Single-photon detectors in micro-electronics technology

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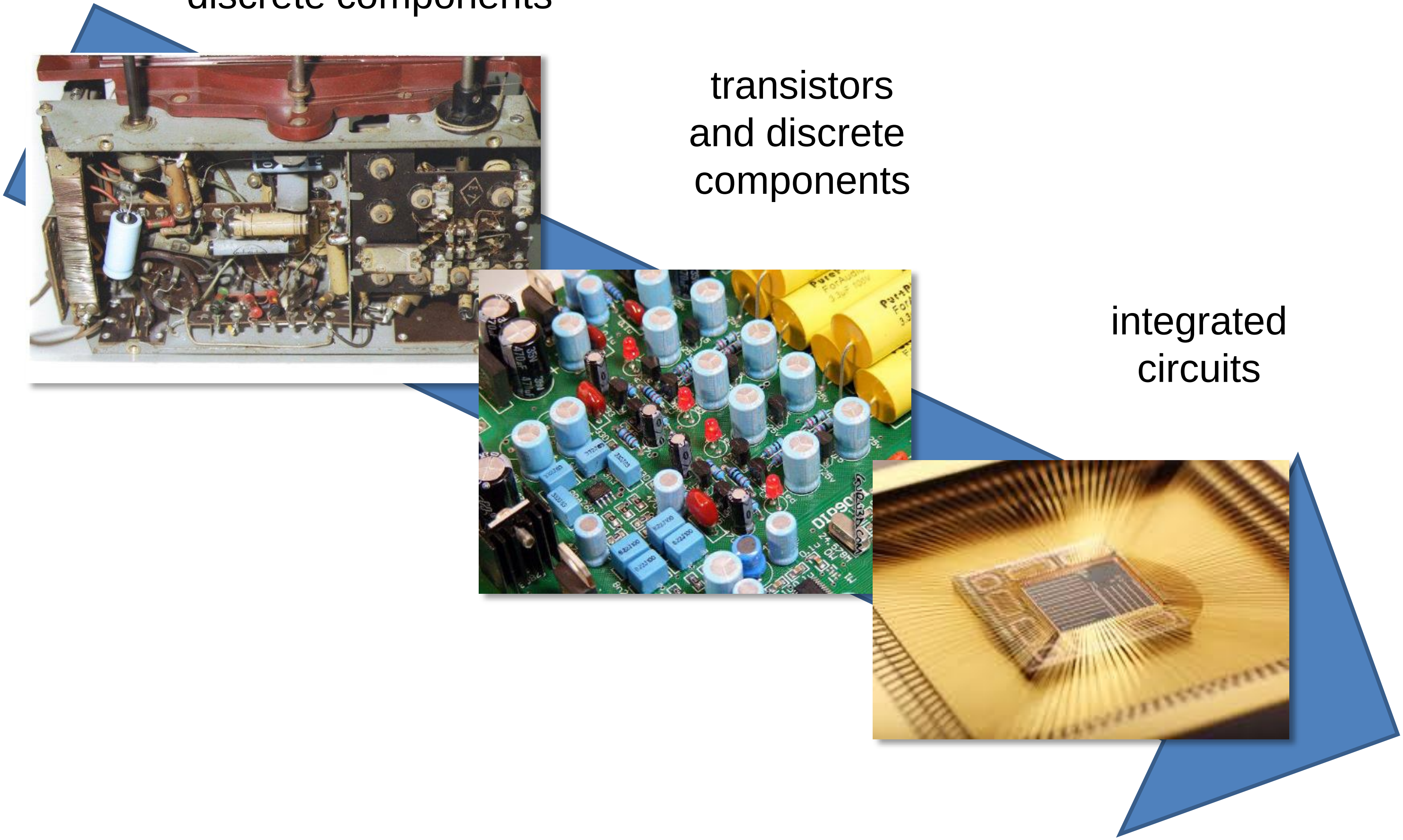
Outlook

- Micro-electronics technology
- Single-photon detection why and where
- Approaches at single photon detection
- Single photon detection using impact ionization in semiconductors
- Overview of SiPM parameters
- New trends in SPAD/SiPM

