Why the maximum quantum efficiency (QE) of a single junction type Solar cell is about 35 % ?

W. Shockley and H. Queisser, " J. Applied Physics, 32(1961)510

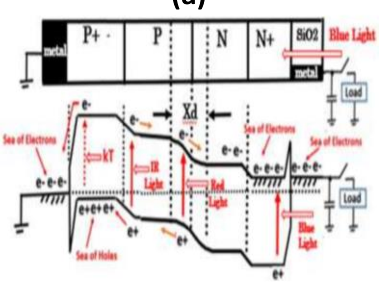
- A photon with an energy less than the band gap(E_G) cannot be converted to the electron energy. QE approaches zero as E_G gets larger and larger.

- A single junction type semiconductor with a very small band-gap has a very small band-bending, resulting in a very small barrier electric field for separating photo electron and hole pairs. QE approaches zero as E_G gets smaller and smaller.

- Light with a wave length of 0.4 µm has a photon energy of E = 1.24/0.4 = 3.1 eV. In a silicon-based solar cell with the band gap of 1.1 eV, cares are needed in order to maintain the hot electron energy of 3.1 eV from being reduced down to 1.1 eV by collisions with other free electrons and orbit electrons in the bulk silicon crystal, before reaching the external output load. The maximum value of QE would be less than 1.1/3.1 = 35.5% for a silicon-based type solar cell.

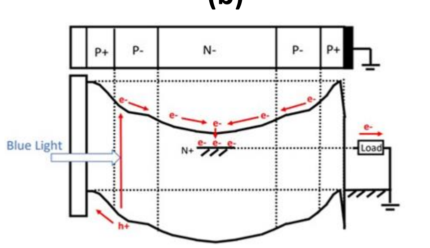
- Short-wave-length high-energy photons have a very short light penetration depth in the silicon crystal. In case of a floating-surface N+PP+ single junction type solar cell, there is no surface electric field in the surface N+ diffusion region. And the case becomes worse since the photo electron and hole pairs, which have been generated at the surface vicinity, stay together at the silicon surface. Soon or later eventually, all of the photo electron and hole pairs are recombined and wasted into heat. In case of the single junction type silicon-based solar cell, QE becomes very small.

(a)



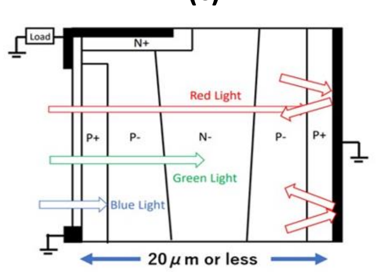
Single Junction N+NPP+ Photodiode type Solar Cell

(b)



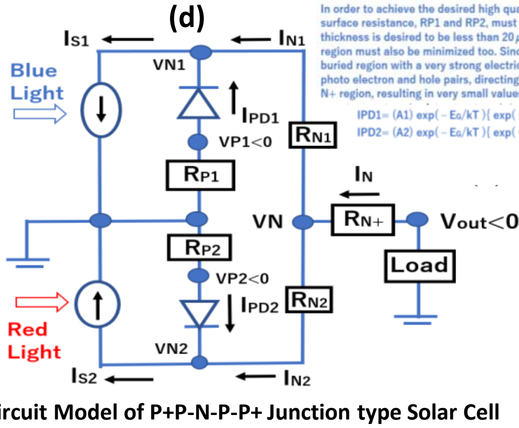
Completely Depleted Buried N- Region with an empty potential of a strong electric field, collecting the photo electrons very effectively.

(c)



Short-wave blue-light cannot penetrate more than 0.1 µm in depth at the silicon crystal surface.

(d)



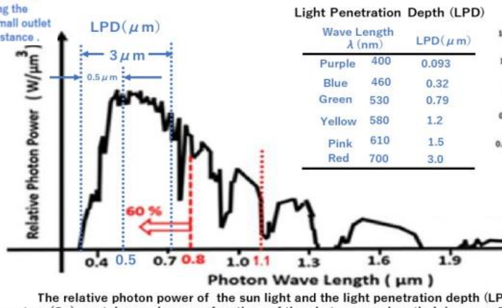
In order to achieve the desired high quantum Efficiency (QE), the P+P surface resistance, RP1 and RP2, must be minimized. The silicon chip thickness is desired to be less than 20 µm. The outlet resistance RN+ region must also be minimized too. Since the completely depleted N- buried region with a very strong electric field helps separating the photo electron and hole pairs, directing them swiftly to the small outlet N+ region, resulting in very small values of RN1 and RN2 resistance .

$I_{PD1} = (A1)\exp(-E_G/kT)\{\exp((V_{P1}-V_{N1})/kT)-1\}$

$I_{PD2} = (A2)\exp(-E_G/kT)\{\exp((V_{P2}-V_{N2})/kT)-1\}$

Circuit Model of P+P-N-P-P+ Junction type Solar Cell

(e)

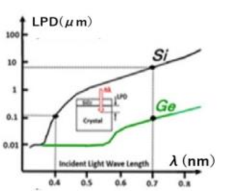


(f)

Light Penetration Depth (LPD)

Wave Length λ (nm)		LPD(µm)
Purple	400	0.093
Blue	460	0.32
Green	530	0.79
Yellow	580	1.2
Pink	610	1.5
Red	700	3.0

(g)



The relative photon power of the sun light and the light penetration depth (LPD) of the silicon(Si) and the germanium (Ge) crystals are shown as functions of the photon wave length λ in µm. The energy band gap (Eg) of the silicon crystal is 1.1 eV. The infrared -light photons with the wave length more than $\lambda = 1.24 / Eg = 1.11$ µm will not be converted into the electron energy in the silicon crystal. Besides, short-wave blue light photons cannot pass thru into the silicon crystal surface more than 0.1 ~0.2 µm in depth. They all will be wasted as heat. However, the surface P+P doping variation scheme invented by Hagiwara in 1975 can create the surface conduction -band bending, enhancing photo electron and hole separations at the silicon surface and results in the high quantum efficiency(QE) for solar cells.