Neuromorphic Electronics

Photo Receptors in CMOS

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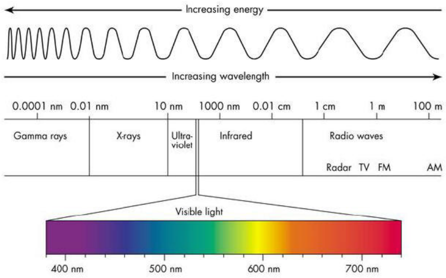

Figure 1.1: Electromagnetic Spectrum

1.1 Fundamentals of Photo Detectors Operation

The transduction of light into electrical signals in a semiconductor is a complex process that depends on may factors: quantum efficiency, wavelength of the incident light, doping concentration of the semiconductor, etc. The electrical signals are electrons that 'jump' from the valence band to the conductance band excited by photons absorbed by the detector. A photon is an elementary particle that represents the basic unit of light or electromagnetic radiation. Not do all photons can excite electrons from the valence band to the conductance band. Only those whose energy E_{ph} exceed a certain threshold (semiconductor bandgap E_g) can create them. This imposes conditions for the wavelength detection depending on the semiconductor material. The energy of one photon can be described by:

$$E_{ph} = \frac{h \cdot c}{\lambda} \tag{1.1}$$

where h is the Planck constant, c is the speed of the light and λ is the light wavelength. Thus,

$$\lambda_c = \frac{h \cdot c}{E_g} = \frac{1.24}{E_g(eV)}[\mu m] \tag{1.2}$$

If $\lambda > \lambda_c$, the energy of the incident photon will not be enough to create one electron and light will pass through the semiconductor. In the case of silicon, $E_g = 1.12eV$ and $\lambda_c = 1.11\mu m$. So typically, silicon conductors can detect light within the visual spectra (See Fig. 1.1) and even are capable of detecting early infrared light.

Unfortunately, the number of electrons that incide in the silicon is not the same than the number of excited electrons created by then. This number is always lower and depends on several parameters. For this reason, we define a figure of merit called *quantum efficiency* which is the number of electrons per incident photon at a given wavelength. Quantum efficiency is determined by several parameters. Just to mention a few: the absorption coefficient of the semiconductor, the semiconductor's overlaying material, the recombination life time and the diffusion length. So we can state that the quantum efficiency has a strong dependence with technology. For this reason, there are dedicated fabrication processes optimized for light detection. The depletion region is a spatial region between two silicon regions with different doping concentrations. In this region there are electrics fields that attract the electrons created by the incident photons. Quantum efficiency will be determined by the efficiency of charge collection in this region. In the next sections, we will discuss briefly the influence of some of these factors on the light transduction into photo current.

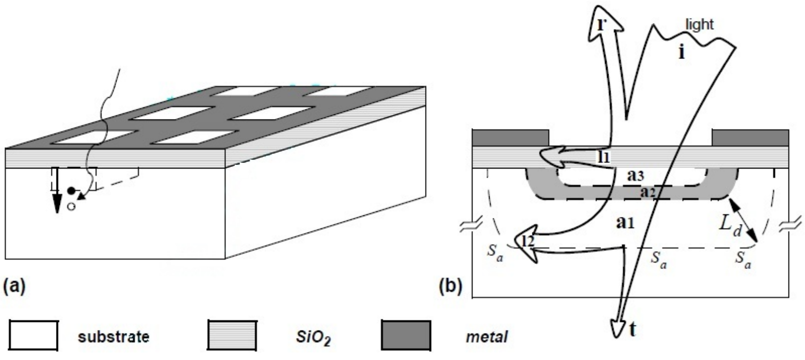

Figure 1.2: Layout of a 2-D pixel array and cross section illustrating the light absorption process.

