19.10 A Single Photon Detector Array with 64×64 Resolution and Millimetric Depth Accuracy for 3D Imaging

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3D imaging, the capability of reproducing a depth map from an arbitrary object or scene, has a variety of uses in science, engineering, medicine and entertainment. Depth can be optically determined by measuring the time-of-flight (TOF) of a light source pulsed at a fixed repetition rate. At least two implementations of this concept have been proposed in the literature. In the first approach a rangefinder uses a single collimated laser beam to scan the scene by means of a high-precision, high-cost mechanical device [1]. The second approach is based on an array of conventional CMOS pixels independently measuring TOF from the target's reflection of a wide cone of light [2]. Due to major per-pixel read-out circuitry, only small linear arrays of pixels are practical and limited accuracy is achieved at a cost of powerful lasers. Recently, a 3D imager achieving sub-millimeter depth accuracy with very-low system power dissipation was demonstrated [3]. The core of the system, an array of 8×4 single photon avalanche diodes (SPADs), exhibits low jitter and high sensitivity, thus requiring low photon count to achieve picosecond TOF precision.

In this paper, a 3D imager of the second generation based on SPAD technology is presented. The main improvements include a complete pixel redesign to enable higher sensitivity, pitch reduction, and a massive array expansion. TOF is now computed on each pixel independently by means of an accurate CMOS time-to-digital-converter (TDC). The imager achieves millimeter accuracies to 3.75m. The light source, an uncollimated low-power pulsed laser with 635nm wavelength, enables a scene of several cubic meters to be surveyed. The sensing element is a 32×32 pixel array fabricated in 0.8μm CMOS technology. A lateral resolution of 64×64 pixels is achieved by means of a low-cost micro-scanning device embedded in the chip package.

SPAD technology is described in detail in [4]. Figure 19.10.1 shows the cross-section, photomicrograph, and schematic of a pixel. The photo-multiplication region is formed at the deep n-well—p+ junction. When reverse-biased above the breakdown voltage V_{bd} by an excess voltage V_e, the optical gain is infinity. To avoid overheating the device, the avalanche is quenched via a resistive load. During avalanche, a steep current pulse is generated that, in turn, causes a voltage pulse. The voltage pulse is regenerated by means of an inverter designed to generate a digital output. After the quenching phase, the SPAD must return to the original bias voltage; during this time, known as *dead time*, it remains inactive. The probability an avalanche is triggered is the *photon detection probability* η. Thermal and tunneling generation effects produce spurious pulses at a given rate, or *dark count rate* (DCR).

The schematic of a pixel shows a SPAD detector, quenching transistor T_q, an inverter, and a switch to route the digital signal to the nearest column. The switch is controlled by ROWSEL that activates the entire row. PMOS T_q replaced the poly resistance in [3] to save area. Lateral n-well inter-diffusions [3] are replaced by p-wells (Fig. 19.10.1). Though edge breakdown prevention is as effective, pixel pitch is reduced by 23%. Since the output of SPADs is digital, the sensor architecture may be highly simplified. Figure 19.10.2 illustrates the optical response of a pixel. Due to the high sensitivity of SPADs, remarkable dead time and the absence of read-out noise, a dynamic range of 120dB is obtained. Figure 19.10.3 shows the photomicrograph of the die. The architecture includes the SPAD array, row and column decoders, a power supply bus for core and V_{op}, and a 15b counter for 2D sensor operation for a total area of $7mm^2$.

A depth map is evaluated by measuring TOF of a ray of light as it is independently reflected by each point in the scene. Depth is computed as d = TOF (c/2), where c is the speed of light. A CMOS TDC is started by the laser trigger and stopped by the pulse generated by a SPAD. The device, a ATMD-F1 by ACAM, employs a technique based on racing set-up times on a delay line whose mean propagation delay is locked by a PLL for temperature stability. Depth accuracy is enhanced by averaging M independent measurements.

The fillfactor of SPADs is generally 1~10%, compared to 20~60% in CMOS APS. Due to the single photon sensitivity of SPADs, this parameter is not critical for performance. A small fillfactor however, in combination with zero optical crosstalk, is used to our advantage to enhance x-y resolution. The idea is to simulate higher pixel density by capturing several images of the same object from different points of view. This task can be achieved by exploiting the movement of the target or by transversally rotating the lens [5]. In this design the choice is to fix the lens and the target and to move the SPAD array instead, using the translational forces of low-cost piezo-electric actuators. This solution allows a simple, robust and compact micro-mechanical setup, no closed-loop control, and high accuracy. The maximum possible x-y resolution enhancement is $E_{max}=\lfloor X/x\rfloor\lfloor Y/y\rfloor$, where X, Y are horizontal and vertical pitch and x, y are horizontal and vertical sizes of the pixel active area. In this case, for a X/Y pitch of 58μm and a 7μm active area diameter, E_{max}=64, while E=4 is selected. The micro-scanning scheme is depicted in Fig. 19.10.4 for E=4. The actuators were embedded into the package of the sensor, thus minimizing the impact on miniaturization.

