Photonics and Optical Communication
(Course Number 300352)
Spring 2007
Optical Source
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Photonics and Optical Communication

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6. Optical Detectors

In the following we will discuss the operating principles and the application of photo detectors in optical communication systems.

6.1 Introduction

Optical receivers and transmitters are of essential importance for the overall performance of optical communication systems. The function of an optical detector is to convert the optical signal into an electrical signal, which can then be further processed.

Schematic sketch of an optical transmitter and receiver of an optical communication system. Ref: Agilent Technologies, Back to Basics in Optical Communications Technology.
6.1 Introduction

The improvement on optical receiver and transmitter side is of major interest to network operators, because less repeater are needed and the spacing between repeaters can be increased.

The following performance criteria of optical detectors are of major important for applications in optical communication systems:

- Sensitivity has to be matched to the emission spectra of the optical transmitter
- Linearity (Linear relationship between the intensity and the electrical signal)
- High quantum efficiency / high spectral sensitivity
- Fast response time
- Stability of performance (temperature sensitivity)
- Reliability and Robustness
- Low Noise
- Low Cost
6.2 Classification of optical detectors

In general, we can distinguish between three groups of optical detectors. The first and by far the most important group are **diodes**. The group of diodes can again be separated in different subgroups: pn diodes, pin diodes, Schottky diodes and Avalanche photodiodes.

The second and third group are photoconductors and photo transistors.

**Classification of optical detectors**

- Diodes
  - Pn-diodes
  - Pin diodes
  - Avalanche photodiodes
  - Schottky diodes
- Photo conductors
- Photo transistors

In the following we will discuss the operating principle of optical diodes and photo conductors and compare their advantages and disadvantages.
6.3 Optical detection principle

The conversion of an optical into an electrical signal requires the absorption of the incident light. The absorption leads to an excitation of an electron from the valence to the conduction band. What is left in the valence band is a vacancy, which we call a “hole”. Therefore, we speak about the photo-generation of electron-hole pairs, because the absorption always leads to the generation of a hole and an electron. (That does not necessarily mean that both carriers contribute to the electronic transport, but the generation creates both species.)

If now a photon gets absorbed in the material the electron-hole pairs have to be separated by an electric field. The energy of the photon has to be sufficiently high to excite an electron from the valence to the conduction band.

Photogeneration of an electron hole pair.

Ref.: J.M. Senior, Optical Fiber Communications
6.4 Absorption

The absorption of a photon produces an electron hole-pair and thus a photocurrent. The absorption of the photons depends on the absorption coefficient $\alpha$ in the medium. The absorption coefficient is strongly wavelength dependent. The photocurrent caused by the absorption of photons can be calculated by

$$I_{ph} = P_0 \cdot \frac{e \cdot \lambda}{h \cdot c} \cdot (1 - R) \cdot [1 - \exp(-\alpha_0 d)]$$

where $P_0$ is the optical power, $\lambda$ is the wavelength of the incident light, $h$ is the Planck constant, and $e$ is the elementary charge.

The term $R$ accounts for the reflection at the interface of the detector and air, $(1-R)$ is the light absorbed in the detector and the exponential term considers the absorption in the medium. $d$ is the thickness of the absorber.
6.4 Absorption

The absorption coefficient strongly depends on the wavelength. This is shown in the figure for some common semiconductor materials. We can distinguish the materials in terms of direct and indirect semiconductor materials. We already discussed that direct semiconductors are the preferred materials for the realization of optical sources like LEDs and semiconductor laser diodes. Silicon and germanium are the best known candidates out of the family of indirect semiconductors.

Optical absorption for some common semiconductor photodiode materials (silicon, germanium, gallium arsenide, indium gallium arsenide and indium gallium arsenide phosphide).

Ref.: J.M. Senior, Optical Fiber Communications
6.4 Absorption

Silicon and germanium have direct and indirect optical transitions but the lowest energetic transition is an indirect optical transition. The fact that silicon and germanium are indirect semiconductors leads to the strong wavelength dependent absorption of the material. The direct semiconductors exhibit a sharp transition in the optical absorption.

