Tuesday, 1/13/26

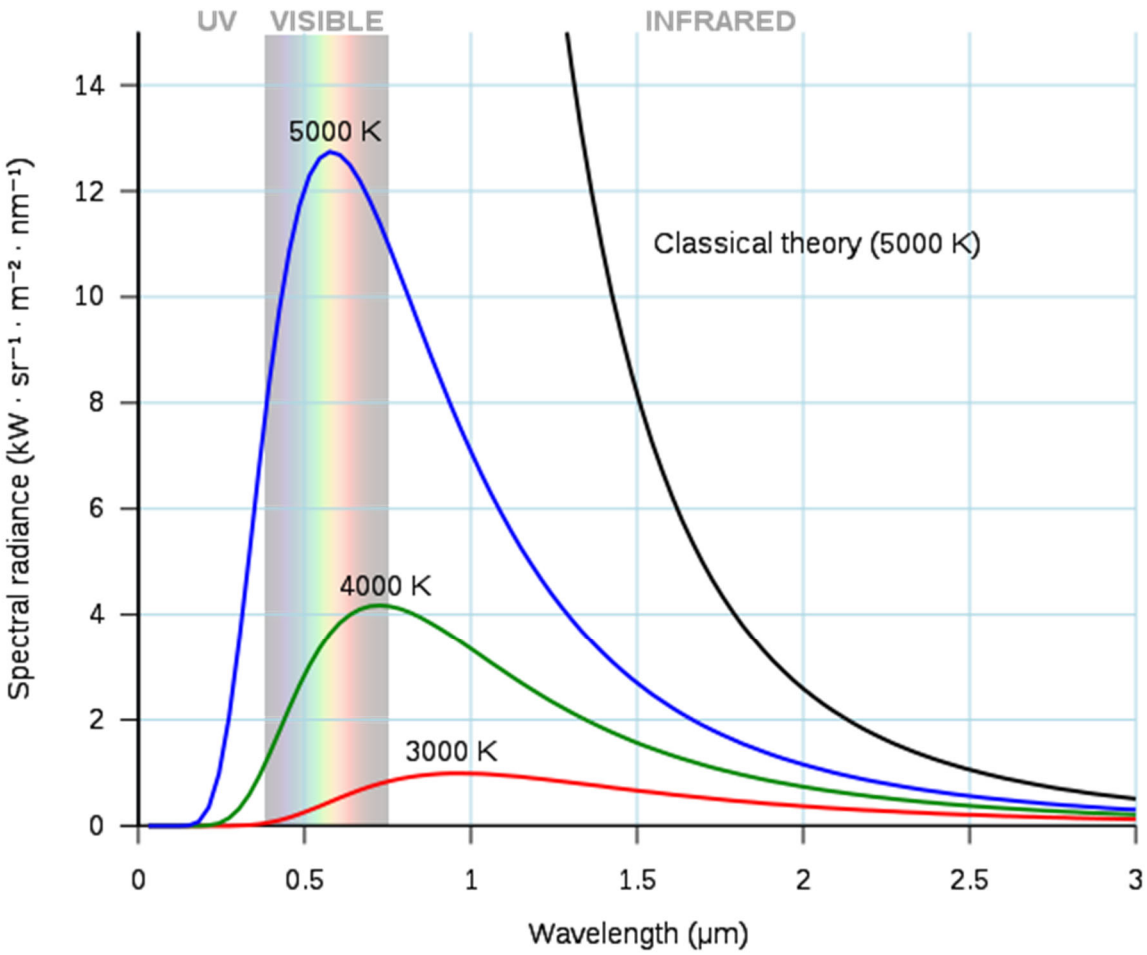
The Sun's Spectral Distribution

a. Background

All objects above absolute zero temperature emit thermal radiation.

An ideal thermal radiation emitter is called a "Black Body Emitter."

→ emits a continuous spectrum dependent on temperature



(https://commons.wikimedia.org/wiki/File:Black_body.svg)

As the temperature decreases, the peak of the black body radiation curve decreases and moves to longer wavelength (lower frequencies). Visible range: approximately 380 to 740 nm. Note: 273.15 K = 0°C

b. The Sun

The sun is almost a perfect block body emitter at a temperature of approximately 6000 K (5743 K to be more specific):

