Maximum Theoretical Efficiency of PV Cells

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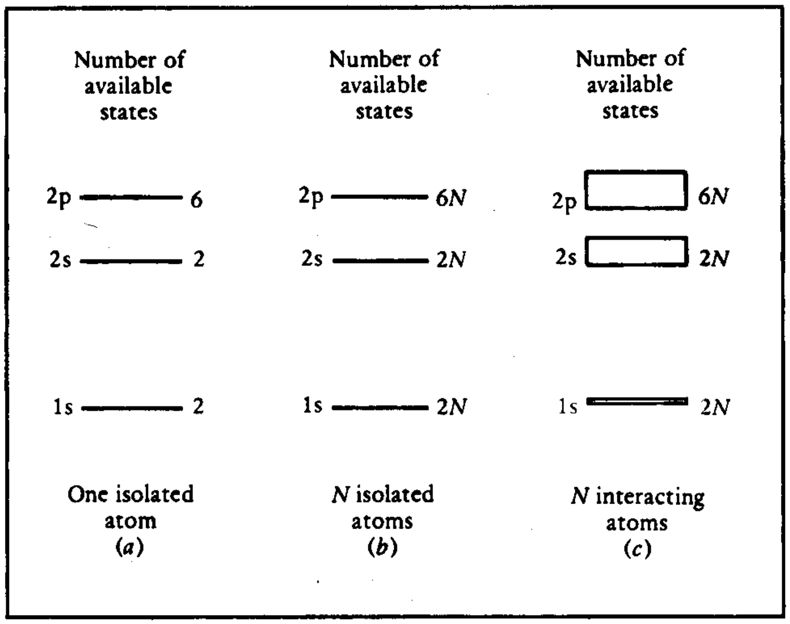
UC San Diego MAE 119
Lecture Notes

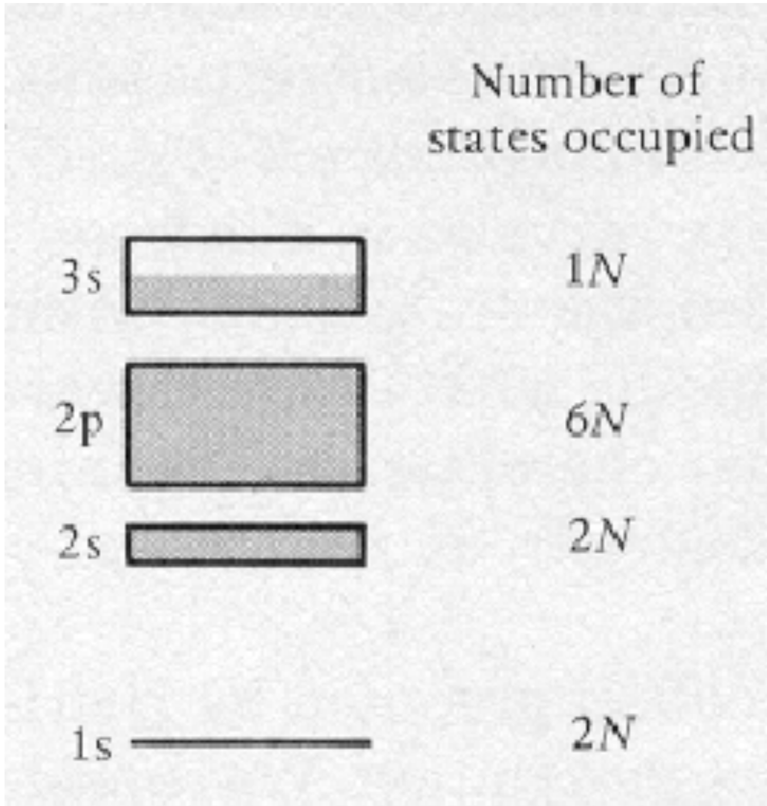
Band Theory of Solids: From Single Attoms…to Solid Crystals



- Isolated Li atom (conducting metal)
  - Has well-defined, isolated allowable electron energy levels
- N isolated atoms
  - N x isolated atom levels
- Strongly interacting Li atoms
  - Interaction shifts (or splits) individual **energy bands** into isolated regions separated by **forbidden bands**

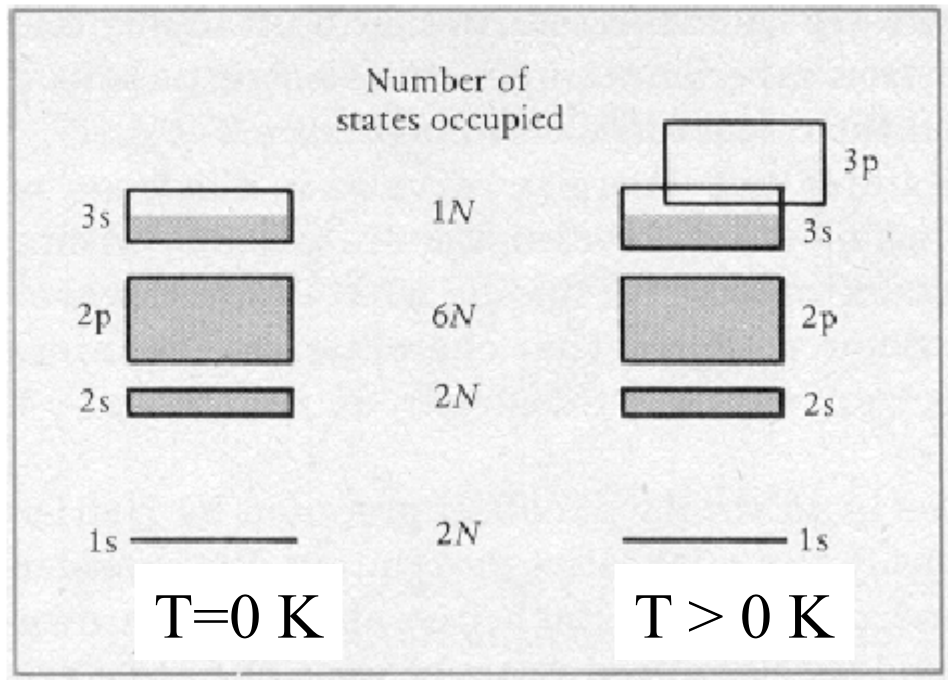
Band Theory of Solids: Conductors

- Next, consider N interacting sodium atoms at 0 deg K
  - Electrons in config $1s^2 2s^2 2p^6 3s^1$
  - Shells filled to 3s, which has 1 electron