Micro-electronics

Electronics evolution



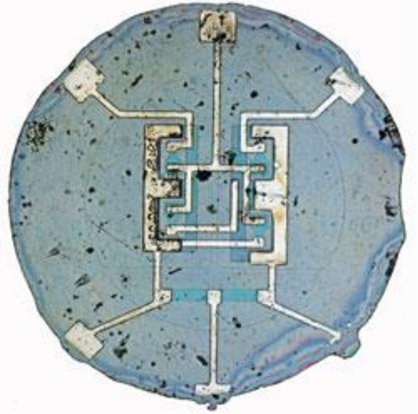
valves and
discrete components

transistors
and discrete
components

integrated
circuits

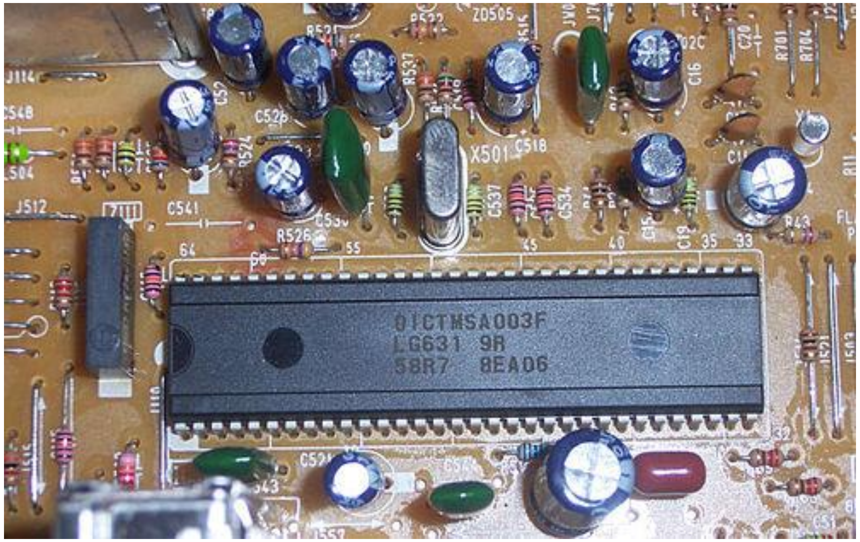
Micro-electronics

1958, Jack Kilby,
Texas Instruments.
First integrated circuit.
Nobel prize 2000



Nel **1961**, Fairchild commercializes first integrated circuit

SSI 10 components
(small scale integration)



Micro-electronics

1970 VLSI

very large scale integration

thousands of components

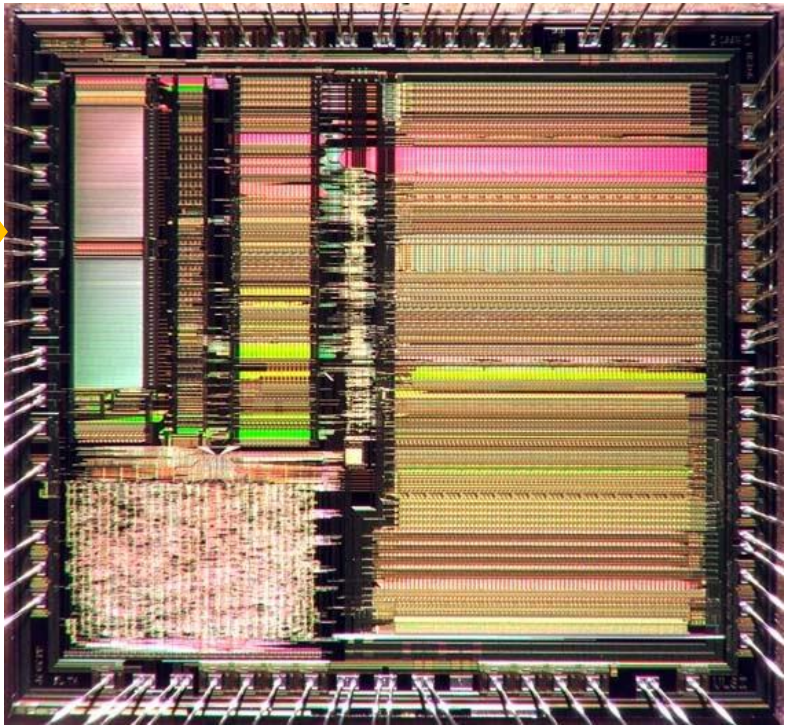
(first microprocessors)