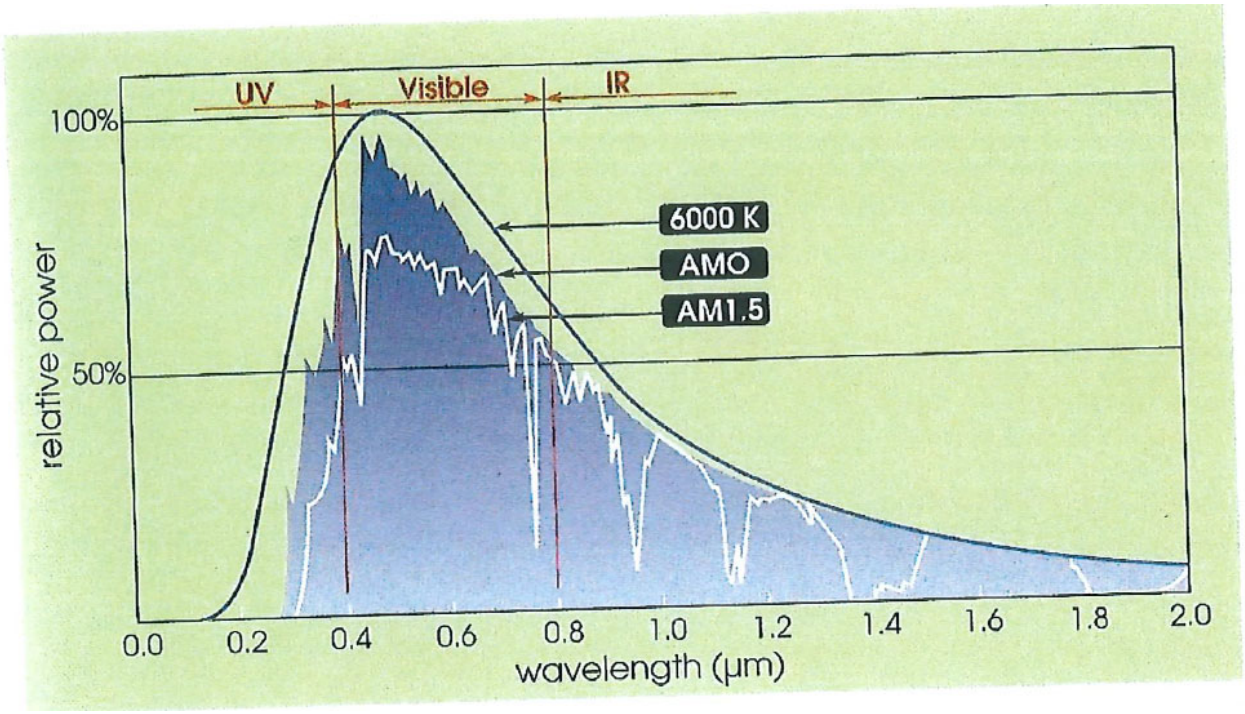


Fig. 1.8 (textbook, p. 9). Spectral distribution of the sun

"AM" or "Air Mass" refers to the amount of air that sunlight must travel through before reaching the PV device.

AM0 → refers to sunlight just outside of the earth's atmosphere (corresponds most closely to a 5743 K black body). Note: the listed temperature for the surface of the sun is 5778 K.

Also observe in Fig 1.8:

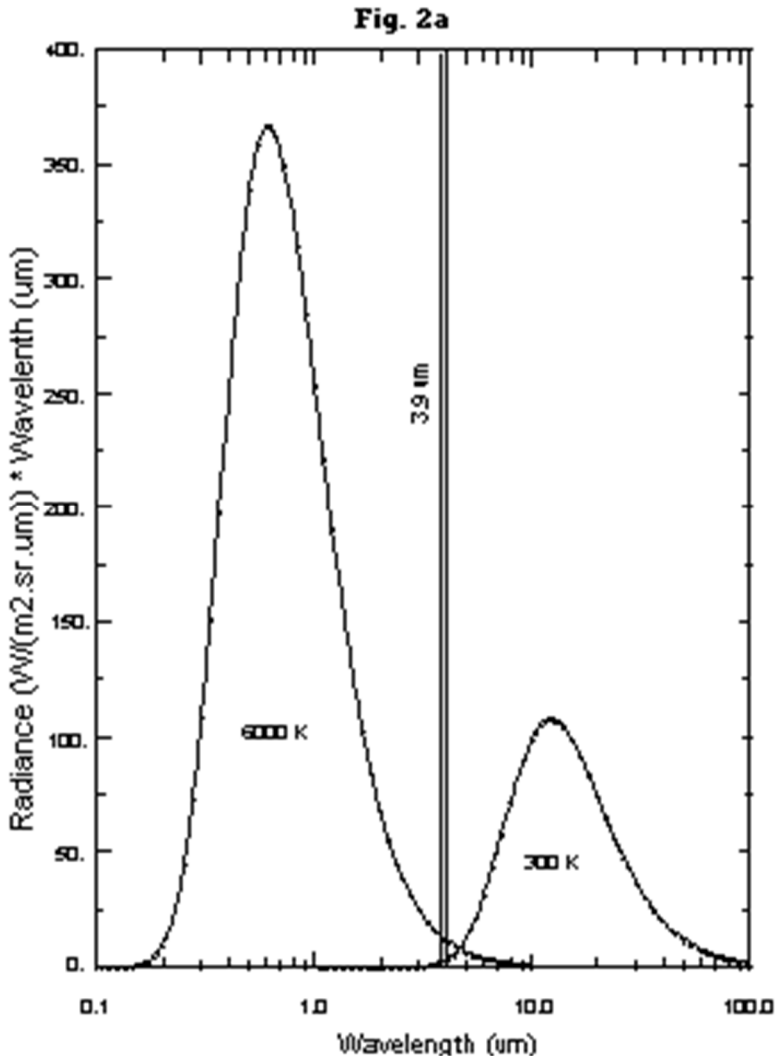
Visible light spectrum: 0.4 μm (violet) $\leq \lambda \leq$ 0.8 μm (red)