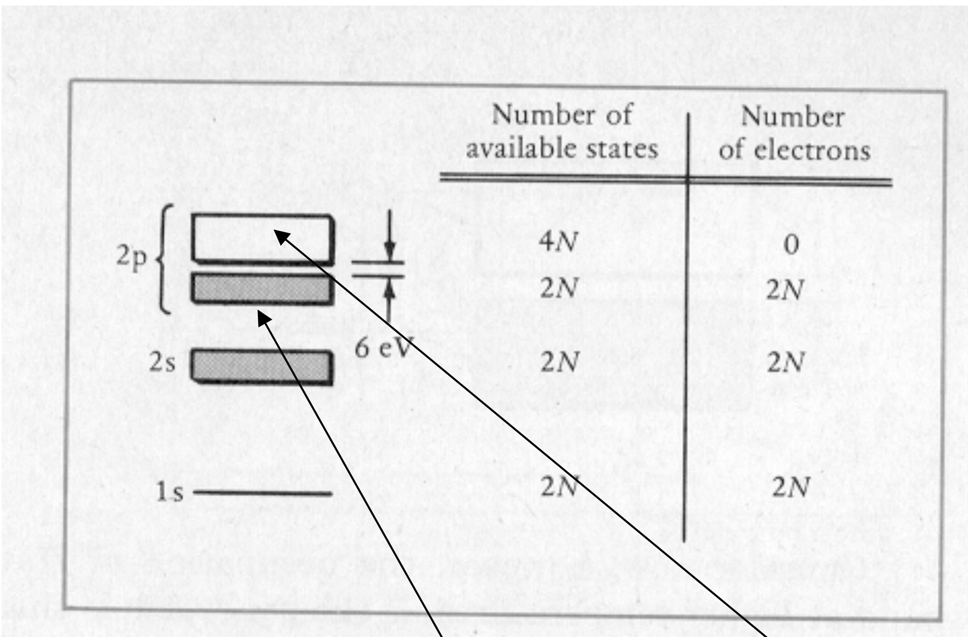


Band Theory of Solids: Conductors

- Next, consider N interacting sodium atoms w/ T>0
  - Electrons in config $1s^2 2s^2 2p^6 3s^1$
  - Shells filled to 3s, which has 1 electron
  - This Valence electron is weakly bound =>> if T High enough can move to mobile state ➔ conductor!



Band Theory of Solids: Insulators



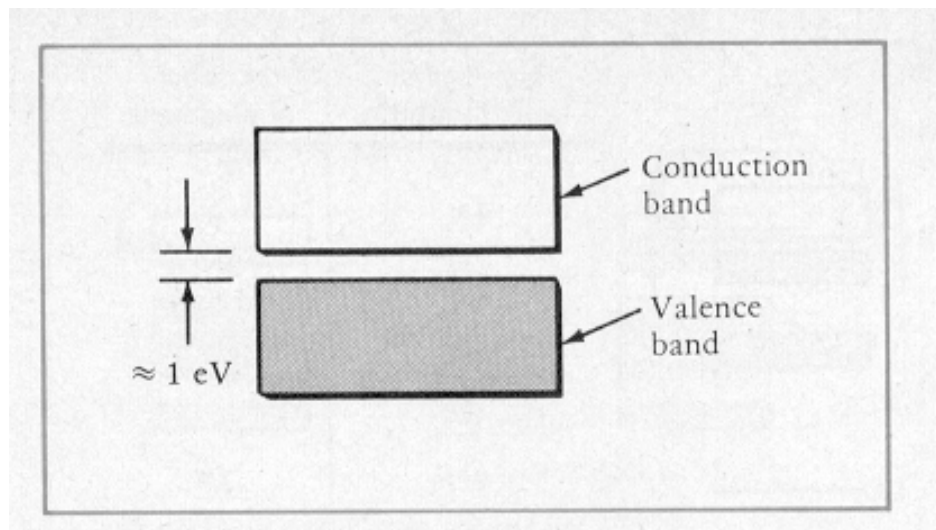
Lower levels: VALENCE BAND
Upper levels: CONDUCTION BAND

- Carbon in Diamond Form
  - Electrons in $1s^2 2s^2 2p^2$ State
  - 2p band has 2N electrons, but 6N states
  - BUT… crystal structure splits 2p into two distinct bands
  - ***BAND GAP is ~6 eV >> Temperature (~0.02-0.1 eV)***

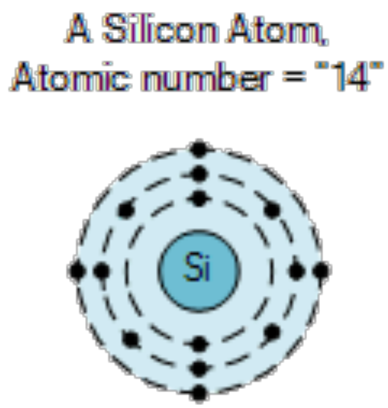
Thus…Diamond is An Insulator

Band Theory of Solids: Semiconductors

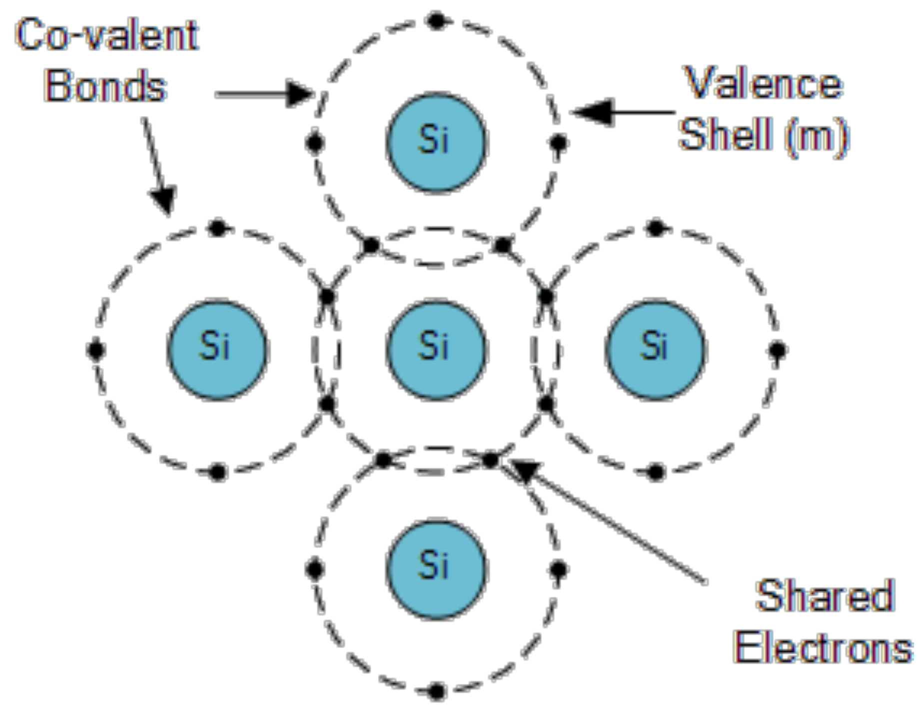
- ***Some crystalline materials have smaller band-gap energy***
- At low temperatures behave like insulators
  - E_{bg}~1eV >> Temperature
- With an electric field
  - Electrons gain energy
  - Can move into upper (conduction) band



