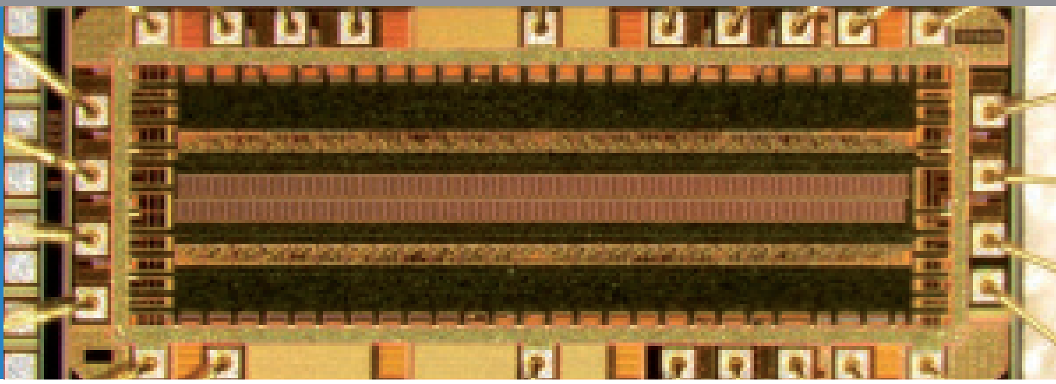
FRAUNHOFER INSTITUTE FOR MICROELECTRONIC CIRCUITS AND SYSTEMS IMS



1 *Chip microphotograph of SPAD linear sensor*

SPAD-BASED SENSORS FOR SPECTROSCOPY APPLICATIONS

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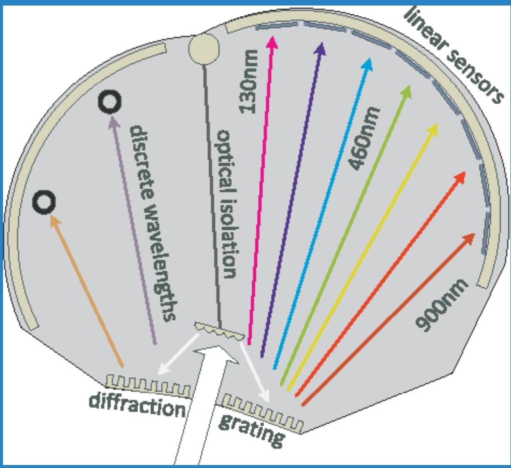
To analyze the properties of different materials various spectroscopy techniques are utilized. Common requirements for photodetectors used in these applications are high sensitivity, low noise, high operating speed, and a capability to perform time-resolved measurements.

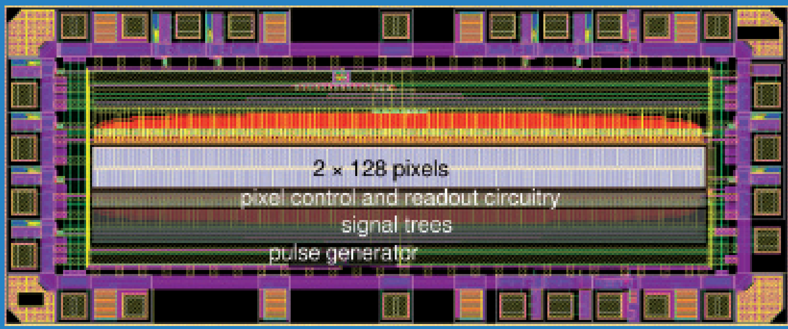
Numerous spectroscopy systems use conventional photomultiplier tubes (PMT) as photodetectors due to their high sensitivity in the ultra-violet (UV) region and timing resolutions in the sub-nanosecond range. Since PMTs require high voltage and have limited, if at all, lateral resolution in the millimeter range, a large amount of PMTs is required to build a reasonable spectrometer. This results in an increase of both size and cost of the product. Furthermore, PMTs are bulky, sensitive to magnetic fields, and cannot be integrated into a CMOS IC.

