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Chapter 1
Why Optoelectronic Circuits in Nanometer CMOS?

Highly integrated communication systems are required to fulfill the growing demand for higher data rates in telecommunication networks. The optical fiber links are the best candidates to deal with large volumes of data since they provide superior performance compared to conventional electrical links in terms of bandwidth, channel loss, electromagnetic interference, reflection, and crosstalk. Optical receivers and transmitters are known to be the most important building blocks in optical communication systems. But since the down-scaling of CMOS structure sizes, clock frequencies of digital logic grew tremendously and the chip area necessary for logic functions decreased dramatically. Digital signal processing, equalization, error correction and the physical layers causing a lot of overhead became much more important. Therefore there is a general trend to integrate optical receivers and transmitters with a lot of digital circuitry together reducing their price in large volume production considerably. Low cost and high performance optical receivers are required for high data rate telecommunication networks. Fully integrated optical receivers with integrated silicon photodiodes provide advantages over hybrid implementations, including low-cost, reduced parasitic capacitance, no bond-wire inductance. Nanometer CMOS technologies have been rapidly advanced, enabling the implementation of integrated optical receivers for data rates of several Giga-bits per second. In particular, low-cost silicon CMOS optoelectronic integrated circuits become very attractive because they can be extensively applied to short-distance optical communications, such as local area network, chip-to-chip and board-to-board interconnects. The next sections in this chapter give a brief overview of the current long-haul optical communication systems, short distance optical communication like fiber to the home, in-home network and optical interconnect. CMOS optoelectronics for short-distance optical communications and optical interconnect will be also discussed. Optical sensors is another growing field of application for nanometer optoelectronic CMOS circuits. One very important field are image sensors, where the pixel count of camera chips grew up to more than 10 Megapixels thanks to the shrinking of CMOS structure

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sizes. New applications are time-of-flight based distance sensors with high pixel counts also needing small-sized transistors for processing the distance information. Optically based medical investigation methods like PET and MRI require a high spatial resolution, i.e. many pixels, and complex signal processing fostering nanometer CMOS circuits.

1.1 Long-Haul Communication

The silica glass optical fiber (GOF) has three transmission windows, around the wavelengths 850 nm, 1.31 and 1.55 μm, Fig. 1.1 [1]. The single-mode fiber (SMF) has a loss of about 0.3 dB/km at the 1.31 μm wavelength. Because the lower loss of 0.2 dB/km at 1.55 μm this wavelength is preferred for long-haul communication. The first transmission window around 850 nm is used for short reach optical communication due to its higher loss compared to 1.55 and 1.31 μm. For traditional fiber, centered at approximately 1310 nm is a window of 200 nm and the total bandwidth in this region is about 25 THz. Centered at 1550 nm is a window of similar size ($\Delta\lambda = 200$ nm), which consists of three bands, S-band (1460–1530 nm), C-band (1530–1560 nm), and L-band (1560–1630 nm). Combined, these two transmission windows provide a theoretical bandwidth of 50 THz [2]:

$$BW = \frac{c}{\lambda^2}\Delta\lambda \tag{1.1}$$

where $c = 3 \times 10^8$ m/s.

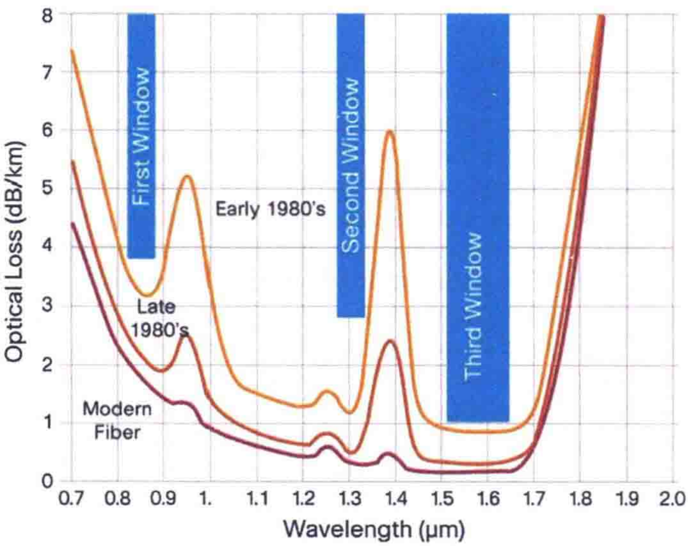

Fig. 1.1 Attenuation versus wavelength and transmission windows [1]