Ultraviolet (UV) spectrum: $\lambda <$ 0.4 μm

Infrared (IR) spectrum: $\lambda >$ 0.8 μm

c. Greenhouse Effect

Some of the energy the earth receives from the sun is irradiated back into space. As such, the earth is also a black body, but a cooler one than the sun:



(https://rammb.cira.colostate.edu/training/tutorials/goes_39um/energy_1.asp)

Whereas the sun approximates a 6000 K black body, the earth approximates a 300 K black body. The earth absorbs the sun's energy and radiates some energy back at longer wavelengths (lower frequency).

However, not all of this energy irradiated by the earth makes it into space. Some of the irradiated energy is captured by gases in the earth's atmosphere, heating the atmosphere, through the process called the "greenhouse effect."

Observe the regions of lower measured irradiance into space:

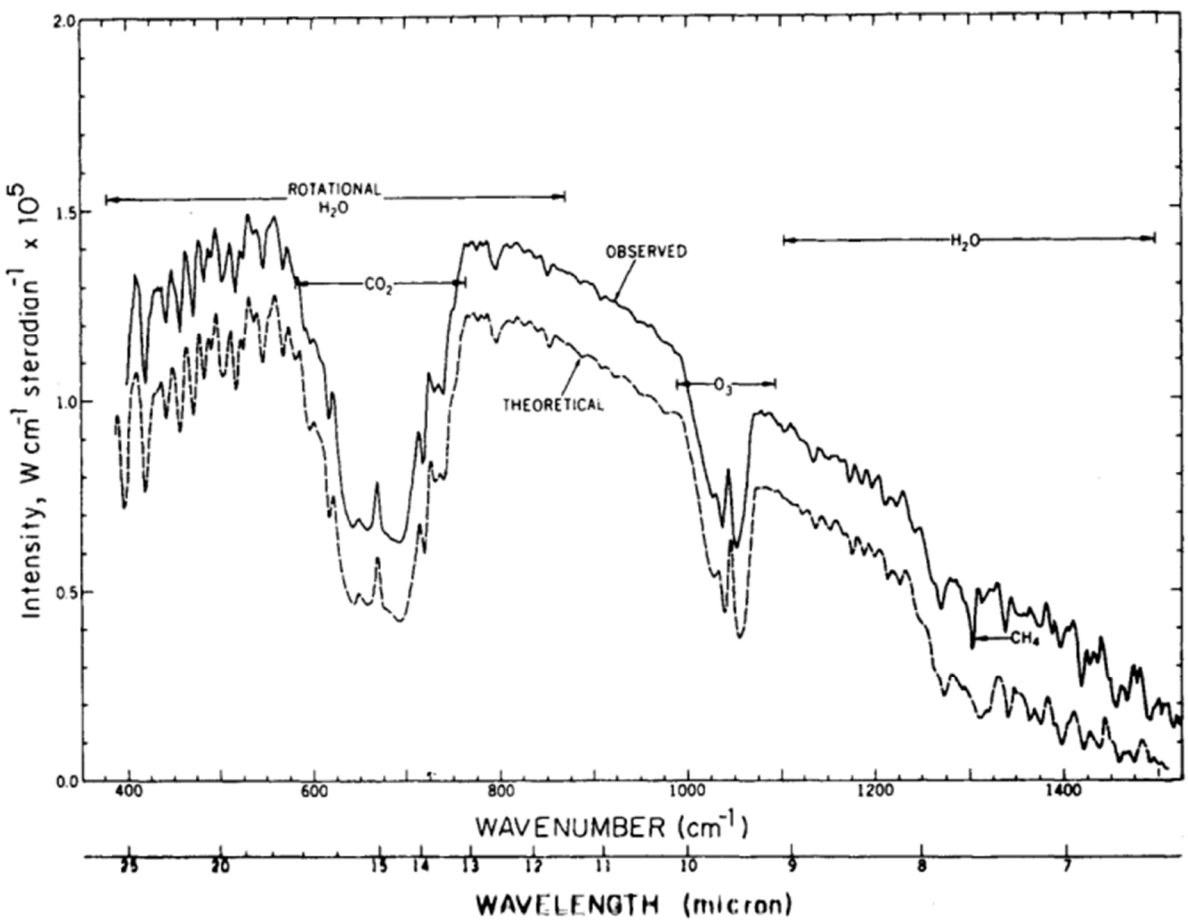


Fig 6.1. Observed and theoretical spectra for clear skies over the Gulf of Mexico, April 23, 1969. The observed spectrum is displaced upward by 0.2 x 10^{-5} W cm^{-2} steradian^{-1} wavenumber^{-1}

(https://scienceofdoom.files.wordpress.com/2010/08/olr-toa-goody-1989.png)

These regions are due to radiation absorption by various gases in the atmosphere. So how does this heat the atmosphere?

