Light and electromagnetic radiation Energy Harvesting

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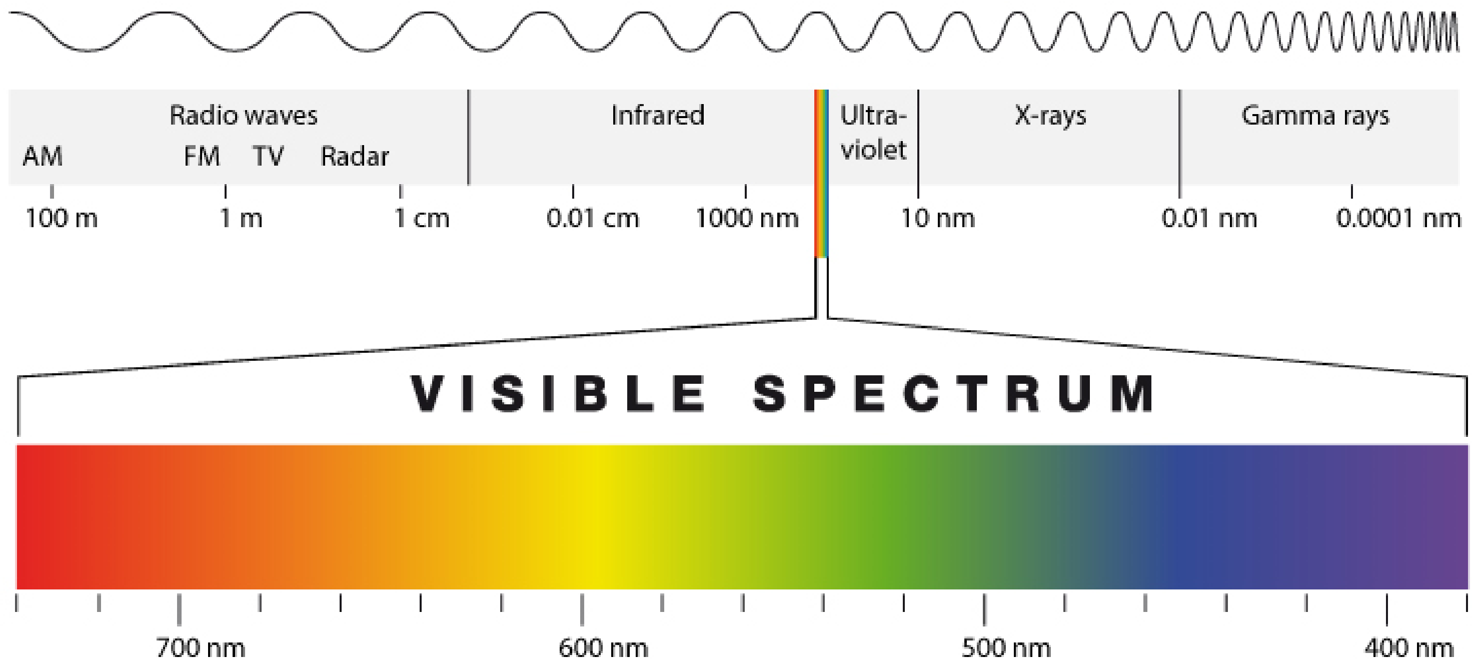
NiPS Summer School 2017

Energy Harvesting: models and applications

Gubbio, ITALIA

Electromagnetic spectrum

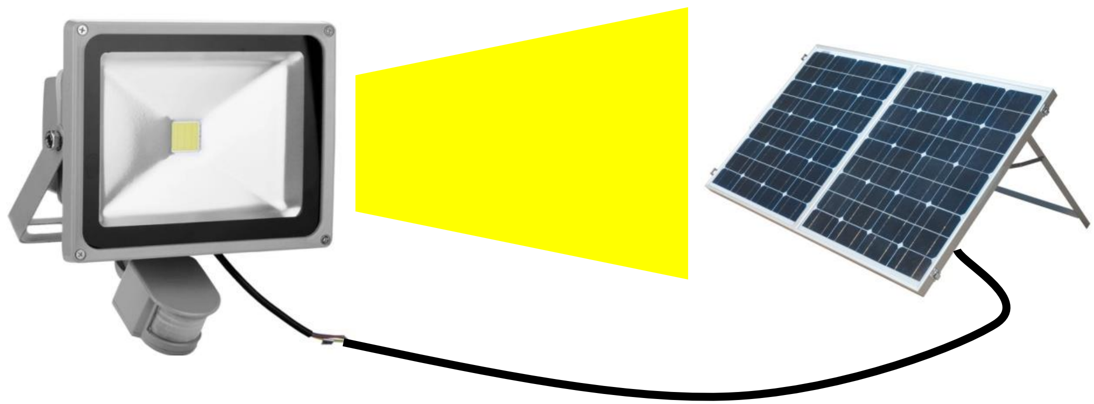


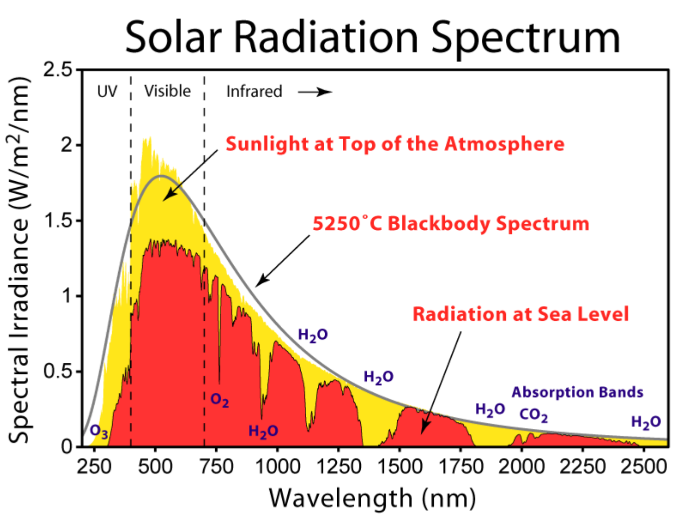
The energy of the single photon is inversely proportional to the wavelength:

$$c = \lambda \cdot \upsilon$$

$$E = h\,\upsilon$$

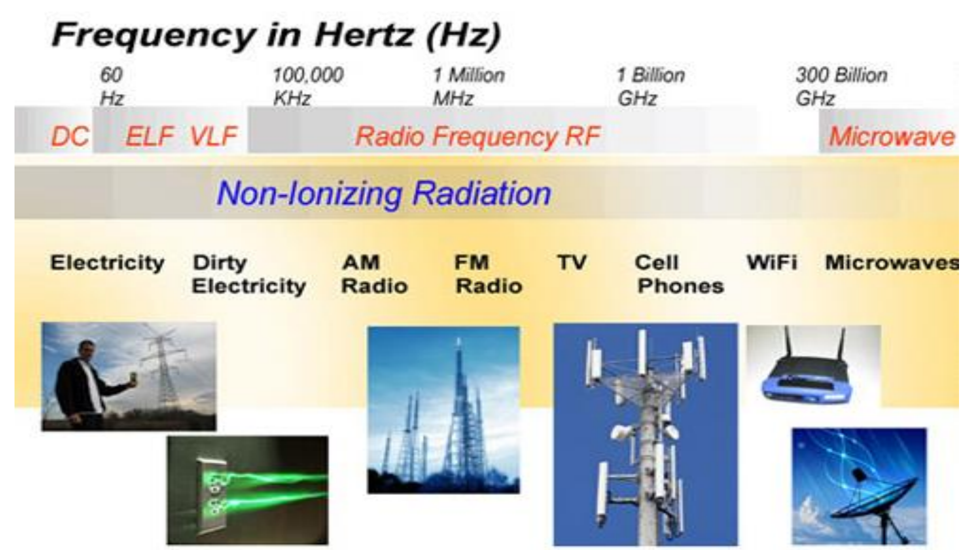
Radiation harvesting





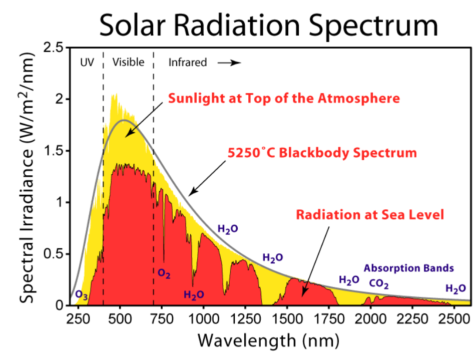
Natural

Man-made

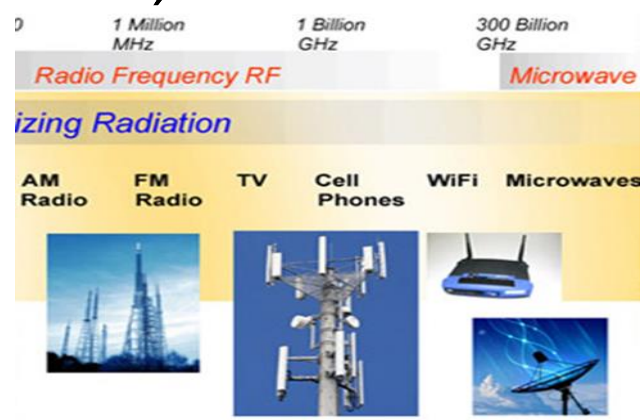


Outline

- Light (solar) harvesting
  → Device and materials

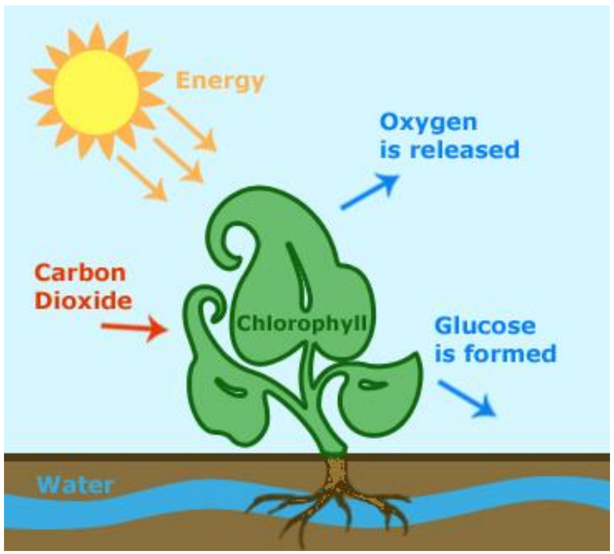


- EM harvesting (microwaves, rf)
  → Device and materials



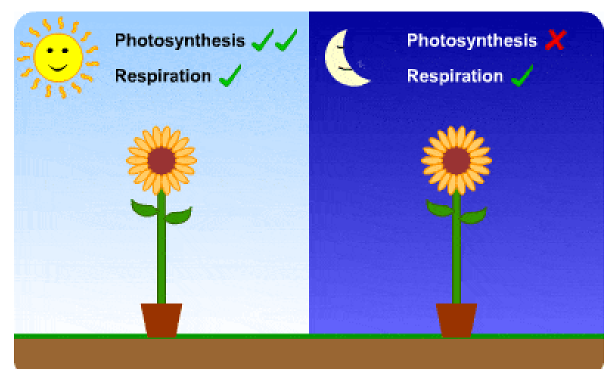
Plants

- We don't always need (transistor) electronics

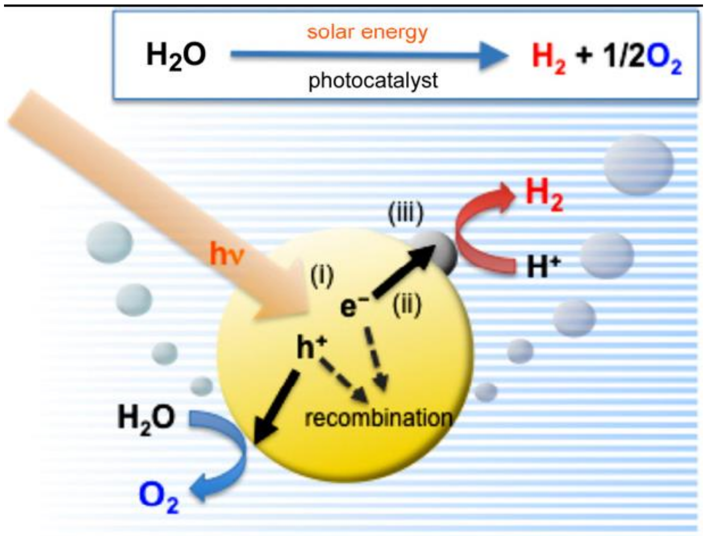


Photosynthesis
and
Respiration

Energy is collected into
a chemical storage system



Photocatalytic water splitting



R. Abe, J. Photochem. Photobiol. C 11 (2010)

Artificial photosynthesis

Dissociation energy: 1.23 eV (infrared), but there must be absorption so λ<180nm

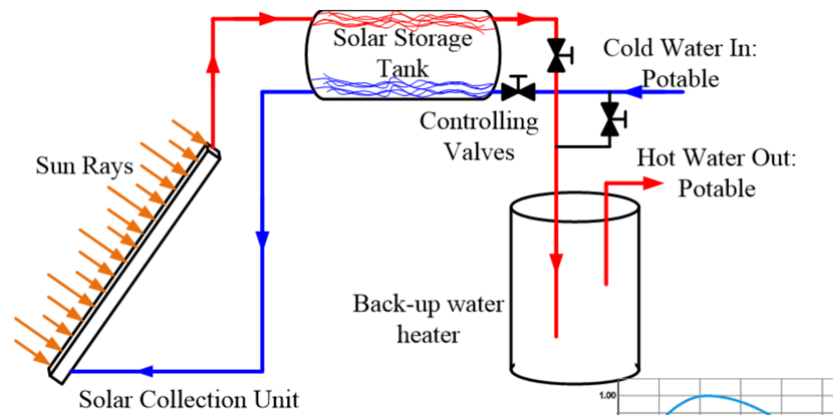
Ongoing research on the best way to promote this reaction.

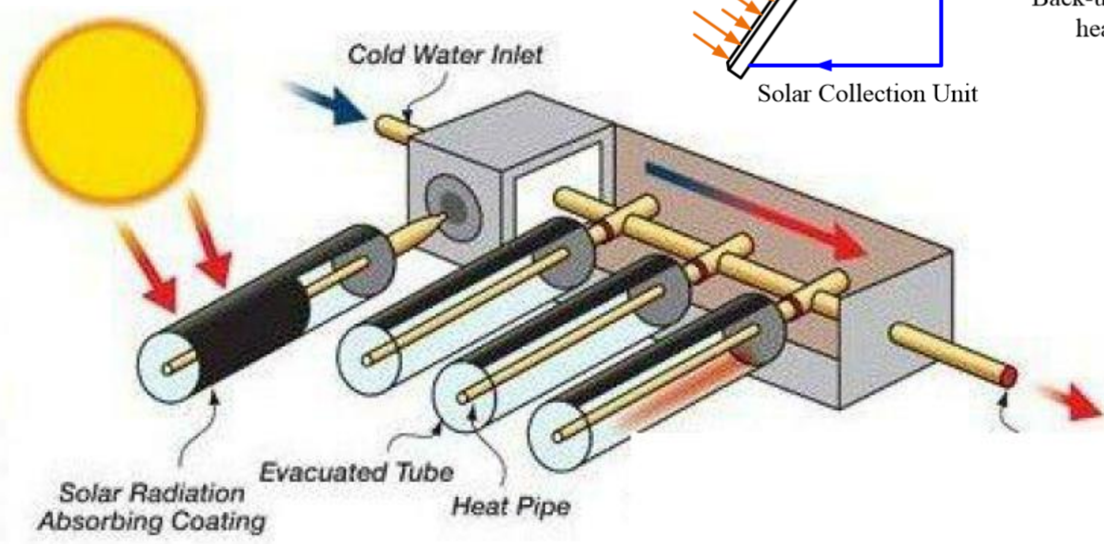
Catalyst agents: TiO2, K3Ta3B2O12, Cd(1-x)ZnxS,...

Solar thermosyphon systems

We can also acquire energy in the form of heat.

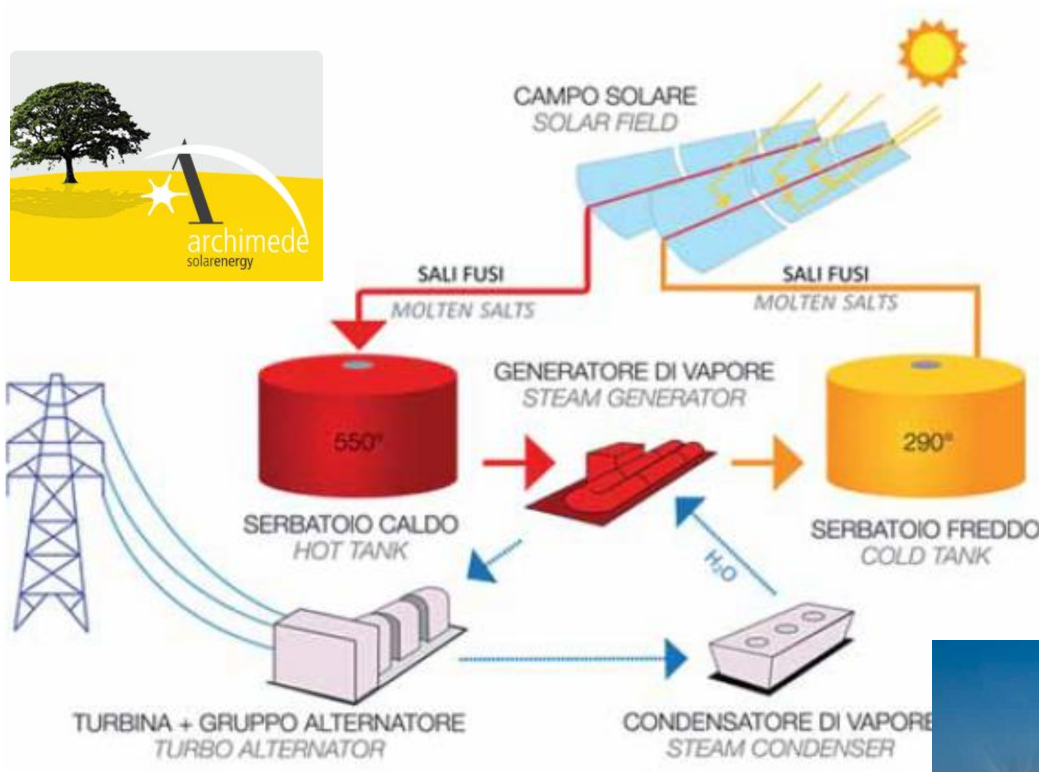
Efficient system (reducing heat losses in the transport, only radiation limits efficiency)





Solar thermodynamic power plants

La tecnologia del solare a concentrazione a sali fusi con specchi parabolici linearei | *CSP parabolic trough molten salt technology*

