EEE 460 Optoelectronics Lab Project Group No: 04

Project Title: OptoElectronic Integrated Circuit **(**OEIC) Design

Project Details:

LED	Yellow
LASER	1100 nm

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LED

We were assigned to design a yellow LED. Wavelength of yellow light is 580nm. Both N doped $GaAs_{1-x}P_x$ and $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ emits yellow light for a certain value of x. But Luminous efficiency is higher for $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ as shown in Figure 1.Hence we chose **$(Al_xGa_{1-x})_{0.5}In_{0.5}P$** for designing **the yellow LED**.

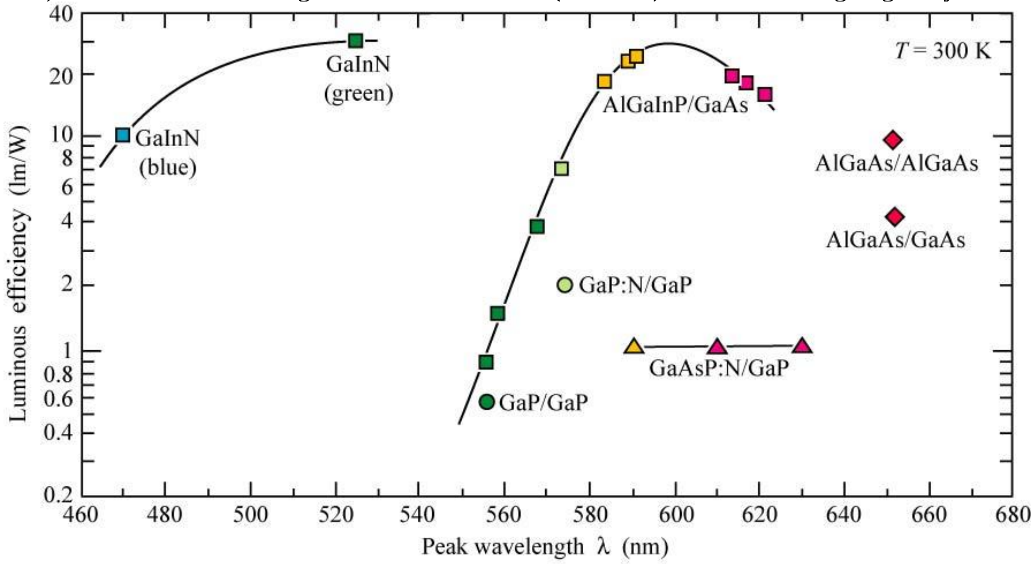


Figure 1: Luminous efficiency vs Peak wavelength for different material

Substrate:

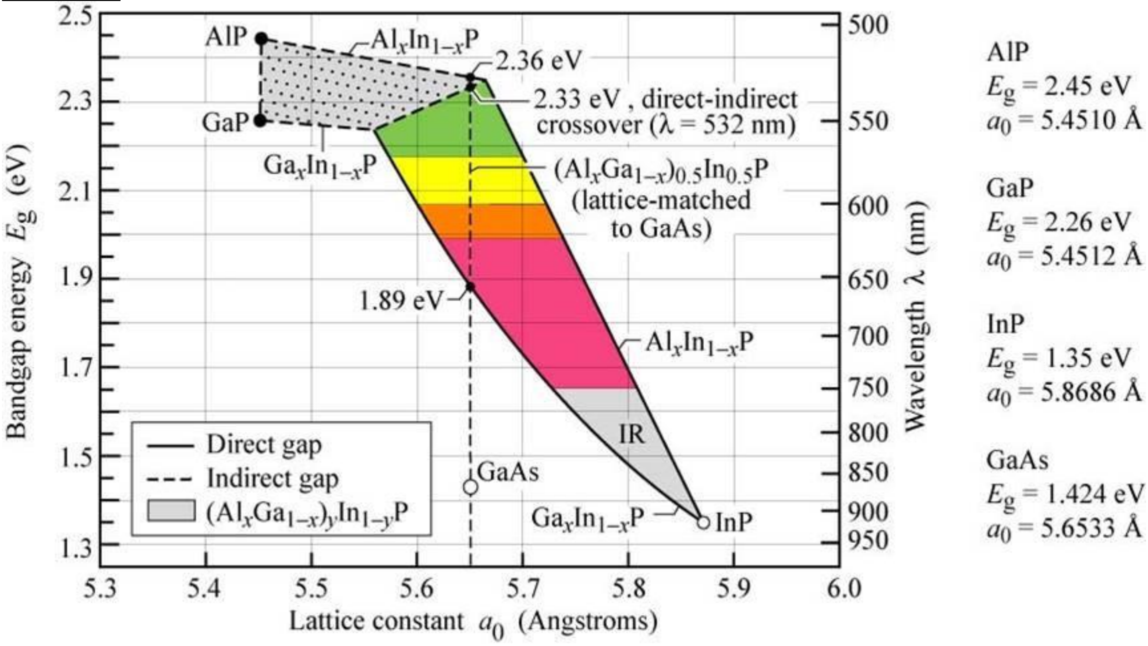


Figure 2: Band gap energy and corresponding wavelength vs Lattice Constant of $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ at 300K

The dashed vertical line in Figure 2 shows $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ is lattice matched to GaAs. Hence **GaAs** is chosen as the **substrate.**

Calculation of alloy composition, x:

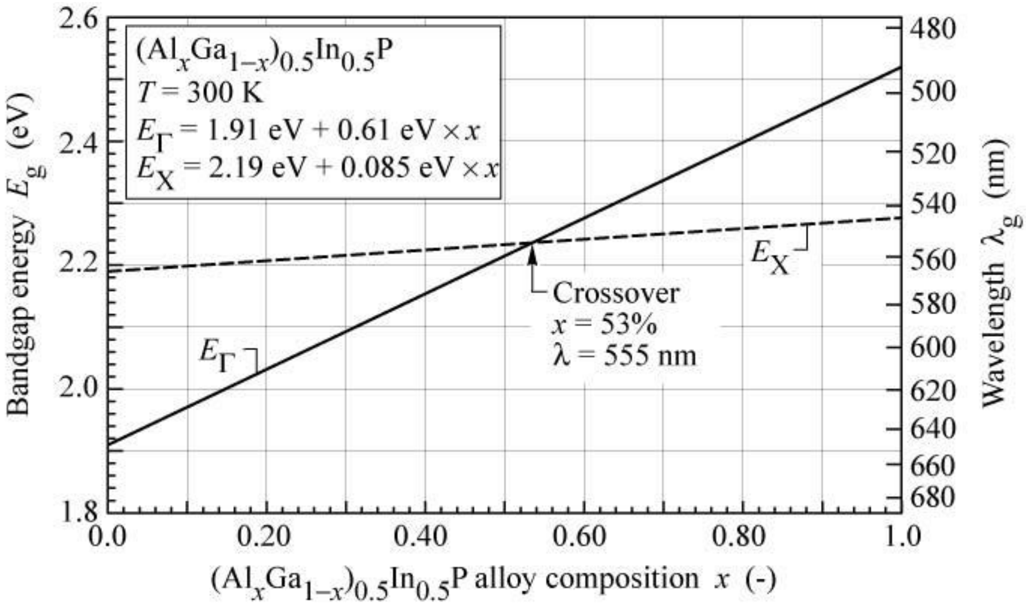


Figure 3: Bandgap energy and wavelength vs $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ alloy composition

Here,Yellow light wavelength 580nm. Hence corresponding energy= $\frac{1243}{580}$ eV = 2.143 eV

From figure 3, we find 580nm wavelength is in direct bandgap region. Hence,putting E=2.143eV in the equation given in Figure 3,we get,

$$2.143=1.91+0.61x$$

Which gives, **x= 0.38**

Therefore**, $(Al_{0.38}Ga_{0.62})_{0.5}In_{0.5}P$ on GaAs substrate** is chosen as desired LED material.

<u>Material Properties:</u>

From **reference 1**,we get,
Electron effective mass, me= 0.094*m0
Hole effective mass,mh= 0.62*m0
From **reference 2**,we get,
electron mobility,mu_e= 100
hole mobility,mu_h= 7

From **reference 3**,
refractive index of semiconductor,nr1= 2.5
From **Labsheet**, we take,
Coefficient for band-band recombination,Br= 1e-10;
conc. of recombination centers sr= 1e-14
capture cross-section,Nt= 1e2;
refractive index of air,nr2 = 1
ideality factor,nf= 1
Area in cm^2,A = 1e-2
n type doping profile,Nd = 5e17
p type doping profile, Na = 1e15
excess carrier in p side, del_n = 1e18
excess carrier in n side, del_p = del_n

<u>Necessary Equations:</u>

Hole concentration in n type, p_No = ni^2/Nd
Elec concentration in p type, n_Po = ni^2/Na
Fermi-level for electron, Efn = -kbT*log(Nd/ni)
Fermi-level for hole, Efp = kbT*log(Na/ni
Diffusion coeffecient of elec, Dn = kbT*mu_e
Diffusion coeffecient of hole, Dp = kbT*mu_h;
Diffusion lifetime of elec, tau_r_N = 1/(Br*(Nd+p_No+del_p))
Diffusion lifetime of hole, tau_r_P = 1/(Br*(n_Po+Na+del_n))
Diffusion length of elec, Ln = (Dn*tau_r_N)^0.5*1e-2

