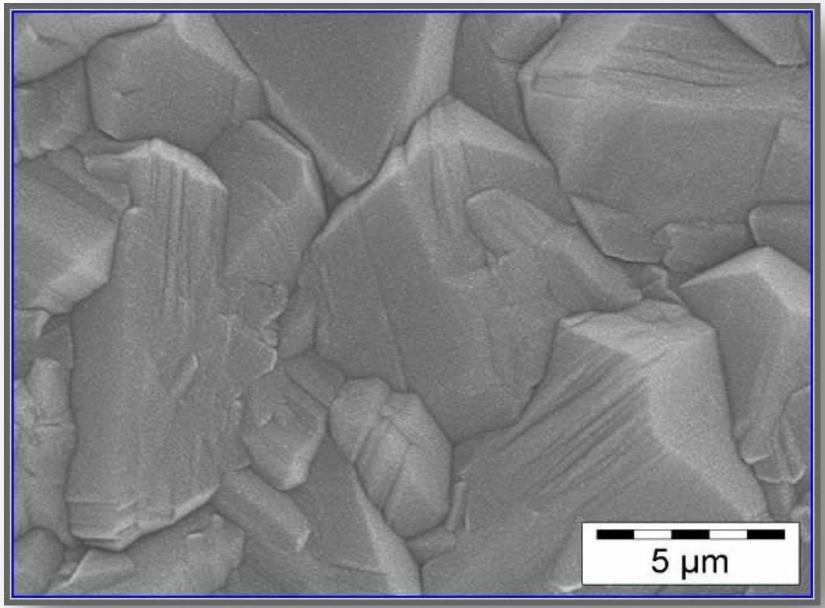




Electrical and thermal properties are determined by the grain structure.

Polycrystalline and MEMS

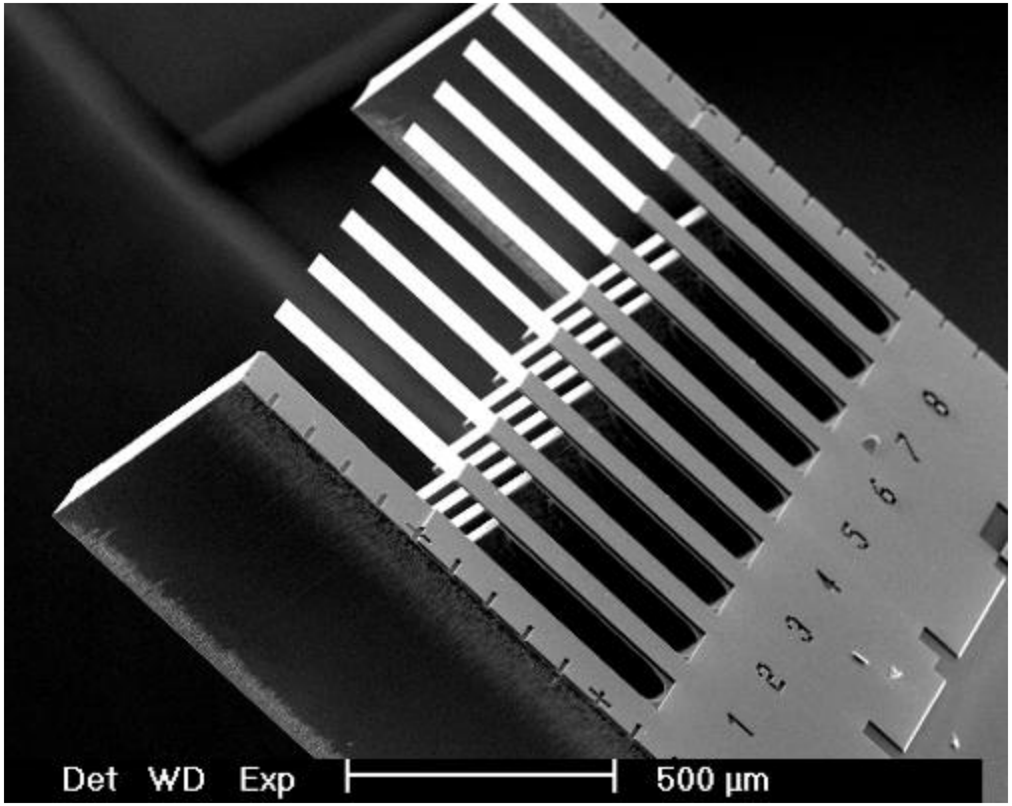
- Polycrystalline solids consist of some metals and metal alloys, fabricated diamonds, and polysilicon.
- The imagine to the right is of a polycrystalline diamond.
- Silicon can be either polycrystalline or single crystal.



Polycrystalline Diamond
[Courtesy of Prof. Dean Aslam, Michigan State University]

Polysilicon Micro-structures

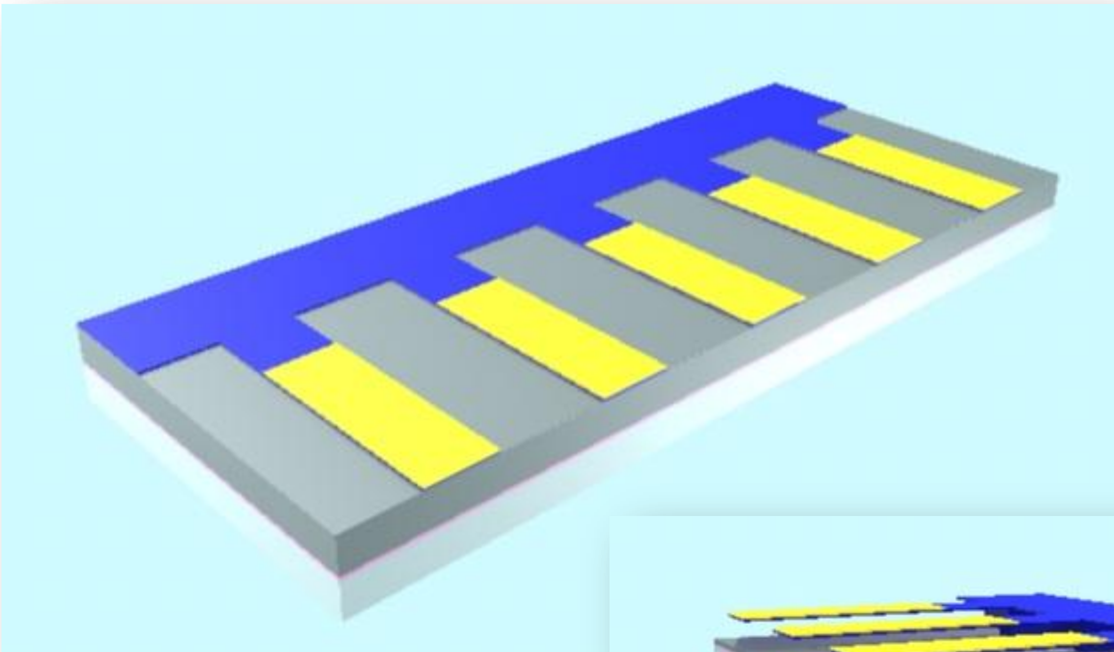
- Polycrystalline silicon (also referred to as polysilicon or poly) is used as a structural material for MEMS.
- The microcantilever is a common microstructure found in MEMS sensors and actuators.
- These cantilevers are etched from a polysilicon thin film and coated with a “sensing” coating.

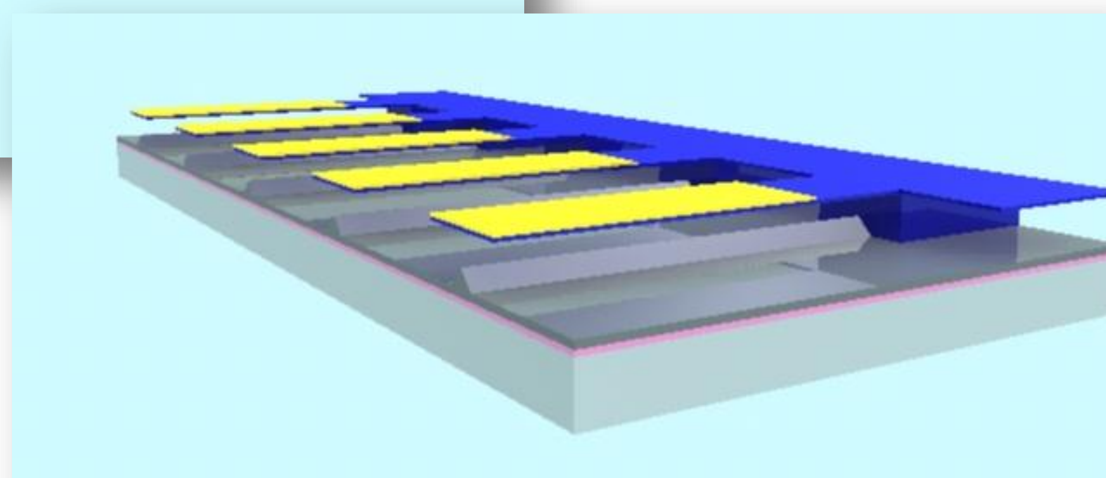


Microcantilever Chemical Sensor Array

[Image courtesy of Dr. Christoph Gerber, Institute of Physics, University of Basel]

Crystalline Silicon (Si) and MEMS





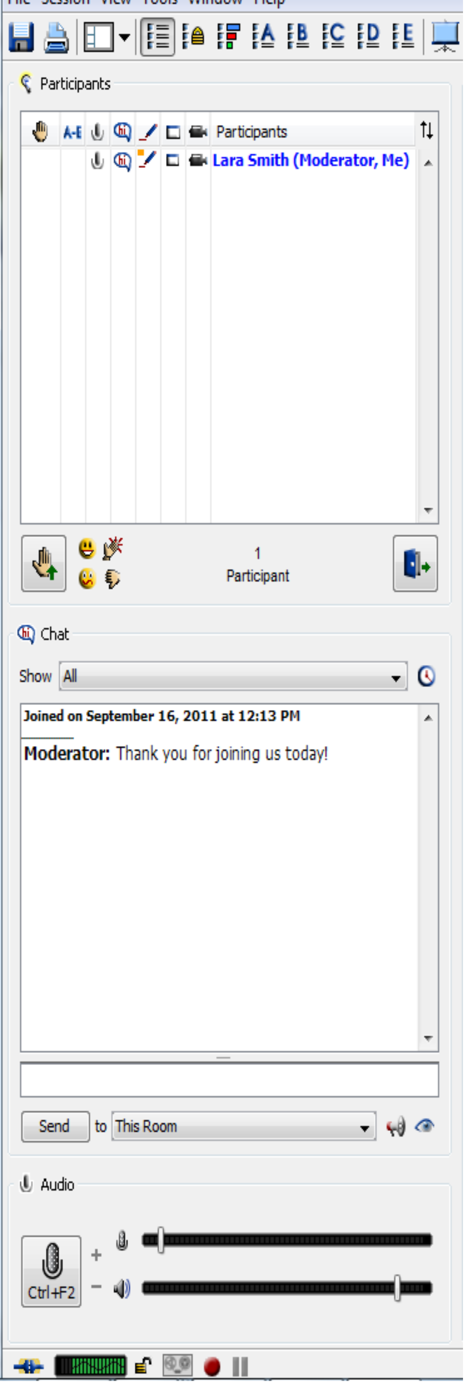
Polysilicon Microcantilevers

Link to animation:

http://youtu.be/dnXPLDQwFFk

Crystal Silicon (Si) and MEMS

- Polysilicon crystals are melted to form single-crystal Si wafers or substrates.
- Single crystal Si is used for bulk micromachining.
- Single crystal Si substrates are used in surface micromachining for mechanical platforms.
- Single crystal Si is the primary electronic material from which integrated circuit (IC) devices are fabricated.

