CCDS

Lesson 4

CCD OPERATION

The predecessor of the CCD was a device called the BUCKET BRIGADE DEVICE developed at the Phillips Research Labs

The BBD was an analog delay line, made up of capacitors such that an analog signal was moving along one step at each clock cycle.

The charge-coupled device was invented in 1969 at AT&T Bell Labs by Willard Boyle and George E. Smith (Nobel prize 2009)

The lab was working on semiconductor bubble memory when Boyle and Smith conceived of the design of what they termed, in their notebook, "Charge 'Bubble' Devices".

A description of how the device could be used as a shift register and as a linear and area imaging devices was described in this first entry.

The essence of the design was the ability to transfer charge along the surface of a semiconductor from one storage capacitor to the next. The initial paper describing the concept listed possible uses as a memory, a delay line, and an imaging device. (source Wikipedia).

The first working CCD made with integrated circuit technology was a simple 8-bit shift register.

The Apogee ALTA U10

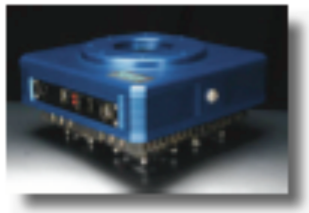
High Performance Cooled CCD Camera System
ALTA U10

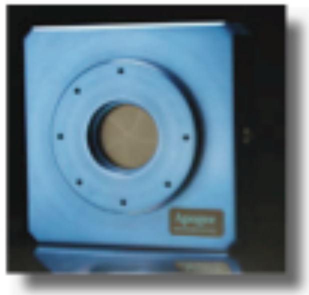
The Alta U10 uses a very large format 4-megapixel full-frame front-illuminated sensor, ideal for applications requiring a large field of view with higher dynamic range.

Imaging Area of CCD

- 2048 x 2048 array, 14 x 14 micron pixels
- 5 MHz 12-bit and 1 MHz 16-bit digitization
- 32Mbyte camera memory
- USB 2.0 interface: no plug in cards or external controllers
- Programmable, intelligent cooling to 45°C below ambient
- Binning up to 8 Horizontal x 2048 Vertical
- Subarray readout and fast sequencing modes
- Precision time delayed integration (TDI) and kinetics mode readout
- Programmable fan speed for low / zero vibration
- Two serial port outputs for control of peripheral devices
- General purpose programmable I/O port
- External triggering and strobe controls
- ActiveX drivers and MaxIm DL/CCD software included with every system
- Field upgradeable firmware
- Fused silica windows
- Runs from single 12V supply with input voltage monitor
- Compact enclosure
- Programmable status indicators

- Astronomy
- Radiology
- Optical testing
- Non-destructive testing





CCD SPECIFICATIONS

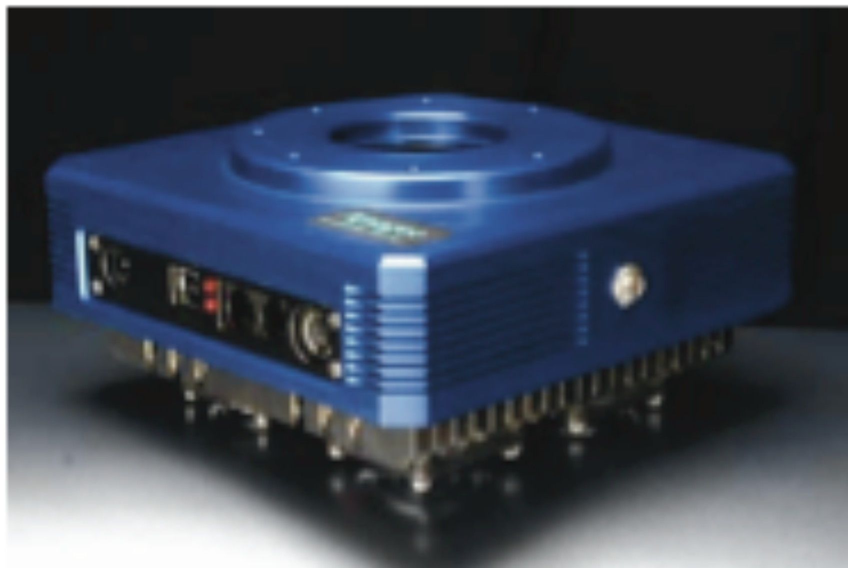
CCD	Atmel THX7899
Array Size (pixels)	2048 x 2048
Pixel Size	14 x 14 microns
Imaging Area	28.7 x 28.7 mm (822 mm2)
Imaging Diagonal	40.5 mm
Video Imager Size	2.53"
Linear Full Well (typical)	270K electrons
Dynamic Range	>80 dB
QE at 400 nm	0.5%
Peak QE (720 nm)	38%
Anti-blooming	none

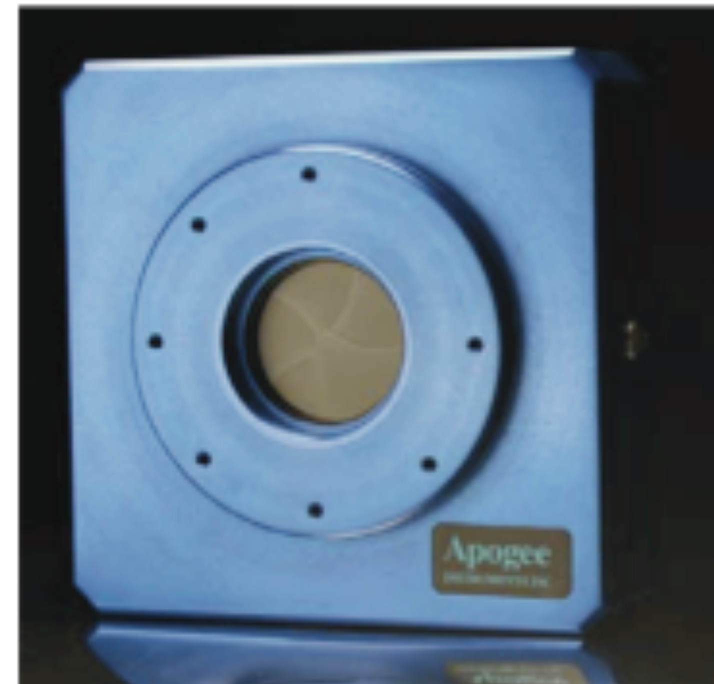
For complete CCD specifications, including cosmetic grading, see data sheet from manufacturer.

AIS Apogee IMAGING SYSTEMS

151 N. Sunrise Ste 902
Roseville CA 95661 USA
tel 916 218 7450
fax 916 218 7451
www.ccd.com

Camera views





CAMERA SUMMARY DESCRIPTION

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CAMERA SPECS

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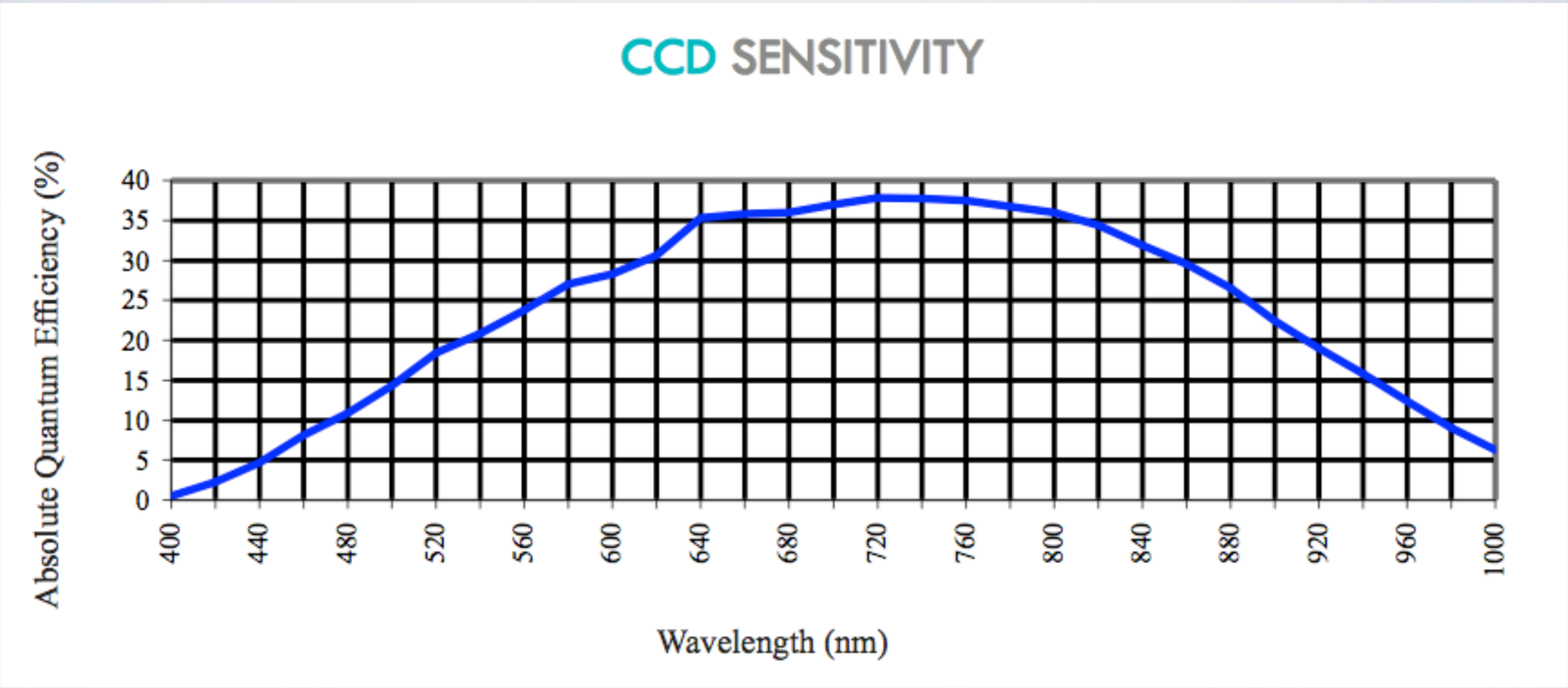
CAMERA SPECS, cont.

PC Interface	USB 2.0
Max. Cable Length	5 meters between hubs; 5 hubs maximum (max. total of 30m)
Digital Resolution	16 bits at 1 MHz and 12 bits at 5 MHz
System Noise (typical)	12 e^- RMS at 1 MHz and 2 counts at 5 MHz
Pixel Binning	1x1 to 8 x 2048 on-chip
Exposure Time	30 milliseconds to 183 minutes (2.56 microsecond increments)
Image Sequencing	1 to 65535 image sequences under software control
Frame Sizes	Full frame, subframe, focus mode
Cooling (typical)	Thermoelectric cooler with forced air. Maximum cooling 45°C below ambient temperature
Dark Current (typical)	1 e^-/pixel/sec (-25°C)
Temperature Stability	± 0.1°C
Camera Head Size	D2. Low profile: D6. Aluminum, hard blue anodized. 6" x 6" x 2.5" (15 x 15 x 6.35 cm) Weight: 3.1 lb. (1.4 kg)
Mounting	3.5" bolt circle. 2" 24 tpi thread. Optional Nikon F-mount or Canon FD mount.
Back Focal Distance	Standard: 1.025" (2.60cm). Low profile: 0.460" (1.17 cm). [optical]
Operating Environment	-22° to 27°C. Relative humidity: 10 to 90% non-condensing.
Cable Length	Standard: 15 ft (4.5m)
Power	40W maximum power with shutter open and cooling maximum. AC/DC "brick" supply with int'l AC input plug (100-240V, 50-60 Hz). Alternate 12V input from user's source.
Shutter	Standard: Melles Griot 43mm. Low profile: no shutter.
Remote Triggering	LVTTL input allows exposure to start within 25 microseconds of rising edge of trigger

QUANTUM EFFICIENCY



DETECTION MODES

Photon detectors:

Produce a signal that depends on an individual photon change the quantum state of electrons in the detector, i.e. current/voltage, chemical reactions or a pulse of free electrons (vacuum photomultipliers).

Thermal detectors:

Convert the energy of photons into heat. (IR, XR, Gamma)...bolometers..

Wave detectors:

Measure interference. Radio and microwave.

EFFICIENCY

Photography is highly inefficient.

Quantum efficiency, $$QE = \frac{N_{\mathrm{det}}}{N_{in}}$$

100% indicates no photon lost.