The 3D imager is tested with a pulsed laser with repetition rate f_R=40MHz, thus ensuring a range D=3.75m. The light is focused onto the sensor chip by means of a standard camera lens. Figure 19.10.5 shows the electro-optical setup, with the fabricated micro-scanner in the inset. A peak power $\hat{P}_s$=250mW was selected with pulse width T_P=100ps. The time uncertainty $\sigma(\tau)$ of one measurement is estimated to 350ps, while the TDC resolution was set to 60ps. Utilizing $M=10^4$ measurements, a 100-fold theoretical improvement, or an rms depth accuracy $\sigma(d)$=0.53mm, is expected, while the measured overall rms accuracy is 1.3mm. The degradation is due to non-uniform illumination thereby effectively reducing the average number of valid TOF measurements achievable per pixel. The imager is used to take detailed depth maps of a human face as shown in Fig. 19.10.6.

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[5] O. Landolt et al., "Visual Sensor with Resolution Enhancement by Mechanical Vibrations," *Proc. Advanced Research in VLSI*, pp. 249-64, 2001.

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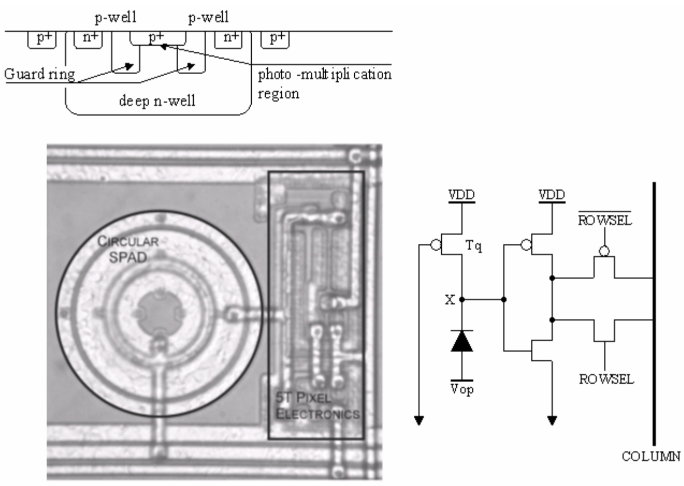

Figure 19.10.1: Simplified cross-section, photomicrograph and schematic of a pixel. VDD=5V, V_{op}=-25.5V, and $V_e = |V_{op}|+VDD-V_{bd}$.

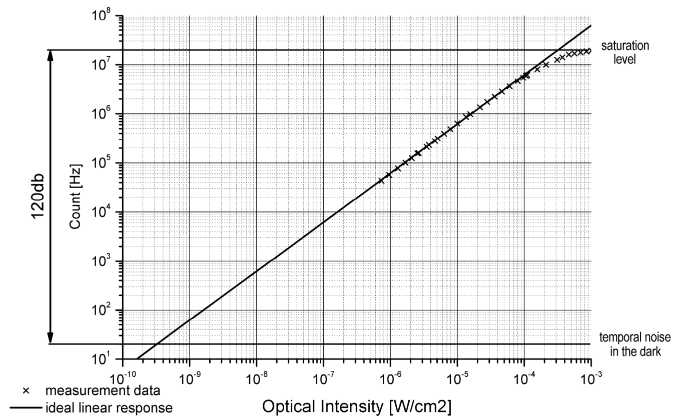

Figure 19.10.2: Pixel optical response and dynamic range.

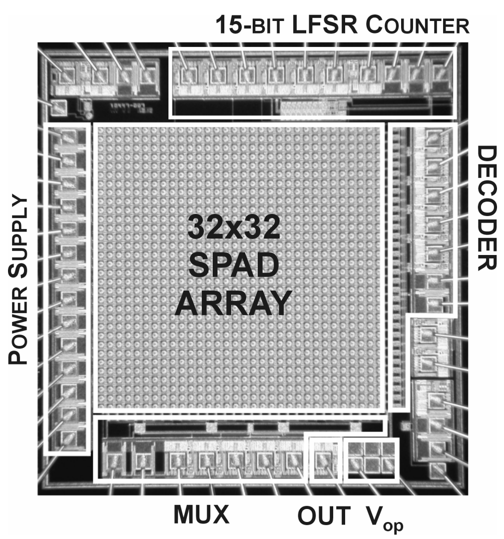

Figure 19.10.3: Chip photomicrograph.