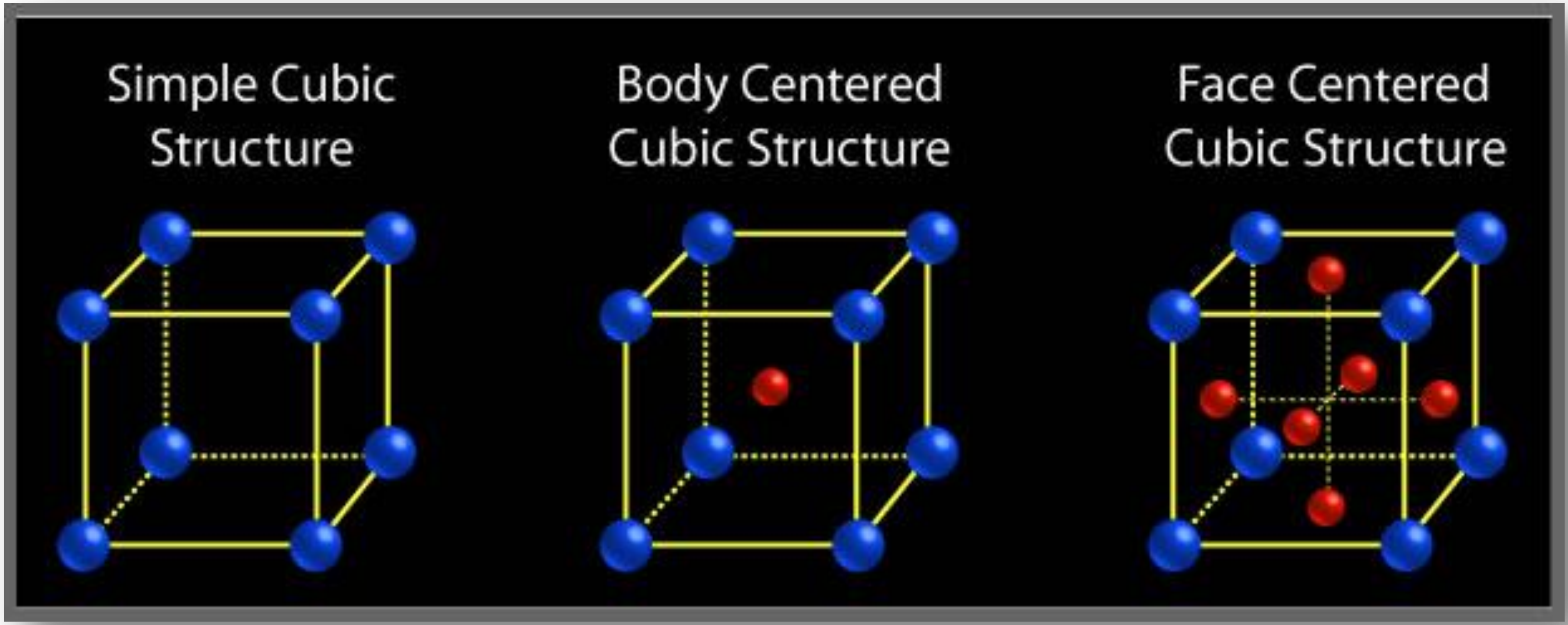


Type your questions into the chat box

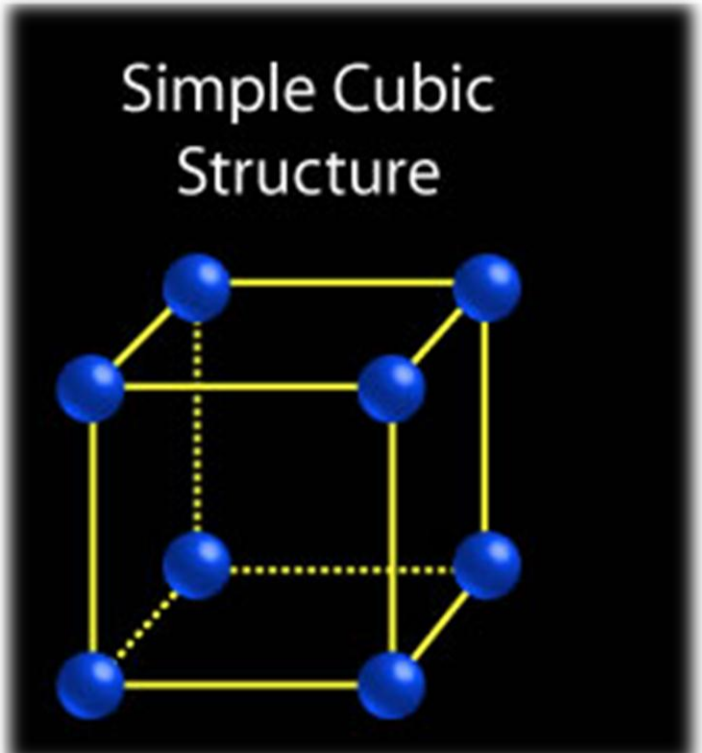
The Unit Cell

There are several different configurations for unit cells.

Here are just a few examples



The Unit Cell



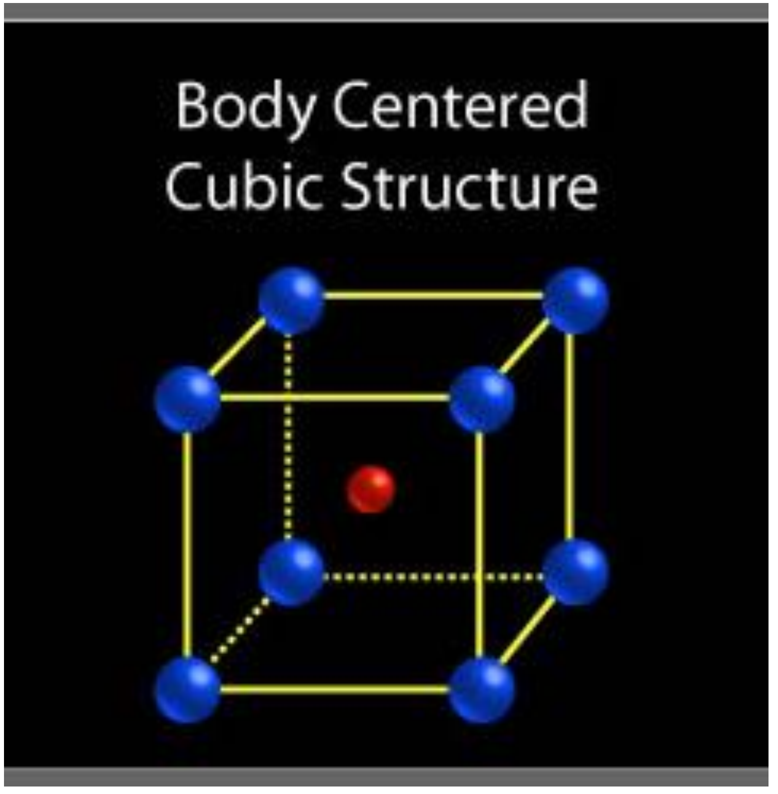
The *Simple Cubic Structure* is a unit cell consisting of **one atom**.

- Unit cells form a lattice and the edge of the unit cell connects to equivalent points.
- Each of the atoms you see in the *simple cubic structure* contributes ONLY 1/8 of itself to the unit cell.
- http://departments.kings.edu/chemlab/chemlab_v2/bcc.html

Let's Take a Poll

How many whole atoms in a Body-Centered Cubic cell?

a. One
b. Two
c. Four
d. Eight
e. Nine



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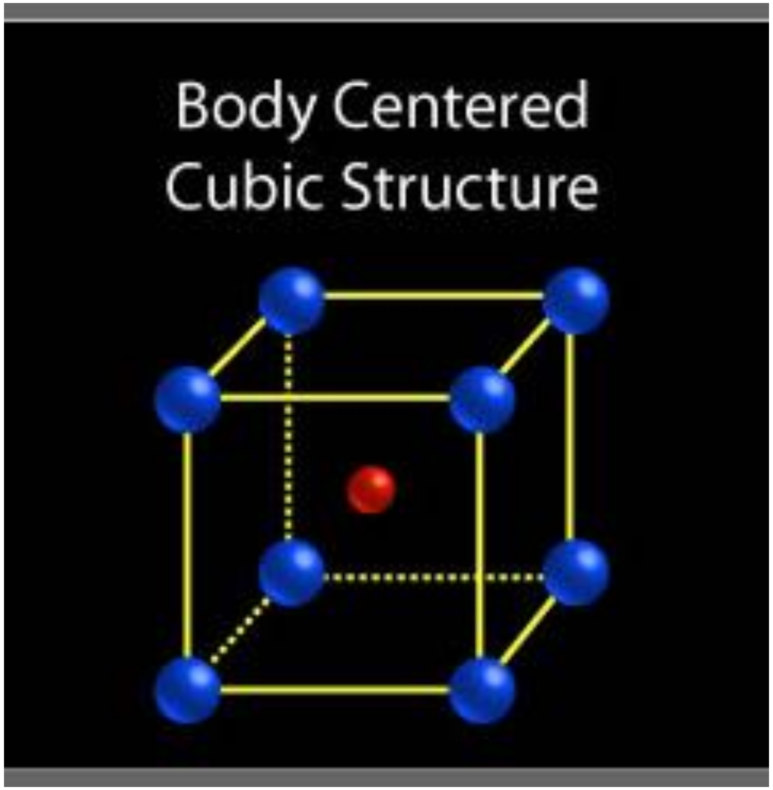
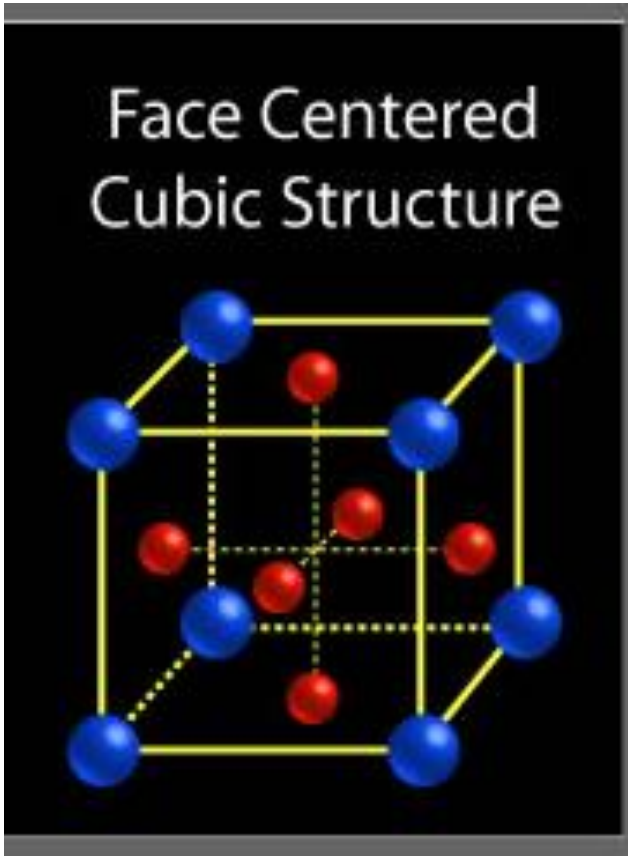


Answer:
TWO (*ONE atom from the eight corners, then the stand-alone atom on the center)*

Let's make sure you really do get it.

How many whole atoms in this Face-centered Cubic cell?

a. Four
b. Six
c. Seven
d. Eight



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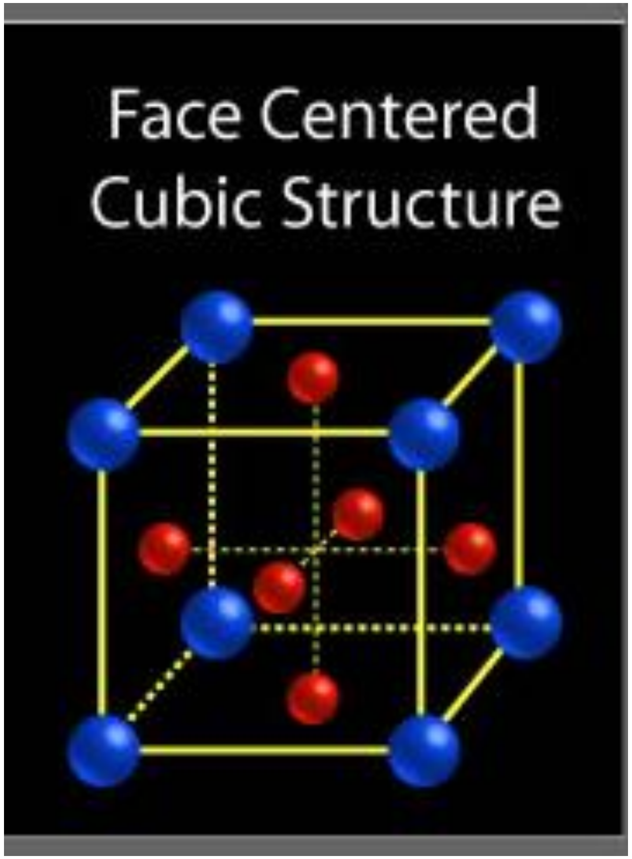
How many whole atoms in this Face-centered Cubic cell?

a. **Four**

b. Six

c. Seven

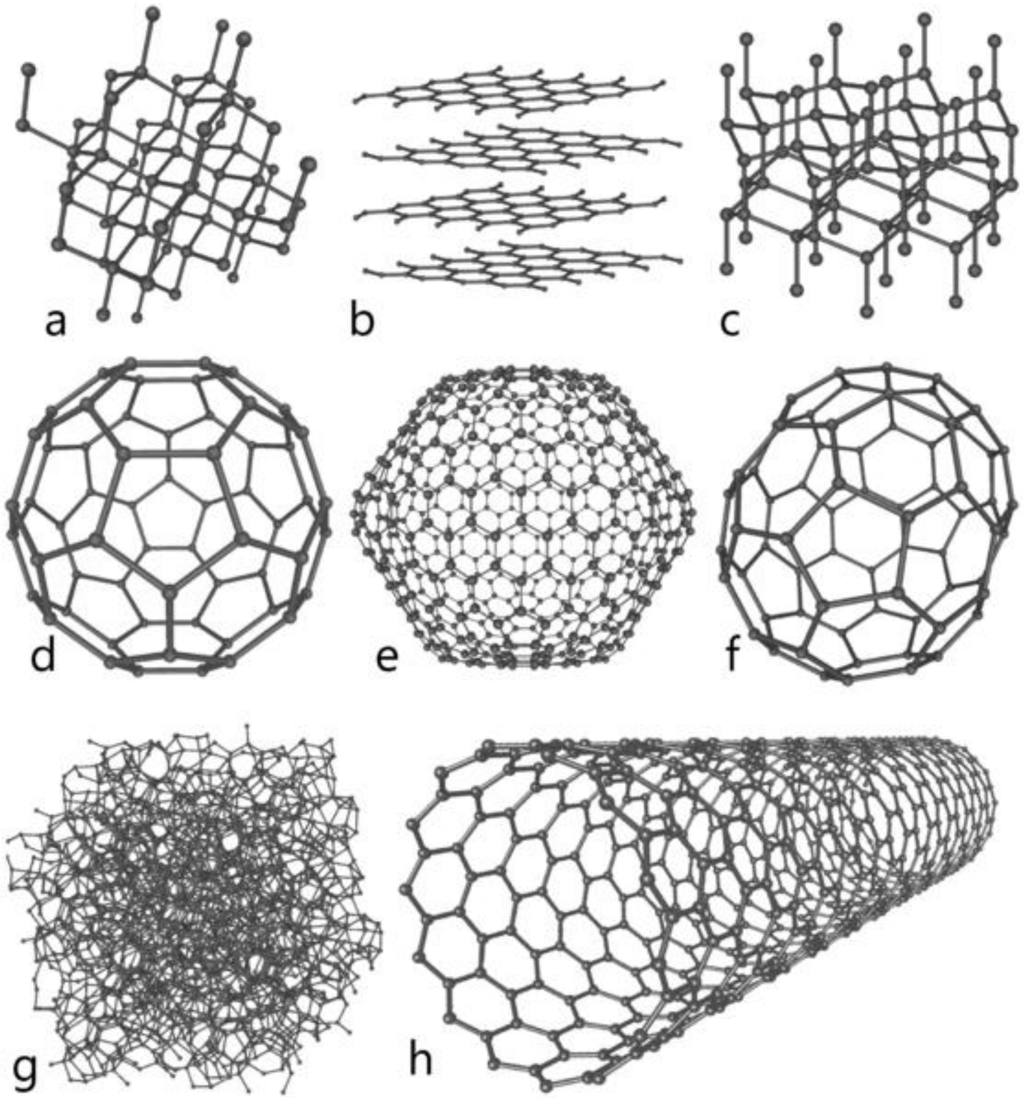
d. Eight



Answer:

FOUR *(ONE atom from the eight corners, then ONE-HALF an atom from each of the face) centered atoms: 1 + ½ * 6 = 4)*

The Many Faces of Carbon



a) Diamond
b) Graphite
c) Lonsdaleite
d) C_{60} (Buckminsterfullerene or buckyball)
e) C_{540}
f) C_{70}
g) Amorphous carbon
h) single-walled carbon nanotube or buckytube

Created by and Courtesy of Michael Ströck (mstroeck) – Wikipedia Creative Commons

Making Single-Crystal Silicon Wafers

Start with pure silicon (99.999999999% pure!).

