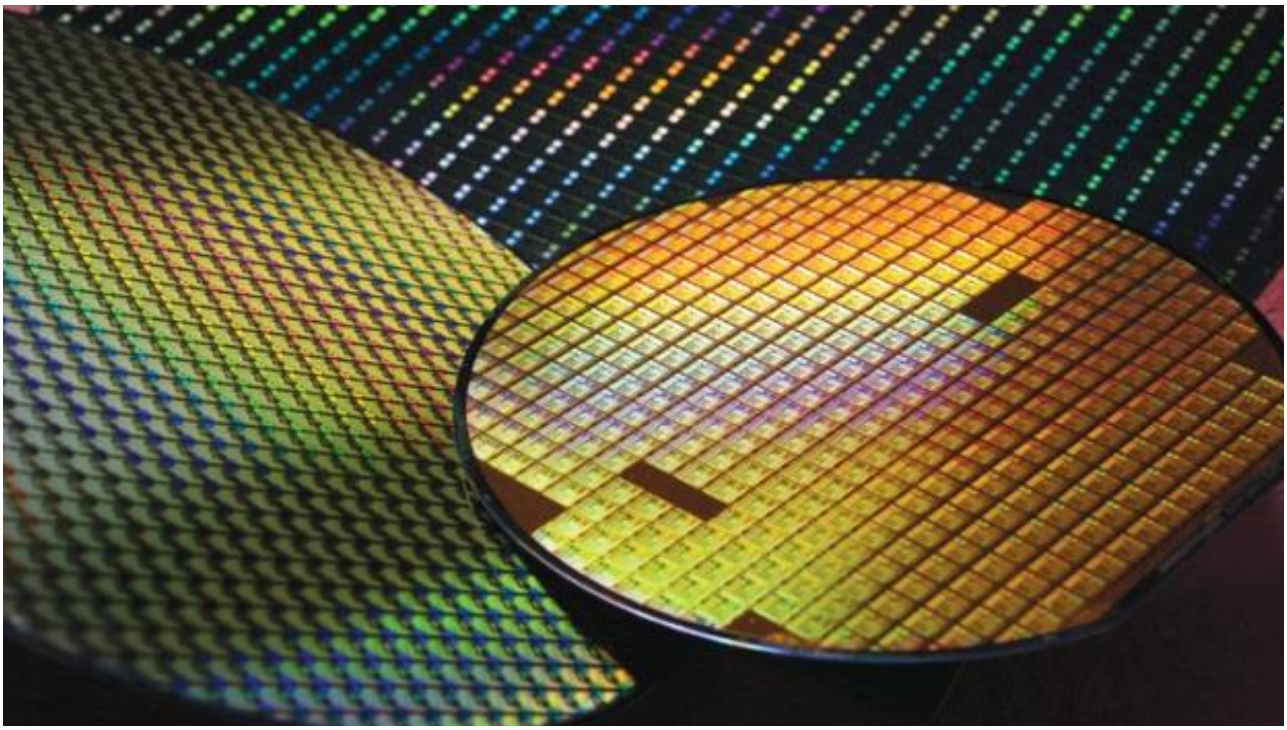
MSE 160 – Semiconductor characterization

60



61

Outline

- Semiconductor wafer synthesis
- Semiconductor resistivity measurement
- Final presentation Q & A

62

Modern computers use single crystal Si wafer substrates

63

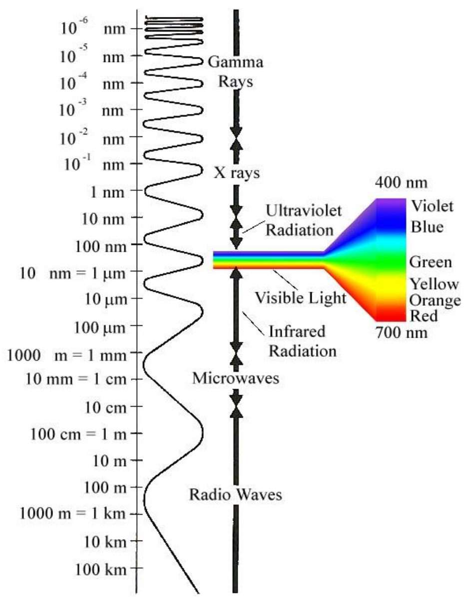
Modern computers use single crystal Si wafer substrates

Why is Si black?

64

Semiconductors can have bandgap in the visible range

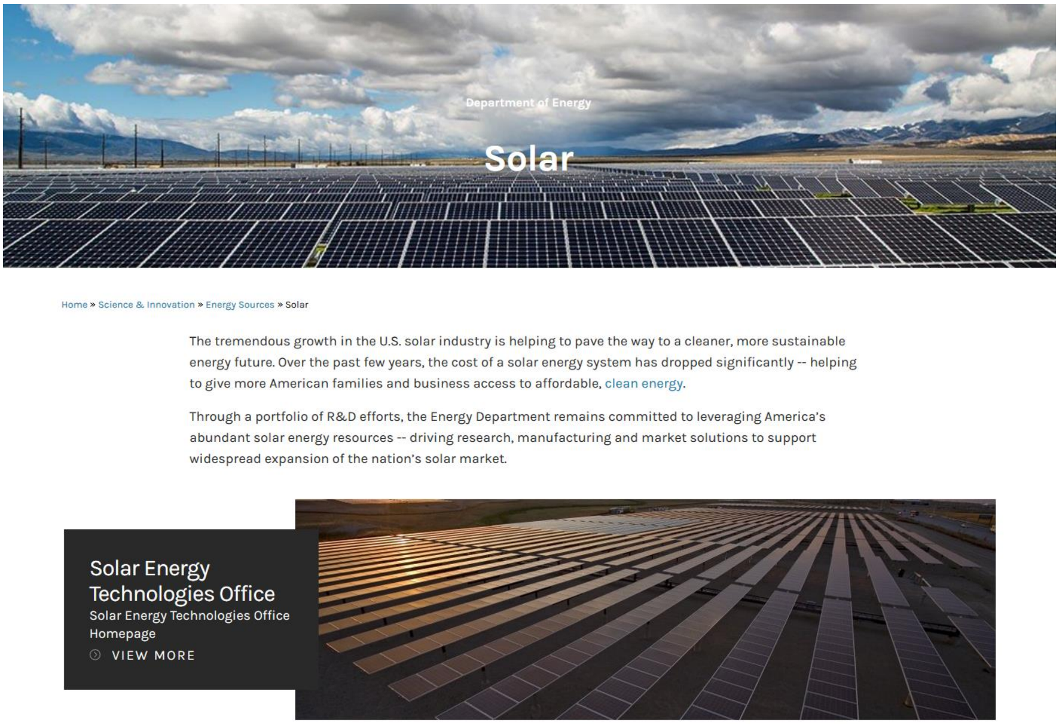
Increasing wavelength (m)



Increasing Photon Energy (eV)

Color & Energy
Violet ~ 3.17eV
Blue ~ 2.73eV
Green ~ 2.52eV
Yellow ~ 2.15eV
Orange ~ 2.08eV
Red ~ 1.62eV

65


Department of Energy
Solar
Home » Science & Innovation » Energy Sources » Solar
The tremendous growth in the U.S. solar industry is helping to pave the way to a cleaner, more sustainable energy future. Over the past few years, the cost of a solar energy system has dropped significantly -- helping to give more American families and business access to affordable, clean energy.
Through a portfolio of R&D efforts, the Energy Department remains committed to leveraging America's abundant solar energy resources -- driving research, manufacturing and market solutions to support widespread expansion of the nation's solar market.
Solar Energy Technologies Office
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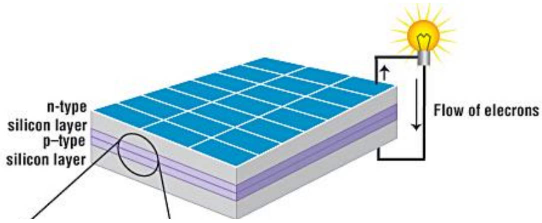
VIEW MORE

66


Solar Cell Manufacturing
SUN: 20 TW/ PER HOUR
EARTH USES: 16 TW/ PER YEAR
0:16 / 2:56

