7.4 CMOS Imager Technologies for Biomedical Applications

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Apart from the ongoing debate about using CMOS active pixel sensors (APS) or CCD imagers for today's consumer and commercial applications the emerging biomedical market presents new opportunities to CMOS APS. Prominent examples addressing distinct issues in life style and health care are the possibilities to restore vision through a sub-retinal CMOS imager implant and to fabricate a low-cost intracorporeal video probe through a miniature CMOS imager.

Presented is the design and characteristics of the first CMOS imager chip that has been implanted into a patient's eye with demonstration of partially-restored vision. Also presented and discussed are the design and characteristics of the first miniature APS imager chip based on Thin-Film-on-CMOS (TFC) photodiode technology targeted at low-cost and disposable diagnostic products. Both sensor designs exploit the High-Dynamic Range CMOS (HDRC®) pixel circuit providing a continuous lin-to-log transformation of the photo current into a voltage sense signal [1]. This allows for implementing a retinal implant with characteristics similar to that of the human eye and to operate a miniature TFC imager for video inspection under strongly varying light conditions.

In Germany alone, some 17,000 people turn blind every year, many of them due to retinitis pigmentosa. Restoring vision through a retinal sensor implant, similar to the well-established pacemaker and cochlea implant technologies, is thus a very relevant challenge. There are two competing approaches: With an epi-retinal implant an image is received by a camera mounted to eye glasses and then transferred to a chip that supplies a stimulus signal directly to the ganglion cell/optical nerve interface [2]. The sub-retinal implant, in contrast, directly replaces the malfunctioning rods and cones in the lower part of the retina by a CMOS imager chip having stimulus electrodes at its frontside surface [2,3] (Fig. 7.4.1).

To achieve proper stimulation of the ganglion cells, while preventing from overcharging or damaging cells, constraints to charge (1 to 10nC), current (10 to 100μA) voltage (<2V), pulse duration (500μs) and pulse period (20Hz) need to be observed [2]. Moreover, the chip's size should be at least 3×3mm^2 for a minimum viewing angle of 12° and the electrode spacing should be about 70μm to ensure a properly isolated stimulation of the ganglion cells without any crosstalk [2]. Each pixel includes a HDRC® circuit, consisting of a sub-threshold transistor in series with the photodiode and an operational amplifier (OpAmp), which is used to adjust the signal level in the 1450 pixel cells to a reference signal provided by 9 globally distributed cells, indicating medium light intensity. The power supply bias of the OpAmps in the pixel cells is pulsed in order to directly provide the stimulus charge pulse to the ganglion cells according to the above mentioned constraints and to minimize the average power dissipation of the chip to ~5mW [2], (Fig. 7.4.2). Prior to implantation, the actual imager is tested on chip. Afterwards the test circuit periphery is physically removed from the sensor by dicing (Fig. 7.4.3 and Fig. 7.4.7). After separation, the actual retina implant chip is thinned down to ~50μm thickness, is covered by a passivation layer and receives TiN electrodes (50×50μm^2) [2]. The thin imager chip is mounted onto a tape connecting to the power supply (Fig. 7.4.2). This chip has recently been applied in a clinical trial at the University Eye Clinic Tübingen, Germany, with the result that partial vision could be restored to blind patients for the first time. Note, that this sub-retinal implant has the potential to be fully autonomous if the power supply can be arranged wirelessly by means of RF or infrared power transmission [2].

Visual inspection by endoscopy is an important capability in clinical surgery and medical health care. Also, video inspection inside the human body can be autonomous and lead to new products, such as a video pill [4]. Such diagnostic tools should have minimum size and possibly be disposable, thus making low-cost CMOS technology the preferred choice. The goal is to have a maximum fill factor and to tailor for an optimum trade-off between pixel size and sensitivity.

