Solar Energy Harvesting 11

11.1 Photovoltaic Cells (PVC) Introduction

The sun is a serious and vital source of energy, without which there would be no life on the planet. Plants get most of their energy from the sun by a process called photosynthesis (Jordan et al. 2001). Though fascinating and beautiful, the mechanism of photosynthesis is beyond the scope of this book, and the interested reader is advised to follow up the vast literature on this subject which encompasses physics, chemistry, and biology. But a part of the sun's energy can also be harvested artificially using photoconductive devices (Pohlman, Heeger). This subject and technology has become of supreme importance since the realization that fossils fuels are slowly but surely destroying our planet. The sun emits light over a broad spectrum of frequencies as shown in Fig. 11.1.

The process of photon harvesting is illustrated in Fig. 11.2, and one can see that semiconducting p-n junctions (Chap. 6, this book) are the ideal way to collect the photonic power. But there are restrictions here too. One can see from the diagrams that the photon energy must exceed the bandgap of the material to be absorbed efficiently. So depending on the semiconductor in question, "all" the photons above the bandgap can be harvested, but this also means that the solar photons below the bandgap are not harvested. The latter constitutes in general a non-negligible amount. This implies that semiconducting solar cells are not as efficient as they could be if they collected the entire spectrum. Si or GaAs, which are some of the best *PVCs*, leave out the photons below 1 eV (> 1200 nm), and this is an important loss limiting efficiency to ~20%. Indeed, combination cells which are designed to collect a wider range of wavelengths can nowadays reach efficiencies of 45% (see below); the problem is that they are still too expensive for large-scale commercial application.

Long-wavelength collection can be done with type II semiconducting devices (Delaunay et al. 2008), which are also used for long-wavelength photodetection.

M. Razeghi, *Fundamentals of Solid State Engineering*,
https://doi.org/10.1007/978-3-319-75708-7_11

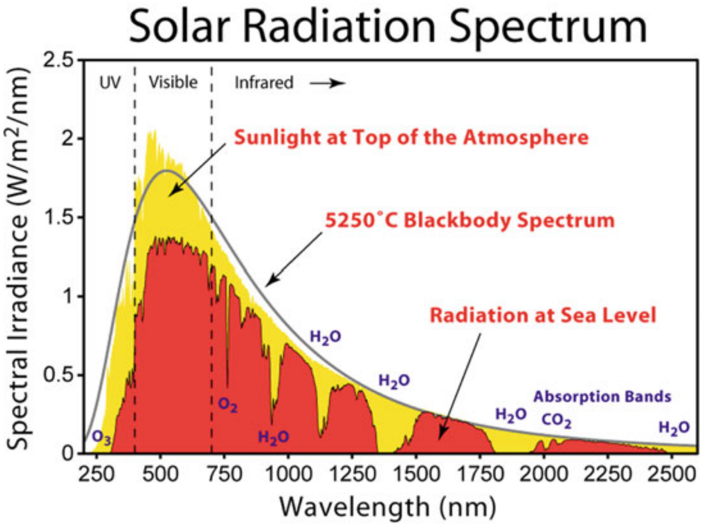


Fig. 11.1 The most important range is in the UV to visible to near-infrared range (300–1000 nm). The total solar power reaching the surface is roughly 1000 W/m^2 on average, a non-negligible amount. The mentioned photon range is ideal for the application of semiconducting p-n junction technology. Remember Fig 9.2 from Chapter 9

Figure 11.3 is a beautiful illustration of a device which can be used for long wavelength (>3 μm; the same geometry is used for making top of the scale photodetectors operating currently at 200 K).

11.2 Examples of Photodiodes

*For commercial use of *PVC* devices, efficiency is not the only criterion. Many applications require mechanical flexibility and thus polymer cells or biocompatibility (plastic electronics implants into the body) (Figs. 11.4, 11.5, and 11.6).

