Solar Cells

ECE 3080/ECE 3040 Lecture

Dr. Doolittle

February 22, 2008

References –

PVCDROM by Dr. Honsberg at the University of Delaware

www.udel.edu/igert/pvcdrom
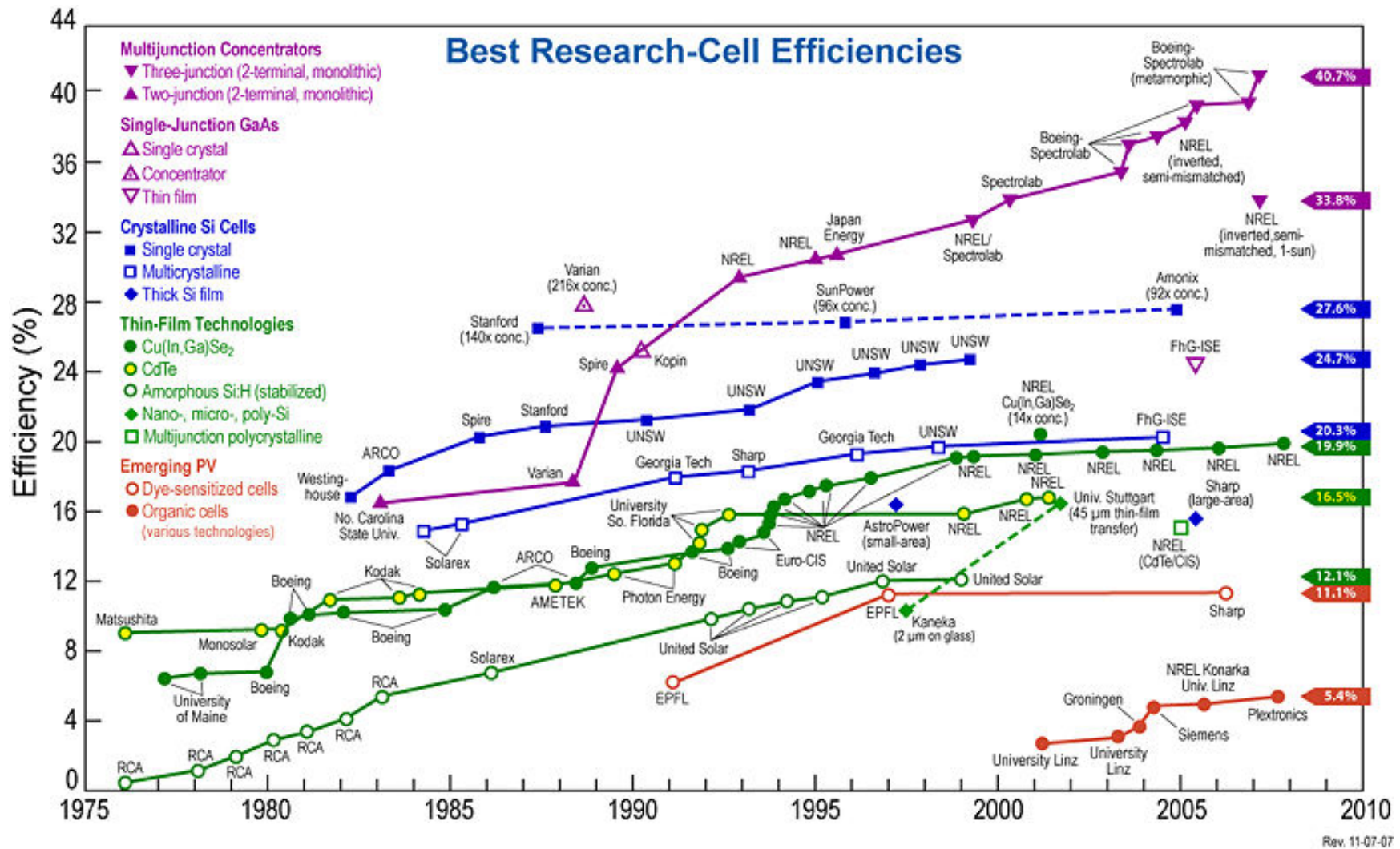
National Renewable Energy Laboratory

www.nrel.gov

University Center of Excellence for Photovoltaics

www.ece.gatech.edu/research/UCEP

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What is the highest efficiency Solar Cell?

Best Research-Cell Efficiencies

GT CRC Roof-Mounted PV System

λ Largest single PV structure at the time of it's construction for the 1996 Olympic games

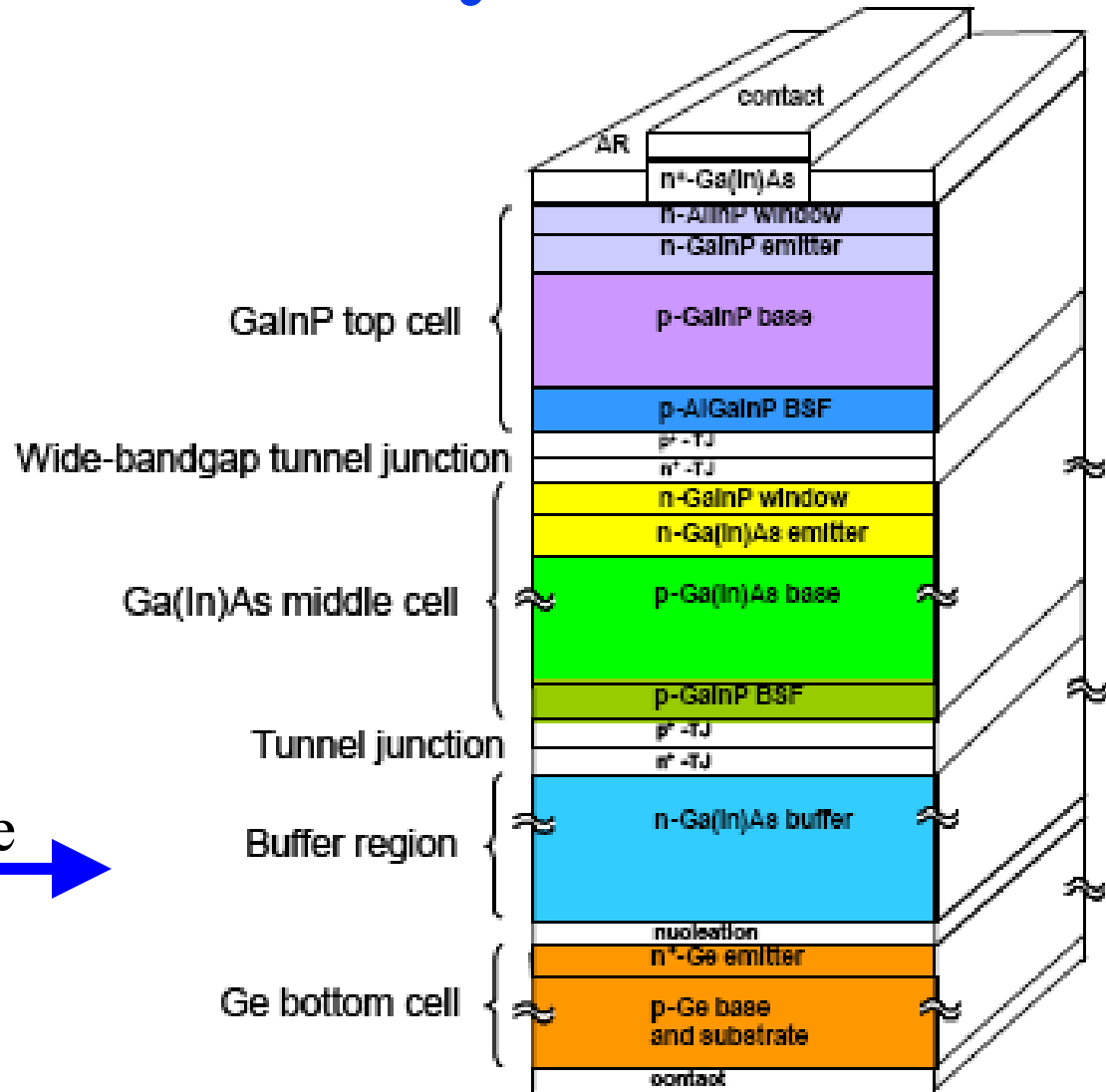λ Produced more than 1 billion watt hrs. of electrical energy that has been fed into the GT power grid
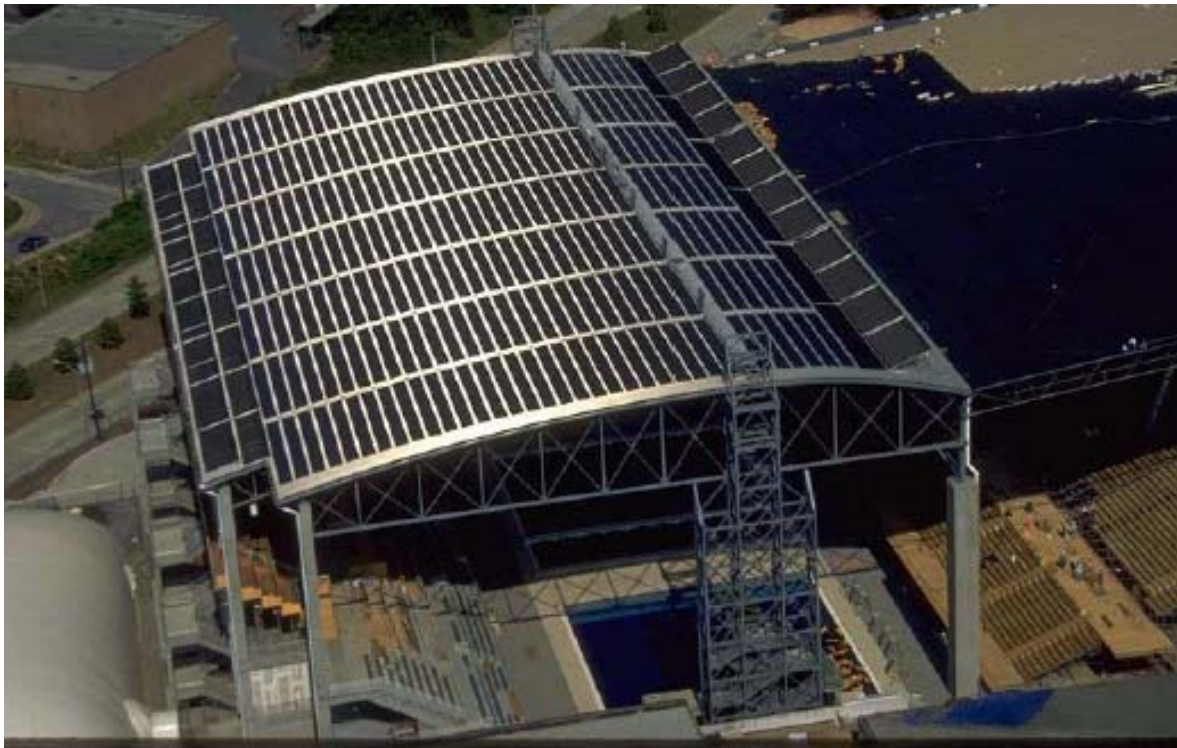
PV - Photovoltaic

