Lecture 21

Photodetectors and Solar Cells

In Lecture 18, we have seen that light-semiconductor interaction generates electron-hole pairs. The excess carriers can significantly influence the conductivity of a semiconductor, which is the key mechanism of several semiconductor components, including the photodetector and solar cell.

21.1 More insight into light-semiconductor interaction

The most abundant source of light (and energy) in our daily life the sunlight, the electromagnetic radiation from the sun, mostly in the form of UV, visible and IR light. Efficient energy conversion of sunlight may be the ultimate solution to the rapid expansion of technological energy requirements, which has been pointed by physicist in the 1960s.[1] However, systems involving sunlight is different from a monochromatic light source due to the following reasons:

1. The sunlight contains photons with energy spans over a wide spectrum (UV to IR, when received on earth).

2. The angle between the sunlight and earth influences the total power that can be received.

3. The intensity of sunlight is reduced due to the existence of atmosphere and molecular absorption.

To account for the atmosphere and the sunlight incident angle, we introduce the quantity of air mass (AM), which is defined as the ratio between the sunlight in atmosphere L and the average thickness of atmosphere L_0:[2]

$$AM = \frac{L}{L_0} \tag{21.1}$$

AM0 refers to the light outside the atmosphere ($L = 0$). AM1 is the sunlight is normal to the ground when collected on the ground ($L = L_0$), and is the maximum amount of sunlight that can be received on earth. In practice, the quantity AM1.5 is usually used,

meaning the angle between sunlight and the normal direction of earth, is 48.2 degrees, corresponding to the case of most major cities (Figure 21.1 left). Another important feature is the wavelength-dependent sunlight irradiance $I(\lambda)$, defined as the sunlight power per unit area within a small energy range (unit: W·m^{-2}·nm^{-1}). As shown in Figure 21.1 right, the AM0 irradiance can be approximated by a black body radiator of 5778 K.[3] The AM1.5 irradiance is attenuated due to the absorption of atmosphere, and intensity at some energy ranges are strongly reduced (specific absorption bands) due to IR stretching / vibration of gaseous molecules. The total power we can get from AM1.5 is:

$$P_{\mathrm{AM1.5}} = \int_0^\infty I(\lambda)\mathrm{d}\lambda \approx 1000\,\mathrm{W} \cdot \mathrm{m}^{-2} \tag{21.2}$$
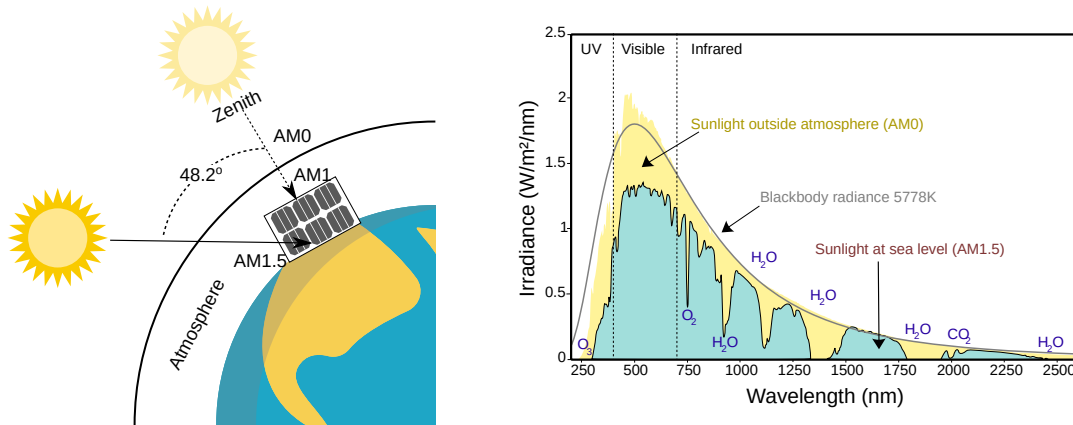
which is called the solar constant.

Figure 21.1: The air mass and sunlight spectrum. Left: definition of air mass (AM) with different sunlight angles. Right: sunlight irradiance spectra at AM0 and AM1.5. The strong absorption bands in IR range correspond to the molecules in atmosphere.