Photography has QE in the range 0.5-5%

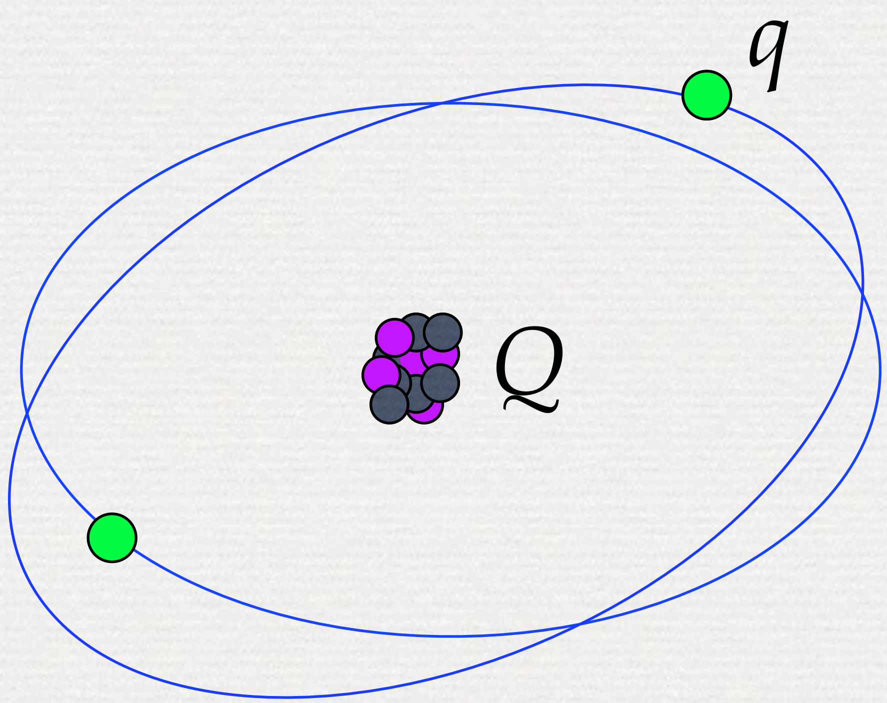
Solid state devices have QEs in the range 20-95%.

Quantum yield is the # of detection events (i.e for CCD creation of a e-h pair) per incident photon.

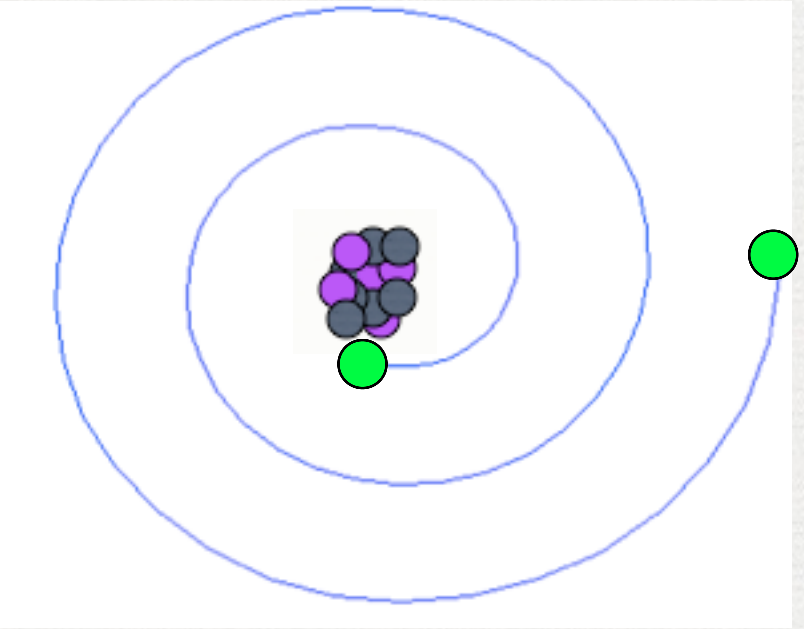
i.e. If a γ has energy less than 5 eV, the qy is 1 (recall 3.65 eV is the energy required to remove an electron in Si.

WHY DO DIFFERENT ELEMENTS HAVE DIFFERENT SPECTRA?

A mechanical view of an atom

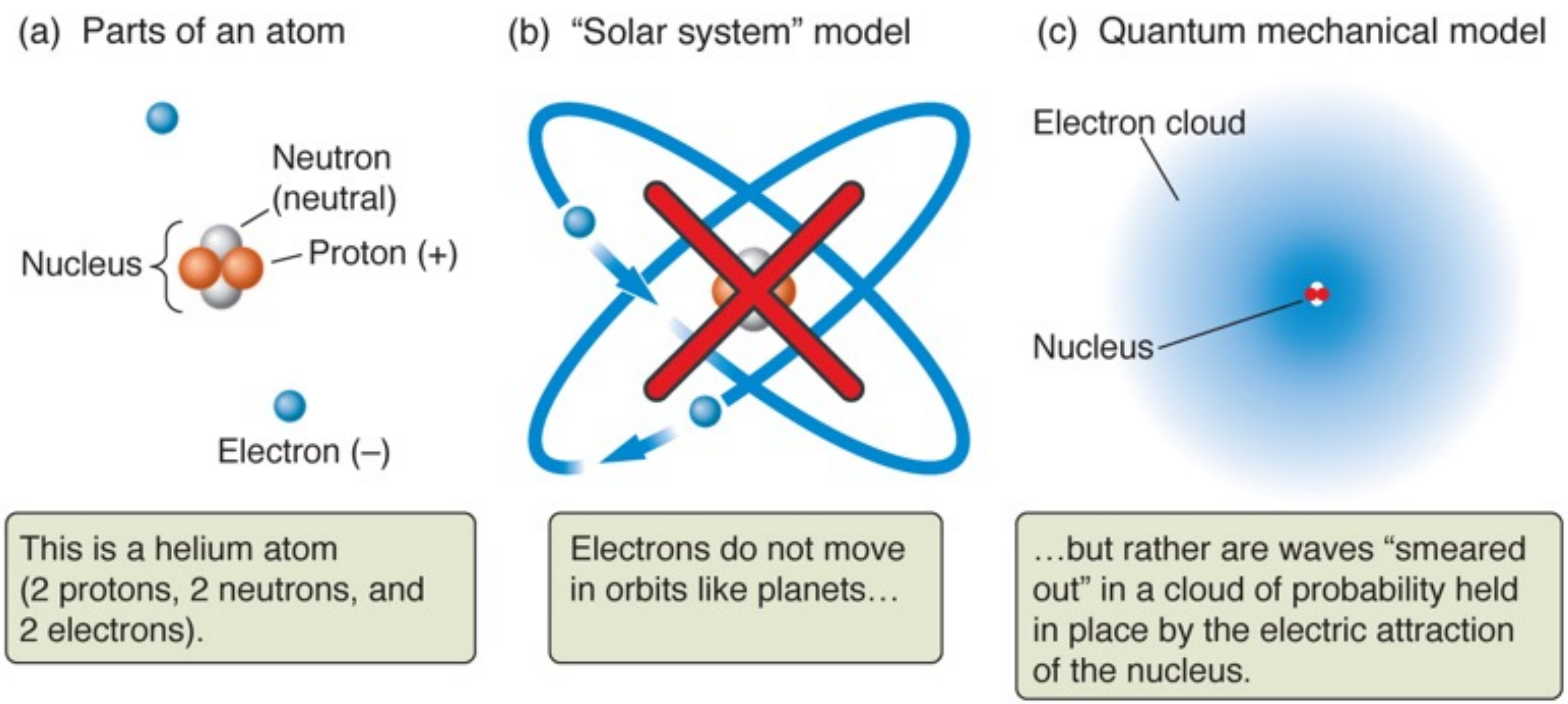


$$F_{Coulomb} = k\frac{qQ}{r^2}$$



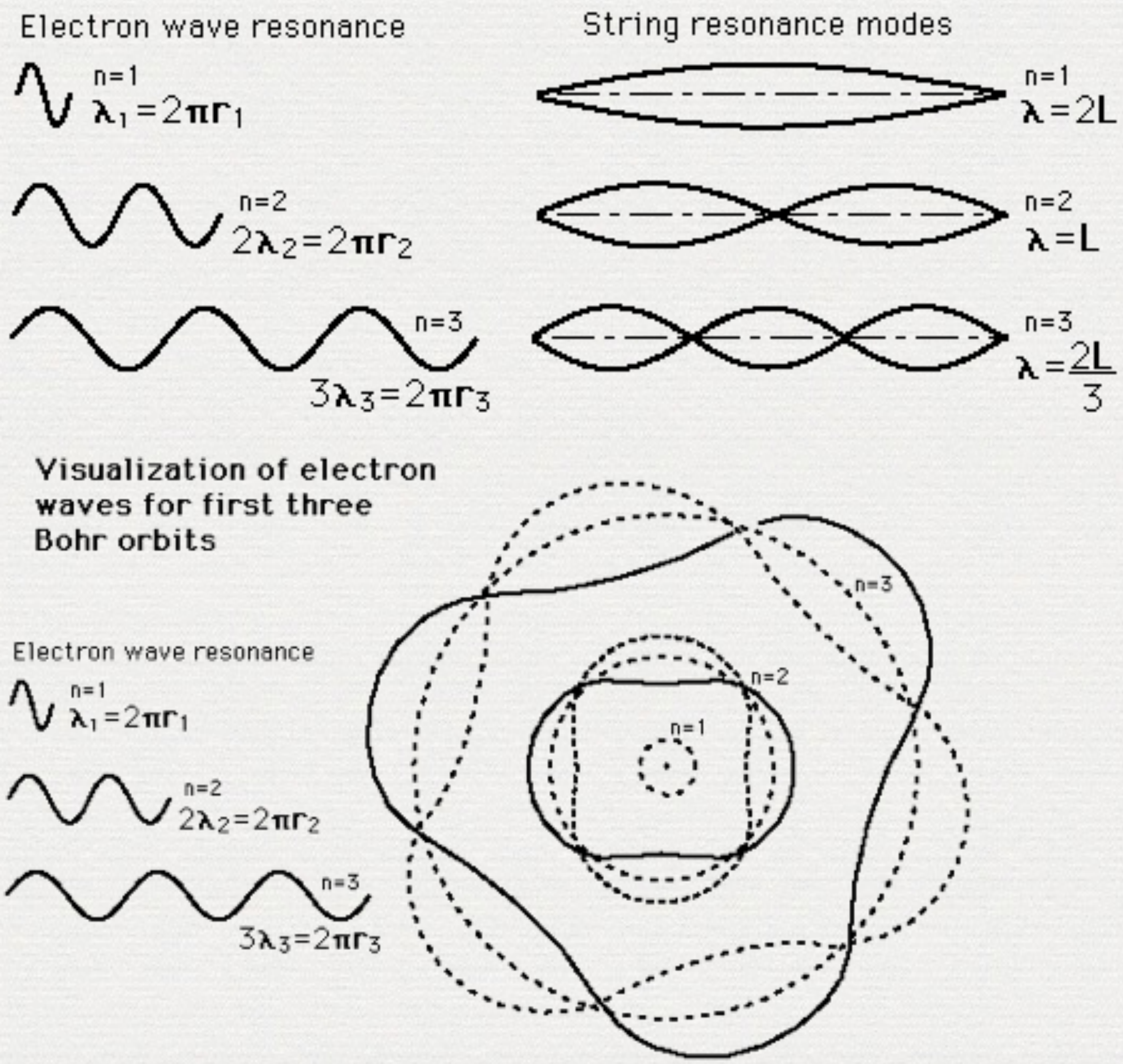
But if the electron radiates it looses energy!!! and if it looses energy

- Atoms have a dense nucleus of *protons* and *neutrons*.
- *Electrons* surround the nucleus in a "cloud."



