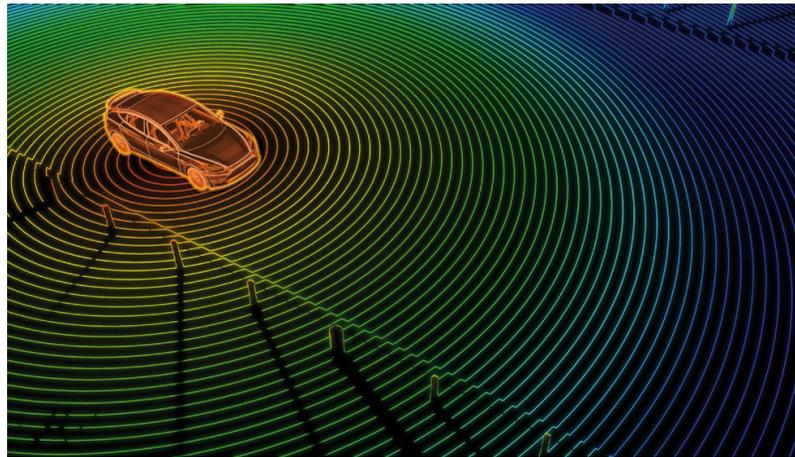


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# SOLID-STATE LIDAR

Werner Brockherde, Fraunhofer IMS, Duisburg

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DVN LiDAR Conference - Sulzbach, November 20<sup>th</sup>, 2018

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# OUTLINE

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- LiDAR for Automated Driving
- LiDAR sensor trade-offs
- Single Photon Avalanche Diodes in CMOS
- SPAD for LIDAR
- Design example
- Summary

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# LIDAR FOR AUTOMATED DRIVING

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- Besides Video and Radar, LiDAR will be indispensable in AD !
- LiDAR/LaDAR = Light/Laser Detection and Ranging
- Range determination by **time-of-flight** measurement
- LiDAR has been mostly used in long-range geoscience and military applications with use of active laser illumination in SWIR
- In automotive: **size, costs, and reliability** become most important

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# LIDAR FOR AUTOMATED DRIVING

## - THE TRADE-OFFS -

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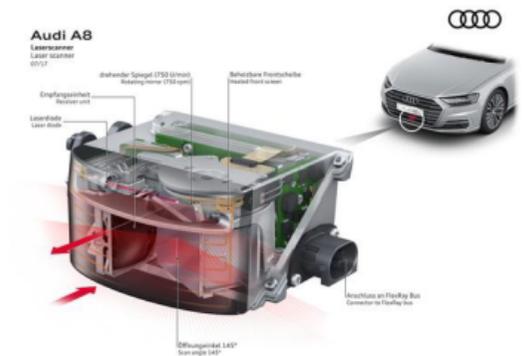
Many different approaches are on the way.

What is the best LiDAR sensor?

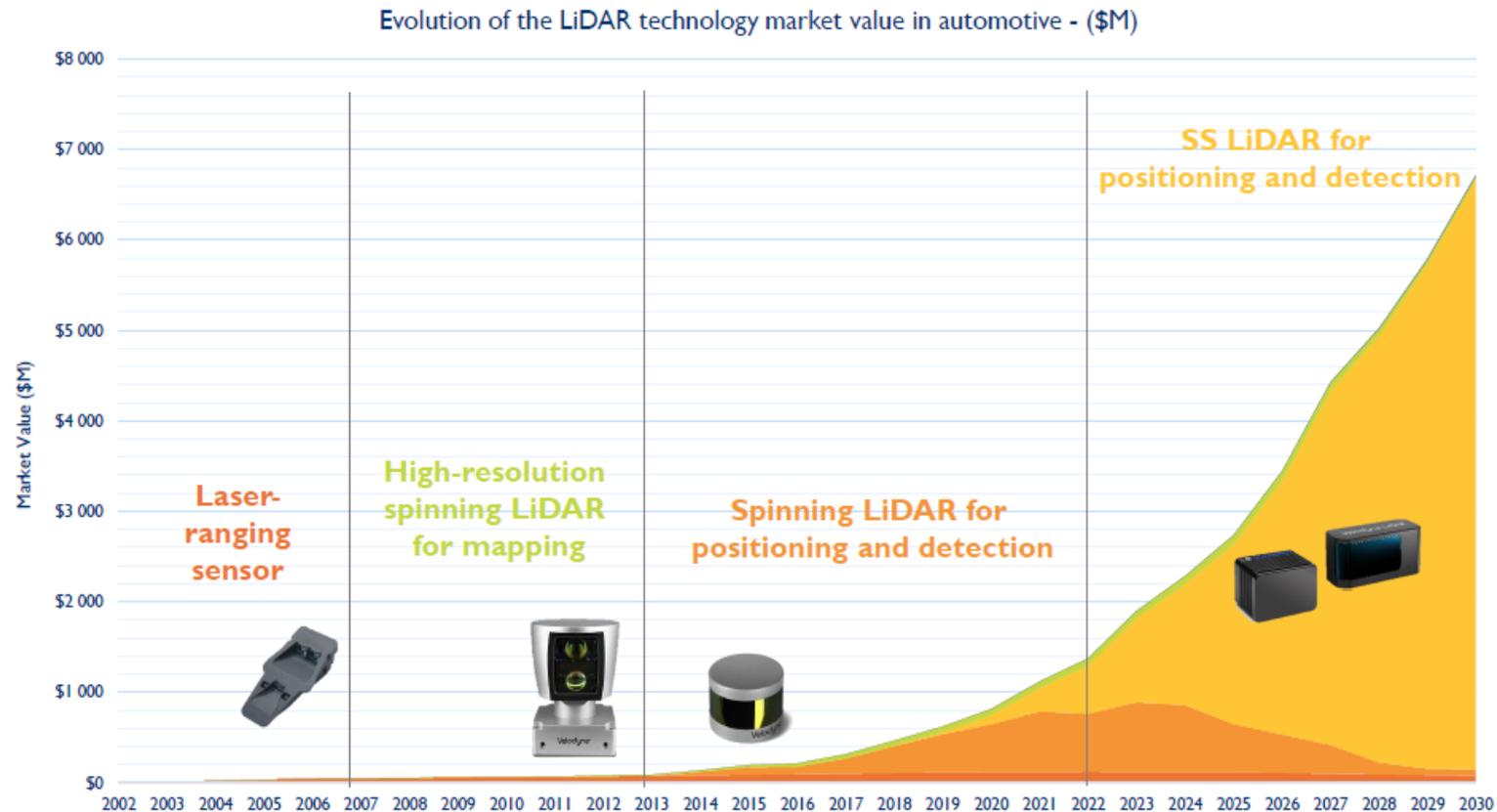
Method	Scanning	vs	Flash
Wavelength	1550 nm	vs	905 nm
Illumination	EEL	vs	VCSEL
ToF principle	i-ToF	vs	d-ToF
Detector	APD (array)	vs	SPAD array