By 1980 the long distance optical fiber communication cables under the sea were tested. The optical fiber has a very low loss allowing long distances between amplifiers/repeaters. Optical communication links are capable of sending 1.28 Tbit/s data over a distance of up to 4000 km, without any electrical regeneration and a 2.4 Tb/s WDM signal (120 channels × 20 Gb/s) was transmitted over 6200 km [3]. An ultra-low loss high frequency coaxial copper cable operating at 40 GHz has an attenuation of about 2100 dB/km and a capacitance of 80 nF/km [4]. Due to the copper cables' high loss, communication systems using copper cables longer than one kilometer require signal repeaters for satisfactory performance. Many copper cables are required to replace one fiber cable to achieve the same data rate distance product. The high data rate distance product of the optical fiber is due to the absence of high loss, capacitive loading, inductive effects, and of cross talk common to long parallel electric conductor lines.

1.2 Fiber to the Home (FTTH)

Often 1.55 μm(0.2 dB/km) and 1.3 μm(0.3 dB/km) wavelengths are used for fiber to the home (FTTH). The 850 nm wavelength, however, also can be used for short-range data communication like FTTH, although its higher loss compared to 1.55 and 1.3 μm wavelengths disqualifies 850 nm for long-haul applications. For 850 nm wavelength, the commercial low-cost vertical-cavity surface-emitting lasers (VCSEL) can be used as transmitters. The loss of a multi-mode GOF is about 2.5 dB/km for a wavelength of 850 nm. These loss values are very low compared to the copper wire losses. For example, a coaxial cable has a typical loss of 500 dB/km for a signal at 10 GHz. A typical multi-mode fiber has a bandwidth distance product of 2 GHz· km at 850 nm whereas a Cat-6 unshielded twisted pair (UTP) has a bandwidth distance product of only 20 MHz· km [5] (Fig. 1.1). The most important driving forces for FTTH are the broadband applications such as IPTV, videophone, and online gaming which need more bandwidth than can be achieved by electrical links. The time taken to transfer large files (10 Gbit) using various access technologies like ADSL and VDSL is around 80 h and 50 min respectively. So, there is a limitations of ADSL and VDSL access network technologies to move such large data files over a few meters. Only FTTH provides realistic transfer times of 6 min compared to the other technologies [6]. In the near future, due to the large required data rate VDSL will be replaced by FTTH [6]. The biggest barrier for massive FTTH deployment is that the costs of FTTH systems are still high compared with VDSL. VDSL equipment costs are very low and VDSL equipment does not need installation of new copper or fiber cables, and the bandwidth provided by VDSL is enough for current applications. The transition from copper wire to optical fiber systems to migrate to FTTH cannot be achieved until new forms of technology capable of delivering high data rates with substantial cost reductions are developed. FTTH needs hardware and non-hardware improvements, such as transmission system components, network design, construction, operation, and maintenance [6]. The development of high performance low cost optical receivers is one of the important needs to enable low cost FTTH.

