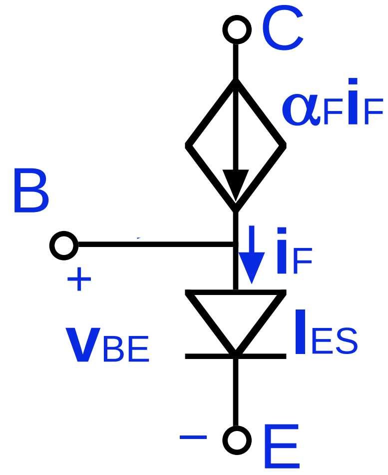
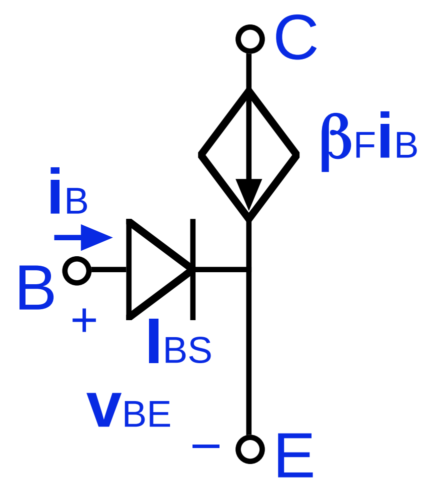
6.012 - Microelectronic Devices and Circuits

Lecture 8 - BJTs Wrap-up, Solar Cells, LEDs - Outline

- **Announcements**
  - **Exam One -** Tomorrow, Wednesday, October 7, 7:30 pm
- **BJT Review**
  - **Wrapping up BJTs** (for now)
  - **History -** 1948 to Today
- **p-n Diode review**
  - **Reverse biased junctions -** photodiodes and solar cells
    - **In the dark:** no minority carriers, no current
    - **With illumination:** superposition, $i_D(v_{AB}, L)$; photodiodes
    - **The fourth quadrant:** optical-to-electrical conversion; solar cells
    - **Video:** *"Solar cell electricity is better electricity - putting 6.012 to work improving our world (a true story)"*
  - **Forward biased junctions -** light emitting diodes, diode lasers
    - **Video:** *"The LEDs Around Us"*
    - **Diode design for efficient light emission:** materials, structure
    - **The LED renaissance:** **red, amber, yellow, green, blue, white**

BJT Modeling: FAR models/characteristics





$$\alpha_F \equiv -\frac{i_C}{i_E} = \frac{(1-\delta_B)}{(1+\delta_E)} \approx \frac{1}{(1+\delta_E)}$$

$$\beta_F \equiv \frac{i_C}{i_B} = \frac{(1-\delta_B)}{(\delta_E+\delta_B)} \approx \frac{1}{\delta_E}$$

Defects

$$\delta_E = \frac{D_h}{D_e} \cdot \frac{N_{AB}}{N_{DE}} \cdot \frac{w_{B,eff}}{w_{E,eff}} \qquad \delta_B \approx \frac{w_{B,eff}^2}{2L_{eB}^2}$$

Design

Doping : npn with $N_{\mathrm{DE}} >> N_{AB}$

$w_{B,eff}$: very small

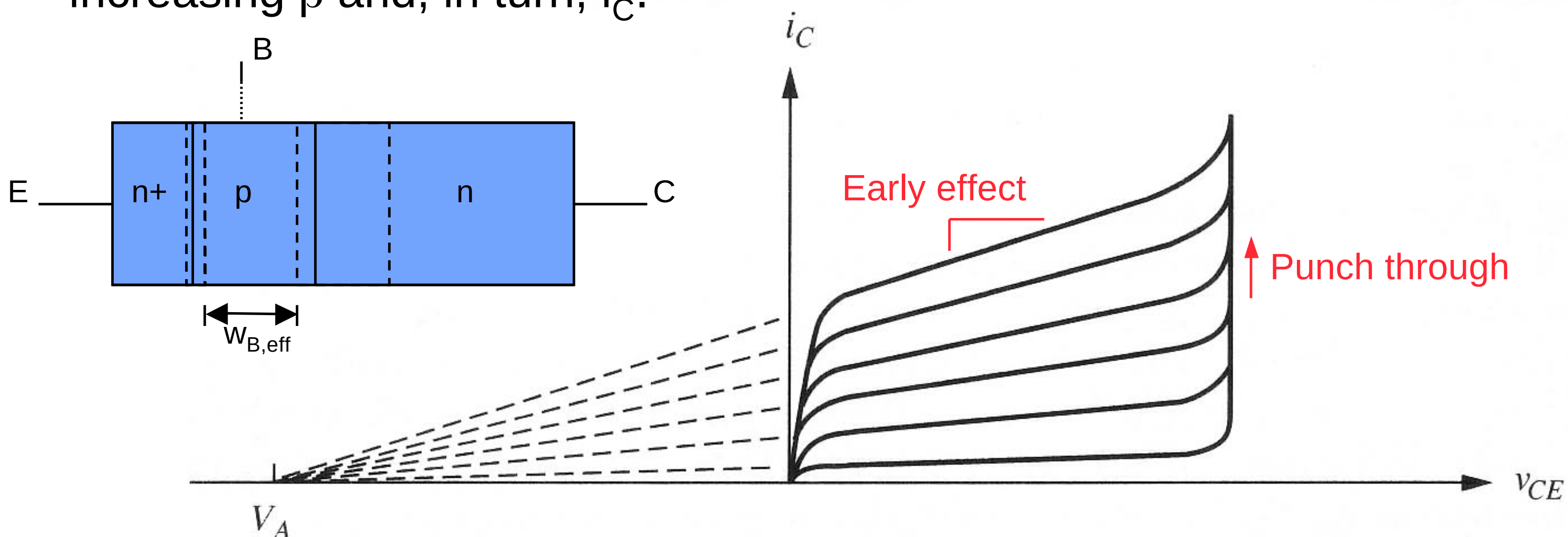
L_{eB} : very large and $>> w_{B,eff}$

BJT's, cont.: What about the collector doping, N_{DC}?

An effect we didn't put into our large signal model

- **Base width modulation -** the Early effect and Early voltage:

  The width of the depletion region at the B-C junction increases as v_{CE} increases and the effective base width, $w_{B,eff}$, gets smaller, thereby increasing β and, in turn, i_C.



To minimize the Early effect we make $N_{DC} < N_{AB}$

- We will take this effect into account in our small signal LEC modeling.

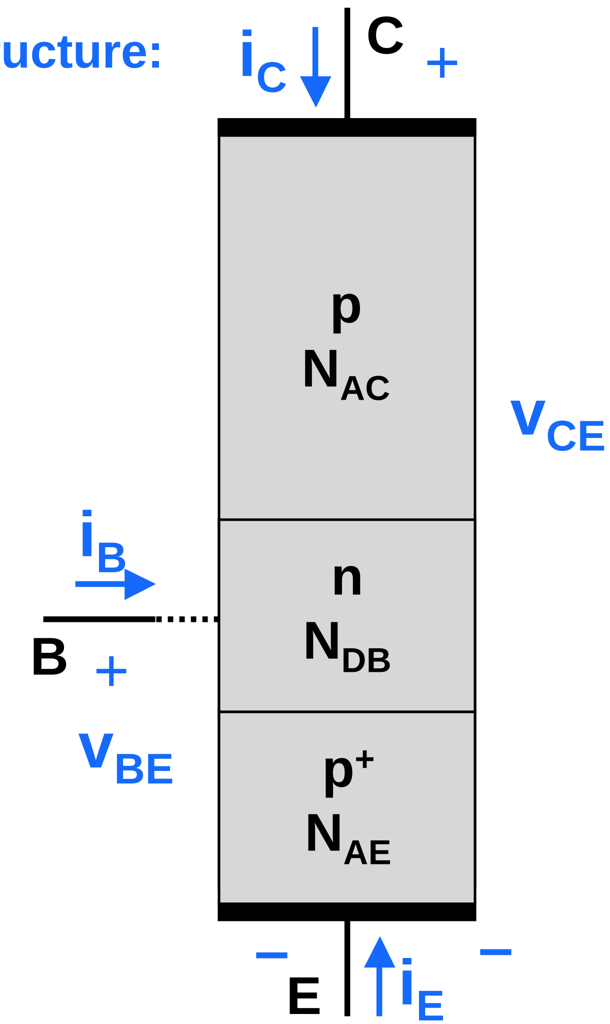
- **Punch through -** base width modulation taken to the limit

  When the depletion region at the B-C junction extends all the way through the base to the emitter, I_C increases uncontrolably. Punch through has a similar effect on the characteristics to that of reverse breakdown of the B-C junction.

pnp BJT's: The other "flavor" of bipolar junction transistor

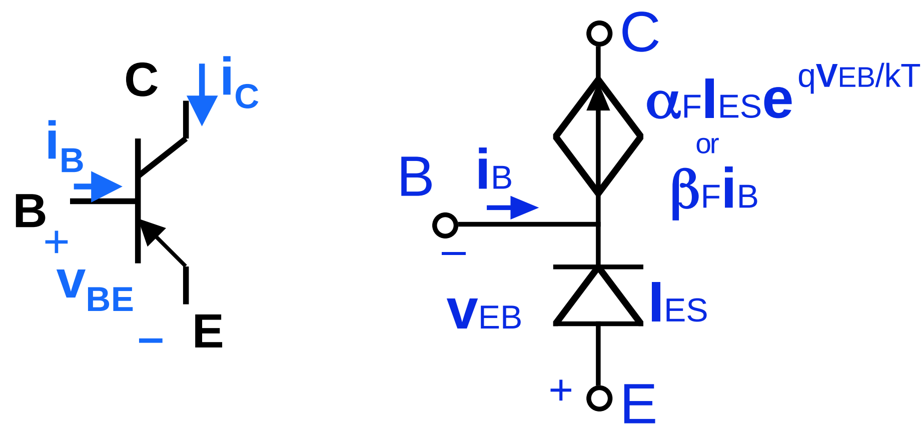
pnp

Structure:

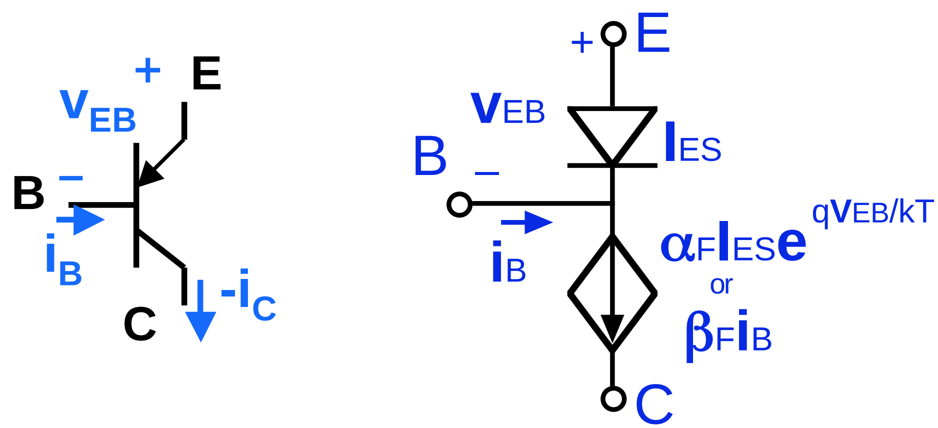


Symbol and FAR model:

Oriented with emitter down like npn:



Oriented as found in circuits:



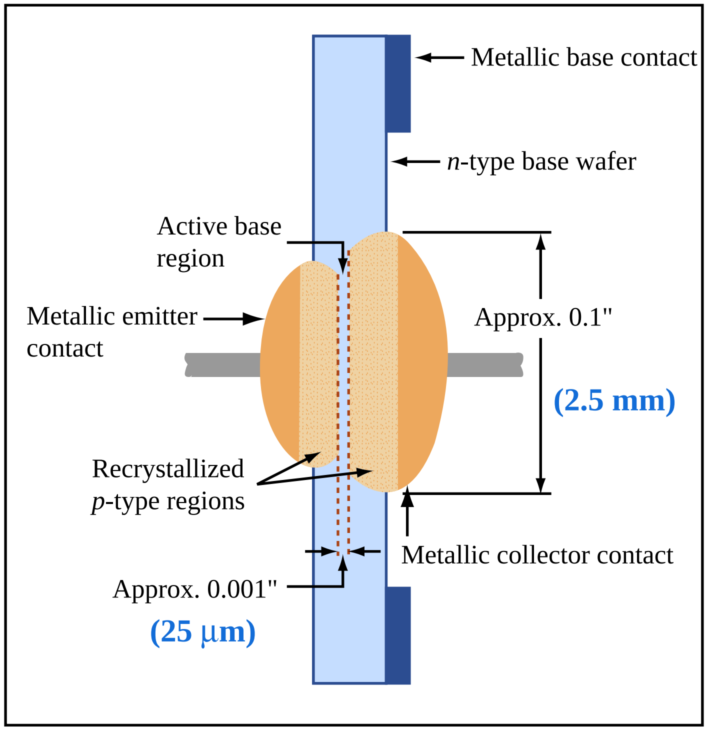


Figure by MIT OpenCourseWare.

Alloy junction BJT - Early1950's

Early Bipolar Junction Transistors

- the first 10 yrs.

Photograph of grown junction BJT (showing device width of 5 mm) removed due to copyright restrictions.

Grown junction BJT - mid-1950's

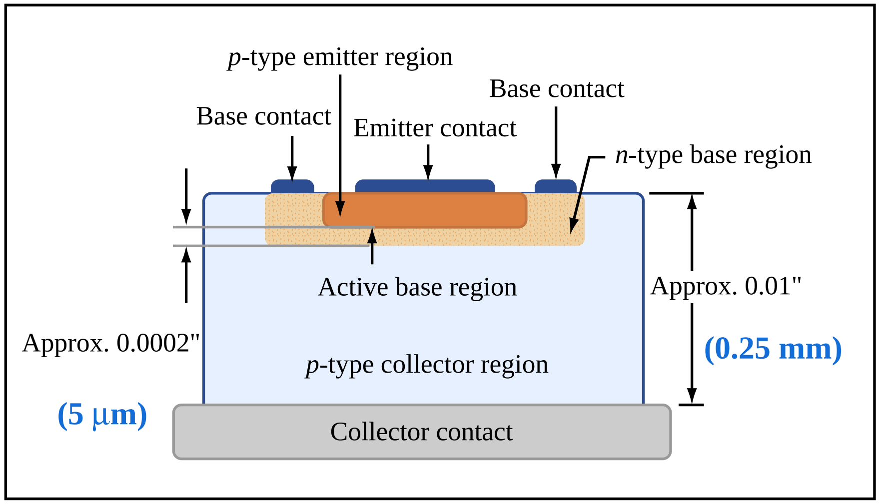
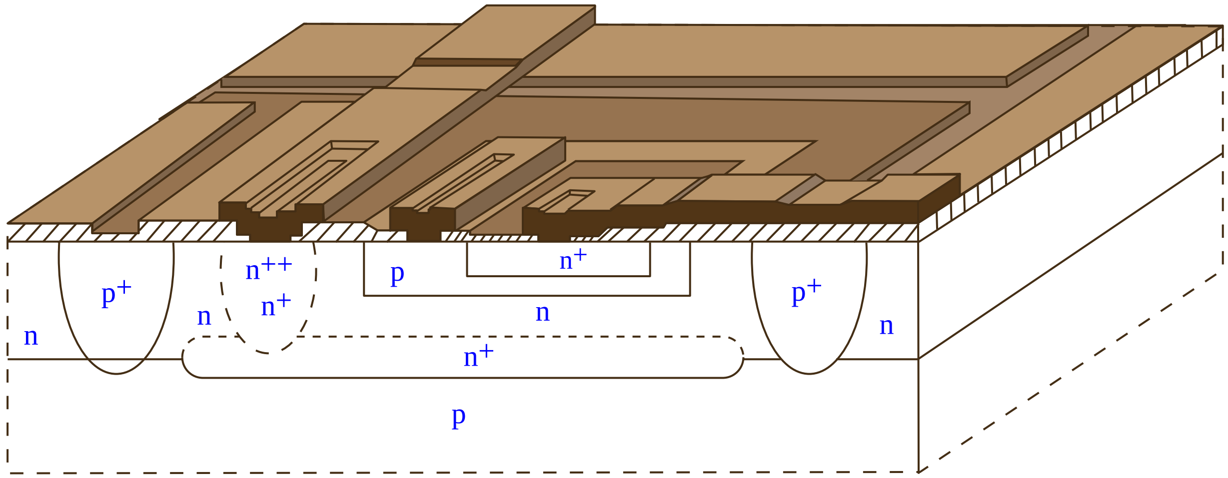


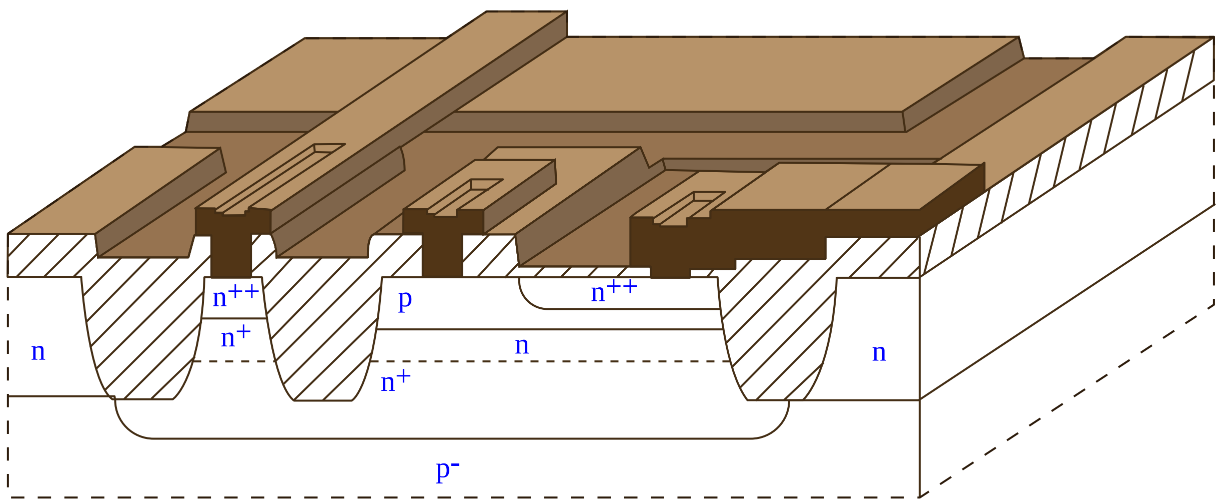
Figure by MIT OpenCourseWare.

Diffused junction BJT - late-1950's

Integrated Bipolar Junction Transistors
- integrated circuit processes.