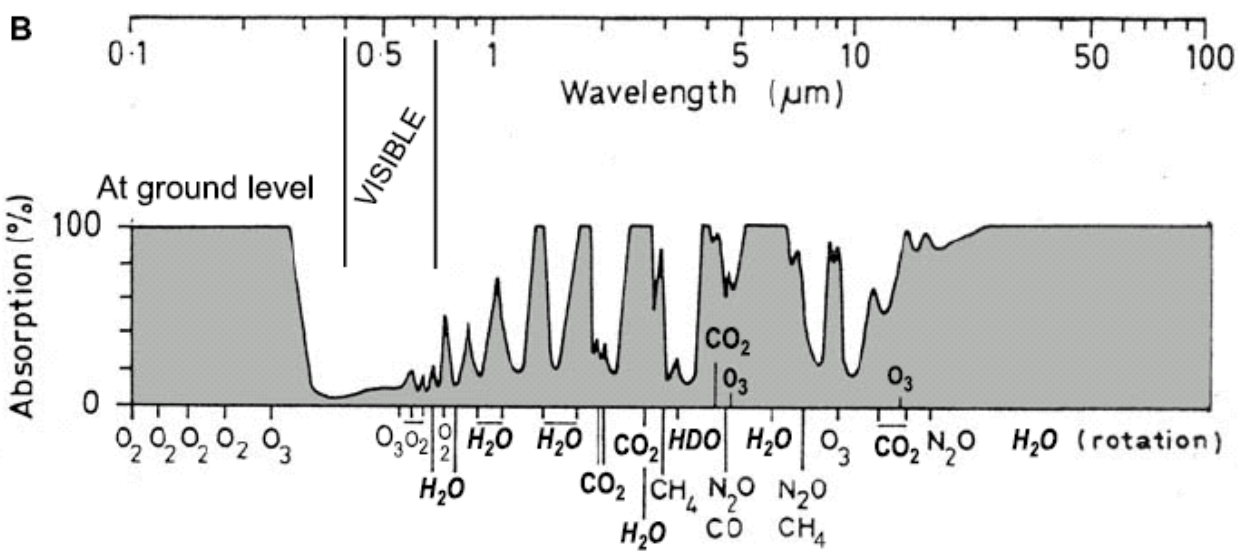
CO_2 is a polar molecule and a trace gas in the atmosphere. As such, the three atoms form several configurations of spring-mass-dampers, with electrostatic springs, that each possess a natural frequency. There are three main vibration modes, each with a different natural frequency. One of these natural frequencies occurs at a wavelength of approximately 15 μm (a wavenumber of 667 cm^{-1}). The other two are at higher frequencies where there is less irradiated energy present.

These mechanical natural frequencies are dielectric relaxation frequencies: electromagnetic energy at that frequency (such as from the energy irradiated from the earth) will excite the CO_2 molecule to vibrate, absorbing energy in the process.

When the vibrating CO_2 molecule collides with one of the much more numerous N_2 molecules in the atmosphere, it transfers this absorbed energy to the N_2 molecule, heating the atmosphere.

There are real unanswered questions as to the extent that increasing atmospheric CO_2 affects climate. There is only so much irradiated energy at 15 μm to be absorbed: at what CO_2 level is absorption saturation reached? What is the effect of absorbing all of the 15 μm irradiated energy at a lower altitude? What about other polar molecule gases in the atmosphere (H_2O, O_3, CH_4, etc.)? What about positive and negative feedback loops in the environment (more CO_2 – more plant growth – more photosynthesis – more CO_2 converted to O_2 and carbon stored as sugar). What about long-term climate cycles?

As far as this class is concerned, we are more interested in the sunlight reaching the earth, as opposed to energy irradiated from the earth. Consider the atmospheric absorption spectrum shown below:



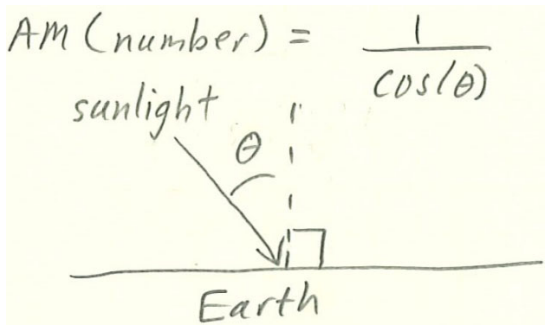
(https://www.researchgate.net/figure/A-Radiation-absorption-spectrum-of-the-Earth-atmosphere-in-wavelength-range-from-01_fig4_302399795)

Observe that the best atmospheric window for the sun's energy to reach the earth's surface is in the visible light band.

The AM0 spectrum is useful for satellite PV applications.

AM1 → the sunlight spectrum at earth's surface when the sun is directly overhead.

The "number" after "AM" comes from:



AM2 → $\theta = 60^o$ → the path length through the atmosphere has doubled.