Si as a Semiconductor Material



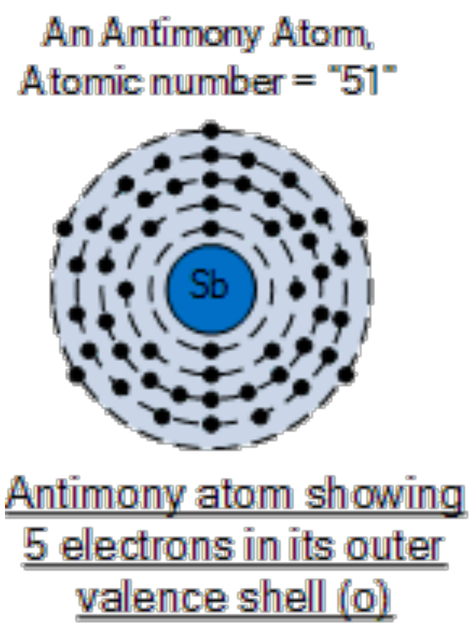
Silicon atom showing 4 electrons in its outer valence shell (m)

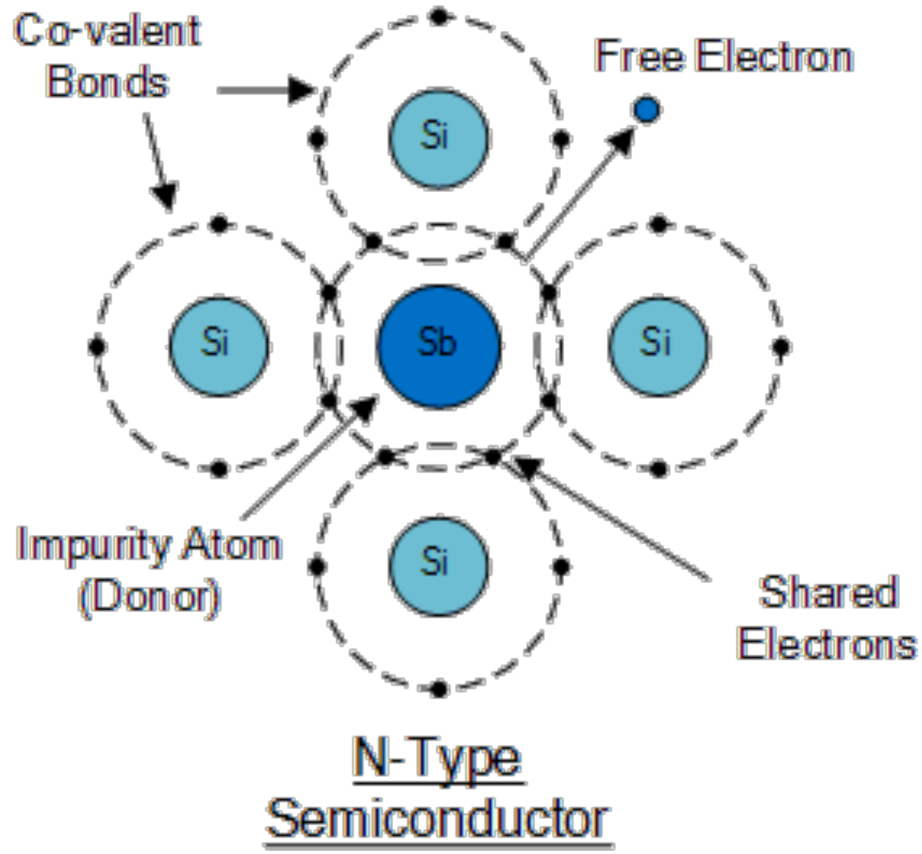


Silicon Crystal Lattice

http://www.electronics-tutorials.ws/diode

N-type Semiconductor Materials

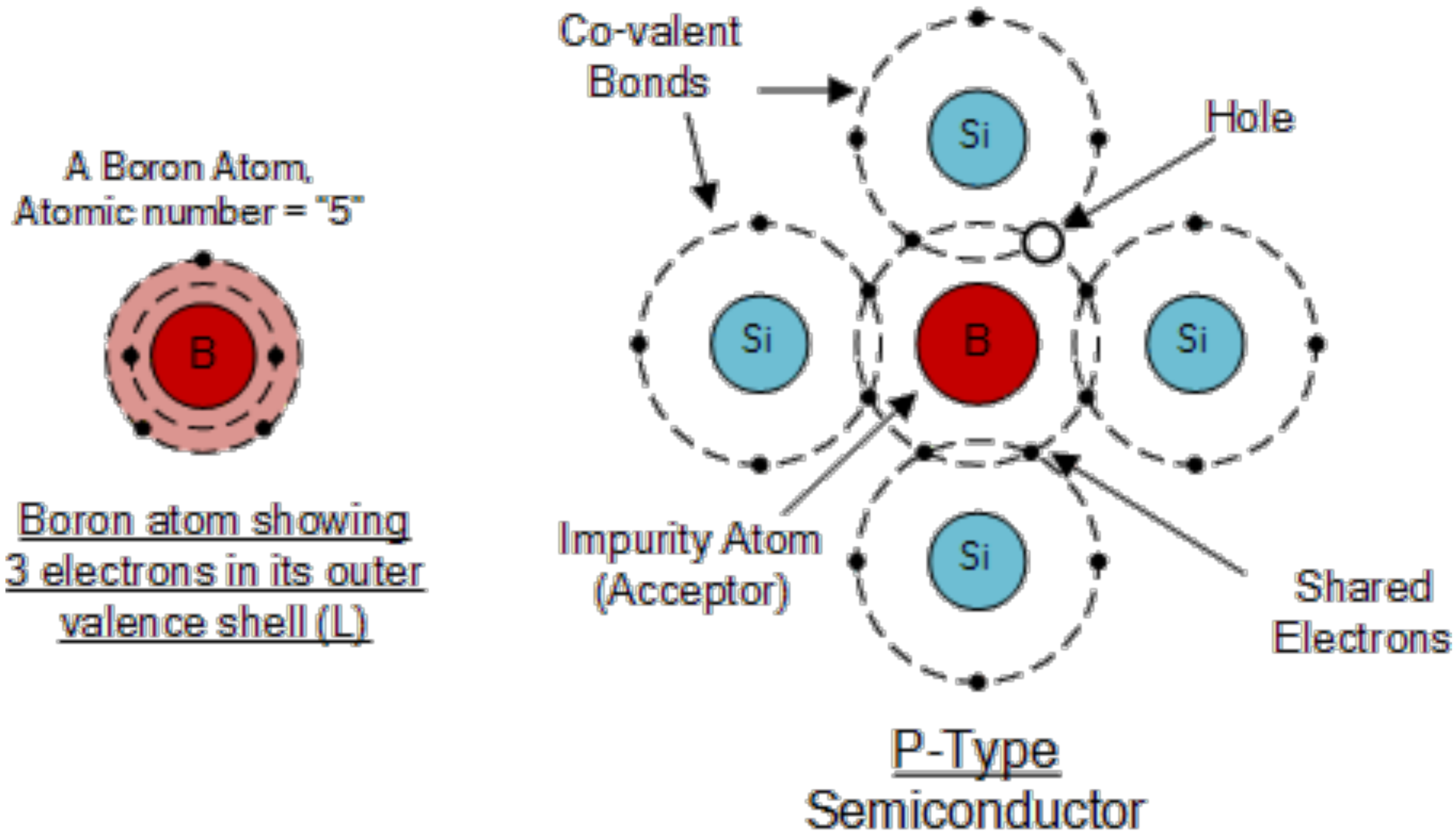




N-type Si has an extra electron for each dopant atom,
This electron is mobile

http://www.electronics-tutorials.ws/diode

P-type Semiconductor Materials



P-type Si has a "hole" (i.e a missing electron) that acts like
A mobile positive charge

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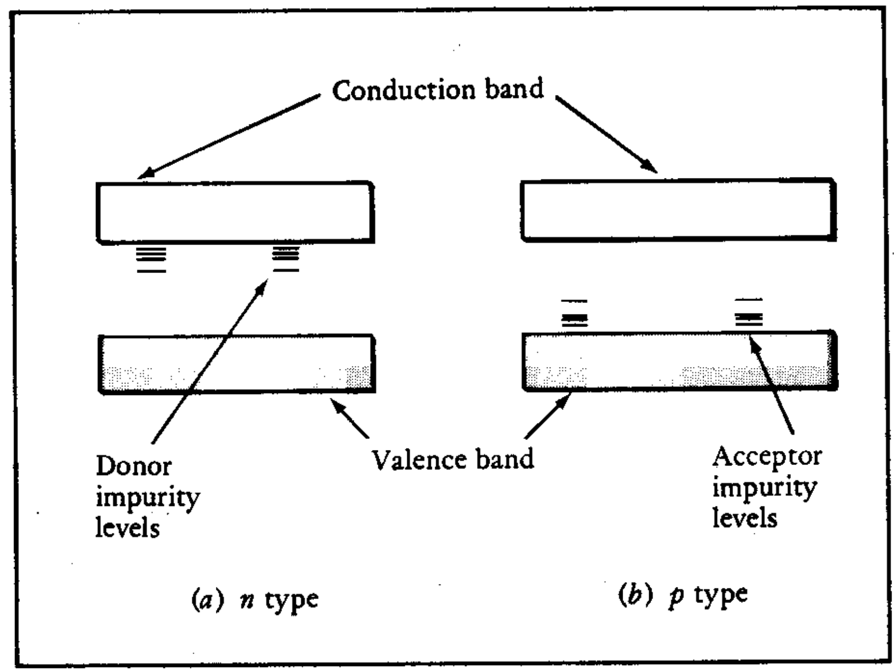
Dopants create allowed energy states between the pure material valence and conduction bands