Junction isolated integrated BJT - 1960's onwards

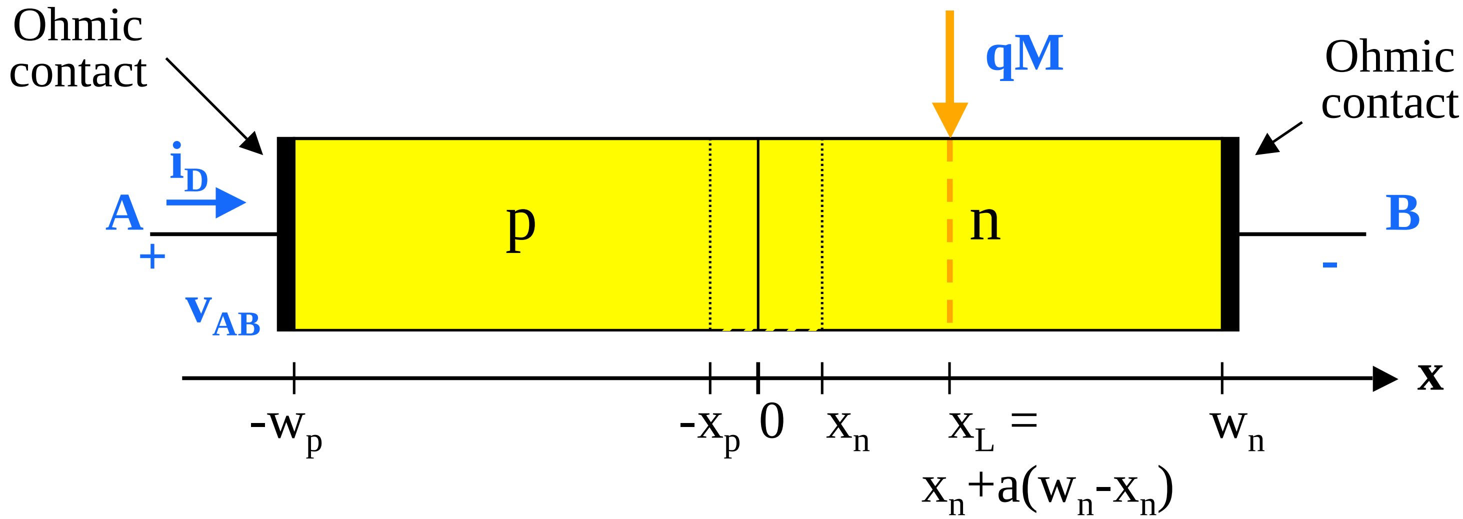


Oxide isolated integrated BJT - a modern process

Figure by MIT OpenCourseWare.

Photodiodes - *illuminated p-n junction diodes*

Consider a p-n diode illuminated at $x = x_n + a(w_n - x_n)$, $0 \leq a \leq 1$.



What is $i_D(v_{AB}, M)$? Use superposition to find the answer:

$$i_D(v_{AB}, M) = i_D(v_{AB}, 0) + i_D(0, M)$$

We know $i_D(v_{AB},0)$ already…

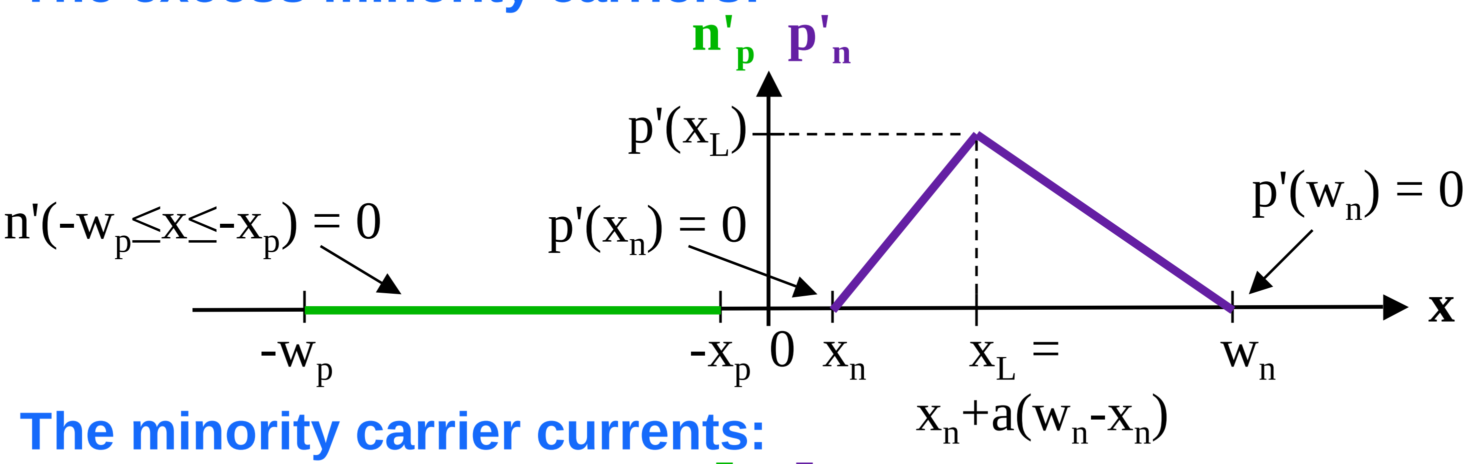
$$i_D(v_{AB}, 0) = I_S(e^{qv_{AB}/kT} - 1)$$

The question is, "What is $i_D(0,M)$."

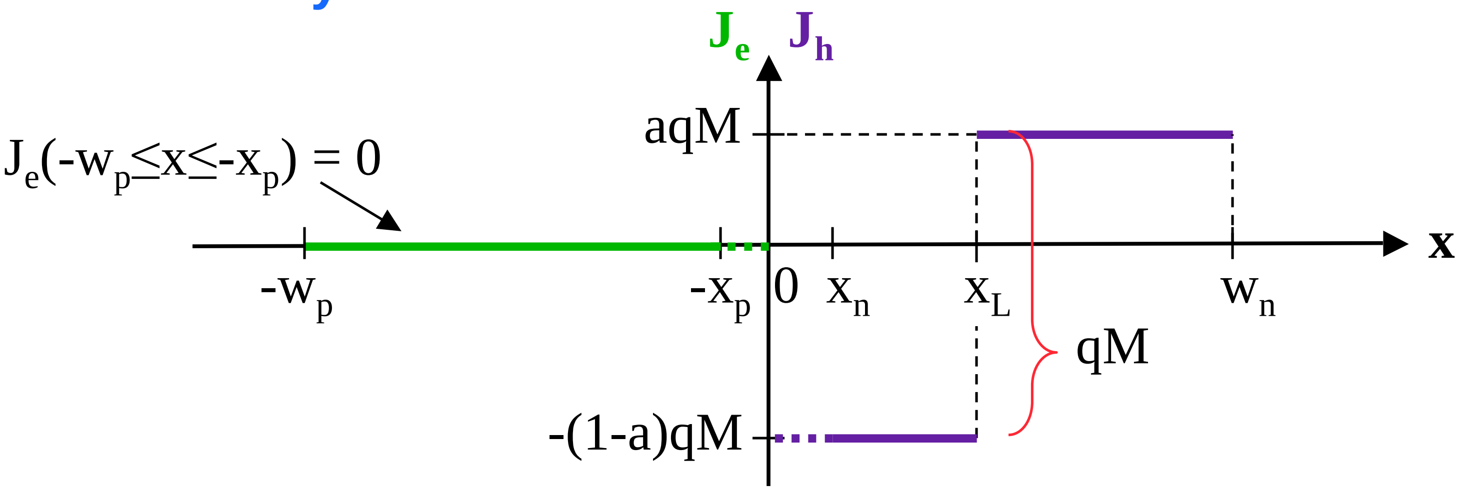
$$i_D(0, M) = ?$$

Photodiodes - cont.: *the photocurrent, $i_D(0,M)$*

The excess minority carriers:



The minority carrier currents:



The photocurrent, $i_D(0,M)$:

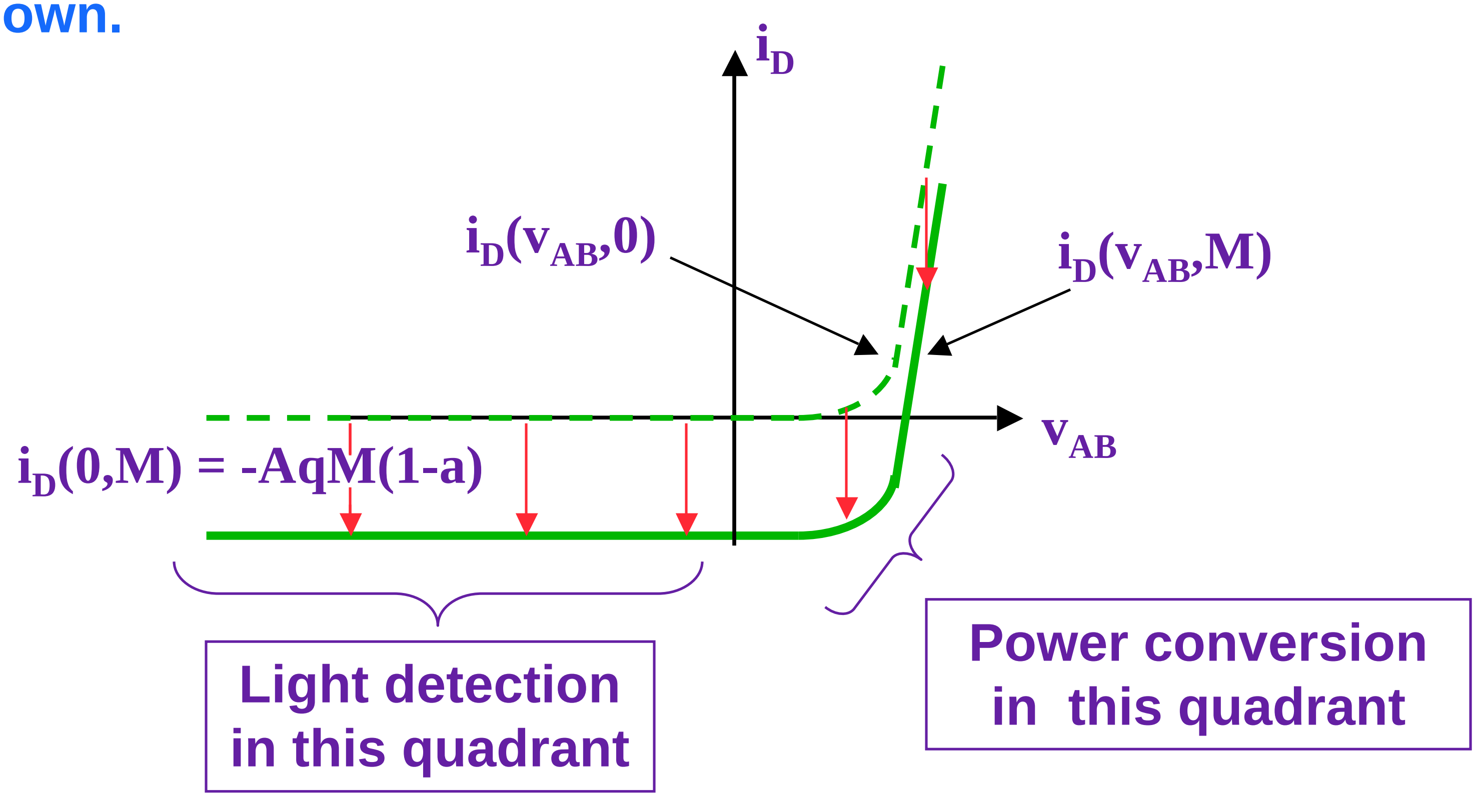
$$i_D(0,M) = -AqM(1-a)$$

Photodiodes - cont.: *The i-v characteristic and what it means.*

The total current: $i_D(v_{AB}, M) = i_D(v_{AB}, 0) + i_D(0, M)$

$$= I_S\left(e^{qv_{AB}/kT} - 1\right) - AqM\left(1 - a\right)$$

The illumination shifts the ideal diode curve vertically down.



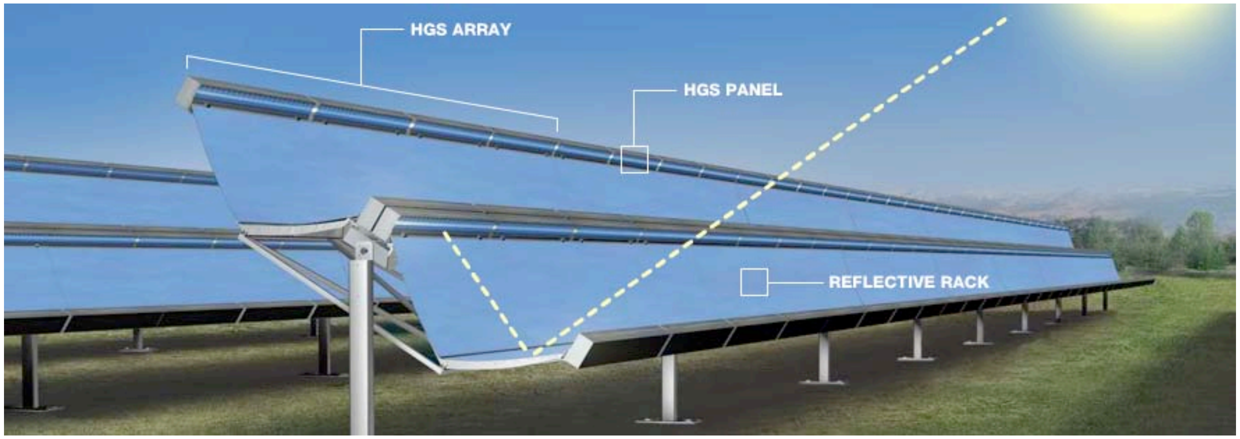
Photovoltaic Energy Conversion: *Solar cells and TPV, cont.*

Efficiency issues:
1. $h\nu : E_g$ mismatch
2. V_{oc} and fill factor
3. Intensity (concentrator) effect

1. $$h\nu \begin{cases} < E_g & \text{not absorbed; energy lost} \\ > E_g & \text{excess energy, } (h\nu - E_g)\text{, lost} \end{cases}$$

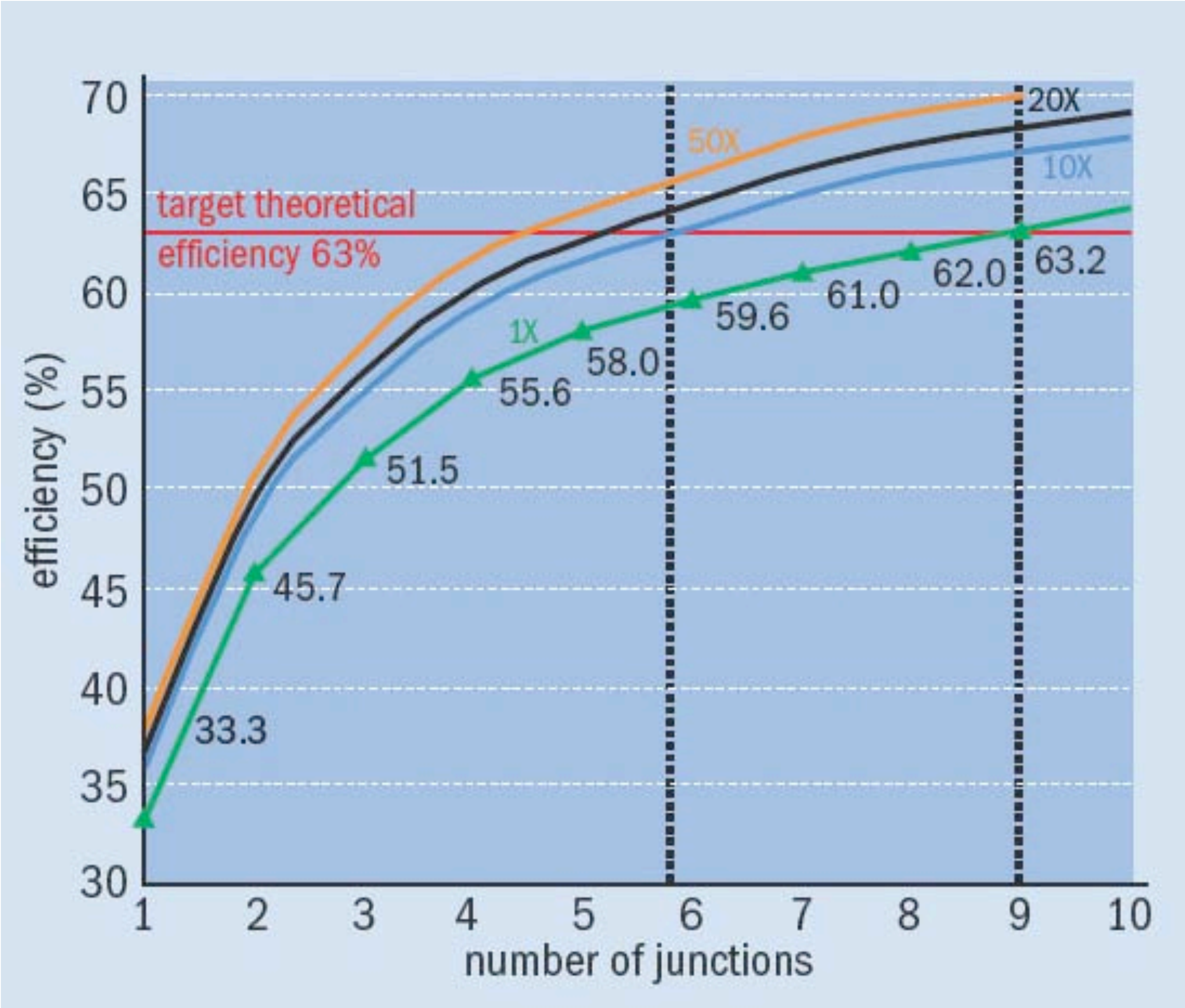
2. $$v_{OC} = \frac{kT}{q} \ln\left(\frac{q\eta_i L}{I_S}\right) \qquad P_{out\,\max} < -i_{SC} v_{OC} = \eta_i L \cdot kT \ln\left(\frac{q\eta_i L}{I_S}\right)$$

3. $$L \uparrow \Rightarrow \eta \uparrow$$



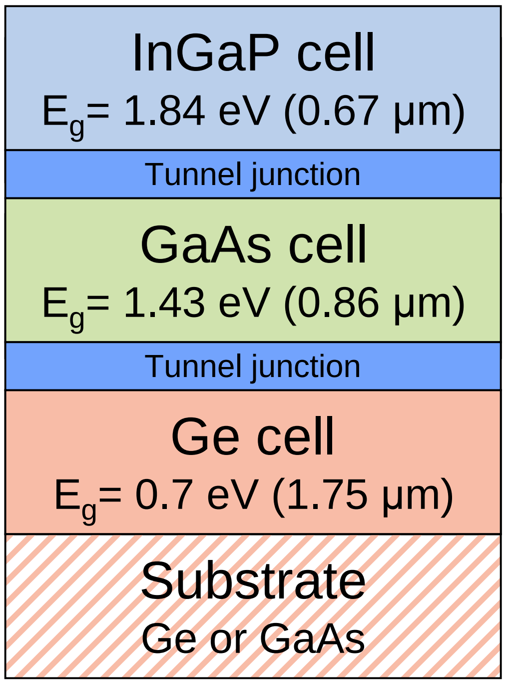
Skyline Solar parabolic reflector/concentrator multi-junction cell installation photo-illustration from website.