Diffusion length of hole, Lp = (Dp*tau_r_P)^0.5*1e-2
Reduced mass, mr = (me*mh)/(me+mh)
Thermal velocity of electron, vth = sqrt((3*kbT*q)/mr)*1e2
Indirect recombination lifetime, tnr = (sr*vth*Nt)^-1
Spontaneous Emmission Rate or Injection Electroluminiscent Rate per unit volume,rsp=

$$R_{sp} = \frac{8\pi n_r^2 (k_B T)^4}{c^2 h^4} \int_0^\infty \frac{\alpha(\nu) u^3}{e^u - 1}$$

Injection Efficiency, nin= (Dn*n_Po/Ln)/((Dn*n_Po/Ln)+(Dp*p_No/Lp))
Radiative Recombination Efficiency(IQE), nr= 1/(1+(tau_r_N/tnr))
Extraction Efficiency,ne=(1/2)*(1-cos(crit_ang))*Ft
Where, crit_ang = asin(nr2/nr1);
Ft= (1/4)*(nr2/nr1)^2*(1-((nr1-nr2)/(nr1+nr2))^2)
Luminous Efficiency, nl= V/P
Where, V=sum(emission*sensitivity)
Reverse saturation current,Is= q*A*((Dn*n_Po)/Ln + (Dp*p_No)/Lp);
Current in mA,I= Is.*exp((V)./(nf*kbT))*1e3

Results:

Emission Spectra:

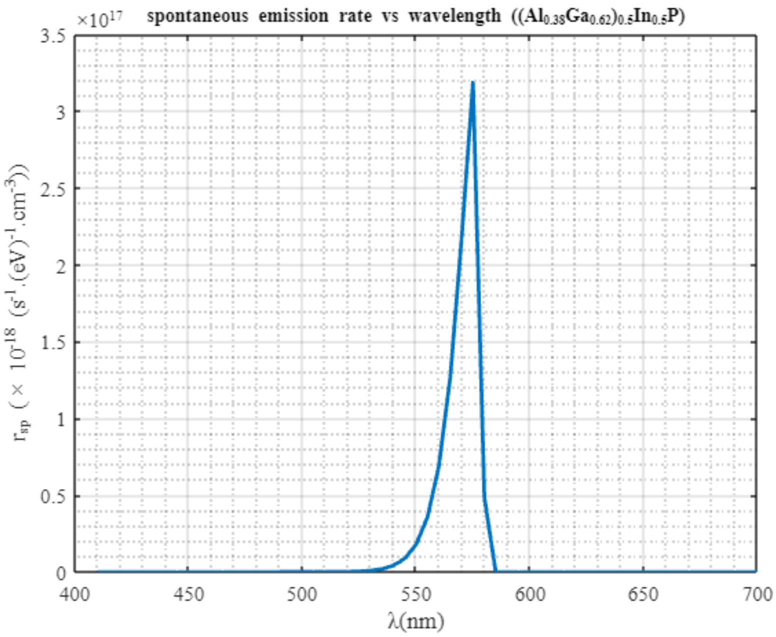


Figure 4: Spontaneous emission rate vs wavelength

From Figure 4, we find emission spectra show its peak at approximately 580nm

L-I Characteristics:

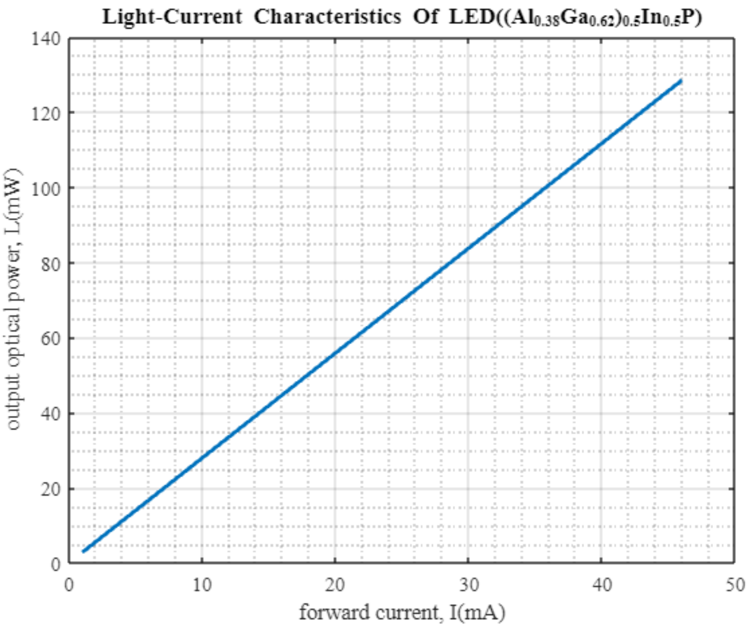


Figure 5: Output Optical Power vs Forward Current

I-V Characteristics:

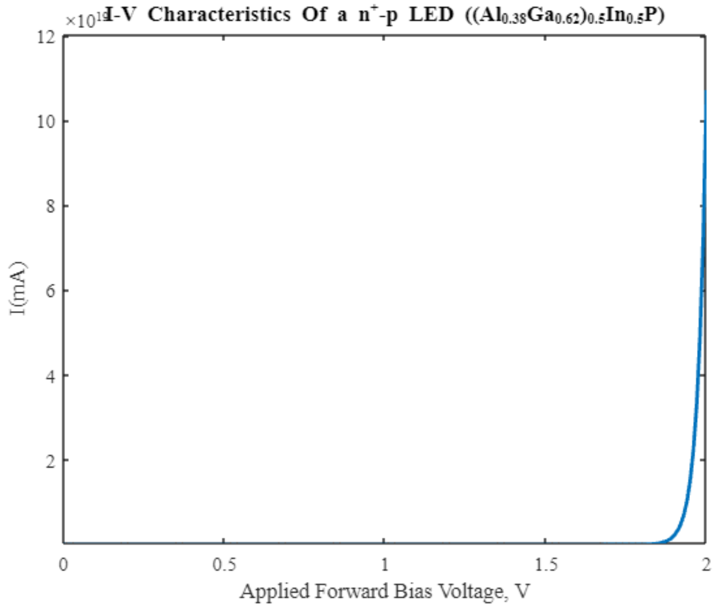


Figure 6: Current vs applied forward bias Voltage

Efficiency:

Injection efficiency, ni	99.95%
Rediative recombination efficiency, nr	99.99%
Extraction efficiency, ne	0.1363%
Luminous efficiency, nl	91.84%

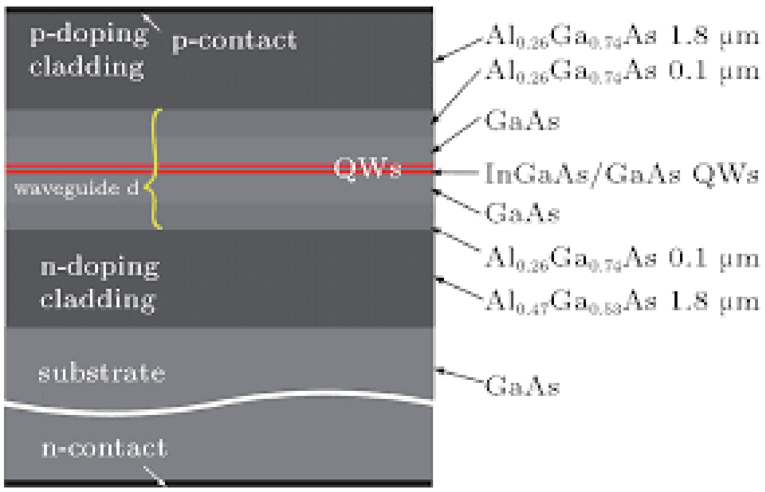
References:

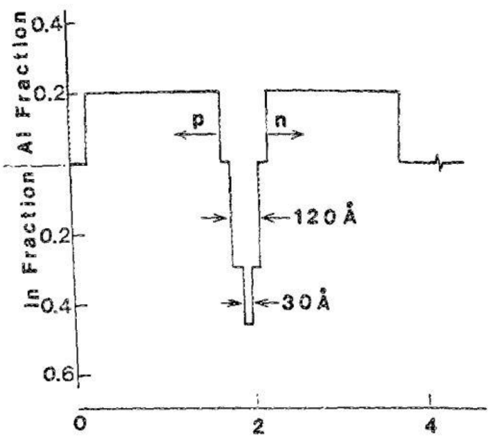
1) https://www.researchgate.net/publication/257950231_Efficiency_droop_in_AlGaInP_and_GaInN_light-emitting_diodes
2) https://aip.scitation.org/doi/10.1063/1.349041

3) https://aip.scitation.org/doi/10.1063/1.355824
4) https://aip.scitation.org/doi/10.1063/1.123810