Highest Efficiency Device

- GaInP/GaInAs/Ge by Spectrolab (A Boeing Company) achieved 40.7% efficiency in 2007.
- Current devices employed on satellites have efficiencies ~28.3%
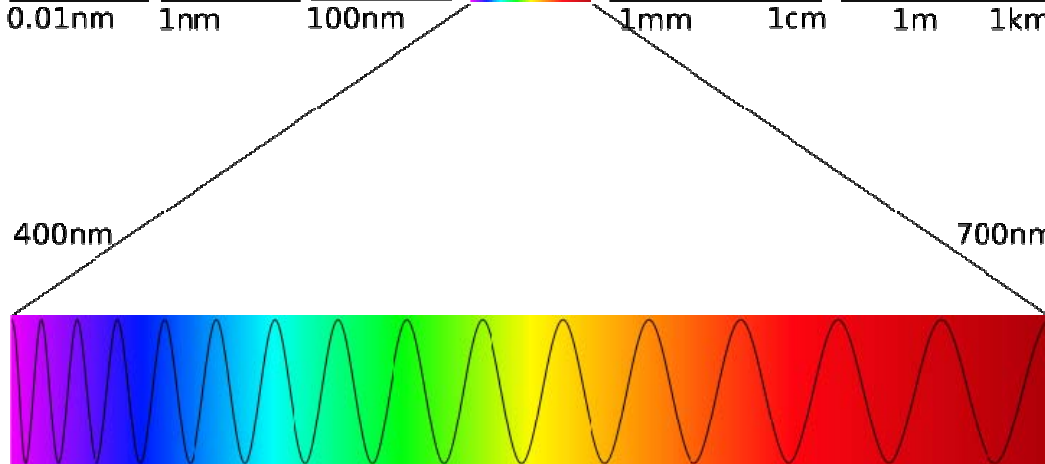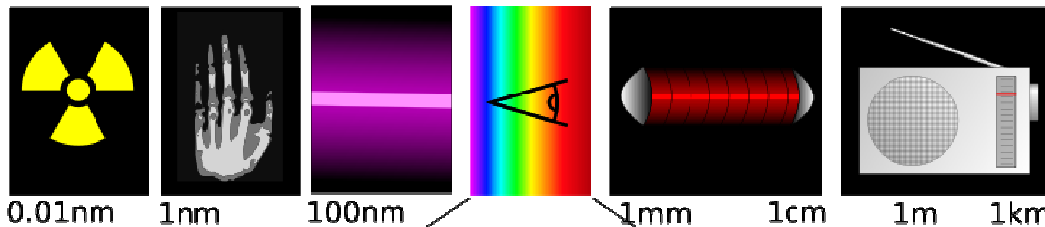- An approximate device structure

contact

AR

n$^+$-Ga(In)As

n-AlInP window

n-GaInP emitter

p-GaInP base — GaInP top cell

p-AlGaInP BSF

p$^+$-TJ / n$^+$-TJ — Wide-bandgap tunnel junction

n-GaInP window

n-Ga(In)As emitter

p-Ga(In)As base — Ga(In)As middle cell

p-GaInP BSF

p$^+$-TJ / n$^+$-TJ — Tunnel junction

n-Ga(In)As buffer — Buffer region

nucleation

n$^+$-Ge emitter

p-Ge base and substrate — Ge bottom cell

contact

Law et. al, Conference Record of the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion, pp. 1879.

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Energy of a Photon

$$E_{[eV]} = \frac{hc}{\lambda} = \frac{1.24}{\lambda_{[\mu m]}}$$

$h = 6.626 \times 10^{-34} \, [J \cdot s]$
$c = 3 \times 10^{8} \, [m/s]$
$J = 1.602 \times 10^{-19} \, [eV]$
λ is the wavelength of light in meters

0.01nm   1nm   100nm   1mm   1cm   1m   1km

400nm   700nm

	Bandgap [eV]	Wavelength [μm]
Ge	0.67	1.85
Si	1.12	1.107
GaAs	1.42	0.873
GaN	3.4	0.365

Photovoltaic Effect

λ Solar cells are:
   – p-n junctions
   – Minority carrier devices
   – Voltage is not directly applied

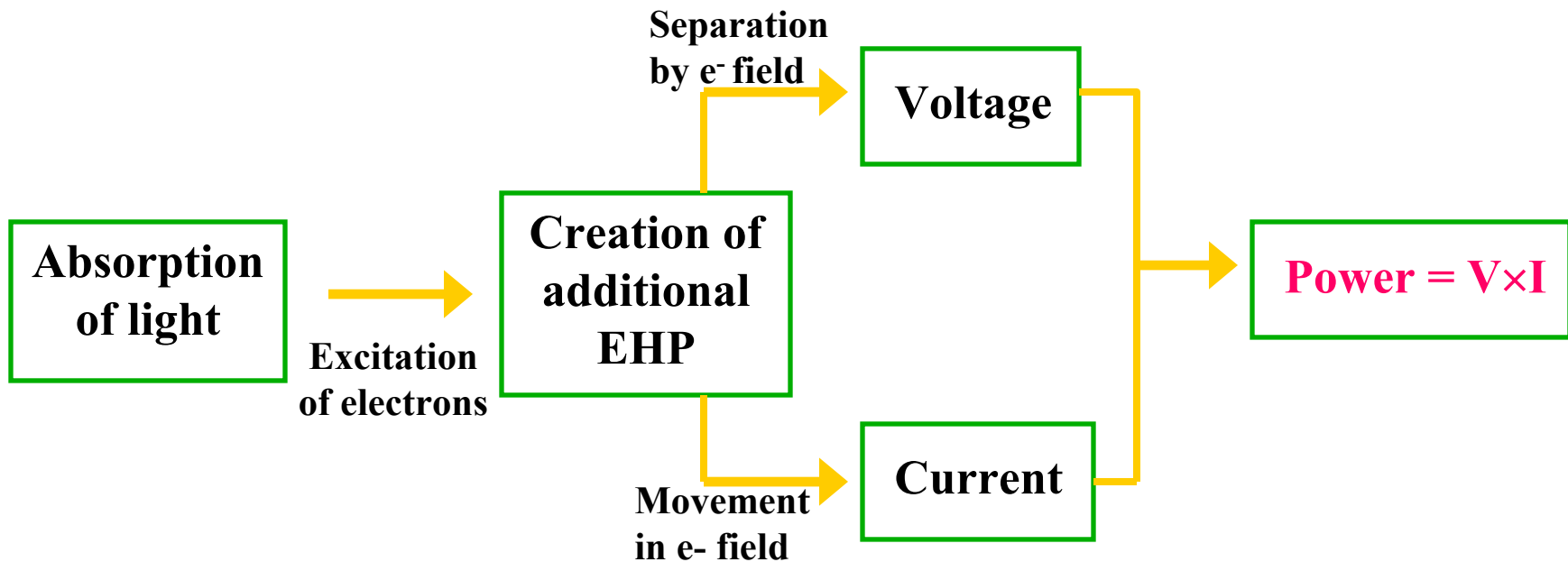λ The photocurrent produces a voltage drop across the resistive load, which forward biases the pn junction.