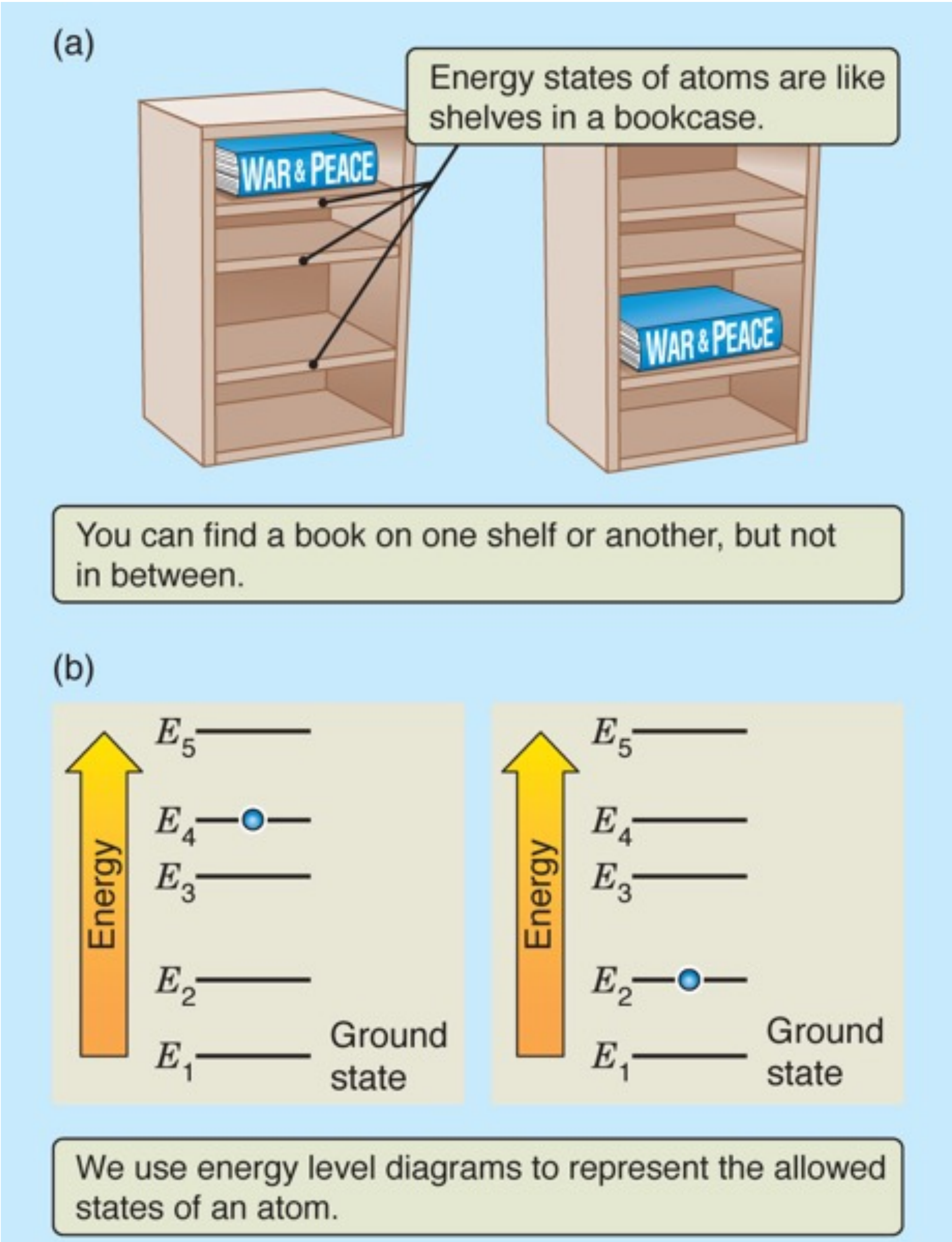
from **Understanding Our Universe**
Palen | Kay | Smith | Blumenthal

BOHR'S ATOM I

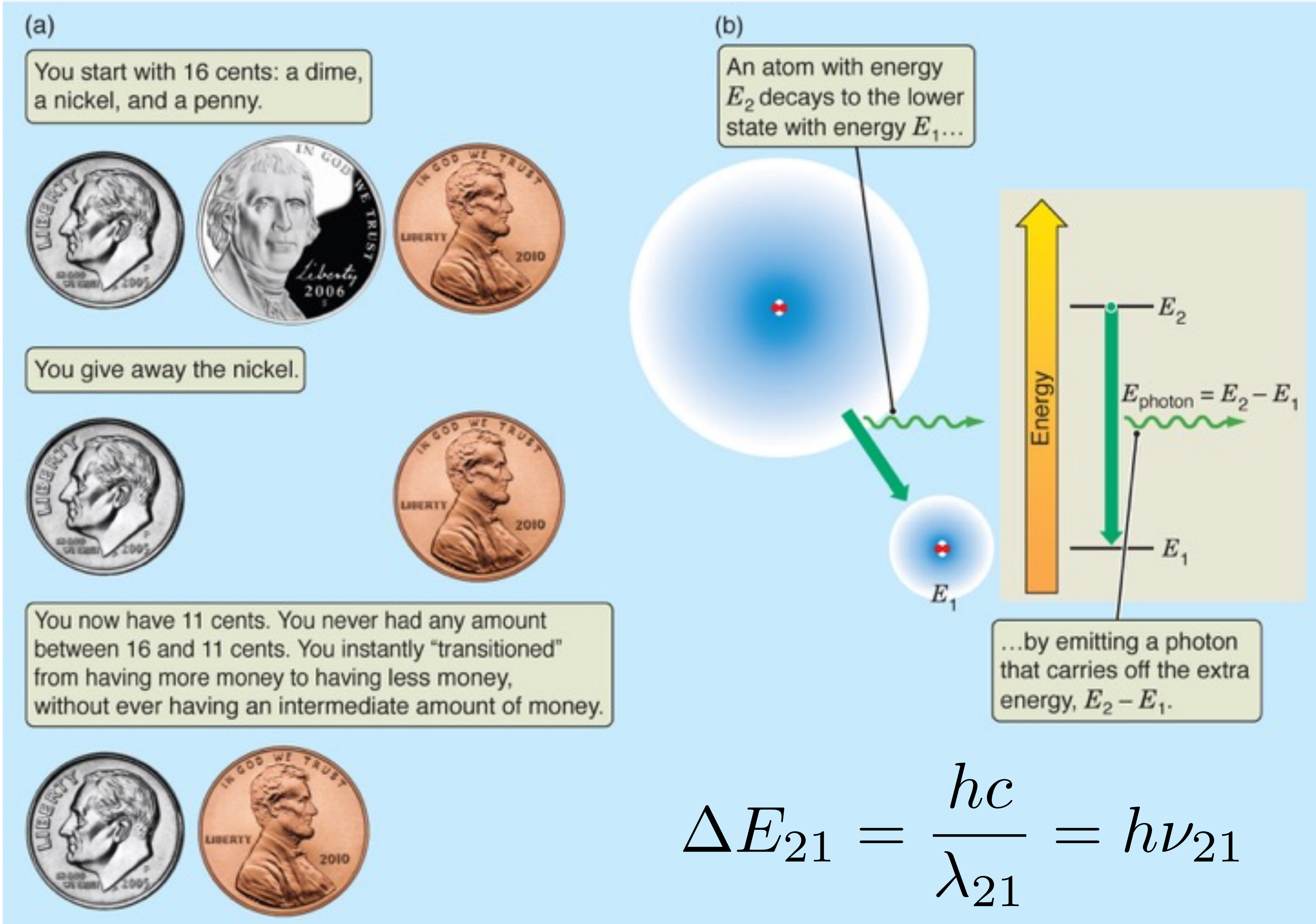


Electrons behave also like waves (dual nature of matter).

Electrons can have orbits such that the energy corresponds to a standing wave on that particular orbit.



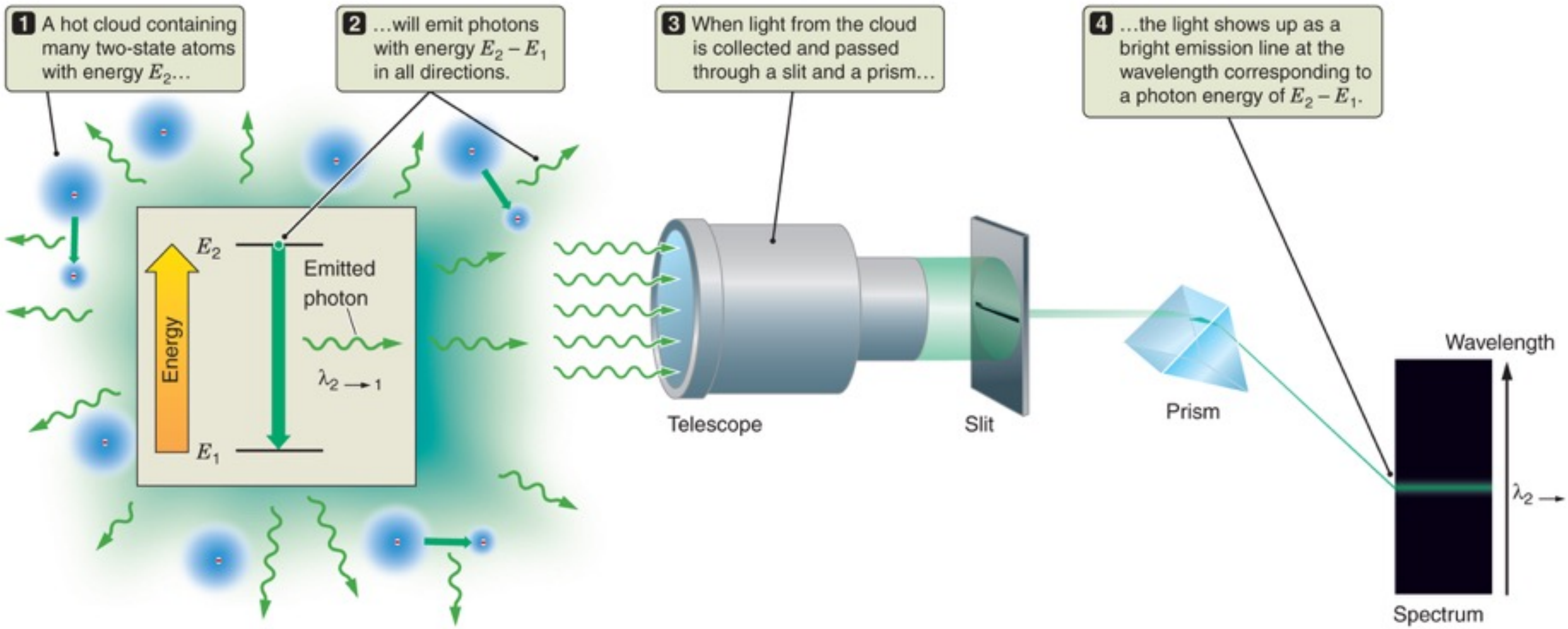
- Electrons can only have certain energies; other energies are not allowed.
- Each type of atom has a unique set of energies.
- Energy level diagram.



$$\Delta E_{21} = \frac{hc}{\lambda_{21}} = h\nu_{21}$$

- In order to go from one energy level to another, it must emit or absorb exactly the right amount of energy.

from **Understanding Our Universe**
Palen | Kay | Smith | Blumenthal



- *Emission*: an electron emits a photon and drops to a lower energy state, losing energy.
  - The photon's energy is equal to the energy *difference* between the two levels.