# LIDAR - METHODS: SCANNING LIDAR

- Mechanical scan
- Subsequent pointing to object area
- High optical power density
- → High distance range
- Tx and Rx use same aperture
- Single detector element
- Low framerate
- Bulky and expensive



# LIDAR - METHODS – MARKET PERSPECTIVE

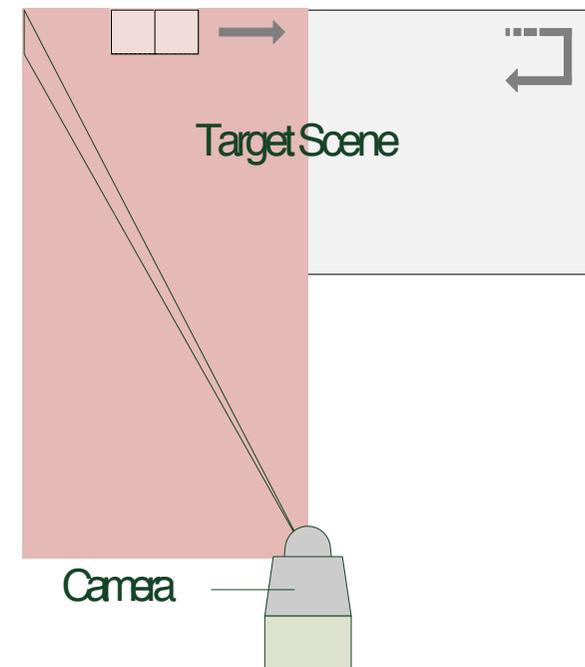


Source:  
Yolé 2017



# LIDAR - METHODS: BEAM STEERING

- **Using Micro Mirrors or Optical Phased Arrays**
- Subsequent pointing to object area
- High optical power density
- Medium/High distance range
- **Detector array required**
- Low/moderate framerate
- Small size and potentially low cost

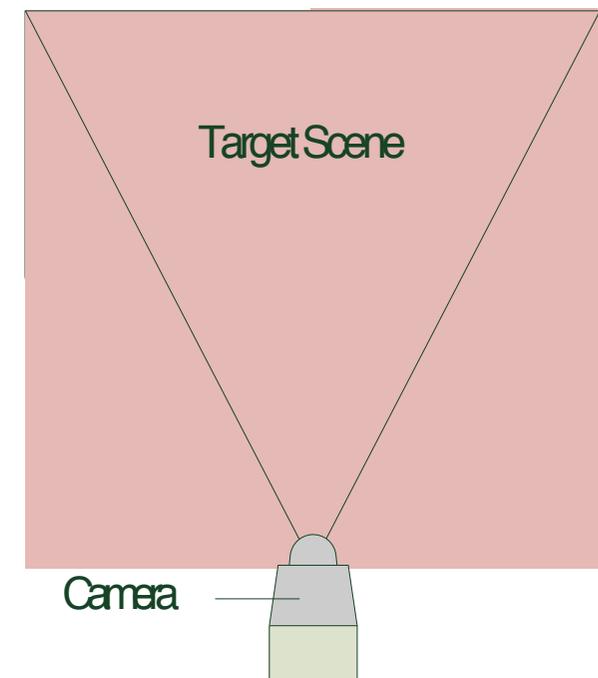


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# LIDAR - METHODS: FLASH LIDAR