hν

P   -- +
         -- + E-Field   N
I$_L$ -- +

I$_F$

I$_{total}$ + V -

R
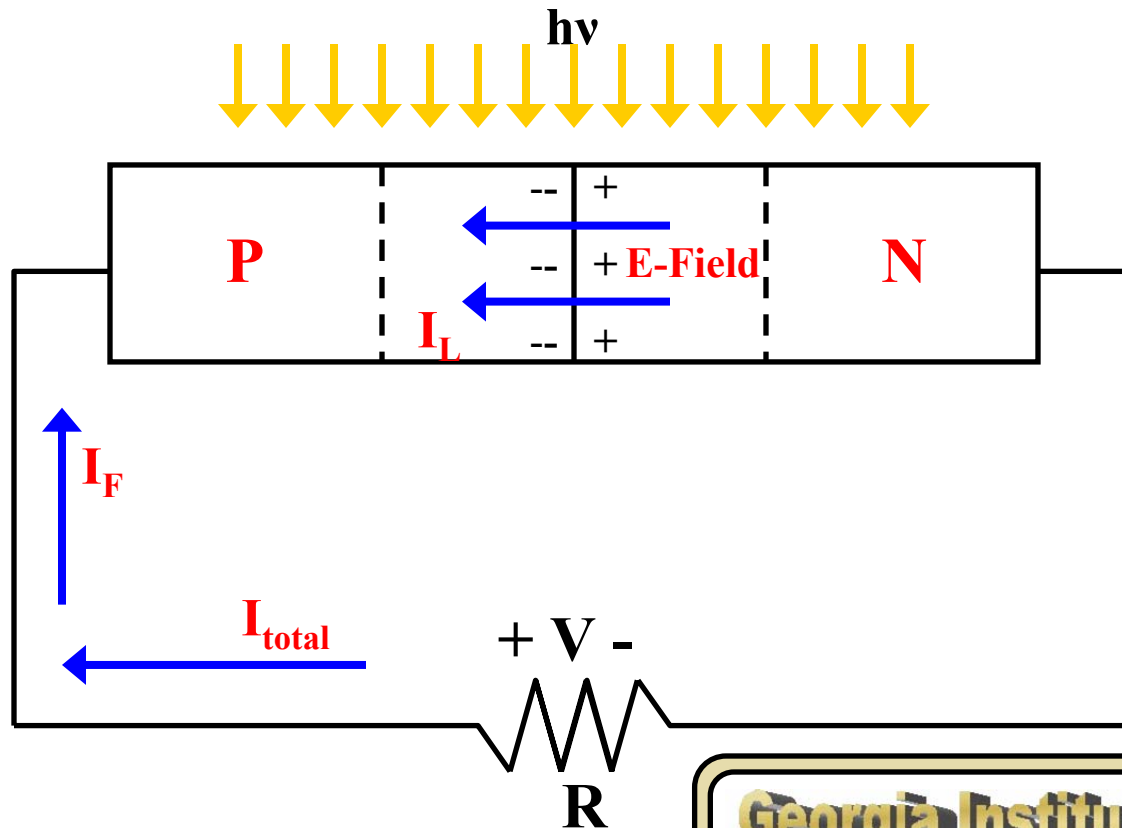
Photovoltaic Effect

λ **Fundamental absorption is from:**

   –   **annihilation or absorption of photons by the excitation of an electron from the valence band to the conduction band**
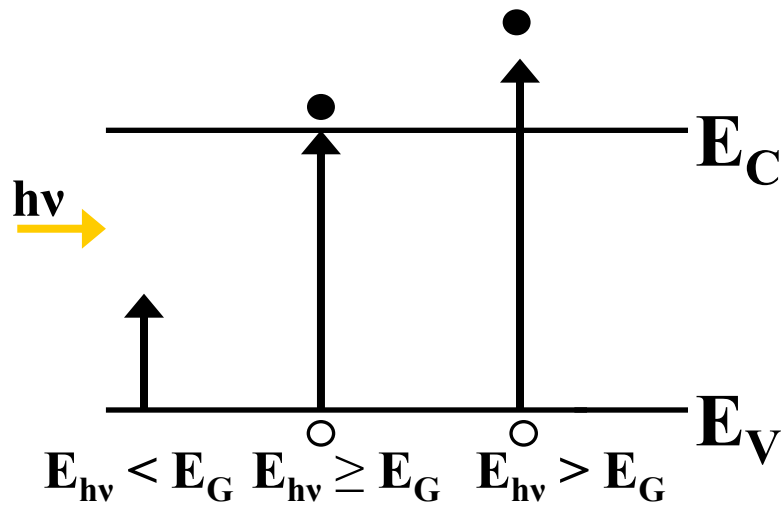
   –   **leaves a hole in the valence band**

λ **Ideally, each incident photon with $E_{h\nu} > E_G$ will create one electron flowing in the external device**

```
                          Separation
                          by e⁻ field      ┌──────────────┐
                                       ──▶ │   Voltage    │───┐
                                           └──────────────┘   │
┌──────────────┐      ┌──────────────┐                        │   ┌──────────────┐
│  Absorption  │      │  Creation of │                        ├──▶│ Power = V×I  │
│   of light   │ ───▶ │  additional  │                        │   └──────────────┘
└──────────────┘      │     EHP      │                        │
     Excitation       └──────────────┘                        │
     of electrons                     ──▶ ┌──────────────┐    │
                          Movement         │   Current    │───┘
                          in e- field      └──────────────┘
```
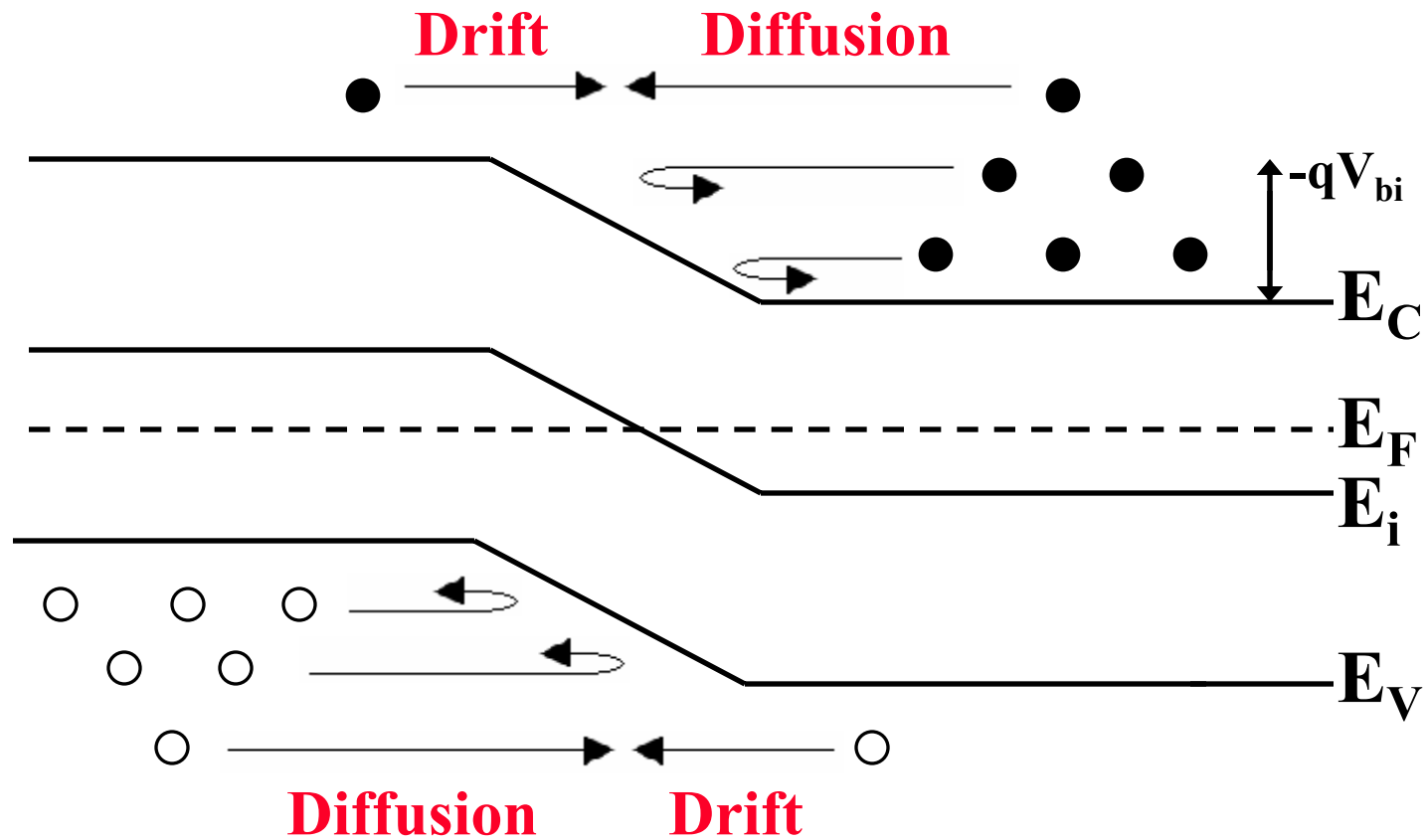
λ **$E_{h\nu} < E_G$: semiconductor is transparent to light**

Ilumination and Generation

❖ Incident light on a solar cell causes an electron to be excited from the valence band into the conduction band (creating electron-hole pairs) everywhere in the device.

❖ $E_{hv} < E_G$: the device is transparent to the incident light.

❖ $E_{hv} \geq E_G$: photons are absorbed and EHP are photogenerated in the device.