The photo-absorption of semiconductor is also dependent on the wavelength λ and the bandgap E_{g}. The energy of a photon, expressed using the wavelength λ, is expressed as:

$$E = h\nu = \frac{hc}{\lambda} = \frac{1.24}{\lambda/[\mathrm{m}]}\,\mathrm{eV} \tag{21.3}$$

The photon will not be absorbed (although can be scattered or reflected) by the semi-conductor if $h\nu < E_{\mathrm{g}}$. On the other hand, when $h\nu \geq E_{\mathrm{g}}$, the photon can be absorbed by the semiconductor, by exciting one electron from VB to CB. However, this does not mean that all photon energy $h\nu > E_{\mathrm{g}}$ can be used. In fact, if the energy of the excited electron is much higher than E_{c} (with a large kinetic energy), it is usually dissipated by relaxation to the CB edge and generating a phonon (heat). Therefore it is not possible to achieve perfect photo-conversion using single-gap semiconductor: when E_{g} is larger, a larger portion of sunlight cannot be absorbed; when E_{g} is smaller, the heat-loss becomes more significant. Therefore combining the two effects discussed above there should be a optimal value of E_{g} that can maximize the energy conversion efficiency, known as the Schockley-Quessier limit.[4]

Consider the real solar irradiance spectrum (AM1.5) in Figure 21.1, we can a spectrum of usable solar energy as a function of wavelength (21.2). The optimized gap is ~1.34 eV, giving maximum efficiency of 33.7%,. Silicon is actually quite close to this limit, with E_g of 1.1 eV and theoretical efficiency of ~30%. In practice, commercial single crystal Si solar cells can already reach efficiency over 22% [5], which close to the Shockley limit.
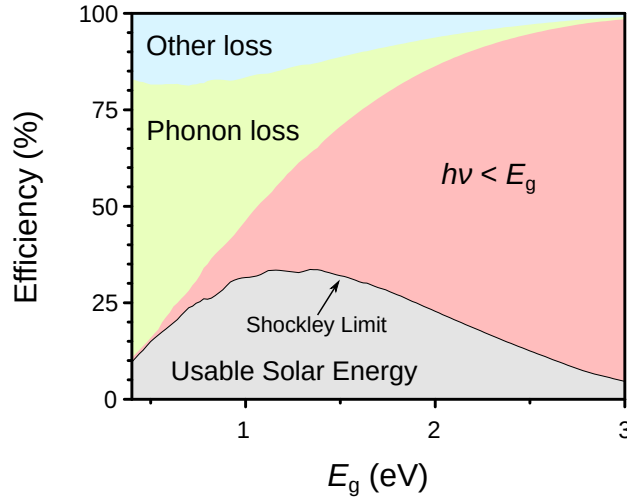

Figure 21.2: The usable solar energy as a function of bandgap from the Shockley-Quessier model. The energy at each wavelength is divided into usable energy (grey), non-absorbed photons (pink), phon loss (green) and other loss (blue). The Shockley-Quessier limit is the maximum of the grey region at $E_g \approx 1.34$ eV

The discussion of the theoretical light conversion above neglects the fact that light has to travel a finite length before it is fully absorbed. Consider in a 1D system, the light intensity at position x from the surface of the semiconductor is $P(x)$ (in unit of [photons/time/area] or [power/area]). When the light further travels a distance of dx, the amount of light that absorbed within this distance, is proportional to $\Phi(x)$ (Figure 21.3a):

$$\frac{dP(x)}{dx} = -\alpha P(x) \tag{21.4}$$

where α is the absorption coefficient (also known as the attenuation / extinction coefficient), and with a unit of m^{-1}. The integral form of $P(x)$ is:

$$P(x) = P_0 \exp(-\alpha x) \tag{21.5}$$

where P_0 is the light intensity outside the semiconductor. Equation 21.5 has the same form with the Lambert-Beer law in chemistry. The values of α for typical semiconductors (Si, GaAs and Ge) are shown in Figure 21.3b. We observe that α changes rapidly near the bandgap, and the slope of such transition is material-dependent (much steeper slope for GaAs than Si and Ge). Such phenomenon can be explained by the nature of photon-carrier