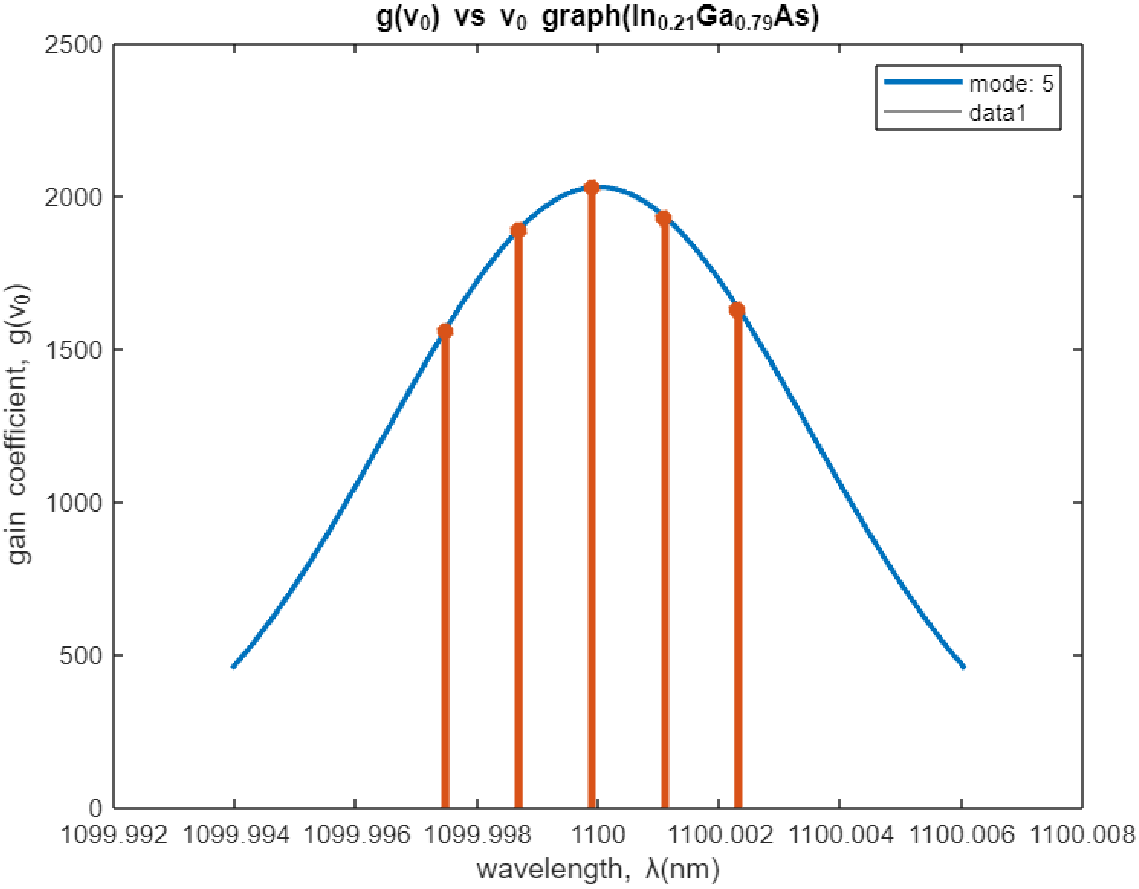
Design of LASER

Laser emission wavelength = 1100 nm

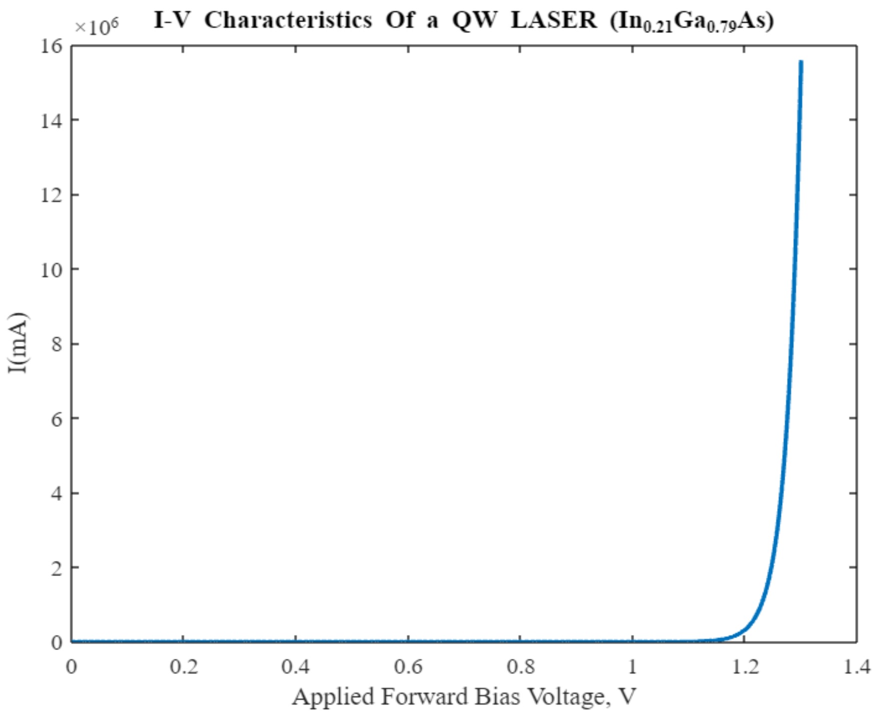




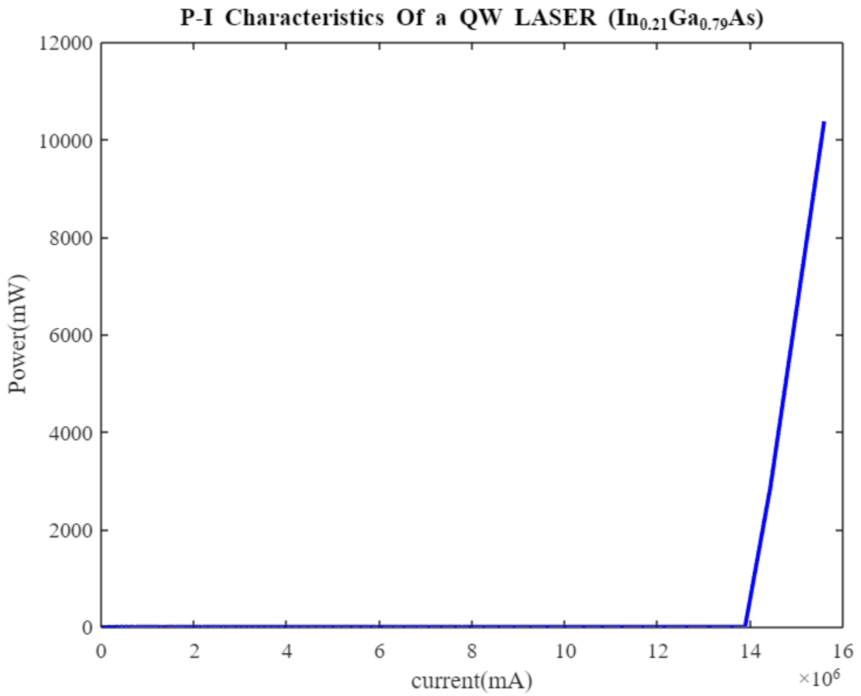
Gain Curve:



I-V Characteristics:



L-I Characteristics:



Efficiency:

Slope efficiency, ni	0.64%
Internal Quantum Efficiency, n_IQE	99.99%
External Quantum Efficiency, n_EQE	6.18e-21%
External Differential Quantum Efficiency, n_EDQE	9.16e-20 %
Extraction efficiency, n_EE	68%
Power Conversion efficiency, n_PCE	0.33%

Design of Photodetector

Laser emission wavelength = 1100 nm

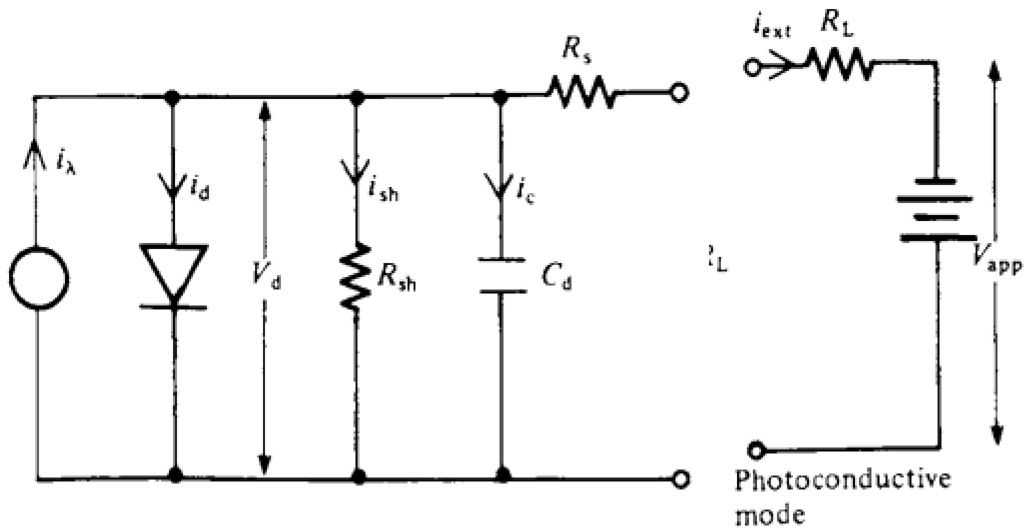
So, chosen photodiode material is InGaAs p-i-n since its range is 800-1700 nm. We chose type photodiode for it is cheaper than avalanche type photodiode (PD). The bandgap corresponding to 1100 nm is 1.13 eV. Bandgap of InAs and GaAs are 0.35eV and 1.43 eV. So, using Vegard's law the composition for In and Ga have been determined to be 0.271 and 0.729 respectively. GaAs is used as the substrate.