AM1.5 → $\theta = 48.19^o$ → a standard used for solar simulators and for assessing PV cells and systems.

d. Deep Notches in the Solar Spectrum Reaching Earth

These are due to absorption by various atmospheric gases: H_2O, CO_2, O_3, etc.

Note: Ozone (O_3) essentially completely absorbs wavelengths below 0.3 μm (UV).

The large notch below 0.8 μm is due to scattering by molecules and particles in the atmosphere.

e. Light Received by Terrestrial PV Systems

Terrestrial PV systems receive more light than just direct irradiation from the sun.

Consider Fig. 1.7 (p. 10 in the textbook):

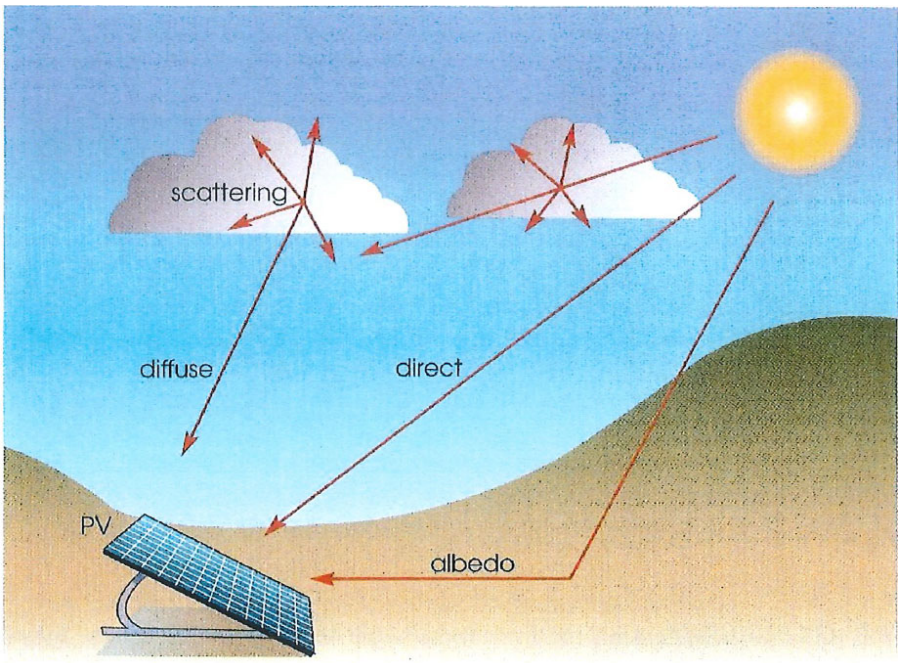


Figure 1.7 From Sun to PV through the Earth's atmosphere.

One light component the PV system receives is direct sunlight.

However, some sunlight is scattered by clouds and dust, and reaches the PV system in an approximately isotropic manner. This received light component is called "diffuse radiation."

In bright sunshine:

Direct sunlight → ~ 70% AM0

Diffuse sunlight → ~ 7% AM0

Some light that reaches the PV system can come from a reflected sunlight component. This is called "Albedo." It is very location dependent.

On a cloudy day, the diffuse sunshine component is greatest.

f. Energy in the Solar Spectrum

Consider the Plank-Einstein relation: $E = \frac{hc}{\lambda} \approx \frac{1.239}{\lambda}$, where:

E is photon energy in eV

h is Plank's constant: 6.626×10^{-34} J·s

c is the speed of light: $3x10^8$ m/s

λ is wavelength in μm

Example:

A photon at λ = 550 nm: E = 2.2 eV.

This is important in semiconductor PV: a minimum energy, called the Bandgap Energy or E_G, is required to create an electron-hole pair in the semiconductor crystal lattice.

If the photon's wavelength is too long: $E < E_G$ and no electron-hole pair is created.

If the photon's wavelength is too short: $E > E_G$ and an electron-hole pair is created, along with waste heat.

** This is a major source of low efficiency in PV**

Review of Solid State Physics

1. Background

We will primarily focus on the semiconductor material, silicon (Si)

In a bulk of Si material, covalent bonds exist between the Si atoms.

Si has an E_G of 1.1 eV (corresponds to a λ of 1.13 μm).