Multi-junction cells - efficiency improvement with number



"Photovoltaics take a load off soldiers," Oct. 27, 2006, online at:
http://www.solar.udel.edu/CSOctSOL-Darpa-reprint.pdf

Multi-junction cells, cont. - 2 designs

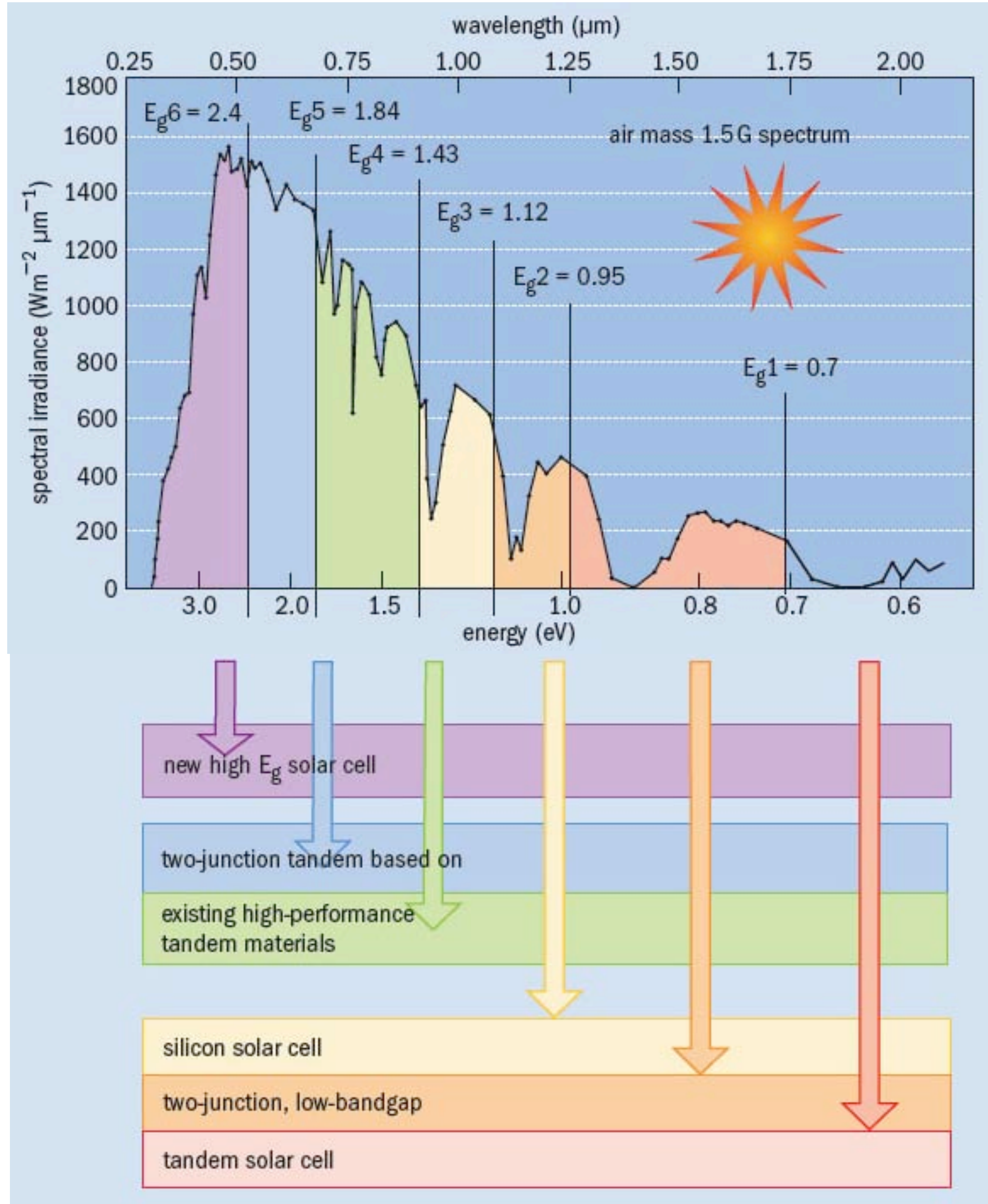


A 3 -junction design

(3 lattice-matched cells connected in series by tunnel diodes)

A 6 -junction design*

(3-tandem multi-junction cells set side-by-side)

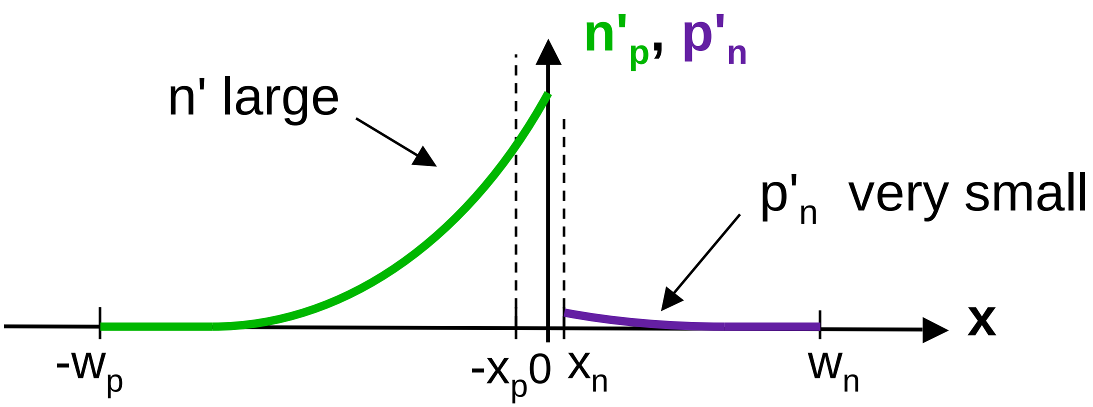


* "Photovoltaics take a load off soldiers," Oct. 27, 2006, online at: http://www.solar.udel.edu/CSOctSOL-Darpa-reprint.pdf

<u>Light emitting diodes</u>: what they are all about

The basic idea

In Si p-n diodes and BJTs we make heavy use of the very long minority carrier lifetimes in silicon, but in LEDs we want all the excess carriers to recombination, and to do so creating a photon of light. We want asymmetrical long-base operation:



Why have people cared so much about LEDs?

a cool, efficient source of light
rugged with extremely long lifetimes
can be turned on and off very quickly,
and modulated at very high data rates

<u>Light emitting diodes</u> - typical spectra

- LED emission - typ. 20 nm wide

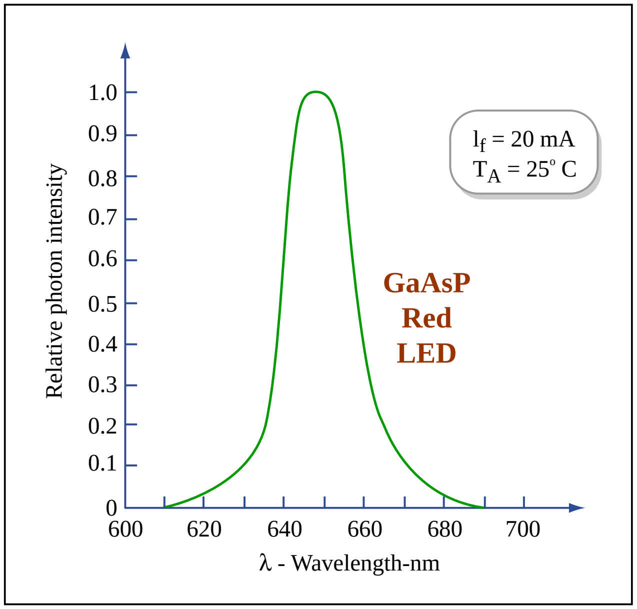


Figure by MIT OpenCourseWare.