TABLE 5.2 **Typical characteristics of some *pn* junction–, *pin*-, and APD-type photodiodes based on GaP, GaAsP, Si, Ge, InGaAs, InAs, and InSb, covering the range from the ~200 nm in the UV (GaP), to ~5 μm in the infrared (InSb)**

Photodiode	λ_{range} (nm)	λ_{peak} (nm)	R at λ_{peak} (A W^{-1})	Gain	I_d for 1 mm^2	Features
GaP *pin*	150–550	450	0.1	<1	1 nm	UV detection[a]
GaAsP *pn*	150–750	500–720	0.2–0.4	<1	0.005–0.1 nA	UV to visible, covering the human eye, low I_d
GaAs *pin*	570–870	850	0.4–0.5	<1	0.1–1 nA	High speed, low I_d
Si *pn*	200–1100	600–900	0.5–0.6	<1	0.005–0.1 nA	Inexpensive, general purpose, low I_d
Si *pin*	300–1100	800–1000	0.5–0.6	<1	0.1–1 nA	Faster than *pn*
Si APD	400–1100	800–900	0.4–0.6[b]	10–10^3	1–10 nA[c]	High gains, fast
Ge *pin*	700–1800	1500–1580	0.4–0.7	<1	0.1−1 μA	IR detection, fast
Ge APD	700–1700	1500–1580	0.4–0.8[b]	10–20	1−10 μA[c]	IR detection, fast
InGaAs *pin*	800–1700	1500–1600	0.7–1	<1	1–50 nA	Telecom, high speed, low I_d
InGaAs APD	800–1700	1500–1600	0.7–0.95[b]	10–20	0.05−10 μA[c]	Telecom, high speed, and gain
InAs *pn*	2−3.6 μm	3.0−3.5 μm	1–1.5	<1	>100 μA	Photovoltaic mode; normally cooled
InSb *pn*	4−5.5 μm	5 μm	3	<1	Large	Photovoltaic mode; normally cooled

Notes: I_d is the typical dark current under normal operating conditions. The dark current depends on the device area, and the values are typical for 1 mm^2. [a]FGAP71 (Thorlabs); [b]At M = 1; [c]At operating multiplication.

Photodiode Equivalent Circuit:



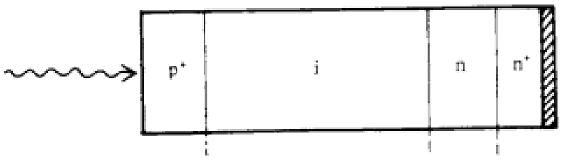
Photocurrent Equation:

$$i_{ext} = i_{ph} = \frac{n_e I_o A e \lambda_o}{hc}$$

$$V_{ext} = \frac{kT}{e} \ln\left(\frac{n_e \lambda_o A}{hci_o}\right) + \frac{kT}{e} \ln(I_o)$$

Fraction of the incident power that is absorbed within the i layer is:

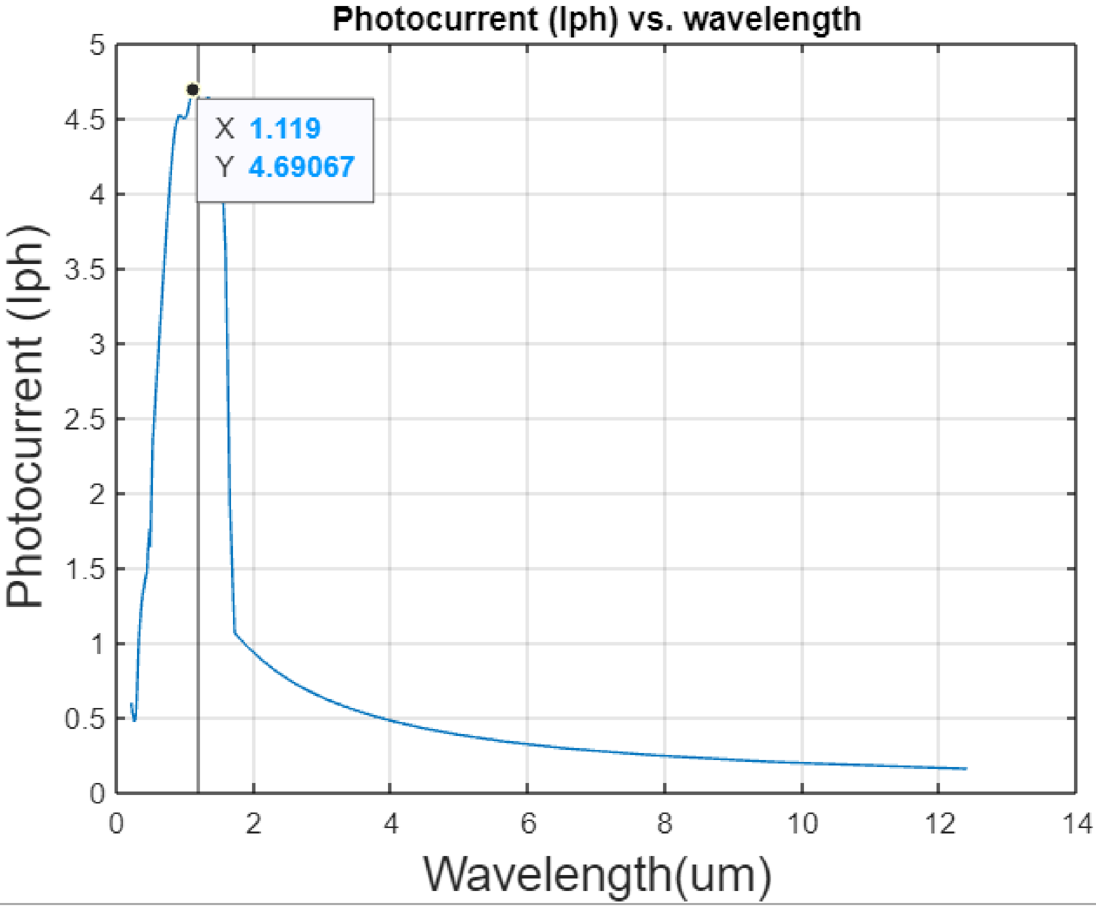
$ne = (1 - R)[\exp(-\alpha * wp) - \exp[-\alpha * (wp + wi)]]$; wp and wi are the thickness of p and I regions. α is the absorption coefficient.



R is the surface reflectance given by the formula:

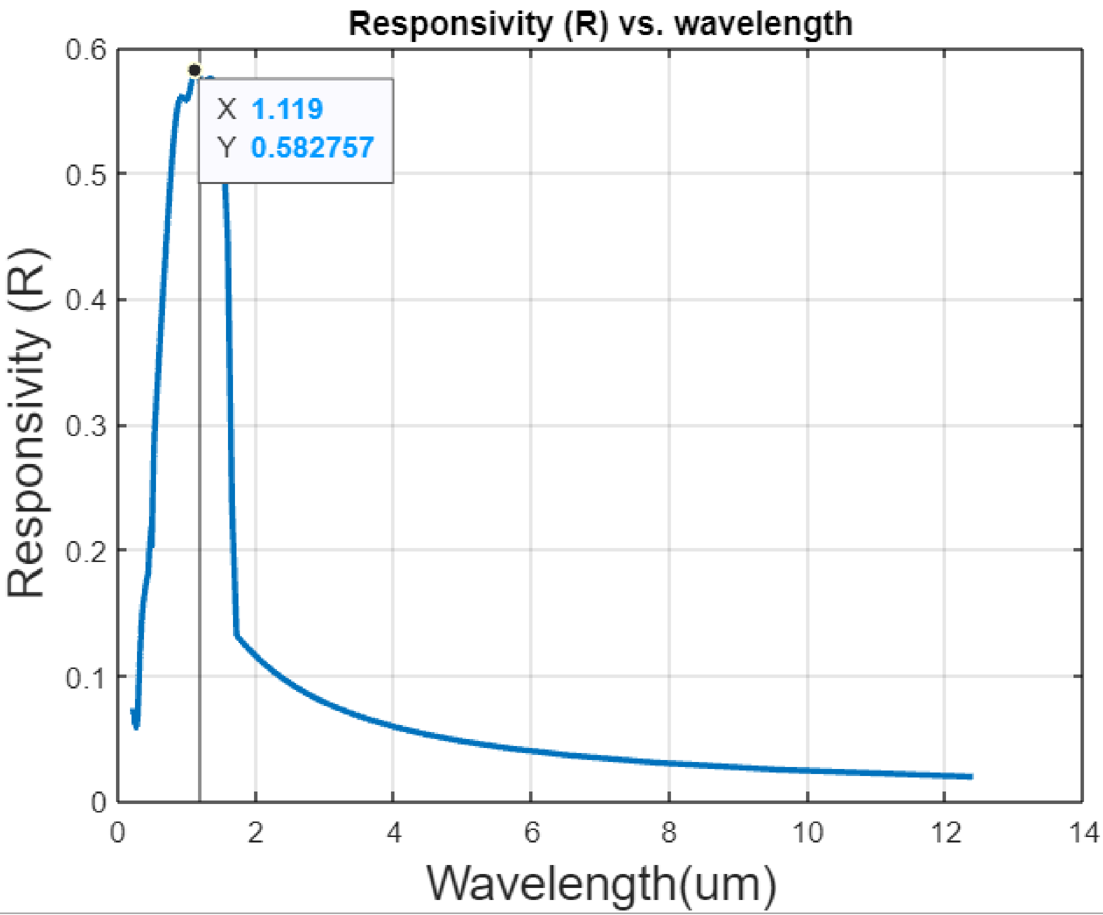
$R = \frac{(n-1)^2+k^2}{(n+1)^2+k^2}$, where n + ik is the complex refractive index.