Presented is the first miniature CMOS imager chip having an optimized pixel size vs. sensitivity tradeoff by means of using Thin-Film-on-CMOS (TFC) photodiodes in an amorphous silicon (α-Si) layer above the CMOS. With this technology the fill factor is increased from 30% to ~90% (Fig. 7.4.4). A sandwich of p-i-n or n-i-p α-Si is deposited and patterned on top of the 0.25μm CMOS foundry wafers. A common top contact is formed by depositing a layer of ZnO. That layer needs to be sufficiently thin to be transparent for the incident light. The ZnO top layer is connected to the CMOS circuitry by an aluminum (Al) ring at the periphery of the imager field (Fig. 7.4.8). As a result of the non-planarity of the TFC layer and the spacing of the base metal contacts between pixels the fill factor is ~90% instead of the ideal value of 100% (Fig. 7.4.4). For the application to endoscopy a minimum number of input/output (I/O) nodes has to be realized. The sensor has a pixel field with 208 columns and 186 rows (Fig. 7.4.8). The readout path consists of a two-stage multiplexer circuit reducing the 208 columns to a single-ended analog video output. The synchronization information for post processing is modulated onto the analog output signal. All control signals like reset, addressing and the power supply for the digital circuits are generated on chip. Thus, only four I/Os (power supply, ground, system clock, analog video output) have to be connected to the chip.

The higher bandgap of α-Si (~1.8eV) compared to that of silicon (1.12eV) results in a potentially lower dark current (<10^{-10}A/cm^2) if compared to conventional silicon photodiodes. Owing to the short diffusion length of charge carriers in α-Si (100 to 150 nm) no physical pixel separation is needed (Fig. 7.4.4). This also results in lower dark fixed pattern noise (FPN) for the TFC sensor compared to the conventional device, though the photo response non-uniformity is somewhat larger for TFC, at least at the current stage of α-Si process development (Fig. 7.4.6). In comparison to the control sensor, the TFC imager has a nearly two-fold higher spectral sensitivity (Fig. 7.4.5) and a lower minimum detectable illumination (0.1lux vs. 0.3lux) due to the larger fill factor (90% vs. 30%). The high dynamic range (>120dB) is a result of the three-transistor HDRC® pixel cell used (Fig. 7.4.4). In comparison to state-of-the-art miniature CCD or CMOS imagers (Fig. 7.4.6) the TFC sensor is the best choice if the focus is on low-cost products since it uses a 0.25μm CMOS foundry technology and only has four I/Os, thus allowing for simplifying or even automating the chip assembly and packaging process (Fig. 7.4.5). The well-known degradation effects in TFC diodes are less crucial since the focus is on disposable, low-cost products.

References:

[1] B. Hoefflinger, ed., *High-Dynamic-Range (HDR) Vision*, Springer, Heidelberg, 2006.

[2] E. Zrenner, et al., "Subretinales Mikrophotodiodenarray als Ersatz für degenerierte Photorezeptoren?," *Der Ophthalmologe*, vol. 98, pp. 357-363, Apr. 2001.

[3] A. Dollberg, et al., "A Fully Testable Retinal Implant," *Proc. IASTED Conf. on Biomed. Eng.*, pp. 255-259, Feb. 2003.

[4] A. Arena, et al., "Intracorporeal Videoprobe (IVP)," *Medical and Care Compunetics 2*, vol. 114, pp. 167-174, June 2005.

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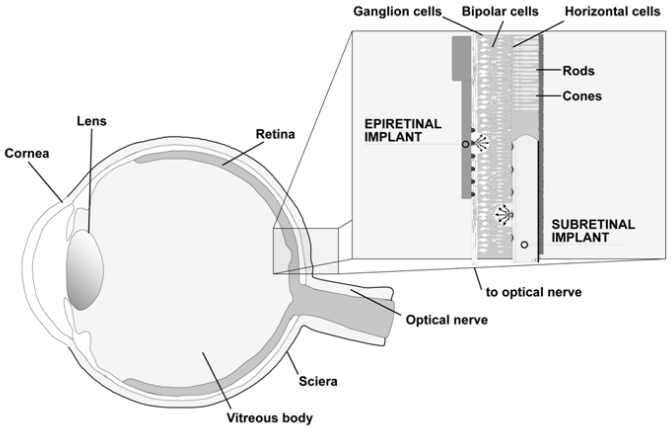

Figure 7.4.1: Schematic illustration of the human eye with a part of the retinal tissue with both an epi-retinal and a sub-retinal chip shown in the highlight.