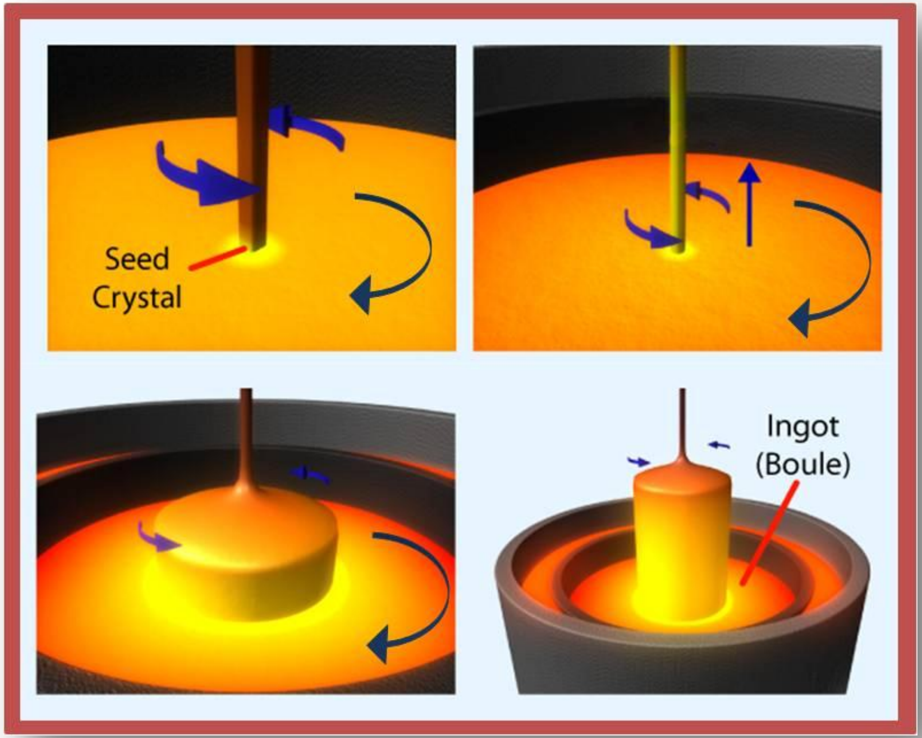
A polysilicon crystal rod is made to produce a single-crystal ingot using the Czochralski (CZ) process.

Source: Wilipedia, Warut Roonguthai

German Wikipedia, original upload 29. Dez 2004 (ingot by by Stahlkocher)

Making Single-Crystal Silicon Wafers

- A seed crystal is lowered into the molten silicon *(top left image)*.
- Silicon atoms attach to the seed as a crystalline structure.
- The seed and the crucible with the molten silicon are rotated in opposite directions as the seed is slowly pulled upward.
- The slower the "pull", the larger the diameter of the crystal ingot that forms.

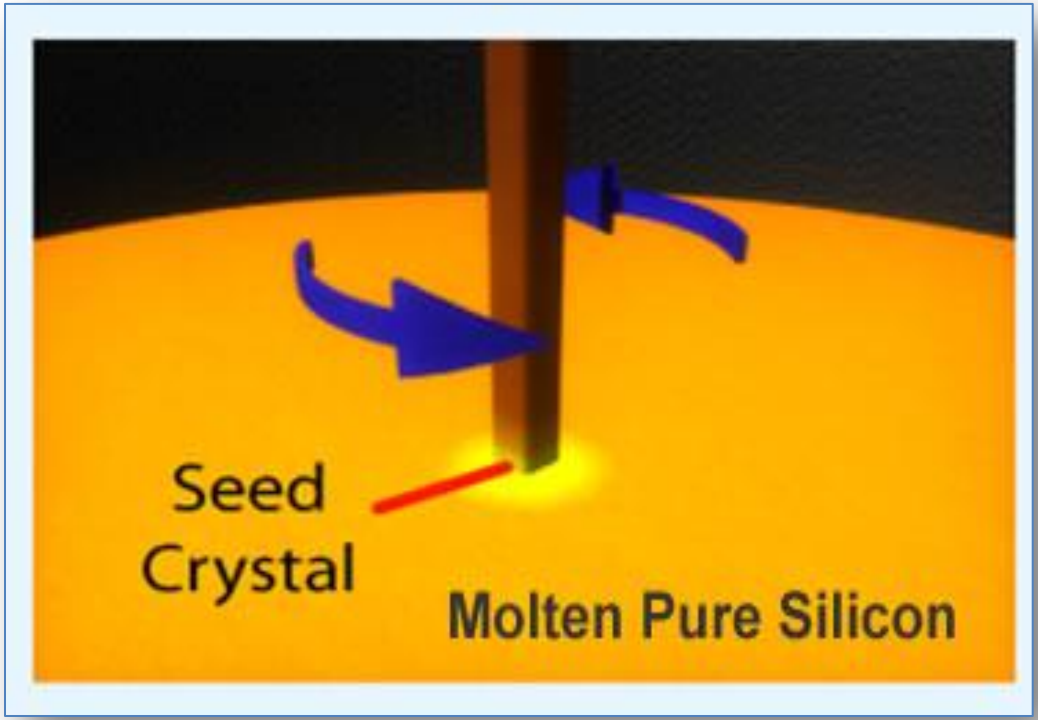


The Czochralski (CZ) Method of Growing an Ingot of Silicon Crystal

Growing Single-Crystal Silicon

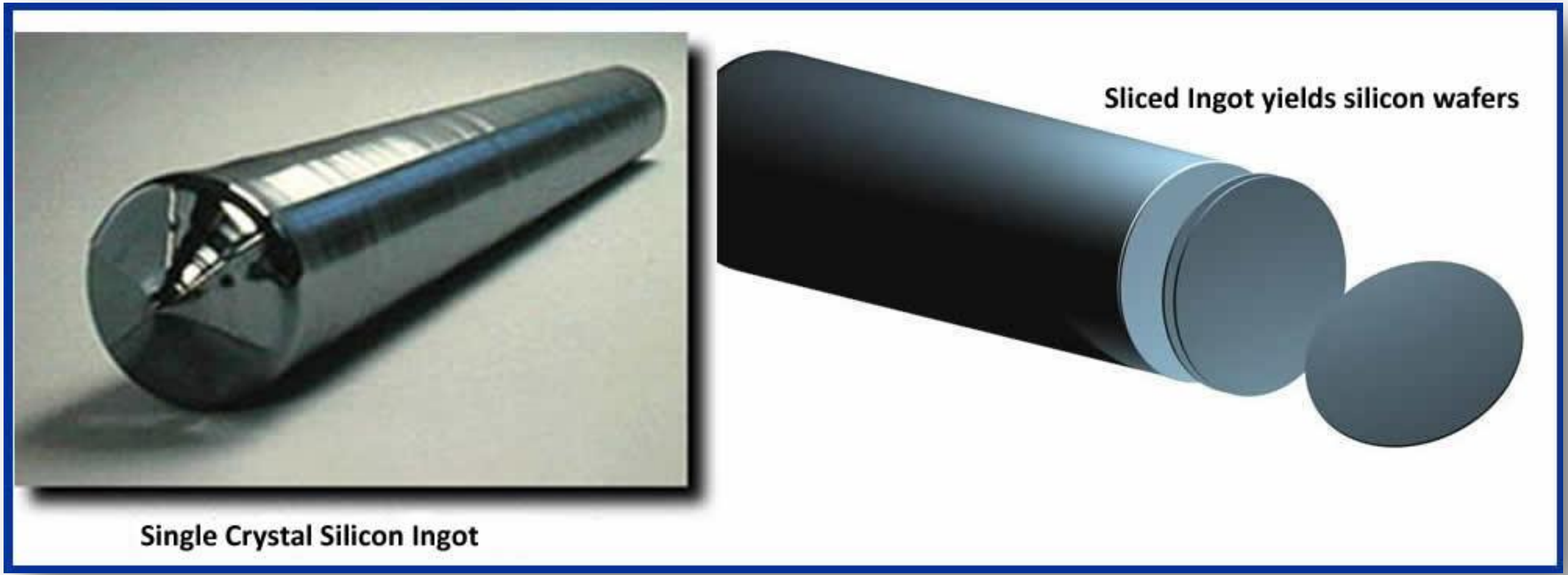
The seed crystal acts as a starting point for the alignment of the atoms in the molten silicon.

The alignment of the seed crystal relative to the molten silicon determines the orientation of the subsequently grown silicon crystal.



Ingot to Wafer

- The ingot is cylindrical in shape.
- The ingot is ground to a perfect cylinder.
- The cylinder is sliced into thin wafers using diamond coated wires.
- Each slice is polished to create silicon wafers.



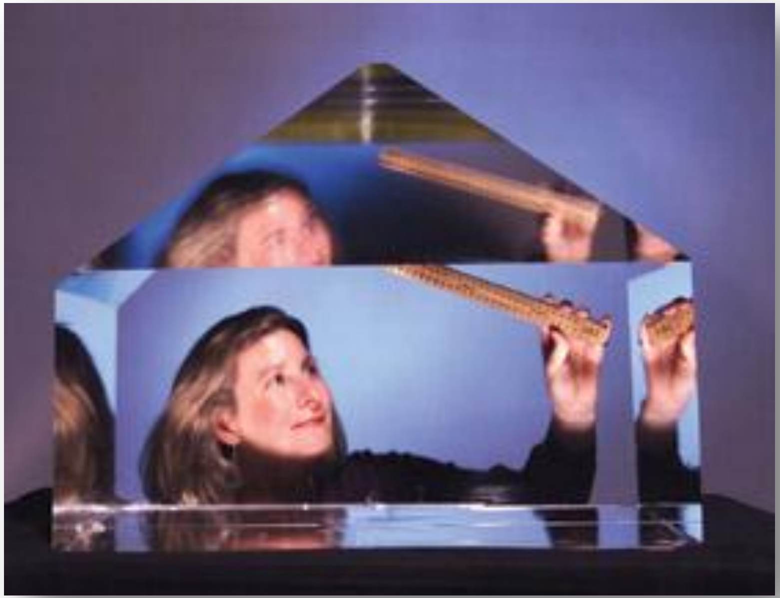
Unit Cell to Wafer

http://www.youtube.com/watch?v=MlsxGjJuL7s&feature=youtu.be

KDP Crystal

This picture is of a huge KDP (potassium dihydrogen phosphate) crystal grown from a seed crystal in a supersaturated aqueous solution at the Lawrence Livermore National Laboratory.

This crystal is to be cut into slices and used for frequency doubling and tripling.



[Image is public domain and was produced by LLNL]

MEMS and Crystal Structures

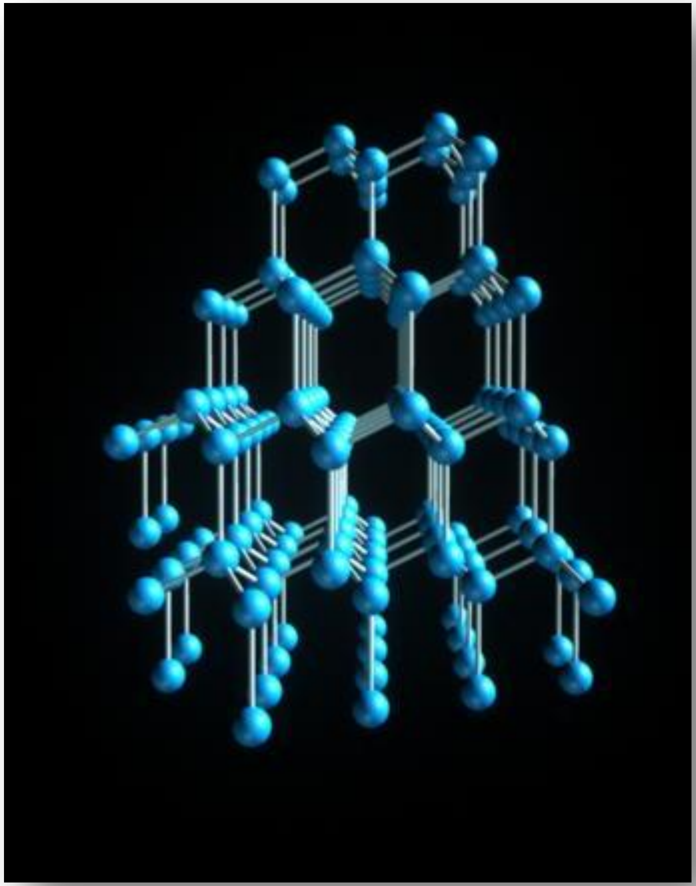
Crystals are

- Strong,
- Electrically stable,
- Poor conductors of heat, and
- Offer different planes that can be used for different purposes.

Planes?