Photocurrent vs Wavelength:



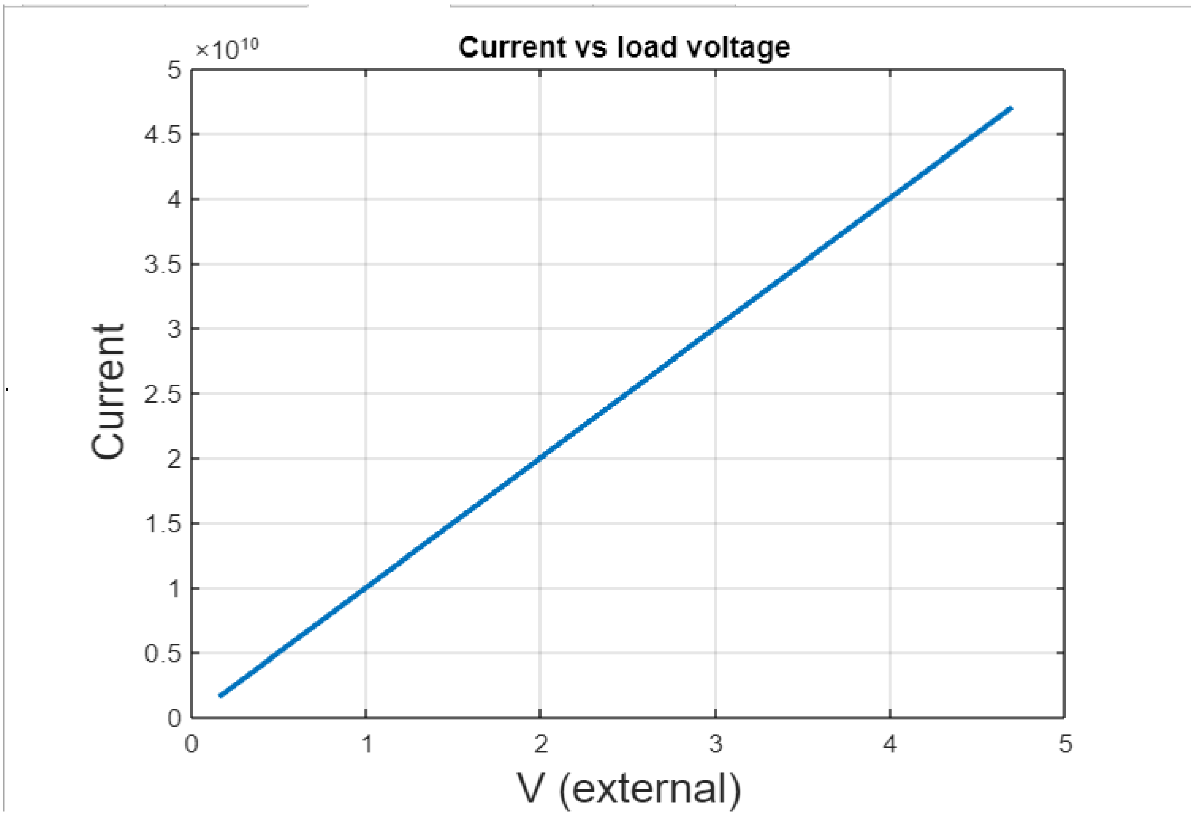
Irradiance of light, Io = 500Wm^-2
wp = 0.005 %um
wi = 1; %um
For this particular wp and wi we see that Iph, the photocurrent is maximum at 1100 nm.

Responsivity vs Wavelength:

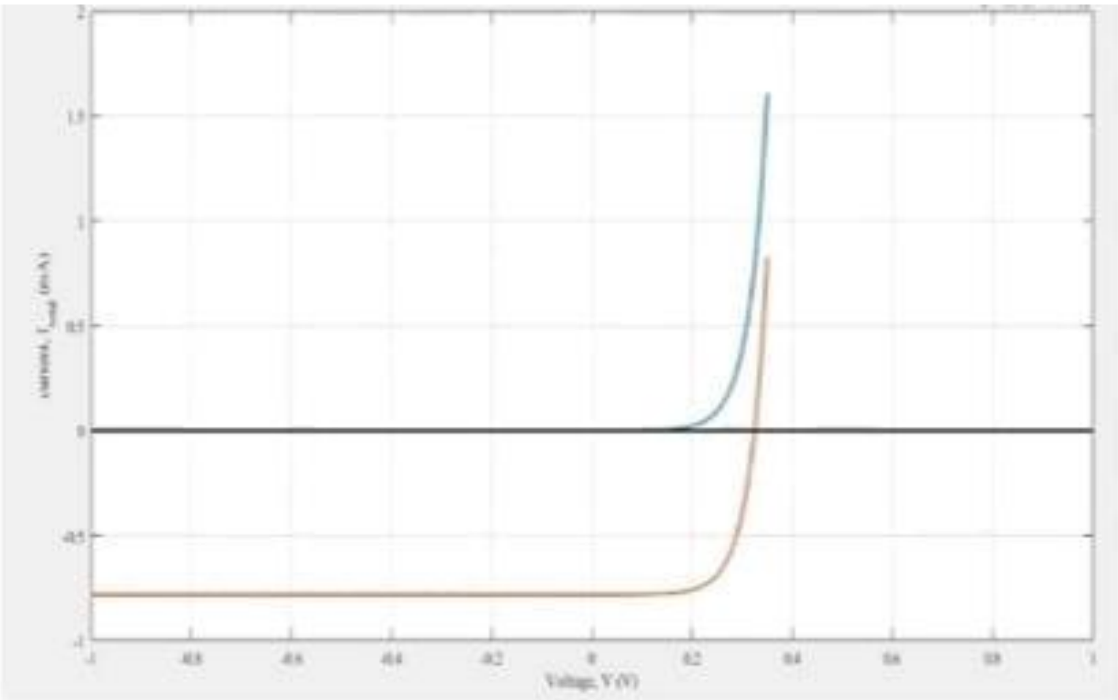


Responsivity, R = ne*lambda

Current vs load voltage:



I-V curve:



Gain calculation:

$$\text{Rate of electron flow} = \frac{I_{ph}}{e} = \frac{wdJ_{\text{ph}}}{e} = \frac{w\eta_i I\lambda\tau(\mu_e + \mu_h)E}{hc} \quad \textbf{(5.10.7)}$$

However, the rate of electron (*i.e.*, EHP) photogeneration is

$$\text{Rate of electron generation} = (\text{Volume})g_{\text{ph}} = (wd\ell)g_{\text{ph}} = w\ell\frac{\eta_i I\lambda}{hc}$$

The photoconductive gain is then simply

Photo-conductive gain

$$G = \frac{\text{Rate of electron flow in external circuit}}{\text{Rate of electron generation by light absorption}} = \frac{\tau(\mu_e + \mu_h)E}{\ell} \quad \textbf{(5.10.8)}$$

Gain = 0.61

Noise equivalent power and specific Detectivity calculation:

$$\text{NEP} = \frac{P_1}{B^{1/2}} = \frac{1}{R}\left[2e(I_d + I_{ph})\right]^{1/2}$$

$$D^* = \frac{A^{1/2}}{\text{NEP}} \quad \textbf{(5.12.8)}$$

Specific detectivity

NEP at 1100 nm = 6.672 e -14 W Hz^-1/2

D* = 6.7e12 cm Hz^(1/2) W^-1

Dark Current = 6 nA

TABLE 5.5 Typical noise characteristics of a few selected commercial photodetectors

Photodiode	GaP Schottky	Si *pin*	Ge *pin*	InGaAs *pin*	PbS (PC) −10°C	PbSe (PC) −10°C	InSb (P… −10°…
λ_{peak} (μm)	0.44	0.96	1.5	1.55	2.4	4.1	5.5
I_d or R_d	10 pA	0.4 nA	3 μA	5 nA	0.1−1 MΩ	0.1−1 MΩ	1−10 k…
NEP (W Hz$^{-1/2}$)	5.4×10^{-15}	1.6×10^{-14}	1×10^{-12}	4×10^{-14}			−
D^* (cm Hz$^{1/2}$ W^{-1})	1×10^{13}	1×10^{12}	1×10^{11}	5×10^{12}	1×10^{9}	5×10^{9}	1×1…

Notes: PC means a photoconductive detector, whose photoconductivity is used to detect light. For PC detectors, what is important i… the dark resistance R_d, which depends on the temperature.

NEP, D*, Id all match with the typical values of InGaAs pin photodiode.

Typical Characteristics of $In_{0.271}Ga_{0.729}As$ pin:

Photodiode	Lamb range (nm)	Lamb peak (nm)	R lamb peak (AW 1)	Ga	Id 1 mm
$In_{0.271}Ga_{0.7}$ As pin	800 170	119	0.5	0.6	6n

Solar Cell:

Open-Circuit Voltage

The open-circuit voltage, V_{OC}, is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current. The open-circuit voltage is shown on the I-V curve in Fig. 4.2.