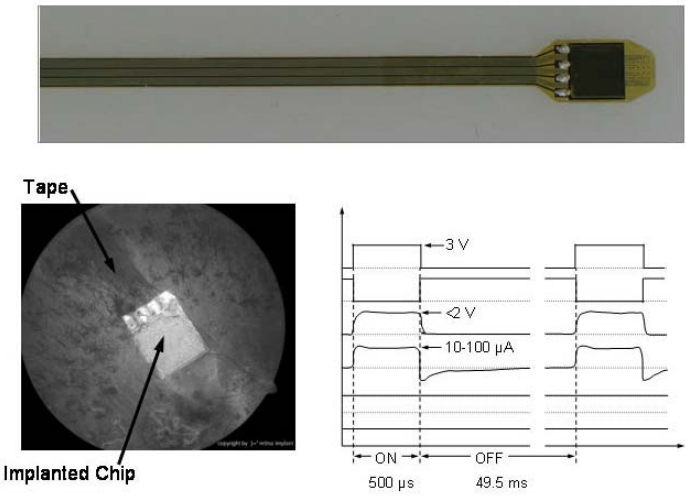

Figure 7.4.2: Photographs of the tape with I/Os and mounted retina-implant chip (top) and of the chip after being implanted into the retina (bottom; left); pulse diagram of the chip under operation (bottom; right).

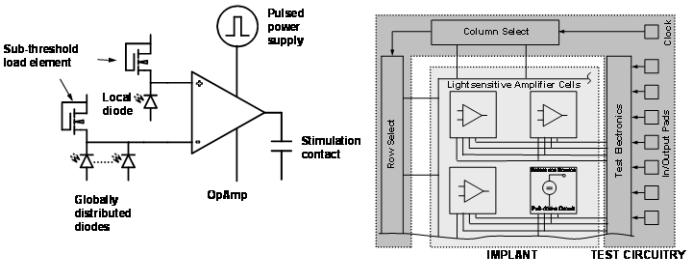

Figure 7.4.3: Circuit schematic of the pixel cell of the sub-retinal implant (left) and layout schematic (right) of the chip, indicating the chip section to be implanted (light grey) and the test circuit periphery to be removed after on-chip testing (dark grey).

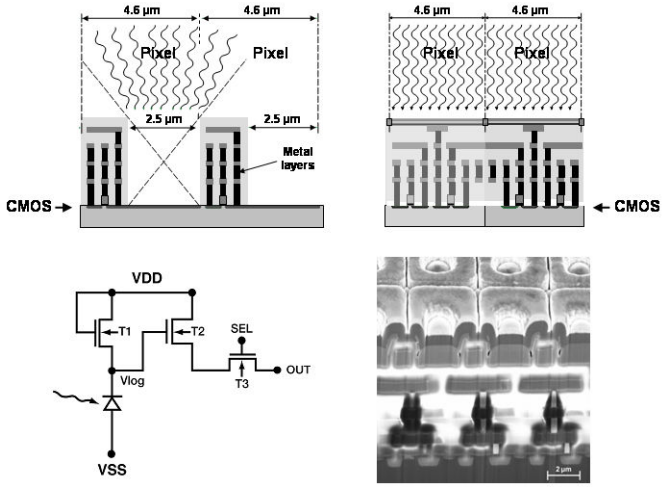

Figure 7.4.4: Schematic cross sections of two conventional CMOS pixel cells (top; left) and two TFC pixel cells (top; right); schematic of the three-transistor HDRC pixel circuit (bottom; left) and photographic cross section of the TFC pixel (bottom; right).