❖ $E_{hv} > E_G$: energy generated is lost as heat to the device.

$$E_C$$

hν →

$$E_V$$

$E_{hv} < E_G$ $E_{hv} \geq E_G$ $E_{hv} > E_G$

Diode at Equilibrium

Drift   Diffusion

$-qV_{bi}$

E_C

E_F

E_i

E_V
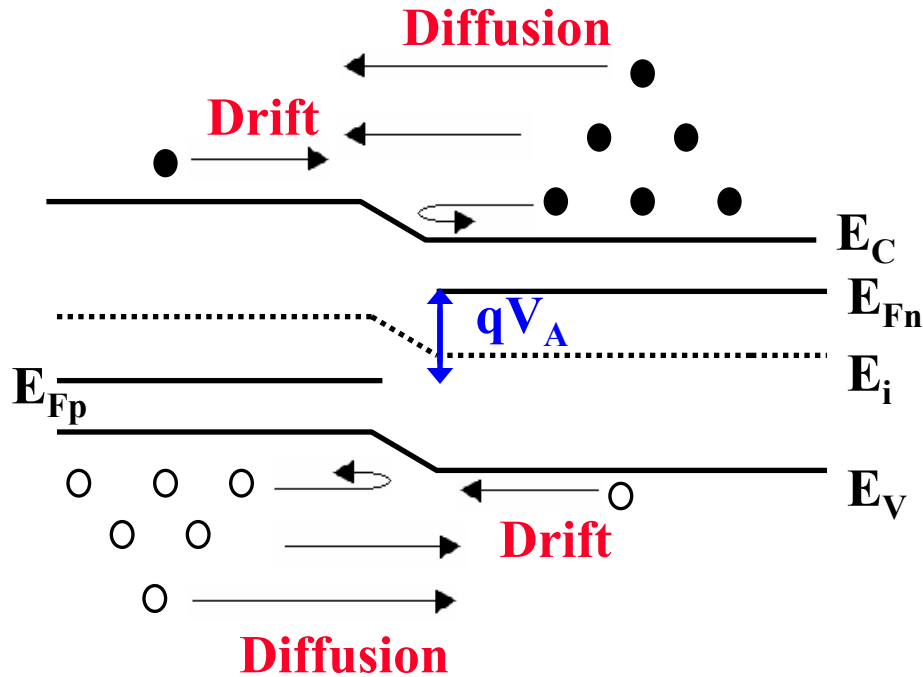
Diffusion   Drift

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Depletion Region

❖ Every EHP generated in the:
  o Depletion region
  o Within a diffusion length ($L = \sqrt{D\tau}$) away from the depletion region are:
    ▪ Swept across the junction by an electric field.
❖ Referred to as **photocurrent** and is in the "reverse bias" direction. All other EHP recombine before they can be collected.
❖ **Photocurrent** is always in the "reverse bias" direction, therefore the net solar cell current is also in the "reverse bias" direction.
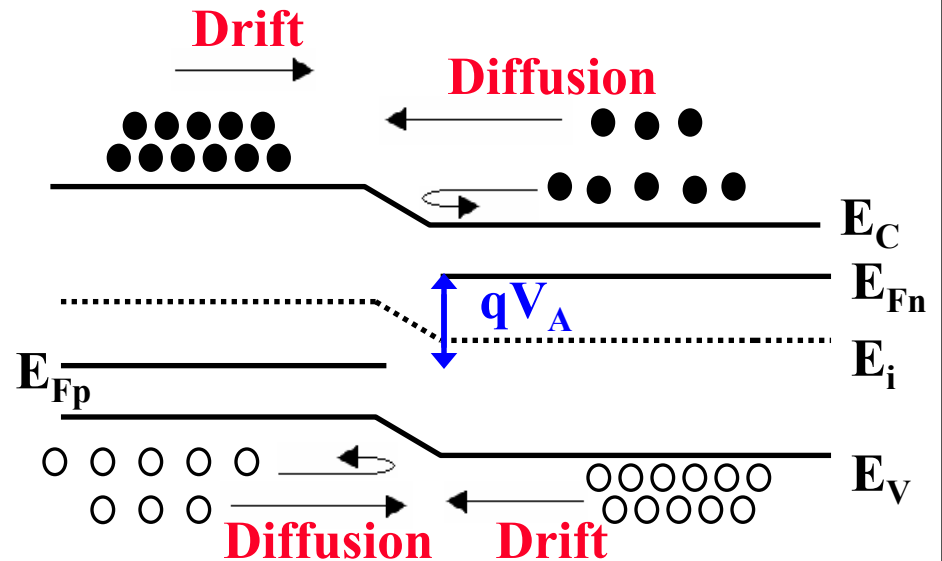
Forward Bias

Diffusion

Drift

E_C

E_{Fn}

qV_A

E_i

E_{Fp}

E_V
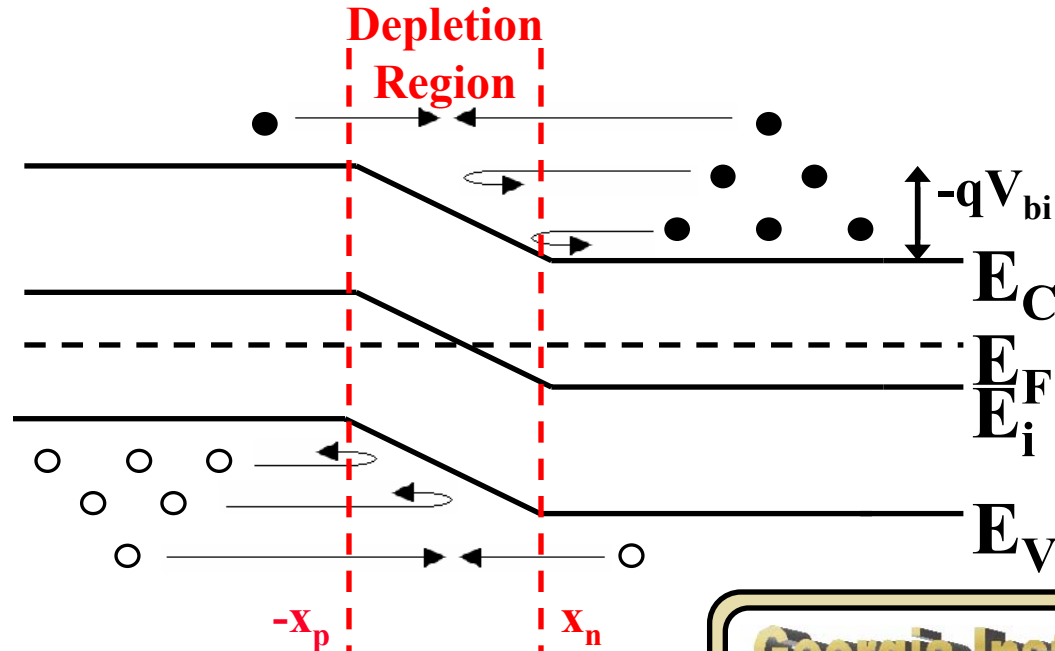
Drift

Diffusion

❖ **Voltage applied externally.**

❖ **Current is dominated by Diffusion.**

Photogeneration

❖ **Voltage is generated internally from EHP being swept across the junction by an electric field.**

❖ **Current is dominated by Drift.**

Drift

Diffusion

E_C

E_{Fn}

qV_A

E_i

E_{Fp}

E_V

Diffusion   **Drift**

Law of the Junction

❖ V_A is the difference between Fermi level on the n-side and the p-side when a voltage is applied to a pn junction.

$$V_A = (kT/q)\ln\{(n_{p(x=-x_p)} \times p_{n(x=x_n)}/n_i^2\}$$

❖ It is related to the minority carriers in each region.

❖ V_A will be the same in the forward bias case and in the photogenerated case.
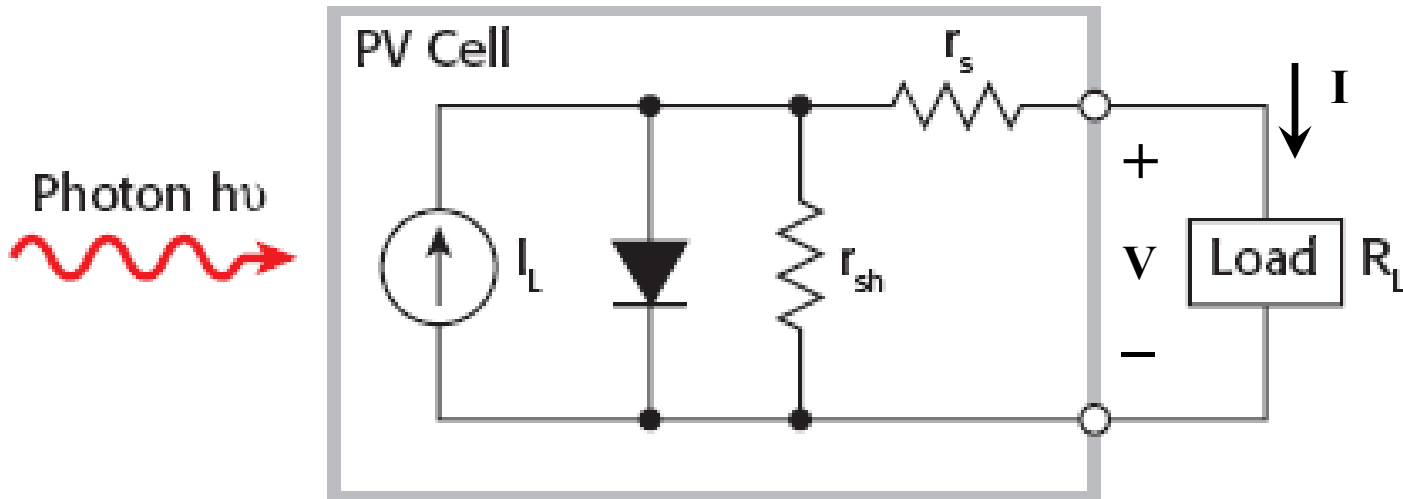
Current Collection