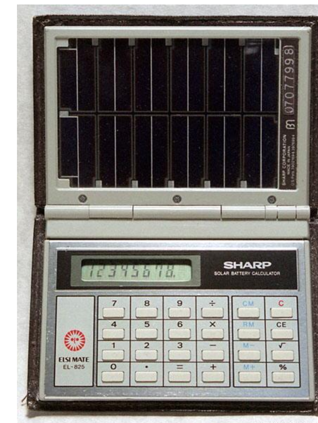


Angelantoni group: http://www.archimedesolarenergy.it/

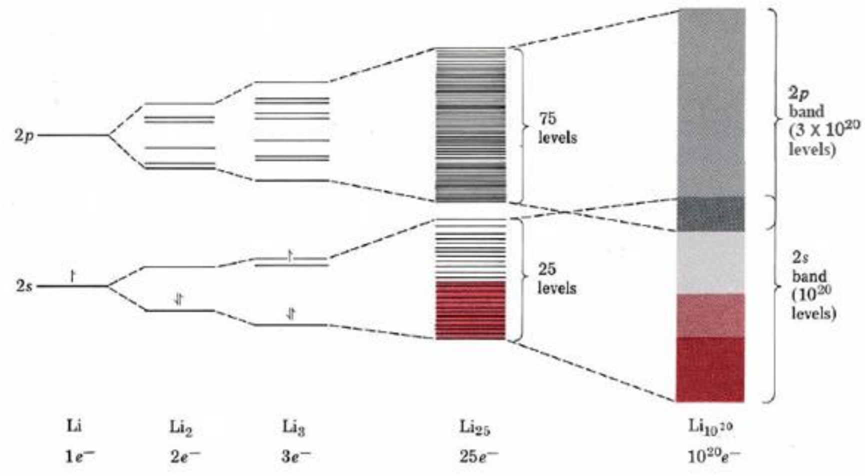
The heat is stored in high temperature (550 °C) moltens salts → night operation

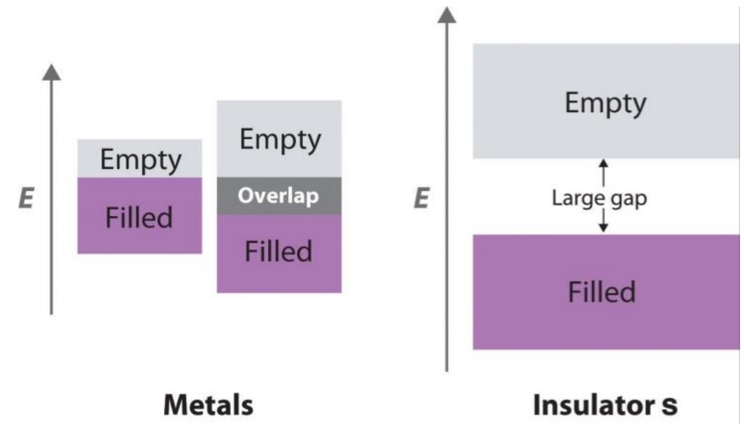
Photovoltaic devices

- Direct electric energy
- High power (EH) ~100 W/m^2
- Scalable (~ mW/cm^2 , solar plants)

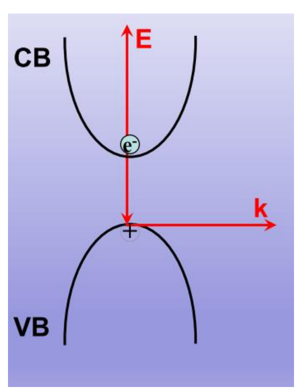


Band theory of solids





Bands form from the separated energy levels of free atoms

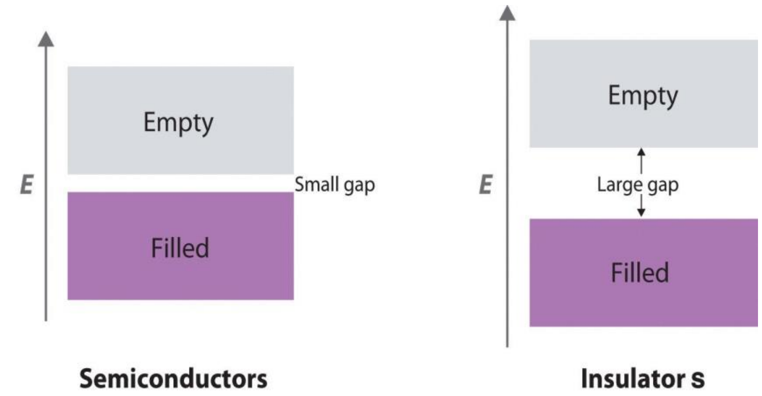


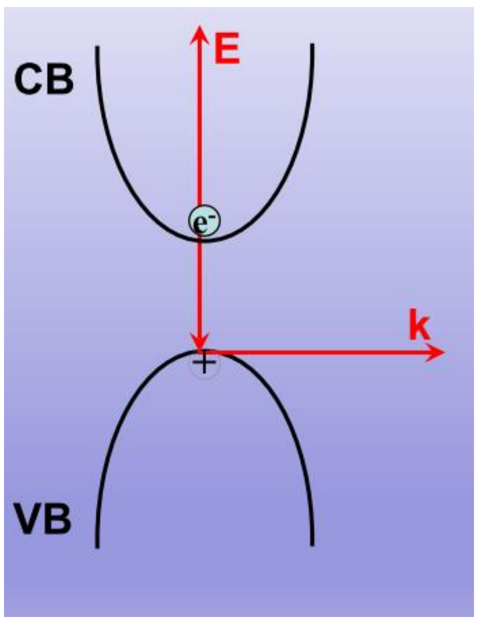
According to the filling of the bands we have different conduction properties

Conduction needs unoccupied electronic states

Semiconductors

Semiconductors are <u>insulators</u> with a small energy gap bewtween valence and conduction band



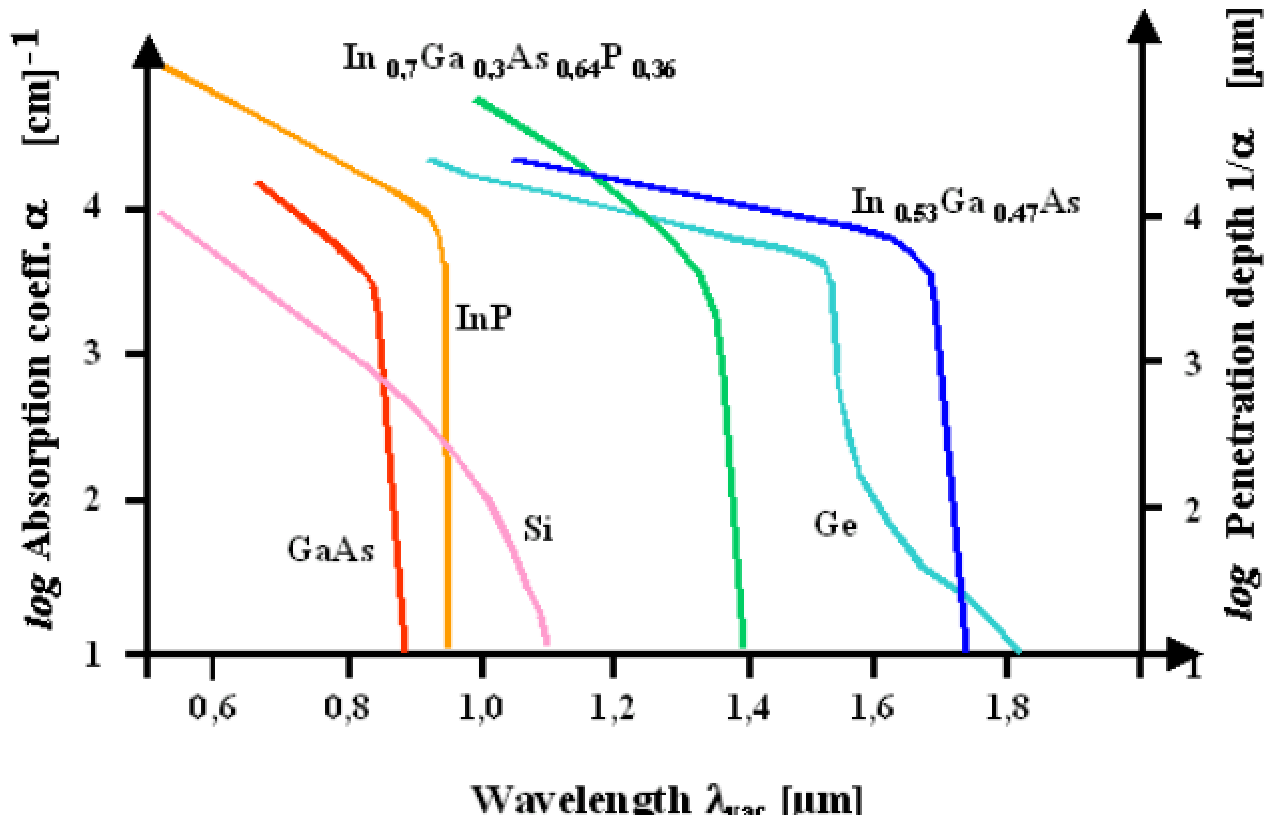


$E_g = 1.1$ eV (Si)
$E_g = 0.67$ eV (Ge)
$E_g = 1.41$ eV (GaAs)

$$\sigma_i = n_i e(\mu_e + \mu_h) = C \cdot e(\mu_e + \mu_h) \cdot T^{\frac{3}{2}} \exp\left(-\frac{E_G}{2kT}\right)$$