interaction. During the photon absorption process ($h\nu \rightarrow$ e+h), both energy and momentum are conserved. Due to the relative small momentum of photon compared with electron / hole, strict photon absorption (without any phonon process) is only possible between VB and CB states of the same momentum. For a direct bandgap material (for instance GaAs), the extrema of CB and VB coincide, therefore any photon with energy larger than E_g will be effectively absorbed, leading to a sharp increase of α near E_g in the absorption spectrum. On the other hand, in an indirect bandgap material (Si, Ge), photons with $h\nu$ slightly larger than E_g is poorly absorbed, since such absorption process involves 2 steps: (i) excite one electron to a "virtual" energy level and (ii) transfer the excited electron to VB by generating a phonon to compensate the momentum difference. As a result, the absorption spectrum of indirect semiconductor is usually broad near E_g. The difference between the photon absorption in direct / indirect bandgap semiconductors can be seen in Figure 21.3d.
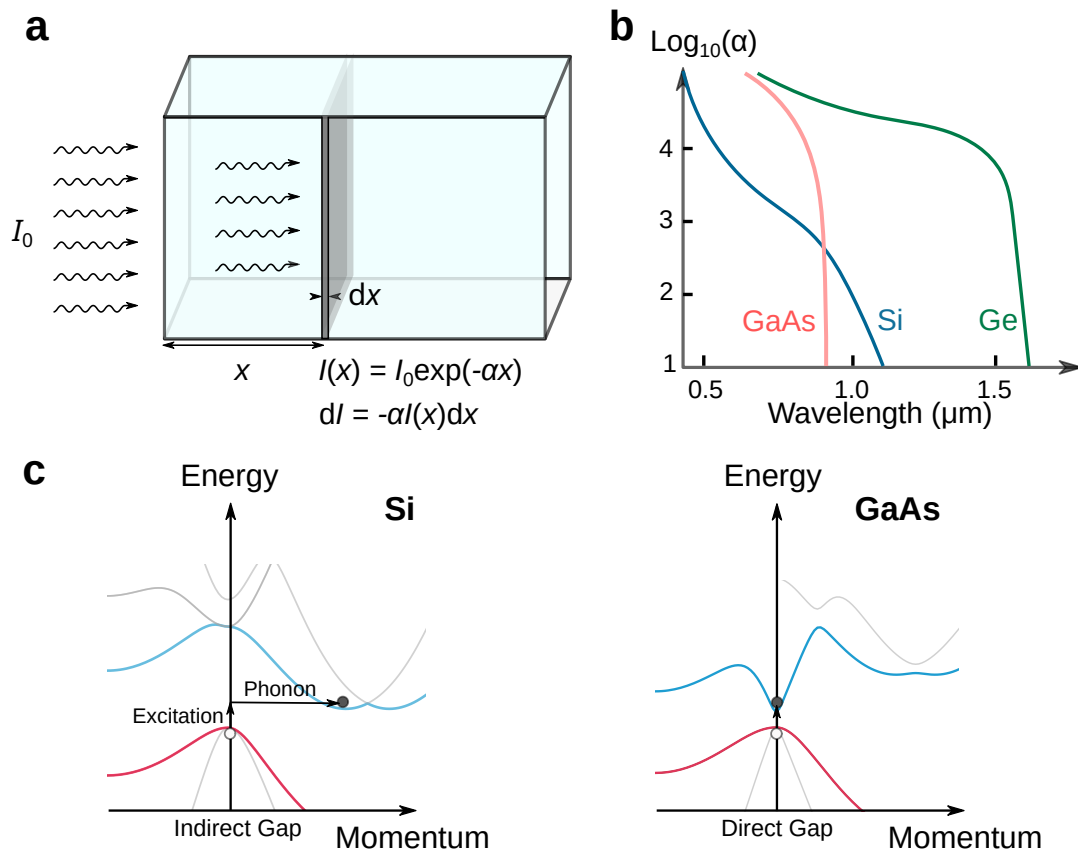

Figure 21.3:   Light absorption in a semiconductor. (a) The light absorption in a finite distance. (b) Absorption coefficient α of different semiconductors as a function of light wavelength. (c) Difference between the photon-carrier interaction in an indirect gap material (Si, left) and a direct gap material (GaAs, right). The band structures are taken from *ab initio* calculations, and the CB / VB are labeled in blue / red, respectively.

With the knowledge above, we will discuss two applications of light-semiconductor

