Breaking Wafers Activity
The Crystallography Learning Module
Instructor Guide

Notes to Instructor

Breaking Wafers is an activity for the *Crystallography Learning Module*. This activity will help the participants to further explore the crystal structure of silicon. A kit for this activity can be acquired through http://scme-nm.org while supply lasts and the center is funded. See **Supplies / Equipment** below for the contents of the kit as well as other needed supplies.

The *Crystallography Learning Module* consists of the following:

- Knowledge Probe (KP) - Pre-quiz
- Crystallography Overview for MEMS PK
- Growing Crystals – Hot Ice Activity
- The Miller Index Activity
- **Breaking Wafers - Activity (SCME kit available through website)**
- An Origami Crystal - Activity
- Crystallography Assessment

This companion Instructor Guide (IG) contains all of the information in the PG as well as answers to the Post-Activity questions.

Instructional YouTube Video

There is a YouTube instructional video that can be used to support this activity. Below is the link:

Breaking Silicon Wafers Activity (https://youtu.be/vXk6Uhq74nU)

Description and Estimated Time to Complete

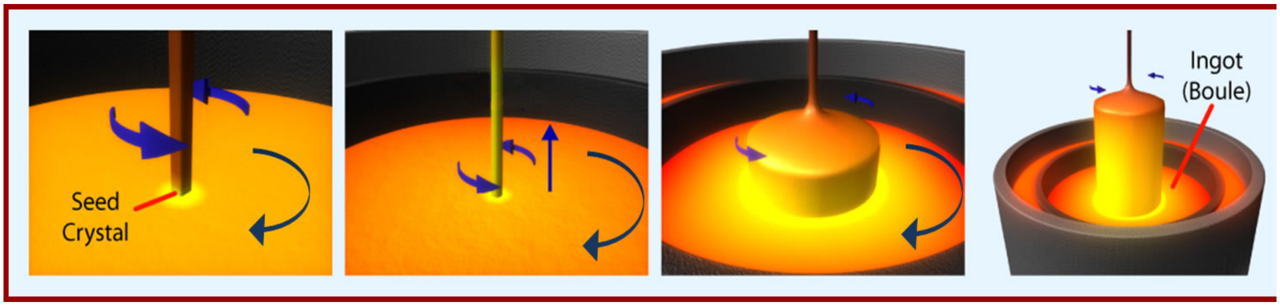
In this activity you will further explore the crystal planes of silicon by breaking two silicon wafers. By the end of this activity, you should be able to tell from a piece of silicon the specific crystal orientation of the silicon crystal. If you have not reviewed the reading material for this activity, please stop and read the Crystallography Overview PK.

Estimated Time to Complete

Allow at least 15 minutes to complete this activity.

Introduction

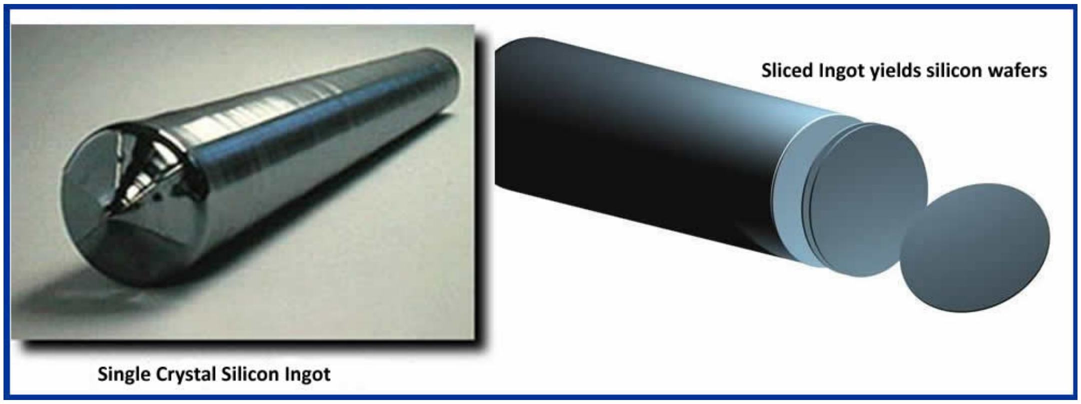
MEMS (microelectromechanical systems) are fabricated using monocrystalline silicon wafers. The wafers are cut from a silicon ingot that is formed by melting chunks of polycrystalline solids in a large crucible. Once melted a "seed crystal" is placed in the liquid silicon to stimulate crystal growth for a specific crystal orientation. Over several hours a long ingot of pure monocrystalline silicon is slowly pulled from the melt. Below are the steps for "growing" this monocrystalline ingot.