11.3 The Current Voltage Characteristic of a Solar Cell (Figs. 11.7 and 11.8)

$$L = \text{width}$$
$$v_d = \text{drift-velocity}$$
$$\tau = \text{recombination-time}$$

$$\eta = \frac{v_d \tau}{L}[1 - \exp[-L/v_d \tau]] \tag{11.1}$$

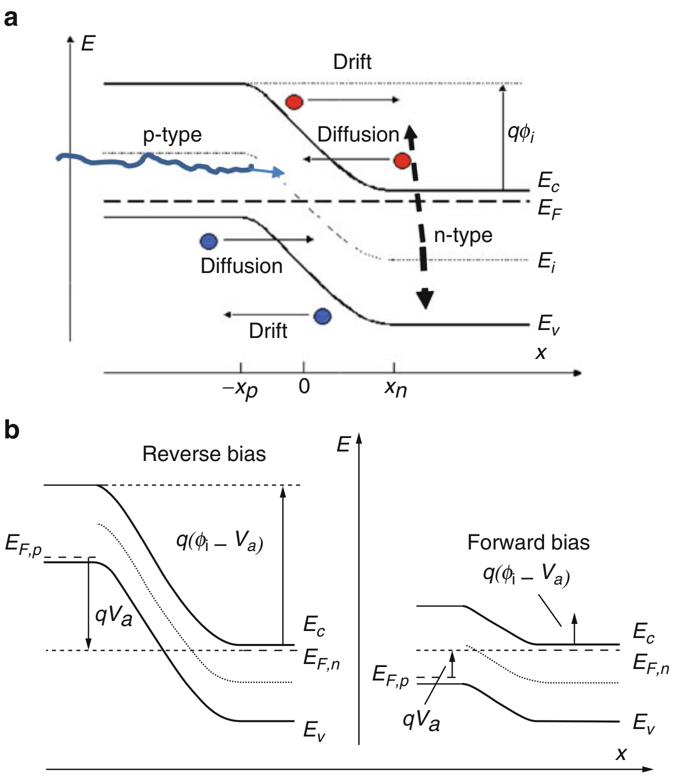


Fig. 11.2 (**a**) A photon (blue wiggly line) comes into the high-field region and excites an electron (red) hole (blue dot) pair across the gap of a p-n junction semiconductor. The electron and hole are subject to an internal space charge field which makes them drift into the electrode regions where they are absorbed, thus creating a current without an applied bias. This current can heat a resistor in series and thus constitutes harvested solar energy. (**b**) Showing (left) a semiconductor junction under reverse and (right) forward bias. Note that reverse biasing enhances the internal field and facilitates charge collection

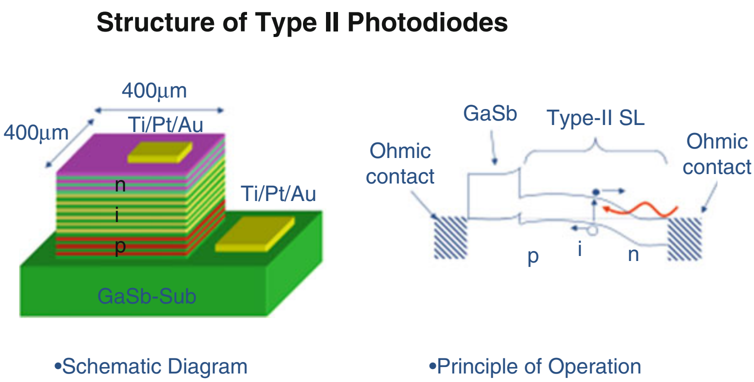


Fig. 11.3 Type II photon detection or light-harvesting structure (Delaunay et al. 2008)

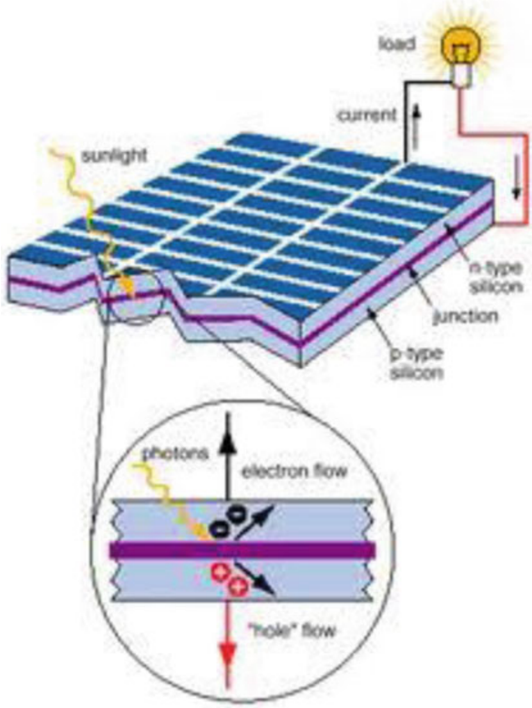


Fig. 11.4 Schematic representation of a photo-harvesting device

Let us now consider the limit in which charges generated in the cell can only drift and are collected at the perfect absorbing electrode, or they recombine in the material with lifetime τ.