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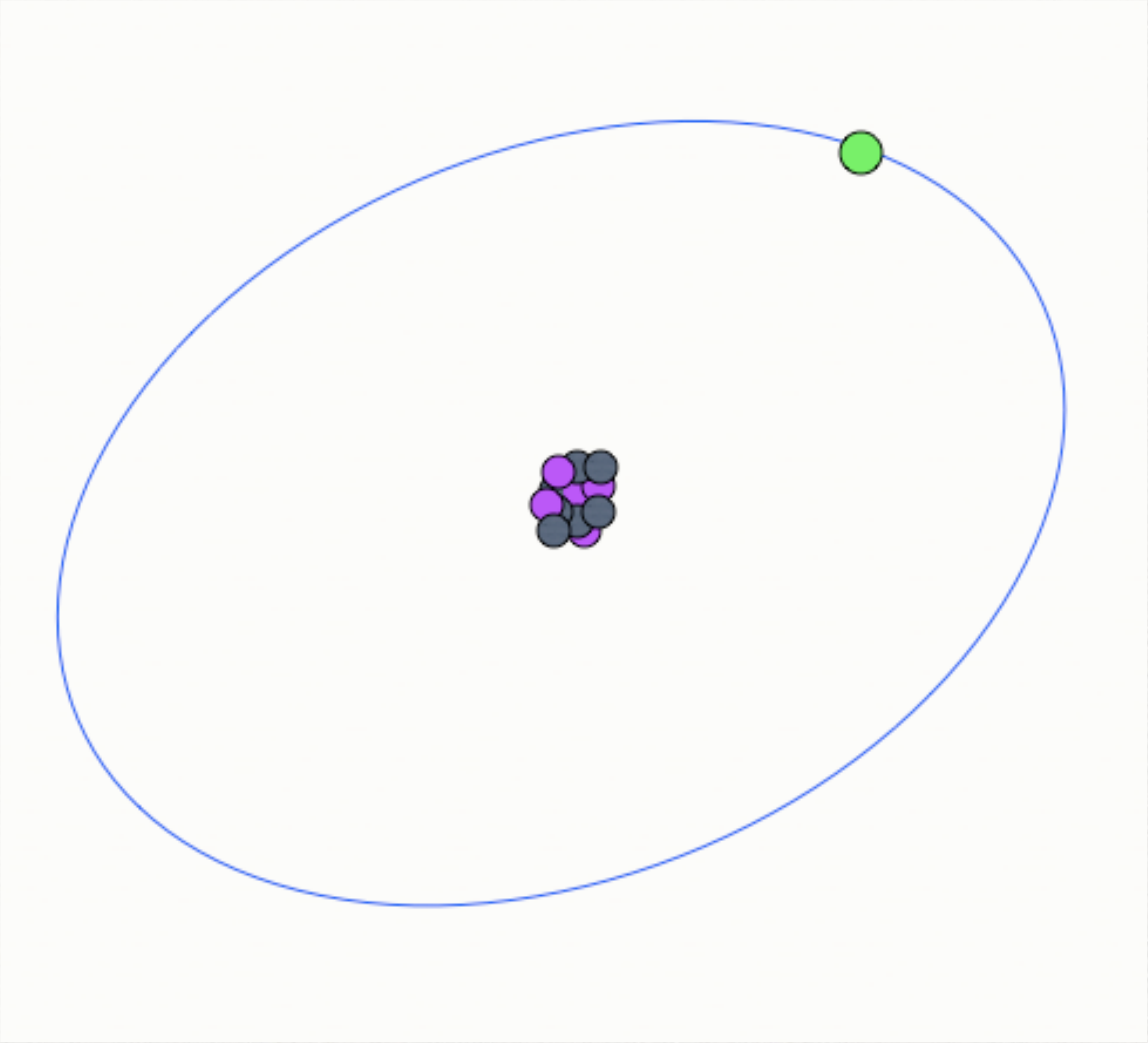
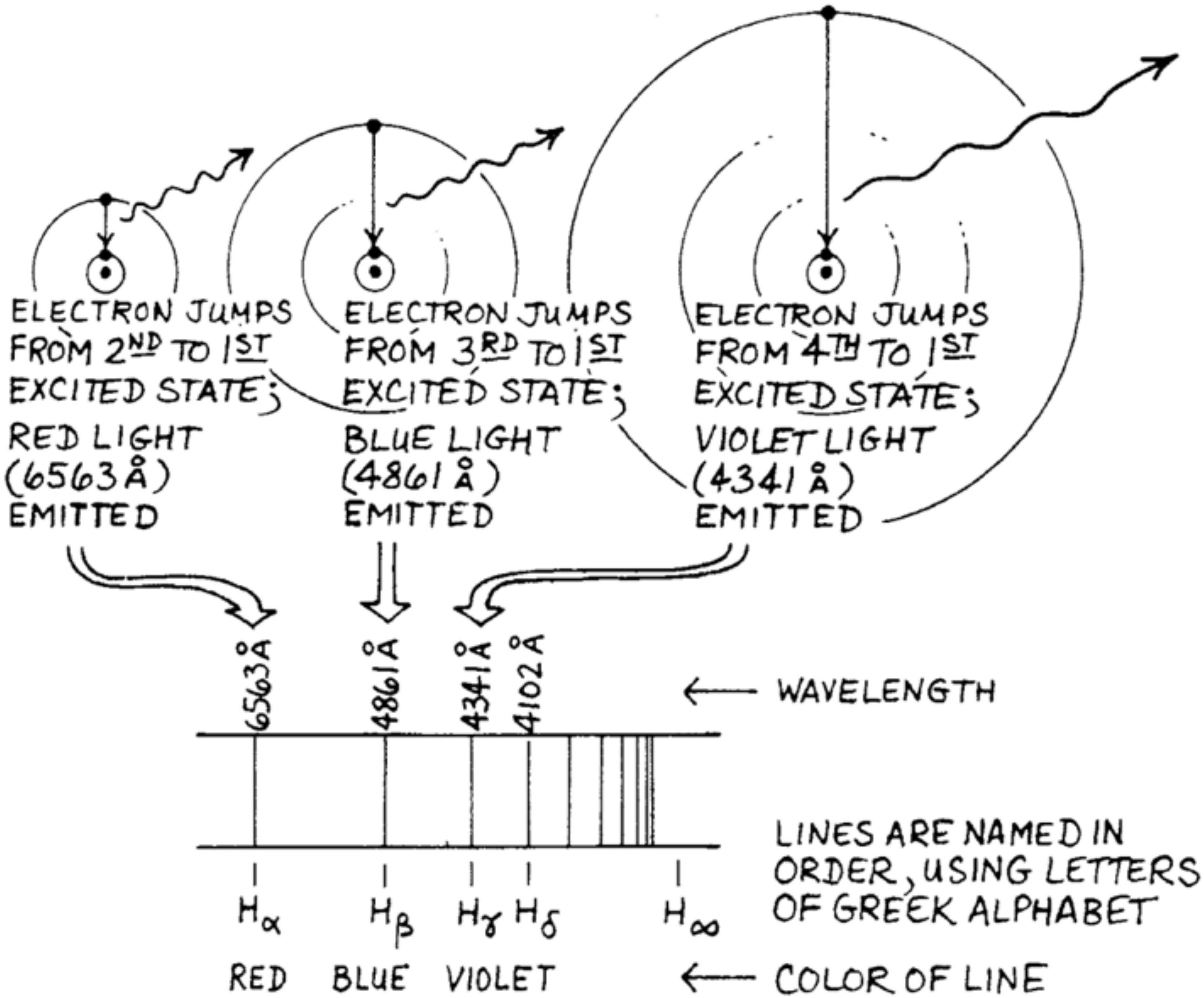
BOHR'S ATOM II

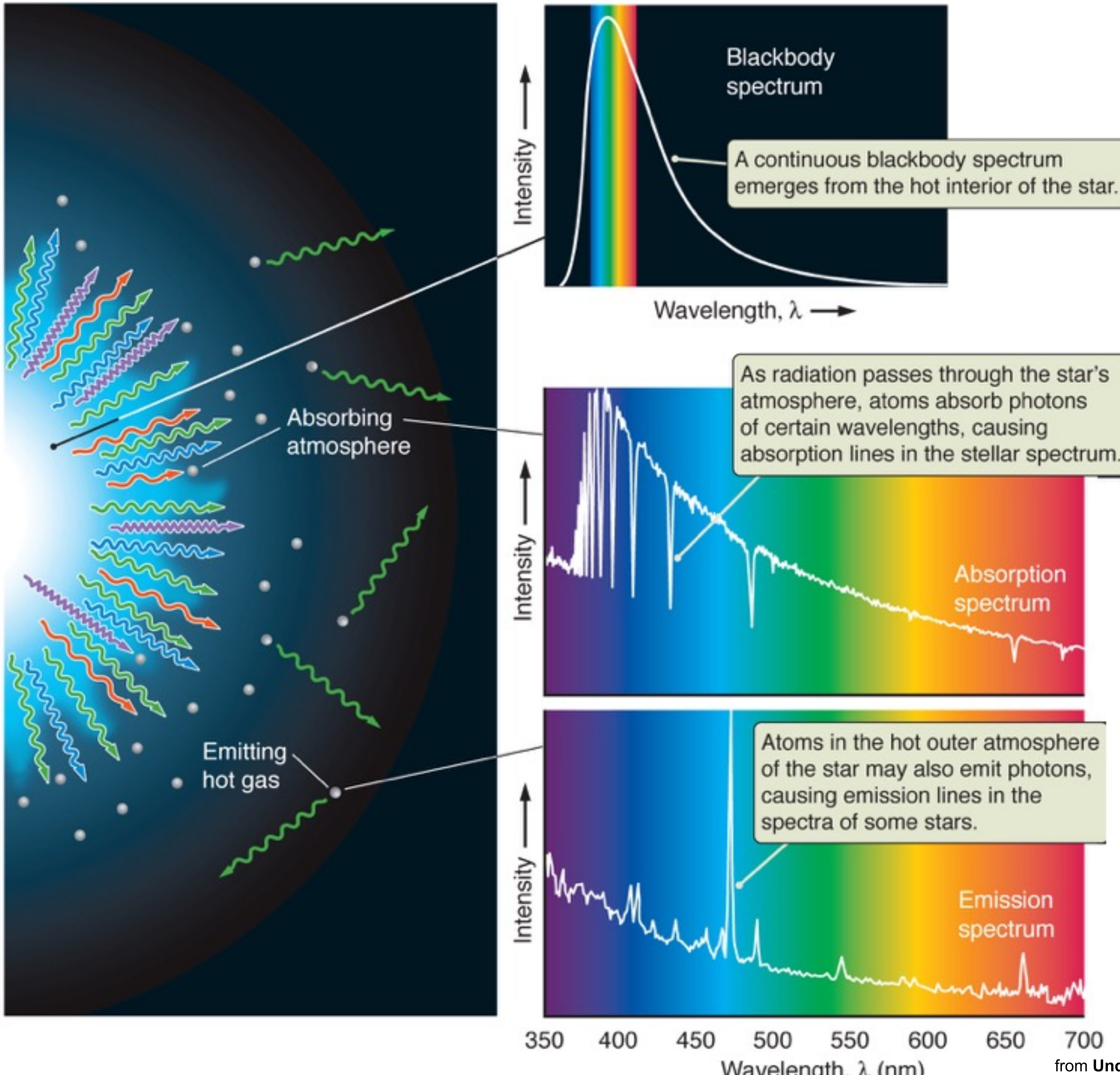


Electrons behave also like waves (dual nature of matter). Electrons can have orbits such that the energy corresponds to a standing wave on that particular orbit. The light emitted is proportional to the energy lost.

Hydrogen Emission Spectrum



- The wavelengths at which atoms emit and absorb radiation form unique spectral fingerprints for each atom.
  - Specifically look at the dark *absorption lines* in stars’ spectra.
- They help determine a star’s temperature, composition, density, pressure, and more.



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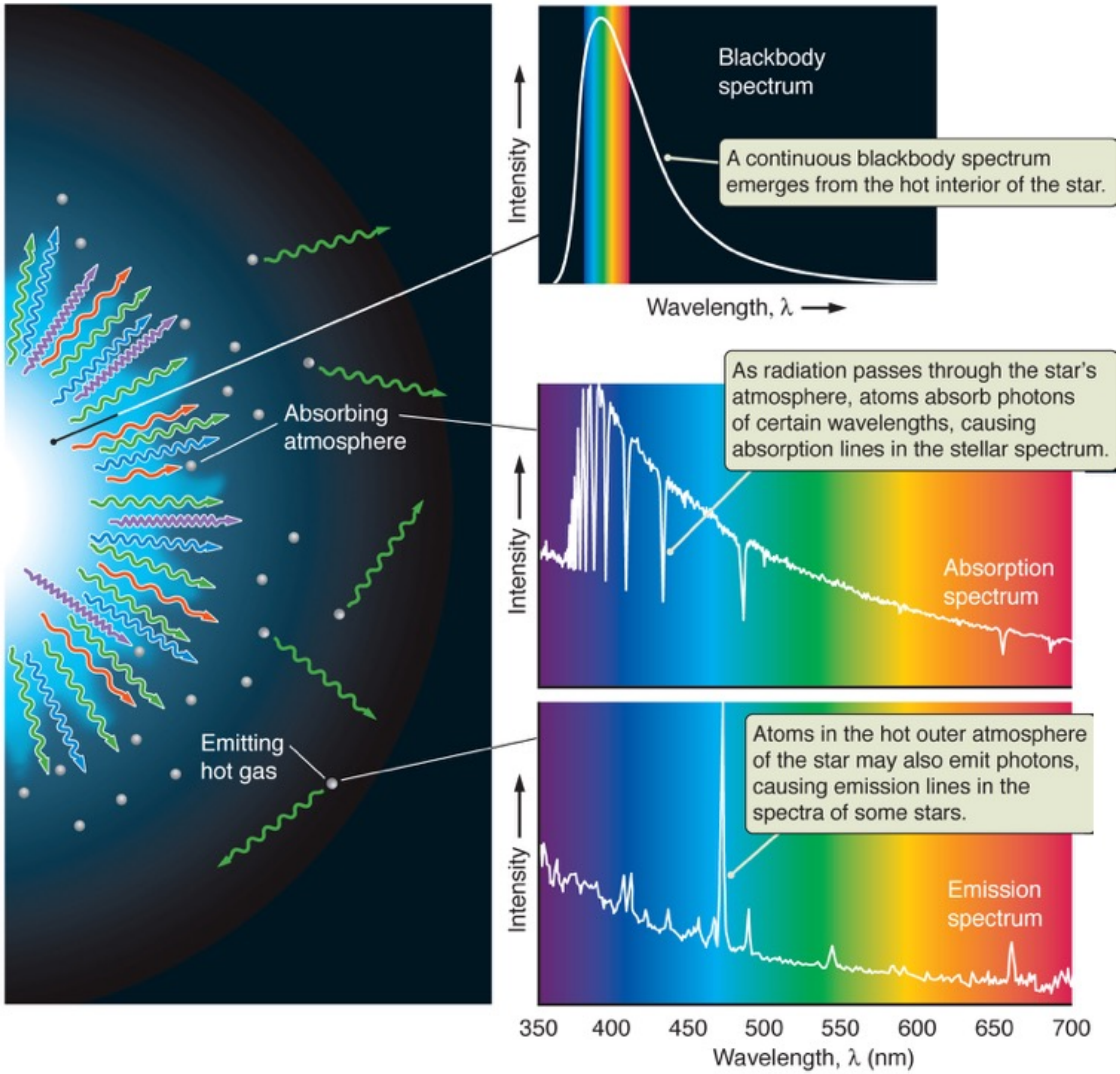


- Some light leaving the star is absorbed by atoms or molecules in the star's atmosphere.
  - Makes absorption lines.
  - Sometimes see emission lines.