Based on the absorption coefficient you can see what material is suitable for what kind of wavelength region. For example, in the case of silicon the optical bandgap at room temperature is 1.14eV, which corresponds to a wavelength of 1100nm. Up to 1100nm silicon is still absorbing even though the absorption coefficient for wavelength >1000nm is already relatively low. That means silicon is not suitable as an optical detector for a DWDM system which operates at a wavelength of 1550nm. Silicon is transparent for such a wavelength.

The behavior of germanium is different. The optical bandgap of germanium is 0.67eV, which corresponds to a cut-off wavelength of more than 1850nm. However, the absorption coefficient is already very low for such a high wavelength.
6.4 Absorption

Germanium detectors are reasonable sensitive up to a wavelength of 1600nm. Therefore, germanium can be (theoretically) used as an optical detector for DWDM systems. However, due to the small optical bandgap the leakage current of germanium diodes is very high.

Gallium arsenide has an direct optical bandgap of 1.43eV. It can be used for the manufacturing of GaAs based LEDs and laser diodes in the short wave band.

In order to increase the absorption in the infrared part of the spectrum, which is necessary for the optical communication system, we have to add indium to the semiconductor. Indium will reduce the optical bandgap of gallium arsenide.

An overview of the optical bandgaps at room temperature is given in the table.

<table>
<thead>
<tr>
<th>Material</th>
<th>Indirect</th>
<th>Direct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.14</td>
<td>4.10</td>
</tr>
<tr>
<td>Ge</td>
<td>0.67</td>
<td>0.81</td>
</tr>
<tr>
<td>GaAs</td>
<td>—</td>
<td>1.43</td>
</tr>
<tr>
<td>InAs</td>
<td>—</td>
<td>0.35</td>
</tr>
<tr>
<td>InP</td>
<td>—</td>
<td>1.35</td>
</tr>
<tr>
<td>GaSb</td>
<td>—</td>
<td>0.73</td>
</tr>
<tr>
<td>In_{0.53}Ga_{0.47}As</td>
<td>—</td>
<td>0.75</td>
</tr>
<tr>
<td>In_{0.14}Ga_{0.86}As</td>
<td>—</td>
<td>1.15</td>
</tr>
<tr>
<td>GaAs_{0.86}Sb_{0.12}</td>
<td>—</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Overview of the bandgaps of some photodiode materials.

Ref.: J.M. Senior, Optical Fiber Communications
6.5 Sensitivity and Efficiency of optical Detectors

Like we determined the efficiency of the light emitting devices we can determine the (quantum) efficiency of detectors.

6.5.1 The Quantum efficiency

The quantum efficiency is defined by:

\[ \eta = \frac{\text{number of electrons collected}}{\text{number of incident photons}} \]

Quantum efficiency

One of the major factors which influences the quantum efficiency is the absorption coefficient. The quantum efficiency is generally below unity, but can be for its maximum very close to unity.
6.5.2 Spectral responsivity

The quantum efficiency does not take into account the photon energy. Therefore, the responsibility can be very helpful to describe the spectral sensitivity of the devices. The spectral responsivity is given by:

\[ SR = \frac{I_{ph}}{P_0} \]

where \( I_{ph} \) is the photocurrent and \( P_0 \) is the incident optical power. The unit of the spectral responsivity is A/W.

The spectral sensitivity can be derived from the quantum efficiency by:

\[ SR = \eta \cdot \frac{e \cdot \lambda}{h \cdot c} \]
6.5.2 Spectral responsivity

It can be seen that the responsivity is increasing with the wavelength of the incident photons. The difference between the ideal and the real diode can be explained by thermal losses for lower wavelengths and a reduced absorption coefficient for higher wavelengths.

Responsivity of an ideal and a real silicon photodiode.

Ref.: J.M. Senior, Optical Fiber Communications


6.6 Operating principle of Photodiodes

The electron-hole pairs generated in a photodiode are separated by the electric field. The electric field distribution in the diode is determined by an internal and an external electric field component. The internal field is created by the build-in potential which leads to the formation of a depletion region. The build-in potential is formed due to the difference in the Fermi level in the p- and the n-region. The external electrical field is due to the external applied bias voltage.