GaAsP Red LED

- Important spectra to compare with LED emission spectra

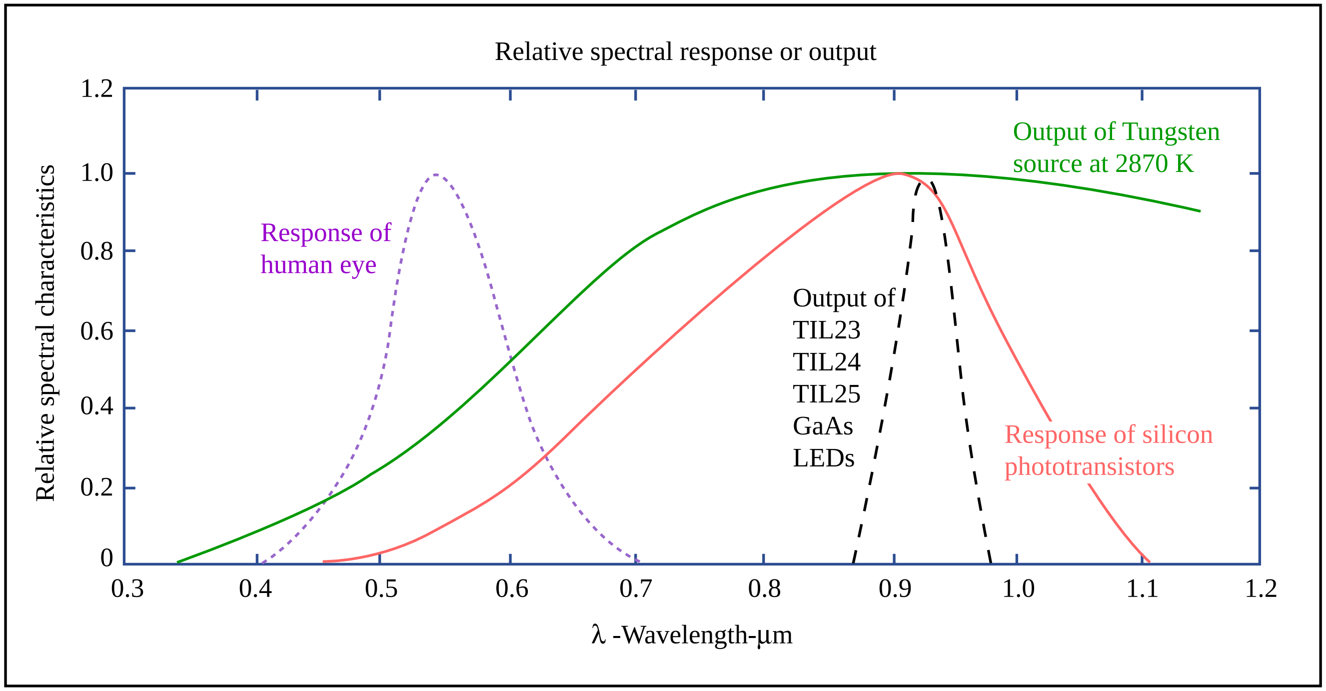


Figure by MIT OpenCourseWare.

Light emitting diodes: historical perspective

LEDs are a very old device, and were the first commercial compound semiconductor devices in the marketplace. Red, amber, and green LEDs (but not blue) were sold in the 1960's, but the main opto research focus was on laser diodes; little LED research in universities was done for many years.

Then…things changed dramatically in the mid-1990's:

In part because of new materials developed for red and blue lasers
(AlInGaP/GaAs, GaInAlN/GaN)

In part because of packaging innovations
(Improved heat sinking and advanced reflector designs)

In part due to advances in wafer bonding
(Transparent substrates for improved light extraction)

In part due to the diligence of LED researchers
(Taking advantage of advances in other fields)

Light emitting diodes - design issues

Significant challenges in making LEDs include:

1. **Choosing the right semiconductor(s)**
   - efficient radiative recombination of excess carriers
   - emission at the right wavelength (color)

2. **Getting the light out of the semiconductor**
   - overcoming total internal reflection and reabsorption

3. **Packaging the diode**
   - good light extraction and beam shaping
   - good heat sinking (for high intensity applications)

Compound Semiconductors:

Diamond lattice (Si, Ge, C [diamond])

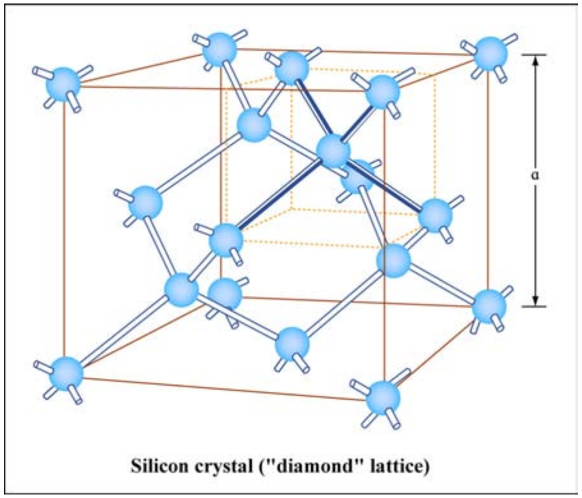


Figure by MIT OpenCourseWare.

Zinc blende lattice (GaAs shown)

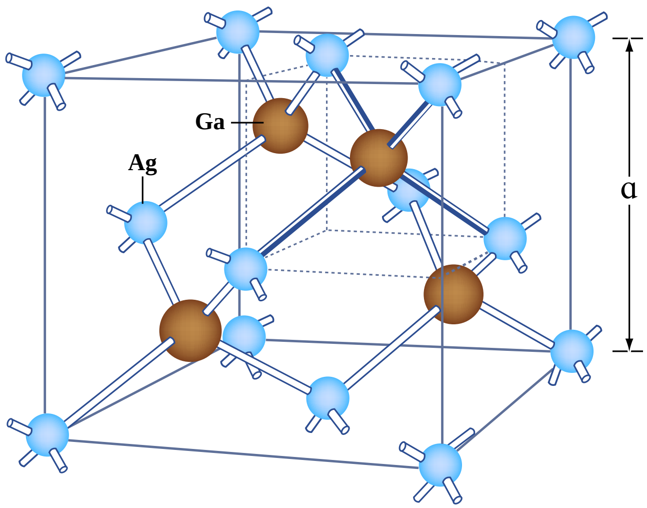


Figure by MIT OpenCourseWare.

A wide variety of bandgaps.
The majority are "direct gap"
must for efficient optical emission).

II	III	IV	V	VI
	B 5	C 6	N 7	O 8
	Al 13	Si 14	P 15	S 16
Zn 30	Ga 31	Ge 32	As 33	Se 34
Cd 48	In 49	Sn 50	Sb 51	Te 52
Hg 80	Tl 81	Pb 82	Bi 83	Po 84

Materials for Red LEDs: GaAsP and AlInGaP

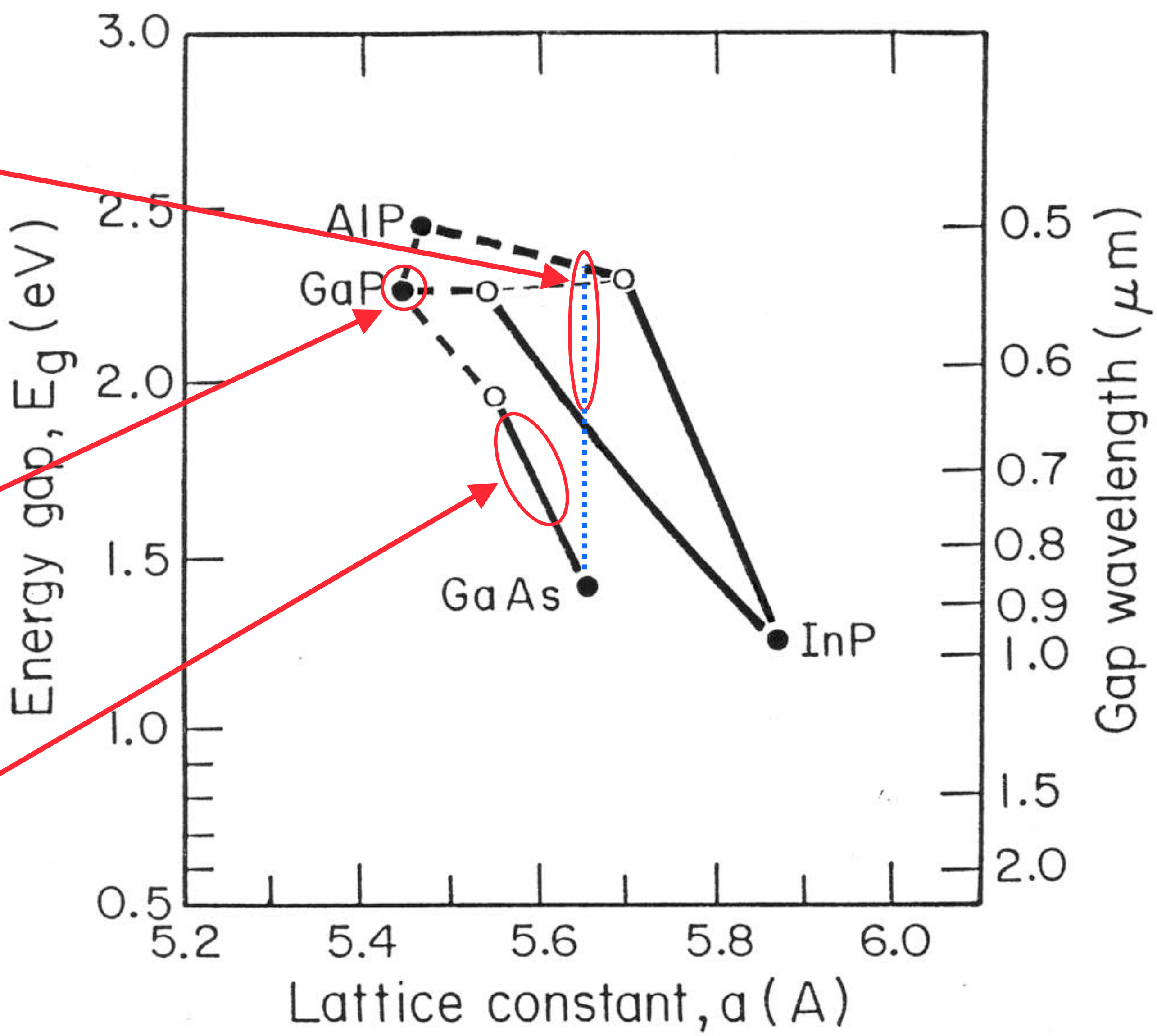
Modern AlInGaP red LEDs grown lattice-matched on GaAs, and then transferred to GaP substrates

- Kish, et al, APL 64 (1994) 2838.

GaP red LEDs grown GaP and based on Zn-O pair transitions

Early GaAsP red LEDs grown on a linearly graded buffer on GaAs

- Holonyak and Bevacqua, APL 1 (1962) 82.