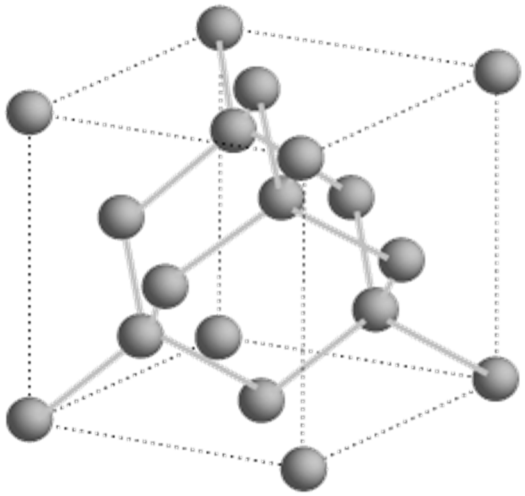
a. Single Crystal Si

→ has a regular crystal structure throughout the entire bulk

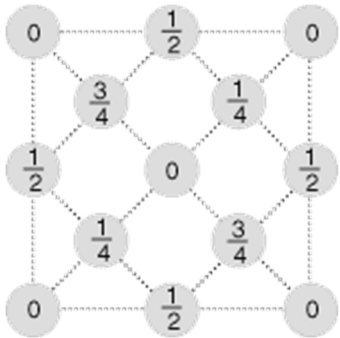
→ has a diamond crystal structure

→ each Si atom has 4 e^-'s to share in covalent bonds with 4 neighboring Si atoms in the crystal lattice

Silicon Crystal Structure



after Kittel



The above illustration shows the arrangement of the silicon atoms in a unit cell, with the numbers indicating the height of the atom above the base of the cube as a fraction of the cell dimension.

Silicon crystallizes in the same pattern as diamond, in a structure which Ashcroft and Mermin call "two interpenetrating face-centered cubic" primitive lattices. The lines between silicon atoms in the lattice illustration indicate nearest-neighbor bonds. The cube side for silicon is 0.543 nm. Germanium has the same diamond structure with a cell dimension of .566 nm.

(http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/sili2.html)

b. Polycrystalline Si

→ also called “polysilicon” or “multicrystalline Si”

→ the bulk material consists of many small single crystals attached to each other at grain boundaries

c. Amorphous Si

→ has a non-crystalline structure

→ Si atoms form a continuous random network

→ due to the disordered nature, some Si atoms have a dangling bond (i.e. it is only covalently bonded with 3 other Si atoms)

2. Conventional Microelectronics

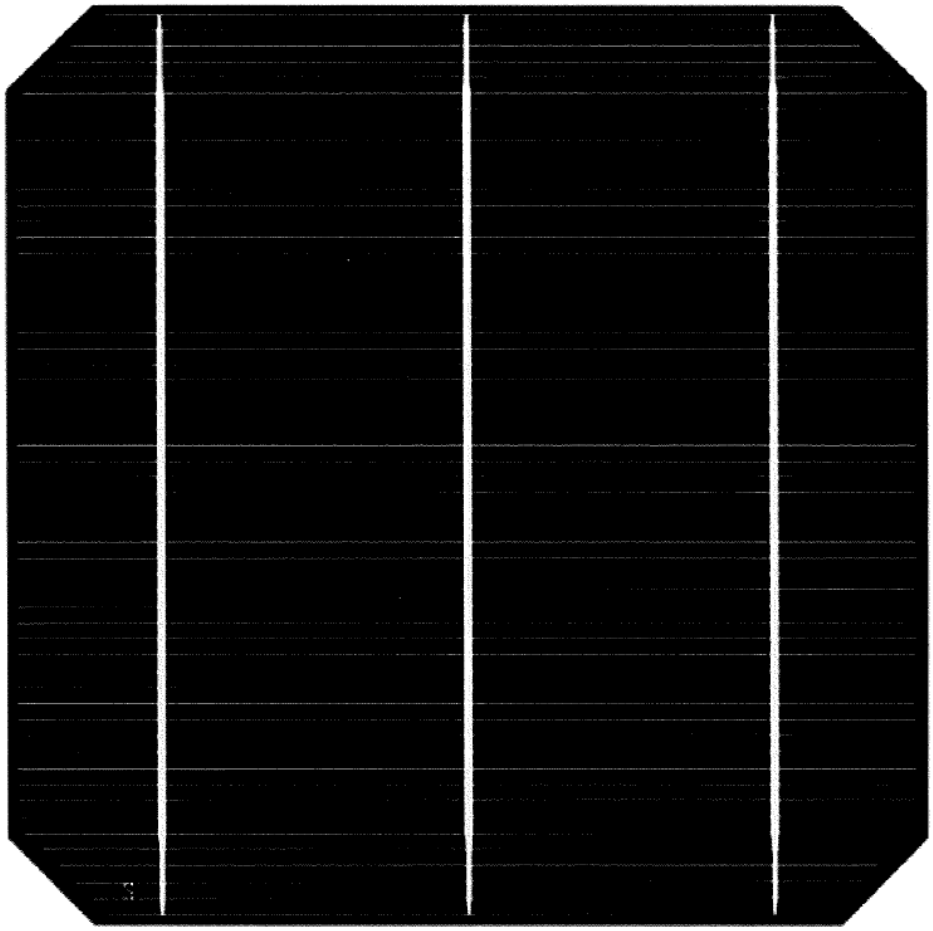
This includes transistors, diodes, and integrated circuits.

These devices are usually fabricated in/on a single crystal Si wafer.