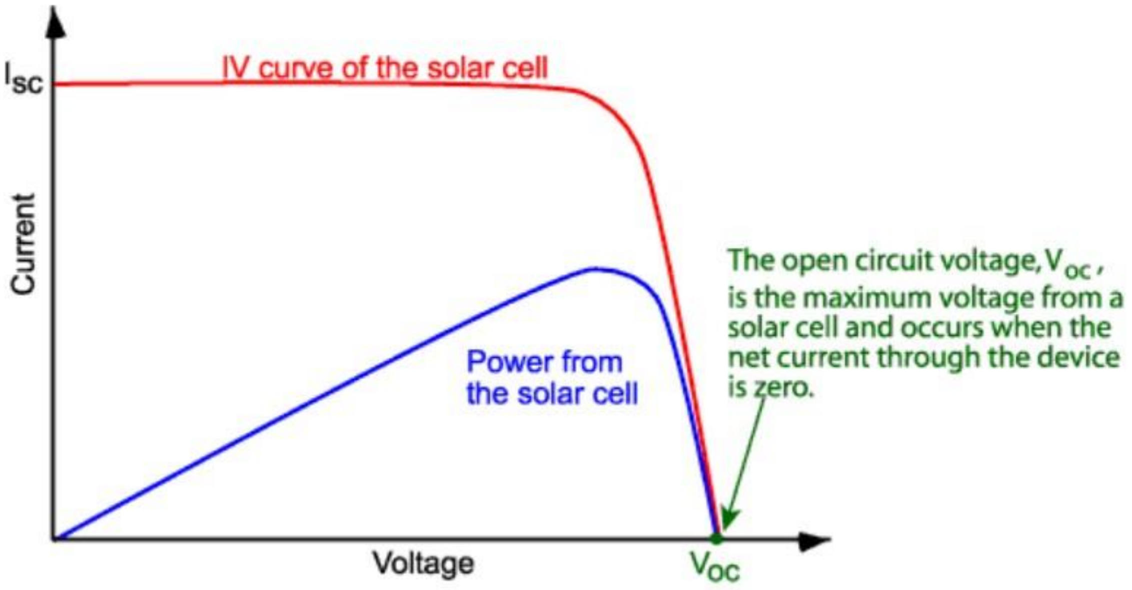


Fig. 4.1 IV curve of a solar cell showing the open-circuit voltage

An equation for V_{oc} is found by setting the net current equal to zero in the solar cell equation to give:

$$V_{OC} = \frac{nkT}{q} \ln\left(\frac{I_L}{I_0} + 1\right)$$

Where Dark Current Io can be found using this equation:

$$I_o = -qA\left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p\right)$$

Where D represents the Diffusion Coefficient and L represents the Diffusion Length. Also subscript n and p belong to the side of n type and p type where the minority charge will be diffused. Also we have to take care of cross sectional areal and minority charge carrier density of both edges.

The V_{OC} can also be determined from the carrier concentration:

$$V_{OC} = \frac{kT}{q} \ln\left[\frac{(N_A + \Delta n)\Delta n}{n_i^2}\right]$$

where kT/q is the thermal voltage, N_A is the doping concentration, Δn is the excess carrier concentration and n_i is the intrinsic carrier concentration. The determination of V_{OC} from the carrier concentration is also termed Implied V_{OC}.

Short-Circuit Current

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). Usually written as ISC, the short-circuit current is shown on the IV curve in Fig. 4.3

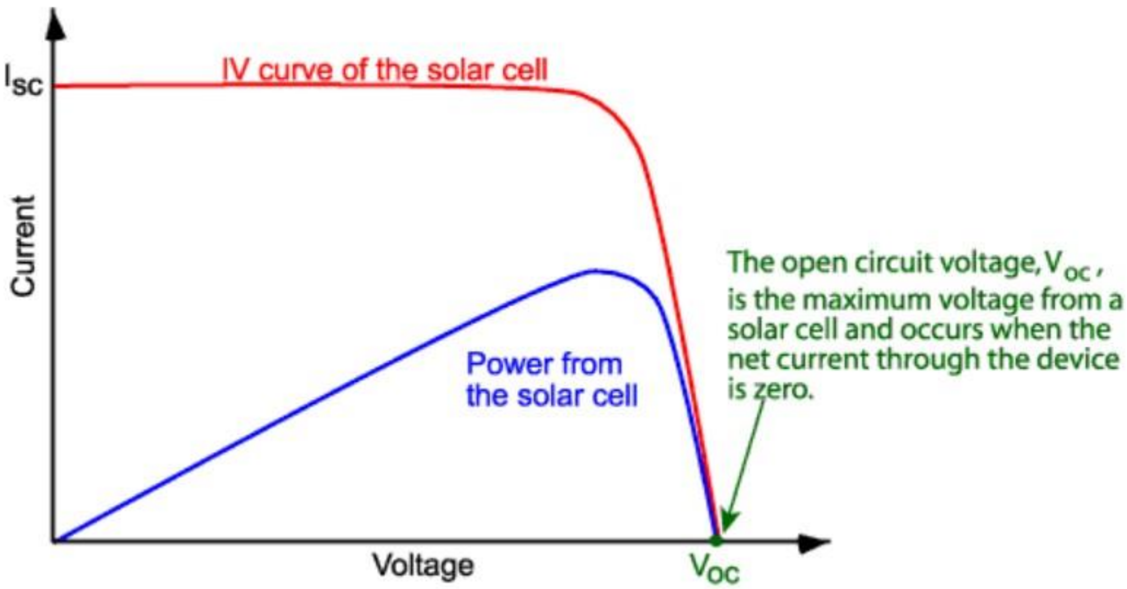


Fig. 4.2 IV curve of a solar cell showing the open-circuit voltage

Fill Factor

The short-circuit current and the open-circuit voltage are the maximum current and voltage respectively from a solar cell. However, at both of these operating points, the power from the solar cell is zero. The "fill factor", more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of
V_{oc} and I_{sc} so that

$$FF = \frac{P_{MP}}{V_{OC} \times I_{SC}}$$

Series Resistance

Series resistance in a solar cell has three causes: firstly, the movement of current through the emitter and base of the solar cell; secondly, the contact resistance between the metal contact and the silicon; and finally the resistance of the top and rear metal contacts. The main impact of series resistance is to reduce the fill factor, although excessively high values may also reduce the
short-circuit current.

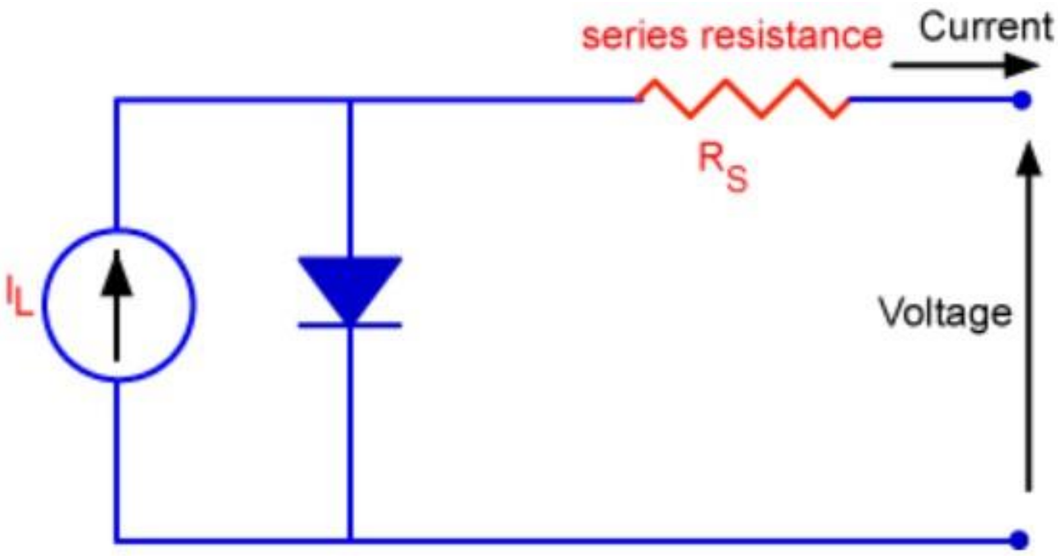


Fig 4.3 Schematic of a solar cell with series resistance.

Shunt Resistance

Significant power losses caused by the presence of a shunt resistance, R_{SH}, are typically due to manufacturing defects, rather than poor solar cell design. Low shunt resistance causes power losses in solar cells by providing an alternate current path for the light-generated current. Such a diversion reduces the amount of current flowing through the solar cell junction and reduces the voltage from the solar cell. The effect of a shunt resistance is particularly severe at low light levels, since there will be less light-generated current. The loss of this current to the shunt therefore has a larger impact. In addition, at lower voltages where the effective resistance of the
solar cell is high, the impact of a resistance in parallel is large.

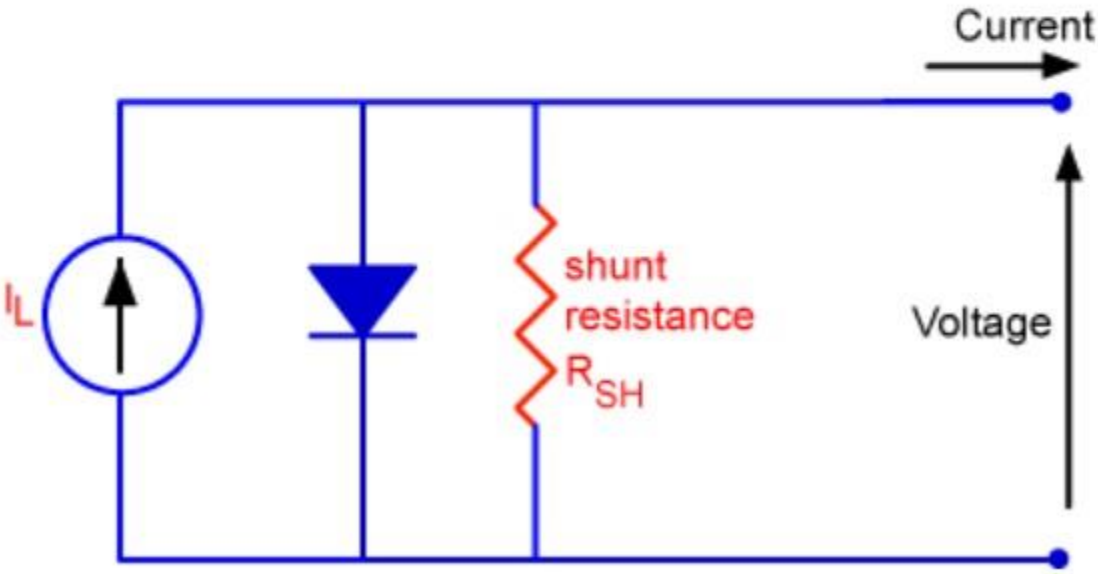


Fig 4.4 Circuit diagram of a solar cell including the shunt resistance.