interactions, namely the photodetector (Figure 21.4a) and photodiode / solar cell (Figure 21.4b), in the next sections.
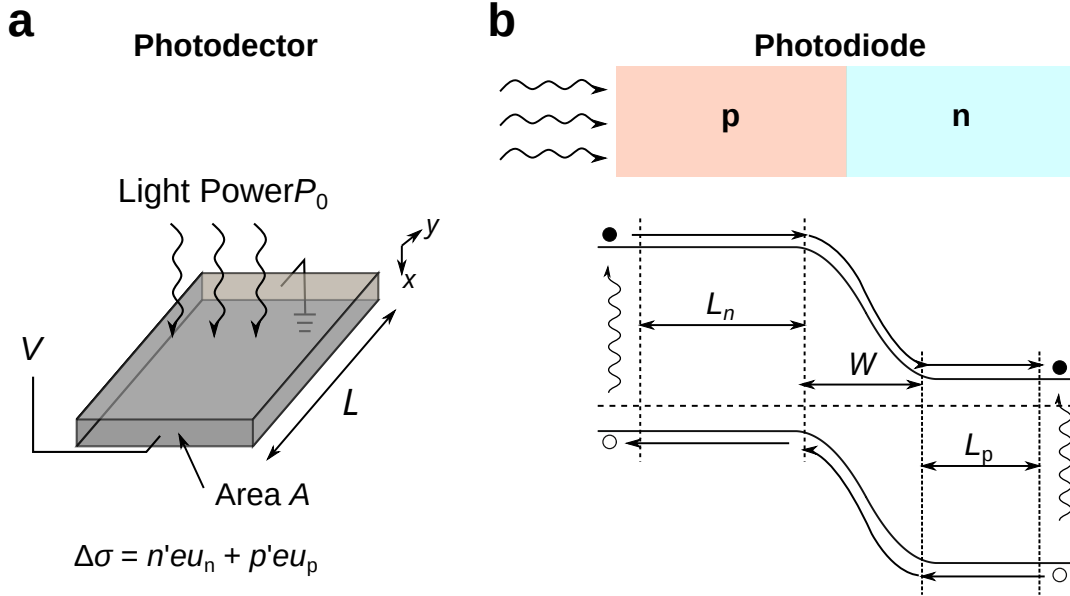
a

Photodector

b

Photodiode

Figure 21.4: Semiconductor components that make use of the light-semiconductor interaction: (a) photodetector and (b) solar cell (photodiode).

21.2 Photodetector

A photodetector (or photoconductor) is a semiconductor component that makes use of increases conductivity of a semiconductor after illumination. Consider the system in Figure 21.4a, where a monochromatic light with total power P_0 is shed on the top of a semiconductor slab. At distance x from the top surface, the number of photon absorbed, is:

$$N_{\mathrm{ph}}(x) = \frac{P(x)}{h\nu} = \frac{P_0 \lambda \exp(-\alpha x)}{hc} \tag{21.6}$$

Not every photon absorbed can be converted to e-h pair, but rather with a quantum yield $\eta < 1$. Therefore, the numbers of e-h pairs generated per volume is:

$$g(x) = \frac{N_{\mathrm{ph}}(x)\eta}{AL} = \frac{P_0 \lambda \eta}{hcAL} \exp(-\alpha x) \tag{21.7}$$

where A is the cross-sectional area and L is the length of the semiconductor slab. The steady-state equation of continuity along the y-direction for electron is:

$$\frac{\mathrm{d}n}{\mathrm{d}t} = u_{\mathrm{n}} k_{\mathrm{B}} T \underbrace{\frac{\mathrm{d}^2 n}{\mathrm{d}y^2}}_{0} + u_{\mathrm{n}} e \frac{\mathrm{d}}{\mathrm{d}y} [\underbrace{n \left(\frac{\mathrm{d}\psi}{\mathrm{d}y}\right)}_{0}] + g(x) - \frac{n'}{\tau_{\mathrm{n}}} = 0 \tag{21.8}$$

where n' is the excess electron density that $n = n_0 + n'$, and τ_n is the recombination lifetime of electron. Use the same approach for holes, we get the steady-state excess carrier densities n' and p':

$$
\begin{aligned}
n' &= g(x)\tau_n \\
p' &= g(x)\tau_p
\end{aligned}
\tag{21.9}
$$

Plug these into Equation 21.7, we can get the average number of excess carriers generated:

$$
n' = \int_0^\delta n'(x)\mathrm{d}x = \frac{P_0\lambda\eta\tau_n}{hcAL\alpha}(1 - \exp(-\alpha\delta))
\tag{21.10}
$$

and

$$
p' = \frac{P_0\lambda\eta\tau_p}{hcAL\alpha}(1 - \exp(-\alpha\delta))
\tag{21.11}
$$

where δ is the thickness of the slab. This means, if $\delta \gg \alpha^{-1}$, light is almost completely absorbed by the semiconductor slab. Use the Drude model of conductivity, that $\sigma = neu_n + pep_p$, we can calculate the increase of conductivity due to excess carriers:

$$
\Delta\sigma = \frac{1}{\delta}\int_0^\delta (n'eu_n + p'e\tau_p)\mathrm{d}x = \frac{P_0\lambda\eta e}{hcAL\delta\alpha}(\tau_n u_n + \tau_p u_p)[1 - \exp(-\alpha x)]
\tag{21.12}
$$

And the change of current due to illumination, ΔI_{ph}, is:

$$
\Delta I_{ph} = \Delta\sigma AV = \frac{P_0\lambda\eta e}{hc\delta\alpha}\frac{V}{L}(\tau_n u_n + \tau_p u_p)[1 - \exp(-\alpha x)]
\tag{21.13}
$$

The design of a good photodetector should usually follow these principles:

1. The quality of semiconductor is high (with high η, τ and u)

2. The contrast between dark- and photocurrent is large (high signal-to-noise ratio).

3. The bandgap is properly chosen properly (larger E_g for UV sensor and small E_g for IR sensor)

However, a photodetector cannot harvest energy from light, since there would be no current without applied bias V. This can be achieved using a photodiode, in which the excess carriers are spontaneous separated.