QUANTUM NUMBERS

Quantum numbers					
n	*l*	*m*	*s*	Name of configuration	Number of states
1	0	0	±1/2	1s	2
2	0	0	±1/2	2s	2
2	1	–1	±1/2		
		0	±1/2	2p	6
		+1	±1/2		
3	0	0	±1/2	3s	2
3	1	–1	±1/2		
		0	±1/2	3p	6
		+1	±1/2		
3	2	–2	±1/2		
		–1	±1/2		
		0	±1/2	3d	10
		+1	±1/2		
		+2	±1/2		
4	0	0	±1/2	4s	2

FERMI PRINCIPLE

- Fermions are particles with half integer spin. Bosons are particles with integer spin.
- Pauli exclusion principle: No two identical fermions can occupy the same quantum state.
- No two electrons bound in the same atom can have the same 4 quantum numbers.
- Spectroscopic notation: ny^x n main quantum number, x number of electrons in the level, y encodes the value of l :

l	0	1	2	3	4	5	6	7, 8, . . .
Designation	s	p	d	f	g	h	i	k, l, etc.

EXAMPLE: SOME ELECTRONIC CONFIGURATIONS

Element	Atomic number	Electron configuration of the ground state
Hydrogen	1	$1s^1$
Helium	2	$1s^2$
Boron	5	$1s^2\ 2s^2\ 2p^1$
Neon	10	$1s^2\ 2s^2\ 2p^6$
Silicon	14	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$
Argon	18	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6 = [Ar]$
Potassium	19	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^1 = [Ar]\ 4s^1$
Scandium	21	$[Ar]\ 3d^1\ 4s^2$
Germanium	32	$[Ar]3d^{10}\ 4s^2\ 4p^2$
Krypton	36	$[Ar]3d^{10}\ 4s^2\ 4p^6 = [Kr]$
Rubidium	37	$[Kr]\ 5s^1$

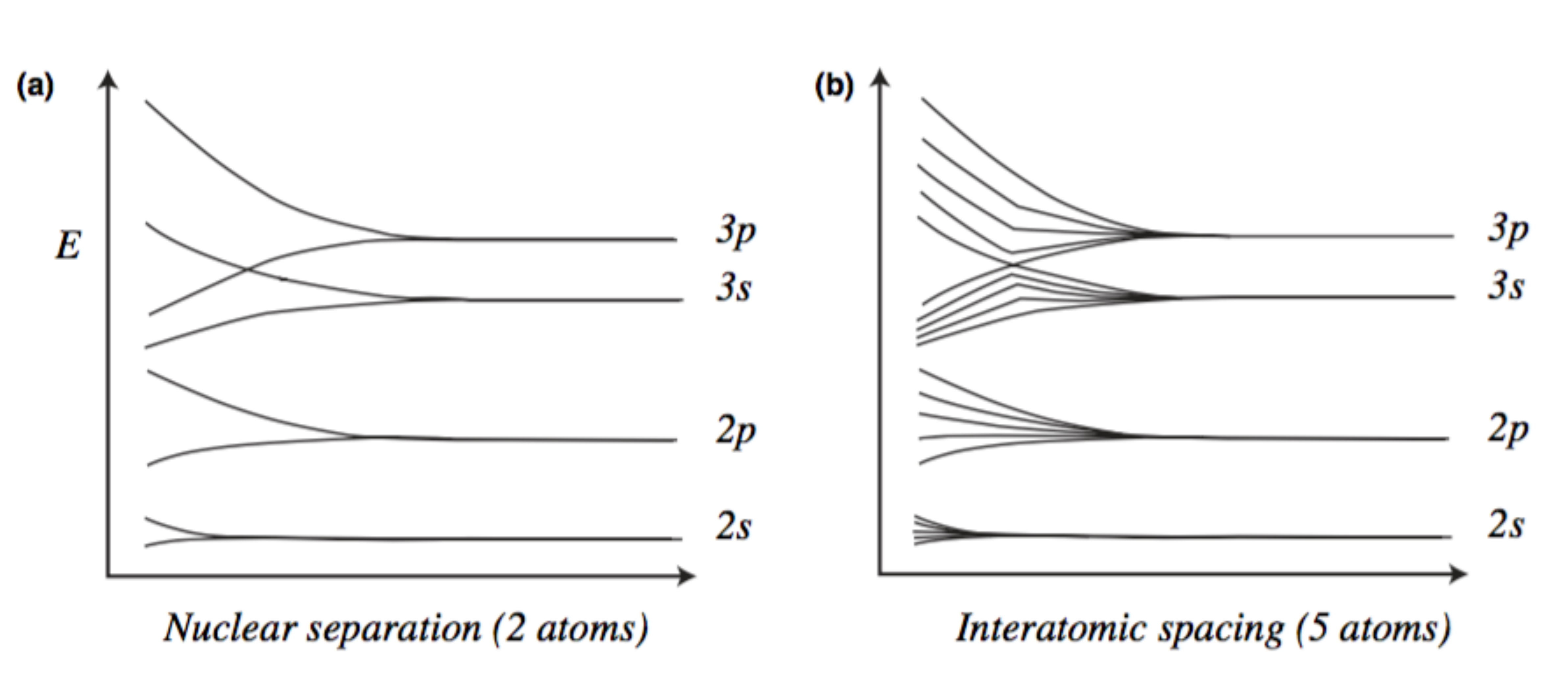
MOLECULES

- In general greater number of electronic states.
- Internal degrees of freedom.
- An approximation:

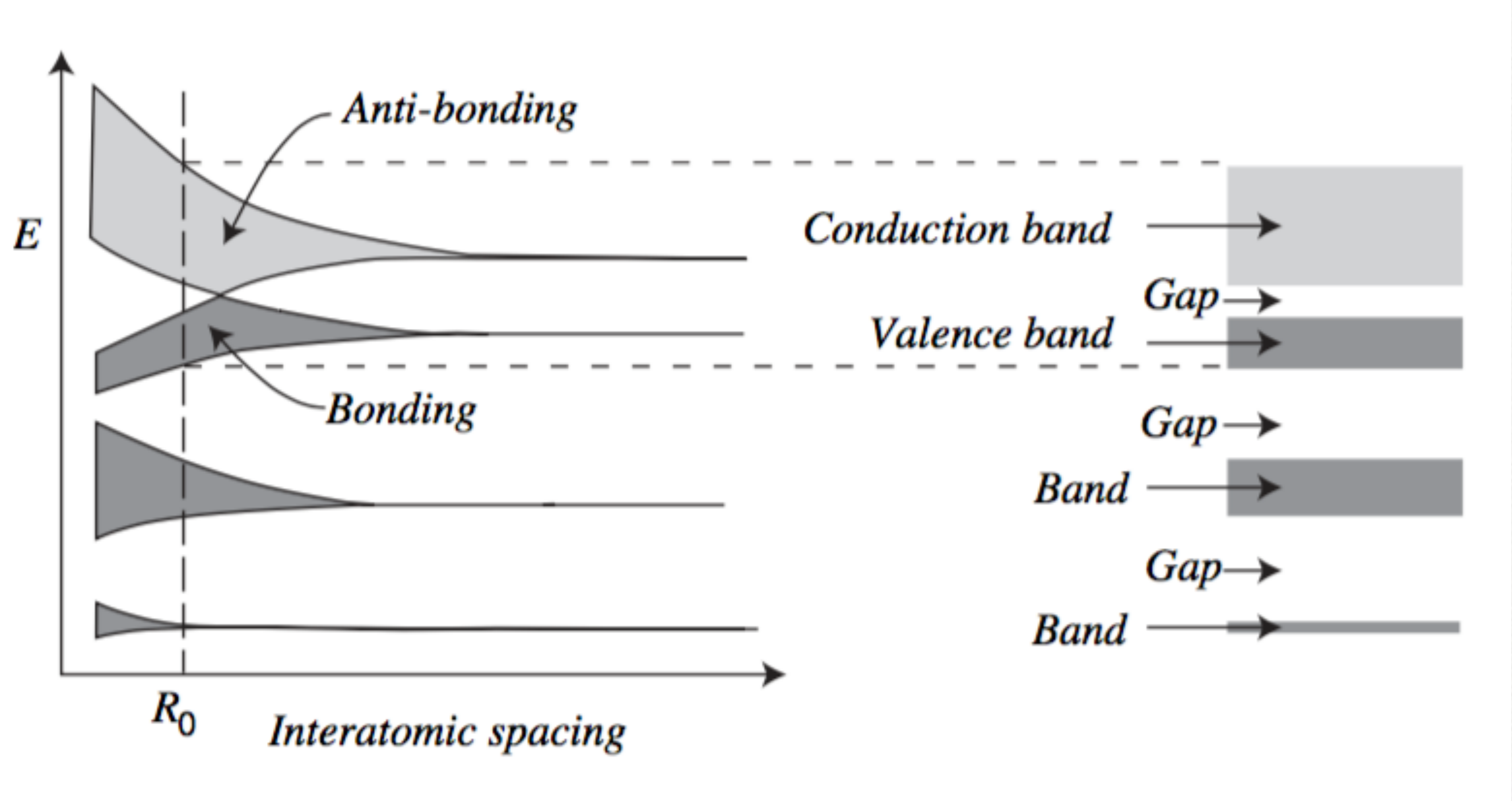
$$E = E_{electron} + E_{vibration} + E_{rotation}$$

SOLID STATE: SILICON

- A crystal is a very large molecule where atoms and bonds repeat periodically in space.