1.3 In-Home Network

In-building networks are using a wide range of transmission media like coaxial copper cables, twisted copper pair cables, free-space optical links, wireless links, etc. Each of these networks is optimized for a particular set of services; this complicates the introduction of new services and the creation of links between services (such as between video and data services). A single broadband multi-services network could provide an efficient solution to host and connect all existing and upcoming services together. The target for the data rate delivered to homes could be up to 1.25 Gbit/s in case of fiber to the home (FTTH) or up to 125 Mbit/s in case of very high bit rate digital subscriber line (VDSL2) technology [7]. The in-building network must not be a bottleneck for the future broadband services such as high definition internet protocol television (IPTV), multi-room and multi-vision configuration and high definition video transfer via the TV set. The home network can be used to share multimedia contents stored in a storage medium inside the house for offline future use [7]. Figure 1.2 shows a view for the next generation of home networks [8]. Copper links like twisted pair and coaxial cables are used to deliver telecom services within the building. For the future required broadband services the copper transmission medium suffers from serious shortcomings. Twisted pair has a limited bandwidth and is susceptible to electromagnetic interference (EMI). Coaxial cables have a larger bandwidth, but large thickness and the large effort required to establish a reliable connection introduces practical problems during installation. Moreover, the coaxial cable is not perfectly immune to EMI and has a certain attenuation. Optical fibers are used for long-haul communication and they represent an alternative for short-reach transmission inside building because of their higher bandwidth and they offer complete immunity to EMI [9, 10].

Glass optical fibers (GOF), however, are not suitable for use in building network because of the high cost involved for precise handling. Also the high bandwidth of the GOF is never necessary in this short distance application. On the other hand, it is important to have very simple and low-cost solutions. The cheap Poly-Methyl-Methacrylate Plastic Optical Fiber (PMMA-POF) is an excellent candidate for implementing such a short distance network. POF systems provide benefits compared to GOF and copper wire, which include simpler and less expensive components, operation in the visible range (the transmission windows are 530, 570 and 650 nm), greater flexibility and resilience to bending, shock and vibration, ease in handling and connecting (standard step-index POF core diameters are 1 mm compared to 8–100 μm for glass fibers), use of simple and inexpensive test equipment. Finally, POF transceivers require less power than copper transceivers. These advantages make POF very attractive for use within in-building networks [10]. To overcome the problem of the POF's high transmission loss very sensitive receivers must be used to increase the transmitted length over PMMA POF. There are two methods to solve the SI-POF's problem of limited bandwidth: the first method is to use multilevel signaling like Multilevel Pulse Amplitude Modulation (M-PAM) and Multilevel Quadrature Amplitude Modulation (M-QAM) [11]. Also the data rate limited by the POF's bandwidth can

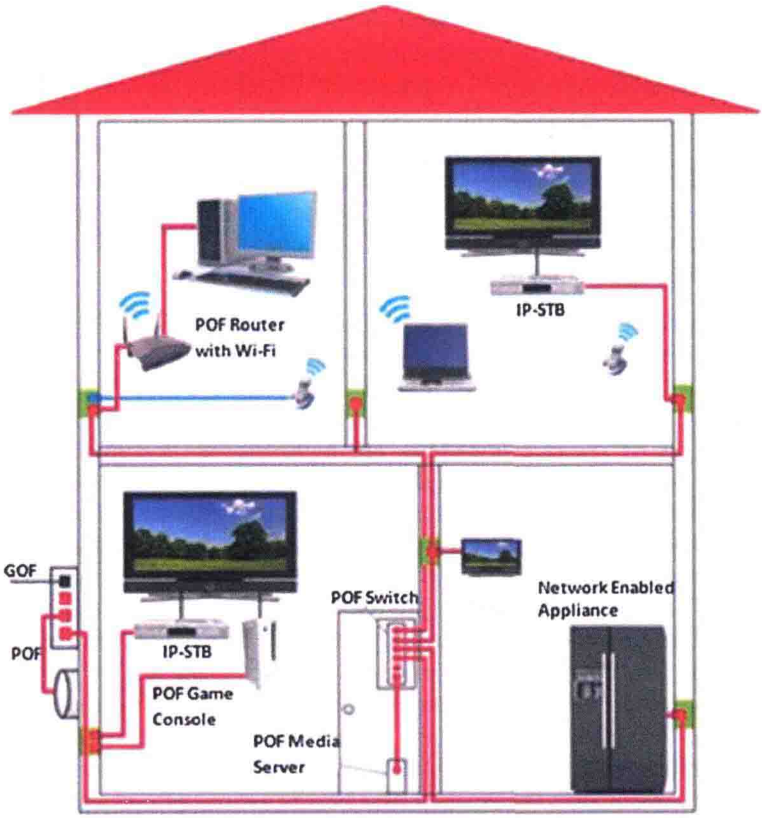

Fig. 1.2 The next generation of home network [8]