hν
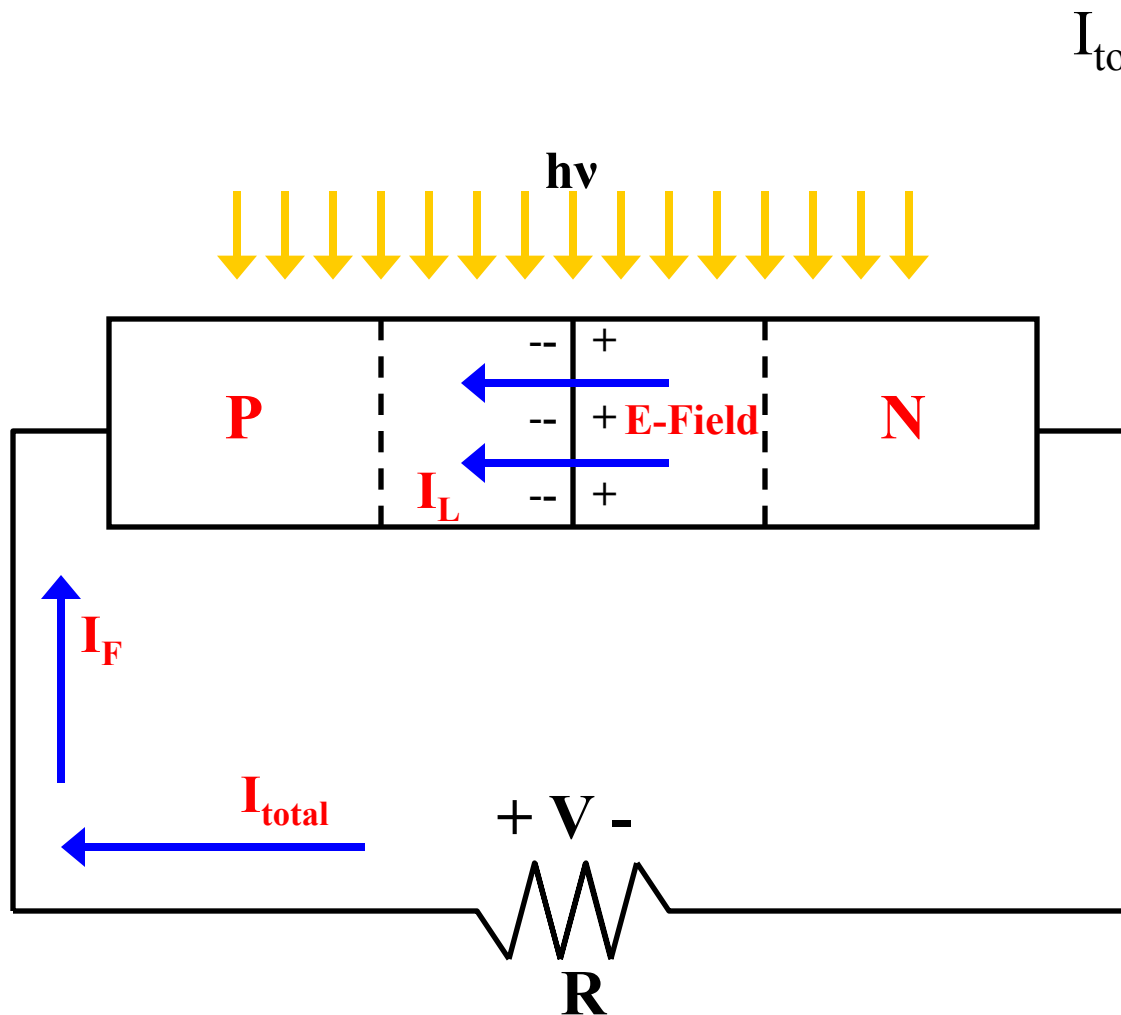
$I_{total} = I_F - I_L$

$= I_s\{\exp(qV/kT) -1\} - I_L$

I_F = Forward-bias current

I_L = Photocurrent

I_s = Ideal reverse saturation current

P

-- +
-- + E-Field
-- +

I_L

N

I_F

I_{total}

+ V -

R

Solar Cell Equivalent Circuit

- λ   Using the Ideal diode law: $I = I_O(e^{\{qV/kT\}} - 1)$
- λ $I = I_L - I_O(e^{\{[V+Ir_S]/nV_T\}} - 1) - (\{V + Ir_S\}/r_{shunt})$
- λ I_L is the light induced current or short circuit current (I_{SC})
- λ $V_{OC} = kT/q \ (\ln \{[I_L/I_{OC}] + 1\})$
- λ r_S is the series resistance due to bulk material resistance and metal contact resistances.
- λ r_{Sh} is the shunt resistance due to lattice defects in the depletion region and leakage current on the edges of the cell.
- λ $V_T = kT/q$
- λ n – non ideality factor, = 1 for an ideal diode

IV Curves

λ **V_m and I_m** – the operating point yielding the maximum power output

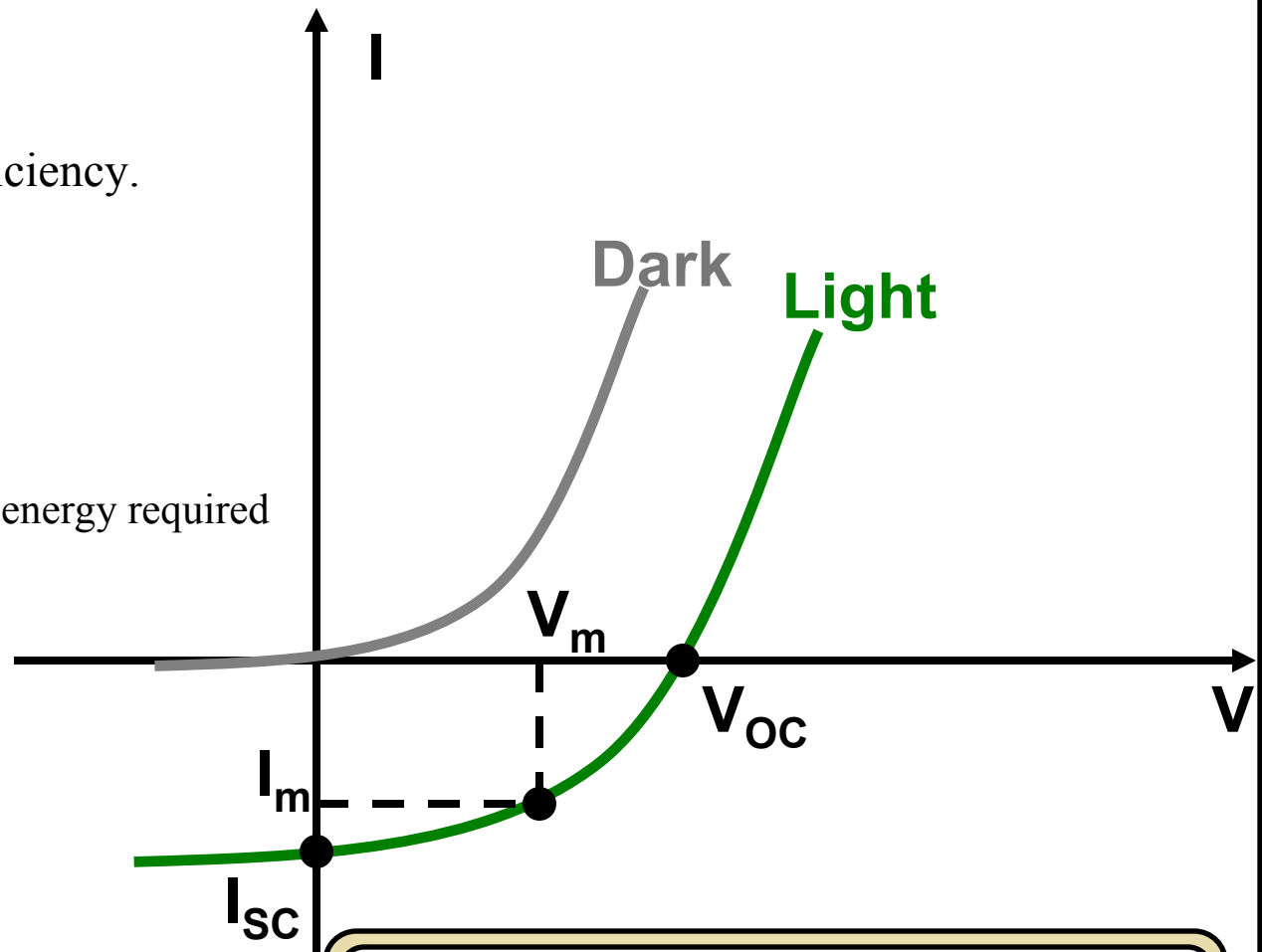λ FF – fill factor – measure of how "square" the output characteristics are and used to determine efficiency.