67

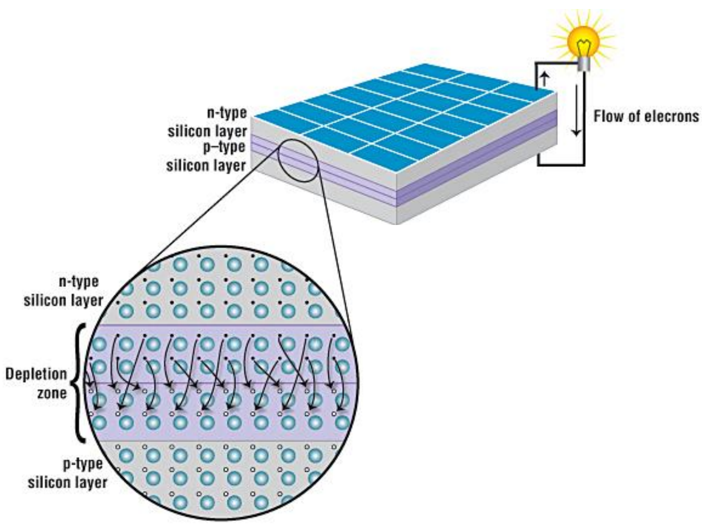
A photovoltaic cell is a p-n junction



Anthony Fernandez "How a Solar Cell Works"
American Chemical Society, acs.org

68

A photovoltaic cell is a p-n junction



Anthony Fernandez "How a Solar Cell Works"
American Chemical Society, acs.org

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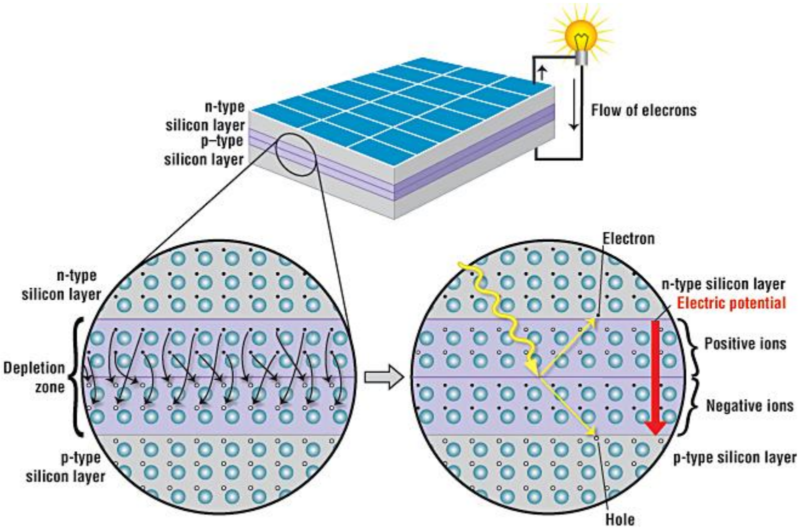
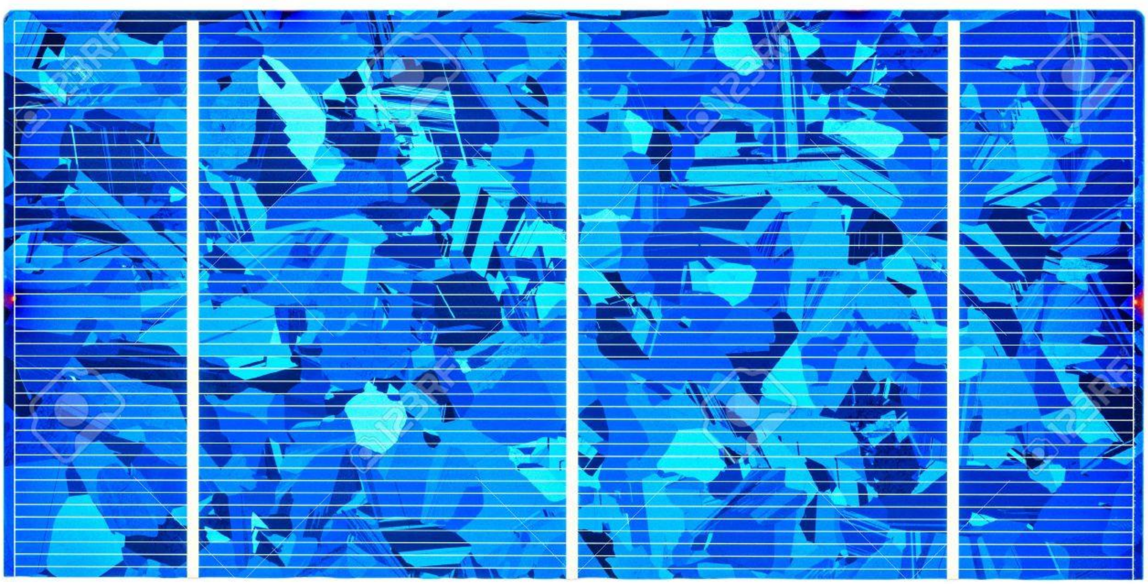
A photovoltaic cell is a p-n junction

