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].

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) and pulse period (20Hz) need to be observed [2]. Moreover, the chip's size should be at least 3x3mm² 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 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 output) have to be connected to the 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^-10A/cm²) 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:

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Figure 7.4.1: Schematic illustration of the human eye with a part of the retinal tissue with both an epiretinal 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).

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).