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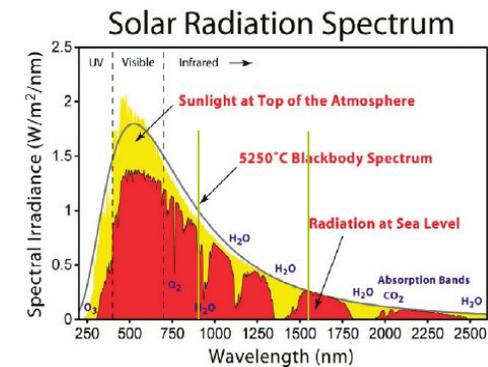
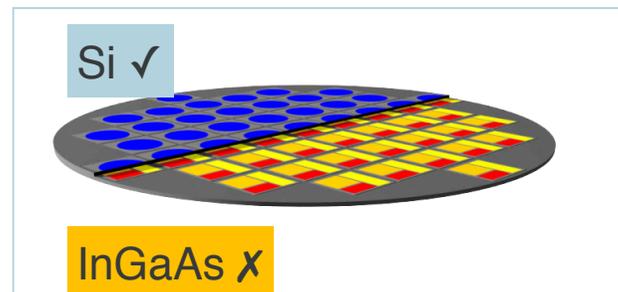
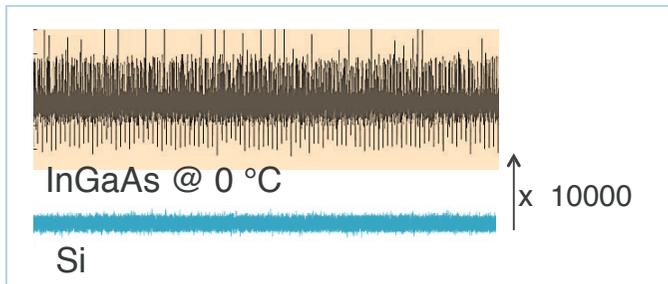
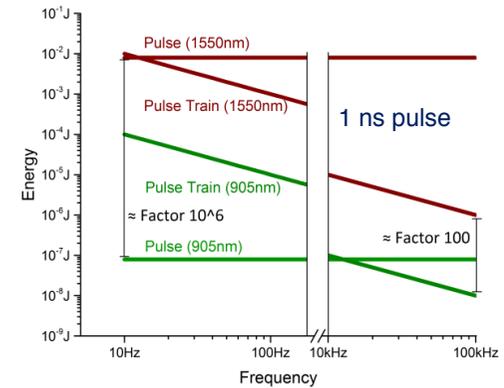
- Complete scene is taken in a flash
- Solid state solution possible
- **No moving parts**
- Low optical power density
- Medium distance range
- Detector array required
- **High Framerate**
- **Small size and potentially low cost**



# LIDAR - WAVELENGTH

- Eye-safe laser power
- Sun irradiation on earth
- Detector dark noise
- Wafer bonding
- System costs

	Si (905 nm)	InGaAs (1550 nm)
Eye-safe laser power	1	100x
Sun irradiation on earth	2.5x	1
Detector dark noise	1	10000x
Wafer bonding	yes	no
System costs	1	10...100x



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# LIDAR – LASER TYPE

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	EEL	VCSEL
■ Wavelength	ok	ok
■ Fabrication process	mirror post processing	fully automated
■ Fabrication costs	medium	high
■ Power efficiency (pulse)	high	medium
■ Max. power	high	medium
■ Array integration	difficult	easy

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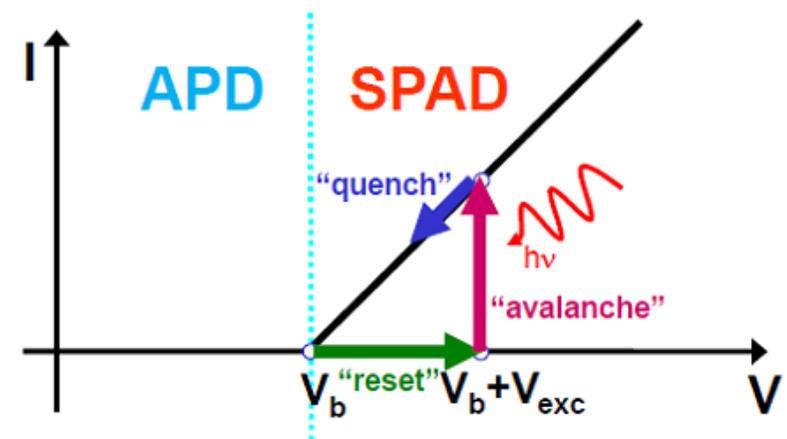
# OUTLINE

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- LiDAR for Automated Driving
- LiDAR sensor trade-offs
- **Single Photon Avalanche Diodes in CMOS**
- SPAD for LIDAR
- Design example
- Summary

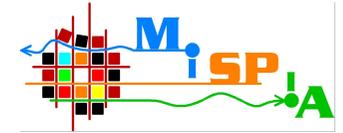
# SPAD OPERATING PRINCIPLE

- Single-Photon-Avalanche-Diode (SPAD) is an APD operated in „Geiger-Mode“
- Fast operation with good time resolution
- Very few photons can be detected
- Highest „Gain“  $\sim 10^6$
- No analog signal processing
- Robust biasing
- Dead-time after detection
- CMOS integration possible