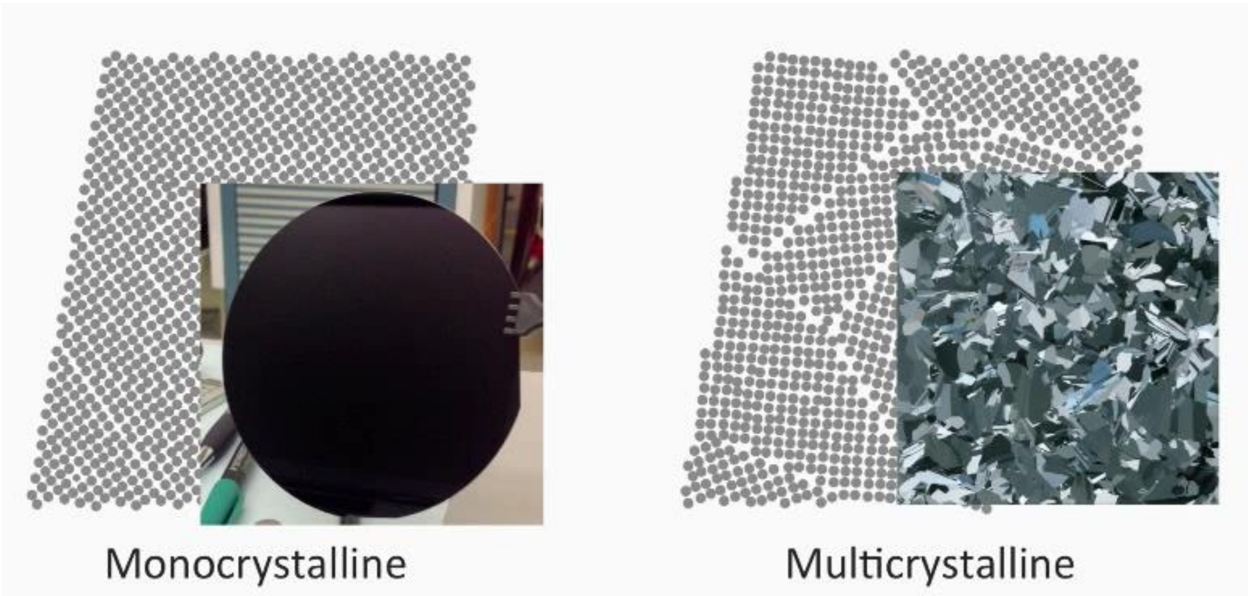


Anthony Fernandez “How a Solar Cell Works”
American Chemical Society, acs.org

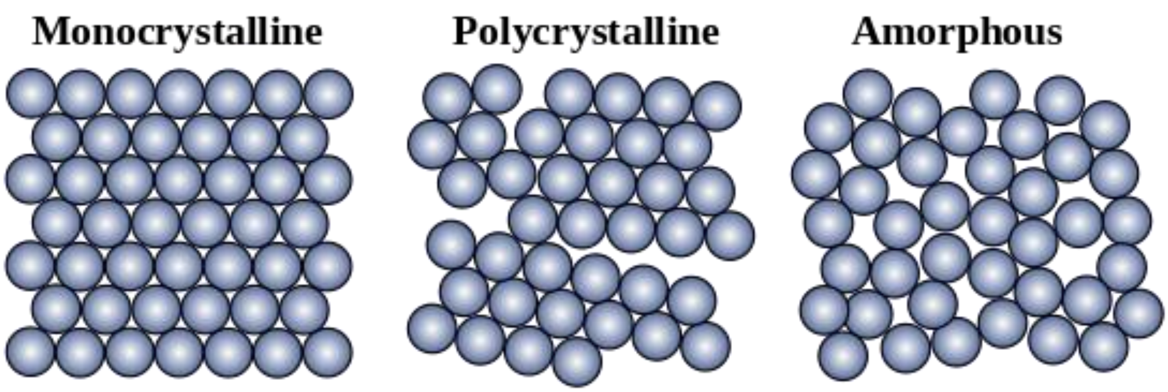
70



71

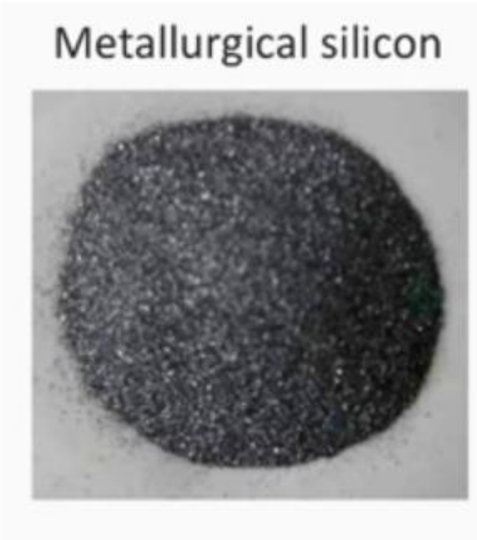

Monocrystalline
Multicrystalline

72


Monocrystalline
Polycrystalline
Amorphous

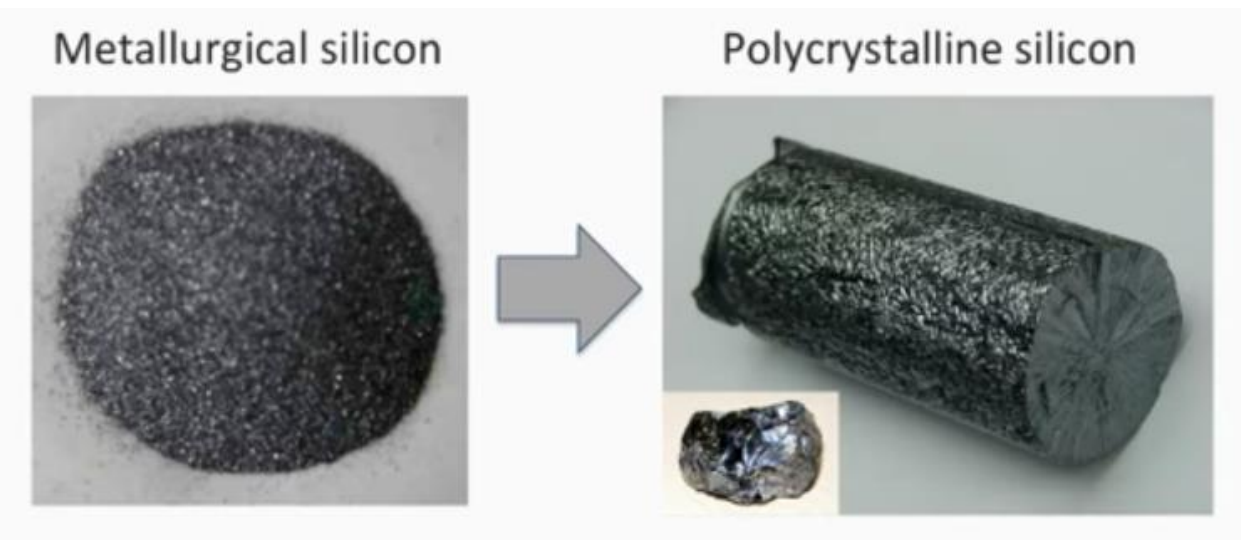
73

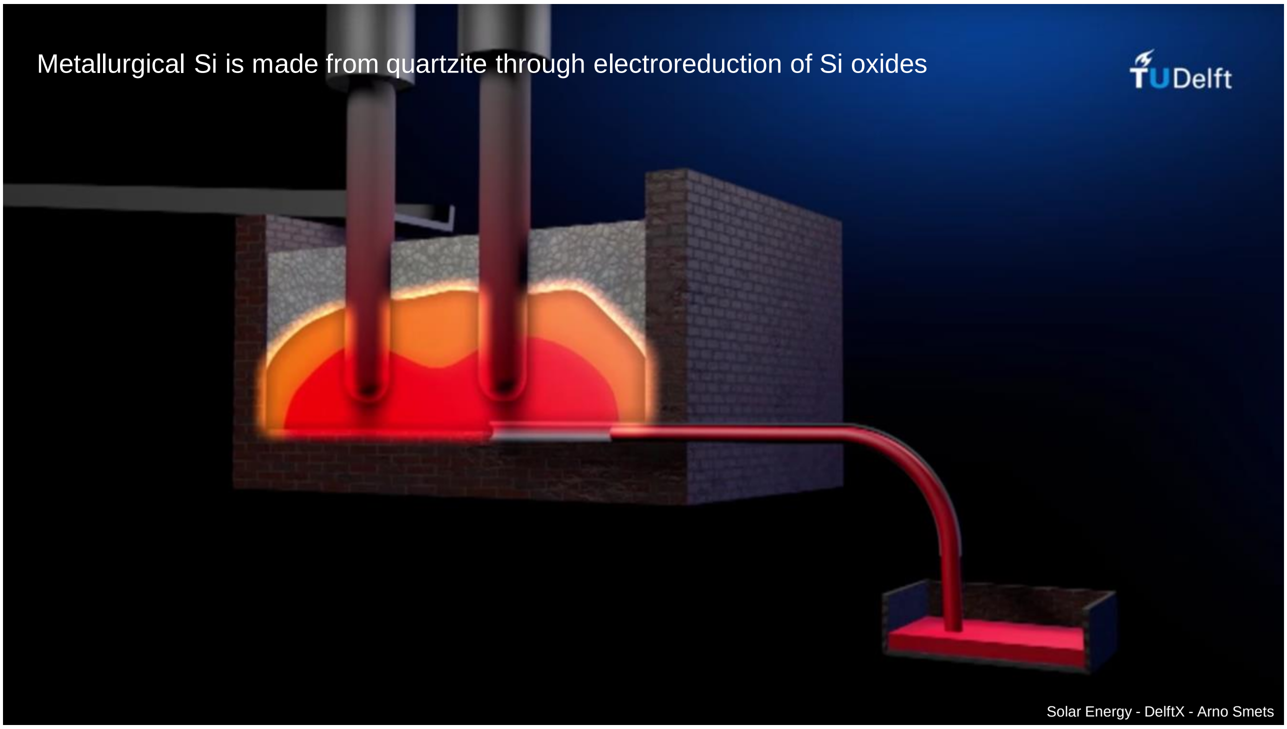
Si manufacturing is grounded in materials synthesis



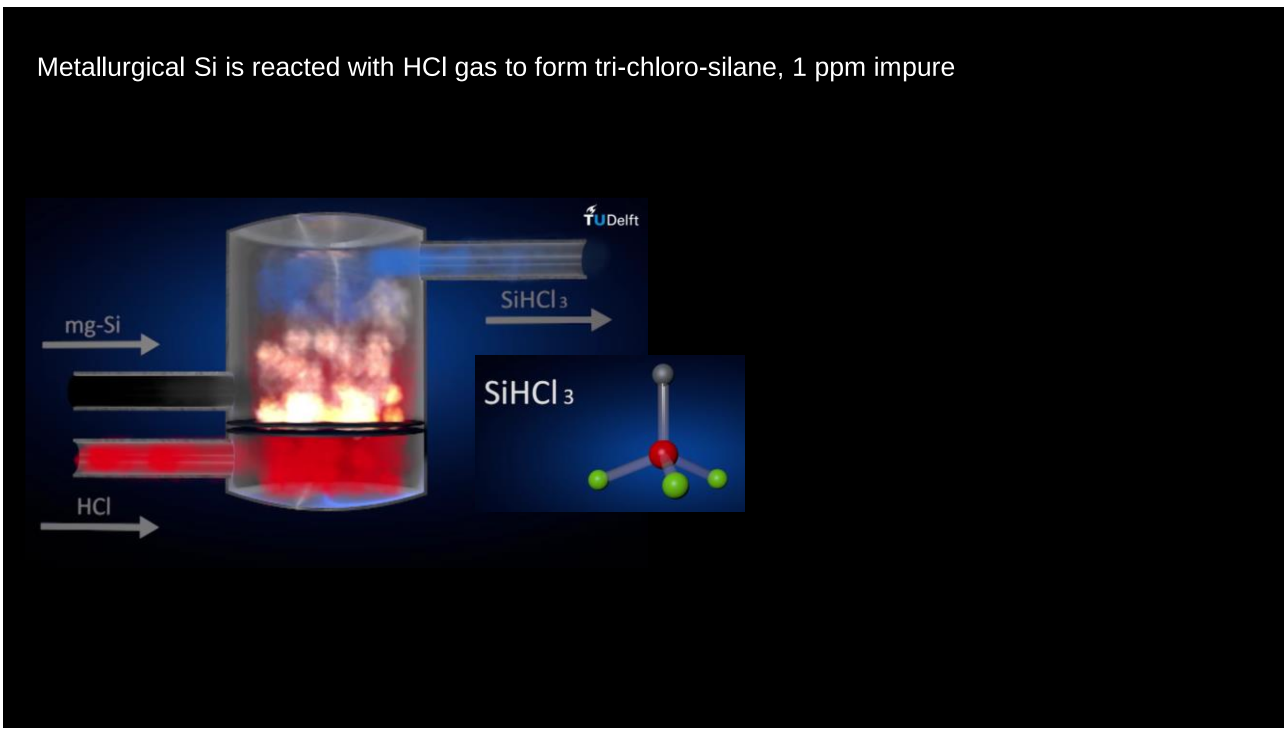
70% of mg-si is for Al alloying for automotive.
30% for other Si for e.g. silicones.
1% for poly and mono Si