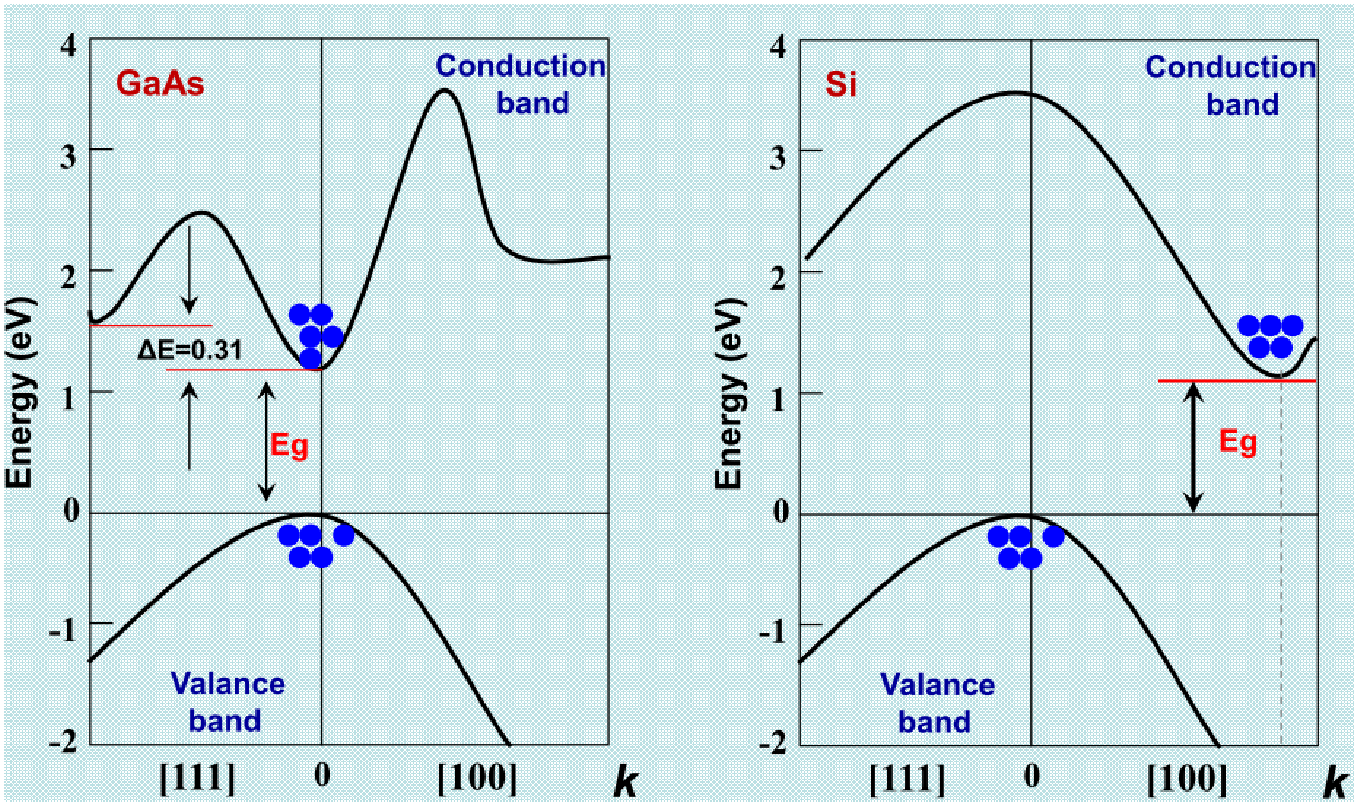
In intrinsic semiconductors the conducibility depends on holes and electrons. Their number is related to temperature.

Light absorption



The energy needed to bridge the gap can also be provided by photons

Direct and indirect gap

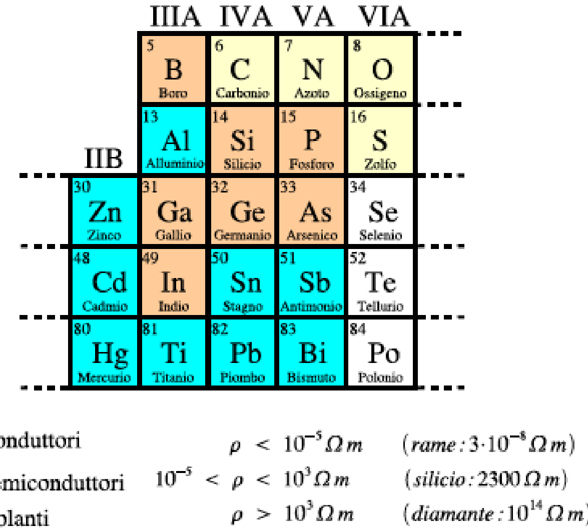


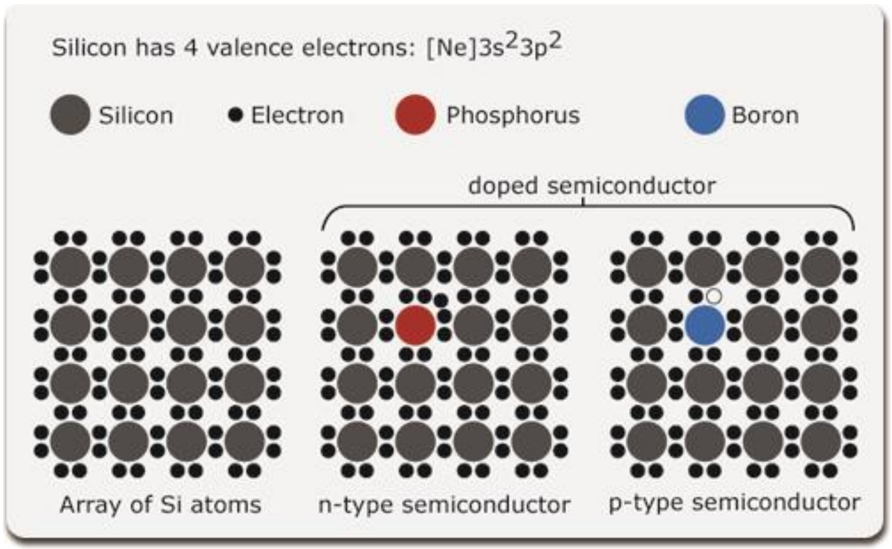
According to whether the smallest energy difference occurs at the same momentum value or not, we speak of direct or indirect gap semiconductors.

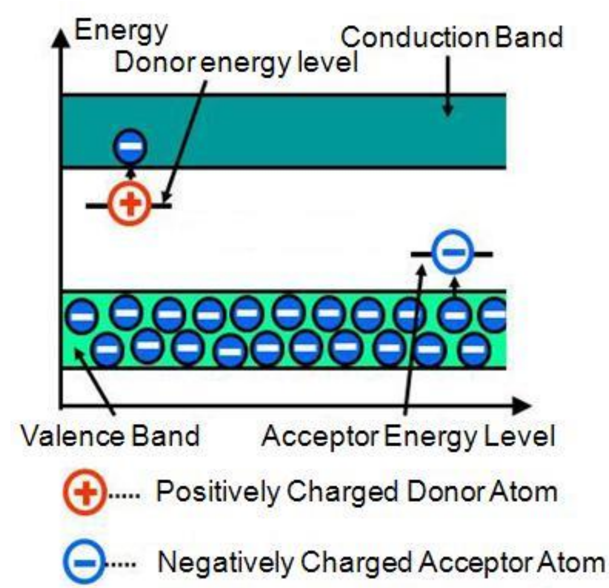
Indirect transition are less probable as they require the presence of a phonon

Doping

At room temperature silicon conductivity is low.
We can increase it by doping.