$\eta = \text{quantum} - \text{efficiency} =$

$\text{charge} - \text{collected} - \text{per} - \text{photogenerated} - \text{charge}$

$$\eta = \frac{v_d \tau}{L}[1 - \exp[-L/v_d \tau]] \quad (1)$$

$L = \text{width}$

$v_d = \text{drift} - \text{velocity}$

$\tau = \text{recombination} - \text{time}$

Equation 11.1 is the expression for the *QE (quantum efficiency)* η in the drift limit (no back diffusion) (called the *Hecht formula*).

11.3.1 Solar Cell IV Characteristic Curve

It explains how much power can be extracted for a given photogenerated current IV.

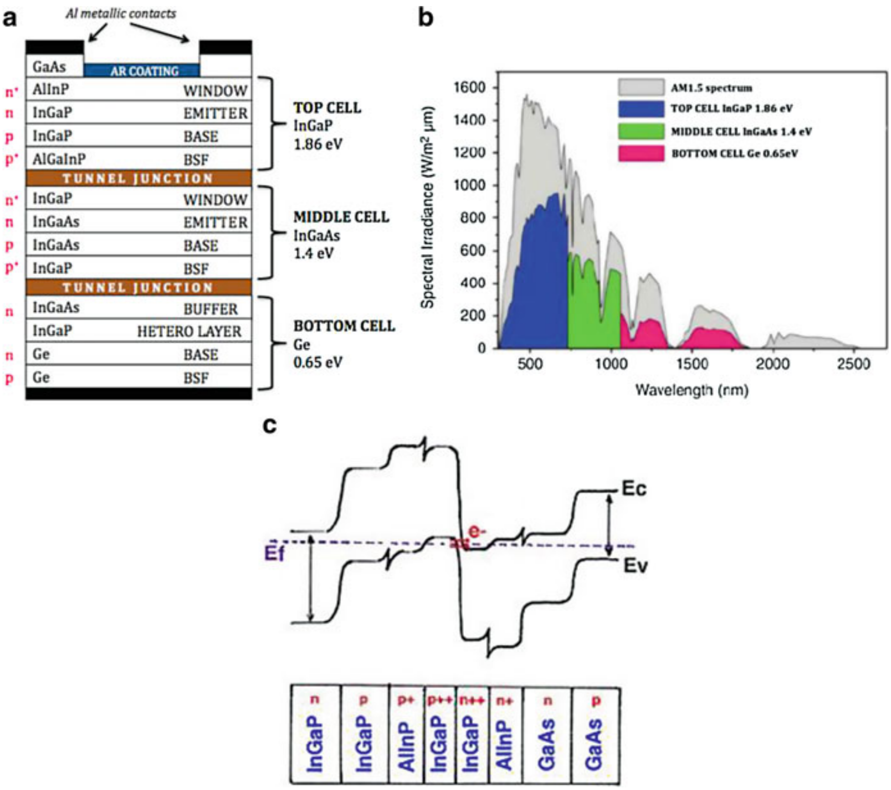


Fig. 11.5 (**a**) (top figures = example of *multijunction cell* structure (left) and harvesting ranges (right), lower figure corresponding band structure) Combination cells which harvest a wider region of the sun's spectrum. Note how the interfacial barrier is designed to be thin enough for carriers to tunnel through, lower figure. (**b**) Band structure of a multijunction cell showing the way the two modules work together. Electrons generated in one module recombine with holes through thin barrier in the other to produce a current (Yamaguchi et al. 2005)

11.4 General Expression for the Quantum Efficiency

Let us consider the semiconductor channel in a p-n junction and model it as a one-dimensional system since the planar motion is uniform. Light impinges from the left a shown in Fig. 11.10 and creates e-h pairs which drift diffuse into the electrodes. This time the electrodes are not considered a being totally absorbing, but they have finite surface recombination velocities s_1 and s_2. The width of the depletion layer is taken as w and $t + w$ is the total length.

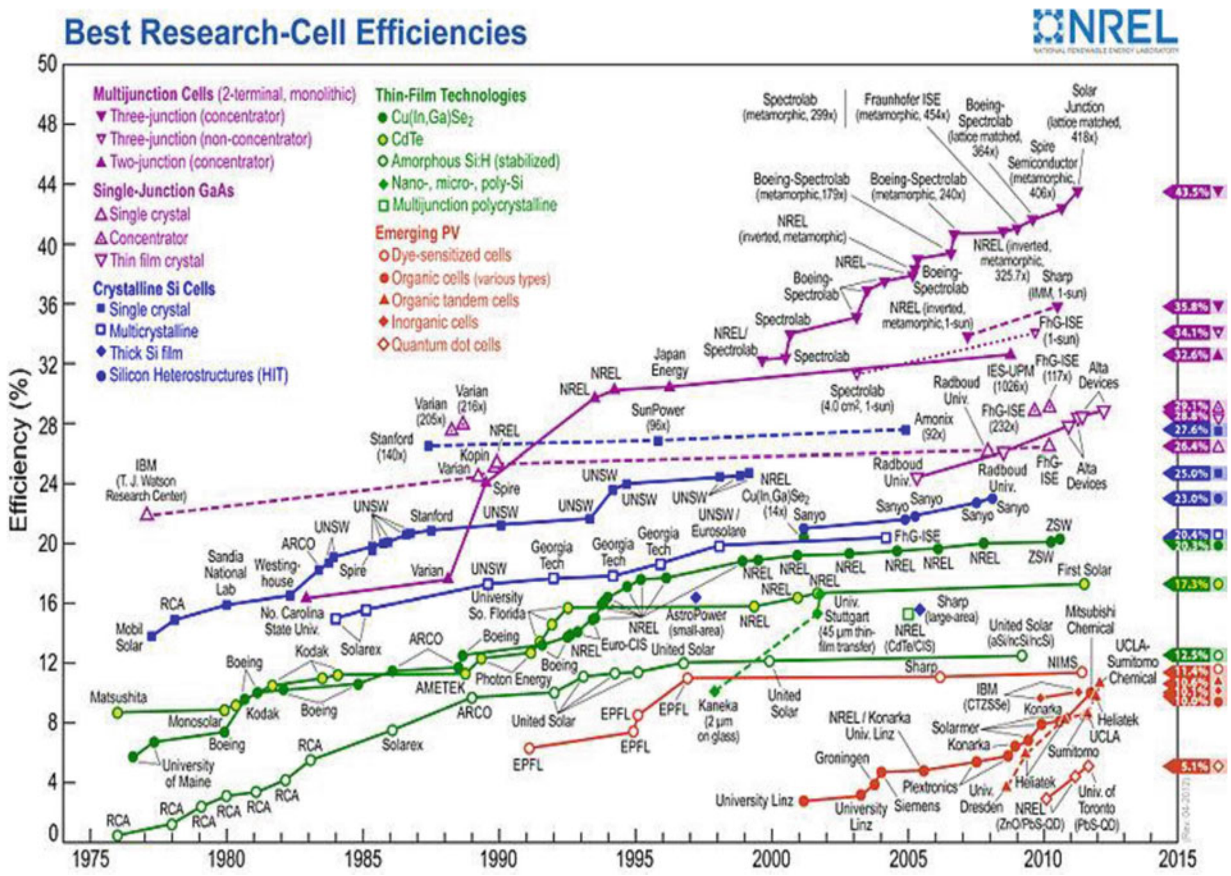


Fig. 11.6 Map of best current solar cell efficiencies in all technologies; this map has to be updated every 6 months