Designed P-V Cell

Our PV Cell Structure is drawn in Fig.4.1 with combination of n-type and p-type layer or two si crystal. For Practical scenario we have considered an Anti-Reflectig-Coating here to restrict the right reflection from the incident light on the deplation barrier.

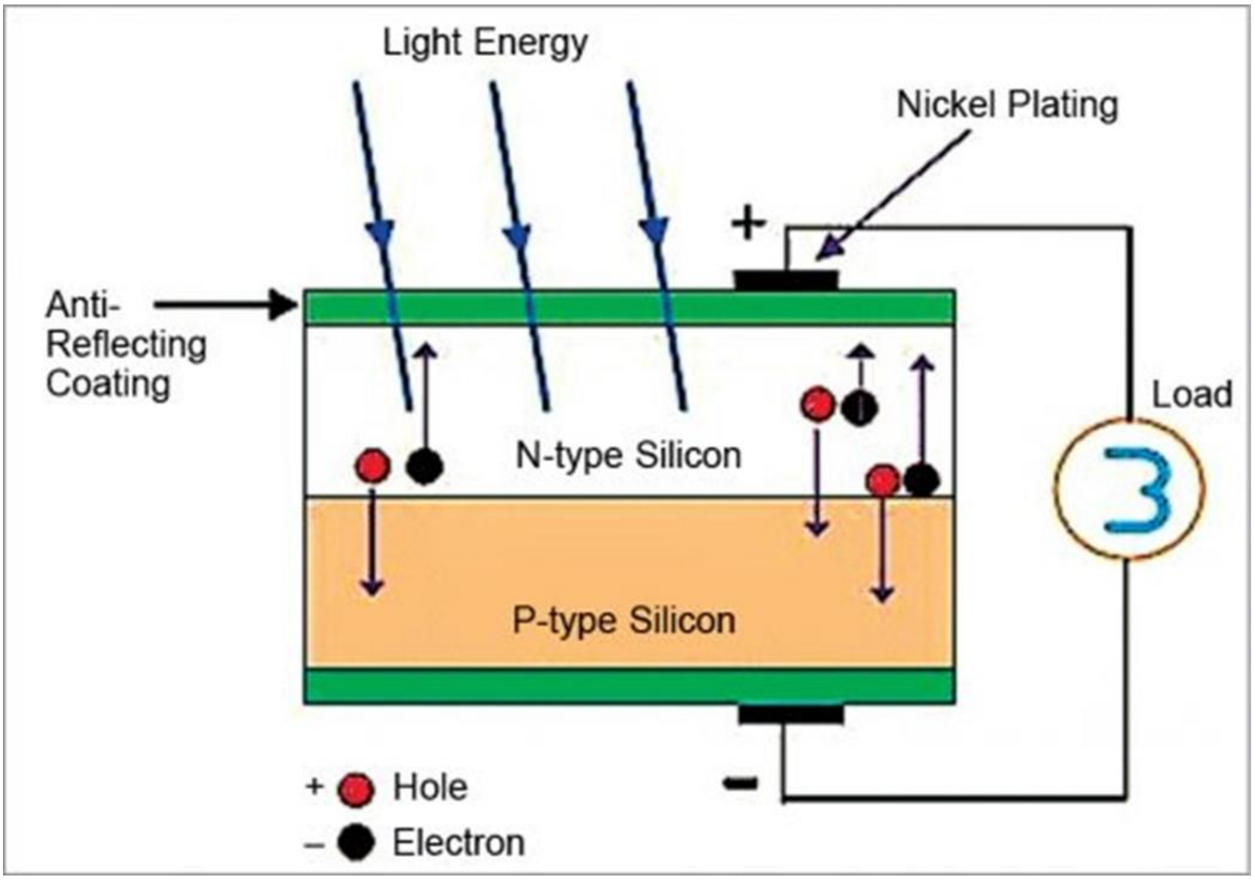
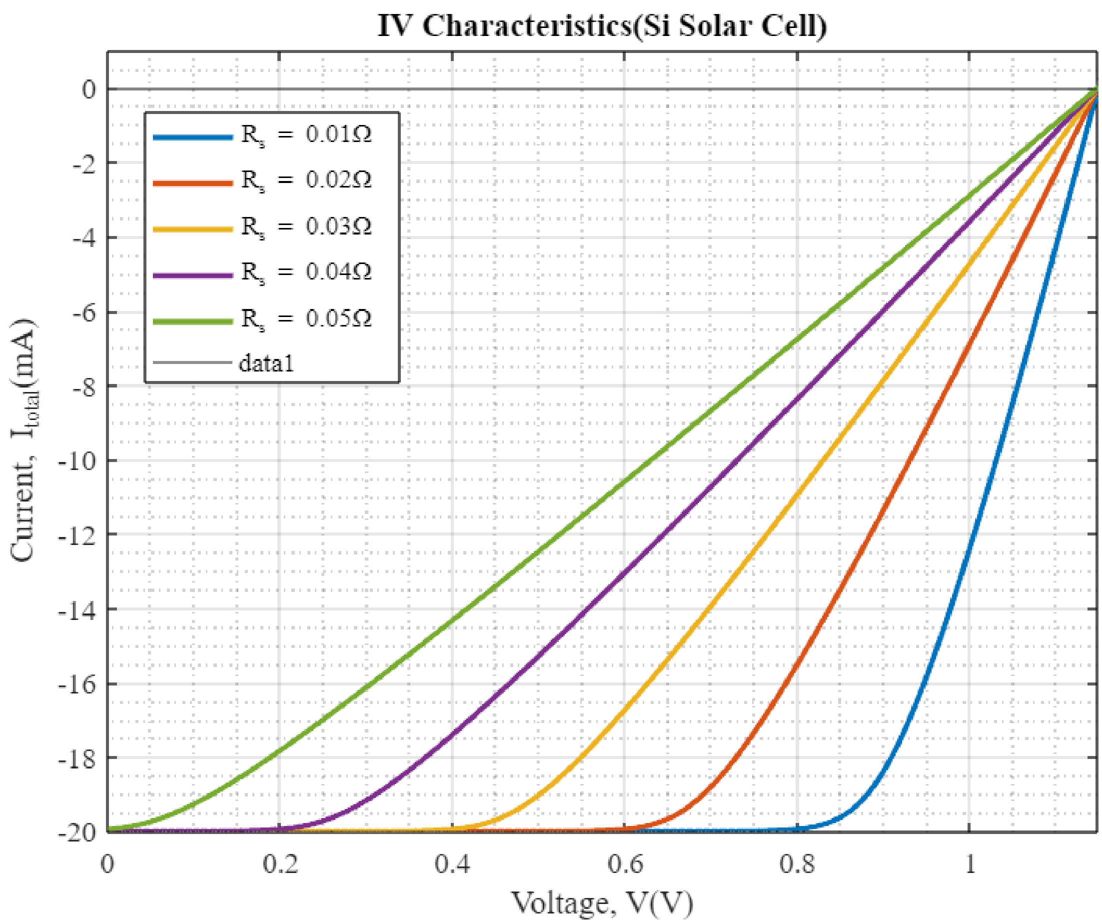
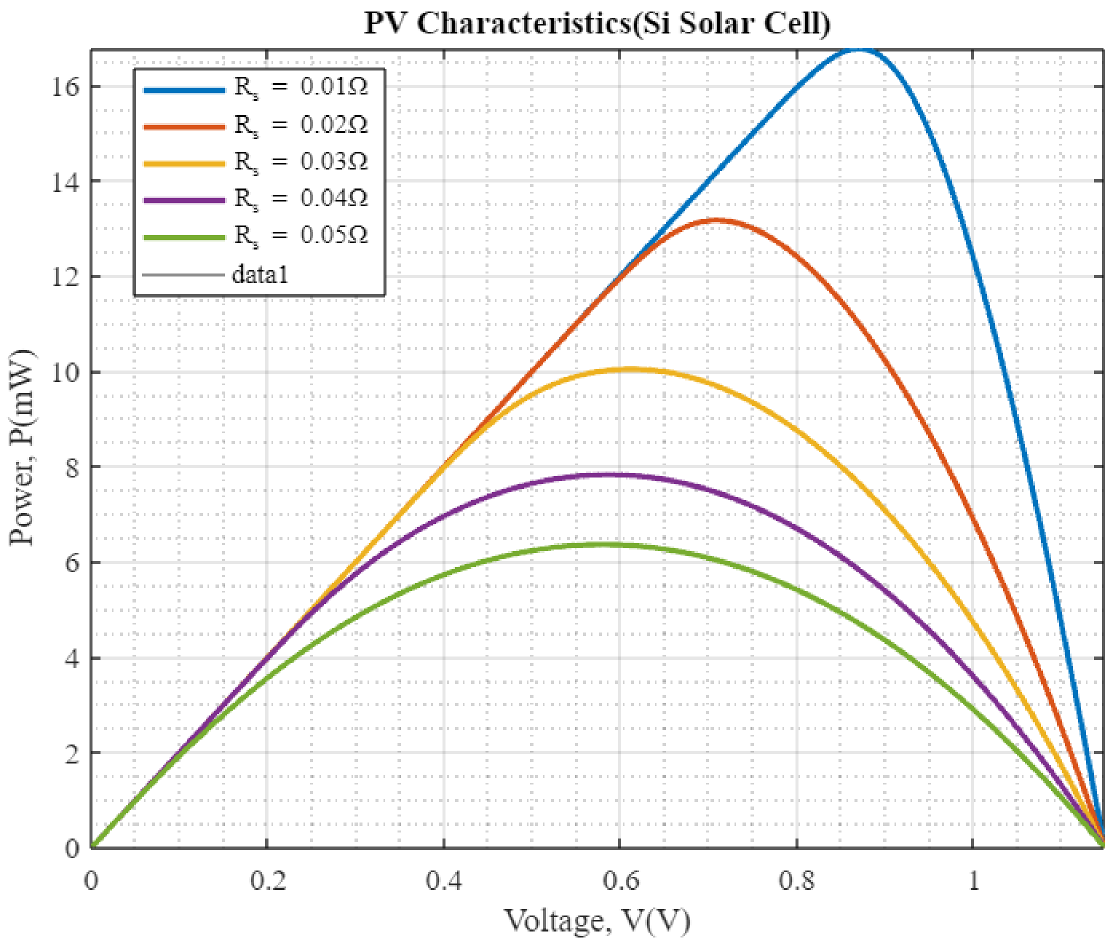
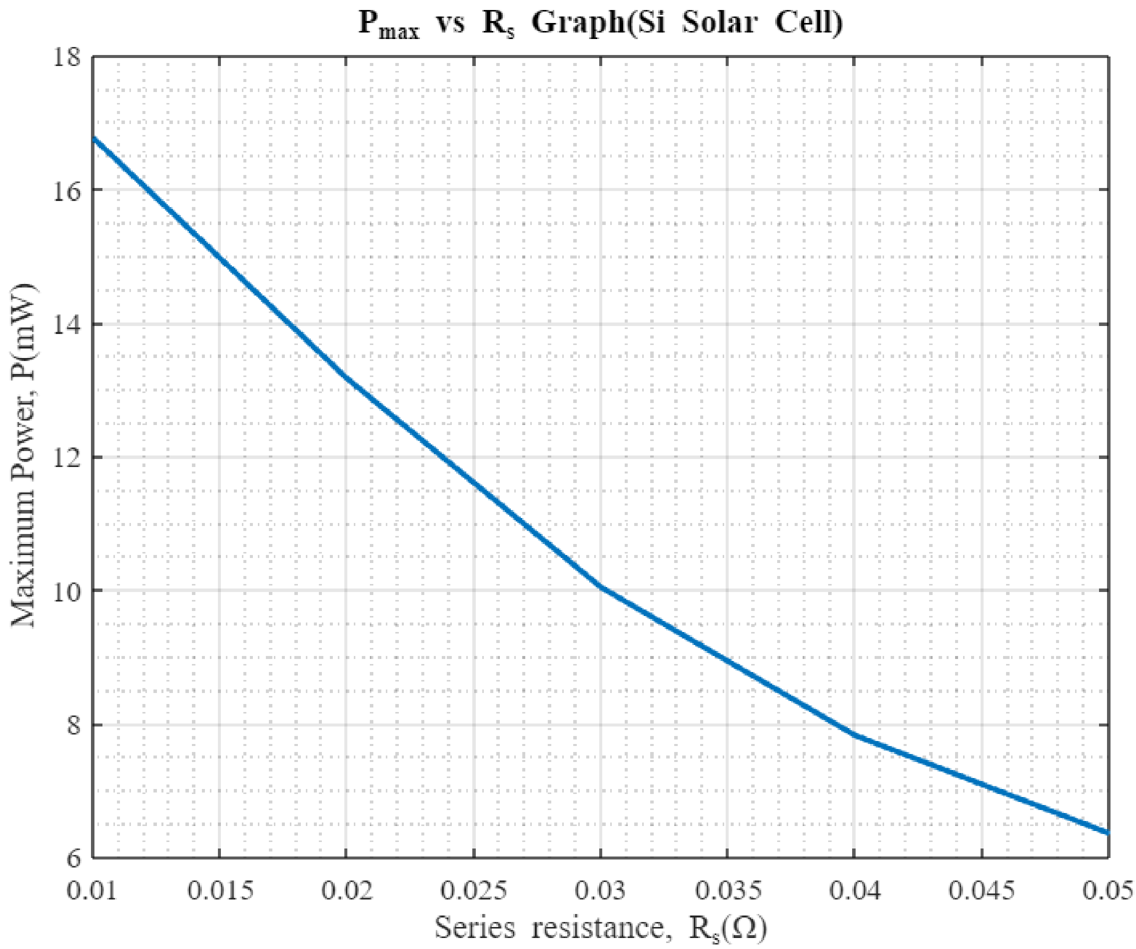