be increased by using spectral efficient modulation techniques like Discrete Multi-Tone (DMT) [12–15]. In the second method, equalization techniques can be used to compensate for the SI-POF limited bandwidth. Fixed or adaptive equalizers can be used for pre/post-equalization with different digital or analog equalization methods to increase the POF's bandwidth [11].

1.4 Optical Interconnects

Until now, electrical transmission is preferred for low data rates ($\leq$10 Gb/s) and short distance communication systems ($\leq$tens of meters) because of its lower material, electrical transmitters and receivers costs. The data rate distance product of electrical communication links is limited by physical loss coming from dielectric and skin effect losses of electrical interconnection, inductive and capacitive effects involved with the wire line, and cross talk between adjacent lines. For the required future higher bandwidths, the wire-line interconnects are approaching the theoretical channel capacity limit defined by Shannon theory [16]. For example, the widely used FR-4 copper trace material has a loss around 2.0–3.0 dB/inch at 12.5 GHz. The insertion loss and return loss increases with respect to the data rate. At 25 Gbps the insertion loss is far beyond the equalization dynamic range. The current electrical transmission technology cannot scale to 25 Gbps unless additional components, such as a repeater, which adds more power, cost, and complexity, are used [17]. The data rate of electrical lines is limited to:

$$B \leq B_o \frac{A}{L^2} \tag{1.2}$$

where A is the wire cross-sectional area, L is the wire length, and B_o is a constant = 10^{16} to 10^{18} b/s for off chip lines [18]. For high data rate and long wire length the required wire cross-section area should be increased. This will lower the line density and limit the maximum number of lines for parallel transmission. According to Moore's law the speed is doubled every 18 months. As data rates and wiring density is increasing, the difficulties of electrical interconnection through wires are increasing. The optical fiber has a negligible loss compared to the electrical wire. So, optical links are attractive for relatively long lines at high data rates and limited cross-sections [18]. As the data rate increases the microprocessor I/O pin numbers increase. The optical interconnect can provide the solution to the large number of high data rate I/O pins and minimize the power consumption per pin. The electrical signal charges the wire line to the signaling voltage. The total energy is:

$$E_s \geq C_l V_r^{\,2} \tag{1.3}$$

where C_l is the line capacitance and V_r is the signaling voltage. The longer the wire is the larger the capacitance and the higher the energy [18]. For an optical link, the optical energy required to charge the total capacitance C_d of the photodiode and the TIA input capacitance is [18]:

$$E_P \geq C_d V_r \frac{h\omega}{e} \tag{1.4}$$

where the voltage $\frac{h\omega}{e}$ is numerically equal to the photon energy in electron-volts. There is potentially an energy benefit for optical link when [18]:

$$C_d V_r \frac{h\omega}{e} < C_l V_r^2 \tag{1.5}$$

The optical connections will have a lower dissipated energy than the electrical connection for long distance and low photodiode capacitance. The required future higher data rates and lower power consumption make the optical interconnect competitive with electrical connect, leading to board-to-board, chip-to-chip and on chip