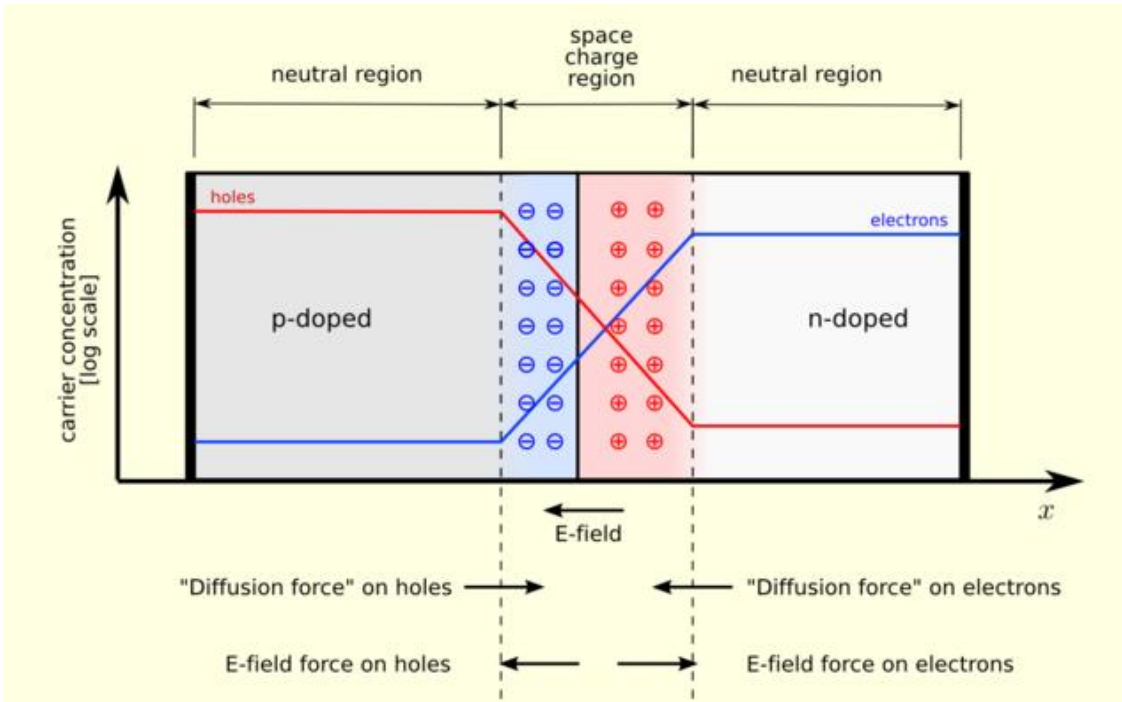






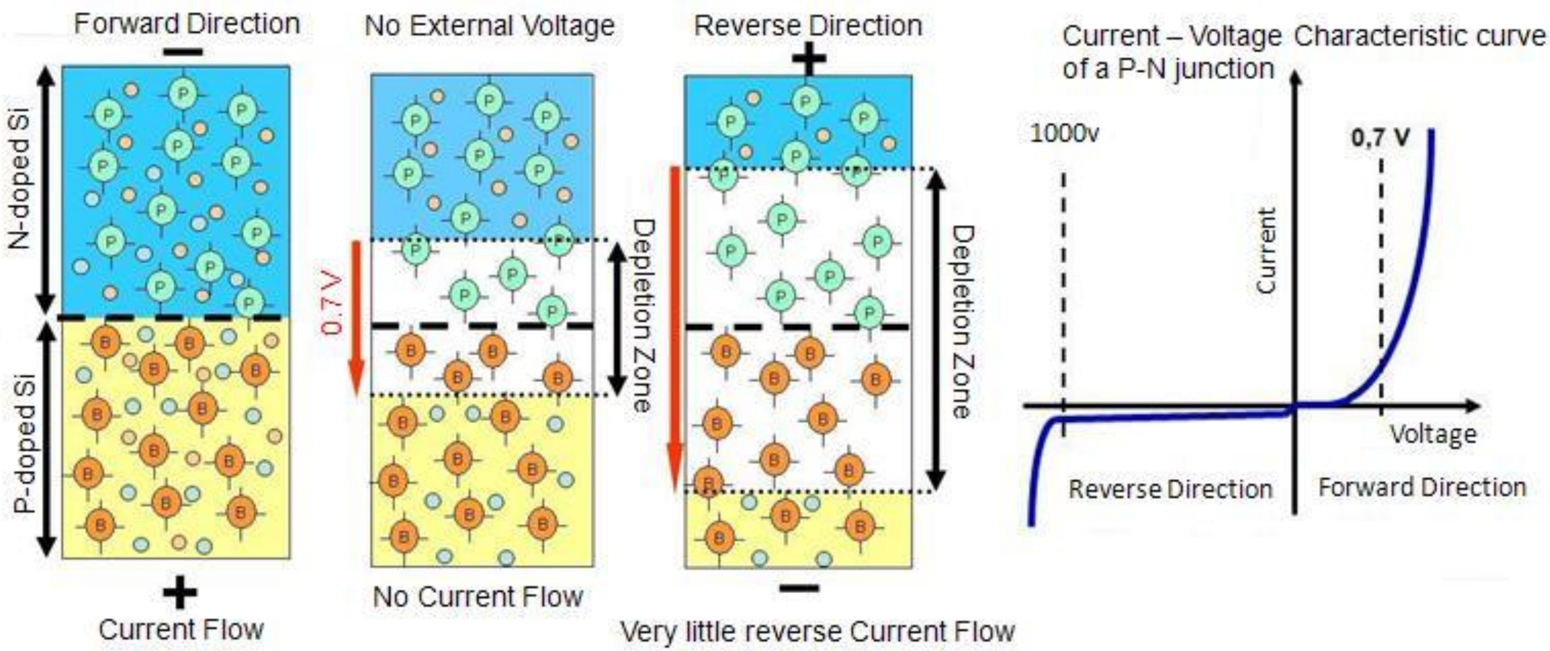
Doping increases the number of carriers of one type:
electrons: n-type semiconductors
holes : p-type semiconductors

pn junction



The contact region, depleted of mobile carriers, is called the Depletion Region (thickness 0.5 – 1.0 μm).

Diode

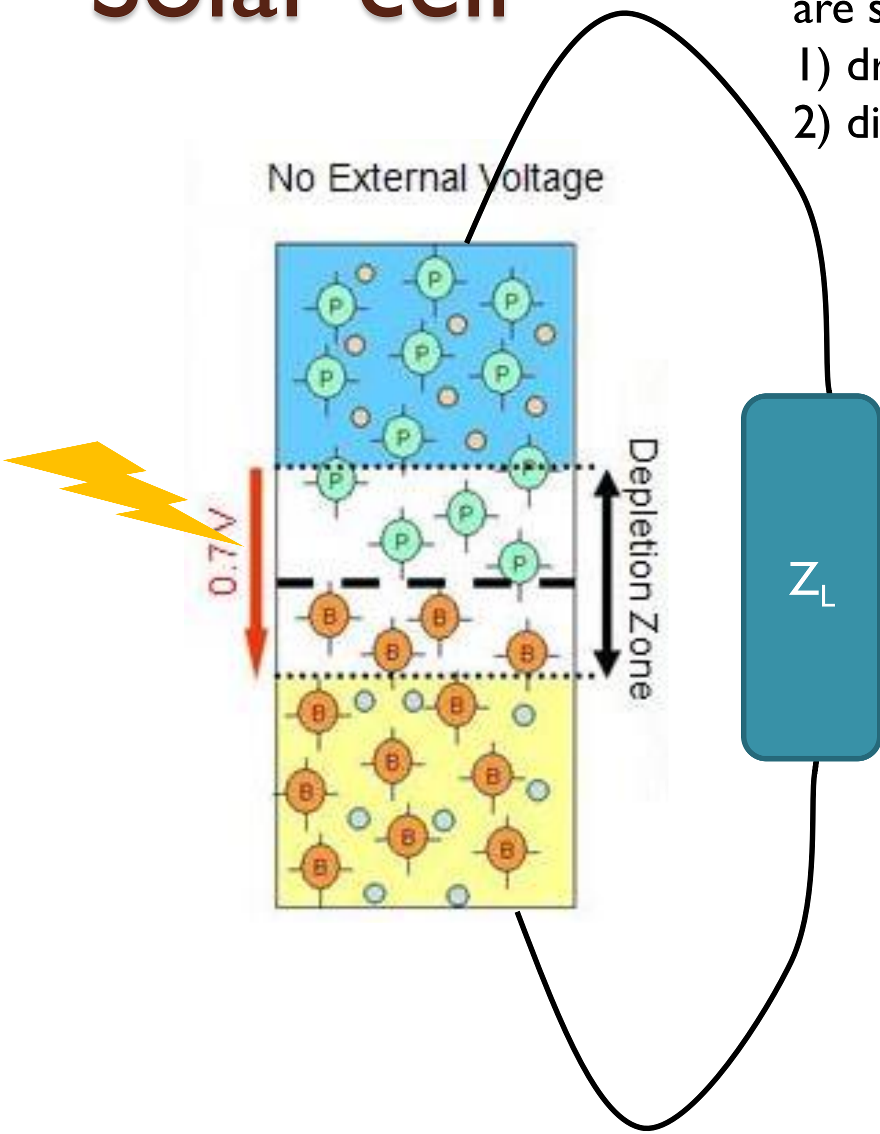


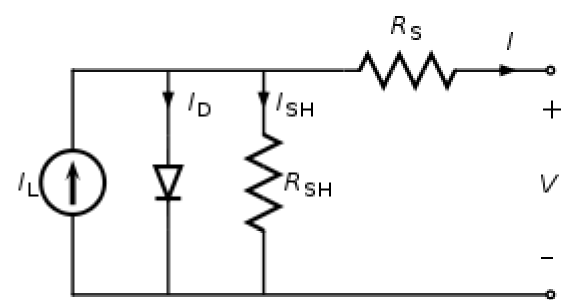
Direct current can flow once the barrier at the depletion region is overcome (0.7 V)
Reverse current cannot flow because the motion of the charge increase the size of the dep. regione.

Solar cell

The carriers generated by the light photons are subjected to:

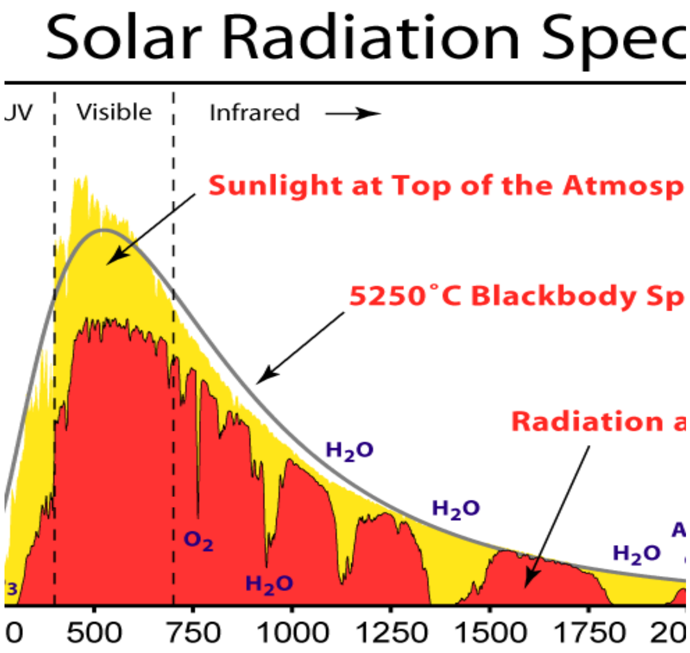
1) drift ,driven by the electric field
2) diffusion from high concentration zones