Si manufacturing is grounded in materials synthesis

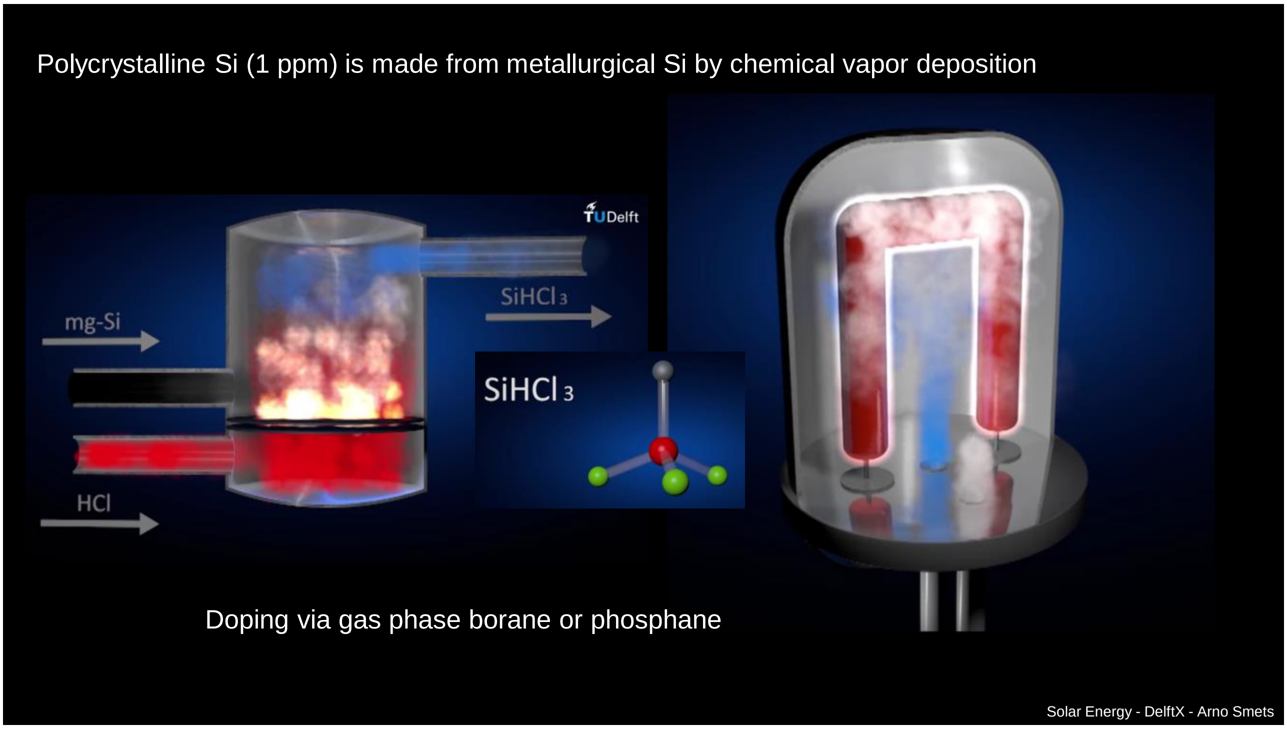



Metallurgical Si is made from quartzite through electroreduction of Si oxides
TUDelft
Solar Energy - DelftX - Arno Smets

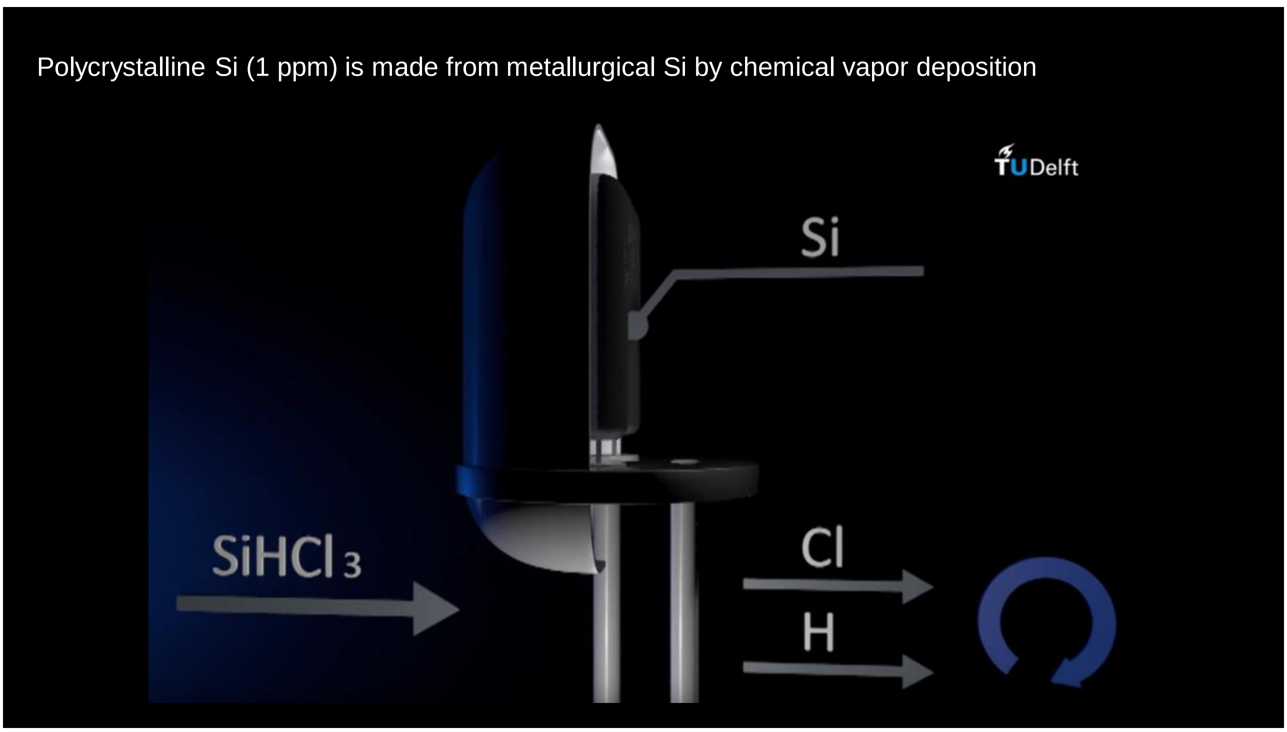
76


Metallurgical Si is reacted with HCl gas to form tri-chloro-silane, 1 ppm impure
TUDelft
mg-Si
HCl
SiHCl3
SiHCl3

77


Polycrystalline Si (1 ppm) is made from metallurgical Si by chemical vapor deposition
TUDelft
mg-Si
HCl
SiHCl3
SiHCl3
Doping via gas phase borane or phosphane
Solar Energy - DelftX - Arno Smets

78


Polycrystalline Si (1 ppm) is made from metallurgical Si by chemical vapor deposition
TUDelft
Si
SiHCl3
Cl
H