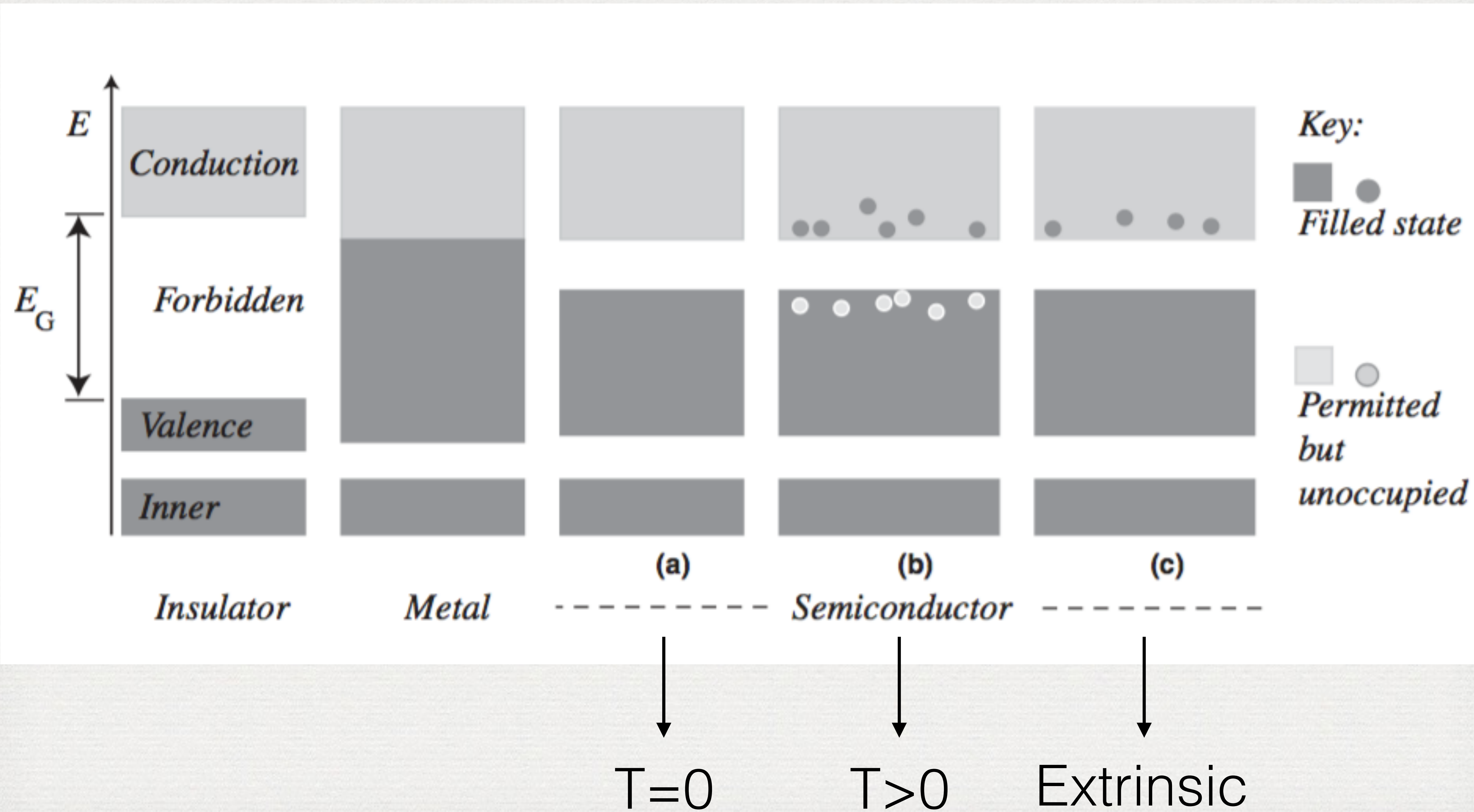


ENERGY LEVELS IN SILICON

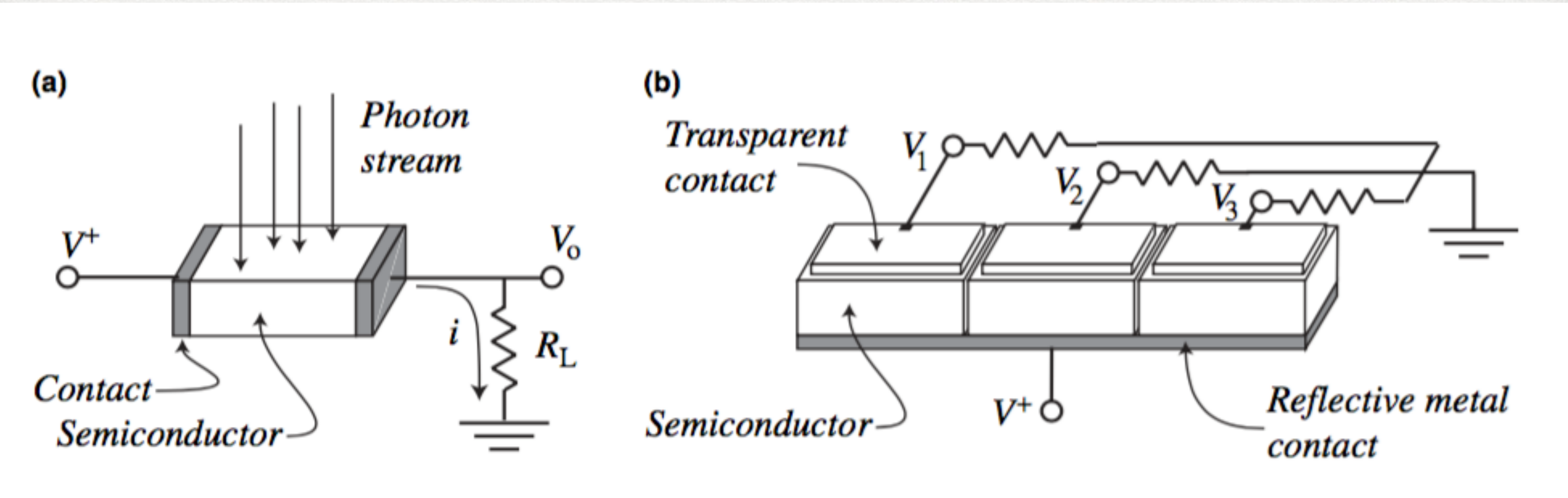


- $E_G = E_C - E_V$ is the energy gap. 1.12 eV at room T.