1.2 Overlaying Material

Fig. 1.2 shows how light can penetrate through a the photo sensing/processing part of a chip. Chips are usually covered by an opaque mask to prevent it of their formation of parasitic photo diodes that could inject noise (photo current) and alter the chip performance. The parts that have to sense light are uncovered as is shown in Fig. 1.2. However, not can all the incident light be sensed. Part of it, is reflected in the oxide/air interface (r in Fig. 1.2). Typically, some anti reflective layers are used on the top of the detector's area to reduce the amount of light that is reflected back. Another part is absorbed before arriving to the semiconductor due to the imperfect transparency of the silicon oxide and/or other cover layers (*I1* in Fig. 1.2). And always some amount of light will pass through the silicon without generating electron-hole pairs (t in Fig. 1.2). Furthermore, some CMOS processes provide silice layers on the drain/source regions and gates to increase its resistance. They also use to create resistances. However, this silicide material is highly opaque to visible light. Some precesses offer the possibility of removing these layers over certain regions of the chip to improve sensitivity to light. Companies usually have dedicated foundries and tailored processes to fabricate photonics devices. Nowadays, new trends in CMOS technology are *backthining*: the chip is illuminated from the bottom and not from the top, or 3D processes: several dies are stacked in 3 dimensions. One specific layer can be dedicated just to sense light. Thus, high spatial resolution and sensitivity can be achieved.

1.3 Light Absorption in Silicon

To measure how fast light (packets of photons) is absorbed in the semiconductor, we define the absorption coefficient. It describes how far a foton can travel through the semiconductor without being absorbed, creating an excited electron. If ρ_0 is the incident power per unit area of monochromatic light incident on the semiconductor surface, then the available power at a depth x from the surface is given by

$$\rho(x) = \rho_0 \cdot e^{-\alpha x} \tag{1.3}$$

Parameter α depends on photon wavelength. Shorter wavelengths are absorbed close to the surface and longer wavelengths are absorbed deeper. Based on this property, color detection is possible stacking photo diodes at different depths [2]. For deep blue light ($400nm$), α in silicon is $50,000cm^{-1}$ and is absorbed at average depth of $3,3\mu m$ from the surface. For red light ($650nm$),

$\alpha = 3000cm^{-1}$ and is absorbed at an averaged depth of $3,3\mu m$. If the absorption coefficient is too high or too low, the excited electron could be created in one region far away of the depletion region and could not be collected. This effect can be seen on the right of Fig. 1.2 represented as *I2*. The light that has been absorbed at different depths has been represented with the letters *a1, a2*, and *a3*.

1.4 Recombination Lifetime

Photon-induced electrons have a finite lifetime in which they are mobile within the silicon substrate before returning to the valence band [3]. This time constant is called the recombination lifetime τ_r and depends on the quality of the silicon and its dopant density. Longer lifetime increases the probability of collection and therefore the quantum efficiency. Recombination can occur in several ways. Direct transitions between the valence and the conductance band yielding a photon are possible. However, this is unlike to happen. Indirect recombination has higher probability. This is mainly due to impurity dopants, phonons and lattice defects in the silicon. Typically, detectors are fabricated in regions that are free of defects. This region has a depth of a few microns and long recombination times. The bulk has a large number of defects and recombination lifetimes are shorter. Long wavelengths typically reach the bulk producing excited electrons with a very low lifetime, reducing quantum efficiency.

1.5 Diffusion Length

Excited electrons in CMOS detectors are collected by an electric field created in the depletion region (shadowed area in Fig.1.2). We can separate the collected carriers into two groups: Those absorbed within the depletion region (they are represented as *a2* in Fig. 1.2) and those who are created outside the depletion region and then they diffuse towards the depletion region where they are also collected (they are represented as *a1* and *a3* in Fig. 1.2). During the diffusion process, some carriers can recombine and being lost.

The diffusion length L_d represents the average distance that an excited electron can travels without recombining. L_d value depends on doping and temperature and can reach hundreds of micrometers in modern CMOS technologies. It decreases when we increase doping and temperature. Obviously, some carries created far away of the depletion region will not be collected. They have been represented as *I2* in Fig. 1.2. The depletion region is small in comparison to the semiconductor's volume. For this reason, in modern technologies, the majority of the carriers absorbed in the depletion region corresponds to photons absorbed outside the depletion region. They have been represented as *a1* and *a3* in Fig. 1.2.