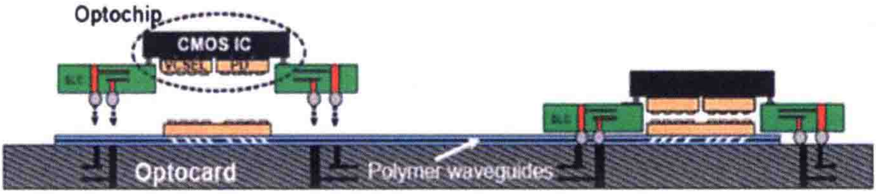

Fig. 1.3 Low cost optical printed circuit board with polymer waveguides [20]

optical communications. Optical links provide higher bandwidth for board-to-board and chip-to-chip on PCB connections, this enables higher connection density, lower latency, reduced power consumption and electromagnetic noise [19]. An example for low cost optical printed circuit boards (Polymer Waveguides) is shown in Fig. 1.3 [20]. On chip optical interconnects offer a potential solution for addressing global wiring issues. Optical Input/Output (I/O) could be a potential first application. On chip interconnects are not expected to replace Cu wires on low-k dielectrics in the lower layers of the on-chip interconnect stack because of delay and power considerations [21].

1.5 Optical Receivers

Long-haul optical communications works at 1.55 and 1.31 μm wavelengths which cannot be detected by silicon photodiodes and InGaAs photodetectors are needed. For in-building optical communication 650 nm laser diodes/VCSELs are well-suited for plastic optical fiber (POF) links. Large photodiodes with responsivities of about 0.5 A/W at 650 nm can be fabricated in cheap silicon technology. Short reach optical communication using cheap 850 nm VCSELs can use silicon photodetectors with data rates less than several Gb/s and responsivity smaller than hundreds of mA/W. For higher data rates and responsivity GaAs photodetectors are needed. The photonic layer needed for the III/V optoelectronic devices can be integrated following two different ways. In the first approach, wire-bonding or flip-chip bonding, the photonic devices are fabricated separately and bonded to the electronics chip. In the second approach, the photonic devices are integrated heterogenously on the circuits by wafer bonding or die to wafer bonding.

However, optical components' costs are still too high for these high volume markets of short-reach interconnects. Low cost, high volume CMOS compatible fabrication processes are required to enable that photonic connections replace the electrical connections. Implementation of optical interconnects for signaling, clock distribution and I/O requires development of a number of optical components like photodetectors and light sources [19]. The optical receiver costs can reduce by using a low-cost semiconductor process. Photodetectors and transistors in GaAs technology achieve superior performance, but GaAs processes are quite costly and they attain

Table 1.1 Time of optical communications commercial deployment (copper displacement) [20, 22]

	WAN	LAN	Rack-Rack	Card-Card	On PCB	Chip-Chip	On Chip
Length	Multi-km	<1 Km	<100 m	>1 m	Several cm	10s of mm	10s of μm
Links	1	1–10	10s	100s	1000s	10 Ks	100 Ks
Date	80s	90s	2000	2010	>2012	>2015	>2020

only limited integration scales. Silicon processes are cheap and allow a high density of integration. An integrated receiver with a monolithically integrated photodetector has economical advantage regarding to the solution with an external photodiode. In single-chip solutions the photodiode bond pad and the receiver input bond pad are not present and since parts of the receiver circuit can be placed around the photodiode, the single chip solution usually requires considerable less chip area than the sum of chip areas of the two-chip solution specially for smaller-size photodiodes. The mass production is one of the drivers to reduce the integrated system cost. Table 1.1 shows the time of optical communication's commercial deployment (copper displacement) [20, 22]. It is clear from Table 1.1 that the large volumes of optical interconnects (PCB, chip to chip, on chip) will be the main drivers to reduce the costs of OEICs.

Figure 1.4 is shown to demonstrate the technical advantages of an optoelectronic integrated circuit (OEIC) [23]. The solution of using a packaged photodiode and a packaged receiver IC soldered to a printed circuit board (PCB) is shown in Fig. 1.4a. CPAD1 is the capacitance of the bond pad of the photodiode. LB1 is the inductance of the bond wire inside the photodiode package. Additionally there are the capacitance of the pin of the photodiode package CPIN1, the capacitance of the copper line on the printed circuit board CLINE and the capacitance of the pin of the receiver package CPIN2. LB2 is the inductance of the bond wire inside the receiver package.