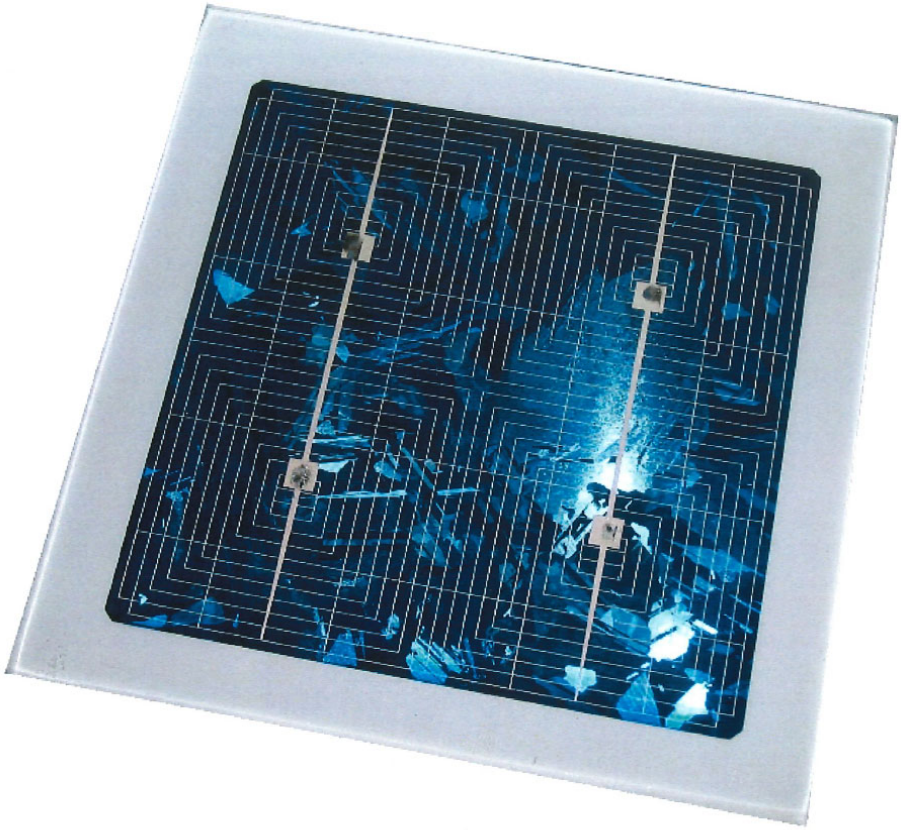
Polysilicon layers may be deposited and patterned on top of the Si wafer.

3. Photovoltaic Devices

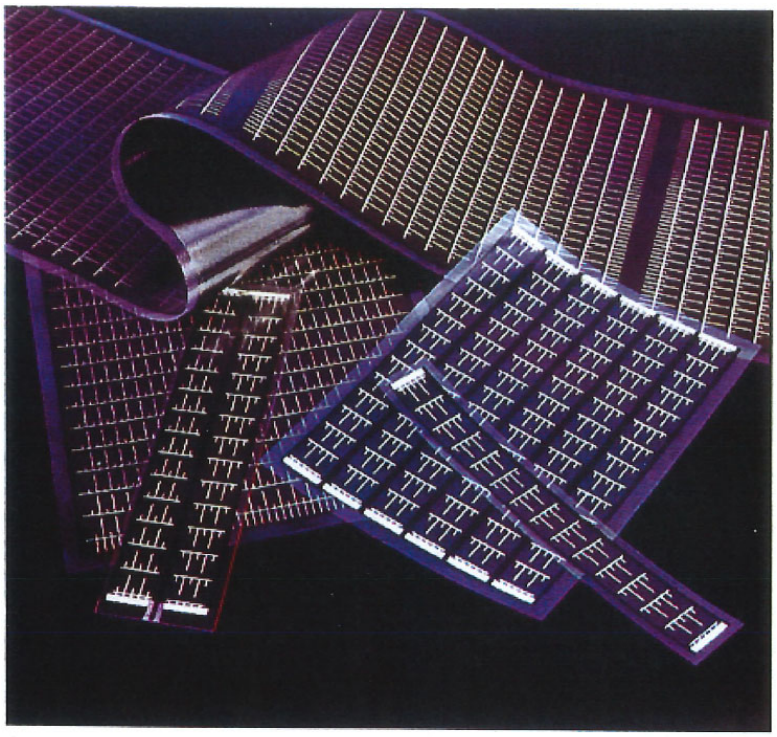
The bulk semiconductor material may be single crystal, polycrystalline, or amorphous.



Monocrystalline Photovoltaic Cell
(CETC Solar Group Corporation)



Polysilicon Photovoltaic Cell
(Wikipedia)



Flexible Amorphous Silicon Modules on a Polyimide Substrate
(Iowa Thin Film Technologies, Inc.)

4. Pure Silicon

Also called "Intrinsic Si."

Above absolute zero: a small number of free e^-'s exist for conduction.

Define n_i as the density of these free e^-'s; n_i is called the "intrinsic carrier density."