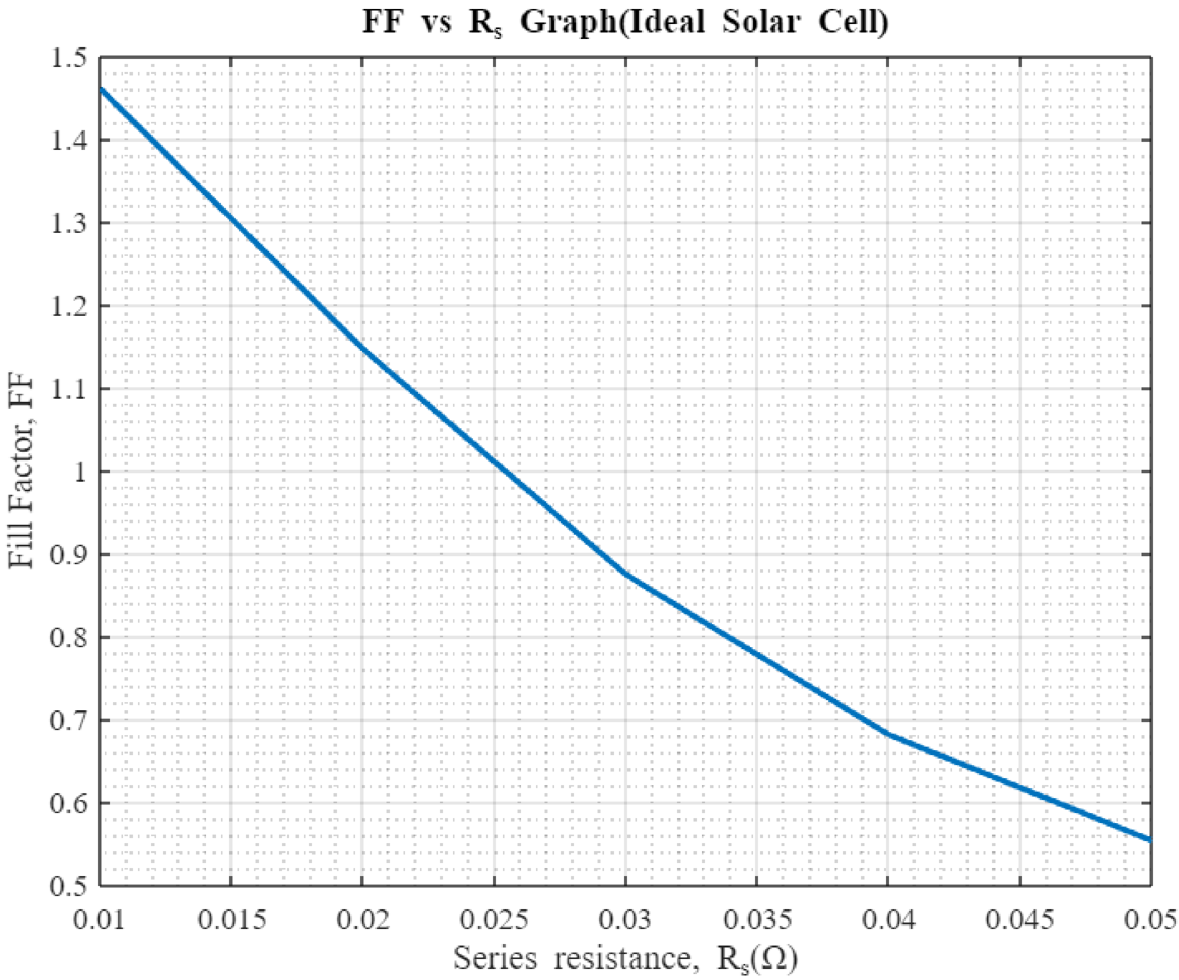
Fig. 4.5 Schematic Diagram of P-V Cell



IV Characteristics(Si Solar Cell)
Current, I_{total}(mA)
Voltage, V(V)
$R_s = 0.01\Omega$
$R_s = 0.02\Omega$
$R_s = 0.03\Omega$
$R_s = 0.04\Omega$
$R_s = 0.05\Omega$
data1
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
0.2
0.4
0.6
0.8
1


PV Characteristics(Si Solar Cell)
R_s = 0.01Ω
R_s = 0.02Ω
R_s = 0.03Ω
R_s = 0.04Ω
R_s = 0.05Ω
data1
Power, P(mW)
Voltage, V(V)
0
2
4
6
8
10
12
14
16
0
0.2
0.4
0.6
0.8
1


P_{max} vs R_s Graph(Si Solar Cell)
Maximum Power, P(mW)
18
16
14
12
10
8
6
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
Series resistance, $R_s(\Omega)$


FF vs R_s Graph(Ideal Solar Cell)
Fill Factor, FF
Series resistance, R_s(Ω)
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05