79

Modern computers use single crystal Si wafer substrates

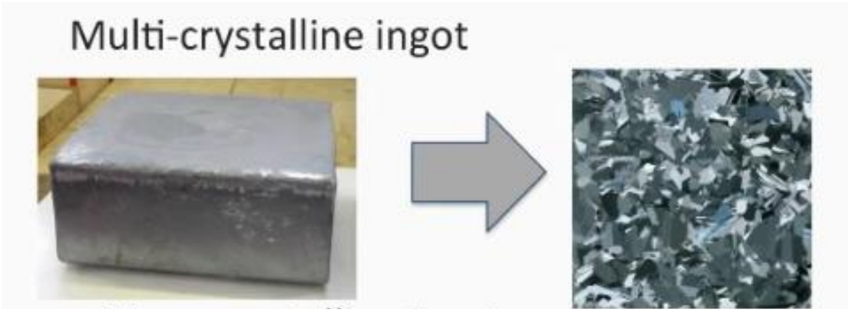
80

Si ingot is prepared from poly Si

https://www.youtube.com/watch?v=8QKzS_w_Ko0&t=320s

81

Multicrystalline ingot is also produced from melt by directional solidification

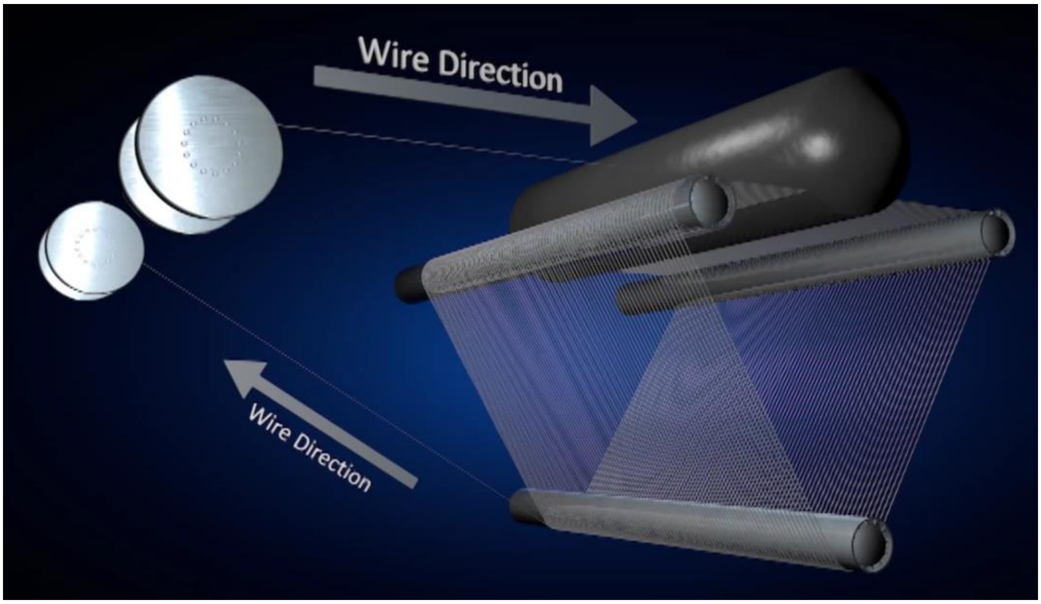


82

Multicrystalline ingot is produced from melt

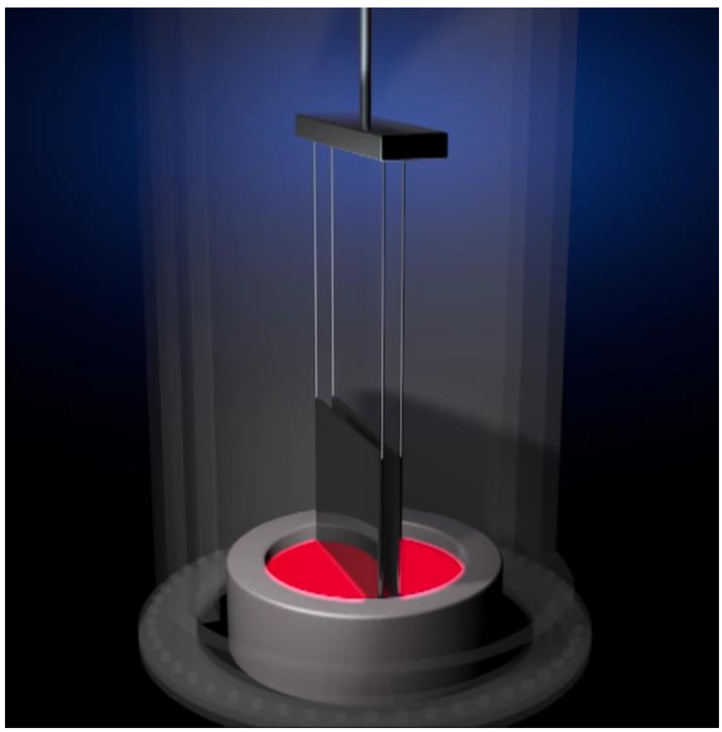
83

Wafers are created from ingot via sawing to ~150 μm



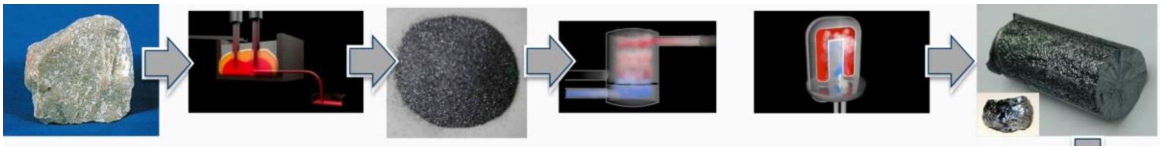
84

Wafers are created from Si ribbon



85

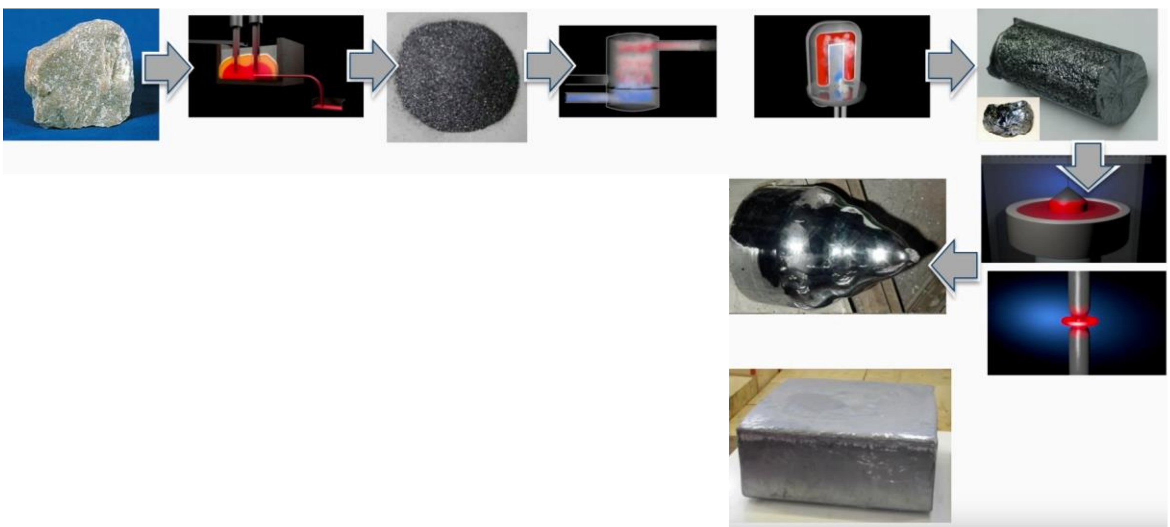
Si manufacturing is grounded in materials synthesis