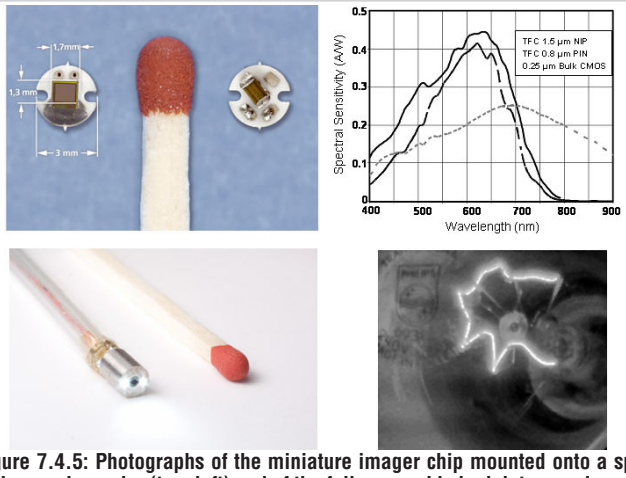

Figure 7.4.5: Photographs of the miniature imager chip mounted onto a special ceramic carrier (top; left) and of the fully assembled miniature endoscope (bottom; left); spectral sensitivities of the NIP and PIN α-Si photodiodes in comparison to bulk silicon diodes (top; right); image of a 100W light bulb taken with the miniature endoscope indicating the high dynamic range (bottom; right).

	Si pixel diode	TFC pixel diode	OmniVision OV6920	Sony CCD ICX257FKW
Resolution	208 x 186	208 x 186	320 x 240	500 x 582
Pixel pitch	4.6 µm	4.6 µm	2.5 µm	2,95 x 1.90 µm
Frame rate @ 1 MHz	30 fps	30 fps	30 fps	25 fps
Chip size	1.1 x 1.5 mm²	1.1 x 1.5 mm²	2.1 x 2.3 mm²	2 x 2 mm²
Imager area	0.98 x 0.86 mm²	0.98 x 0.86 mm²	0.82 x 0.62 mm²	1.48 x 1.1 mm²
Dynamic range	> 120 dB	> 120 dB	50 dB	NA
Supply voltage	single 3.3 V	single 3.3 V	single 3.3 V	-9 to 16 V
Supply current	2.1 mA	2.1 mA	20 mA	3 mA
Dark fixed pattern noise	32 mV	25 mV	NA	NA
Photo response non-uniformity	~2%	~3%	NA	NA
Sensitivity	54 mV/dec	54 mV/dec	NA	NA
Min. detectable illumination (3-dB)	0.3 lux	0.1 lux	NA	NA
Fill factor	~ 30 %	~90%	NA	NA
Number of I/Os	4	4	8	10

Figure 7.4.6: Specifications of the imagers with TFC and bulk-Si pixel diodes in comparison to state-of-the-art CMOS (OmniVision) and CCD (Sony) miniature imager products.

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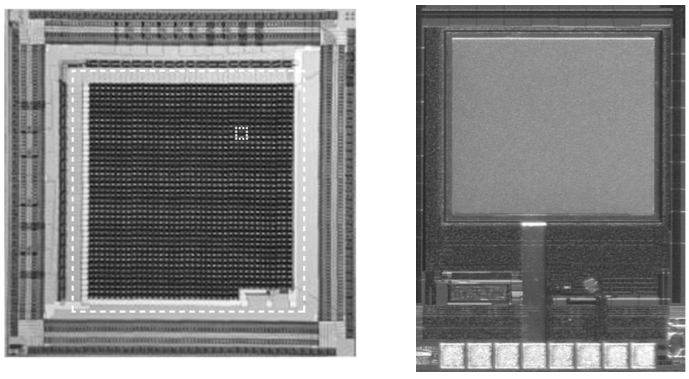

Figure 7.4.7: Micrograph of the retina implant chip (left) with indication of the sawing area with the test circuitry outside (dashed line) and a pixel cell (dotted line), as well as the TFC miniature imager chip (right).

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