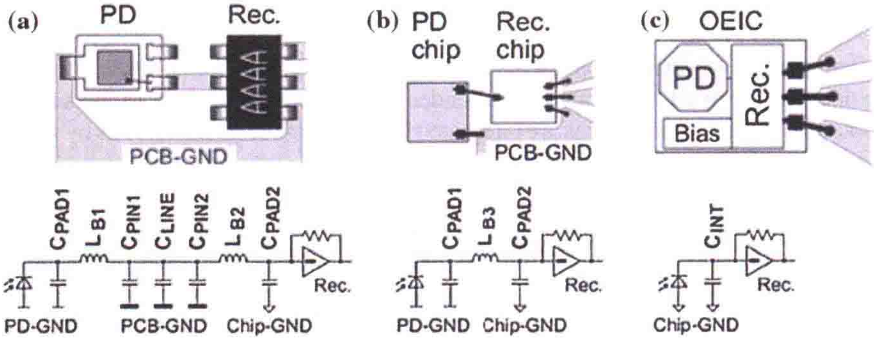

Fig. 1.4 Different ways of connecting the PD and the receiver: **a** packaged photodiode connected to packaged receiver, **b** photodiode die connected to receiver die via bond wires, **c** fully integrated optical receiver [23]

The capacitance of the bond pad at the receiver input is CPAD2. The mentioned parasitic capacitances will add to the junction capacitance of the photodiode and will reduce the bandwidth and worsen the noise behavior of the optical receiver. The parasitic inductances of the bond wires may lead to unwanted gain-peaking in the frequency response of the receiver input stage. Since the photodiode and the parasitic capacitances are not referenced to the same ground as the receiver, it is possible, that noise signals (e.g. switching noise) might be picked up from the ground lines.

The number of parasitic components is much smaller, if both the photodiode package and the receiver package are omitted (Fig. 1.4b). The photodiode chip and the receiver chip are glued to the printed circuit board. The photodiode is connected to the receiver with a bond wire (LB3) directly. The grounds of the photodiode chip and the receiver chip can be connected to the PCB ground with bond wires (as shown in the figure) or the chips can be glued to the PCB with a conductive glue if the chips provide a suitable backside contact. Photodiode and amplifier can be connected analoguously when they both are mounted on a lead frame within one package instead on a PCB.

If the photodiode is integrated to the receiver chip, almost all parasitic components at the input node of the receiver are avoided (Fig. 1.4c). The only remaining component is the parasitic capacitance of the interconnection line between the integrated photodiode and the input stage (C_{INT}). Usually, this capacitance is negligibly small. Therefore neither the bandwidth nor the sensitivity of the optical receiver is degraded by parasitic components. Additionally, the avoidance of bond wires minimizes the risk, that external electromagnetic fields or currents in neighboring bond wires couple noise to the input node of the transimpedance amplifier. Figure 1.5 shows the die photo of a fully integrated optical receiver with integrated photodiode for application together with POF.

Photodetectors can either be integrated on-die, bonded to a CMOS die, or on-package. Ge-based Metal-Semiconductor-Metal (MSM) and PIN diode photodetectors have received significant attention since they have the potential to be CMOS compatible. The key parameters of photodetectors are: high responsivity, high bandwidth at reverse bias less than or equal to 1 V and, stable operation up to 100 °C [19, 21]. Light sources can be off-die (package or board), bonded to a photonics die, or integrated on-die (typically adding III–V capabilities to a CMOS platform). Quantum dots nanophotonic material and high index contrast structures may play a strong role in future optical interconnections. To overcome the indirect silicon band-gap to achieve silicon lasers, silicon nanocrystals are employed. The requirements are high switching speeds. Total power requirements depend on the application, but are typically below 1W. Currently, the key concerns include wavelength stability, reliability at operating conditions and cost of laser arrays [19, 21].