- Pure semiconductor matl's conduction and valence bands separated by E_{gap}
- In pure materials this gap has no allowed states -> no particles in these energy ranges
- IF ADD donor or acceptor impurities then this creates allowed states between the pure-material conduction & valence bands



Physics of maximum theoretical efficiency

- Key Concepts
  - Photon Energy Spectrum
  - Charge Carrier Generation Via Photon Absorption
  - Photon flux & relation to energy spectrum
  - Estimating maximum possible efficiency
  - What does a real cell look like?

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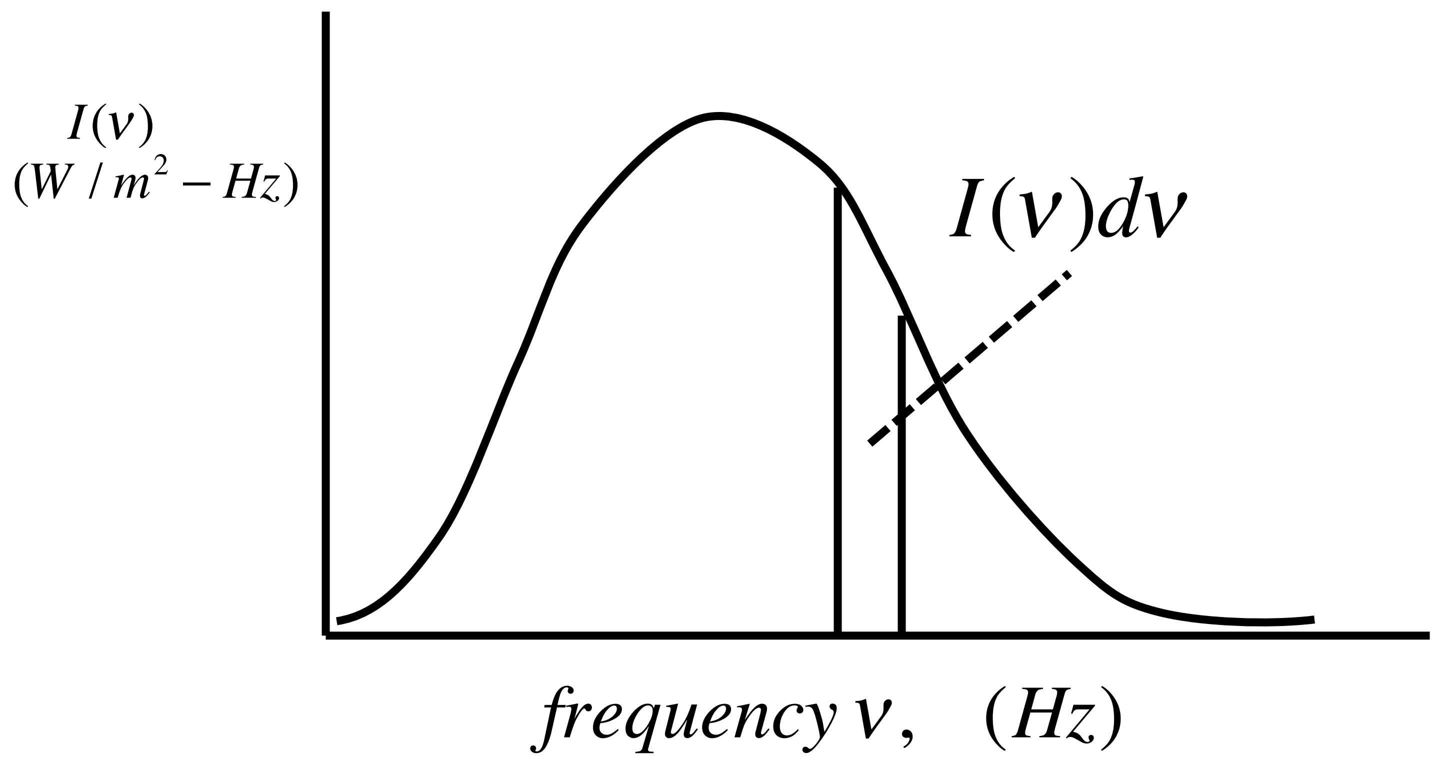
Recall blackbody spectrum:

Blackbody spectrum:

$$I(\nu) = \frac{h\nu^3}{c^2} \frac{1}{\exp\left(h\nu / kT\right) - 1}$$

Total intensity:

$$I_{tot} = \int_0^\infty I(\nu) d\nu$$



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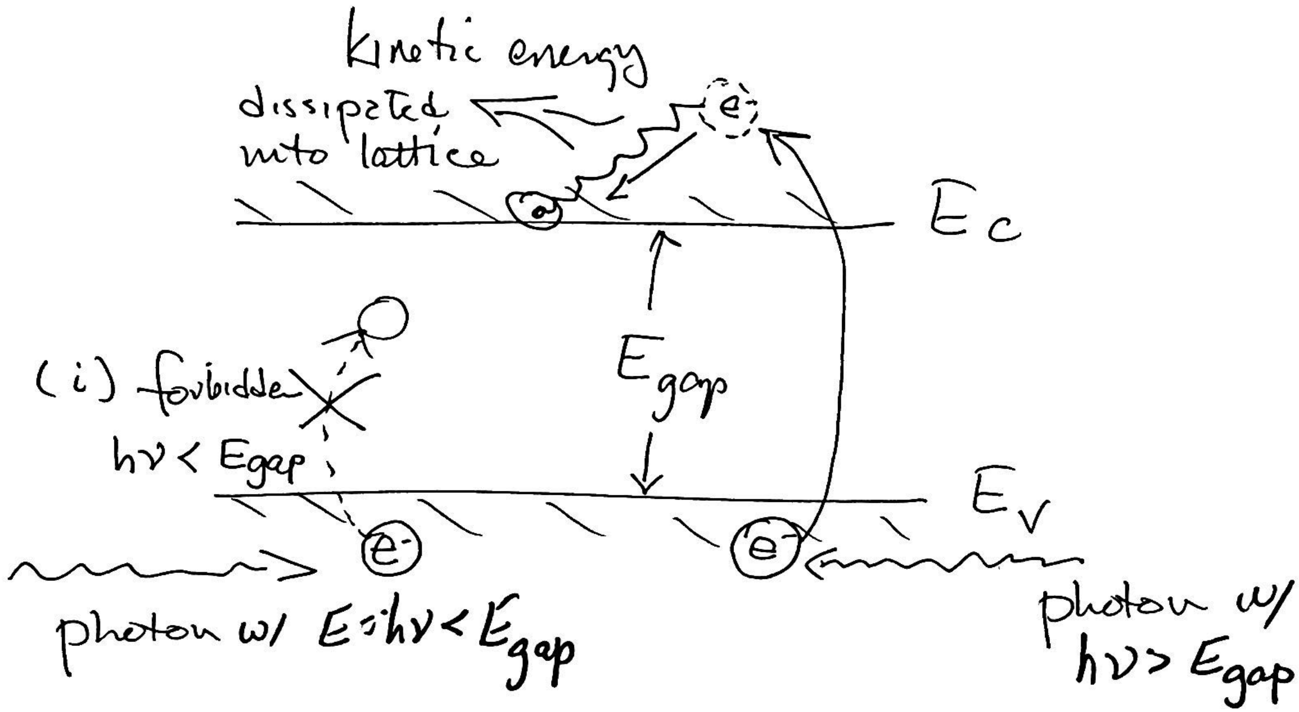
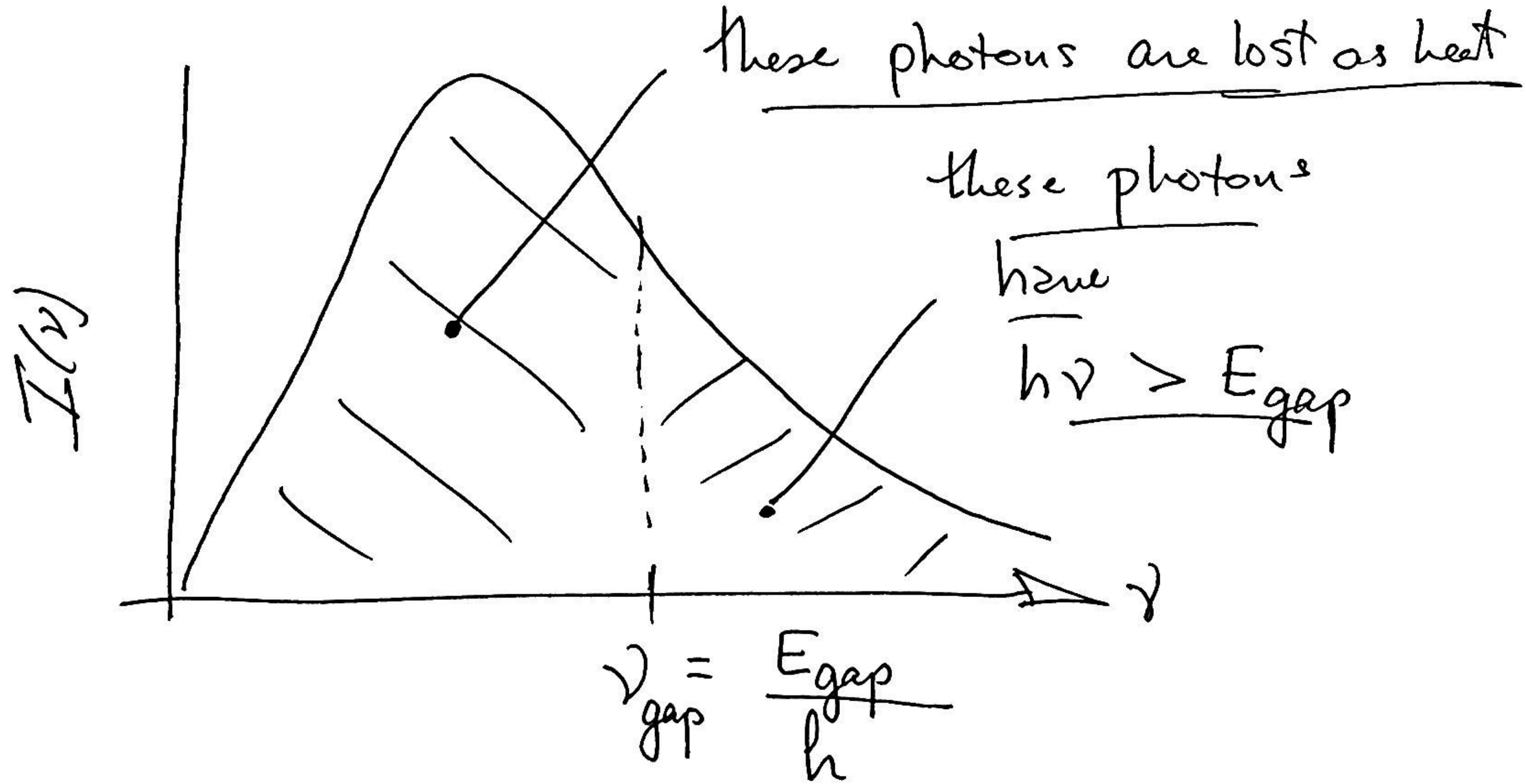
Light absorption can (sometimes) create mobile e-h pairs:



(i) if $E_{photon} = h\nu < E_{gap}$ ⟶ photon cannot dislodge e^- from V-band

What portion of spectrum has photons w/ enough energy?



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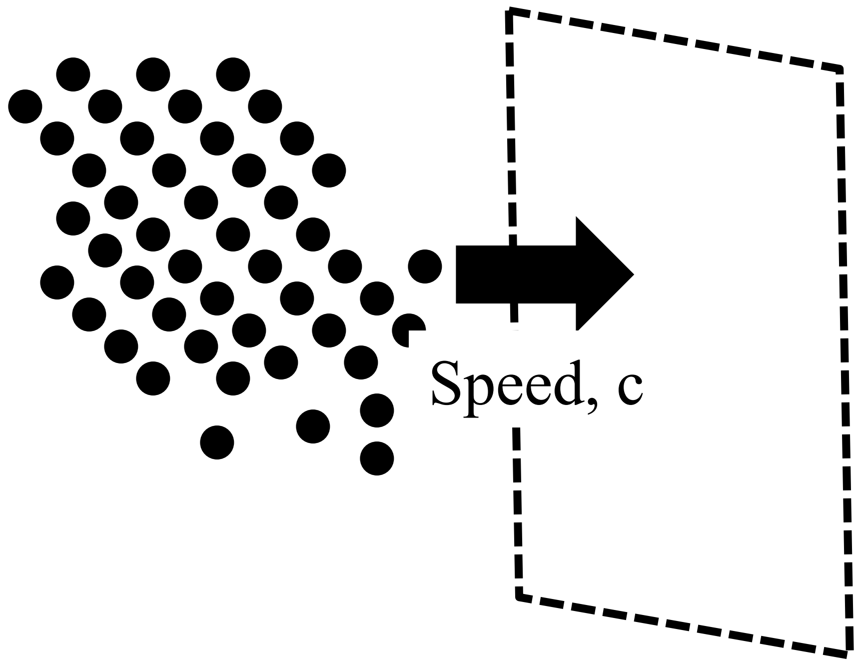
Relation of photon flux to Intensity:

Collection of n photons/unit volume
With frequency in range (ν, $\nu+d\nu$)



Q: How many photons pass thru the surface per unit area/unit time?

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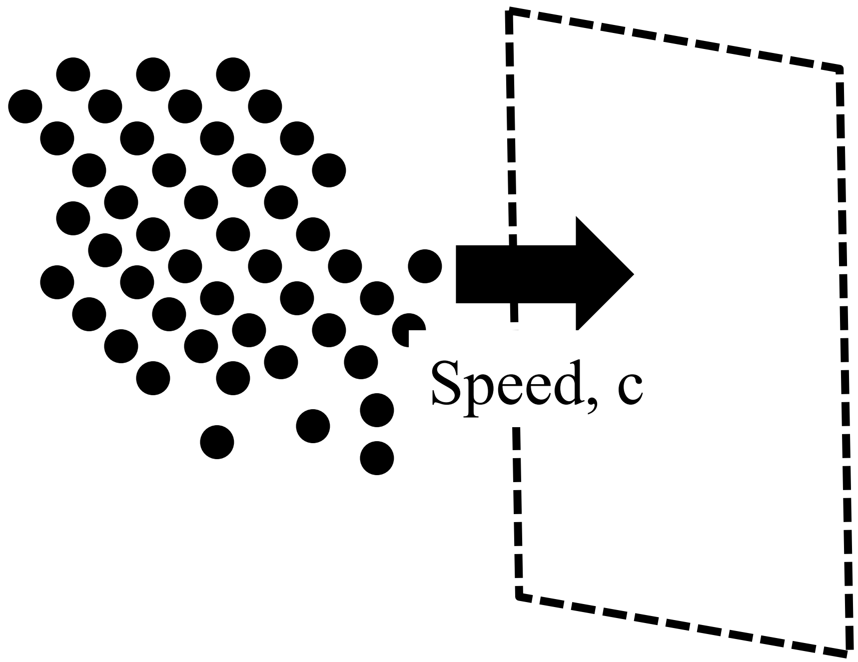

Q: How many photons pass thru the surface per unit area/unit time?