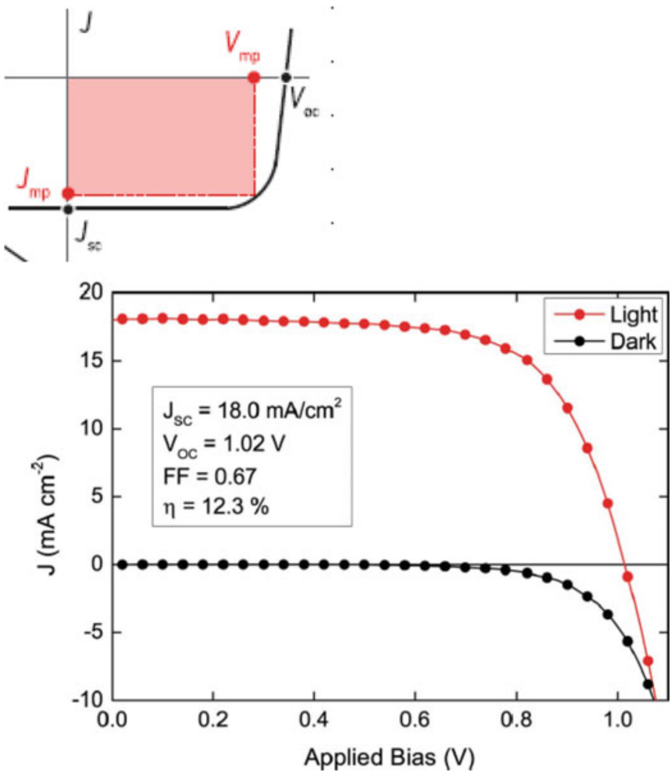


Fig. 11.7 Current voltage characteristic under simulated light of 1.5 suns or 100mw/cm^2 solar irradiation of the best performing perovskite solar cells (η = 12.3%) (From Bail JM, Leed M, Hey A, Henry J Snaith Energy Envir. Sc. Vol.6, p 1739 (2013) "Low-temperature processed meso-superstructured to thin-film perovskite solar cells")

11.5 Some Definitions, Power Collected

Consider Λ = power collection efficiency (not to be confused with quantum efficiency for charge collection η); V_{oc} = *open circuit voltage*, or forward bias at which the bias produced current cancels photocurrent. FF = fill factor of IV curve, deviation of IV curve from perfect rectangular shape; I_{sc} maximum photocurrent at zero bias; see Fig. 11.9.

$$\Lambda = V_{oc} I_{sc} FF / P_{in} \tag{11.2}$$

$$FF = \text{Fill} - \text{factor} \tag{11.3}$$

$$I_{sc} = \text{sat} - \text{current} \tag{11.4}$$

$$P_{in} = \text{total} - \text{power} - \text{incident} \tag{11.5}$$

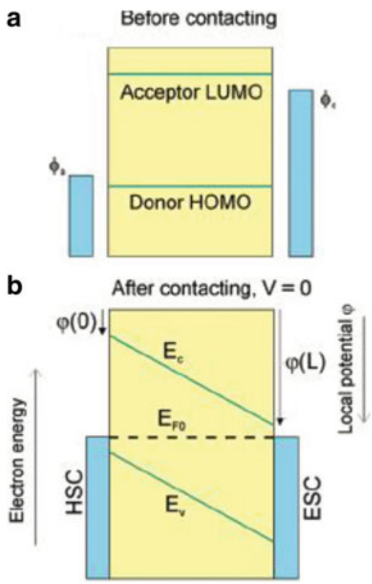


Fig. 11.8 Top diagram, simple semiconductor bands connected to two electrodes where the Fermi energies are roughly matched to the conduction and valence band, respectively, and diagram below the band alignment that follows on contact

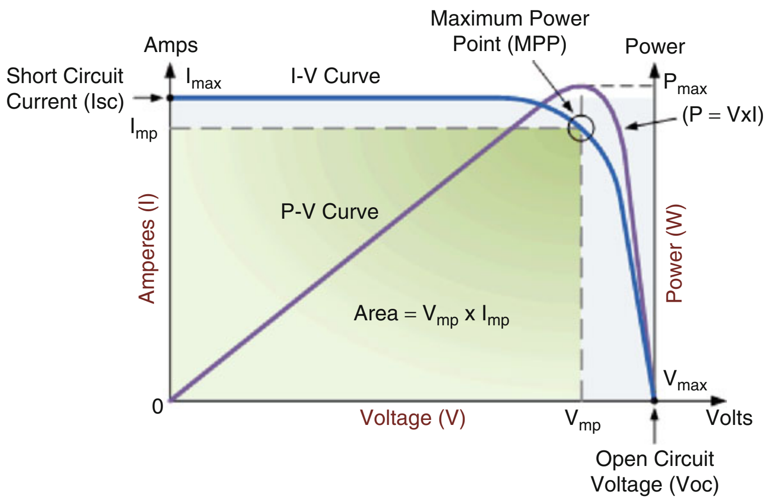
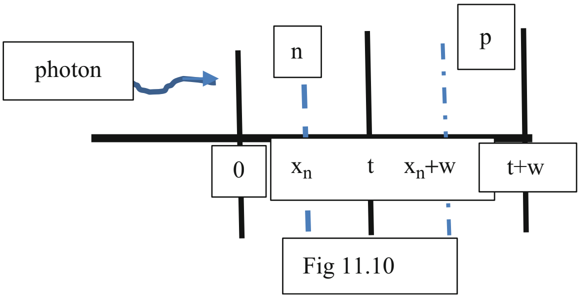