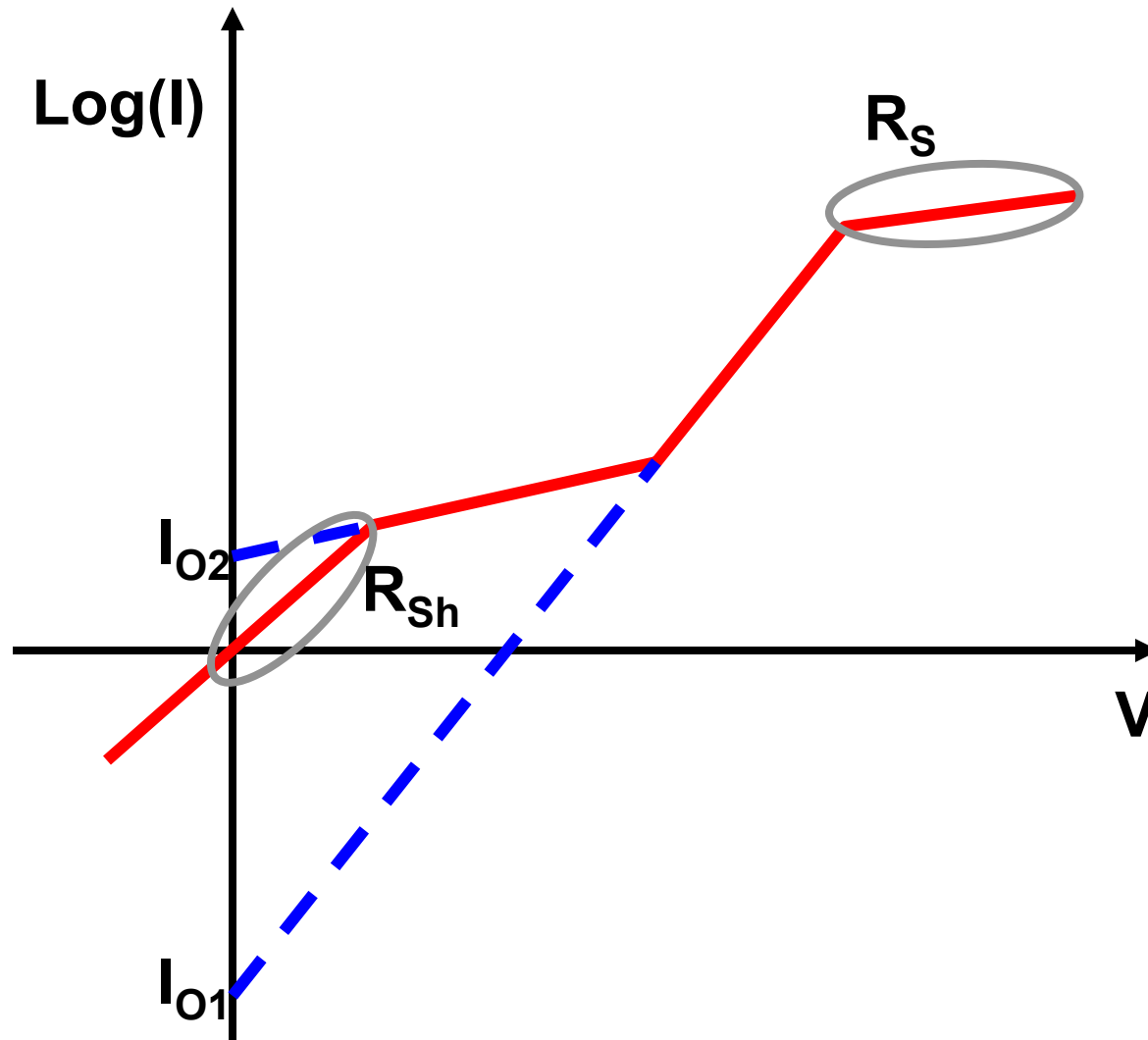$$FF = V_m I_m / V_{OC} I_{SC}$$

λ η - power conversion efficiency.

$$\eta = P_{max} / P_{in}$$
$$= V_m I_m / P_{in}$$
$$= FF V_{OC} I_{SC} / P_{in}$$

λ If $E_G \downarrow$ then:

   – More photons have the energy required to create an EHP
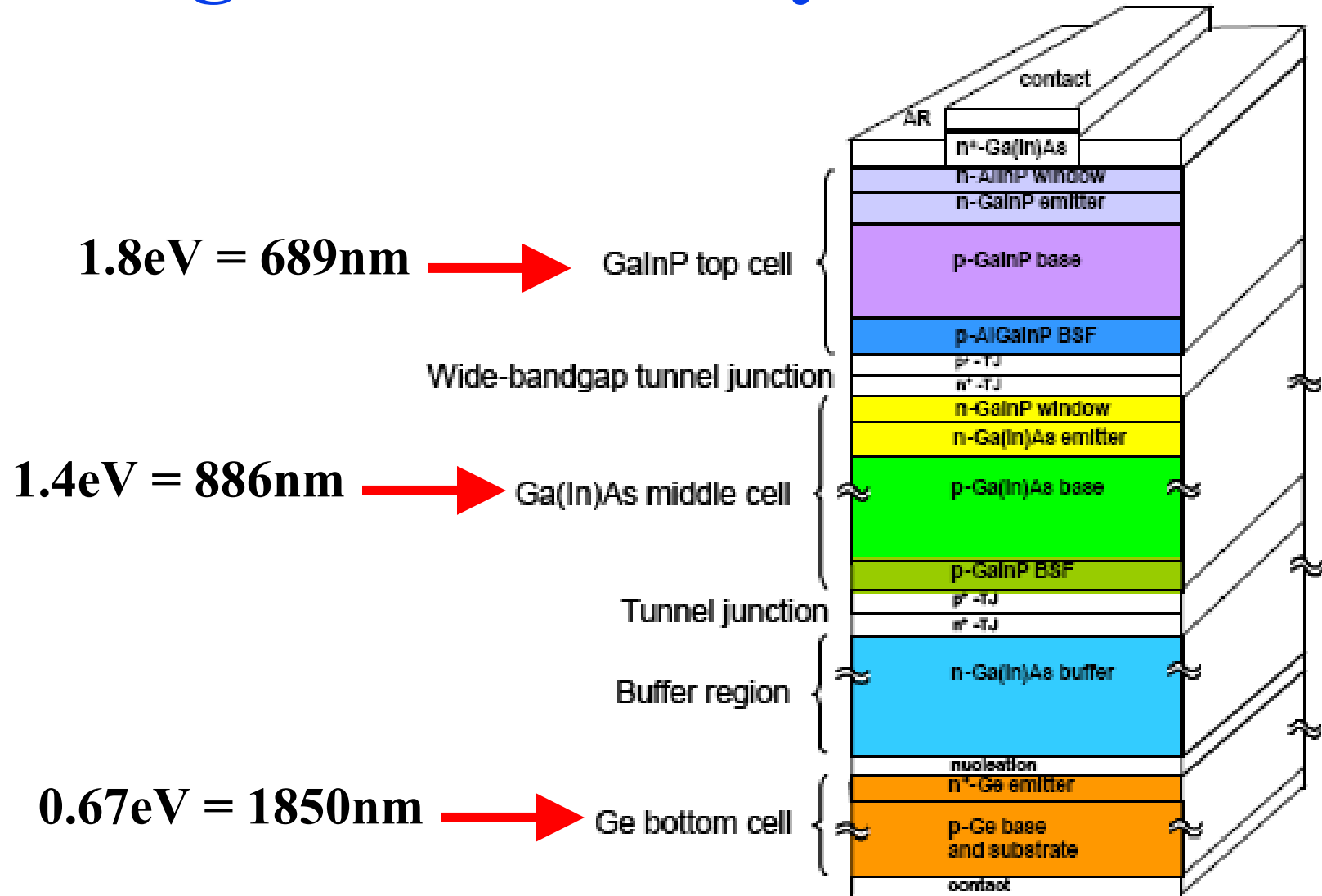
   – $I_{SC} \uparrow$ and $V_{OC} \downarrow$

λ Large R_S and low R_{Sh} reduces V_{OC} and I_{SC}
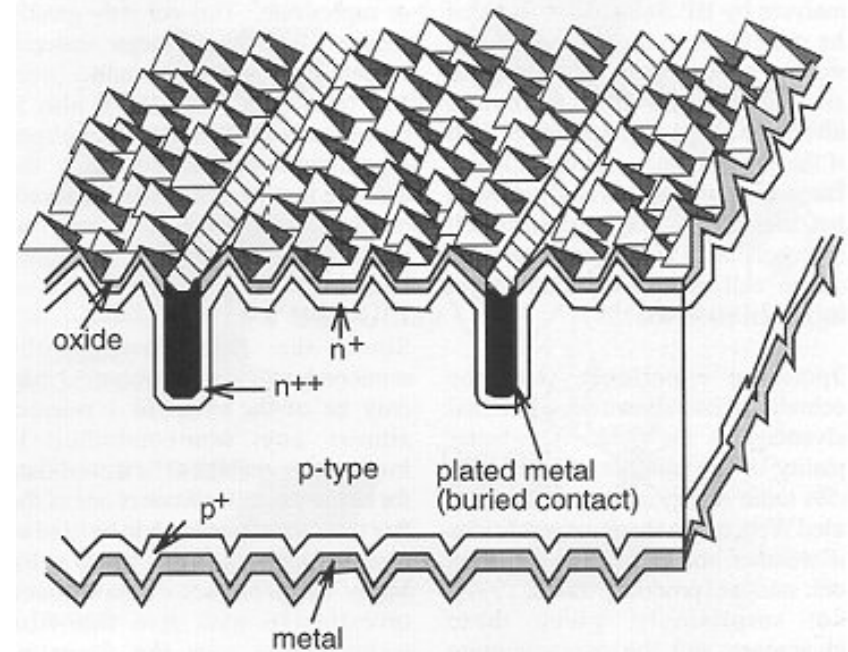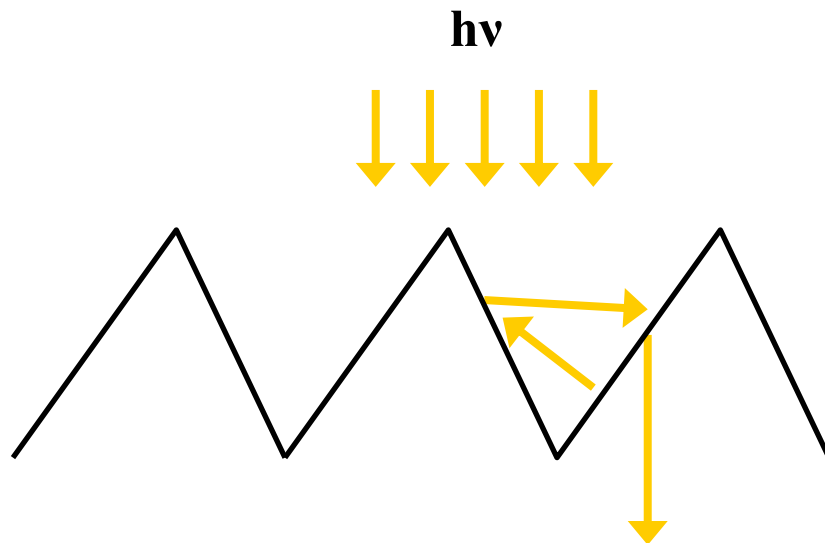
IC Curves – Dark measurement