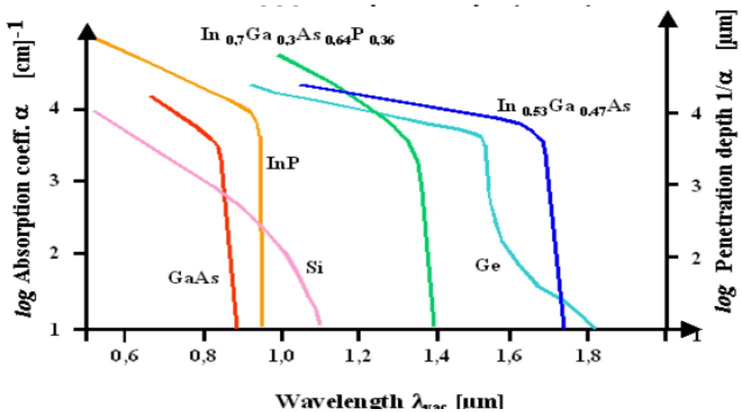




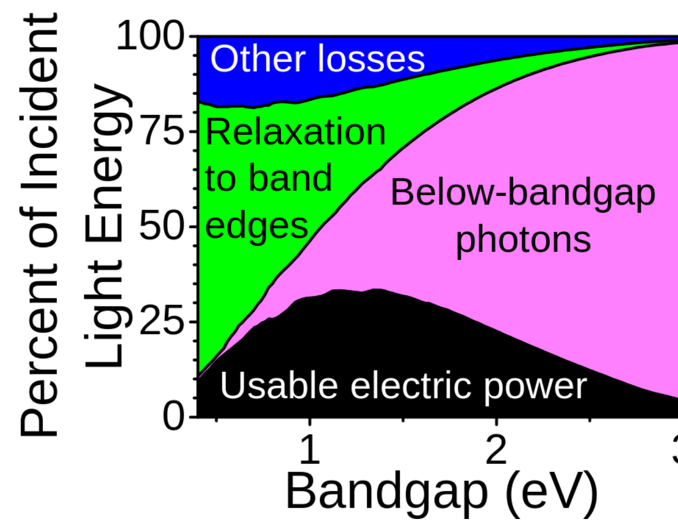
Electric equivalent

Efficiency of solar cells



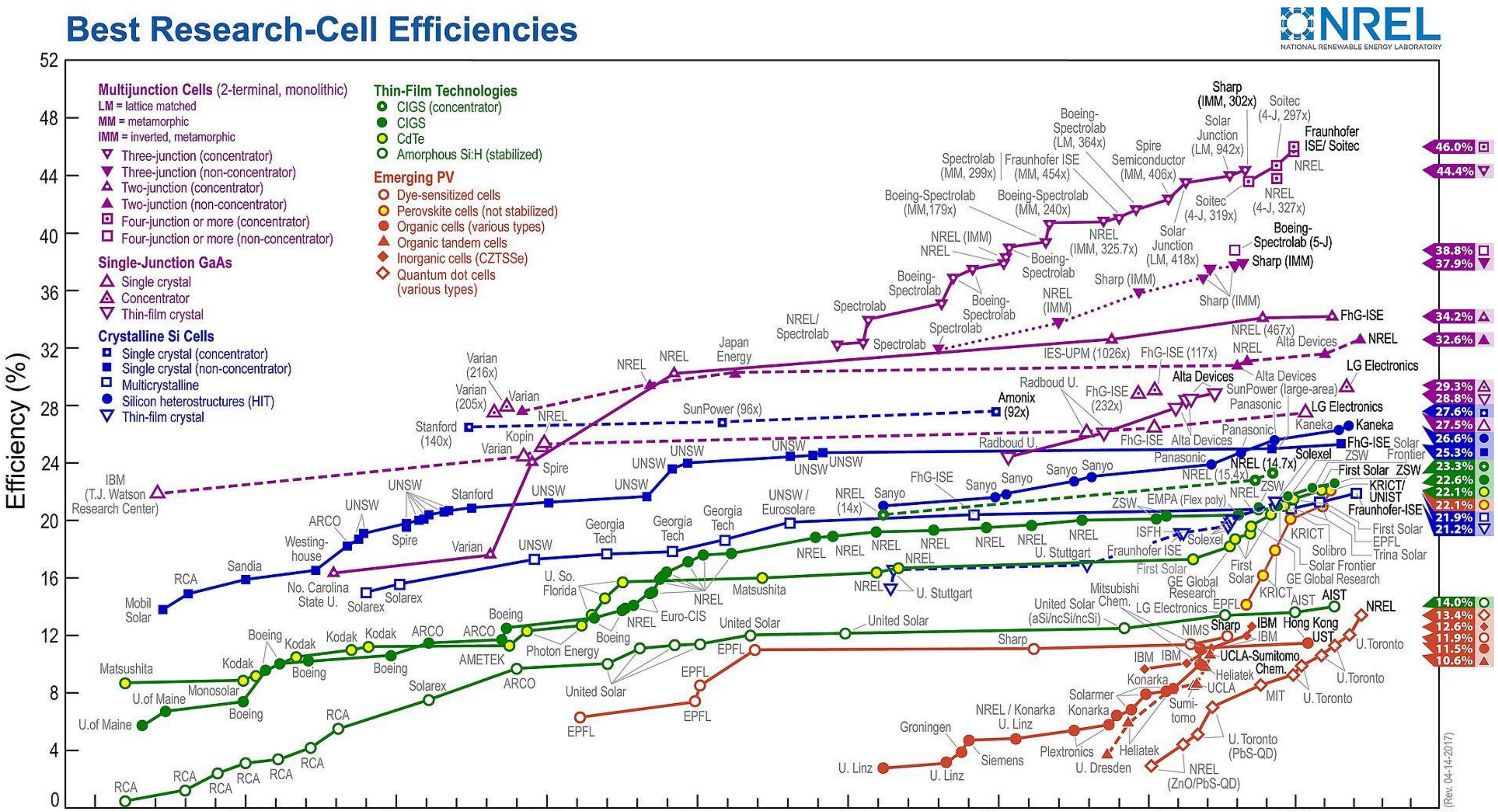


Shockley–Queisser limit for a single junction cell



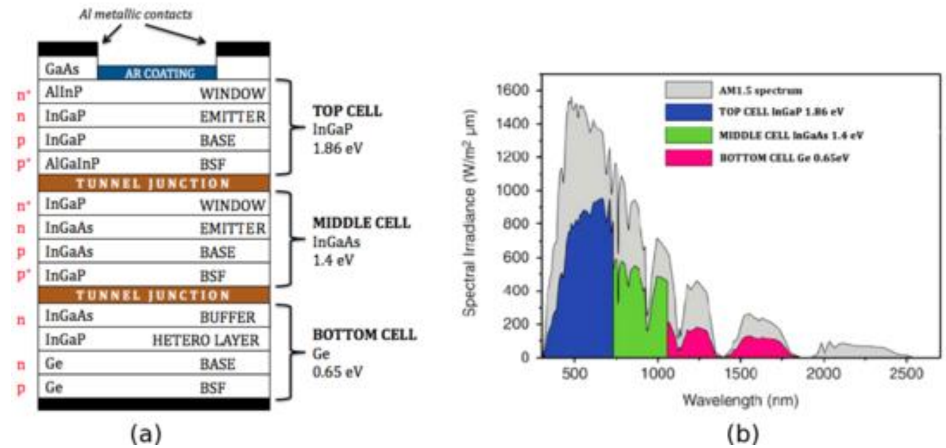
Losses mainly due to
1) photons not absorbed
2) Photons too energetic

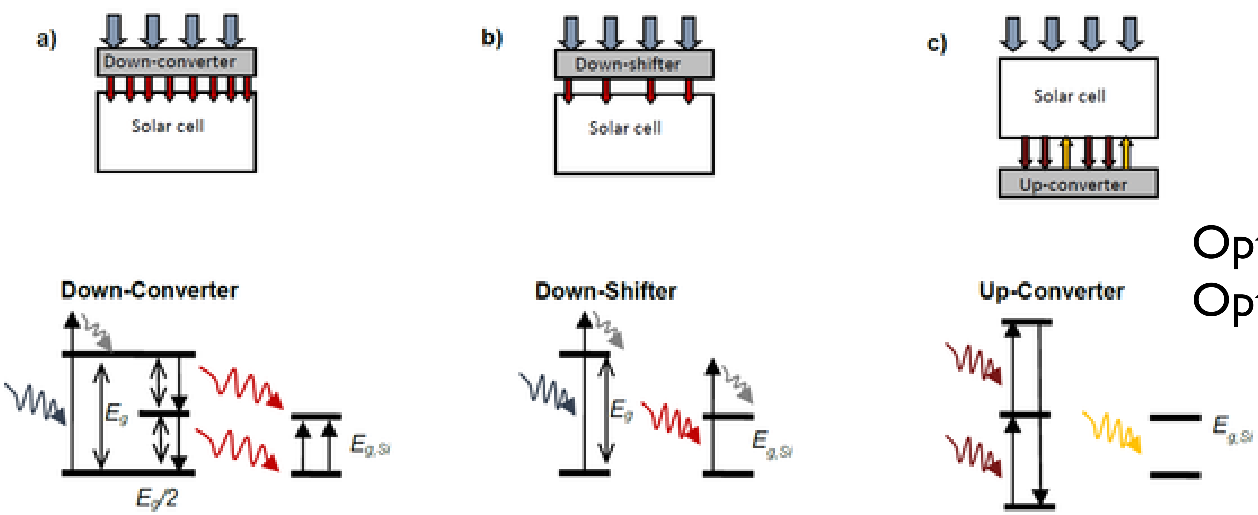
Efficiency of solar cells (II)