1. First we start with very pure polycrystalline silicon material (99.999999999% pure!)
2. The pure silicon is melted in a crucible at 1425°C. (This molten silicon is called "the melt".)
3. A seed crystal is precisely oriented and mounted on a rod then lowered into the melt *(left image)*. Silicon atoms in the melt align to the same crystal orientation of the seed.
4. As the seed crystal is slowly pulled out of the melt, the seed and the crucible are rotated in opposite directions A large crystal ingot or boule is formed by controlling the temperature gradient of the melt, the speed of rotation, and the rate of the pull of the rod. The slower the "pull", the larger the diameter of the crystal ingot that forms. (This process can take several days to complete and is called the Czochralski (CZ) Method of growing silicon.)

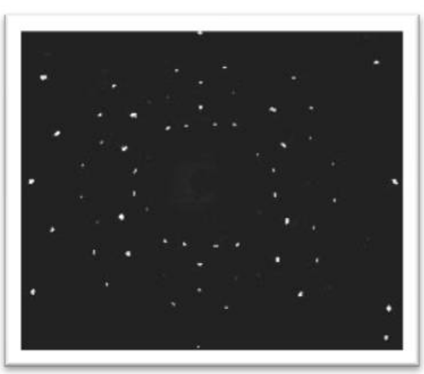
The seed crystal acts as a nucleation site for the alignment of the atoms in the molten silicon. The alignment of the seed crystal relative to the melt determines the orientation of the subsequently grown silicon crystal ingot. The wafers cut from this crystal maintain this orientation.

The resulting ingot is cylindrical in shape, 25.4 mm (~1 inch) to 450 mm (~18 inches) in diameter and several meters long. Once cooled, the ingot is ground to a perfect cylinder. The cylinder is sliced into thin wafers using diamond coated wires or saw blades. Each slice is polished to create silicon wafers, also referred to as substrates. Microsystems are constructed on or within these substrates depending upon the type of process used – surface or bulk, respectively.



To determine the orientation of a silicon crystal wafer, crystallographers use x-rays aimed at a tiny piece of the wafer containing trillions of identical atoms. The specific periodic arrangement of the atoms within the crystal diffracts the x-rays onto an electronic detector or film. The resulting diffraction pattern on the film or detector gives the crystallographer the information needed to determine the actual orientation of the tiny seed crystal and the spacing of the atoms. A computer reconstructs the orientation from the diffraction pattern. The images below show the resulting patterns of three planes of a silicon crystal. Indicate which image represents each of the following planes. *(Think about the spacing of atoms and the number of atoms in different silicon planes.) [Images printed with permission and from the personal collection of Christopher C. Jones[1]]*

a. (111)
b. (100)
c. (110)



________ ________ ________

Answer: (110), (111), (100)

What characteristics helped you to identify the correct orientation of these planes?

The (100) pattern has fewer atoms and right angles are distinct in the pattern. The (111) pattern has the most atoms on the surface.

An easier way to determine the crystal orientation of a silicon wafer is to just break it.

So let's do that in this activity.

Activity Objectives and Outcomes

Activity Objective

- State the crystal orientation of a silicon wafer by breaking the wafer into smaller pieces and observing the resulting shape.

Activity Outcome

By the end of this activity you should be able to look at a piece of a silicon wafer and state its crystal orientation: (100) or (111).

Resources

SCME Crystallography Overview for MEMS PK

Supplies / Equipment

Supplies provided by instructor

- Safety glasses or goggles
- Ice Pick or pointed metal implement (e.g., a Philips screwdriver, a large nail)
- Hammer (For tapping the end of the metal implement)
- Two large sheets of paper or poster paper

Supplies included in kit

- Two silicon wafers of (100) orientation
- Two silicon wafers of (111) orientation
- Wafer holders and packing
- 1 Crystallography Learning Module – Instructor Guide
- 1 Crystallography Learning Module – Participant Guide

Documentation

- Answers to the Post-Activity Questions

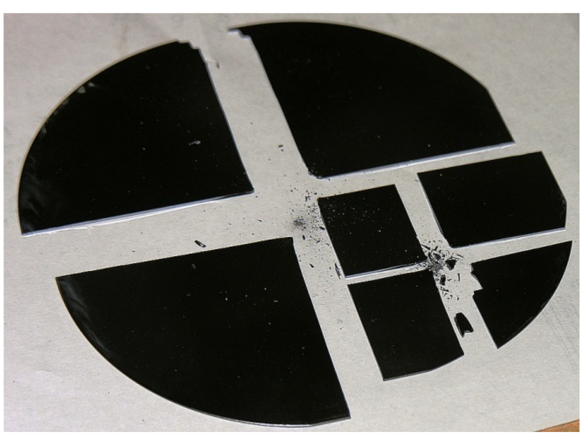
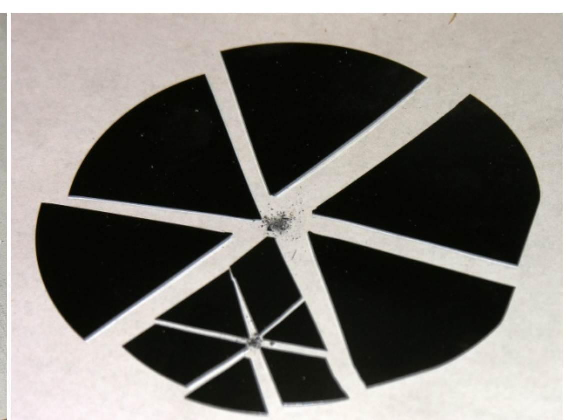
Activity: Breaking Wafers