Fig. 11.9 Illustration of the ideal situation with corresponding definitions (Credgington & Durrant 2012)

In the limit of no back diffusion, all carriers generated by light drift into the electrode or recombine in the bulk unless they recombine in the bulk with lifetime τ. From Fig. 11.10 which explains what is meant by power collection efficiency, we note that if a semiconductor has a low bandgap and thus high dark current at room temperature, then the V_{oc} is small and the IV area is reduced and thus of lower efficiency. Let us now cone the complete formula for the quantum efficiency η in a p-n junction such as in Fig. 11.1. The *saturation current* is just the product of the number of photons absorbed and efficiency η.

Fig. 11.10 Rosencher & de Vinter (2005)



11.6 Complete Mathematical Expression for the Quantum Efficiency

The quantum efficiency (charge collected per charge created) η is divided in three contributions: the n-region, the high-field region DR, and the p-region.

The theoretical evaluation, which involves solving the diffusion equation with boundary conditions, is given below noting that (Movaghar & Schirmacher 1981):

r = reflection coefficient, α = absorption coefficient, and $\gamma_1 = s_1 L_h / D_h$, $\gamma_2 = s_2 L_e / D_e$.

L_e and L_h are the electron and hole diffusion length, respectively. D_e and D_h are the electron and hole diffusion coefficient; *s_1 and s_2 are the surface recombination* velocities at the illuminated and back photodiode surface, respectively.

$$\eta = \eta_e + \eta_{DR} + \eta_p$$

Respectively, n-region, high-field region DR, and p-region:

$$\eta_p = \frac{(1-r)\alpha L_e}{\alpha^2 L_e^2 - 1} e^{-\alpha(x_n + w)} S \tag{11.7}$$

$$S = \frac{(\gamma_2 - \alpha L_e) e^{-\alpha(t+d-x_n-w)} - sh[(t+d-x_n-w)/L_e] - \gamma_2 ch[(t+d-x_n-w)/L_e]}{ch[(t+d-x_n-w)/L_e] + \gamma_2 sh[(t+d-x_n-w)/L_e]} + \alpha L_e \tag{11.8}$$

$$\eta_n = \frac{(1-r)\alpha L_h}{\alpha^2 L_h^2 - 1} \left(\left[\frac{\alpha L_h + \gamma_1 - e^{-\alpha x_n} (\gamma_1 ch(x_n/L_h) + sh(x_n/L_h))}{\gamma_1 sh(x_n/L_h) + ch(x_n/L_h)} \right] - \alpha L_h e^{-\alpha x_n} \right) \tag{11.9}$$

$$\eta_{DR} = (1-r)\left[e^{-\alpha x_n} - e^{-\alpha(x_n + w)} \right] \tag{11.10}$$

$$\gamma_1 = \mathrm{s_1 L_h / D_h}, \quad \gamma_2 = \mathrm{s_2 L_e / D_e} \tag{11.11}$$

The regions x_n, t, and w are defined in the figure; see *A Rogalski ad J Rutkowski Infrared Phys Vol 22 p199 (1982).*

This is the complete mathematical expression for the number of carriers collected per photon when we allow for both diffusion and drift and the fact that the carriers are not necessarily collected with unit absorbing efficiency when they reach the electrode boundaries, but that there can be back reflection expressed by the finiteness of the so-called surface recombination velocities s_1 and s_2. Note that there are three regions of charge generation n,p and depletion region DR. The simple Eq. (11.1) called also the Hecht formula (Hecht 1932) is recovered in the limit that the γ's are infinite, and we only have one carrier type $r = 0$ and only n-region.