A: This is the photon flux, $\phi(\nu) = n(\nu)c$

Relation of photon flux to Intensity:

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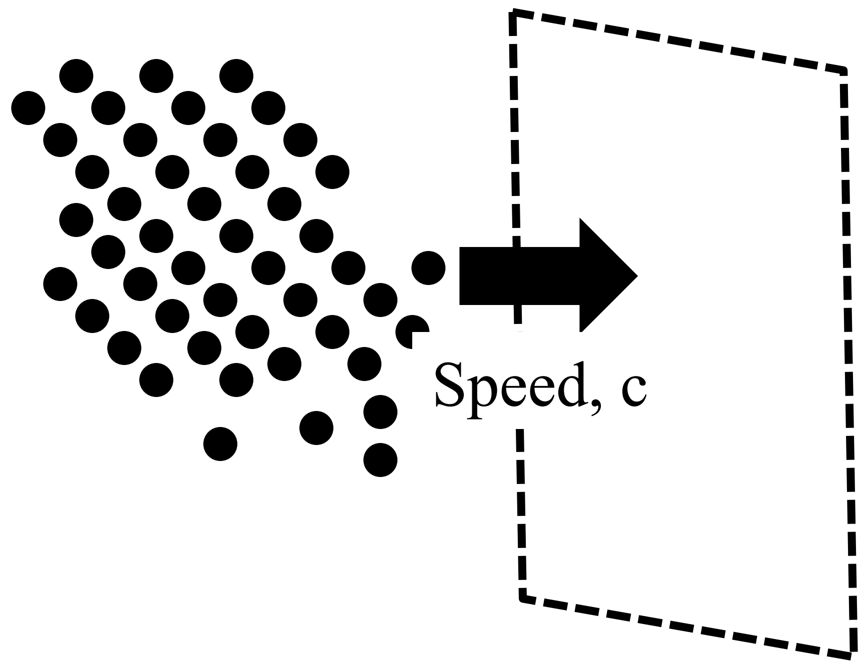
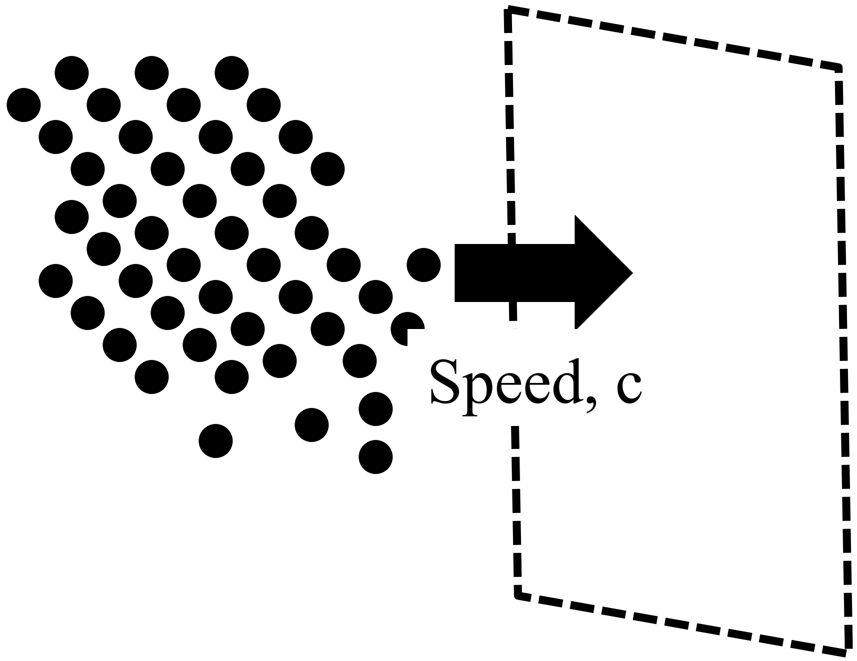


Q: If each photon has energy E=hv, how much energy passes thru surface per unit area and per unit time ?

Relation of photon flux to Intensity:

Collection of n photons/unit volume
With frequency in range (v, $v+dv$)



Q: If each photon has energy E=hv, how much energy passes thru surface per unit area and per unit time ?