Overcoming the SQ limit

Multiple junction cells

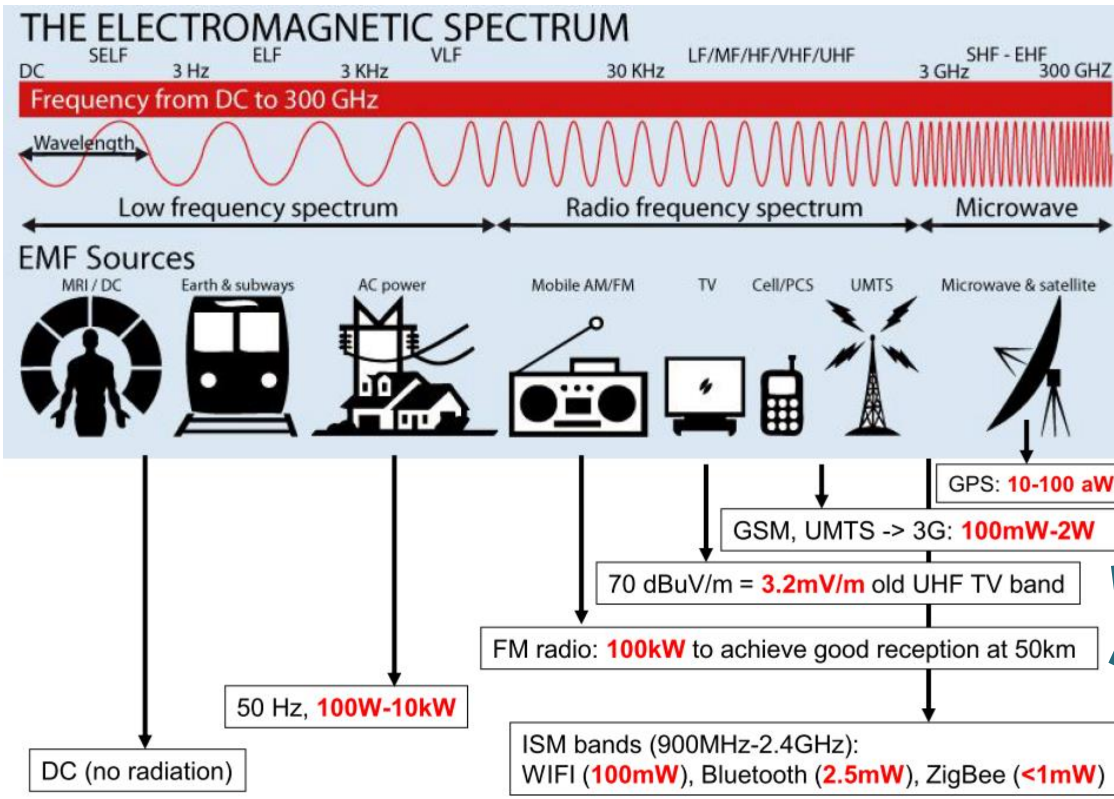




Optical Downconversion

Optical Upconversion

Harvesting of environmental e.m. radiation



Power density

8-160 nW/cm^2
(10 m distance)

1.3 pW/cm^2

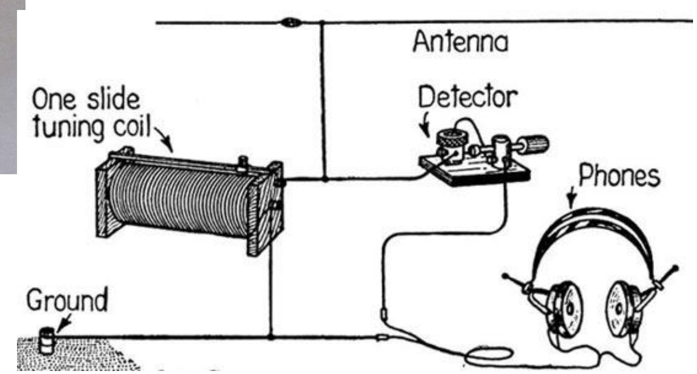
0.3 nW/cm^2
(50 km distance)

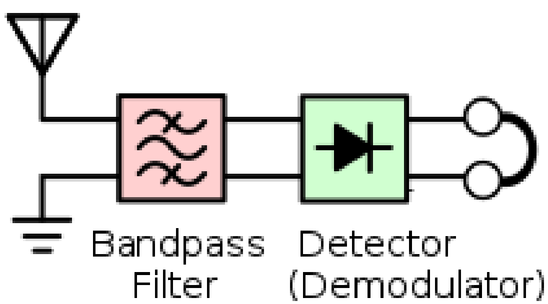
8, 0.2 nW/cm^2 , <80 pW/cm^2
(10 m distance)

Data from Gabriel Abadal Berini «Introduction to energy harvesting from electromagnetic radiation sources" NIPS Summer School 2013

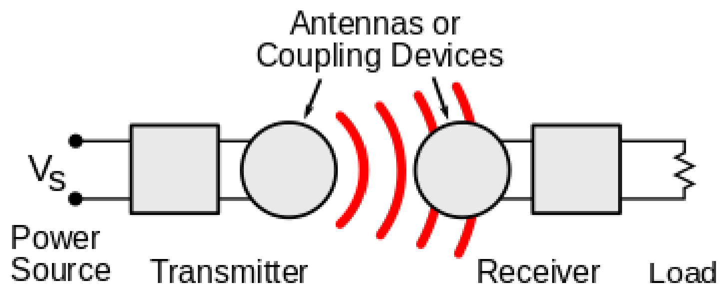
Crystal radio

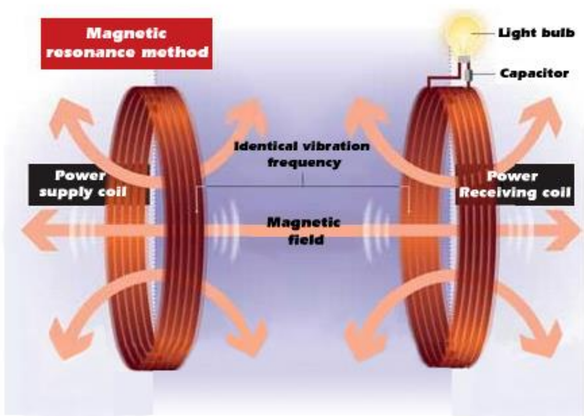
Whether the power you can collect is low or high depends on the device you consider





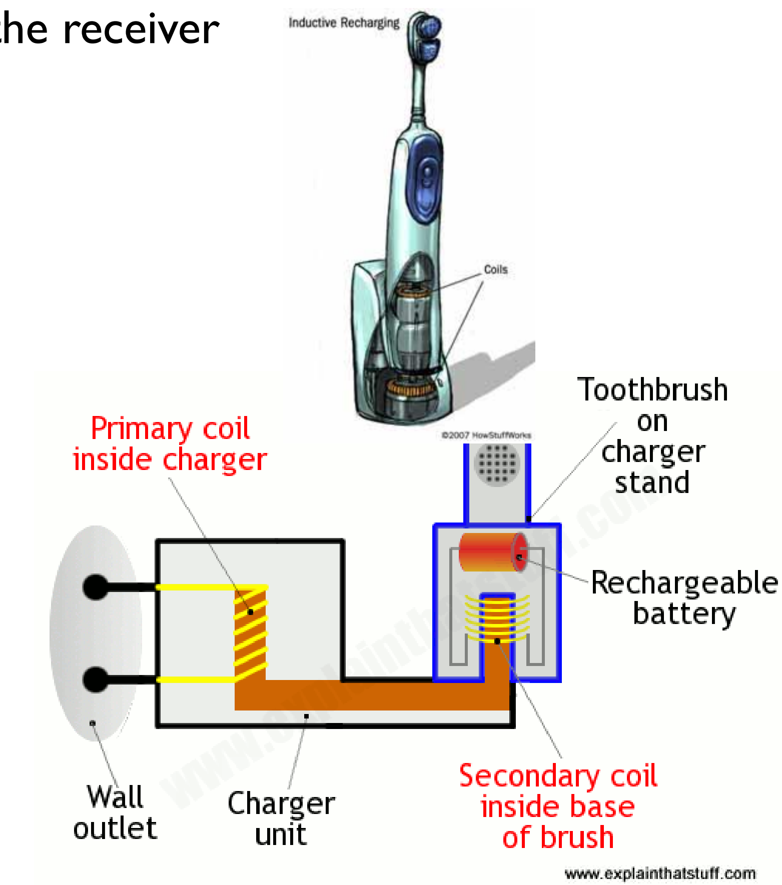
Wireless energy transfer



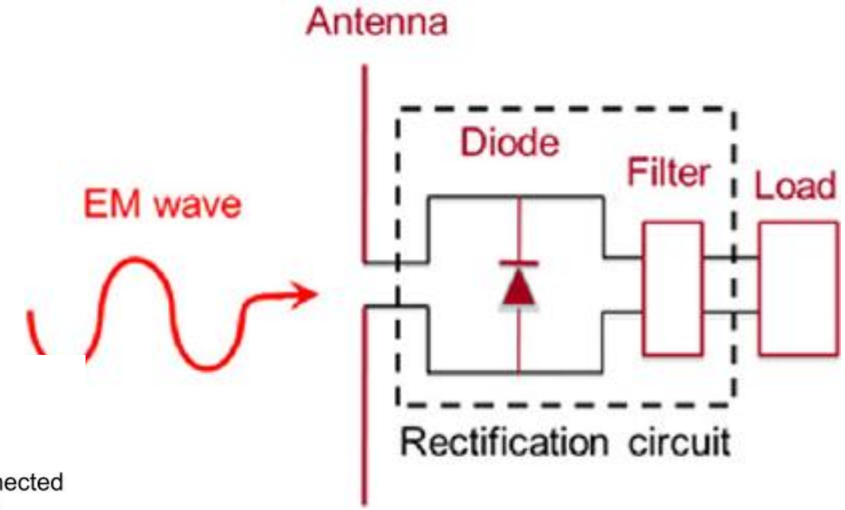


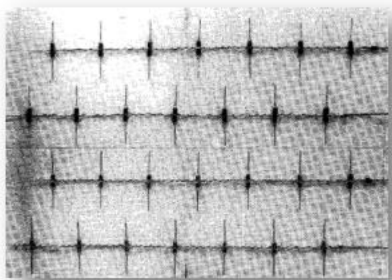
0.9m: 90% efficiency

The radiation is produced in order to power the distant device connected to the receiver