1.6 Photo Charge and Photo Current

If ρ_0 is the incident power of monochromatic light per unit of area penetrating the semiconductor's bulk, the corresponding number of photons is given by

$$\Delta ph = \frac{A \cdot \rho_0 \cdot \Delta T_{int}}{(h \cdot \lambda)/\lambda} \tag{1.4}$$

where A is the detector area, and ΔT_{int} is the time the semiconductor is exposed to light. Previously, we defined the *quantum efficiency*, $\eta(\lambda)$, as the ration between the number of incident photons and the number of collected charges. Hence, we can express it mathematically as

$$\Delta n = \eta(\lambda) \cdot \Delta ph \tag{1.5}$$

As we stated before, the quantum efficiency is a parameter that shows a strong dependence with technology and the incident wavelength λ. It is difficult to model it mathematically and for this reason, it is usually determined experimentally before characterizing sensors. If we combine the two prior equations, the number of detected charges is:

$$\Delta n = \frac{A \cdot \rho_0 \cdot \Delta T_{int}}{h \cdot c} \cdot \lambda \cdot \eta(\lambda) = A \cdot \rho_0 \cdot H \cdot \xi(\lambda) \cdot \Delta T_{int} \tag{1.6}$$

where H is a physical constant defined as $H = (h \cdot c)^{-1}$ and $\xi(\lambda) = \lambda \cdot \eta(\lambda)$ is a function of wavelength.

We define the *photo charge*, Q_{ph}, as the amount of charge detected. Thus,

$$Q_{ph} = q \cdot \Delta n = [A \cdot \xi(\lambda)\Delta T_{int}] \cdot \rho_0 \cdot q \cdot H \tag{1.7}$$

where q is the electron charge. It can also be described in terms of charge per unit time, *photo current*,

$$I_{ph} = \frac{Q_{ph}}{\Delta T_{int}} = [A \cdot \xi(\lambda)] \cdot \rho_0 \cdot q \cdot H \tag{1.8}$$

There is a linear dependence of photo current or photo charge with light power. Such dependence, also called *optical dynamic range* is kept during several decades. The upper limit is usually establish by the optical experimental setup. It is complicated to obtain scenes with an illumination above $50Klux$. The lower limit is determined by the *dark current*. We will explain it in the next section. The terms in brackets of the previous equation can be controlled directly or indirectly by the designer. Engineers usually choose tailored processes of fabrication with high quantum efficiency for the design of photo sensors. The area of the photo receptor is chosen by the designer. It has to be enough to generate a photo current that the front-end circuitry can detect/sense. Making it too high would increase the pixel size and hence, reduce the resolution of our sensor if we have an array of pixels. Therefore, there is an important trade-off between dynamic range and area consumption.

1.7 Dark Current

Dark current limits the minimum detectable photo current in CMOS sensors. It can be defined as the reverse current measured without illumination. The reverse current through a photo diode does not depend on illumination. It depends on the doping of the diode and temperature. According to [6], it can be expressed as

$$I_{dark} = \frac{A_j \cdot q \cdot n_i \cdot W}{2\tau_0} \tag{1.9}$$

where τ_0 is the effective lifetime of minority carriers, W is the width of the depletion region, and A_j is the effective area of influence of the incident light. The parameter τ_0 has a strong dependence with temperature. For this reason, temperature value when the dark current is measured is usually specified. We have to remark that dark current is a limiting factor in photo sensors design. If the photo receptor's area is reduced, the photo current will be reduced in the same way and their ration will remain constant.

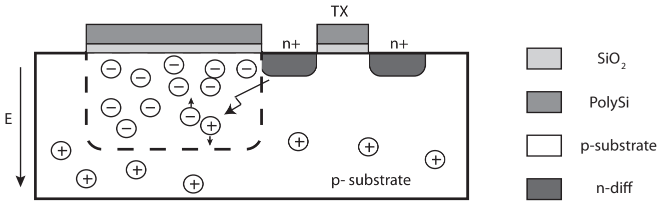

Figure 1.3: Photo gate and discharging transistor TX.

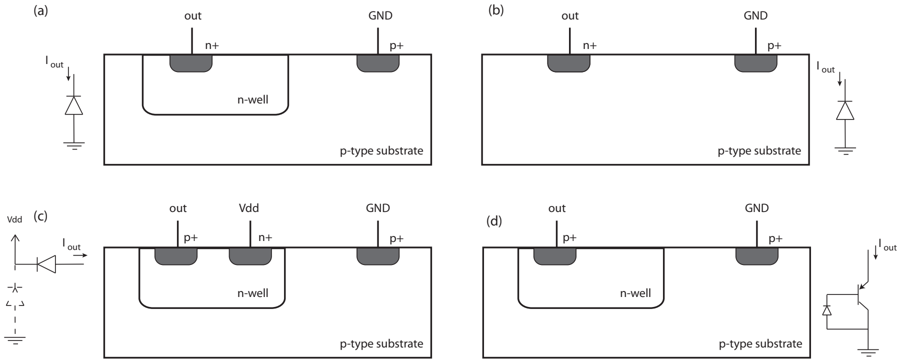

Figure 1.4: Examples of possible junction photo detectors available in CMOS technology