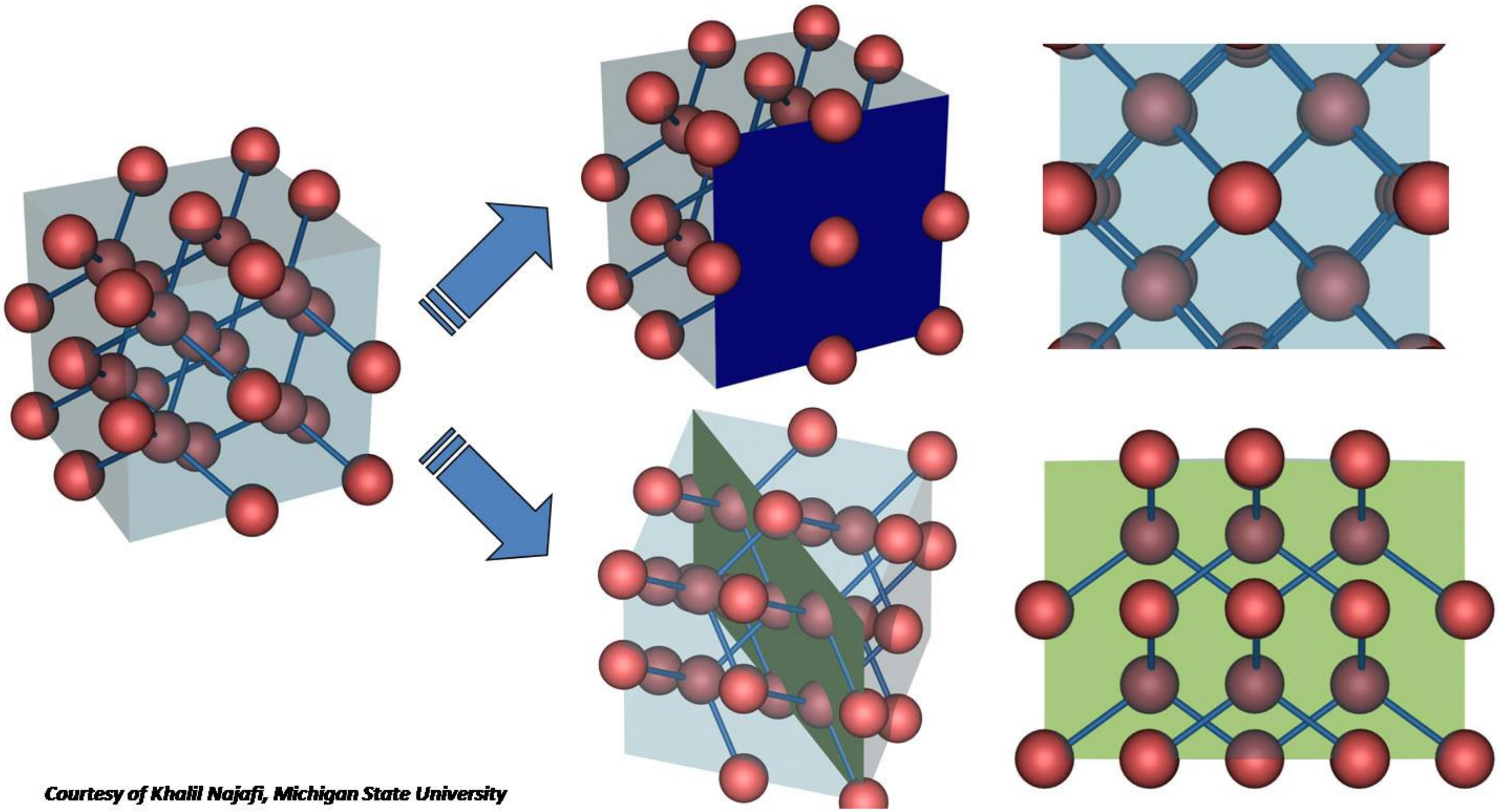
Remember how the lattice structures stack into planes?

Can you identify at least two planes in this carbon crystal structure?



Crystal Orientation

The orientation of the silicon (Si) crystal denotes which crystal plane is exposed on the wafer surface.



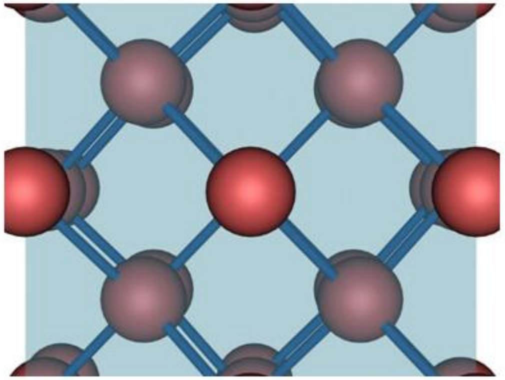
Courtesy of Khalil Najafi, Michigan State University

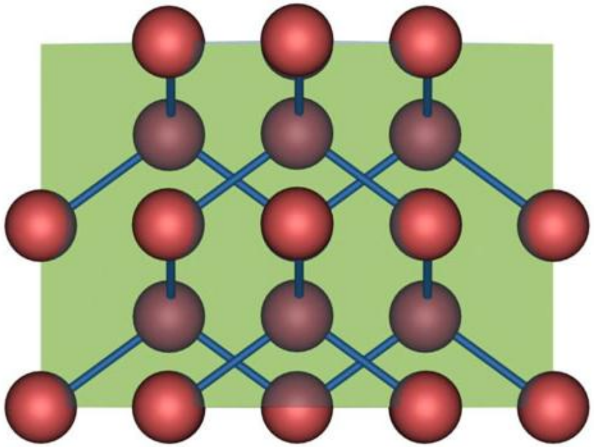
Material Properties of Silicon Planes

The material properties of a silicon wafer change depending on the plane exposed and its arrangement or orientation of atoms.

This orientation affects the

- properties of the wafer,
- number of atoms on the wafer surface, and the
- wafer's conductivity and reaction potential.



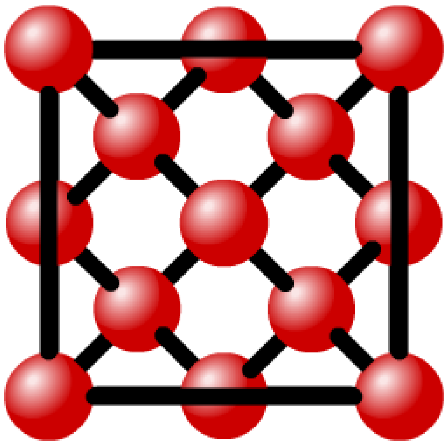


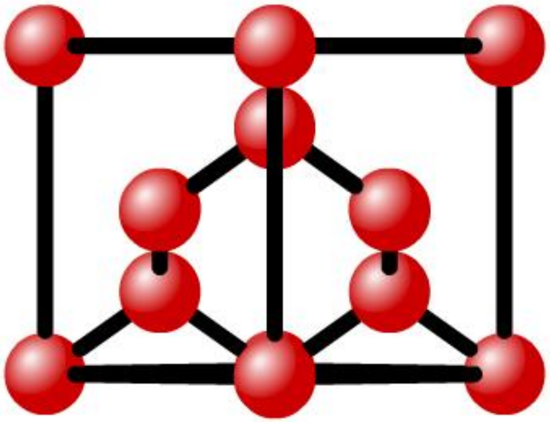
Interactive 3D Viewer

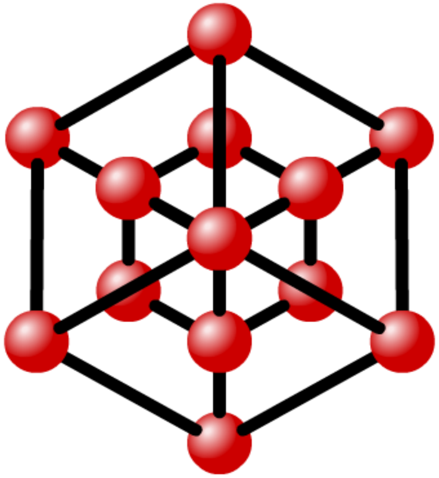
http://www.dawgsdk.org/crystal/en/library/diamond#0001

Crystal Planes

- Crystal planes describe the *orientation of the crystal.*
- Each type of plane is unique, differing in atom count and binding energies and therefore in chemical, electrical and physical properties.
- The Miller Index helps us identify crystal planes.





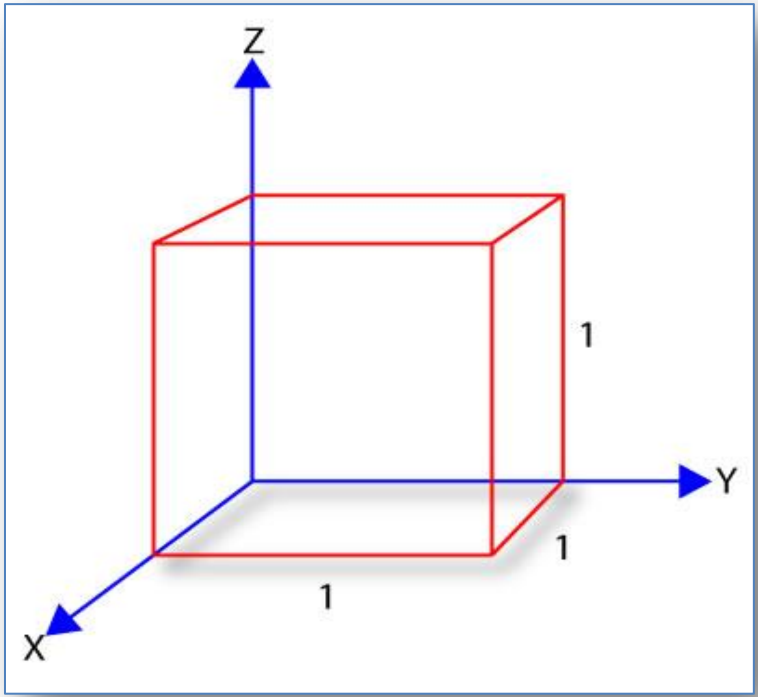


Miller Index

Miller indices are three digits notations indicating planes and direction within a crystal.

These notations are based on x, y, and z axes.

- x-axis vector = [1,0,0]
- y-axis vector = [0,1,0]
- z-axis vector = [0,0,1]

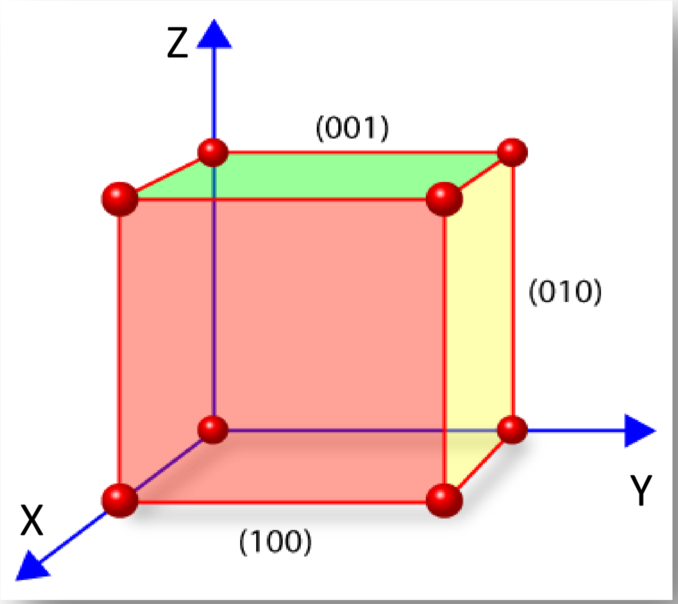


Miller Index

Crystal planes are perpendicular to their corresponding axis.

Each crystal plane has a unique notation.

- (1,0,0) or (100) is perpendicular to the x-axis
- (0,1,0) or (010) is perpendicular to the y-axis
- (0,0,1) or (001) is perpendicular to the z-axis

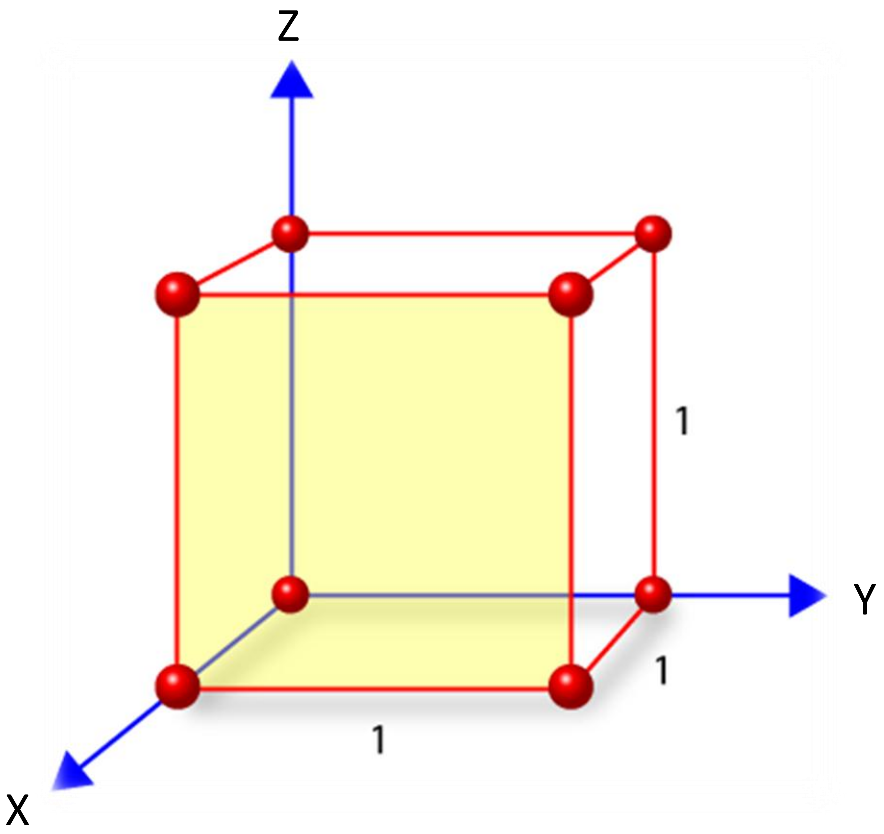


Before going to the next slide, make sure you can see how each plane is perpendicular to its corresponding axis.

Can you identify the planes?