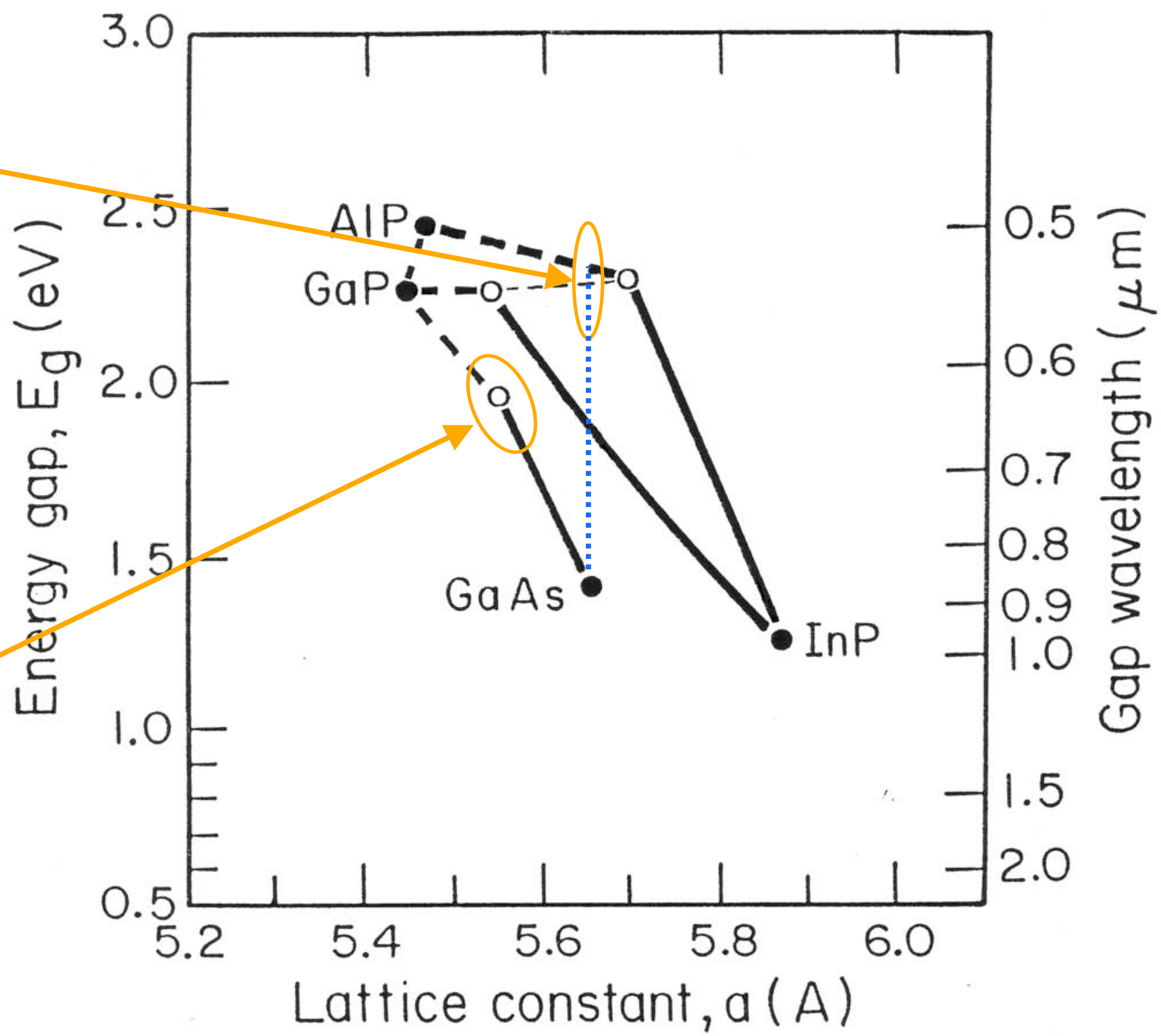
Materials for Amber LEDs: GaAsP, AlInGaP, and GaP

Modern AlInGaP amber LEDs grown lattice-matched on GaAs, and then transferred to GaP substrates

- Kish, et al, APL 64 (1994) 2838.

Early GaAsP amber LEDs grown on a linearly graded buffer on GaAs

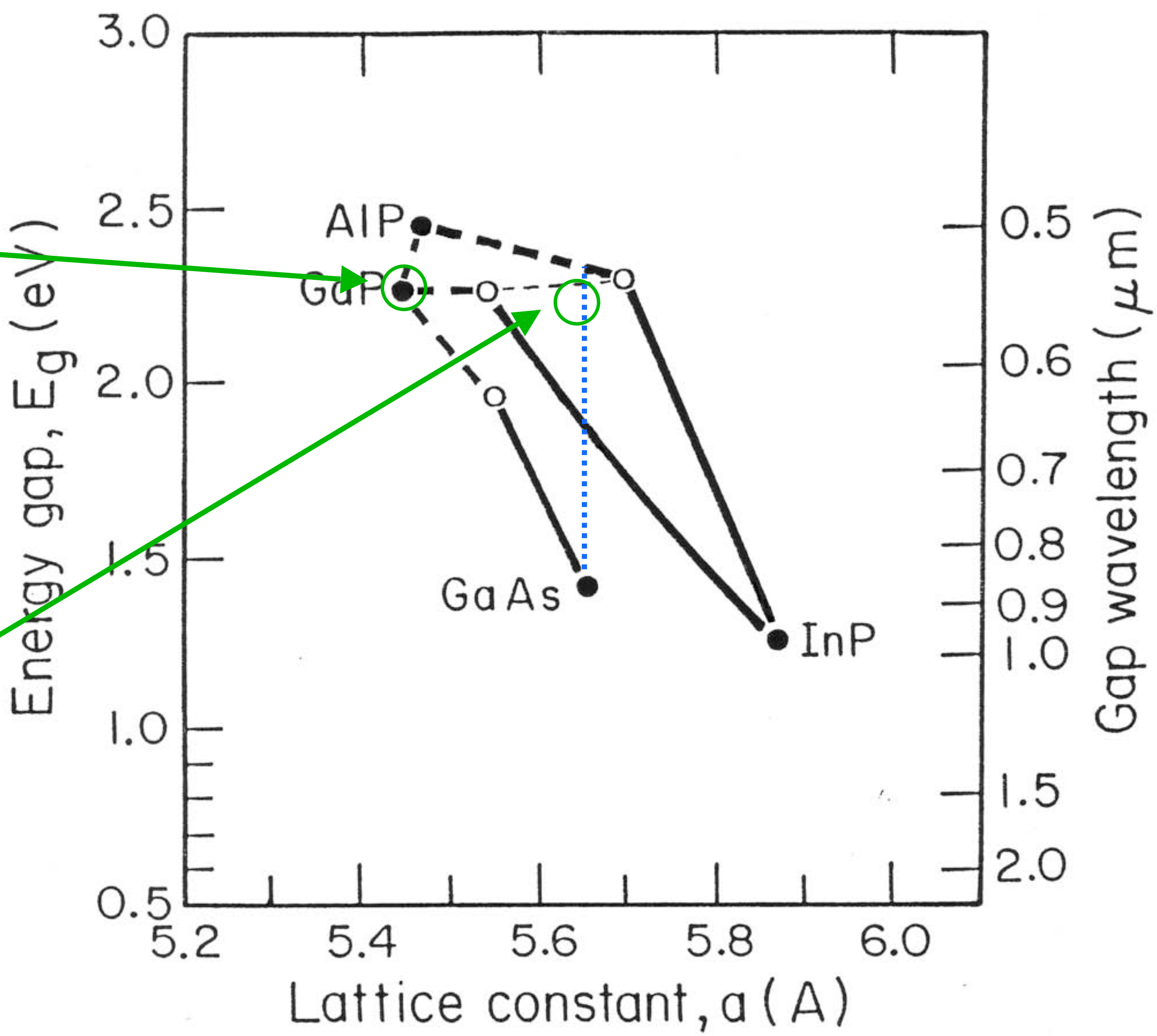
- Holonyak and Bevacqua, APL 1 (1962) 82.



Materials for Green LEDs: GaP, InGaAlP

The first green LEDs were GaP grown by liquid phase epitaxy on GaP substrates and based on N doping. N is an "isoelectronic" donor, with a very small E_d.

InGaAlP grown by MOCVD on GaAs substrates provide modern high brightness LEDs



A material covering the spectrum:

The III-V wurtzite quarternary: GaInAlN

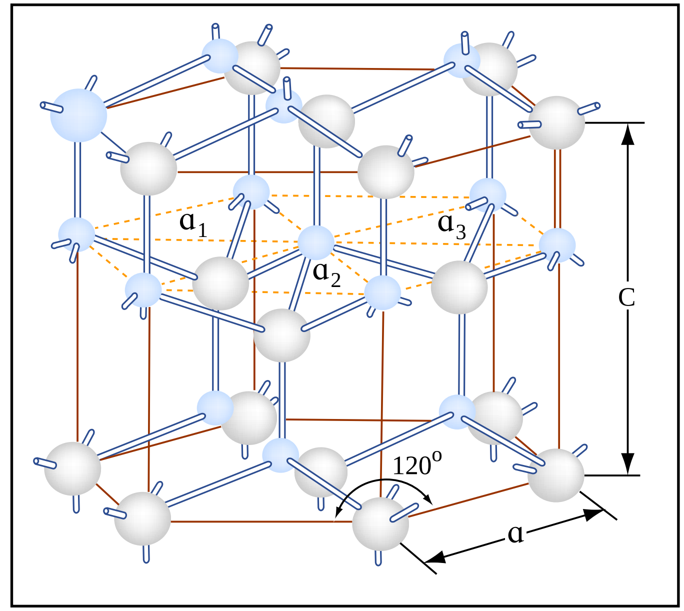


Figure by MIT OpenCourseWare.