A: Energy per unit area/unit time is INTENSITY,

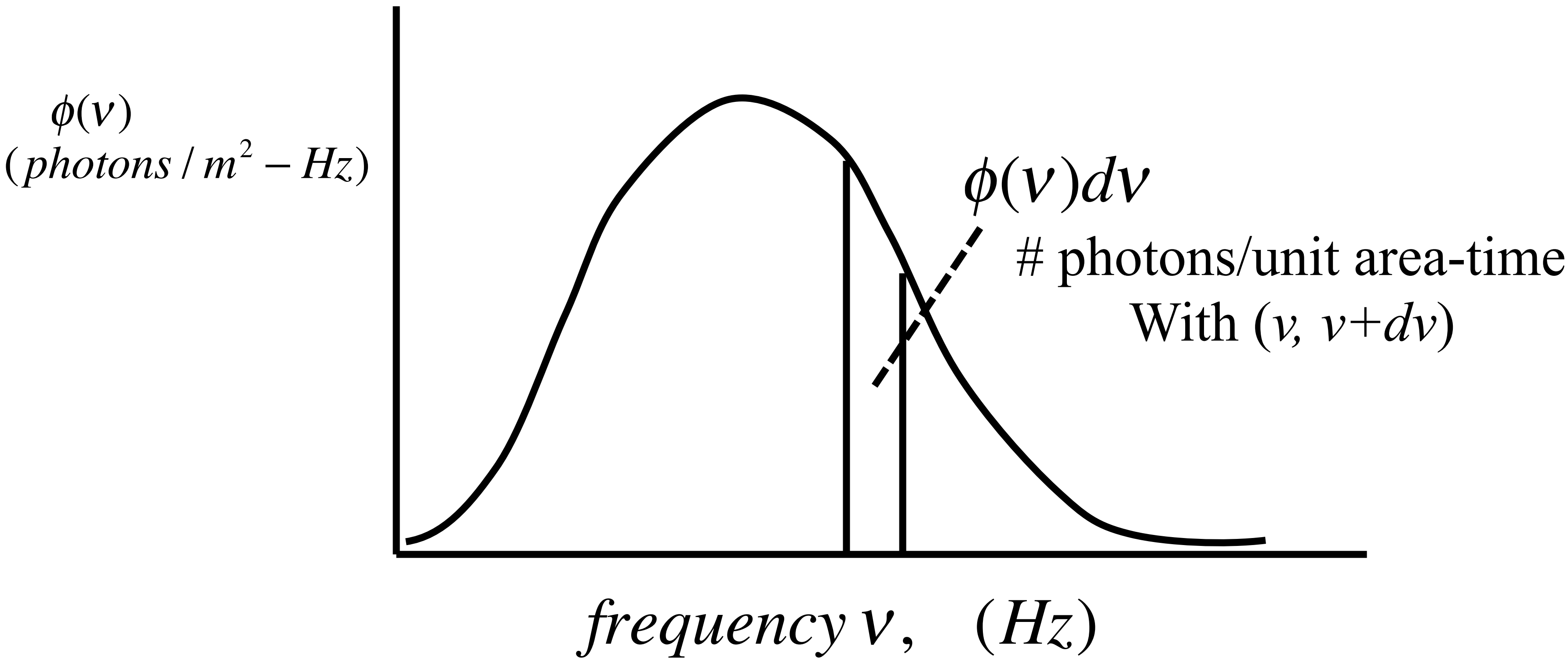
$$I(v) = hv\phi(v)$$

Photon flux of blackbody spectrum:

Blackbody spectrum:

$$\phi(\nu) = \frac{\nu^2}{c^2}\frac{1}{\exp\left(h\nu / kT\right) - 1}$$

Total flux (photons/unit area-time):

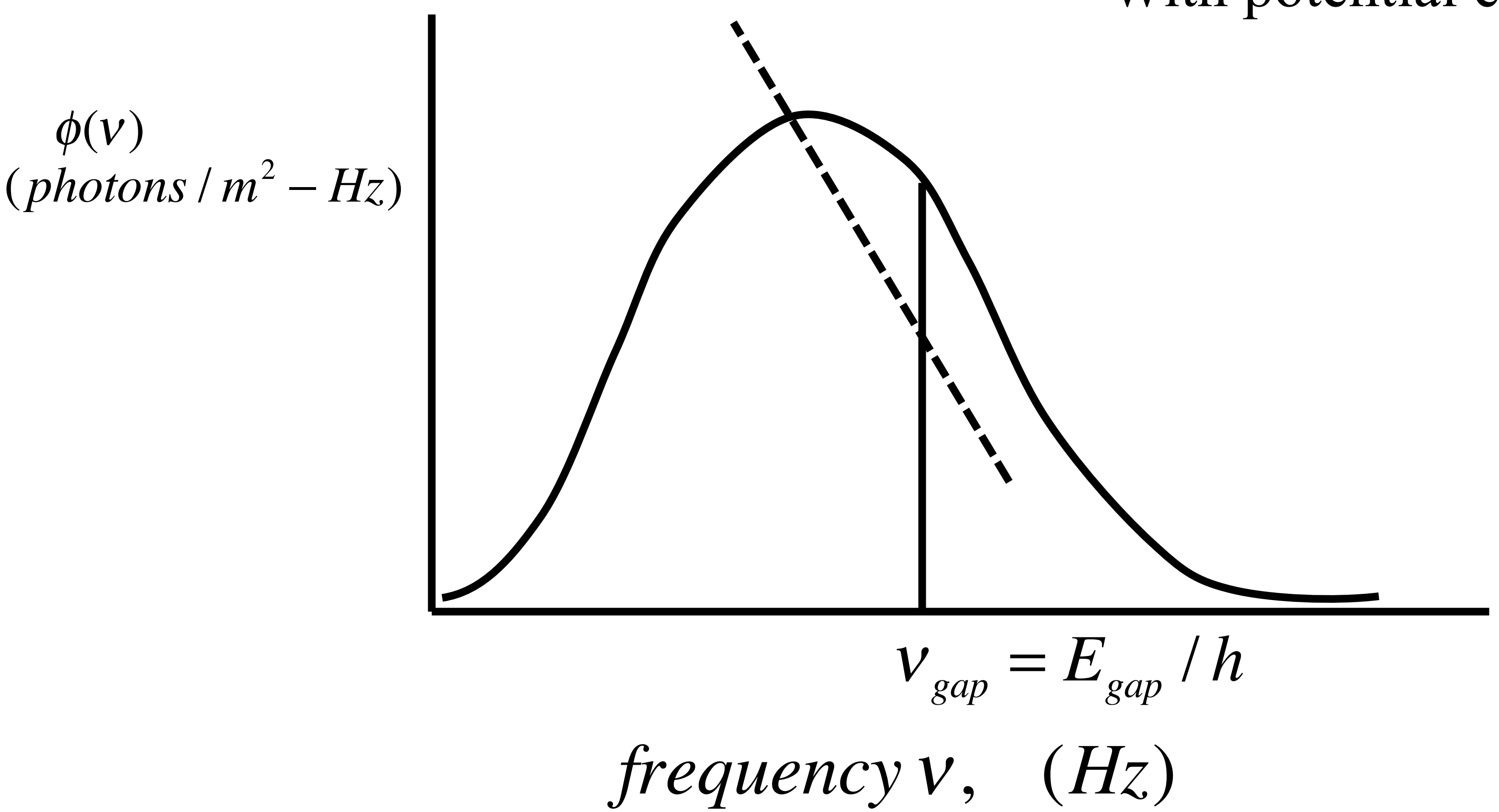


Photon flux of blackbody spectrum:

$$\phi_{gap} = \int_{\nu_{gap}}^{\infty} \phi(\nu)\, d\nu$$

Photon flux with $E > E_{gap}$

⇨ Each of these Photons produce Charge carrier pair With potential energy E_{gap}



Can now estimate max efficiency:

Power produced by e-h pair creation:

$$P_{\max} = \phi_{gap} E_{gap} \quad \text{Where} \quad \phi_{gap} = \int_{\nu_{gap}}^{\infty} \phi(\nu)\, d\nu$$

Maximum incident power (per unit area):

$$I_{tot} = \int_{0}^{\infty} I(\nu)\, d\nu$$

Maximum possible efficiency is the ratio of these two:

$$\eta_{\max} = \frac{P_{\max}}{I_{tot}}$$

Max. PV Cell Efficiency:

Can recast as an integral: $$\eta_{\max} = \frac{15}{\pi^4}\xi_0 \int_{\xi_0}^{\infty} \frac{x^2}{e^x - 1} dx$$

$$where \quad \xi_0 = \frac{qE_{gap}}{k_B T_{bb}}$$

For Si with E_{gap}~1.1 eV and T_{bb}~6000 K

$$\eta_{\max} \sim 0.44$$

A Solar PV Cell is just a p-n junction ("diode") illuminated by light….