11.7 Summary: Discussion

We have given in this chapter a brief description of the semiconducting solar cell used for light harvesting. The focus is on inorganic materials. The subject in general is a vast one with colossal importance to society in view of the gigantic damage being caused by fossil fuels and global warming. Work is going on all over the world in trying to still raise the efficiencies of solar cells. Electric cars and trains will be the dominant form of transport for sure, and the target of getting rid of fossil fuels is now very near. The combination devices illustrated in Fig. 11.5 exhibit great values, and, were it not for the high production cost and maintenance charges, one could consider the problem as almost solved. The difficulty is to harvest a larger part of the solar radiation than, for example, silicon or GaAs (>1 eV), without too many expensive processing and manufacturing steps. Scientists are working to solve this problem by tackling the problem from many directions: new materials and new geometries. We also reported on the important breakthrough made recently in making polymer solar cells such as the system *P3HT/PCBM* (Polman et al. 2016; Street & Schoendorf 2010; Sariciftci et al. 1992) which have reached power efficiencies η_{sp} of ~ 10%. This is a very great success for an organic system, but not good enough yet for mass commercialization which needs ~18%. Polymers can be made plastic, and even woven into garments, and made biocompatible, and this creates a wide range of new applications; for example, in biomedicine,"tattoo electronics" are already in use now. Building electronic circuits in the body and brain, self-powering these devices with PVC, is a great challenge, which is being pursued vigorously with recent applications to making wireless *wifi* brain to spine communication (Capogrosso et al. 2016), in order to cure paralysis and maybe blindness.

In the next chapter, we shall focus on another very exciting topic which is the harvesting of heat, either directly from the sun's infrared rays or from hot bodies created in, for example, "motors," friction, nuclear plants, or even geothermal processes. The heat ray part of the light spectrum is in the wavelength range longer than 5 μm; see Figure 1. Though one could in principle use semiconductors with very low bandgaps, the problem is that such devices would have a huge dark current for a given load which would swamp the photocurrent and deform the ideal square-shaped IV curve into a triangle with smaller fill factor.

Problems

1. Using the Hecht formula Eq. 11.1, calculate the carrier collection efficiency η given that the width of the device is 5 μm, the drift velocity is 10^5 cm/s, and the recombination time is 1 ns.
2. In your own words, explain how the multijunction cell illustrated in Fig. 11.5 a works. How do the two absorbing junctions cooperate to optimize the collection of light over a wider spectrum?
3. Define the power collection efficiency Λ in terms of its components and explain why a square-shaped IV curve is better than a triangular one.
4. If the carrier collection efficiency is 1, what is the single most important factor which limits the solar cell performance in a single junction system?

References and Further Reading

Berthold T et al (2012) Photosynthesis. J Am Chem Soc 134:5563

Capogrosso M et al (2016) A brain–spine interface alleviating gait deficits after spinal cord injury in primates. Nature 539:284–288. https://doi.org/10.1038/nature20118

Credgington D, Durrant JR (2012) Insights from transient optoelectronic analyses on the open-circuit cells. J Phys Chem Lett 3:1465–1478

Delaunay PY, Nguyen BM, Hoffman D, Razeghi M (2008) High-performance focal plane array based on InAs/GaSb superlattices With a 10m cutoff wavelength. IEEE J Quantum Electron 44:462–467.

Hecht K (1932) Zum Mechanismus Des Lichtelektrischen Primarstromes in Isolierenden Kristallen. Z Phys A 77:235–245

Jordan P et al (2001) Nature 411:909

Movaghar B, Schirmacher W (1981) On the theory of hopping conductivity in disordered systems. J Phys C solid state Phys 14:859

Polman A, Knight M, Garnett EC, Ehrler B, Sinke WC (2016) Photovoltaic materials: present efficiencies and future challenges. Science 352(6283)

Rosencher E, de Vinter B (2005). Optoelectronics. Cambridge University Press. 0521771293.

Sariciftci NS, Smilowitz L, Heeger AJ, Wudl F (1992) Photoinduced electron transfer from a conducting polymer to Buckminsterfullerene. Science 258:1474–1476

Savoie B, Movaghar B, Marks T, Ratner M (2013) Simple analytic description of collection efficiency in organic photovoltaics. Phys Chem lett 4:704

Street RA, Schoendorf M (2010) Phys Rev B 81(205):307

Yamaguchi M et al (2005) Multi-junction III-V solar cells: current status and future potential. Solar Energy 79:78