Solar Energy - DelftX - Arno Smets

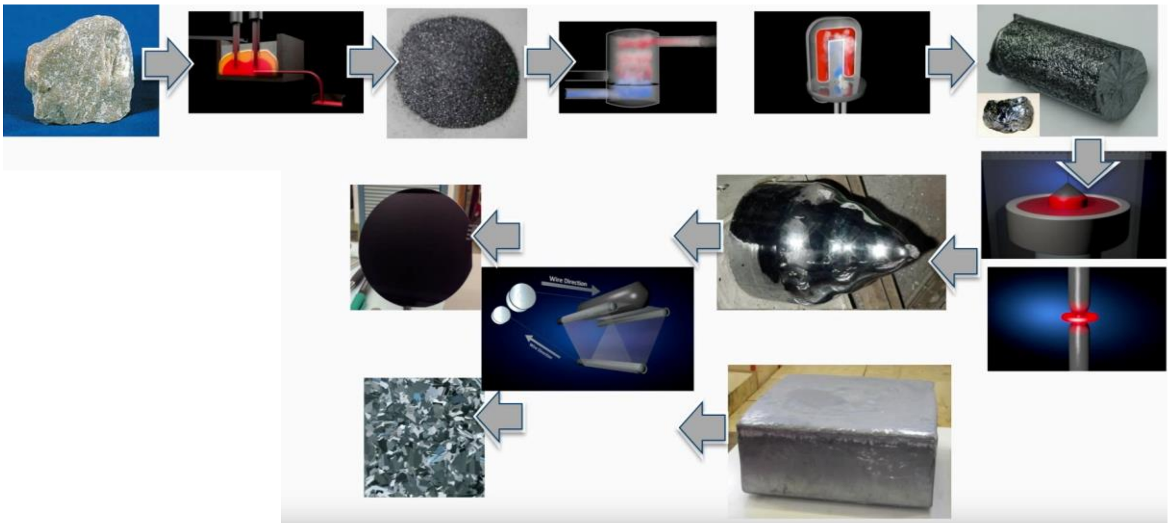
86

Si manufacturing is grounded in materials synthesis



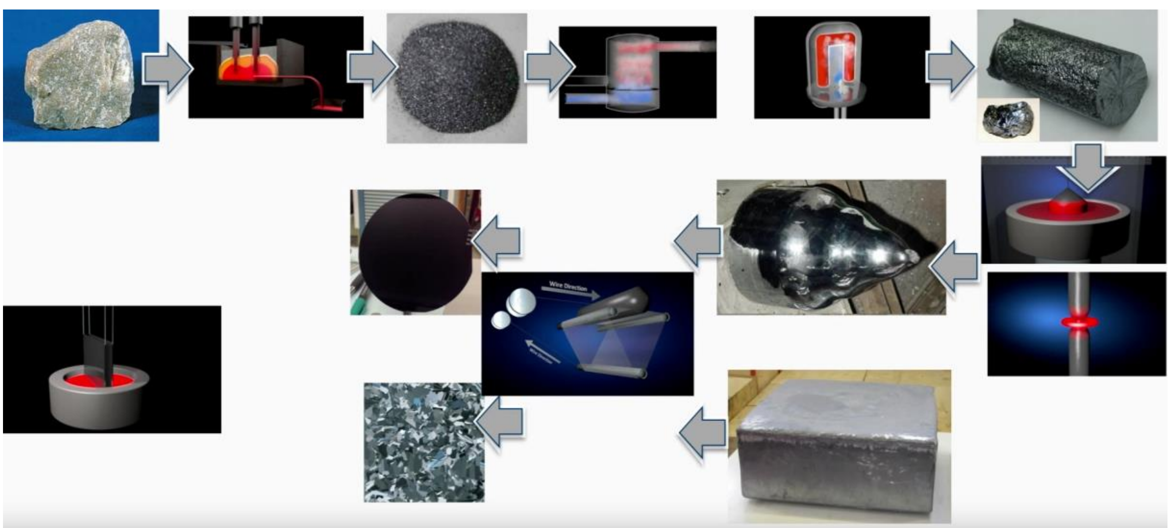
87

Si manufacturing is grounded in materials synthesis



88

Si manufacturing is grounded in materials synthesis



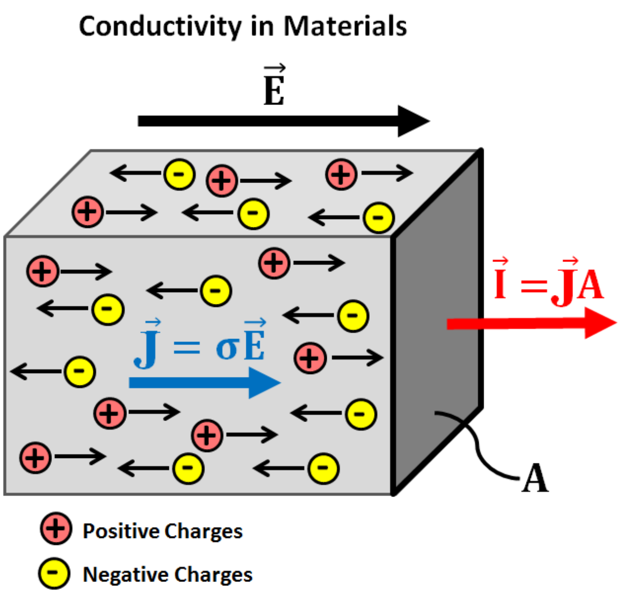
89

Conductivity of semiconductor increases with temperature

How does this differ from metal? What happens in metals as T increases?

90

Conductivity of semiconductor increases with temperature



91

Conductivity of semiconductor increases with temperature

- Electrical conductivity, σ = 1/ρ = $\sum_i (nq\mu)_i$

- *i* = carrier (e.g. electron, hole, ion)
- n = carrier concentration
- q = carrier charge
- μ = carrier mobility

92

Conductivity of semiconductor increases with temperature

- Electrical conductivity, σ = 1/ρ = $\sum_i (nq\mu)_i$

- *i* = carrier (e.g. electron, hole, ion)
- n = carrier concentration
- q = carrier charge
- μ = carrier mobility

- With increasing temperature
  - q does not change
  - μ decreases (because of drift velocity)
  - n increases exponentially

93

Conductivity of semiconductor increases with temperature

- Carrier concentration depends exponentially on temperature

Electron density in conduction band

Conduction band minimum

Fermi level

$$n_0 = N_c \exp[-\frac{E_c - E_F}{k_B T}]$$

Conduction band states

94

Conductivity of semiconductor increases with temperature

- Carrier concentration depends exponentially on temperature

Electron density in conduction band

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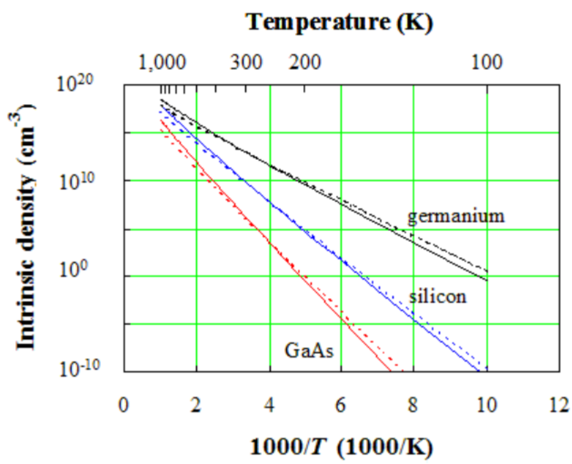
Fermi level

$$n_0 = N_c \exp[-\frac{E_c - E_F}{k_B T}]$$

Conduction band states



95

Conductivity of semiconductor increases with temperature

- Carrier concentration depends exponentially on temperature

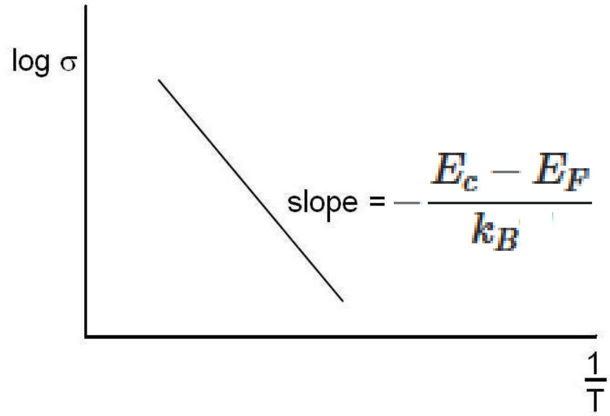
Electron density in conduction band

Conduction band minimum

Fermi level

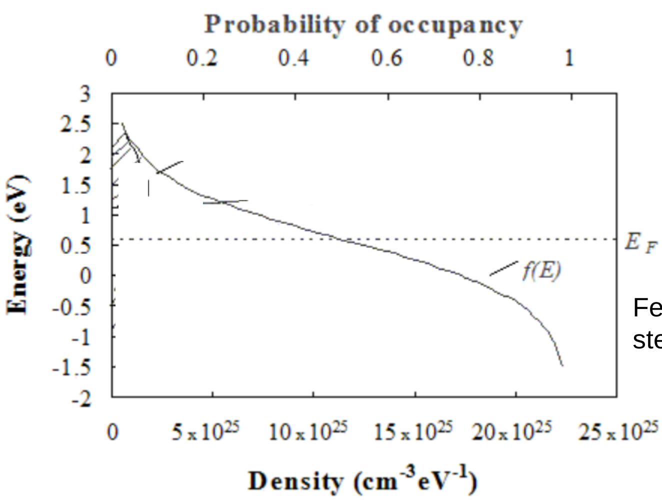
$$n_0 = N_c \exp[-\frac{E_c - E_F}{k_B T}]$$