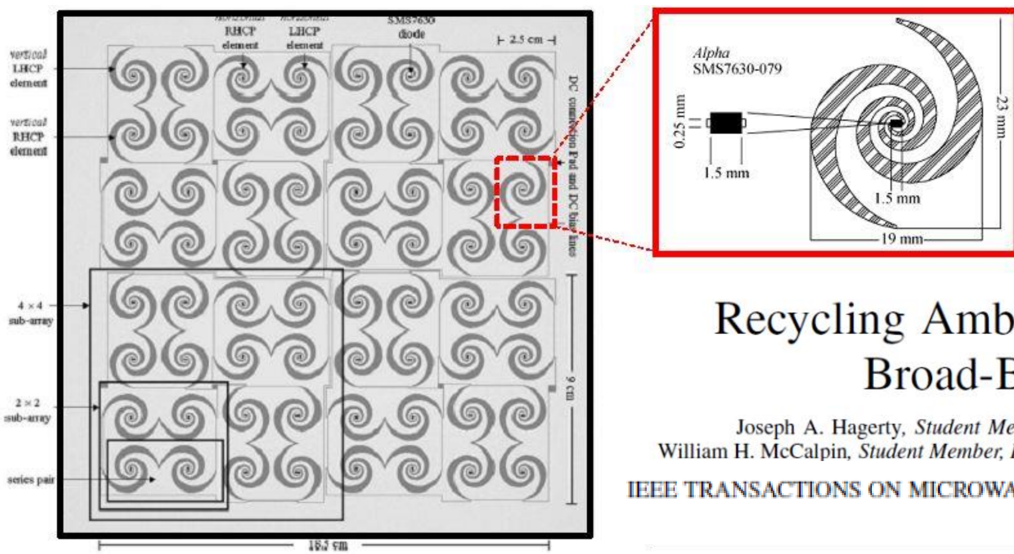
Rectenna





First rectenna (1963):
28 half-wave dipoles connected to bridge rectifiers 1N82G.
7W produced. 40% efficiency

Similar to cat's wisker receiver but it collects the power of the carrier.

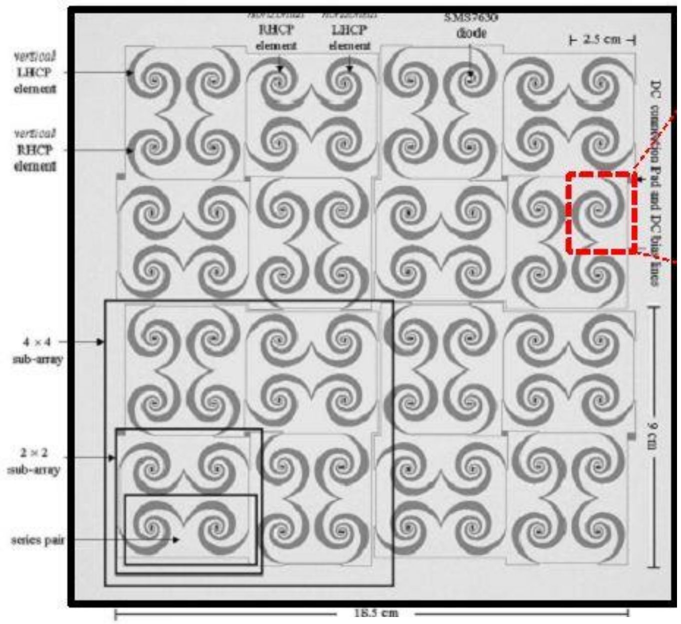


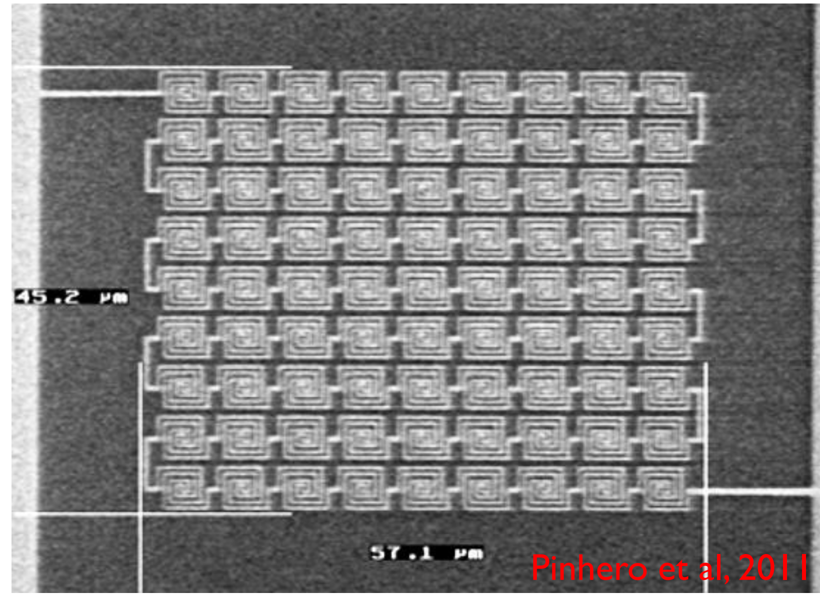
Recycling Ambient Microwave Energy With Broad-Band Rectenna Arrays

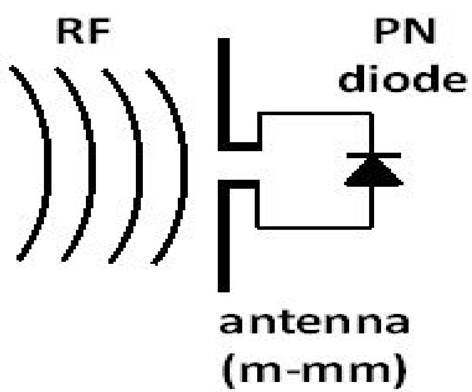
Joseph A. Hagerty, *Student Member, IEEE*, Florian B. Helmbrecht, *Student Member, IEEE*, William H. McCalpin, *Student Member, IEEE*, Regan Zane, *Member, IEEE*, and Zoya B. Popović, *Fellow, IEEE*

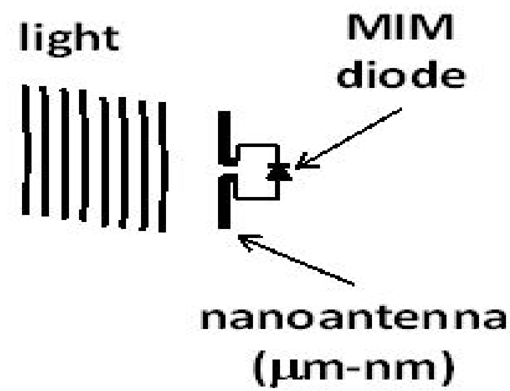
IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 52, NO. 3, MARCH 2004

Sizes



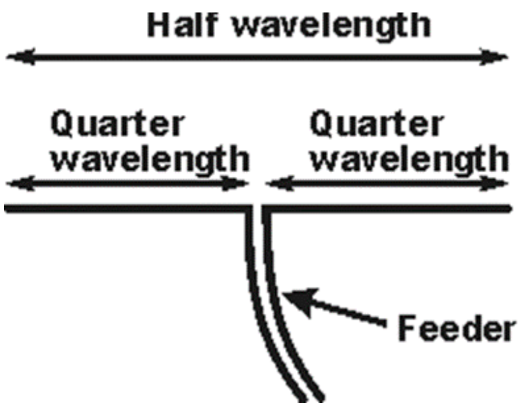




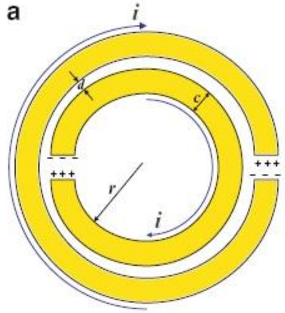


Drawing from Abadal, et al. "Electromagnetic Radiation Energy Harvesting – The Rectenna Based Approach" ICT - Energy - Concepts Towards Zero - Power Information and Communication Technology

RF-Antennas



SRR



DRO

Typical size: λ/2

Exploiting different e.m resonances

- metamaterial – Split Ring Resonator λ/40
- Plasmonic λ/10 - λ/100 (IR or visible)
- Dielectric resonator λ/10

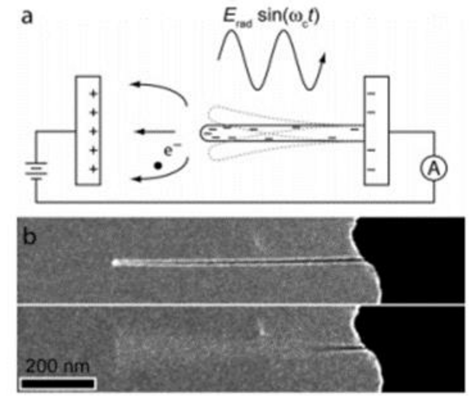
Coupling acoustic to e.m. resonance

$$\omega \approx v/L$$

$$\frac{L_{em}}{L_{ac}} \approx \frac{c}{v_{ac}} \approx 10^4 - 10^5$$

Nanotube Radio

K. Jensen, J. Weldon, H. Garcia, and A. Zettl*



Electromechanical Nanoresonators

Features

- high sensitive (mechanical resonance can be finely monitored)
- wireless (by em waves)
- energy transfer (normal acoustic modes externally stimulated)
- **smaller size**

Conclusions

- Solar energy can be collected and stored by different means
- Photovoltaic cells can collect directly electric energy
- Environmental em radiation can be collected by means of antennas
- Is the energy harvested at microwaves/radio frequency enough to power devices?