What is the Miller notation of the "yellow" plane?

a. (111)
b. (100)
c. (010)
d. (001)
e. (011)



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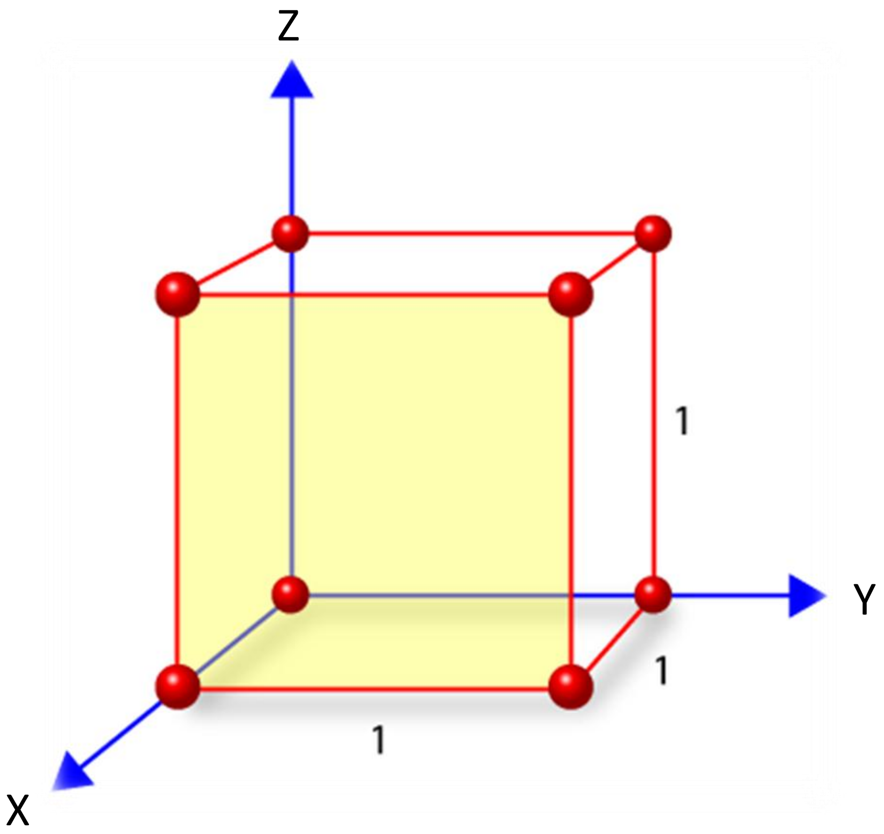
a. (111)
b. (100) **Answer**
c. (010)
d. (001)
e. (011)



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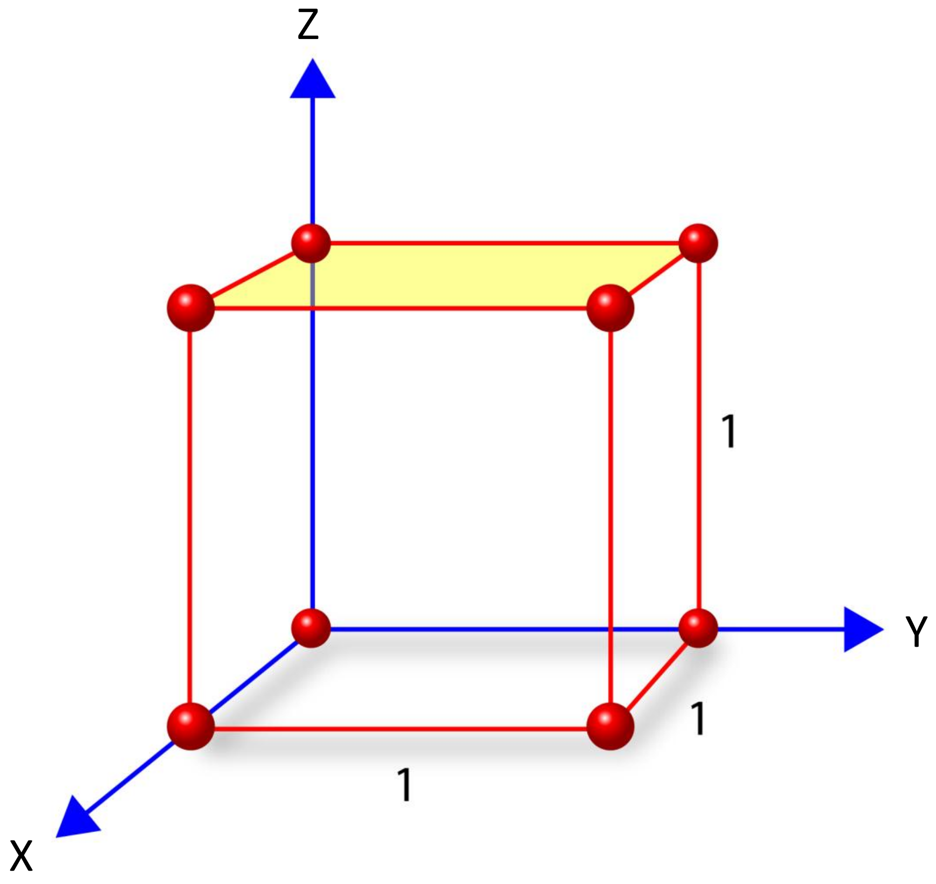

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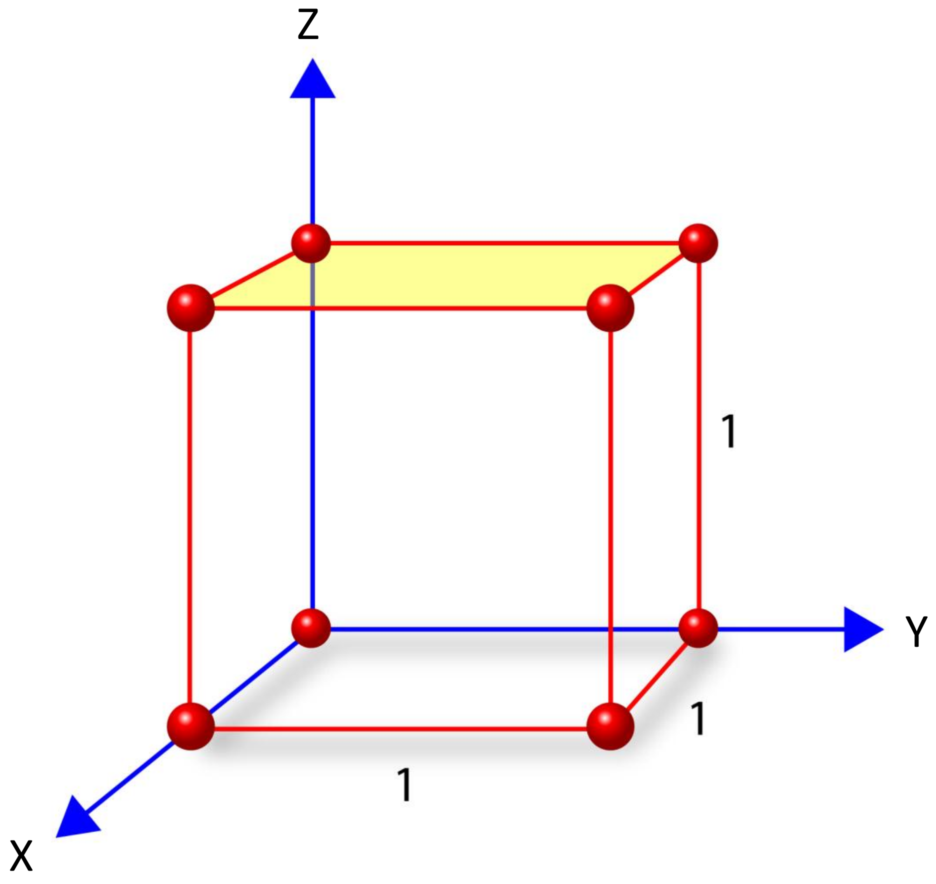
d. (001) Answer

e. (011)



Can you identify the planes?

What is the Miller notation of the “yellow” plane?

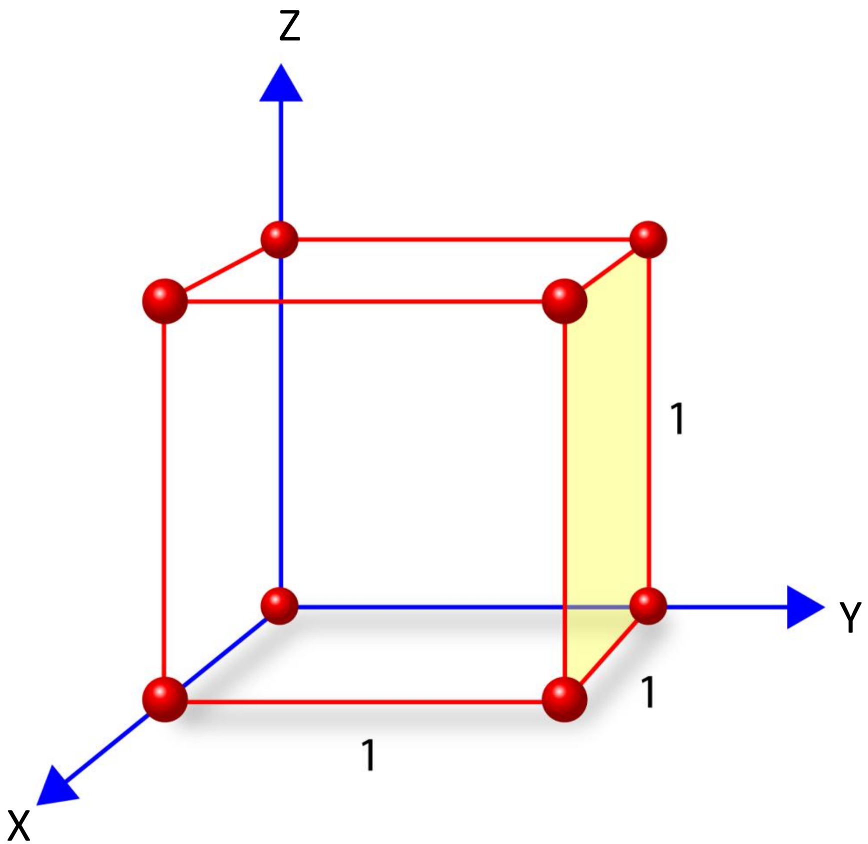
a. (111)

b. (100)

c. (010)

d. (001)

e. (011)



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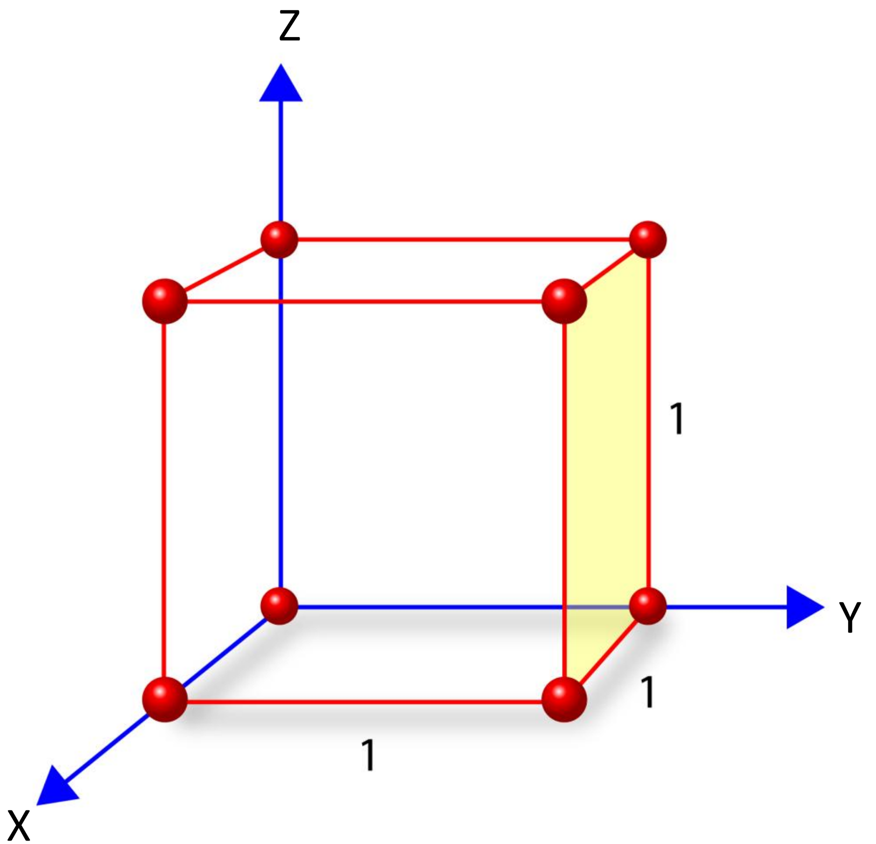

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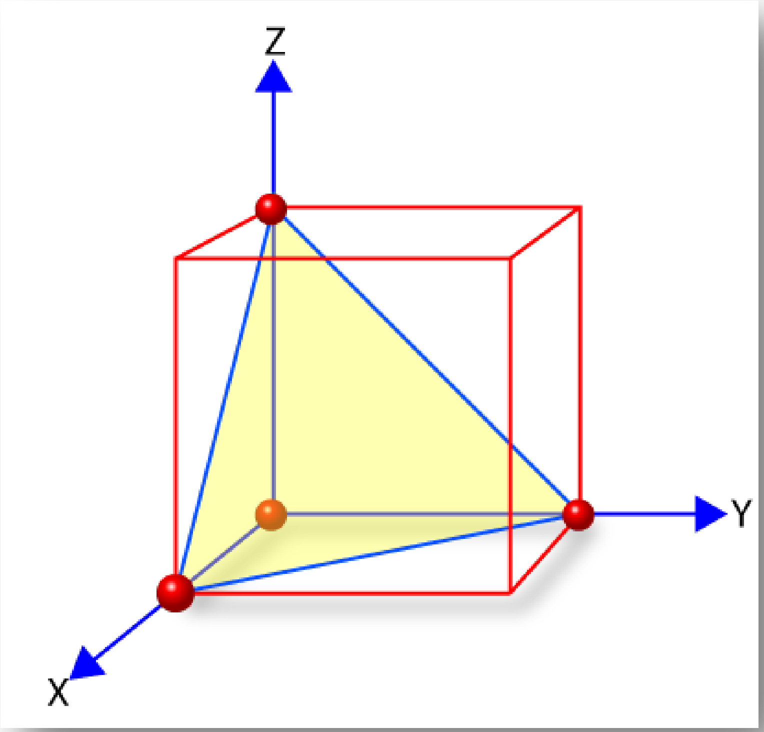