Highest Efficiency Device

1.8eV = 689nm ⟶ GaInP top cell

1.4eV = 886nm ⟶ Ga(In)As middle cell

0.67eV = 1850nm ⟶ Ge bottom cell

Labels in diagram:
- contact
- AR
- n⁺-Ga(In)As
- n-AlInP window
- n-GaInP emitter
- p-GaInP base
- p-AlGaInP BSF
- p⁺-TJ
- n⁺-TJ
- Wide-bandgap tunnel junction
- n-GaInP window
- n-Ga(In)As emitter
- p-Ga(In)As base
- p-GaInP BSF
- p⁺-TJ
- n⁺-TJ
- Tunnel junction
- n-Ga(In)As buffer
- Buffer region
- nucleation
- n⁺-Ge emitter
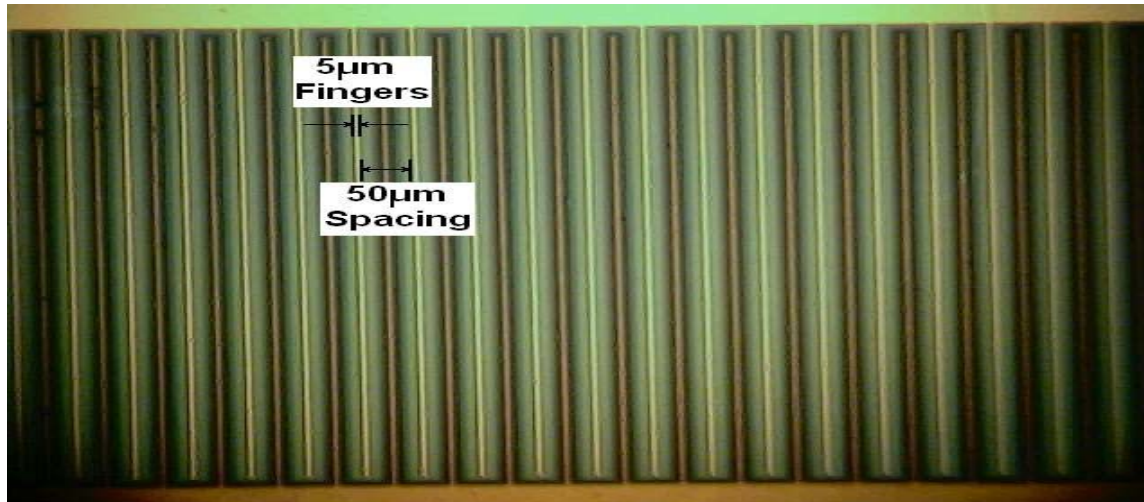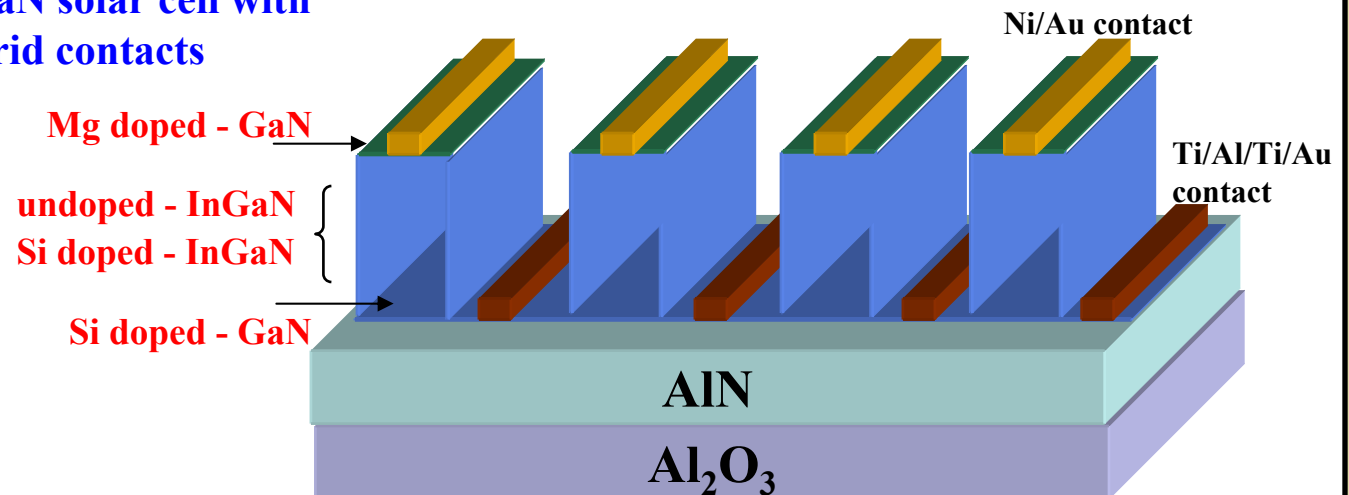- p-Ge base and substrate
- contact

Si Technology

λ Textured top layer

λ Incident light will:

    – Become trapped

    – Bounced around in the texture

    – Absorbed in the device
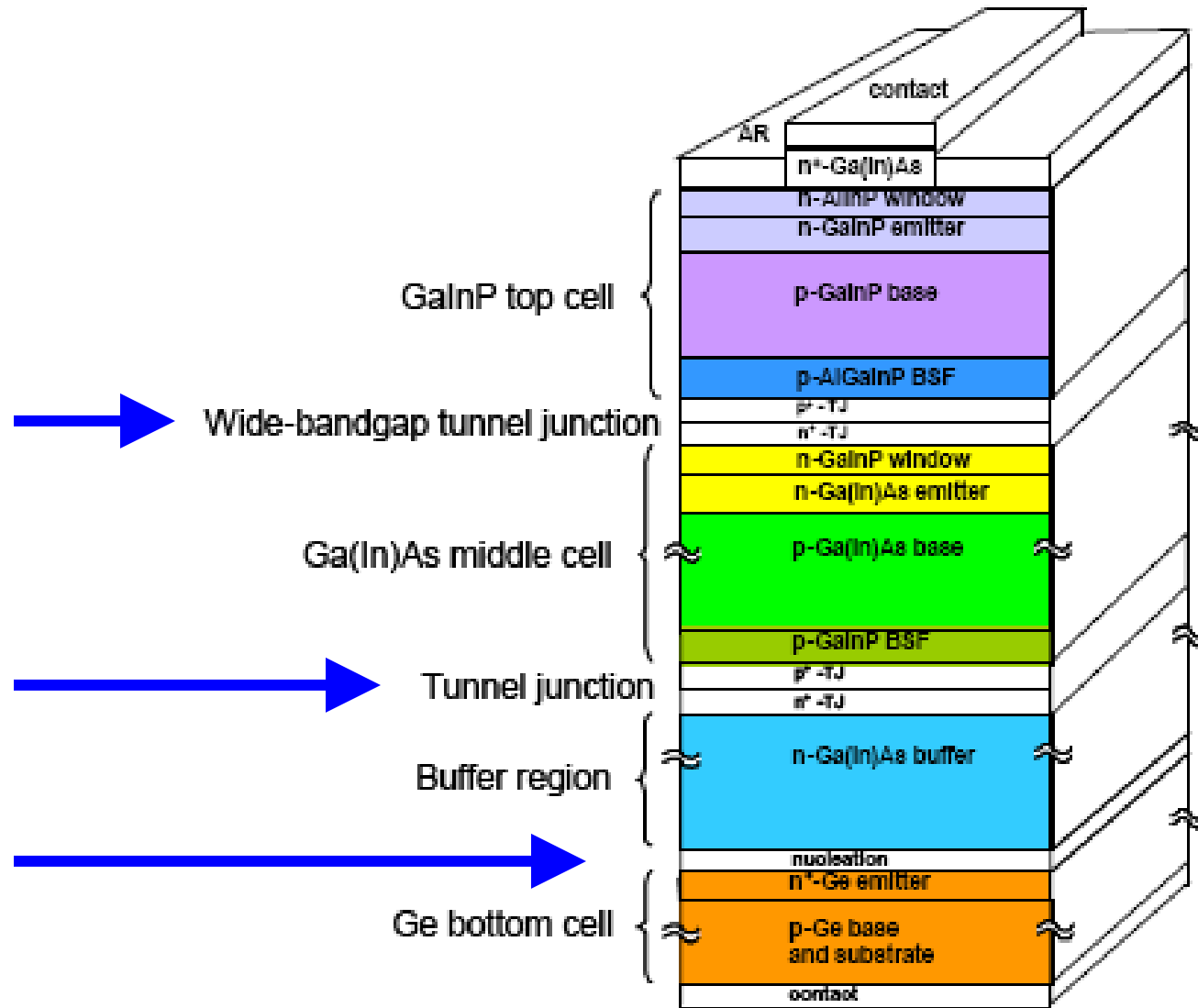
Dr. Doolittle's Solar Cell Research