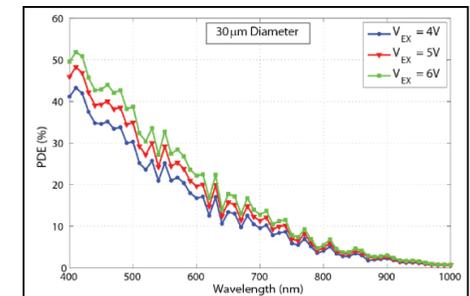
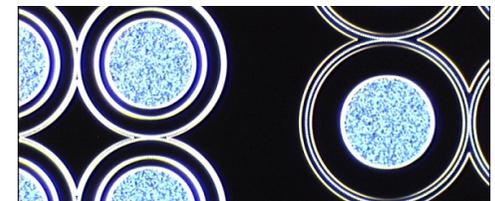
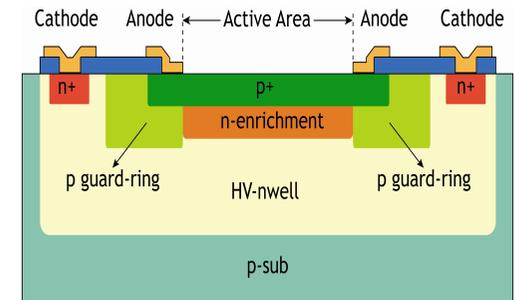
# CHARACTERISTICS OF SPADS

## in IMS 0.35 $\mu\text{m}$ CMOS Process



### SPAD characteristics (30 $\mu\text{m}$ active area)

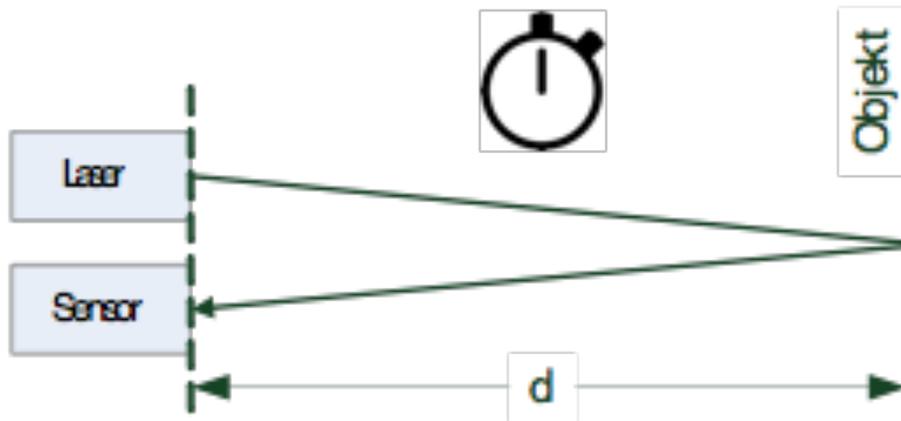
Dark count rate (DCR)	< 50 cps at room temperature
Timing response	< 140 ps FWHM
Uniformity	95% of pixels have close to avg. DCR
Breakdown voltage ( $V_{BD}$ )	26 V
Temperature drift of $V_{BD}$	37.8 mV/K
Afterpulsing probability	< 1% at dead time > 50 ns dead time
Pixel pitch	As low as 10 $\mu\text{m}$
Spectral range	300 nm – 1000 nm
Dynamic range	106 dB
Noise-equivalent Irradiance @ 905 nm	11 pW/cm <sup>2</sup>



# TIME-OF-FLIGHT METHODS

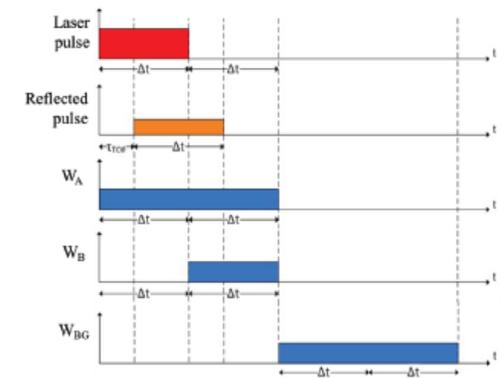
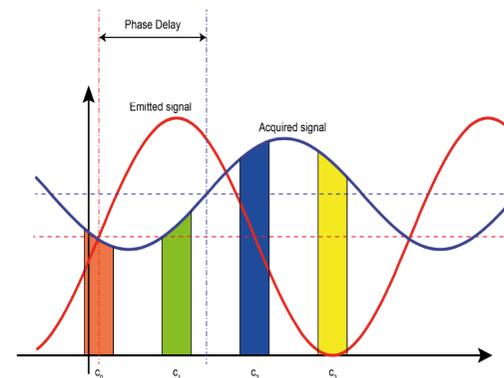
## Direct ToF

- Direct time measurement
- Calculate distance from **photon timing** using time-to-digital converters



## Indirect ToF

- Calculation of distance from **phase**
- Light intensity  $\rightarrow$  Dynamic Range