We try to keep the electric field in the depletion region as high as possible to extract all photo-generated carriers. Only the extracted electron hole pairs contribute to the overall photocurrent.

Operation principle of a photodiode. A reverse bias voltage is applied to the pn photodiode.

Ref.: J.M. Senior, Optical Fiber Communications
6.6 Operating principle of Photodiodes

The photocurrent of an optical detector should be linear. This means that a linear relationship exists between the intensity of the incident light and the photocurrent. In order to extract almost all photo-generated carriers out of the device a reverse bias voltage can be applied to the diode. The reverse bias voltage leads to an increase of the electric field in the depletion region and the depletion region gets wider.

6.7 Diode Device Structure

Various diode device structures exist. In the following the realization and the characteristic device behavior of pn-diodes, pin diodes, Avalanche photodiodes and Schottky diodes will be discussed. Furthermore, the different devices will be compared in terms of their advantages and disadvantages.
6.7.1 Pn-diodes

The pn-junction is the first diode structure which we will discuss. The photo-generated electron hole pairs in the depletion region of the diode contribute to the overall photocurrent. A pn-diode like all other diodes can be operated under short circuit conditions or under reverse bias voltage. Depending on the applied material the quantum efficiency of the diode might be slightly higher for reverse bias voltage. Furthermore, the transient response might be faster.

The signal to noise ratio of the diode is mainly defined by the applied material. The smaller the optical bandgap and the higher the number of electronic defects in the material the higher the leakage current.

Due to the fact the depletion region is very thin (depends on the applied reverse bias voltage and the doping levels in the p- and the n-region) the quantum efficiency of a pn-diode is usually not very high. Most of the light that is absorbed will simply not contribute to the overall photocurrent.

In order to extend the region of carrier extraction an intrinsic layer or a slightly doped layer is usually introduced between the p- and the n-region.
6.7.2 Pin-diodes

As a consequence the depletion region is extended across the intrinsic or lightly doped layer and therefore more photo-generated carriers contribute to the photocurrent. The pin-diode can be realized as an homo-junction or a hetero-junction. If the structure is realized in silicon the device will be usually a homo-junction. Under such conditions all three layers (p-, i- and n-region) have the same optical bandgap. Depending on the application the thickness and the individual layers can be adjusted.

The thicker the i-layer the further the sensitivity can be extend in the near infrared part of the optical spectrum. If there is only an interest in detecting blue or green light the i-layer can be kept short. The pin diode shown on this slide is a crystalline silicon pin diode. Therefore, the diode is only sensitive up to a wavelength of 1100nm. In such a case the i-layer would be already relatively thick (typically a few 100\( \mu \text{m.} \))

Ref.: H. J.R. Dutton, Understanding optical communications
6.7.2 Pin-diodes

Typical materials used for the three optical communication bands:

**Short wave band (800nm – 900nm)**

Silicon pin diodes are the best choice for the short wave band. The diodes are very inexpensive, reliable and easy to handle.

**Medium Wave band (1250 nm - 1350nm)**

In this band germanium and different compound semiconductors are of interest. Germanium has a lower bandgap energy of 0.67eV, so that it can theoretically be used up to 1600nm (but it is typically not used). Indium gallium arsenide phosphide (InGaAsP) is an alternative. The material has an optical bandgap of 0.89eV (depending on the composition of the material) and is perfectly suitable for the medium wavelength band. Of course all diodes based on compound semiconductors are significantly more expensive in manufacturing.
6.7.2 Pin-diodes

Long Wave Band (1500nm - 1600 nm)

For the long wave band the optical bandgap of the material has to be already very small. This causes problems. At room temperature already a large number of carriers is excited due to thermal excitation. This problem can be solved to a certain extend by using heterostructures. A material used here is usually InGaAs (indium gallium arsenide). InGaAs has a bandgap energy of 0.77 eV.

Sensitivity of pin diodes based on various material systems.