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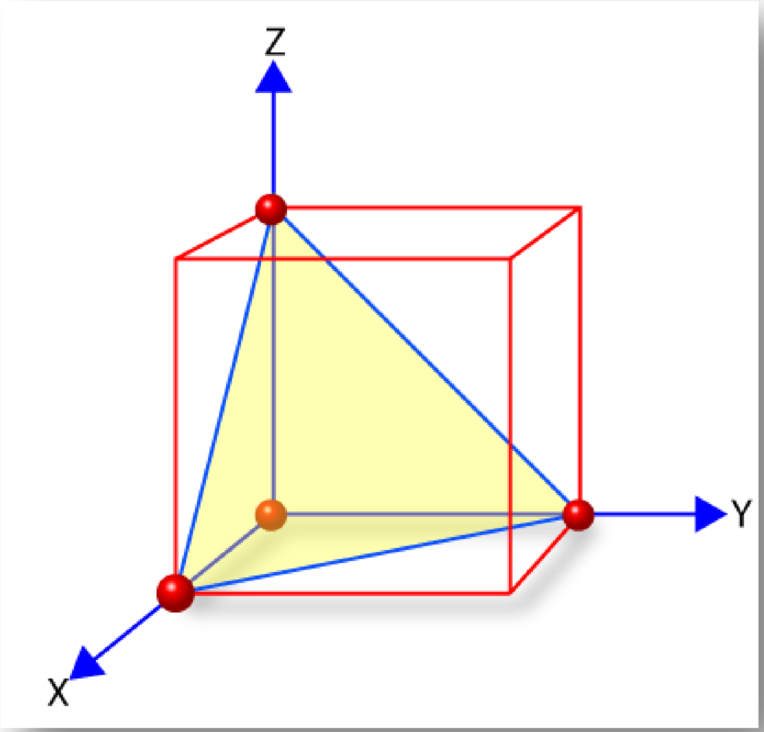


So what does this have to do with MEMS again?

Microsystems consist of structures with defined edges, lengths, widths or thicknesses. They also require certain

- electrical (e.g., resistance),
- mechanical (e.g., bulk modulus), and
- optical (Index of Refraction) properties.

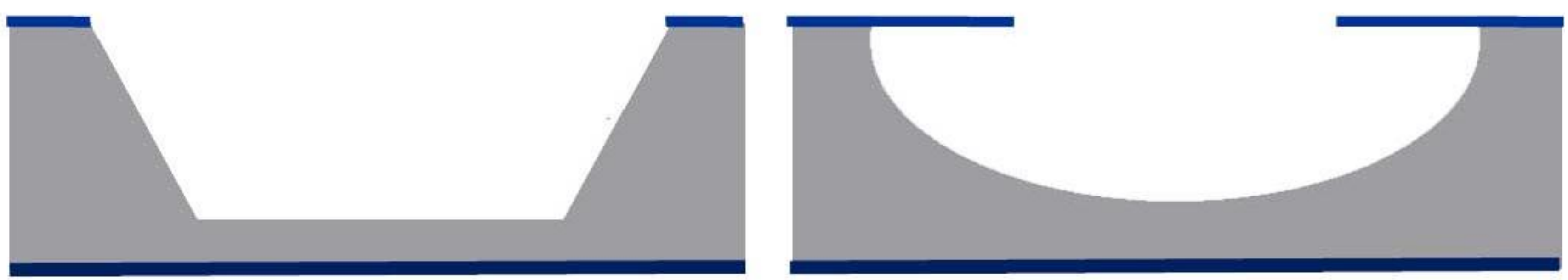
Each of these properties can be different in different orientations.

In order to create micro-size structures, an etch process is used to "etch away" or "remove" unwanted material.

Etch Process and Profiles

In microsystems fabrication the “etch” process is the selective removal of material for the purpose of forming specific shapes or devices, or for removal of bulk material for the release of specific components.

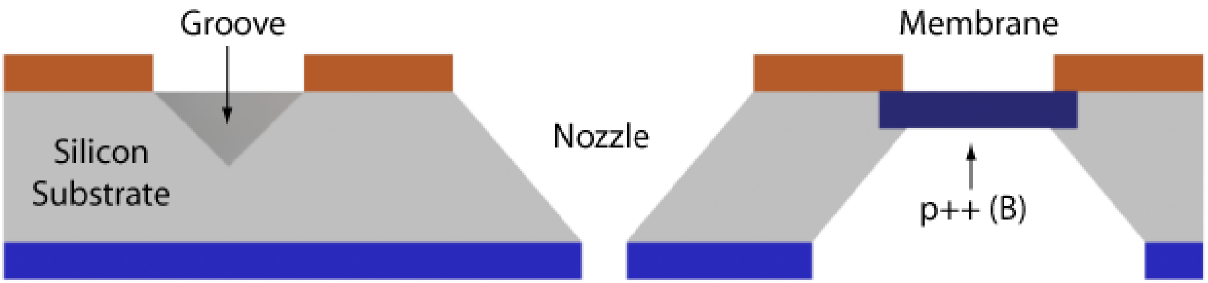
anisotropic isotropic



Selective Anisotropic Etching

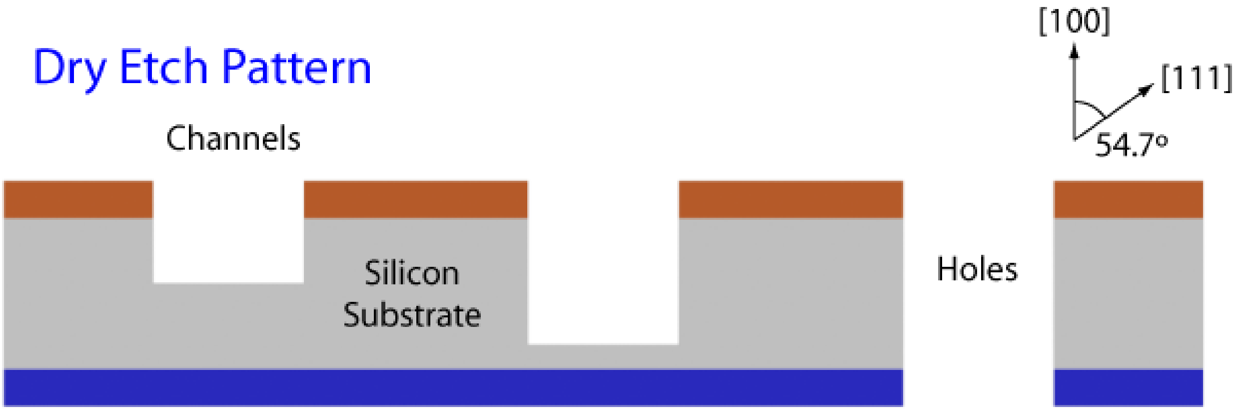
Isotropic and anisotropic etches can be achieved through both wet and dry etch processing.

Wet Etch Pattern

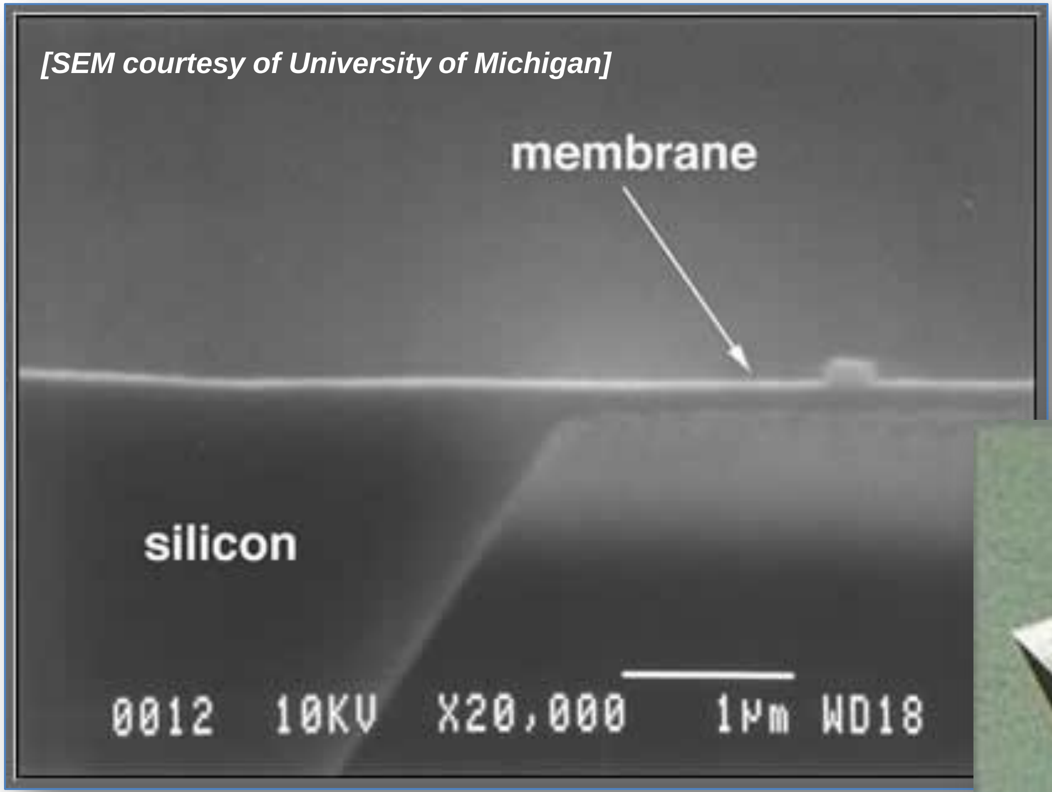


Patterns created with wet anisotropic etching vs. dry anisotropic etching.

Dry Etch Pattern

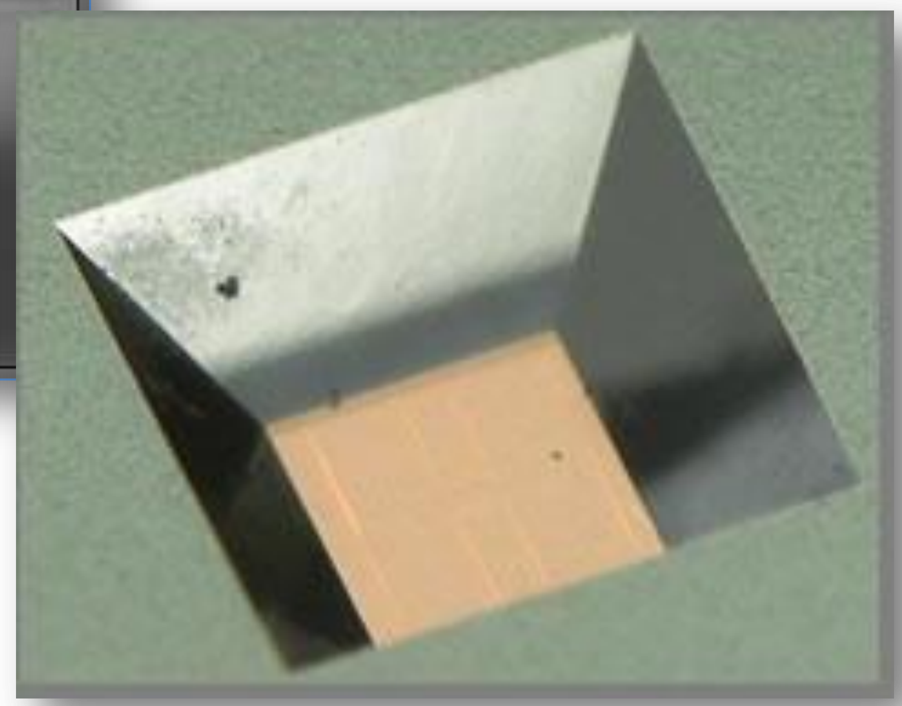


Silicon Crystal Wet Anisotropic Etch



[SEM courtesy of University of Michigan]

[Courtesy of the MTTC / University of New Mexico]

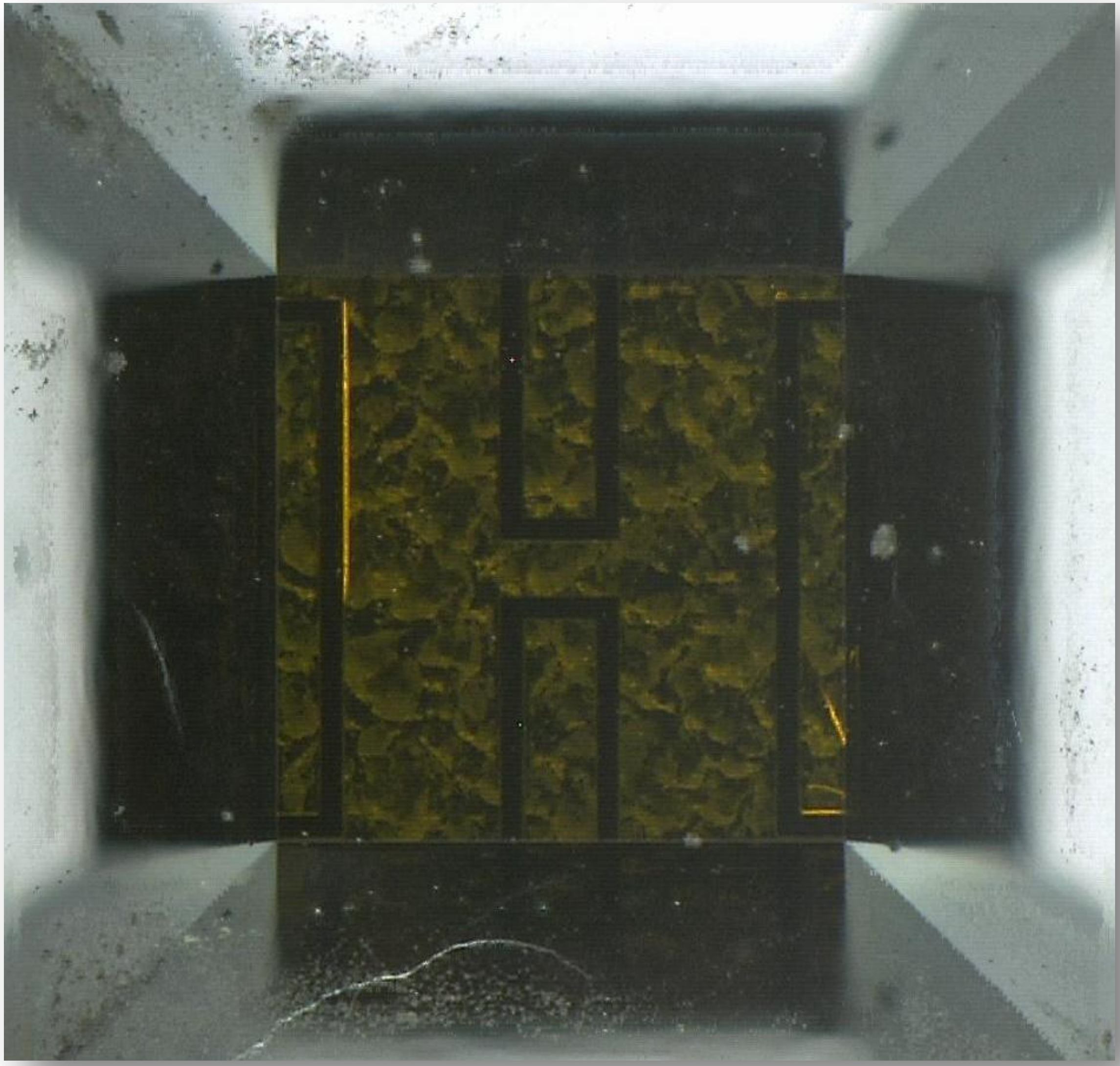


Anisotropic Etch of Silicon Backside

This animation shows the anisotropic etching on the backside of a silicon wafer. The opening formed by the etch as the referenced pressure chamber of a micro-pressure sensor.