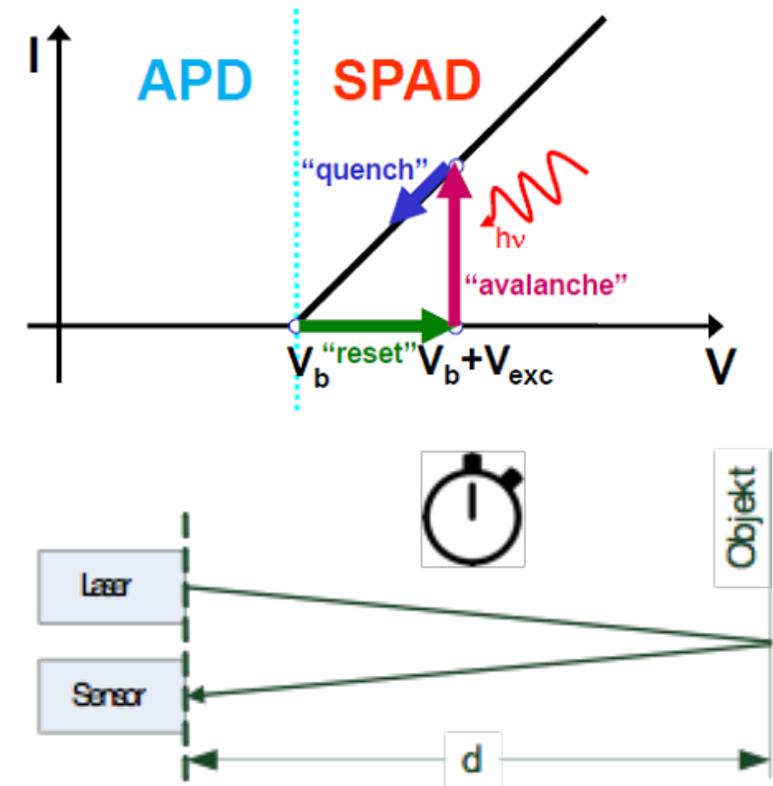


# SPAD FOR LIDAR

## Direct Time-of-flight method using SPADs

### Measurement procedure

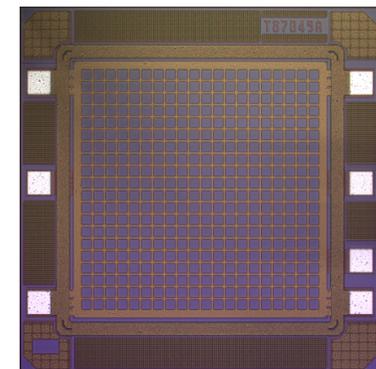
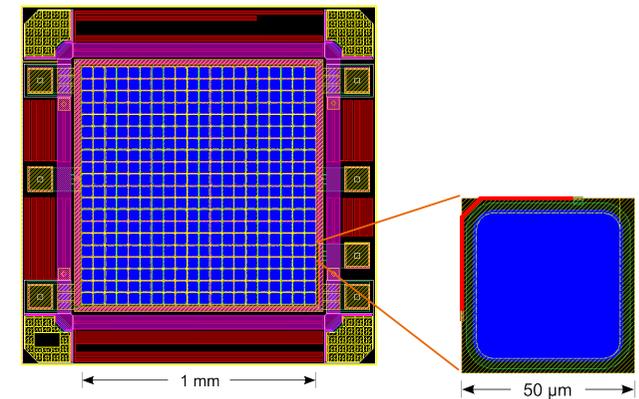
- High optical power density in short pulses
- Direct measurement of first photon
- Counting one event per Laserpuls → no saturation
- Distance calculation from time histogram
- Complex pixel circuitry (TDC) and logic
- Time gating defines distance range
- High range precision possible (few cm)
- Pixel circuitry and statistics support high background light suppression ( $> 80$  klux)



# SPAD FOR LIDAR

## Silicon Photomultiplier SiPM

- 20×20 SPAD-elements on 1×1 mm<sup>2</sup> active area
- Geometric fillfactor: 68% @ 50μm pitch
- Integrated in CMOS with readout circuitry
- Applications:
  - Detector in high-energy particle physics
  - Scanning-LIDAR
  - PET-detector (medicine)