<u>Procedure</u>:

1. Place two pieces of paper or poster paper side-by-side on the table top.
2. Remove one wafer from each of the wafer holders and place them side-by-side on the two pieces of paper.
3. Place another piece of paper over one of the wafers. (This is to minimize wafer shards from flying off the table.)
4. Put on your safety glasses.
5. Place the tip of the ice pick or screw driver close to the center of one of the wafers.
6. With the hammer or your hand, gently, but firmly, tap the handle of the ice pick until you hear the wafer break (snap).
7. Repeat steps 4 and 5 with the second wafer.
8. You will see that that wafers break at either right (90°) angles or at approximately 60° angles.
    a. What is the orientation of the wafer surface plane that breaks at 90° angles: (100) or (111)?
    b. What is the orientation of the wafer that breaks at 60° angles: (100) or (111)?
9. What would be the result of breaking one of the pieces of each wafer?
10. Test out your hypothesis. Break one of the pieces of each wafer.
11. Answer the Post-Activity Questions

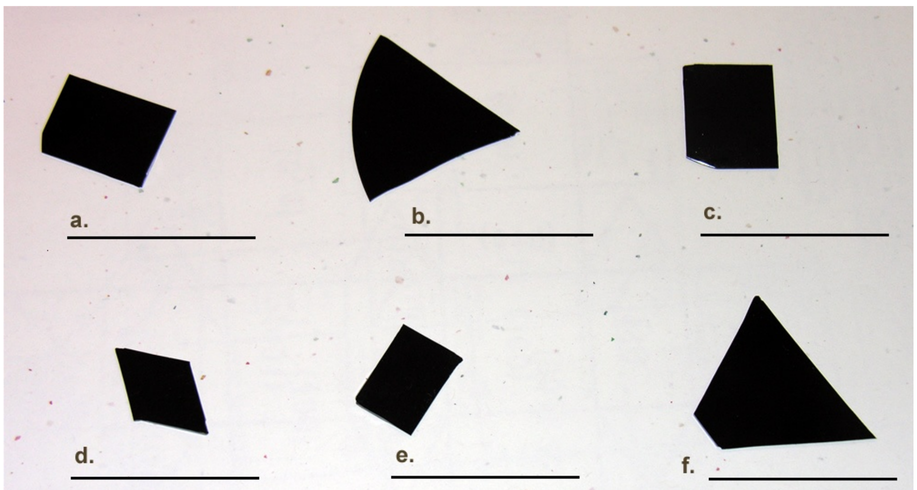
Note to the Instructor:

Below are pictures that show the result of this activity. The picture on the left is the (100) wafer. The picture on the right shows the (111) wafer.

Post-Activity Questions

1. In this activity, you broke two silicon wafers. One wafer had a (100) crystal surface plane orientation and the other a (111) surface plane orientation. In the making of the original silicon ingot, what determined the crystal orientation of the silicon wafer?
2. At what approximate angle did the (111) wafer break?
3. At what approximate angle did the (100) wafer break?
4. Did each wafer continue to break at the same angle when you broke the smaller pieces? Why or why not?
5. Which orientation (100) or (111) has more silicon atoms exposed to the wafer's surface?
6. Why is crystal orientation important in the fabrication of microsystems?
7. Identify the crystal orientation of each of the following pieces of silicon.



Post-Activity Questions / Answers

1. In this activity, you broke two silicon wafers. One wafer had a (100) crystal surface plane orientation and the other a (111) surface plane orientation. In the making of the original silicon ingot, what determined the crystal orientation of the silicon wafer?

   Answer: The alignment of the seed crystal relative to the molten silicon.
2. At what approximate angle did the (111) wafer break?

   Answer: 60° angle
3. At what approximate angle did the (100) wafer break?

   Answer: 90° angle
4. Did each wafer continue to break at the same angle when you broke the smaller pieces?

Why or why not?