21.3 Photodiode

The photodiode is the key component inside modern solar cells. The structure of the simplest photodiode is just a p-n junction that has one side exposed to light (Figure 21.4b). As we learned from Lecture 20 a depletion region with total width W exists at the interface

between the n- and p-doped sides. Outside the depletion region, the diffusion lengths of carriers are:

$$L_n = \sqrt{u_n k_B T \tau_n}$$
$$L_p = \sqrt{u_p k_B T \tau_p}$$

(21.14)

When the carriers are generated inside the region $L_n + W + L_p$, the electrons can diffuse to the depletion region, and therefore can be effectively collected. In other words, basically we want large absorption coefficient, that $\alpha^{-1} < L_p + W + L_n$. To study the effect of the diffusion length, we can think of a simpler example, a p-n junction made of a thin p-doped side and a semi-infinite n-doped side. We assume the thickness of the p-doped side is very small, and all the electron-hole pairs are generated only in the n-doped region ($x > 0$). We can write the steady-state equation of continuity in the n-doped region:

$$\frac{dp}{dt} = u_p k_B T \frac{d^2 p}{dx^2} + g - \frac{p'}{\tau_p} = 0$$

(21.15)

or equivalently:

$$\frac{d^2 p'}{dx^2} = \frac{-g}{u_p k_B T} + \frac{p'}{u_p k_B T \tau_p}$$

(21.16)

with boundary conditions $p'(0) = 0$ (holes collected) and $p'(x \to \infty) = \tau_p g$ (flat band situation). When we assume uniform generation rate $g = \frac{P_0 \lambda \eta}{hcAL}$, the solution to the excess hole concentration is:

$$p' = \tau_p g [1 - \exp(-\frac{x}{L_p})]$$

(21.17)

and the diffusion current of carrier (without bias) is:

$$J_p = -u_p k_B T \frac{dp}{dx} = -\frac{u_p k_B T}{L_p} \tau_p g \exp(-\frac{x}{L_p})$$

(21.18)

where the negative sign indicates that holes flow from right (n-side) to left (p-side). And at the surface of junction, the current that can be collected is:

$$J_p(x = 0) = -\frac{u_p k_B T \tau_p}{L_p} g$$

(21.19)

We see that such current comes purely from the photo-generated holes even without external bias, and this current is called the short-circuit current J_{sc}. With applied bias, the current density becomes:

$$J = J_0 (\exp(\frac{eV}{k_B T}) - 1) - J_{sc}$$

(21.20)

where J_0 is the dark current at negative bias. At a certain external bias V_{oc}, called the open-circuit voltage, the drift current caused by bias balances the photocurrent, and the total current becomes 0. Another important feature of the photovoltatic behavior is the filling factor (FF), which is defined as the maximum power density divided by $J_{sc} * V_{oc}$ (Figure 21.5). A good solar cell requires not only a high power conversion efficiency, but also a higher filling factor.
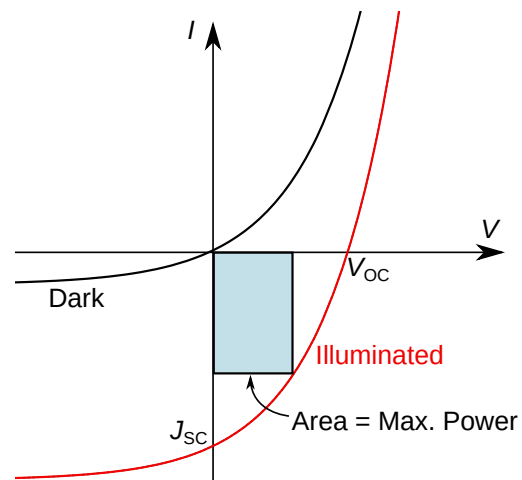
Figure 21.5: Current-bias Performance of a photodiode. The short-circuit current J_{sc}, open-circuit voltage V_{oc} and filling factor FF are shown.

References

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