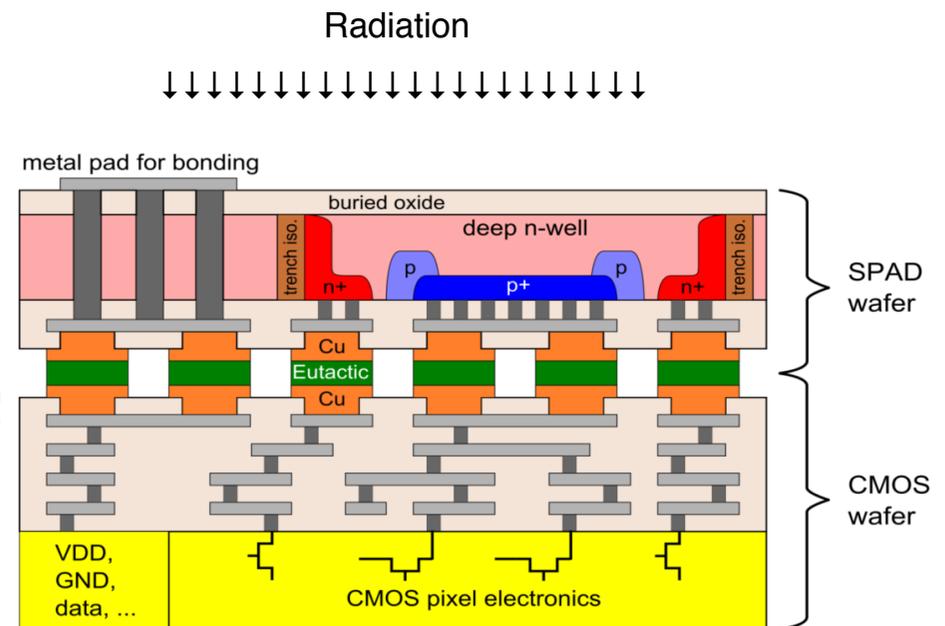


# SPAD FOR LIDAR

## The alternative approach: Backside Illuminated SPAD arrays

- High density CMOS readout circuit
- Optimized Si-wafers for best SPAD performance
- SLID bonding process available
- Wafer to wafer bonding process allows for higher volumes
- Process more expensive, but chip size can be drastically smaller

Schematic cross section of backside illuminated SPAD sensor after integration



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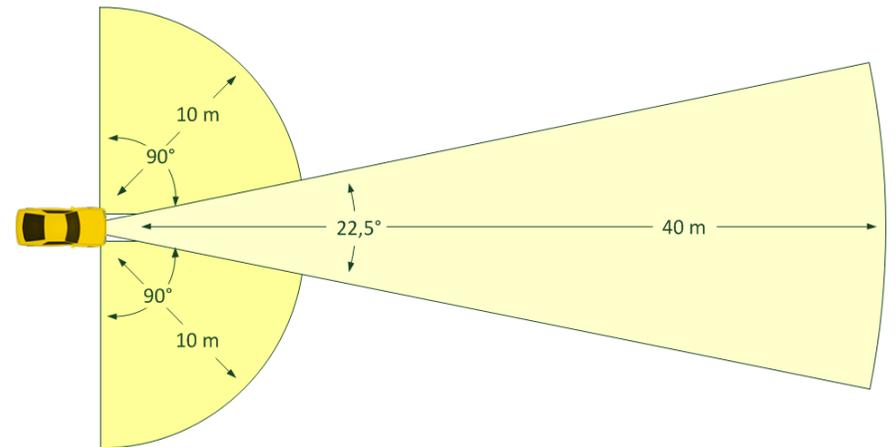
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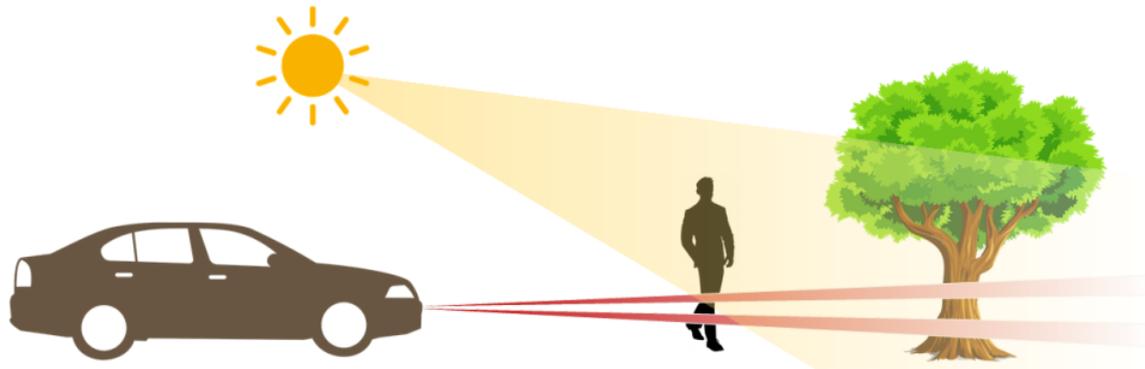
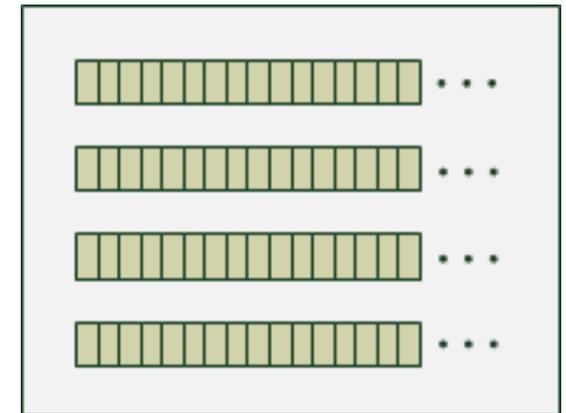
# DESIGN PROPOSAL FOR FLASH LIDAR

- Multiple sheets of light
- Different FoVs and ranges
- Medium ranges < 100 m
- Applications:
  - VRU detection
  - Side traffic
  - Parking assistance



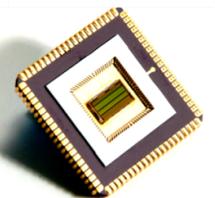
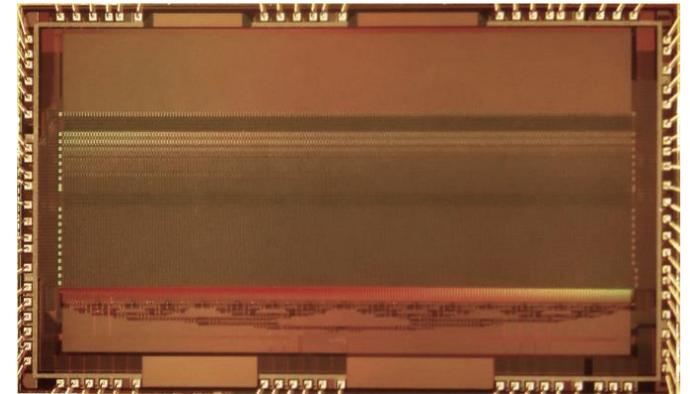
# DESIGN PROPOSAL FOR FLASH LIDAR