Ref: Agilent Technologies, Back to Basics in Optical Communications Technology
6.7.3 Schottky Barrier diodes

During this lecture we concentrate on the device aspect of optical detectors. The sensitivity of the detector has to be matched with the optical spectrum of the incident light. Hence, different materials have to be applied for different optical communication bands (short, medium or long wave bdn). However, sometimes it is not possible to realized pn-diodes for a given wavelength band and/or the performance of the diodes is not sufficient to be applied as a detector in an optical communication system.

One alternative to overcome this limitation could be a Schottky Barrier Diode. A thin metal layer replaces either the p- or the n-region of the diode. Depending on the semiconductor and the metal being involved a barrier is formed at the interface of the two materials. This barrier leads to a bending of the bands. Due to the applied voltage the bands can be bended more or less. In the region of the band bending electron hole pairs can be separated.

Silicon Schottky Barrier diode.

Ref.: H. J.R. Dutton, Understanding optical communications
6.7.4 Avalanche Photodiode (APD)

One way of increasing the sensitivity of the receiver is amplification. APDs amplify the signal during the detection process. The operating principle of a APD is based on the avalanche effect, where a highly accelerated electron excites another electron due to “impact ionization”.

However, in the first step a photon has to be absorbed and a electron-hole pair has to be generated. The device consists of two regions. In region 1 of the device the electron hole pairs are generated and separated. In region 2 of the device the carriers are accelerated and „impact ionized“.

Avalanche Photodiode (APD).
Ref.: H. J.R. Dutton, Understanding optical communications
6.7.4 Avalanche Photodiode (APD)

The device operation works as following: Arriving photons pass through thin $n^+p$-junction. The carriers are absorbed in a $\pi$-region. The absorption leads to the generation of electron-hole pairs in this region. The electric field in the $\pi$-region is high enough to separate the carriers. The electric field across the $\pi$-region is not high enough for the charge carriers to gain enough energy for multiplication to take place.

The electric field, however, in the $n^+p$-region the electric field is significantly higher, so that the charge carriers (in this case electrons only) are strongly accelerated and pick up energy.

Silicon Avalanche Photodiode (APD).

Ref.: H. J.R. Dutton, Understanding optical communications
6.7.4 Avalanche Photodiode (APD)

The electrons collide with other atoms in the lattice, which leads to the production of new electron-hole pairs ("impact ionization"). The newly released charge carriers again will collide with the lattice to produce more electron-hole pairs.

The structure shown on the previous slide is a silicon based avalanche photodiodes. It is of interest to mention that the carrier mobility of holes in silicon is significantly lower than the electron mobility. Furthermore, the impact ionized holes have to travel all the way from the n^+p-region to the right p^+-region, whereas the electron only have to travel to the n^+-region. The probability of having electron multiplication is much higher than the probability of having hole multiplication. Therefore, the electron mainly contribute to the overall current (which is intended).
6.8 Photoconductive detectors

Pn and pin diodes have a clear disadvantage which is the transient response. The transient response is limited by the capacitance of the diode or the transient time of the charges. One way to overcome the limits set by the capacitance of the diode could be a photoconductor structure. The photoconductor is clearly the simplest available detector structure. In the case of a photoconductor the resistivity of the device is changed as a function of the intensity (not a photocurrent). Therefore, we have to apply a voltage to the detector to measure the change in the current flow (Photodiodes can be operated under short circuit conditions).

The photoconductive detector is formed by two adjacent finger contact which are placed on a semiconducting material.

Ref.: J.M. Senior, Optical Fiber Communications
6.8 Photoconductive detectors

Due to the fact that the capacitance of the device is extremely low it should be possible to build very fast optical detectors. The transient time of detectors is limited by the drift velocity (velocity of the carriers caused by the applied electric field) of the carriers.

For the manufacturing it is important to form good ohmic contacts with the semiconductor. Otherwise Schottky barriers are formed which will limit the current flow.

The photoconductive detector is an unipolar device, which means that the current flow is either completely dominated by electrons or by holes. Diodes are bipolar devices, because electrons and hole contribute to the current transport.
References:
