CHAPTER 2

Short range optical interconnection

2.1 Why optical interconnection?

For nearly forty years scientists are using light to "talk" over distance. The birth of optical communications occurred in the 1970s with two key technology breakthroughs. The first was the invention of the semiconductor laser in 1962 [1]. The second breakthrough happened in September 1970, when a glass fiber with an attenuation of less than 20 dB/km was developed [2, 3]. With the development of optical fibers with an attenuation of 20 dB/km, the threshold to make fiber optics a viable technology for telecommunications was crossed. The first field deployments of fiber communication systems used Multimode Fibers (MMFs) with lasers operating in the 850 nm wavelength band. These systems could transmit several kilometers with optical losses in the range of 2 to 3 dB/km. The total available bandwidth of standard optical fibers is enormous; it is about 20 THz. A second generation of lasers operating at 1310 nm enabled transmission in the second window of the optical fiber where the optical loss is about 0.5 dB/km in a Single-Mode-Fiber (SMF). In the 1980s, telecom carriers started replacing all their MMFs operating at 850 nm. Another wavelength window around 1550 nm was developed where a standard SMF has its minimum optical loss of about 0.22 dB/km.

From this small history of fibers it can be concluded that the main research focus was on long-distance communication. Chapter 1 described that the electronics for the long distance channels is typically realized with expensive exotic technologies such as GaAs or InP. The bit-rate for these systems is large, around 100 Gb/s per channel, with low cost per length of the fiber and for a large number of users.

Replacing electrical wires with optical fibers for short distances for a small number of users is still challenging. The goal is to have low cost but high (Gb/s) bit-rates of the system. However, the important question is should we use light (fibers) to directly connect silicon chips and why?

A large study about this issue is published in the literature and some of the results will be briefly presented further in this chapter. In [4, 5, 6], Miller tried to stress the practical benefits of optical interconnects and drawbacks of electrical systems for high-speed communication (>10 GHz). His approach was to analyze the similarities and differences in optical and electrical systems, which will be briefly investigated in the following subsections.

2.1.1 Electrical and Optical Interconnection - Similarities

At the most basic level, optical and electrical physics are very closely linked. In practice, in both the electrical and optical case, it is the electromagnetic wave that carries a signal through a medium (see figure 2.1).

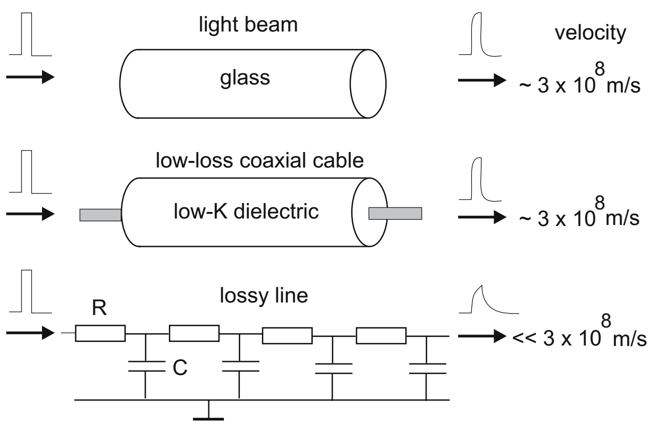

Figure 2.1: Types of optical and electrical propagation and their velocity. One possible model of the lossy line is presented.

It is important to stress that in high-speed communication, it is not electrons that carry the signals in wires or coaxial cables; actually the signal is carried by electromagnetic wave [4]. It is also good to note that signals in wires propagate at the velocity of light (or somewhat lower than light velocity if coaxial cables are filled with a dielectric). Hence it is generally incorrect to say that signals propagate faster in optics. In fact, signals typically travel slightly slower in optical fibers than they do in coaxial cables because the dielectric used in cables has a lower dielectric constant than glass.

In case of electrical interconnection lines on chips, the signals do move at a lower speed, but this speed is determined by the overall resistance (R) and capacitance (C) of the interconnect line [7].

2.1.2 Electrical and Optical Interconnection - Differences

Apart from large similarities, there are important basic differences between optical and electrical physics. The most important one is the higher (carrier) frequency and the corresponding large photon energy. The higher carrier frequency (shorter wavelength, typically in 1 µm range) allows us to use optical fibers to send optical signals without high loss [8]. There are small "wavelength windows" where the loss in the fibers (both singlemode and multimode) is small (<1 dB/km). The dispersion in singlemode and multimode fibers used in short distance communication is small too. In this way it is possible to avoid the major loss phenomena that in general limits the capacity of electrical interconnects on high frequencies: signal and clock distortion and attenuation.

The optical generation and detection for interconnection is in principle quantum mechanical (e.g., counting photons). This is in contrast to a classical source/detection of voltages and currents; for example, detection of light in practice involves counting photons, not measuring electric field amplitudes. Two practical consequences are that all optical interconnections provide voltage isolation (used in opto-isolators), and optics can offer lower powers for interconnects: it can solve the problem of matching high-impedance low-power devices to the low impedance (and/or higher capacitance) of electromagnetic propagation. With optical interconnection, there are no inductive voltage drops on input/output pins and wires that come for free in electrical interconnections.

A signal propagating down an electrical line may start with sharply rising and falling "edges". However, these edges will gradually decrease because of the loss-related distortion and dispersion, as illustrated in figure 2.1. This "softening" of the edges makes precise extraction of timing information more difficult. For the same communication distances, optical systems have relatively little problem with such variations. The dispersion and loss in optical fibers are typically smaller than in electrical wires, which is explained in section 2.3.2. Hence optic interconnect becomes increasingly attractive at high bit rates but also in higher interconnect densities (e.g., high density edge connectors for boards, or even very high density connections of chips), and arguments for optics become increasingly strong as the number of lines on the board increases. However, the disadvantage of optics is in the systems with optical connectors, because the connector size is much larger than the fiber diameter.

Optics also offers several additional opportunities that have essentially no practical analogy in the electrical case, including use of short pulses for improved interconnect performance [9]. A very important advantage of optical fibers is that they can be deployed in environments with large electromagnetic interference (EMI) and radio-frequency interference (RFI), such as airports, factories, military bases etc. In total, the advantages of optical interconnection in comparison with the straightforward electrical connection are summarized below, [4]:

- Immune to noise (electromagnetic interference and radio-frequency interference)
- Signal Security (difficult to tap)
- Nonconductive (does not radiate signals) - electrical isolation
- No common ground required
- Freedom from short circuit and sparks
- No inductive voltage drops on pins and wires
- Reduced size and weight cables (but not connectors)
- Ability to have 2-D interconnects directly out of the area of the chip rather than from the edge
- Resistant to radiation and corrosion
- Less restrictive in harsh environments
- Low per-channel cost [2]

- Lower installation cost in future (Wavelength Division Multiplexing [10])

Despite the many advantages of fiber optic systems, there are some disadvantages. Because of the relative newness of the technology, fiber optic components are still expensive even though the prices decrease dramatically in the last couple of years. Fiber optic transmitters (but not the receivers[1]) are still relatively expensive compared to electrical interfaces. The lack of standardization in the industry has also limited the acceptance of fiber optics. Many industries are more comfortable with the use of electrical systems and are reluctant to switch to fiber optics. However, the huge bandwidth advantage of the optical interconnection will probably force industry to move towards optic interconnect. Note that even with dominant optical interconnect, the on-chip signal processing remains electrical: an electrical-optical optical interface will always be required and probably the total speed in the system will be limited by the electronics.

2.2 Characteristics of light

The operation of optical communication and optical fibers depend on basic principles of optics and the interaction of light with matter. From a physical standpoint, light can be seen either as electromagnetic waves or as photons. Both view points are valid and valuable, but the simplest view for a fiber transmission is to consider light as rays travelling in straight lines and for a light detection to see the light as a number of incident photons on the photodetector surface.

Light is only a small part of the electromagnetic (EM) spectrum. The difference in radiation in different parts of EM spectrum is a quantity that can be measured: length of wave/frequency of EM-field and energy of photons. In some parts of the spectrum, frequency is used the most; in others wavelengths and photon energies are. In figure 2.2 the EM spectrum is presented with typical applications in certain spectral ranges.
In the optical world the most commonly used light quantity is wavelength, measured in micrometers or nanometers. It is inversely proportional to frequency f and proportional to the speed of light c:

$$\lambda = \frac{c}{f} \tag{2.1}$$

[1] A 3 Gb/s data-rate optical receiver in inexpensive CMOS technology is presented in chapter 4.

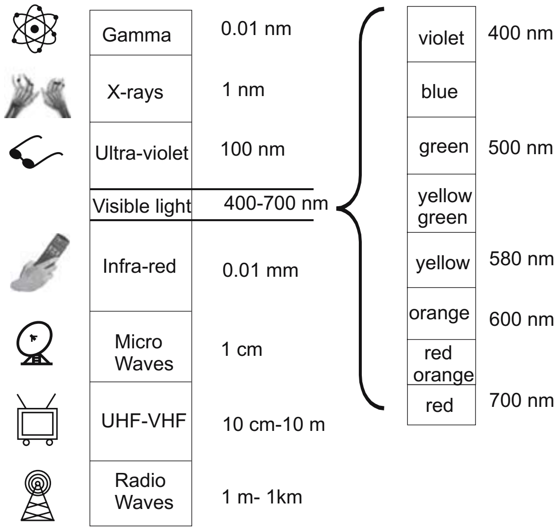

Figure 2.2: The electromagnetic spectrum.

2.3 Optical fiber types

Optical fibers are characterized in general by the number of modes that propagate along the fiber. Basically, there are two types of fibers: single-mode fibers and multi-mode fibers. The basic structural difference is the different core size.

2.3.1 Single-mode fibers

Single-mode fibers have lower signal loss and higher information capacity (bandwidth) than multimode fibers. They are capable of transferring higher amounts of data due to low fiber dispersion[2]. A cross section of a single mode fiber is shown in figure 2.3; this type of fiber is mainly used for long-haul optical communication because of low typical loss (typically lower than 0.2 dB/km).

2.3.2 Multimode fibers

As the name implies, multimode fibers propagate more than one mode; this is illustrated in figure 2.4. The number of modes, M_{n}, depends on the core size and numerical aperture (NA) and can be approximated by:

[2] Basically, dispersion is the spreading of light as light propagates along a fiber. This causes intersymbol interference i.e. an incorrect bit detection at the fiber's output.

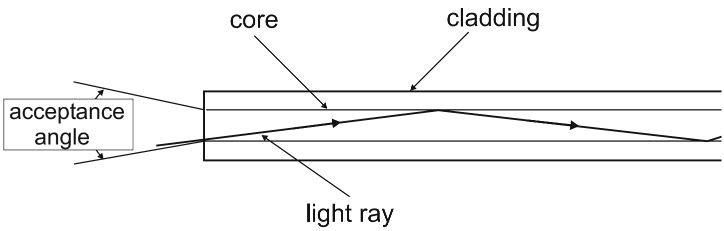

Figure 2.3: Single-mode optical fiber (small core diameter)

$$M_{\mathrm{n}} = \frac{V^2}{2} \quad \text{and} \quad \frac{V^2}{4} \tag{2.2}$$

for step index fiber and gradient index fiber, respectively. V is known as the normalized frequency, or the V-number, which relates the fiber size, the refractive index, and the wavelength. The V-number is:

$$V = \left[\frac{2\pi a}{\lambda}\right] \times \mathrm{NA} \tag{2.3}$$

NA is closely related to the acceptance angle and it is approximately [8]:

$$\mathrm{NA} = \sqrt{n_0^2 - n_1^2} \approx n_0 \sin \Theta_c \tag{2.4}$$

where n_0 and n_1 are refractive index of the core and cladding respectively, and Θ_c is the confinement angle in the fiber core. As the core size and NA increase, the number of modes increases. Typical values of fiber core size and NA are 50 µm to 100 µm and 0.20 to 0.29 respectively.

A large core size and a higher NA have several advantages. Light is launched into a multimode fiber with more ease. Higher NA and larger core size make it easier to make fiber connections: during fiber splicing, core-to-core alignment becomes less critical. Another advantage is that multimode fibers permit the use of light-emitting diodes (LEDs). Single mode fibers typically must use laser diodes due to their small diameter (< 10 µm). LEDs are cheaper, less complex, and last longer and they are preferred for a large number of applications [8].

Nevertheless, multimode fibers have some disadvantages. As the number of modes increases, the effect of modal dispersion increases. Modal dispersion

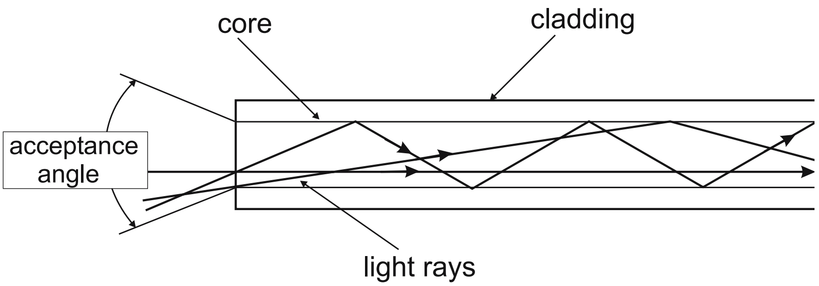

Figure 2.4: Multimode-mode optical fiber with multiple light rays. The angles of the light rays are refracted at the air/fiber interface according to Snell's law.

(intermodal dispersion) is important because, as the pulses spread, they can overlap and interfere with each other, limiting data transmission speed. Typical dispersion values for fiber are measured in nanoseconds per kilometer of fiber. These can be translated into an analog bandwidth limit in the transmission.

For instance, if one ray travels straight through a multimode fiber and another bounce back-and-forth at the acceptance angle Θ_c through the same fiber, the second ray would travel further for:

$$l_1 = l\left(\frac{1}{\cos\Theta_c} - 1\right) \qquad [\mathrm{m}] \tag{2.5}$$

where l is the length of the multimode fiber. The ray that goes down the center of the fiber with speed v will reach the output τ_r seconds before the the ray that bounces at the acceptance angle:

$$\tau_\mathrm{r} \approx \frac{l_1}{v}\left(\frac{1}{\cos\Theta_c} - 1\right) \tag{2.6}$$

Thus, an instantaneous pulse at the start will spread out τ_r seconds at the end. The analog bandwidth of the multimode fiber is inversely proportional to the pulse spread.

For a typical NA values of multimode fibers of 0.20 to 0.29, the acceptance angle calculated using (2.4) ranges from 11.5° to 17°. If we take the speed of the ray in optical fiber to be about $2 \cdot 10^8$ m/s [11], the dispersion t_r can be calculated from (2.6). The analog bandwidth of the multimode fiber as a function of the length of the fiber is presented in figure 2.5.

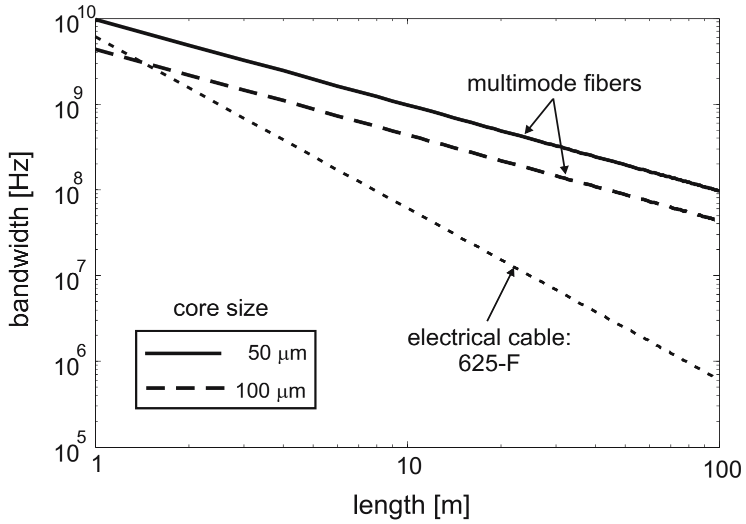

Figure 2.5: The bandwidths of two multimode fibers (core diameters 50 µm and 100 µm) and of an electrical cable as a function of the fiber/cable length.

As far as electrical cables are concerned, the attenuation $A_{\rm tt}$ in dB is proportional to the length of the cable and square-root of the frequency [12, 13]:

$$A_{\rm tt} = e^{-3k_1 l\sqrt{f}} e^{-3k_2 l f} \qquad (2.7)$$

where f is the frequency expressed in megahertz, k_1 and k_2 are parameters defining the electrical cable type and l is the cable length expressed in kilometers. The first exponential term is due to the skin-effect and the second exponential term is due to the dielectric loss. One should notice that the additional advantage of optical fibers is that the fiber-loss is independent of frequency over their normal operating range [11].

For a very small attenuation cable 625-F [13], $k_1 = 0.6058$ and $k_2 = 0.0016$. Since $k_1 \gg k_2$, the bandwidth of the cable $f_{\rm cab}$ is:

$$f_{\rm cab} = \frac{1}{400 k_1^2 l^2} \qquad (2.8)$$

The behavior of the 625-F cable bandwidth is shown in figure 2.5. For larger transmission distances, the bandwidth of the electrical cable drops significantly in comparison with the bandwidth of the multimode fibers.

2.3.3 Plastic optical fibers

Multimode fibers made entirely of plastic have higher losses than silica fibers. Therefore, they have long been outweighed, especially for long distance communication. However, they have also the advantage of being lighter, inexpensive, flexible, and ease of handling. Since the single-mode fibers are proven unsuitable for LAN installations (high connectors cost and costly technical expertise) plastic fibers appear to be a viable solution: the physical characteristics meet the same challenges as copper and glass. It has the ability to withstand a bend radius of 20 mm with no change in transmission, an 1 mm bend without breaking or damaging the fiber.

The main disadvantage of plastic fibers is their high loss. The best laboratory fibers have losses around 40 dB/km. At 650-nm wavelength (for communication using red LED) plastic fibers have loss of about 150 dB/km. Unlike glass-fibers, the loss of plastic fibers is lower at shorter wavelength and is much higher in the near infrared, as illustrated in figure (2.6). As a result, plastic optical fibers have only limited application: they are used mainly for flexible bundles for image transmission and illumination, where light does not need to go far. In communication, plastic fibers are used for short links, like within the office building or cars.

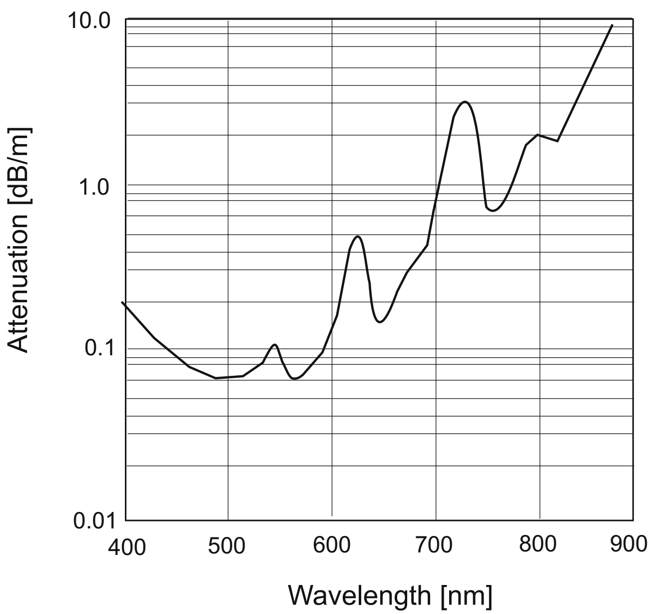

Figure 2.6: Attenuation versus wavelength for a commercial plastic multimode step-index fiber [11]. It typically decreases with wavelength while for the single-mode fibers it increases.

Another important concern is long term degradation at high operation temperatures. Typically, plastic fibers can not be used in applications where the temperature ranges up to 85°C. This leaves only a little margin with engine compartments of car which can get hotter. Plastic fibers are designed similar to glass- fibers;high index cladding (see figures 2.3 and 2.4) encapsulates the low-index core. Commercial plastic fibers are usually multimode.

2.4 High intensity light sources

Light source in the fiber-optic communication system converts an electrical input signal into an optical signal. The important parameters of the source are:

- the dimension of the light-emitting area and the radiation pattern of the optical bundle
- the efficiency
- the lifetime
- the effect of temperature on its transfer characteristics

Typical high-intensity light sources are lasers and LEDs. In this work we aim at short distance communications, for which relatively low wavelengths are used: typically around 850 nm[3].

2.4.1 Lasers

Vertical cavity laser (VCSEL) are realized by sandwiching a light-emitting semiconductor diode between multi-layer crystalline mirrors. The technologies used for VCSEL fabrication are typically InGaN or AlGaAs. Unlike edge-emitting lasers, which require a larger wafer area and power consumption, the laser output from a VCSEL is emitted from a relatively small area (5-50 μm^2) on the surface of the chip, directly above the active region. A VCSEL is shown in figure 2.7. The VCSELs physical structure yields numerous inherent advantages including: compact size and surface area, high reliability, flexibility in design, ability to efficiently test each die while still in the wafer state, low current re-

[3]Long distance communications uses (expensive) lasers operting at 1300 nm and 1550 nm.

quirements, efficient fiber coupling, high speed modulation, and the ability to build multiple lasers on a single semiconductor. A big advantage of VCSELs is that they can be modulated with very high frequencies (>50 GHz).

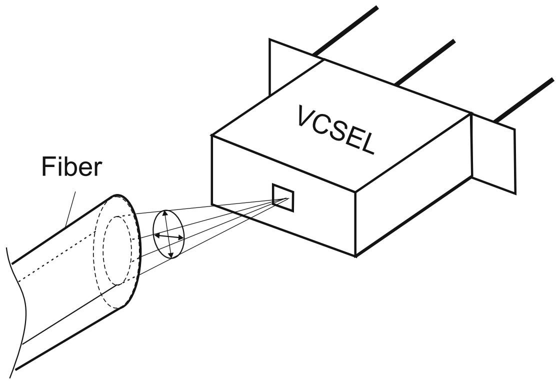

Figure 2.7: VCSEL structure with light emitted from the surface of the chip. Possible coupling with both the single-mode and multimode optical fibers.

2.4.2 Light Emitting Diodes (LEDs)

The working principle of the LED is based on emission of photons due to recombination of holes and electrons. The number of carriers present in the active LED region is proportional to the forward current through the LED. The dimensions of the emitting area of an LED are similar to the core diameter of a multimode fiber.

In most LEDs the light is not completely monochromatic i.e. show relatively broad spectra. The visible light from an LED can range from infrared (at a wavelength of approximately 850 nanometers) to blue-violet (about 400 nanometers).

2.5 Photodetectors - introduction

A silicon photodetector is in general a solid state transducer used for converting light energy into electrical energy. The following subsections present the main photodetector characteristics.

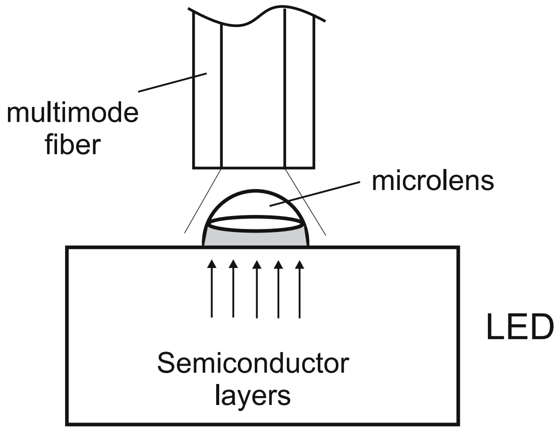

Figure 2.8: A LED coupled to a multimode fiber.

2.5.1 Ideal photodetector

In the ideal case, the photodetector should meet the following requirements:

- detect all incident photons,
- has a bandwidth larger than the input signal bandwidth,
- not introduce additional noise, apart from the quantum shot-noise from the received signal.

In most practical applications, additional requirements can be defined. The photodetector should be small, reliable, its characteristics should not be affected by age and environment and it must be cost-effective.

The requirements for ideal photodetectors are very hard to meet in reality, and the photodetectors usually have limited bandwidths with finite response time. They introduce unwanted noise and the efficiency of detecting incident photons is less then 100%. The lifetime is usually limited and some detectors degrade unacceptably as they age.

Most of the photodetectors used in the today's communications are photon-effect based i.e. they directly generate the photocurrent from interactions between the photon and the semiconductor material. Photodetectors are grouped into four categories: photo-multipliers, photoconductors, photodiodes and avalanche photodiodes. In this book the main focus will be on photodiodes. The limitations of photodiodes in standard CMOS in their quantum efficiency and in the bandwidth will be discussed in the following chapters.

2.5.2 Absorption of light in silicon

Light shining onto a semiconducting material is absorbed in that material. More precisely, in this process the photon energy is absorbed. For low photon energy (i.e. long wavelengths) the only effect is that the semiconductor material heats up. For higher photon energy levels the electrons in the valence band may get sufficient energy to reach the conduction band. Clearly this requires photon energies larger than the bandgap (in eV) of the semiconductor material. In this last case, the single photon created upon absorbtion a mobile electron and a mobile holes in the valence band. Basically, these two types of carriers are seen as a photocurrent at the photodiode terminals.

In the process of light absorbtion, over a certain distance into a material a (material and wavelength related) fraction of the photons is absorbed. The result is then that the light-intensity decreases exponentially with distance into the material [8]. In equation:

$$I \propto e^{-\alpha x} \tag{2.9}$$

where α is the wavelength (and material) dependent absorption coefficient while x is the depth in silicon. The absorption coefficient for silicon can be approximated with the following formula [14]:

$$\alpha = 10^{13.2131 - 36.7985\lambda + 48.1893\lambda^2 - 22.5562\lambda^3} \quad 1/[\mathrm{cm}] \tag{2.10}$$

The wavelength λ of the input light signal is given in [µm].