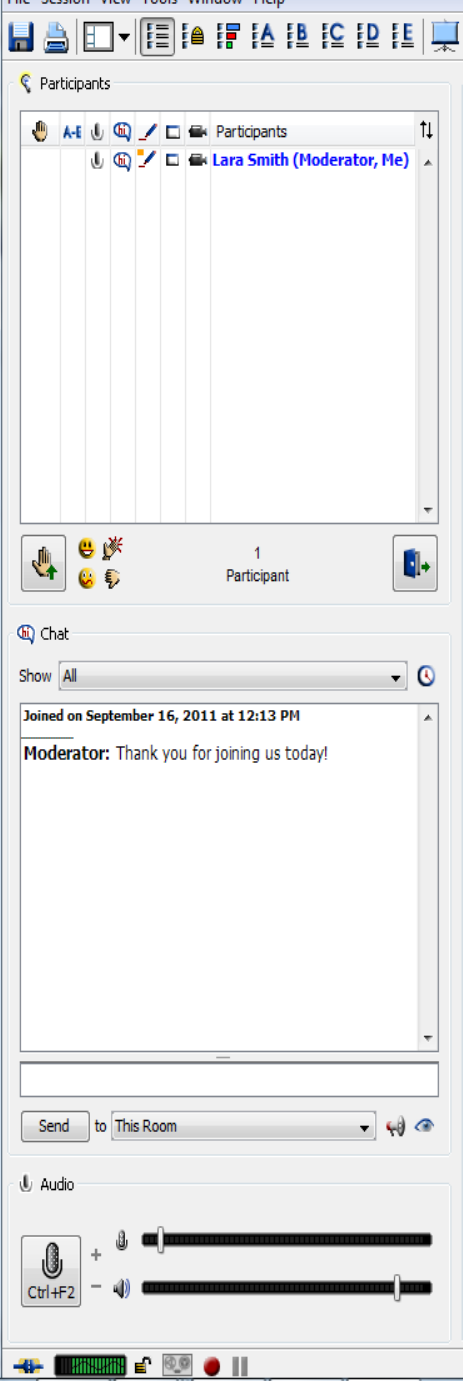
http://youtu.be/oUi_s2KoAEg

Anisotropic Etch of Silicon Backside



This "after etch" image was taken through a microscope.

[Courtesy of the MTTC at the University of NM]



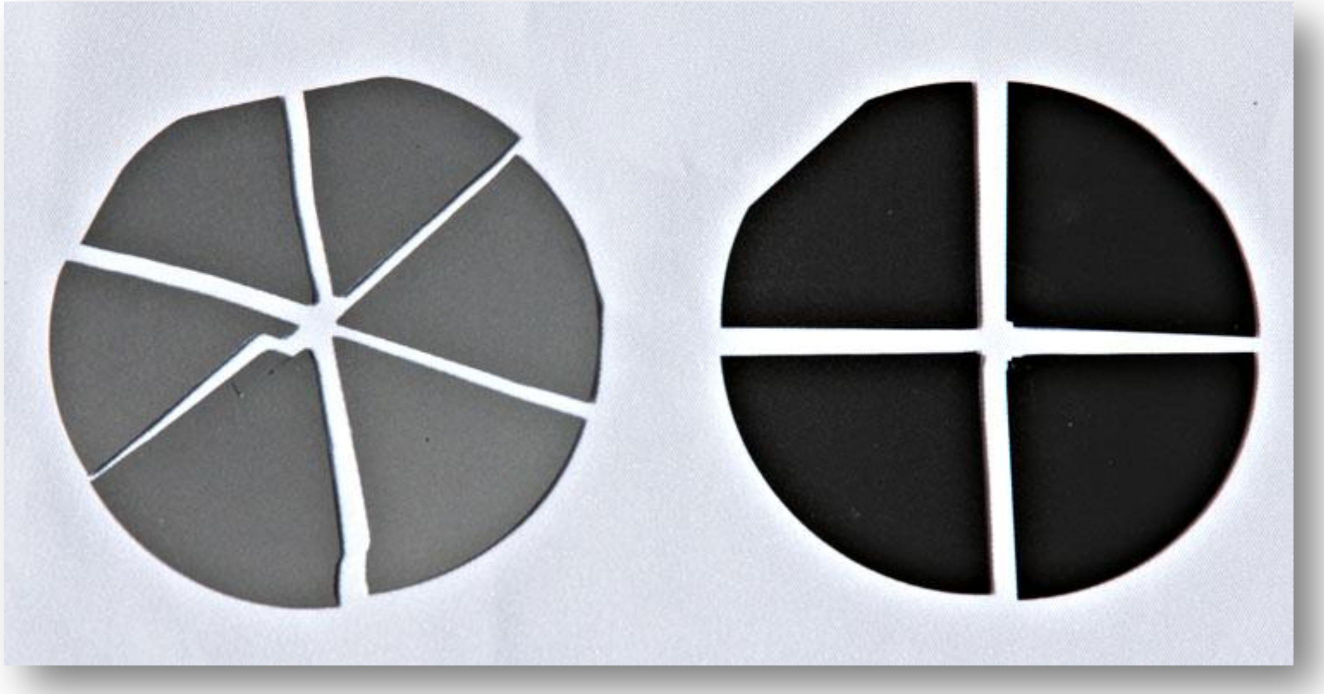
Type your questions into the chat box

Breaking Wafers

One way to determine crystal orientation of a wafer is to break it. Here are two broken silicon wafers. *NOTE: SCME's Crystallography Kit provides silicon wafers for breaking.*

What is the crystal orientation of these wafers, respectively?

a. 100, 110
b. 111, 110
c. 100, 111
d. 111,100



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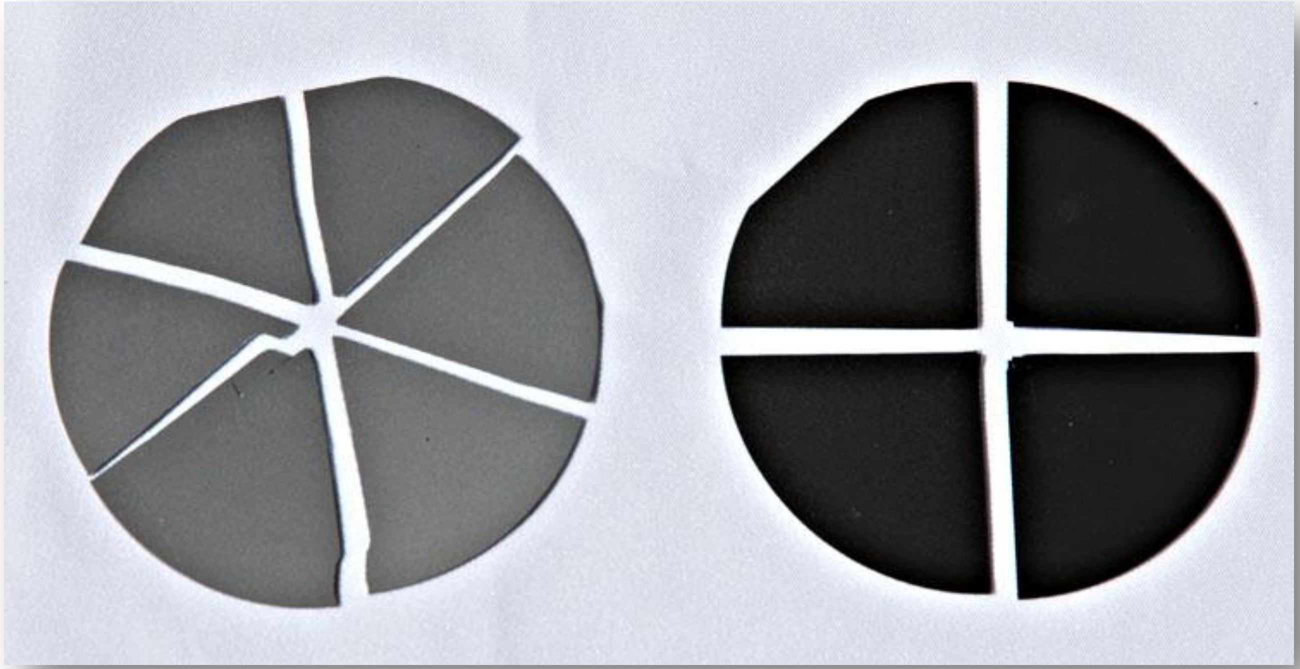
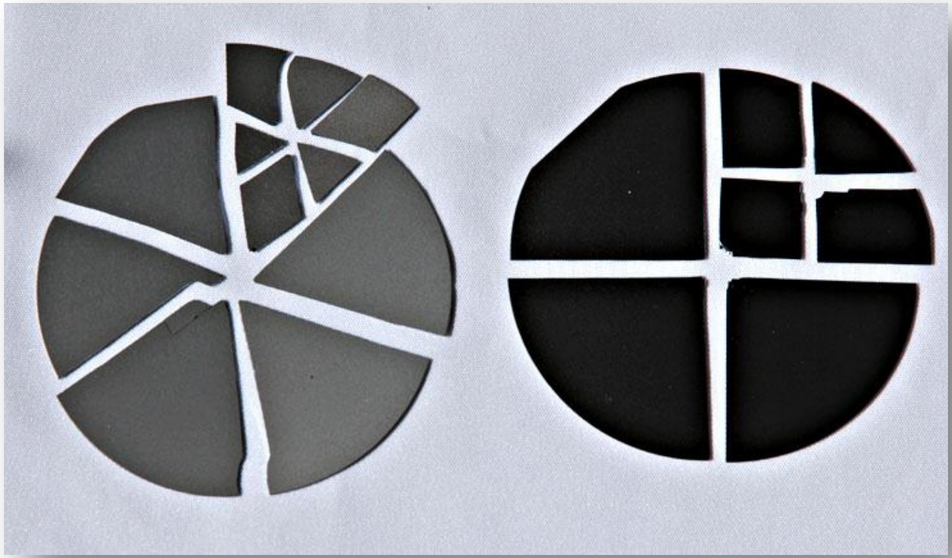


Breaking Wafers

What do you think will happen if we break one of the pieces on each wafer?

a. **They would break in similar shapes at the same angles.**
b. They would break randomly at random angles.
c. I'm multitasking and can't answer right now.



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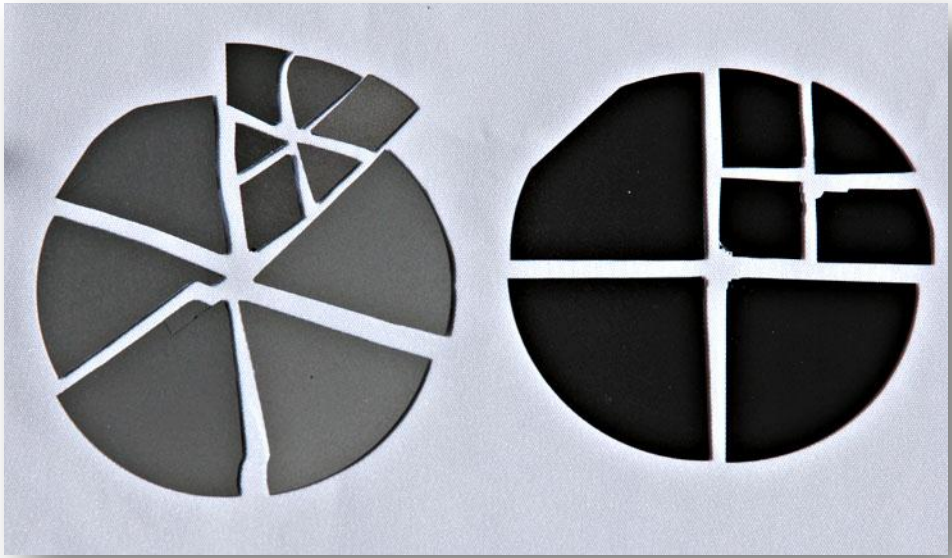
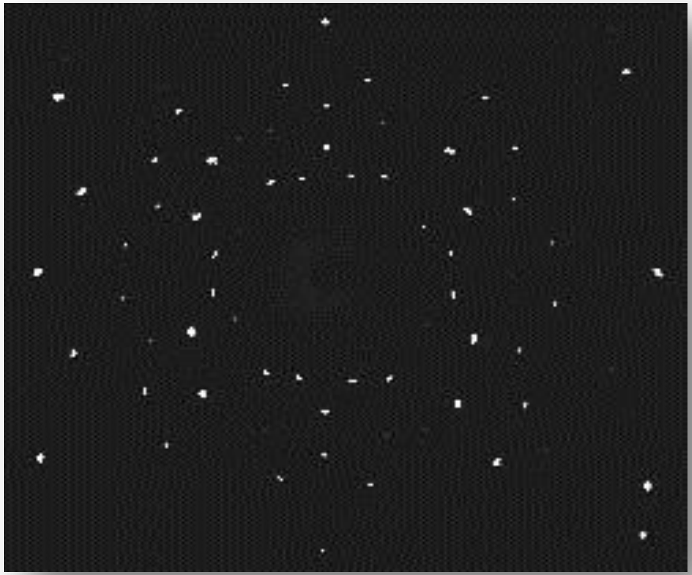


X-ray Diffraction

X-rays are aimed at a tiny crystal containing trillions of identical atoms.

- The crystal scatters the x-rays onto an electronic detector or film.
- The x-rays are said to diffract.
- The resulting diffraction pattern provides information needed to determine the actual orientation of the tiny seed crystal and the spacing of the atoms



X-ray diffraction pattern of a plane of a silicon crystal.

[Image printed with permission from and from the personal collection of Christopher C. Jones]

Can you identify the planes?

What is the Miller notation of the “yellow” plane?

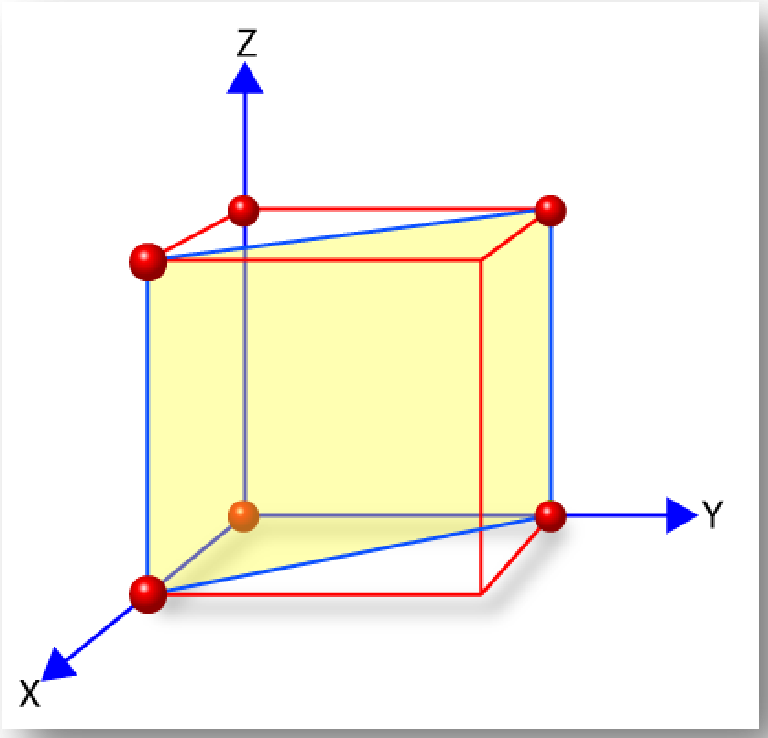
a. (111)

b. (000)

c. (100)

d. (110)

e. (011)



Can you identify the planes?

What is the Miller notation of the "yellow" plane?

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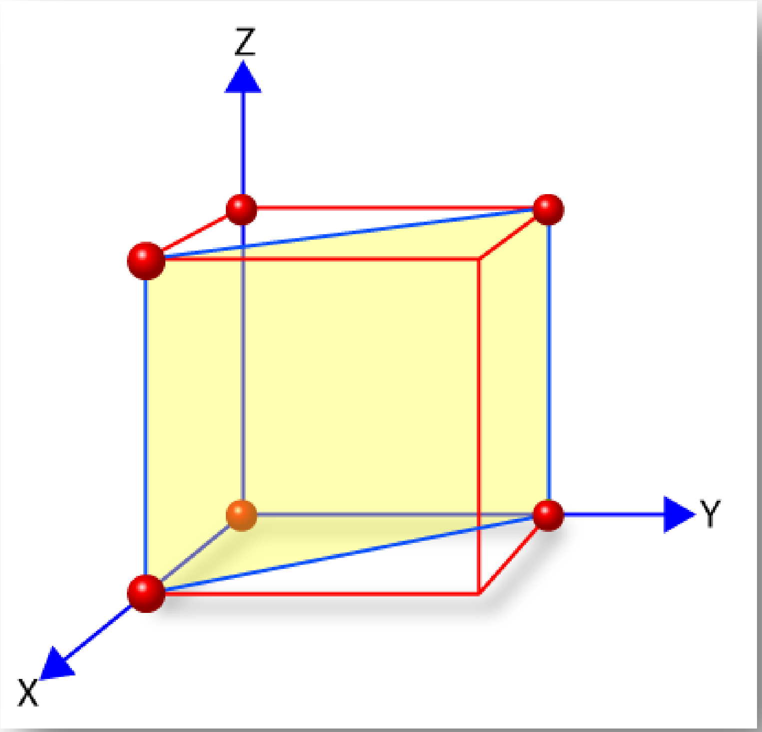
c. (100)

d. (110) **Answer**

e. (011)



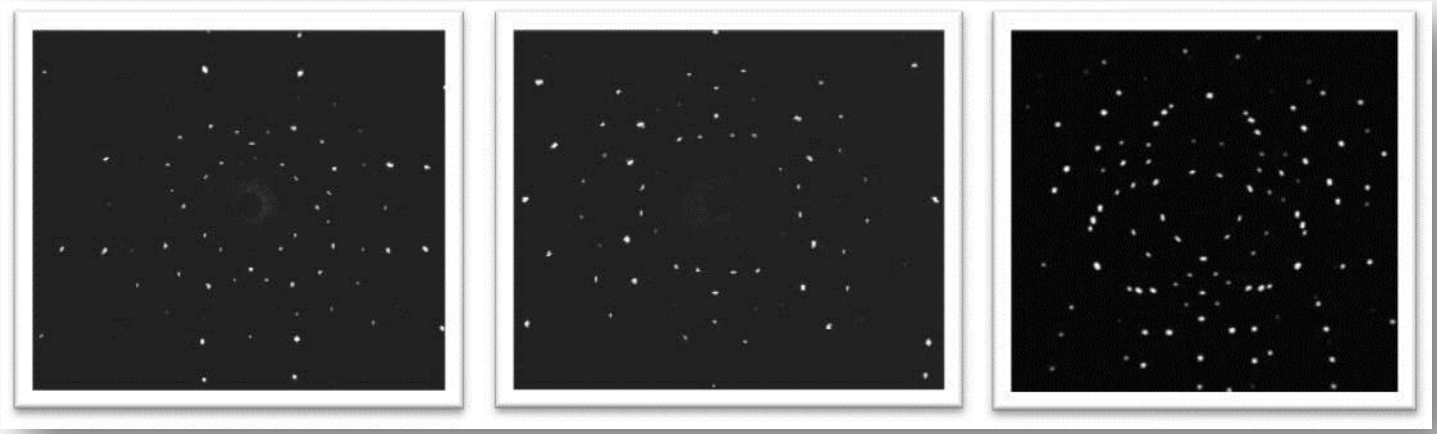
Determining the Orientation

Which planes are seen in these x-ray diffraction images (from left to right?

a) (111), (100), (110)

b) (100) , (110), (111)

c) (110), (100), (111)



Crystal orientation of three different planes of a silicon crystal.
X-ray was used to create these images.
[Images printed with permission from and from the personal collection of Christopher C. Jones]

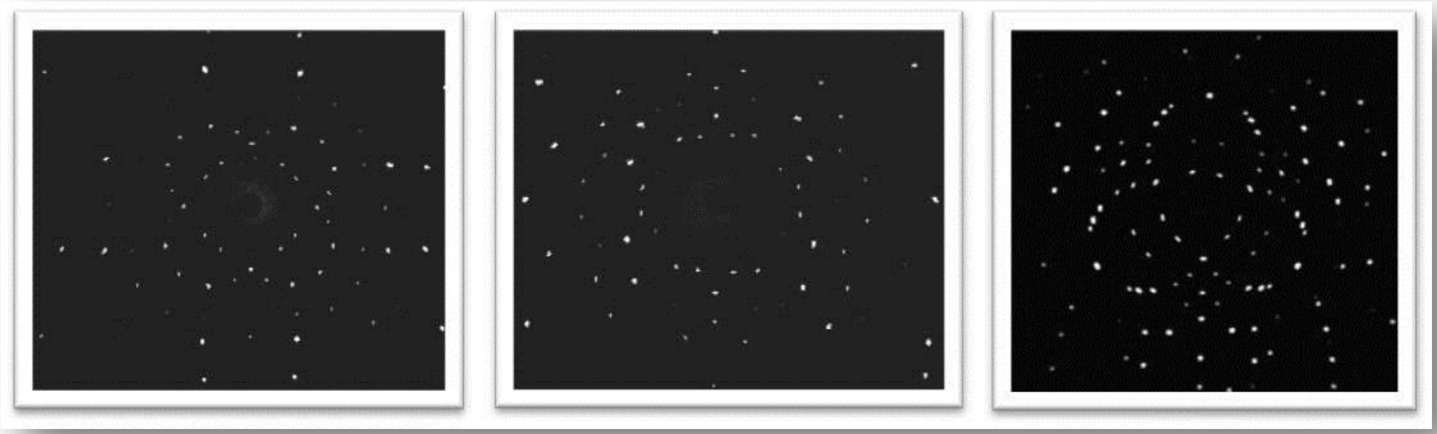
Determining the Orientation

Which planes are seen in these x-ray diffraction images (from left to right?

a) (111), (100), (110)

b) (100) , (110), (111) Answer

c) (110), (100), (111)

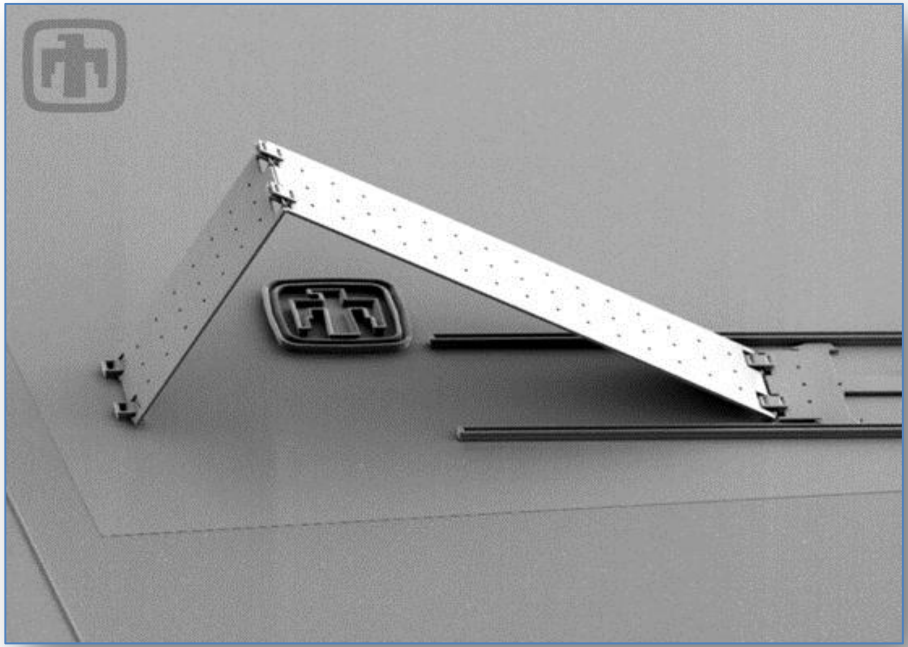


Crystal orientation of three different planes of a silicon crystal.
X-ray was used to create these images.
[Images printed with permission from and from the personal collection of Christopher C. Jones]

Wrap It Up

Because the molecules of crystalline structures "fit together" so well, a crystal is typically very strong. This characteristic is important in the construction of micro and nanosized devices.

Microsystems require a type of crystalline substrate and polycrystalline films to build microsize structures such as cantilevers, diaphragms, gears, comb drives, and electronic circuits.



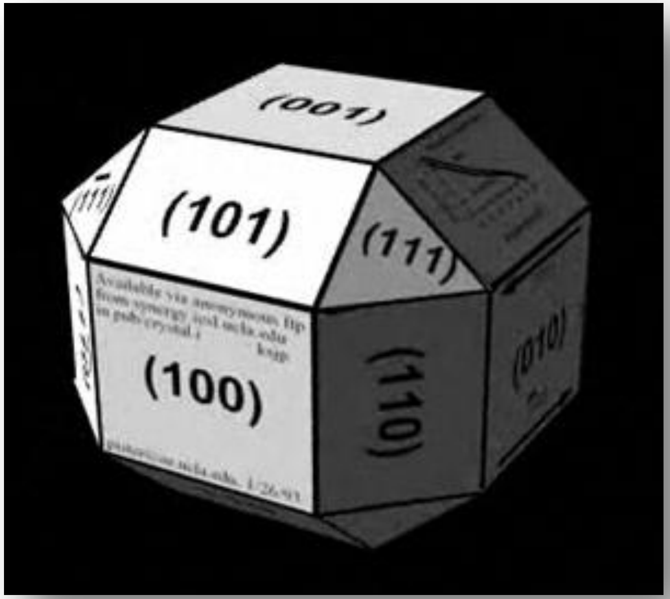
MEMS popup mirror [Courtesy of Sandia National Laboratories, SUMMIT Technologies, www.mems.sandia.gov]

SCME's Crystallography Learning Module

This webinar was based on SCME's Crystallography Learning Module.

- This learning module can be downloaded from the SCME website.
- A Crystallography Kit is also available.
    - Breaking Wafer Activity
    - An Origami Crystal Activity

SCME Website: scme-nm.org



Thank You For Joining Us

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Webinar Resources

To access this webinar recording, slides, and handout, please visit

www.scme-nm.org