BAND STRUCTURE OF MATERIALS

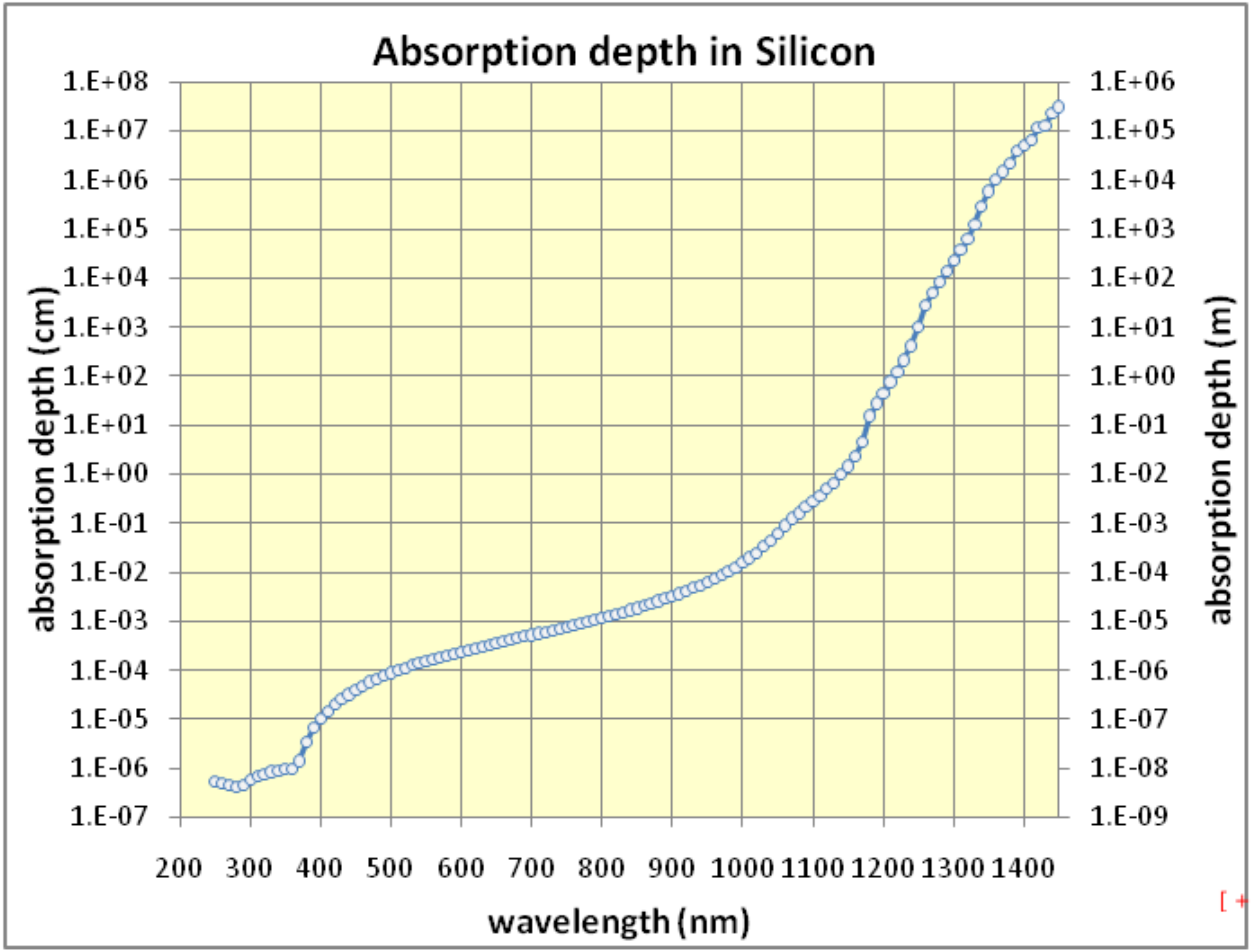


PHOTOABSORBERS

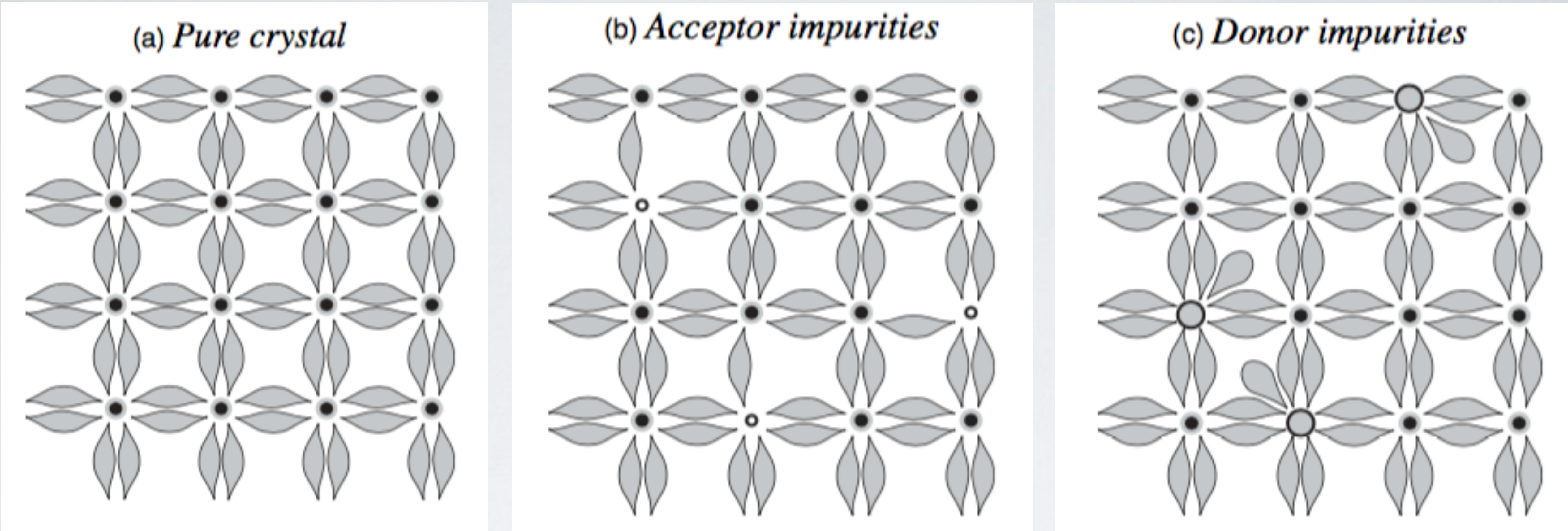


$$R = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2}$$

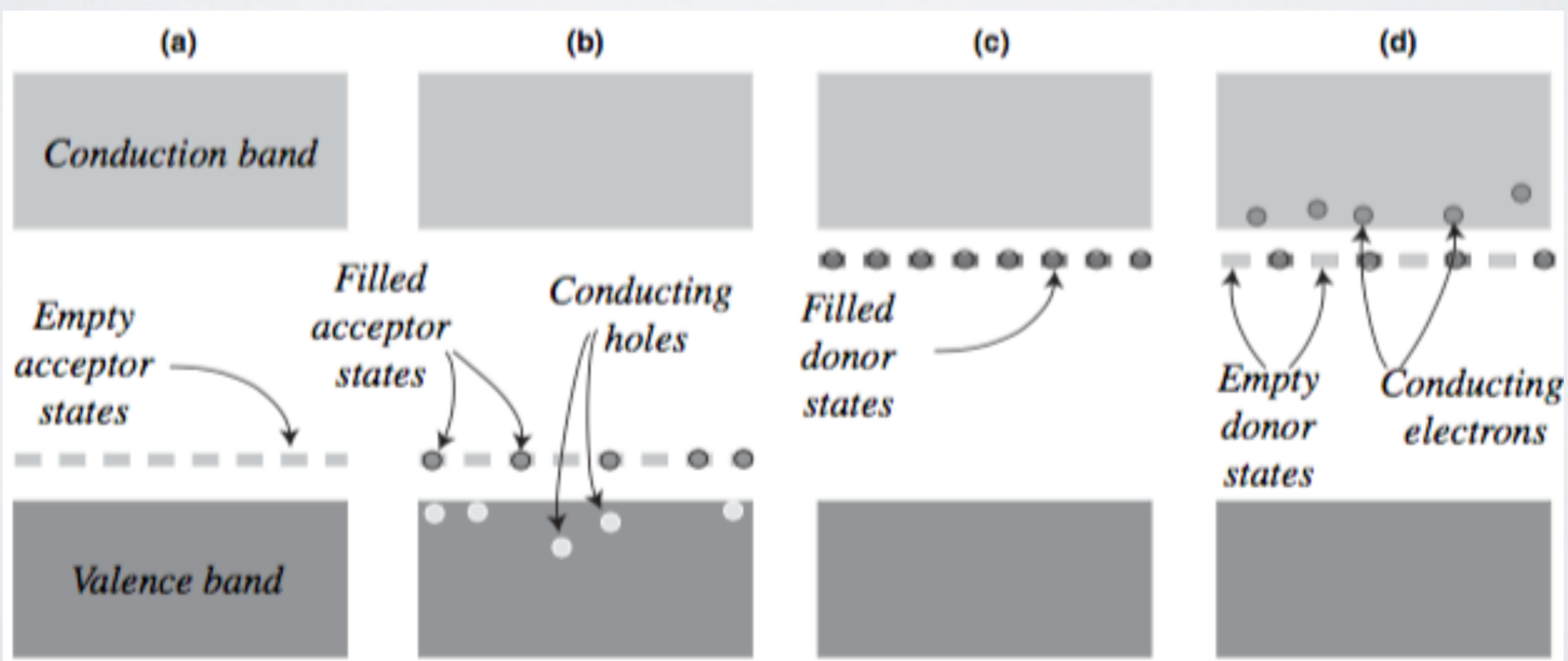
Absorption depth of Si



EXTRINSIC CONDUCTORS

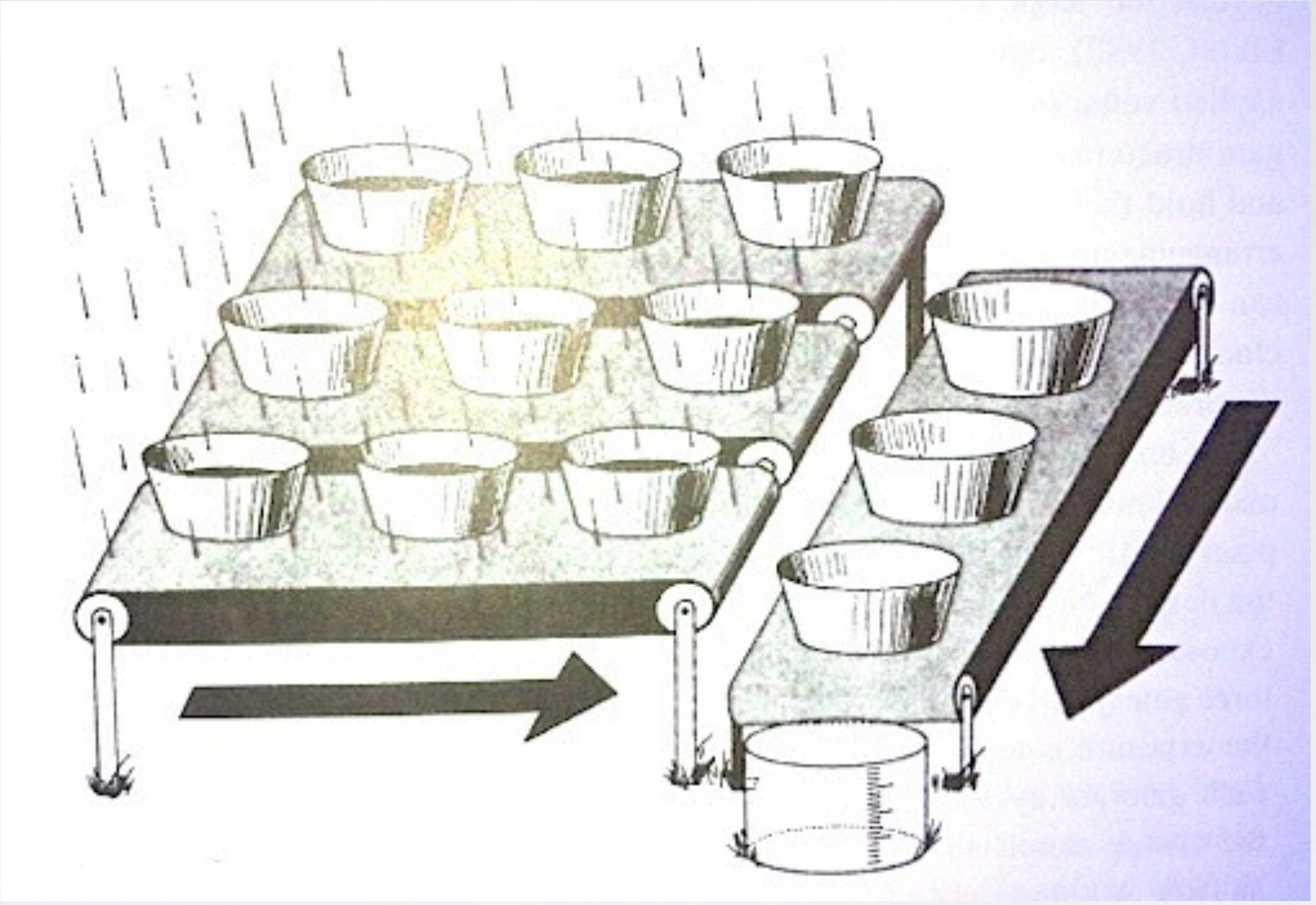


p-type



n-type

What are CCDs?

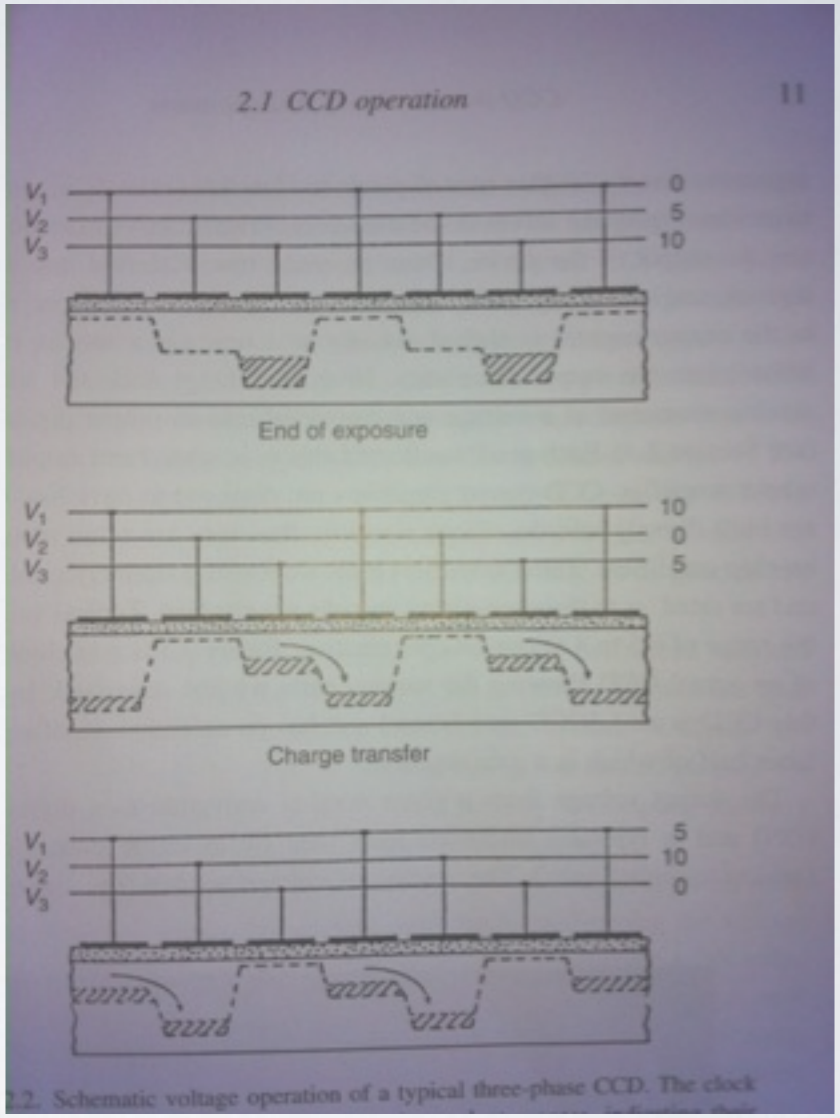


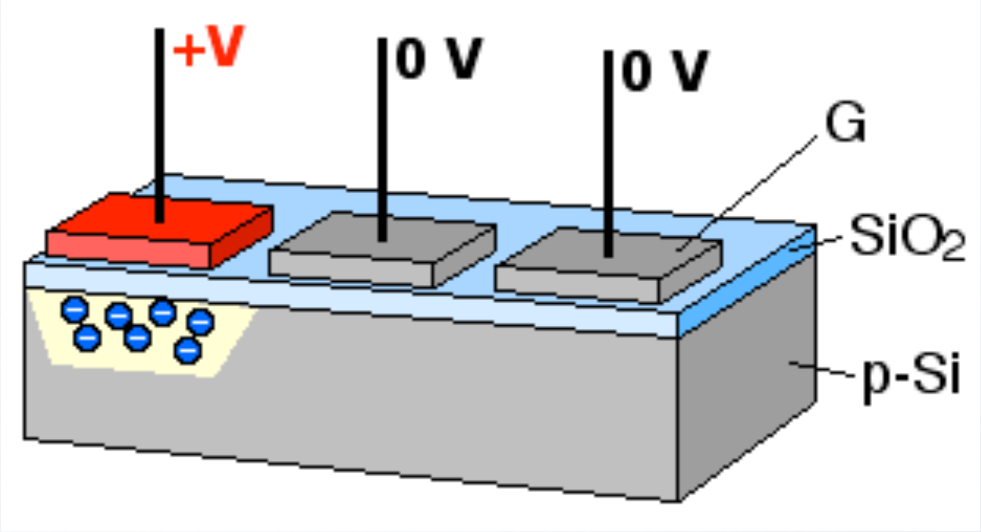
From Steve Howell, Handbook of CCD Astronomy

The rain collecting bucket array analogy: An array of buckets covering a surface collects water. After the rain, each bucket is transported to a belt where it is drained into a meter-bucket. The actual CCD starts with the photoelectric effect. Silicon can absorb photons of the right energy (band gap energy 1.14 eV. It can then absorb between 1.1 and 4 eV (11,000 to 3,000 Å).

CCD OPERATION

Each pixel has a structure allowing applied voltages to be place in subpixel size electrodes: gates.
The gate structures let the pixel collect freed electrons and hold them in a potential well until the end of the exposure. Typically there are three p/pixel.
The voltages are controlled by clock circuits with every third gate connected to the same clock. The gates are cycled to transfer the charges after exposure terminates and readout begins. The efficiency in the charge transferred is CTE.