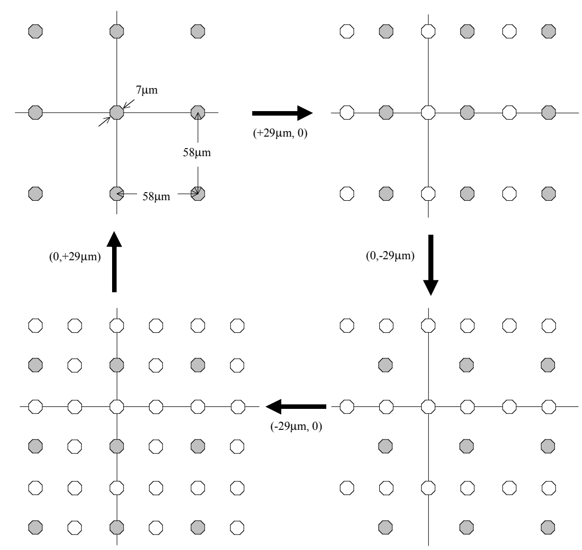

Figure 19.10.4: x-y resolution enhancement via micro-scanning.

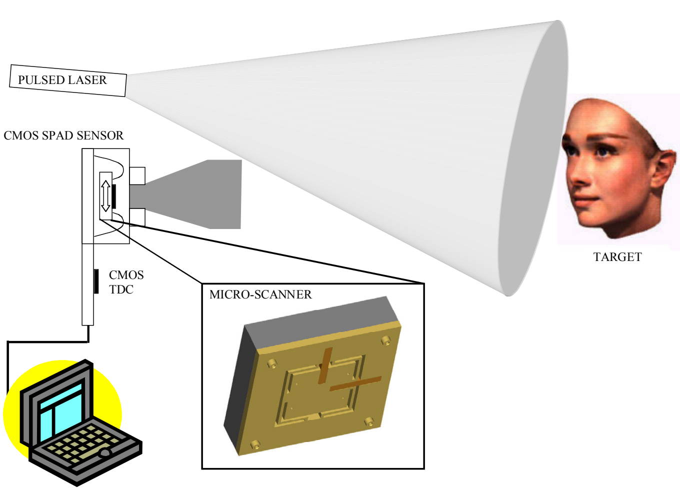

Figure 19.10.5: Camera set-up.

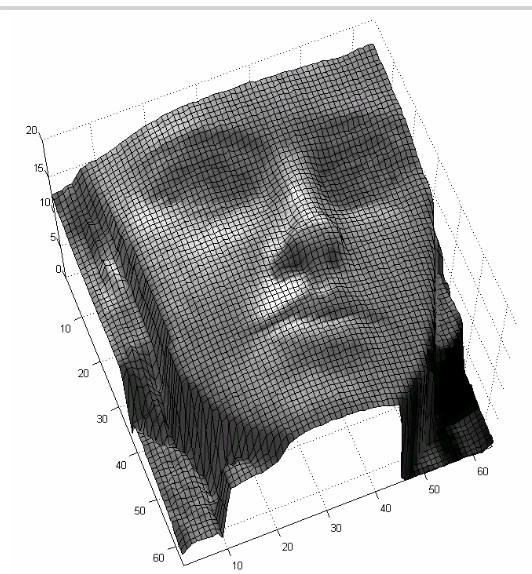

Figure 19.10.6: 3D surface of a human face at a TOF range of 3m.

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	Measure	Symbol	Value	Unit
Pixel	Photo Detection probability	η	12	%
	Dark count rate	DCR	350	Hz
	Fill factor	-	1	%
	Jitter	-	50	ps
	Dynamic range	*DR*	120	dB
	Dead time	t_d	< 40	ns
Sensor	Distance range	*D*	3.75	m
	Time uncertainty	$\sigma(\tau)$	350	ps
	RMS Distance accuracy	$\sigma(d)$	1.3	mm
	Mean number of measurements per second	-	$3x10^4$	1/s
	Power dissipation	P_{tot}	< 6	mW
	Sensitivity	-	$1.3x10^{-3}$	Lx
Source	Repetition rate	f_R	40	MHz
	Peak power	$\hat{P}_S$	250	mW
	Average power	P_S	< 1	mW
	Wavelength	λ	635	nm
	RMS Pulse width	T_p	< 100	ps

Figure 19.10.7: Performance summary.