Conduction band states



96

Calculation of the electron and hole density in a semiconductor

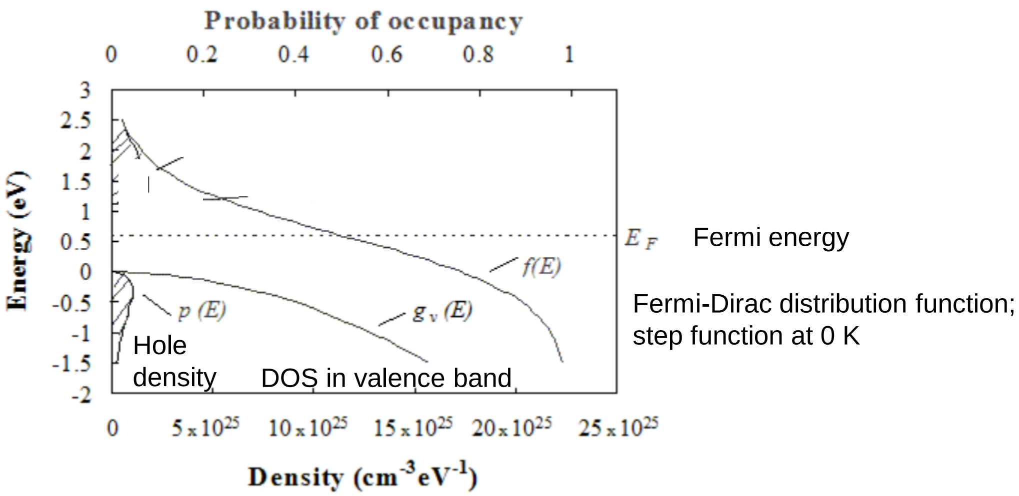


Fermi energy

Fermi-Dirac distribution function; step function at 0 K

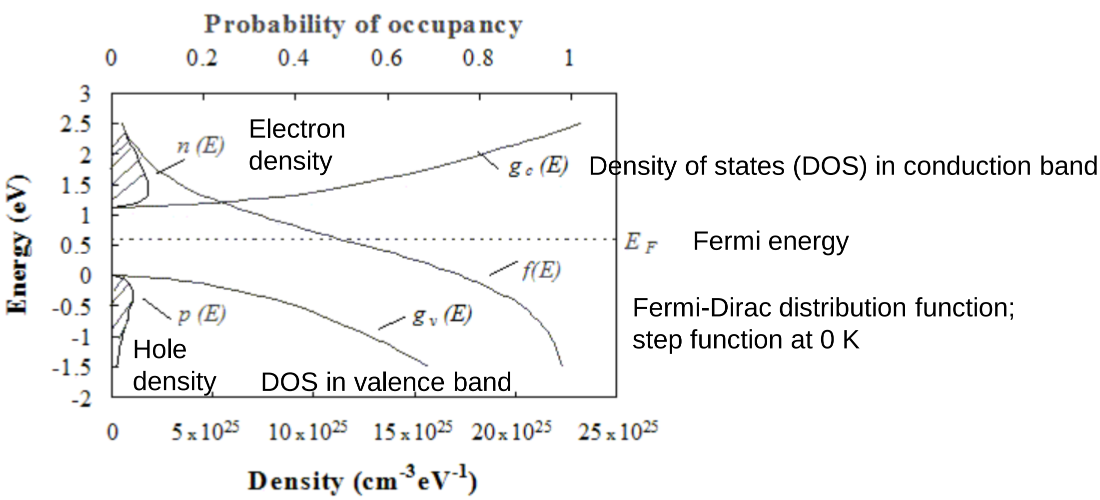
97

Calculation of the electron and hole density in a semiconductor



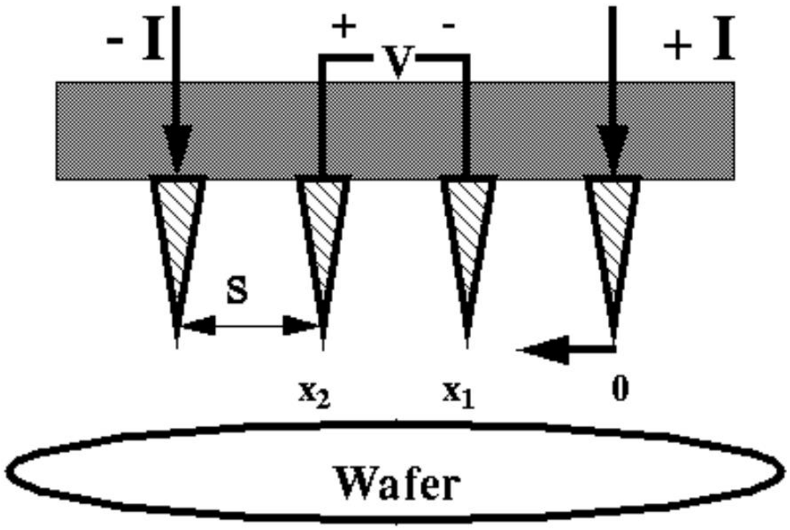
98

Calculation of the electron and hole density in a semiconductor



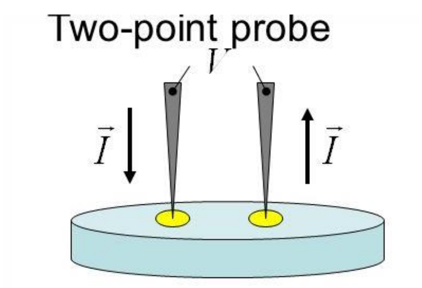
99

4-point probe measures the resistivity of any semiconductor



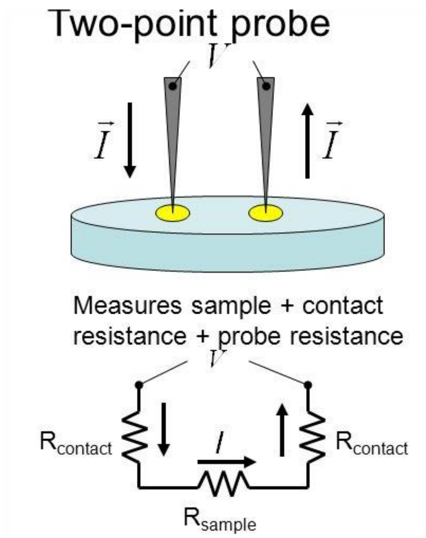
100

2-point probe measures sample, contact and probe resistance



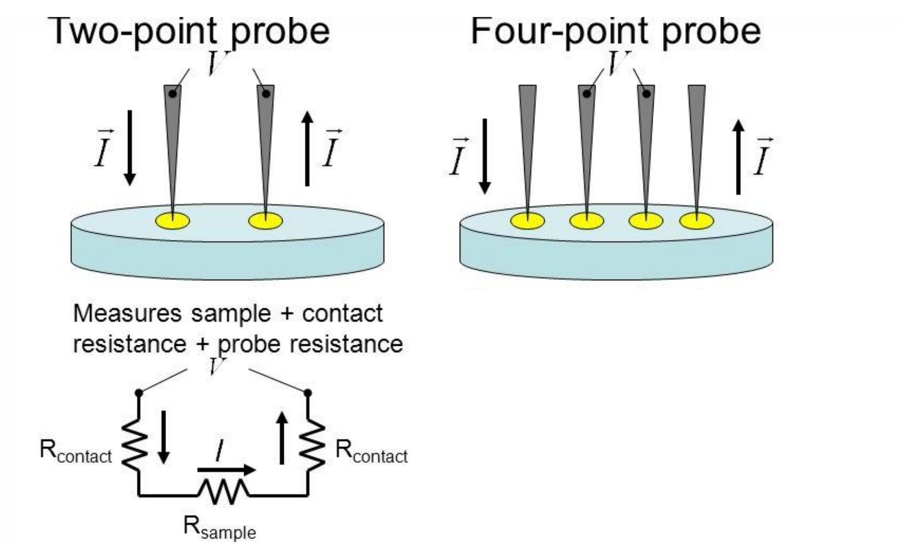
101

2-point probe measures sample, contact and probe resistance



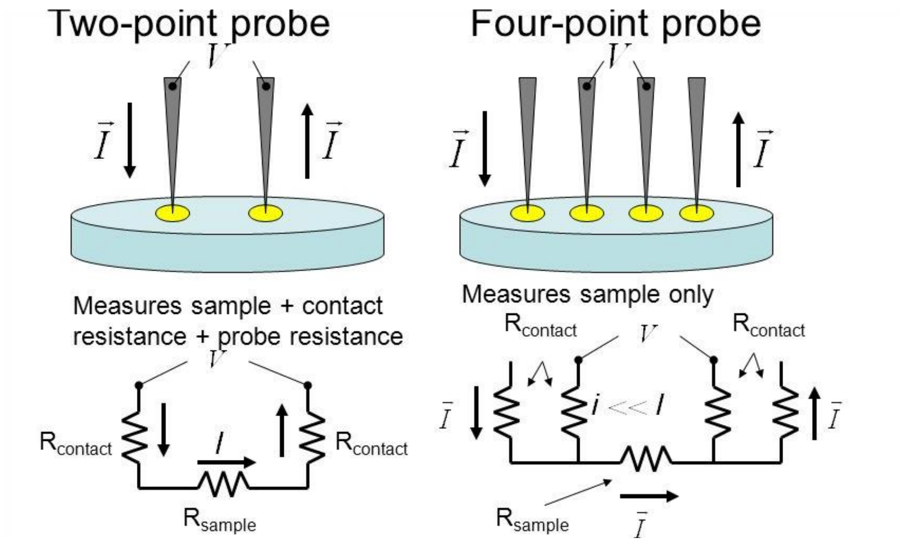
102

4-point probe measures sample only



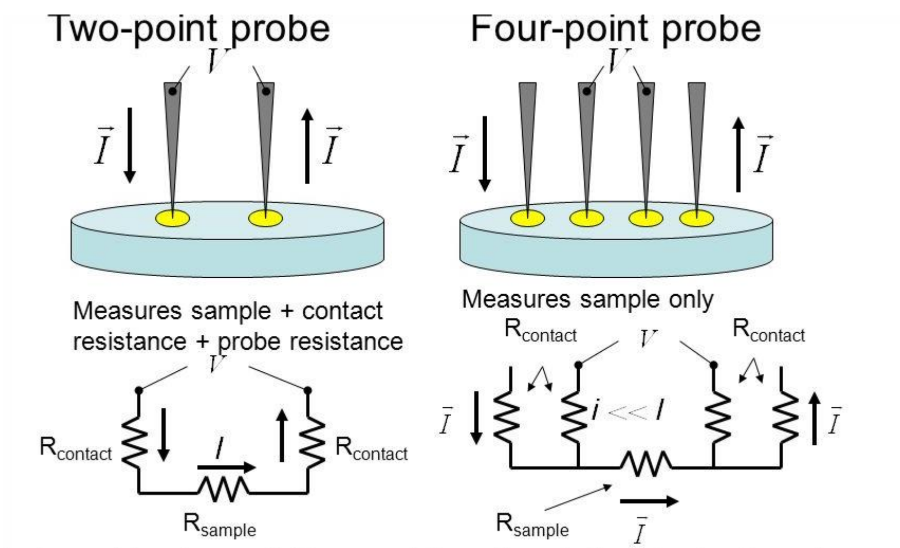
103

4-point probe measures sample only



104

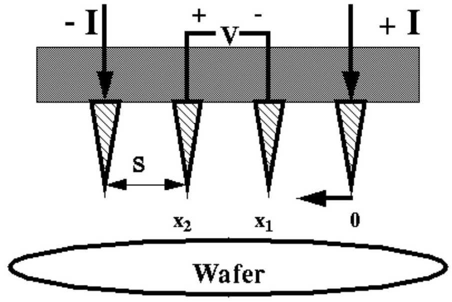
4-point probe measures sample only



In four-point probe, negligible current flows through the voltmeter, the only voltage drop measured is across R_{sample}.

105

4-point probe method applies to bulk and thin films

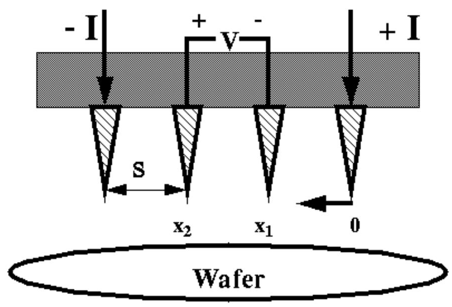


- For bulk samples, thickness t >> s
- Assume spherical protrusion of current emanating from the outer probe tips
- The differential resistance is:

$$\Delta R = \rho\left(\frac{dx}{A}\right)$$

106

4-point probe method applies to bulk and thin films



- Integration between the inner probe tips (where the voltage is measured)
- Assume spherical protrusion of current emanating from the outer probe tips

$$R = \int_{x_1}^{x_2} \rho \frac{dx}{2\pi x^2} = \frac{\rho}{2\pi}\left(-\frac{1}{x}\right)\Big|_{x_1}^{x_2} = \frac{1}{2s}\frac{\rho}{2\pi}$$

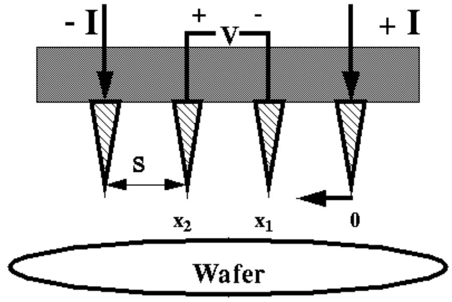
Half sphere

107

4-point probe method applies to bulk and thin films

- superposition of current at the outer two tips: R = V/2I
- the expression for bulk resistivity

$$\rho = 2\pi s\left(\frac{V}{I}\right)$$

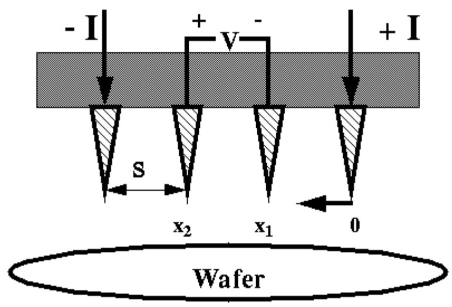


108

4-point probe method applies to bulk and thin films

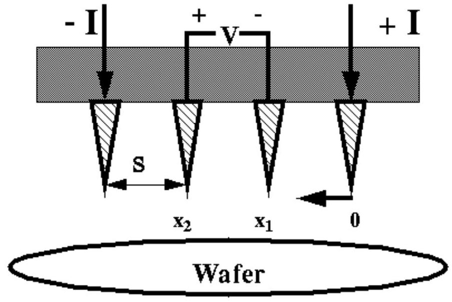
- For thin layers with thickness t << s
- Current rings instead of spheres emanate from the outer probe tips
- The area is thus: $A = 2\pi x t$
- The resistance is:

$$R = \int_{x_1}^{x_2} \rho \frac{dx}{2\pi x t} = \int_{s}^{2s} \frac{\rho}{2\pi t}\frac{dx}{x} = \frac{\rho}{2\pi t} ln(x)\Big|_s^{2s} = \frac{\rho}{2\pi t} ln2$$



109

4-point probe method applies to bulk and thin films



- superposition of current at the outer two tips: R = V/2I

$$\rho = \frac{\pi t}{\ln 2}\left(\frac{V}{I}\right)$$

- Sheet resistivity is per thickness

$$R_s = \rho / t = \frac{\pi}{\ln 2}\left(\frac{V}{I}\right)$$

110

Final presentations are next M-W, any questions?

		characterization		
Week 10	**M/W Group 1 final presentations**	**T/Th Groups 1 & 2 final presentations**	**M/W Group 2 final presentations**	**No Lab**
3/9 – 3/12		No Lecture		No Lecture
Week 11 **3/14 – 3/20**			**M/W Groups semiconductor lab reports due by 1 PM PST**	**T/Th Groups semiconductor lab reports due by 1 PM PST**

111

References (see Class page)

Semiconductors
B. Van Zeghbroeck (2011) Principles of Semiconductors
https://ecee.colorado.edu/~bart/book/book/chapter2/ch2_6.htm#fig2_6_5

Four-point probe

Chan J Friedberg P (2002) Four point probe manual

Silicon wafer synthesis

Throughout

112