It exists tailored fabrication processes to reduce dark current. Some of them offer the possibility of incorporating to the designs *pinned photo diodes*. They used special or additional layers to minimize dark current. They also optimize the depth of the depletion region to improve the absorption of short wavelengths.

1.8 CMOS Photo Detector Structures

In CMOS technology there are two basic types of photo detectors. The first type is based on diodes reverse biased (photo diodes or photo transistors). The second one is known as photo gates. In both cases the depletion region is created in the junction of two different regions connected to different potentials to increase the size of the depletion region. The difference is how the excited electrons are collected. In the photo diodes, one of the terminals of one PN junction is directly connected to photo sensing front-end, so photo current can be directly sensed by the processing circuitry. Photo gates are however isolated and they just accumulate photo charge. Then, this charge is transferred to the photo sensing stage using discharging transistor switches. Fig. 1.4 shows some examples of photo diodes used to detect light. In theory, all the possible PN junctions available in CMOS technology could be used as photo diodes to detect light [5], but their quantum efficiency is different. Phototransistors are similar to photo diodes, but they use three PN junctions. They have more sensitivity to light than photo diodes because they have internal gain. However, they are more noisy and they are not available in all the technologies. Nowadays, they are rarely used. In Fig. 1.4(a),(b) and (c) 3 different photo diodes are shown. The examples (a) and (b) have higher quantum efficiency than (c). Fig. 1.4(d) displays a vertical photo transistor ($p^+/n^-/p^-$) available in CMOS technology. Fig. 1.3 shows a photo gate. Basically is made up by the gate of

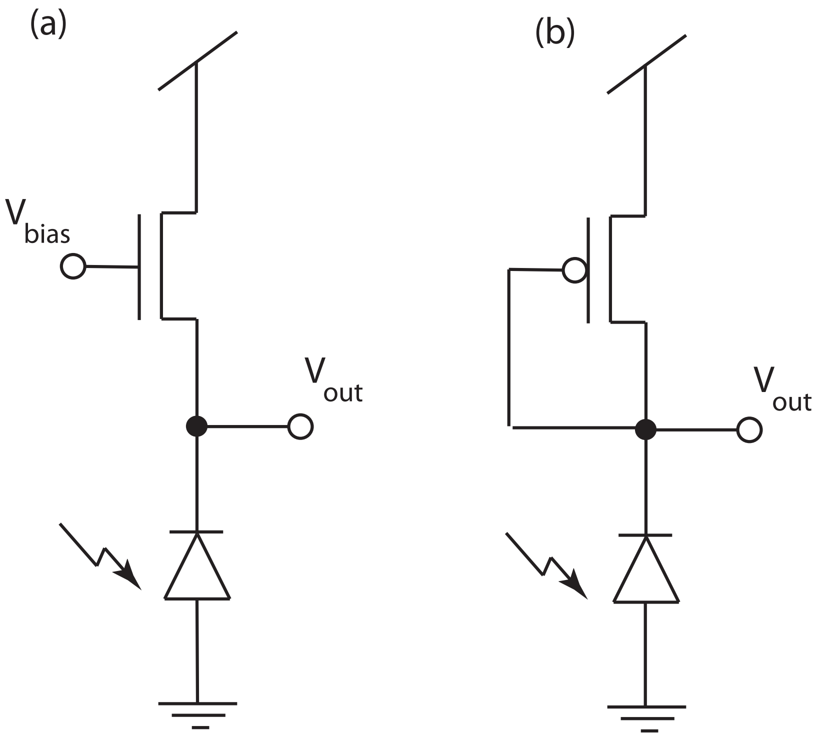

Figure 1.5: Two logarithmic amplifiers. The first one has an adjustable bias to control the output DC level. For the second one, the output voltage only depends on photo current value.