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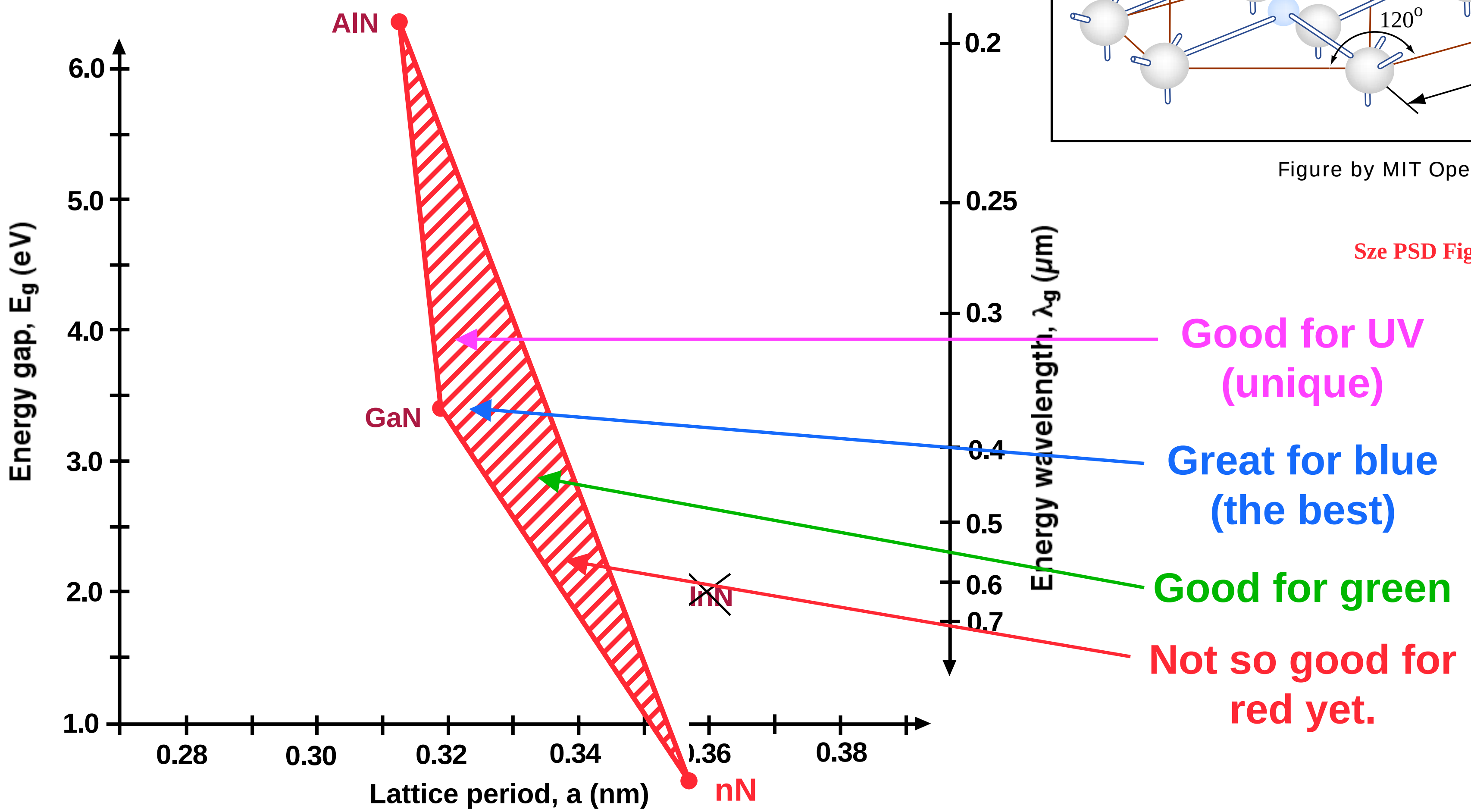
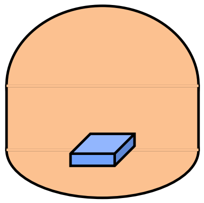


Light emitting diodes: fighting total internal reflection

With an index of refraction ≈ 3.5, the angle for total internal reflection is only 16°.* (Only 2% gets out the top!**)

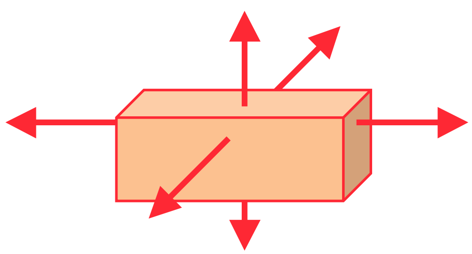
Total internal reflection can be alleviated somewhat if the device is packaged in a domed shaped, high index plastic package:



(With n_{dome} = 2.2, 10% gets out the top!**)

If the device is fabricated with a substrate that is transparent to the emitted radiation, then light can be extracted from the 4 sides and bottom of the device, as well as the top.

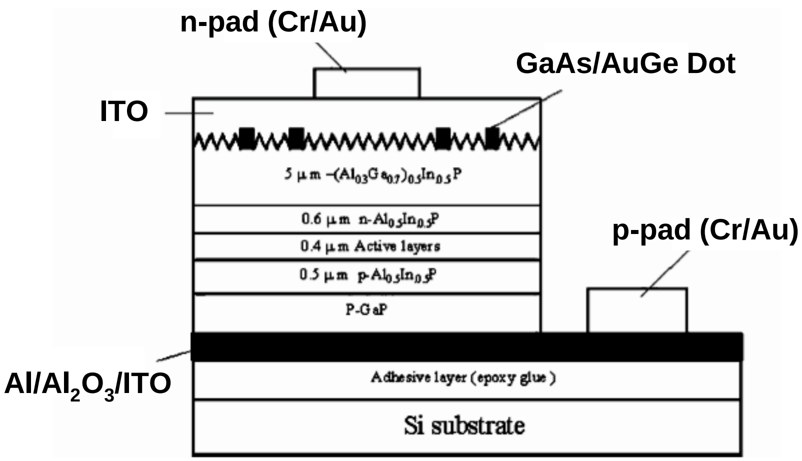
Increases the extraction efficiency by a factor of 6!

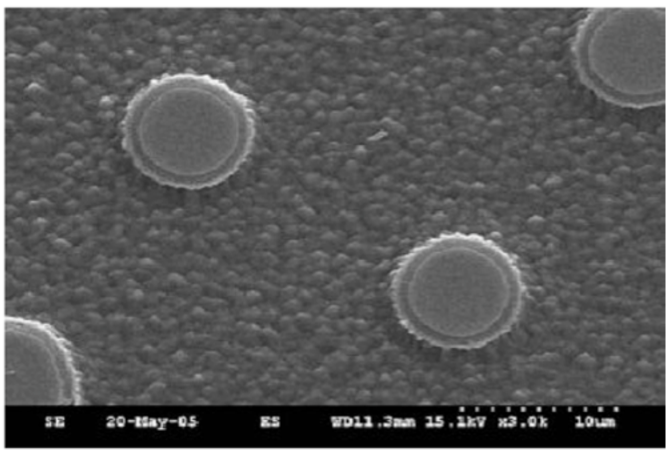


* Critical angle, $\theta_c = \sin^{-1}(n_{out}/n_{in})$, ** Fraction ≈ $(\sin\theta_c)^2/4 = (n_{out}/2n_{in})^2$

<u>Light emitting diodes</u>: the latest wrinkles

Surface texturing, Super-thin (~ 5 μm) devices





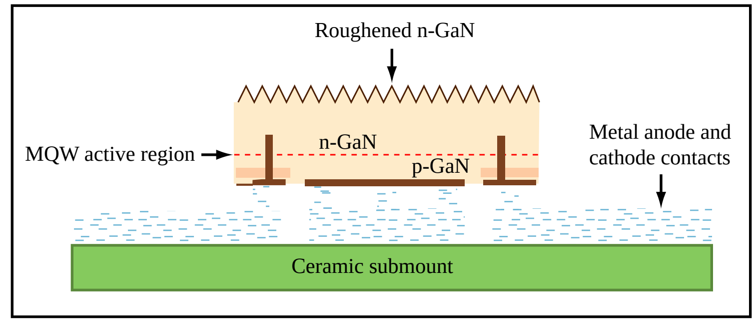


Figure by MIT OpenCourseWare.

Lee et al, "Increasing the extraction efficiency of AlGaInP LEDs via n-side surface roughening," IEEE Photonics Technology Letters 17 (2005) 2289.

Right: Shchekin et al, "High performance thin-film flip-chip InGaN-Gan light-emitting diodes," Applied Physics Letters 89 (2006) 071109. (Already in production by Philips LumiLeds.)

Lecture 10 - BJT Wrap-up, Solar Cells, LEDs - Summary

- **Photodiodes and solar cells**

  Characteristic: $i_D(v_{AB}, L) = I_S(e^{qv_{AB}/kT} - 1) - I_L$

  Reverse or zero bias: $i_D(v_{AB} < 0) \approx - I_L$ **(detects the presence of light)**

  In fourth quadrant: $i_D \times v_{AB} < 0$ **(power is being produced!!)**

- **Light emitting diodes; laser diodes**

  Materials: red: GaAlAs, GaAsP, GaP amber: GaAsP

  yellow: GaInN green: GaP, GaN

  blue: GaN white: GaN w. a phosphor

  The LED renaissance: new materials (phosphides, nitrides)

  new applications (fibers, lighting, displays, etc)

  Laser diodes: CD players, fiber optics, pointers

  Check out: http://www.britneyspears.ac/lasers.htm