- Detection of target area multiple lines
- Detector allows high fillfactor
- Low vertical resolution may be overcome by push-broom effect



# TEST VEHICLE: 192 X 2 LINE SENSOR

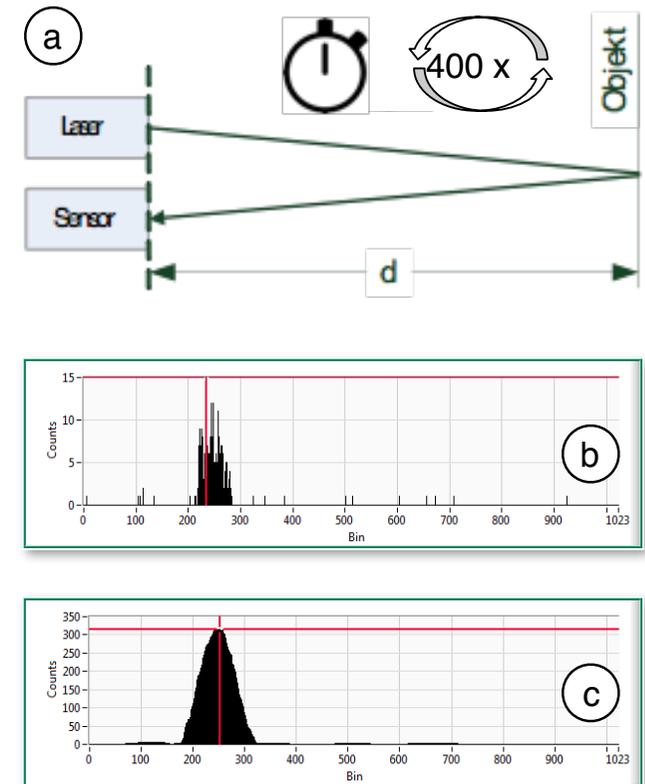
- 192x2 pixel SPAD LiDAR detector
- In-pixel TDCs
- Dynamic Range extension
- Circuitry for background light suppression
- Test with 905nm 75W laser
- FOV (laser): 2x (40,0° x 2,0°)
- Range: > 40 m @ 25fps



# TEST VEHICLE: 192 X 2 LINE SENSOR

## Distance measurement

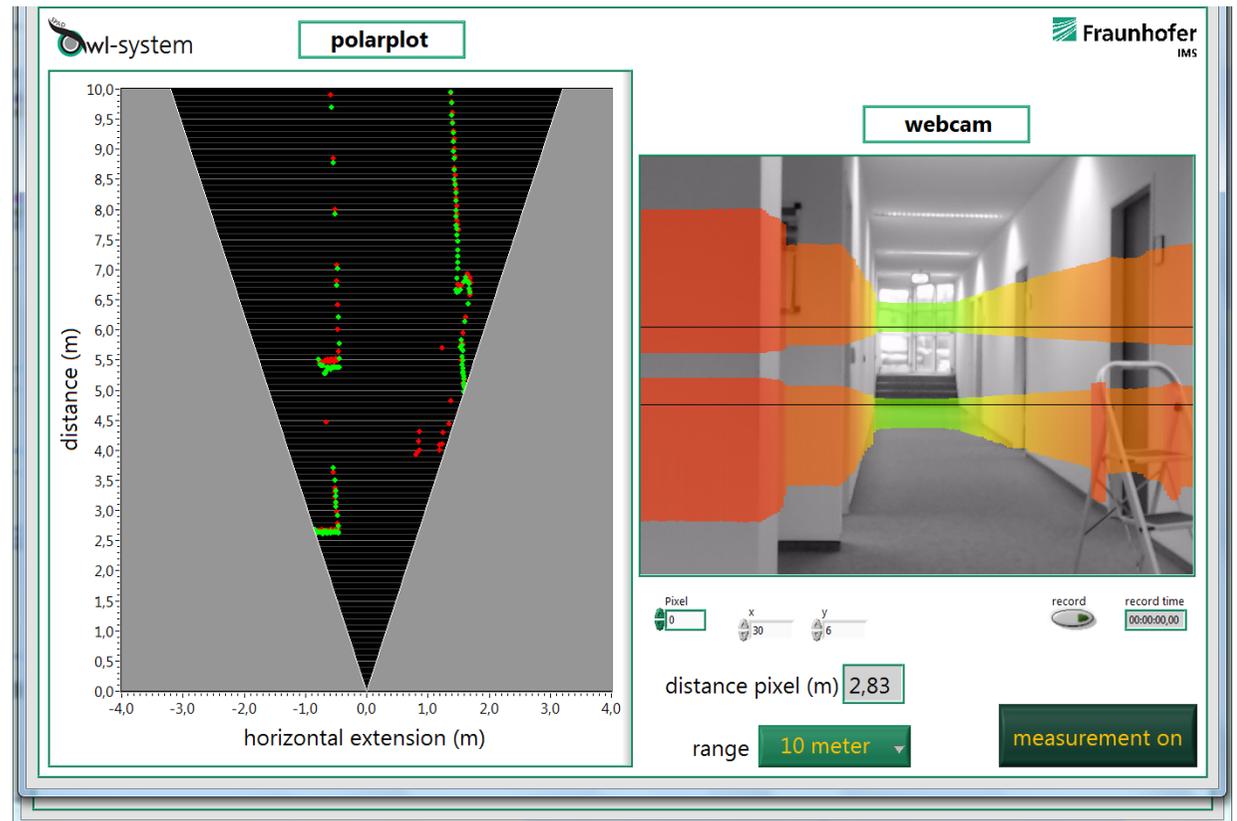
- Laser pulse width:  $\sim 20\text{ns}$
- Repetition rate:  $10\text{kHz}$
- 400 pulses per frame
- Evaluation of timing histogram with filters and dedicated algorithms
- Range resolution ca.  $5\text{cm}$
- Range:  $> 40\text{ m @ } 25\text{fps}$