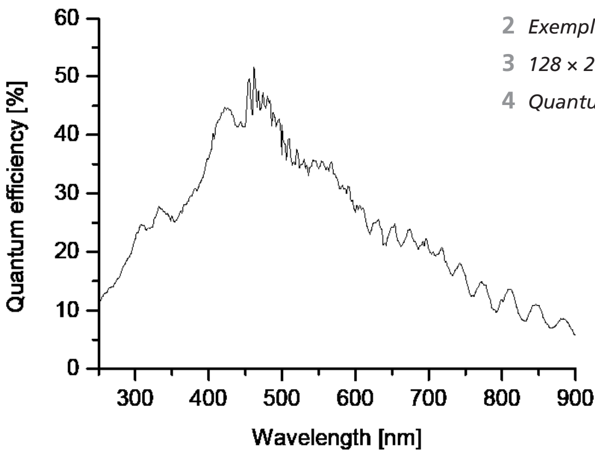
On the other hand, linear sensors based on charge-coupled devices (CCD) feature low voltage requirements and provide high spatial resolution in the micrometer range, but often exhibit only limited time resolution.

SPADs for spectroscopy applications

To enable time-resolved measurements in a sensor with high spatial resolution Fraunhofer IMS has developed a CMOS linear sensor based on single-photon avalanche diode (SPAD) technology. SPADs are small and easy to integrate on an array level, insensitive to magnetic fields, and can be integrated into CMOS. Custom SPAD cells exhibit superior performance in terms of detection efficiency, noise, and timing jitter. SPAD-based sensors provide sub-nanosecond timing resolution and a pixel pitch of as low as 10µm. In addition, fast gating in the nanosecond range is achievable thanks to SPAD-CMOS integration. High sensitivity at wavelengths of 400nm and lower is achieved by applying a post-processed UV-transparent passivation onto the CMOS stack. Therefore, SPAD-based sensors can be successfully used as a favorable replacement for conventional PMT-based approaches in spectroscopy applications.







2 *Exemplary spectrometer application*
3 *128 × 2 pixel linear sensor design*
4 *Quantum efficiency of CMOS SPAD*

Time-resolved Raman spectroscopy benefits from fast gating by allowing the suppression of fluorescence during the measurement even when using short wavelength laser excitation while retaining full sensitivity to the desired Raman signal.

Other applications of SPADs

Due to high sensitivity, good timing resolution, high dynamic range, and relatively low voltage requirements, many applications can benefit from utilization of SPAD-based sensors.

Such applications include, among others:

- Low-light vision
- Scanning LIDAR
- Flash LIDAR
- Fluorescence lifetime microscopy (FLIM)
- Positron emission tomography (PET)
- Fluorescence correlation spectroscopy (FCS)

All these applications are characterized by the requirement of counting single photons in order to acquire the intensity and the shape of the optical wave carrying very weak signal information under real-time measurement conditions. In order to increase the resolution even further and capture ultra-fast events in the picosecond regime, the photon arrival time-stamp is repetitively time-correlated by employing histogram binning analysis method.
This technique is called Time-Correlated Single-Photon Counting and can be implemented on the same CMOS ASIC carrying the SPAD pixel array. Since it is possible to utilize standard CMOS technology, analog and digital electronics for implementing smart photon-counting and photon-timing functionalities can be realized on the same chip.

Therefore, integration of SPADs in CMOS technology offers the possibility of developing novel compact and cost-effective multi-pixel SPAD-based image sensor systems as an alternative to expensive image-intensified charge coupled devices (I-CCD) or electron-multiplying CCDs (EM-CCD).
The proposed custom monolithic integration of a SPAD pixel array and CMOS readout circuit helps the system engineer to define the most suitable approach for each specific application, whether it is a single photon counting with a few pixels, measurement of photon arrival time, or even acquisition of 2D and 3D photon-timing images from a multi-pixel SPAD array. Finally, CMOS SPADs are the only choice to provide real-time imaging at a single-photon level for multi-pixel arrays.

Summary of 128 × 2 SPAD-based CMOS line sensor characteristics

Pixel size (active area)	14 × 76 µm²
Array size	2575 × 175 µm²
Pixel count	128 × 2
Fill factor	60 %
Measurement period	2.95 µs
Typ. gating width	12.5 ns
Breakdown Voltage (V_{Br})	27.5 V
Temperature dependence of V_{Br}	47.7 mV/K
Typ. operation voltage	V_{Br} + 2.5 V
Crosstalk	13 %
DCR per Pixel (excl. 5% „hot“ pixels)	327 Hz (133 Hz)