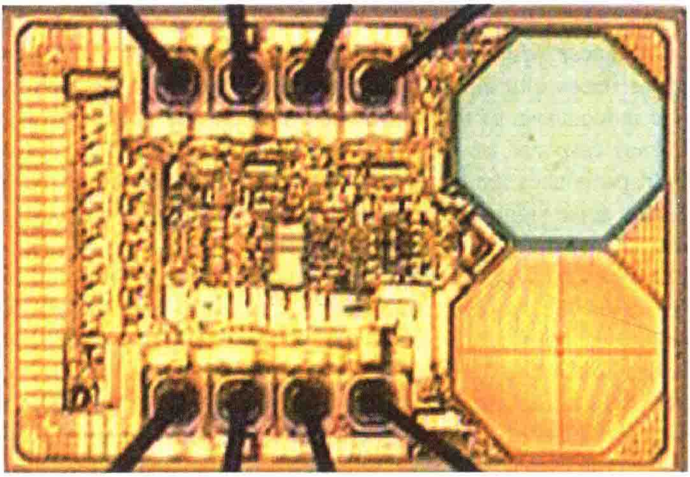

Fig. 1.5 Die photo for fully integrated optical receiver with integrated photodiode [11]

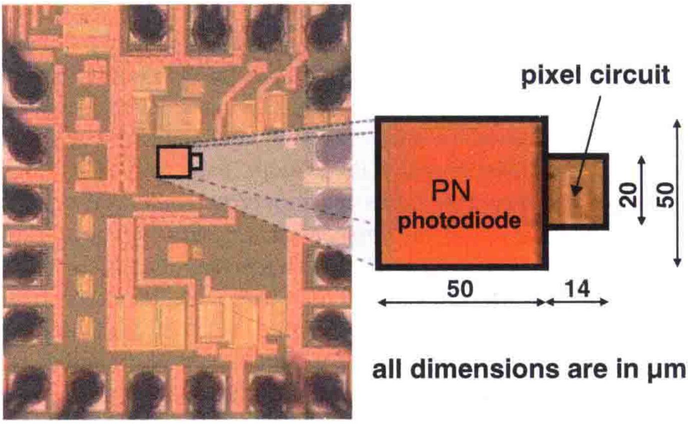

Fig. 1.6 Die photo of a distance sensor pixel in 90 nm CMOS [26]

1.6 Optical Sensors

Optical sensors span a wide range of applications. The ones being most relevant to nanometer CMOS OEICs are image sensors, time-of-flight 3D cameras, and optical sensors for medical applications. In these three applications a high spatial resolution is required. Advanced CMOS APS image sensors contain more than 10 million pixels with a pixel of about 2 µm. Such a small pitch requires very small transistors within the APS pixel, which aims into the nanometer scale CMOS processes. Time-of-flight 3D cameras record not only a two-dimensional image like the CMOS APS imagers.

These 3D cameras also determine the distance to the object point corresponding to each pixel simultaneously. Therefore, they need more transistors in each pixel than the APS pixels. The photodiode area within the 3D pixel has to be larger than that in a APS pixel in order to collect more light, which is necessary to achieve a good distance measurement accuracy being limited by the signal-to-noise ratio. Therefore, small transistors are needed aiming also towards nanometer scale CMOS. Figure 1.6 shows one pixel of a distance sensor in 90 nm CMOS. Up to 40,000 pixels have been realised in one 3D-sensor chip [24]. The newest 3D vision chip contains 2.1 million pixels [25].

Medical diagnostics requires highly sensitive photodetectors and a high spatail resolution. One application is positron electron tomography, where scintillation crystals are used to detect positrons. Such a crystal emits photons in the visible spectral range, which can be detected by silicon photodetectors. Furthermore, a high time resolution is needed implying a complex high-speed signal processing, which aims towards nanometer CMOS OEICs [27].

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