$[n_i] = cm^{-3}$

Consider this relation:

$n_i^2 = BT^3 e^{-E_G/KT}$, where:

$[n_i^2] = cm^{-6}$

E_G is the bandgap energy in eV, and E_G is a material property:

material	E_G (eV)	λ(μm)	color
Si	1.12	1.106	IR
Ge	0.66	1.877	IR
GaAs	1.42	0.8725	IR (near visible)

K is Boltzmann's constant: 8.62×10^{-5} eV/K.

T is absolute temperature in K

B is a material-dependent parameter in $K^{-3} \cdot cm^{-6}$:

material	B ($K^{-3} \cdot cm^{-6}$)
Si	1.08×10^{31}
Ge	2.31×10^{30}
GaAs	1.27×10^{29}

Single Crystal Si Structure:

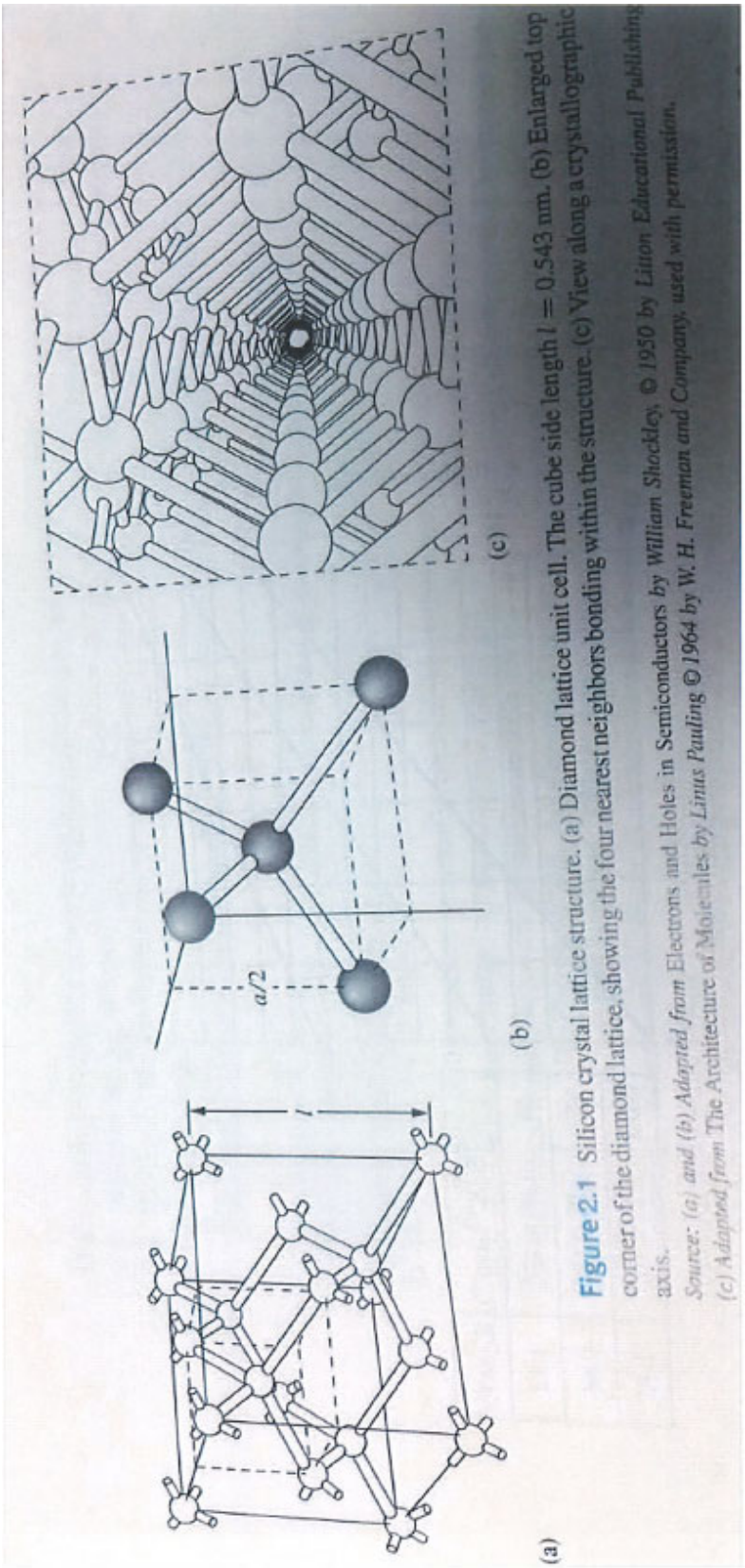


Figure 2.1 Silicon crystal lattice structure. (a) Diamond lattice unit cell. The cube side length $l = 0.543$ nm. (b) Enlarged top corner of the diamond lattice, showing the four nearest neighbors bonding within the structure. (c) View along a crystallographic axis.

Source: (a) and (b) Adapted from Electrons and Holes in Semiconductors *by William Shockley,* © *1950 by Litton Educational Publishing*
(c) Adapted from The Architecture of Molecules *by Linus Pauling* © *1964 by W. H. Freeman and Company, used with permission.*