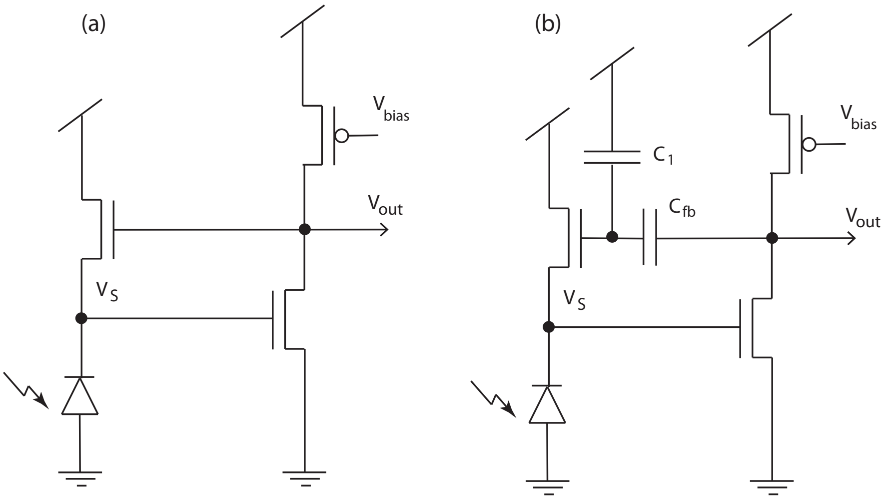

Figure 1.6: (a) Negative feedback amplifier. (b) Negative feedback amplifier with capacitive voltage divider to control the influence of the feedback loop.

a MOS transistor placed over the substrate. The gate is set to a voltage value higher than the substrate. By this way, we can create a depletion region underneath the oxide that can store photo charge. Then, this charge can be transferred using a transistor switch to transfer the charge to the next photo gate or the read-out circuitry. Photo gates are usually connected forming arrays. Their charge is transferred sequencially to the circuitry placed on the chip periphery.

1.9 Logarithmic Receptors

Human eye has a dynamic range of 10 decades. We are capable of distinguish objects and shapes under moonlight (< 1 lux) and we can see with very bright conditions (above 50Klux). Neuromorphic circuits have to cope with these hard constraints. Logarithm amplification is the way forward to compress the huge dynamic range of the input signal into a voltage that can range between GND and Vdd. Fig. 1.5 shows two examples of logarithmic I-V amplifiers. The first one has an adjustable bias. Its output signal is given by the expression:

$$V_{out} = \kappa \cdot V_{bias} - \kappa \cdot V_{T0} - U_T \cdot ln\left(\frac{I_{ph}}{I_S}\right) \tag{1.10}$$

The second one is simpler and avoid the use of one external pin to control the output DC level that is given by

$$V_{out} = n \cdot V_{DD} - V_{T0} - U_T \cdot n \cdot ln\left(\frac{I_{ph}}{I_S}\right) \tag{1.11}$$

We are usually more interested in measured the relative variations or increments of the photo current with respect an static value. The logarithmic amplifier with negative feedback shown in Fig. 1.6(a) offers this possibility and provides stability and robustness against noise. It has an operation range of several decades and its its gain only depends on the relative variations of the photo current. We can assume that the negative feedback loop can compensate all the variations of the input voltage and its small signal gain remains constant during all the operation range. Thus, the average (great signal) voltage level at the output of the amplifier is given by:

$$V_{out} = n^2 \cdot V_{dd} - n \cdot V_{bias} + U_T \cdot n \cdot ln\left(\frac{I_{ph}}{I_S}\right) + V_{T0} \tag{1.12}$$

Negative feedback also makes the sensor more strong against noise and external perturbations. It is also possible to limit or control the effect of the negative feedback placing a capacitive divider [1] in the feedback loop (see 1.6(b)). In that case, the voltage at the output of the amplifier can be expressed as:

$$V_{out} = n^2 \cdot V_{dd} - n \cdot V_{bias} + \frac{C_{tot}}{C_{fb}} \cdot U_T \cdot n \cdot ln\left(\frac{I_{ph}}{I_S}\right) + V_{T0} \tag{1.13}$$

Where $C_{tot} = C_1 + C_{fb}$.

Removing the DC component of this circuit, a sensor capable of detecting the temporal variations of intensity could be created. This is equivalent to detect movement and it is the principle of operation of the transient sensor described in [4].

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