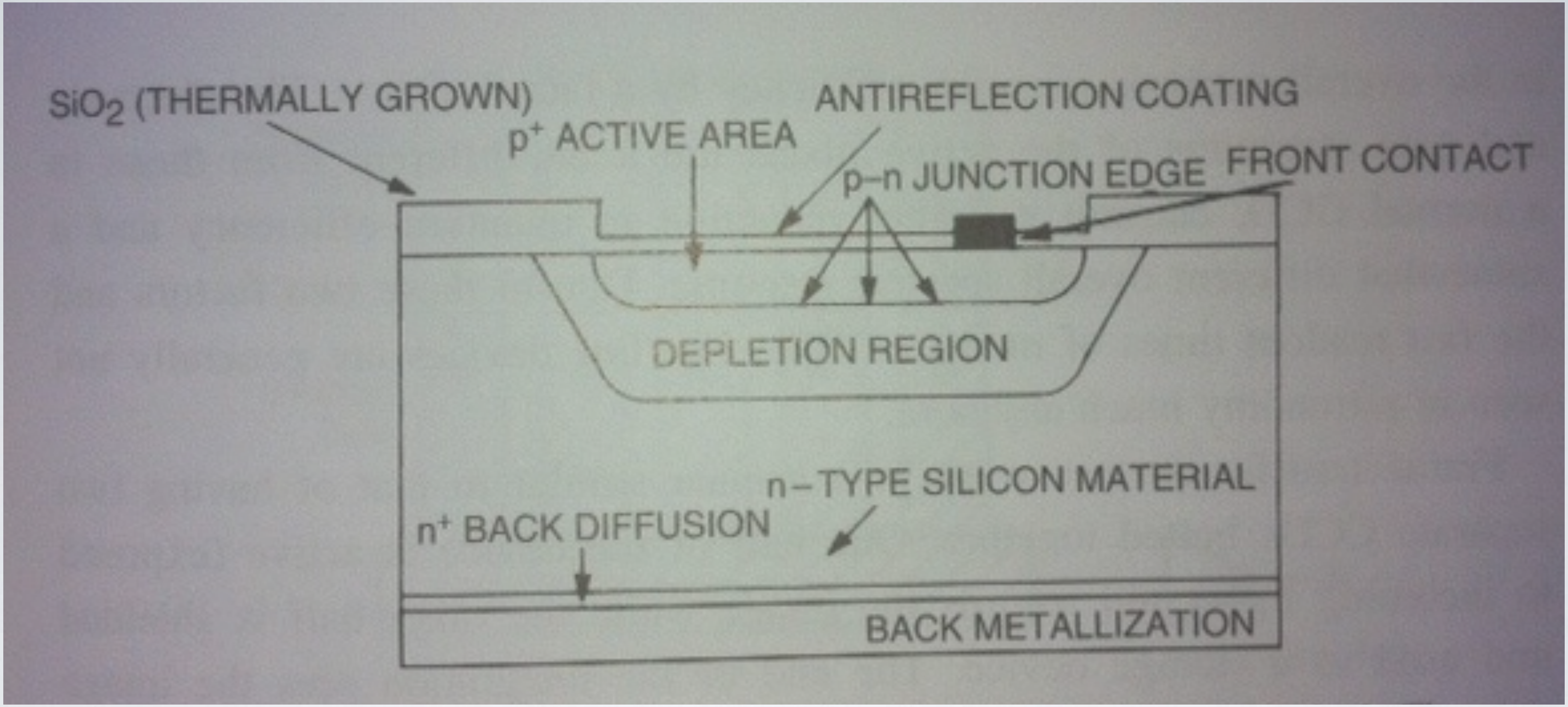
CCD OPERATION II

Each column in the array is connected in parallel. Once clock cycle moves each row up one column. The top one is is shifted off the array into the output shift register (horizontal shift register). Each pixel in the output register is measure as a voltage and converted into and output digital number. The sensed charge is amplified by an output amplifier. Their sensitivity is typically of 0.5 to 4 microV/e. The conversion of the output voltage to a DN is counted as an Analog to Digital Unit (ADU).
The amount of voltage needed to produce 1 ADU is the "gain" of the device. A typical CCD gain 10 e^-/ADU (per 10 e^- 1 ADU). The conversion is performed by an ADC.
Notice that with size the time to complete the operation increases. There are many tricks.

CCD TYPES

Surface channel vs buried channel
In surface channel the transfer occurs on the surface between overlapping gates. transfer rates in video CCDs are MHz.
Problems: traps due to impurities. (one way of eliminating this is through pre-flash or zero flat (raising the charge: the CCD needs to low level prior to exposure).
Better solution is to use a "buried channel" architecture.

Front-sided vs back sided illuminated CCDs
Front sided: light illuminates the front; thickness is 300 microns.
Susceptible to detection of cosmic rays.



FRONT SIDED ILLUMINATED PIXEL

Back sided illuminated

Are thinned to >15 microns and illuminated from behind. No interference with the gates.

Advantage is better QE, better response to shorter wavelengths photons (no need to go through the gates). Disadvantage shallower pixel wells.

Interline and frame transfer

Interline transfer CCDs have each column of pixels (active) paralleled by a shielded column of storage (inactive) pixels.

Interline and frame transfer

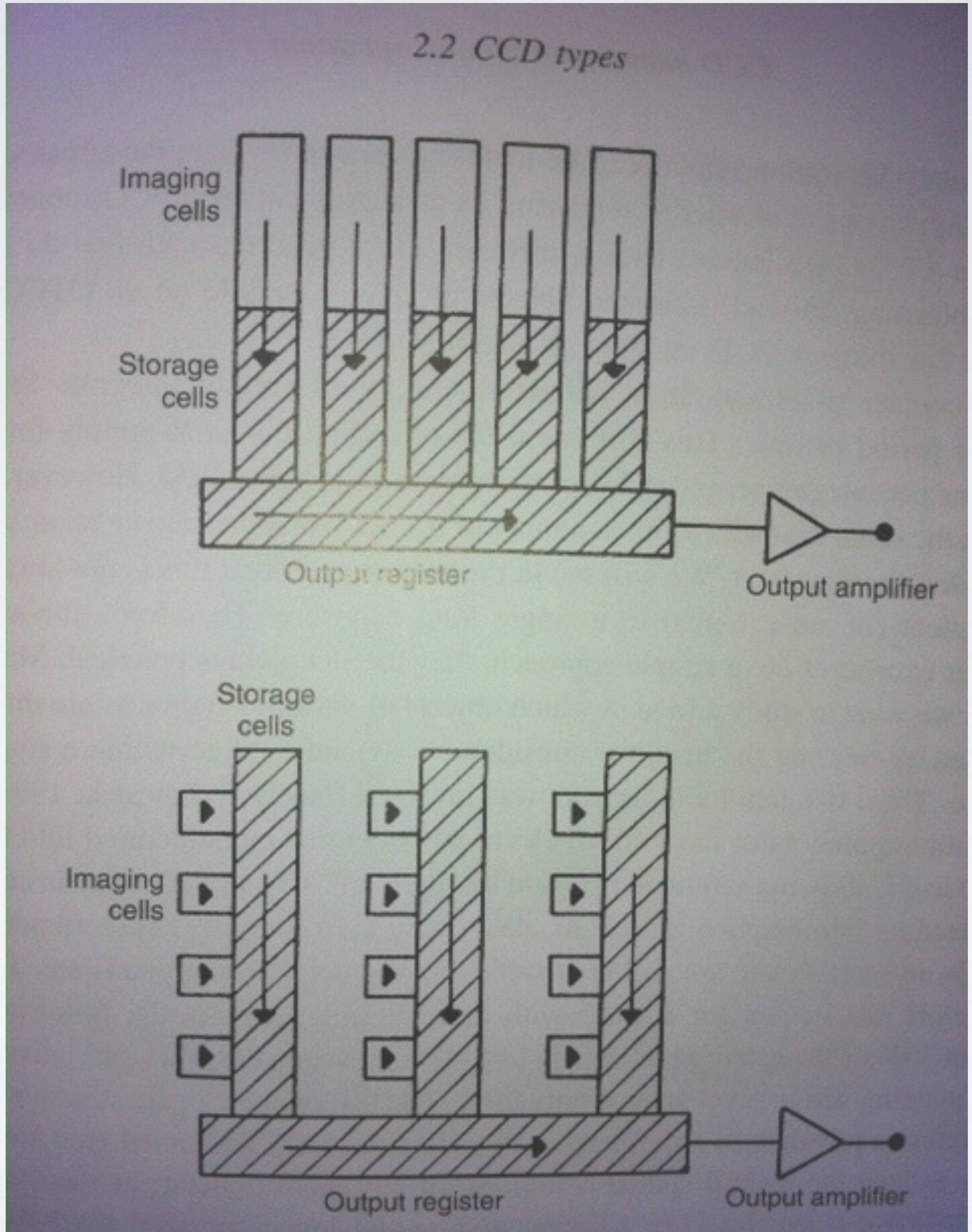
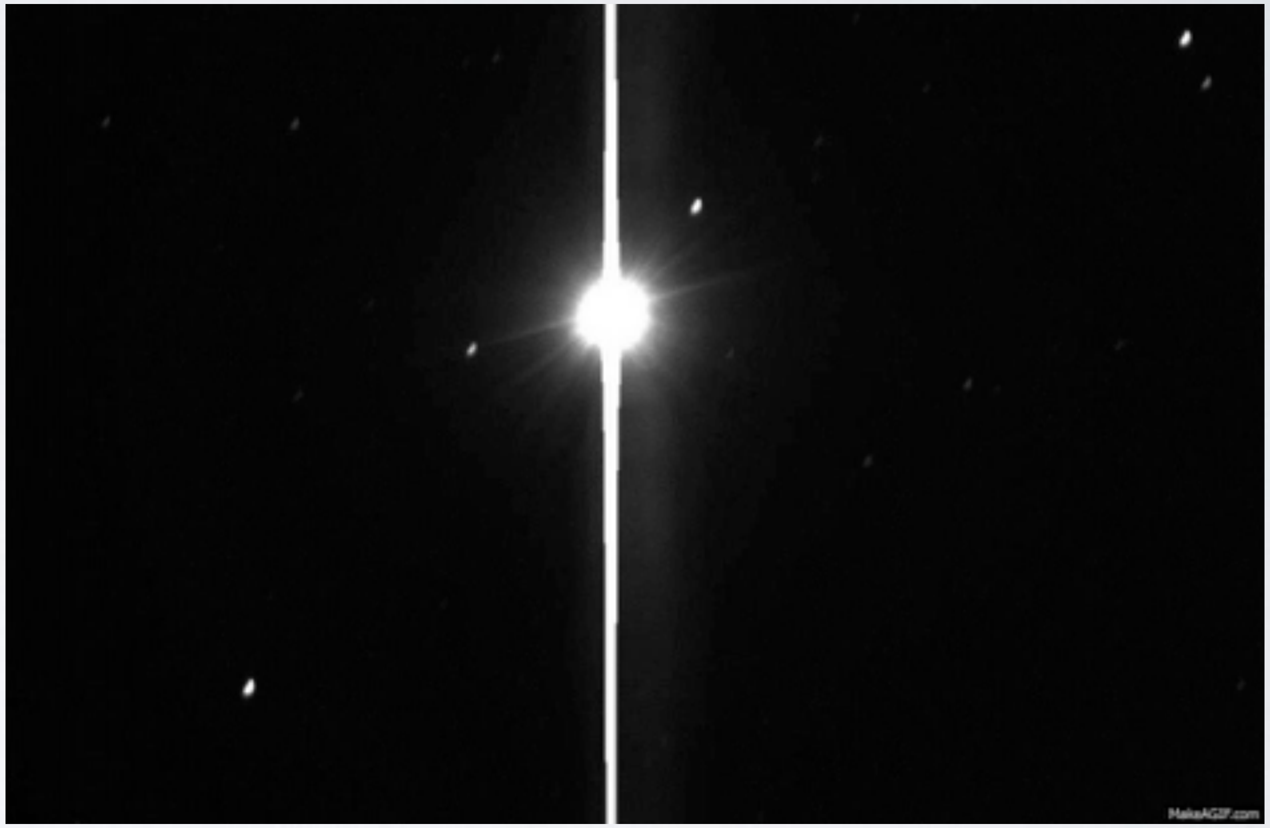


Fig. 2.5. Cartoon view of (top) a frame transfer CCD and (bottom) an interline

Antiblooming CCDs

The full well capacity of a pixel is exceed and bleeding appears.



Other CCDs types

Multipinned phase CCDs
Typically for thermoelectrically cooled devices. It relies on the inversion of all the 3 clock voltages and doping of the 3 gates to lower the dark (thermal) current.

Orthogonal transfer CCDs
Pixels can be shifted horizontally as well as vertically. Lower QE. First used in image motion.

Low light level
They have an extended serial register, clocked at a higher voltage (40-60 V) allowing for a slight chance of avalanche multiplication of electrons, effectively increasing the gain. i.e. for 1% the gain=1.01^N where N i st he number of elements in the register. For a N= 500 the gain is 145.

More stuff

Superconducting tunnel junctions
UV and IR detection

CMOS devices
more commercial. Additional circuitry. QE low.

CCD coatings
Different coatings enhance sensitivity particularly in wavelengths were Si fails.