5μm Fingers

50μm Spacing

Fabricated MBE InGaN solar cell with interdigitated grid contacts

Ni/Au contact

Mg doped - GaN

undoped - InGaN

Si doped - InGaN

Ti/Al/Ti/Au contact

Si doped - GaN

AlN

Al$_2$O$_3$

Schematic of the interdigitated grid contacts

InGaN bandgap:
2.8eV = 442nm

What is a Tunnel Junction?
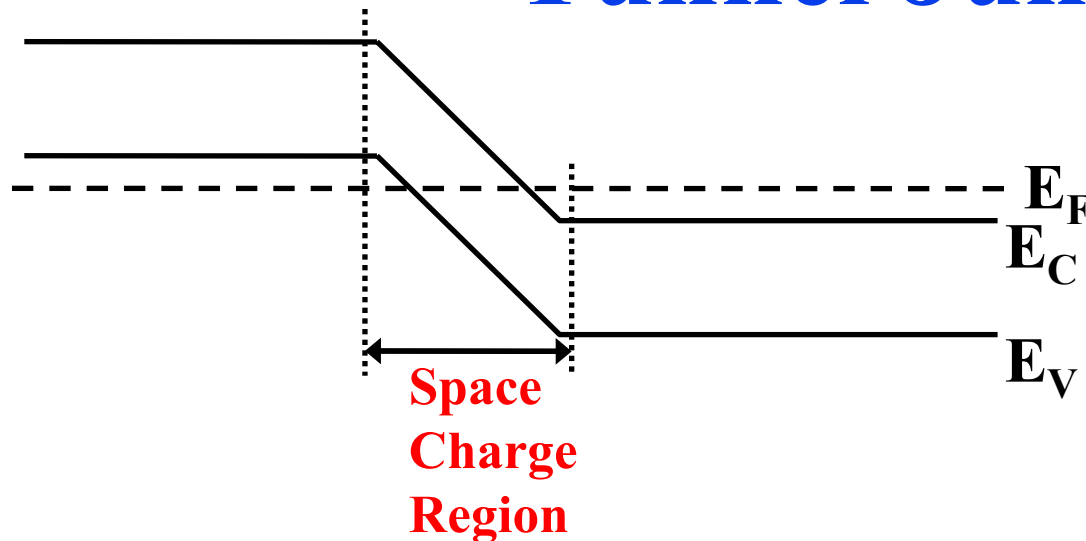
Tunnel Junction

Non-degenerately Doped

n   p   n

E_C

E_V
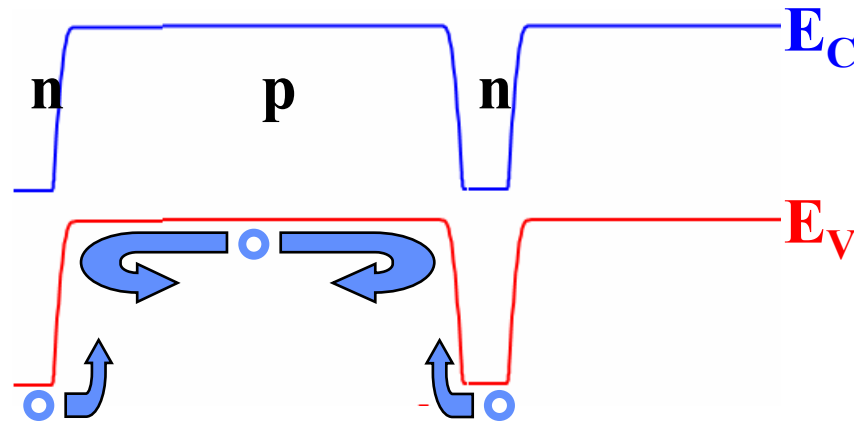
Tunnel junction requires degenerate doping!

Degenerately Doped – highly material

n   p   n

E_C

E_V

Tunnel Junction

E$_F$
E$_C$

E$_V$
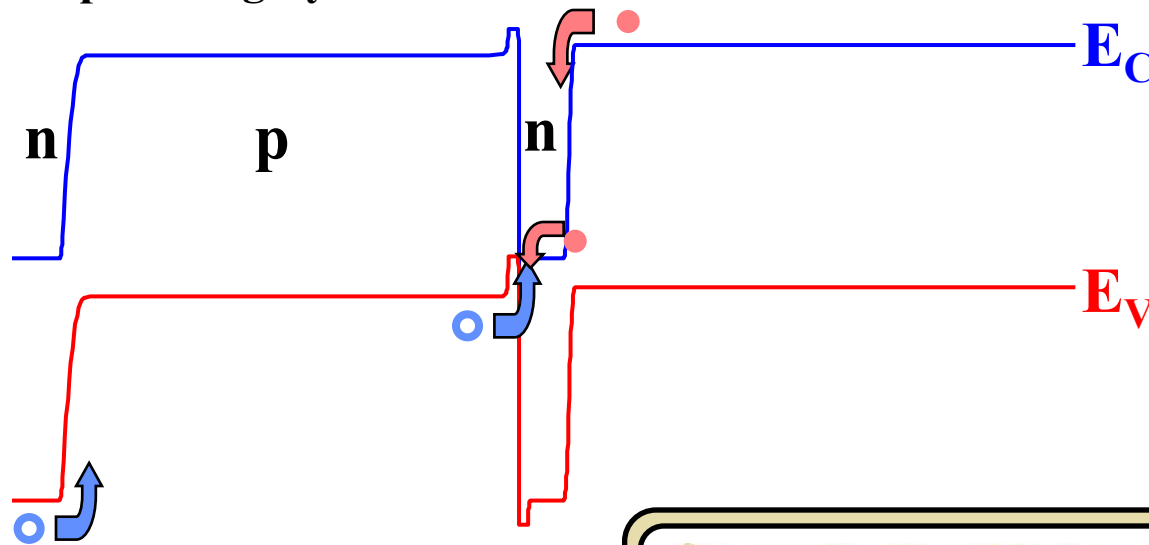
**Space
Charge
Region**

❖ **Energy-band diagram in thermal equilibrium** – n and p-region are degenerately doped

❖ **Large forward-bias** voltage – the maximum number of electrons in the n-region is opposite the maximum number of empty states in the p-region; maximum tunneling current is produced.

❖ **Increased forward-bias voltage** – the number of electrons directly opposite the holes decreases and the tunneling current decreases.

e$^-$
e$^-$

E$_C$

E$_V$
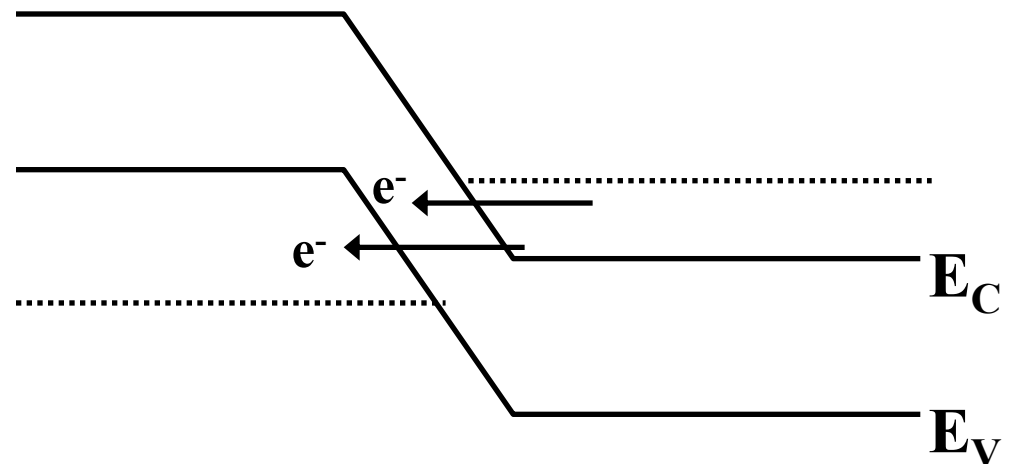
Non-Idealities

❖ Bulk defects – dislocations and stacking faults, due to lattice mismatch with the substrate.

❖ Surface recombination defects – EHP generated by the absorption of light can recombine before they cross the junction, therefore not contributing to the power output of the solar cell.

❖ Bulk recombination defects – EHP generated further away from the junction have a large probability of recombining before they reach the device terminals.

❖ Insufficient photon energy: $h\nu < E_g$

❖ Excessive photon energy : $h\nu > E_g$

❖ Solar cell is too thin – some of the light of the appropriate energy is not coupled into the cell and is passed through the device.

❖ Open circuit Voltage (V_{OC}) losses – recombination of EHP in trap levels in the depletion region that lowers $V_{OC.}$

❖ Fill Factor losses – related to V_{OC}, series resistance, and shunt resistance.

❖ Reflection losses

Anti-Reflection Coating

❖ Prevents incident light from reflecting off of the device.

❖ The AR coating needs to have the correct refractive index for the material system and be transparent.

❖ Deposited as noncrystalline or amorphous layer which prevents problems with light scattering at grain boundaries.

❖ A double layer AR coating reduces the reflection of usable sunlight to ~ 4%.