Photodiodes in CMOS technology are sensitive only for a particular wavelength range. The photon energy $h\nu$ is wavelength dependent and it should be larger than the bandgap of the semiconductor material (in this case silicon) [15]. For relatively large wavelengths the photon energy is not high enough to create an electron-hole pair in silicon; for silicon this is for λ>950 nm. For lower wavelengths on the other hand, λ< 400 nm, excess carriers are generated very close to the photodiode surface. Because typically the surface recombination rate is high then only a small part of the generated carriers contribute to the photocurrent, the usable wavelength sensitivity range of CMOS photodiodes is $\lambda \in [400 - 850]$ nm.

For best performance e.g. the highest speed and responsivity, the photodiode should be designed to allow the largest number of photons to be absorbed in depletion regions; in the ideal case photons should not be absorbed until they have penetrated as far as the depletion region, and should be absorbed before penetration beyond it. The relative depth to which photon penetrates is a function of its wavelength (see chapters 3, 4 and 5). Short wavelength light (around blue and violet) are absorbed close to the photodiode surface while those with longer wavelength (infrared) may penetrate 10ths of micrometers deep in the substrate.

The values of the absorption coefficient and the corresponding 1/e-absorption depths[4] in silicon, are shown in figure 2.9. From this figure we conclude that the difference in absorption coefficient for the two boundaries is very large: $\alpha = 7.5 \times 10^2 \div 5.5 \times 10^4 \quad \text{cm}^{-1}$. As a result, the difference in 1/e-absorption depths for 400 nm and 850 nm light is almost three orders of magnitude.

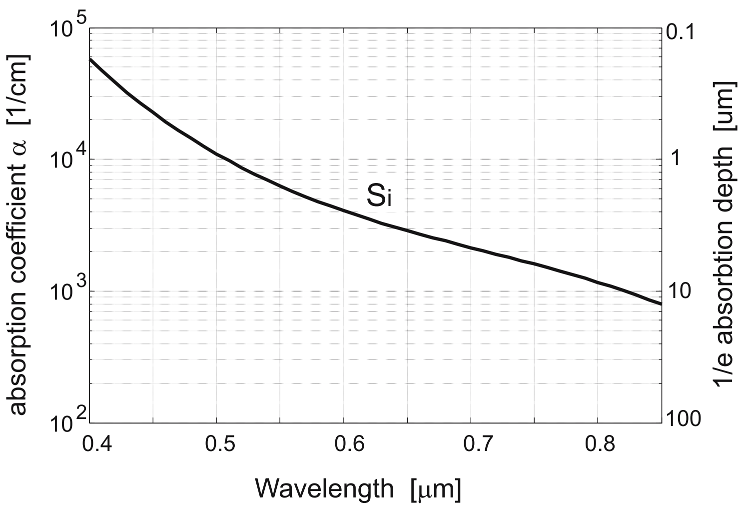

Figure 2.9: The absorption coefficient α for silicon photodiodes versus input wavelength of the light signal λ.

The light intensity drops exponentially inside silicon:

$$\frac{\partial I}{\partial x} \propto \alpha e^{-\alpha x} \tag{2.11}$$

The more light is absorbed in the photodiode, the more excess carriers are generated. We define a parameter $G(x)$ which is the *carrier generation rate* as

[4]The 1/e absoption depth is the depth into the silicon for which the light-intensity is dropped to 1/e of the incidentlight-intensity. This depth is equal to $1/\alpha$ of the input wavelength

a result of the incident light in the unity of time often modelled as:

$$G(x) = \Phi_0 \alpha e^{-\alpha x} \tag{2.12}$$

where Φ_0 is the *photon flux* at the silicon surface generated by a monochromatic optical source and can be further expressed as:

$$\Phi_o = \frac{P_{\text{in}}}{h\nu}(1 - R_{\text{f}}) \tag{2.13}$$

P_{in} is the input optical power density (W/cm^2), $h\nu$ is the photon energy and R_{f} is the reflection coefficient due to the different index of reflections of the "outside world" on the top of the silicon and the silicon itself [8]. During each unit of time, $P_{\text{in}}/h\nu$ photons arrive with a frequency ν. The number of generated carrier pairs is $\sim \eta P_{\text{in}}/h\nu$ resulting in a photocurrent of $\sim \eta e P_{\text{in}}/h\nu$ [8] (where e is electron charge); this is often referred to as photodiode *responsivity*. It is defined as the average photocurrent per unit of incident optical power:

$$R = \frac{e\eta}{h\nu} \tag{2.14}$$

The parameter η is quantum efficiency. The quantum efficiency is often defined as the average number of (primary) generated electron-hole pairs per incident photon. For every photodetector there are typically four quantum efficiency components:

1. efficiency of light transmission to the detector (fraction of incident photons that reach the silicon surface)

2. efficiency of light absorption by the detector (fraction of photons reaching the silicon surface that produce electron-hole (EH) pairs)

3. quantum yield (number of EH pairs produced by each absorbed photon)

4. charge collection efficiency of the photo-detector (fraction of generated minority carriers by presence of light, that cross the pn junction before recombining).