# TEST VEHICLE: 192 X 2 LINE SENSOR

## Distance measurement

- Range: 22m
- 10 kHz pulse rate
- 400 pulses per frame  
75W / 905nm
- 25 fps



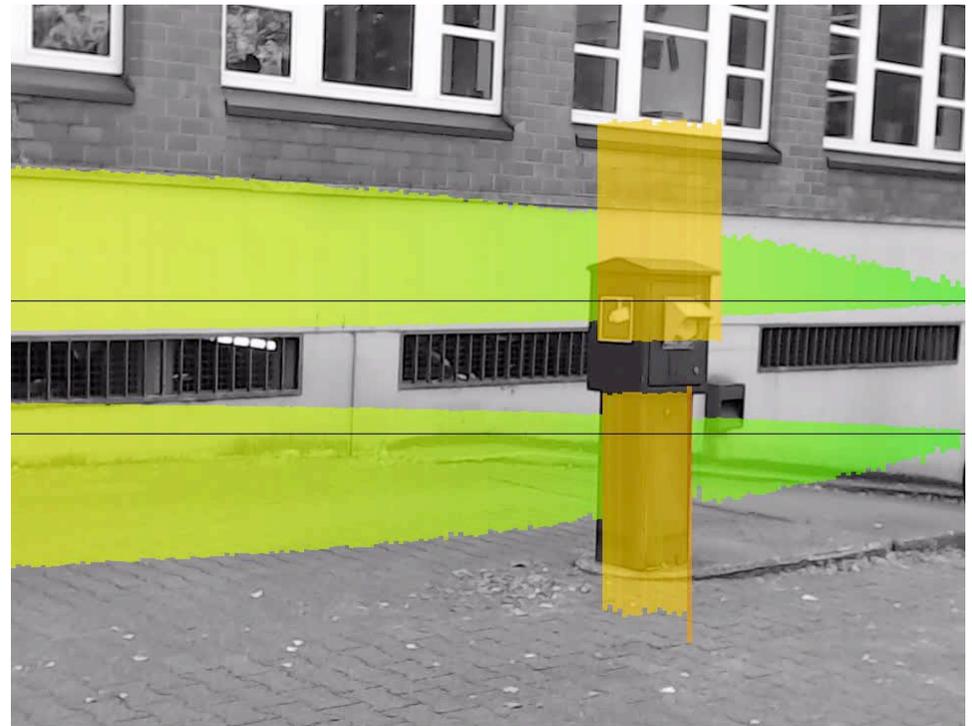
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# TEST VEHICLE: 192 X 2 LINE SENSOR

## Background light suppression

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- Outdoor:
- 20m @ 90klux  
black target
  
- BG light is suppressed



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# SUMMARY AND OUTLOOK

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- For future Automated Driving LiDAR will be indispensable
- Different technologies for different use-cases are in development
- CMOS SPAD based LiDAR detectors allow for solid-state solutions
- Flash LiDAR offers low-cost solutions for many AD requirements
- Challenges as background light suppression are addressed

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**THANK YOU FOR YOUR ATTENTION**

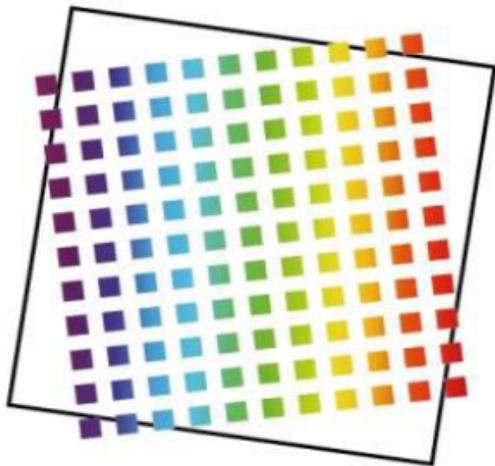
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# SAVE THE DATE

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# CMOS IMAGING

- **08.05.-09.05.2019**
- Workshop for sensor experts and technology professionals
- Topics: LiDAR Automotive, 3D in industrial applications...