Answer: Yes

5. Which orientation (100) or (111) has more silicon atoms exposed to the wafer's surface?

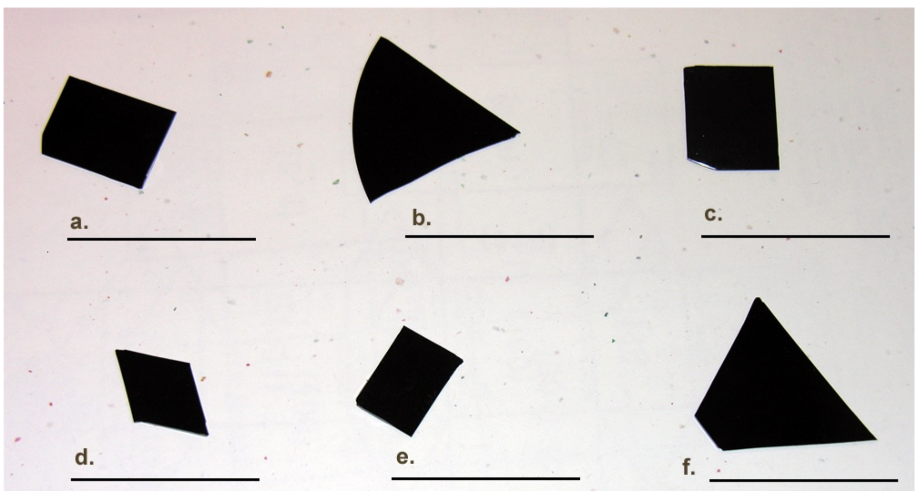
   Answer: (111)

6. Why is crystal orientation important in the fabrication of microsystems?

   Answer: 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. The orientation also determines the outcome (shape) of a wet or dry etch process. Certain orientations work better for specific shapes, etches and etch rates.

7. Identify the crystal orientation of each of the following pieces of silicon.



a. (100)
b. (111)
c. (100)
d. (111)
e. (100)
f. (111)

8. Some devices require a KOH (potassium hydroxide) anisotropic etch of the crystalline silicon. In this process, the (111) plane etches at about 0.0035µm / minute while the (100) plane etches at 1.4µm/minute, about 500 times faster! Briefly explain why the (100) plane etches at a faster rate than the (111) plane. *(You might have to do a little research for this one.)*

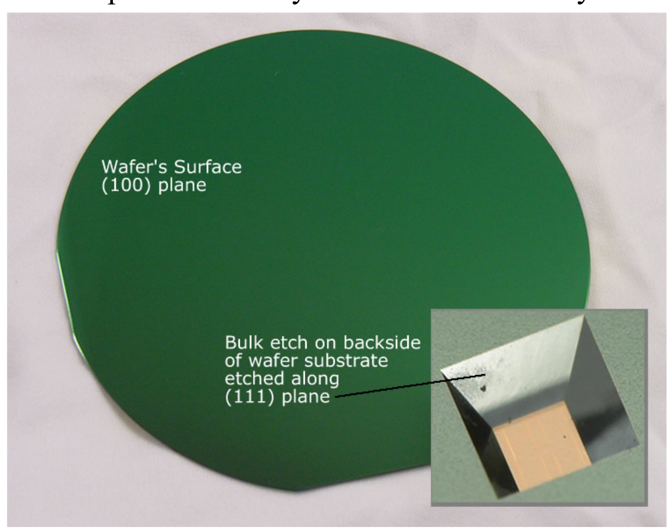
   Answer: Here is the technical answer, but one can go even deeper than this. The participants should find that the etch rate is due to the breaking of bonds and the different number of bonds that need to be broken with different orientations.

If you think about the atoms at the surface of the (100) plane, they have two dangling bonds – that is there are two of the 4 valence electrons free to react with the OH (hydroxides) floating about. In the case of the (111) plane, the surface silicon atoms only have one dangling bond available to react. (Participants can see this in some of the graphics found in the PK)

So… visualize this, the (100) surface silicon wafers have two dangling bonds and two "backbonds" – that is two bonds that are part of the crystal structure. In the (111) case, there are three backbonds out of the four valence electrons of silicon and only one dangling bond. Breaking three bonds is much harder than breaking two bonds.

Summary

The most commonly used orientation for MEMS fabrication is the (100) and less frequently the (111). These crystal orientation determines the electrical and mechanical properties for components of electromechanical systems. An example of when crystal orientation is very important is in the anisotropic etching of crystalline silicon. For example, KOH (potassium hydroxide) is used to etch crystalline silicon; the (111) plane etches at about 0.0035µm / minute while the (100) plane etches at 1.4µm/minute, about 500 times faster! The picture shows the surface of this wafer as the (100) plane and the results of a KOH backside etch that etched along the (111) plane.



References

1. Images of wafers, broken wafers and etched wafers courtesy of the Manufacturing Technology Training Center (MTTC) at the University of New Mexico.

Support for this work was provided by the National Science Foundation's Advanced Technological Education (ATE) Program through Grants. For more learning modules related to microtechnology, visit the SCME website (http://scme-nm.org).