However, during the calculations of the available output photocurrent, typically only the first and the fourth quantum efficiency components are taken into account. The other two components are taken to be equal to one. Typical value of the quantum efficiency in a CMOS photodiode is about 40%-70%.

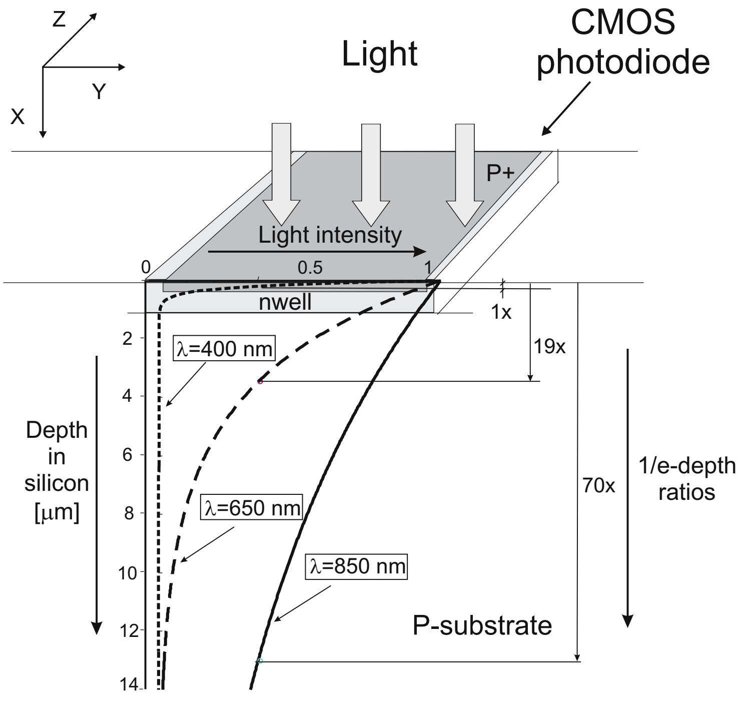

Figure 2.10: The absorption of light inside photodiode in standard CMOS technology. The difference between 1/e-absorption depth among λ = 400, 650 and 850 nm) is large; There is a causal relation between the photodiode responsivity and the bandwidth.

The maximum possible responsivity varies with photon energy. For $\eta = 1$, the maximal responsivity can be simplified as: $R_{\text{ max}} = \lambda/1.24$, where λ in [µm]. For the wavelength sensitivity range of CMOS photodiodes 400 nm<λ<850 nm, the maximum responsivity is in the range 0.32 A/W<$R_{\max}$<0.64 A/W.

The responsivities of a typical Si photodiode, Ge photodiode and InGaAsP photodiode as a function of wavelengths are shown in figure 2.11. In that figure, the maximum responsivity is marked by the line indicated with $\eta = 1$.

In the short-wavelength region (λ = 400 nm), the value of $R_{\max}$ decreases more rapidly than λ; this is caused by increased surface recombination for the shallow absorption depth. For large wavelengths (λ>850 nm) the responsivity of the CMOS photodiodes also declines; minority carriers are generated deep in the substrate and they are recombined with majority carriers.

Figure 2.11 shows that silicon photodiodes are not useful in the longer wave-

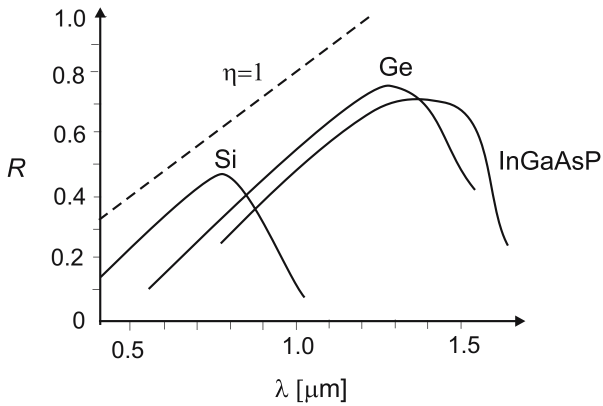

Figure 2.11: Responsivity of a Si photodiode, a Ge photodiode and a InGaAs photodiode as a function of the wavelength

length region λ>950 nm. Other materials have the advantage of a smaller bandgap and higher mobility providing thus higher responsivity and higher bandwidths. However, silicon photodiodes can be integrated with mainstream electronic circuitry which provides low-cost solution for high-speed optical detection. This last point is the main motivation for the work presented in this book.

2.6 High-speed optical receivers in CMOS for $\lambda = 850$ nm-literature overview

This section presents a brief overview of high-speed optical receivers in CMOS technology reported in the literature for $\lambda = 850$ nm. Only a few solutions for optical receivers are reported in standard CMOS; the reported data-rates in standard CMOS is up to 700 Mb/s. Other publications use modified CMOS technology and high-voltage solutions with reported data-rates up to 1 Gb/s.

2.6.1 Using standard CMOS technology

High-speed optical detection is typically achieved in two manners. Firstly "smart" photodiode and full exploitation of the possibilities in a technology can be done. These possibilities include layout issues, using high voltages, adding processing features and more. Secondly, slow standard photodiodes can be used, with electronic postprocessing to boost speed.

CMOS technology with feature size of 1µm

In [16], a data-rate of 622 Mb/s is achieved in a 1-µm CMOS technology with a diode bias voltage of 5 V and with 850 nm light. The reported sensitivity of the detector is -15.3 dBm for a bit error rate (BER) of 10^{-9} which is low compared to the requirements for e.g. the Gigabit Ethernet Standard: -17 dBm for the same BER [17].

Important differences between a typical 1 µm CMOS processes and a 0.18 µm CMOS process (used as demonstrator process in this book) include:

- the depth of the nwell is about 4 µm which is 3-4 times larger than in modern CMOS technology.

  For $\lambda = 850$ nm, a large portion of light (roughly 1/3) is then absorbed in nwells, in comparison with newer CMOS technologies where over 80% of the light is absorbed inside the substrate. As a direct result, the (fast) diffusion inside the nwell contributes significantly to the speed of the photodiode in the 1μm process; in modern CMOS typically the (slow) bulk currents are far dominant. A full analysis of speed aspects is given in chapter 3

- the supply voltage is almost three times higher (5V/1.8V); as a result the depletion region width is about 50% higher which again gives the photodiode in a 1 μm process a speed advantage over diodes in 0.18 μm processes.

- 1 µm CMOS is outdated, and cannot implement electronic circuits in the GHz range.

Together with the depletion region that has a couple of µm depth inside the epi-layer, the amount of the carriers that are generated deep in the substrate is 5 times lower than in modern CMOS technologies[5]. For comparison, the photodiode bandwidth for a modern CMOS process (0.18 µm) is only 1 MHz for $\lambda = 850$ nm (see chapter 3).

[5]Slow diffusion of the substrate carriers that limit the photodiode bandwidth is tremendously reduced (exponential light absorbtion). This will be discussed in detail in chapter 3.

SML detector exploiting layout design

One solution in standard 0.25 µm CMOS technology where 700 Mb/s data-rate is achieved is presented in [18, 19]. The effect of the slowly diffusing carriers is cancelled by subtracting two diode responses: one immediate and one deferred diode responses.

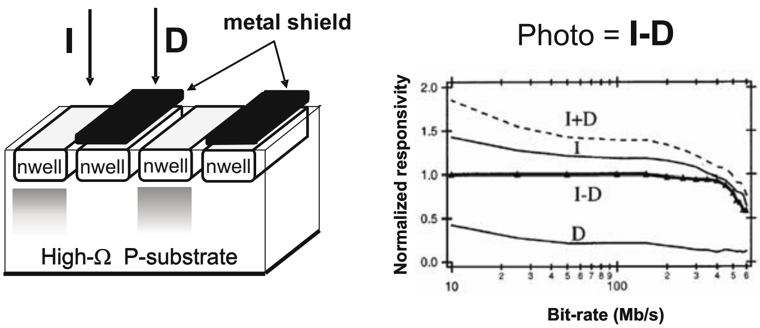

Figure 2.12: Spatially modulated light detector.

The principle of the SML-detector allows one to cancel the effect of the substrate carriers at the cost of lower responsivity. The SML-detector consists of a row of rectangular p-n junctions (fingers) alternatingly covered and non-covered with a light blocking material, as shown in figure 2.12. The masked fingers connected together form the *deferred* (D) detector. The other fingers connected together form the *immediate* (I) detector.

The slow tail in the time-response of both detectors is very similar, since approximately the same number of the substrate carriers diffuse towards the two detectors. The fast overall photodiode response is achieved by subtraction of the two diode responses. This however results in lower responsivity (about 75% of the input signal is lost) and hence lower sensitivity. For 300 Mb/s data-rate and BER=10^{-9} the reported sensitivity was -18 dBm. The detector responsivity for 700 Mb/s [19] was not reported; typically the optical power of the input signal is even higher since the noise in the circuit is increased for higher speeds.

2.6.2 CMOS technology modification

Very high-resistance substrate

A solution for 1 Gb/s optical detection is presented in [20]. An integrated receiver is designed in NMOS technology with a special high-resistive substrate which behaves as a diode intrinsic (I) region. This PIN photodiode is used as a detector designed using n+ and p+ layers inside high-resistive n-substrate. A large intrinsic region ensures both the high speed and the high quantum efficiency of 82%. However, the supply voltage is -32 V. This is unrealistic biasing in modern CMOS processes where typical supply voltage is around 1 V.

Buried oxide layer

In order to increase the photodiode bandwidth, the dominant slow substrate diffusion current [18] can be cancelled by introducing an *buried oxide layer*. The working principle is similar with silicon-on-isolator (SOI) photodetectors. The biggest disadvantage of this technique is a reduced responsivity. The large portion of the excess carriers generated in the substrate do not contribute to the overall photocurrent. In [21], a bandwidth of 1 GHz is reported with the cost of very low[6] responsivity of 0.04-0.09 A/W, corresponding to a sensitivity of 2 dBm to -5 dBm. As a result, the input optical power should be at least 13 dB higher than required in Gigabit Ethernet Standard [17].

[6]Typically, responsivity of the photodiode is > 0.3 A/W corresponding to >40% quantum efficiency.

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