1980 ULSI

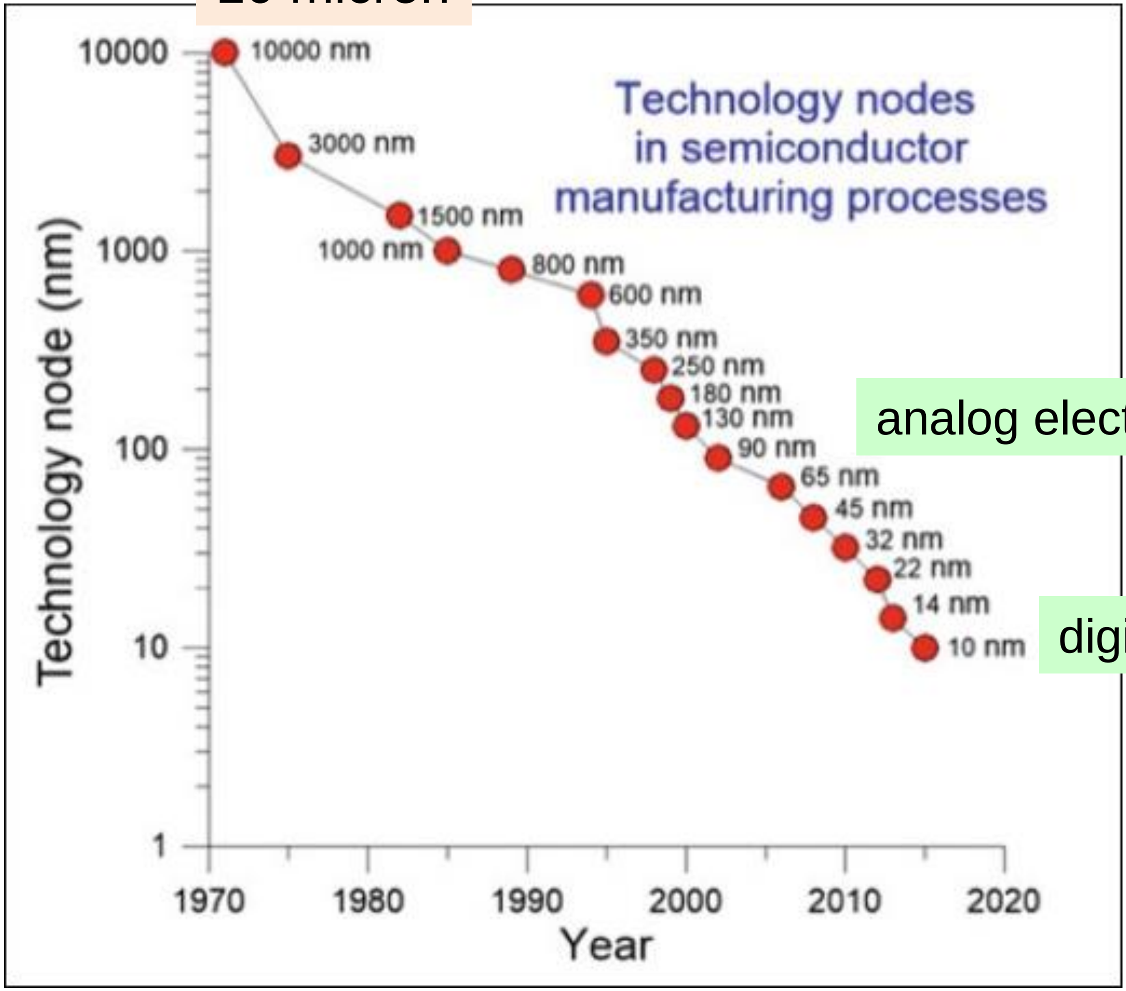
ultra large scale integration

millions of components

(advanced microprocessors)



Micro-electronics



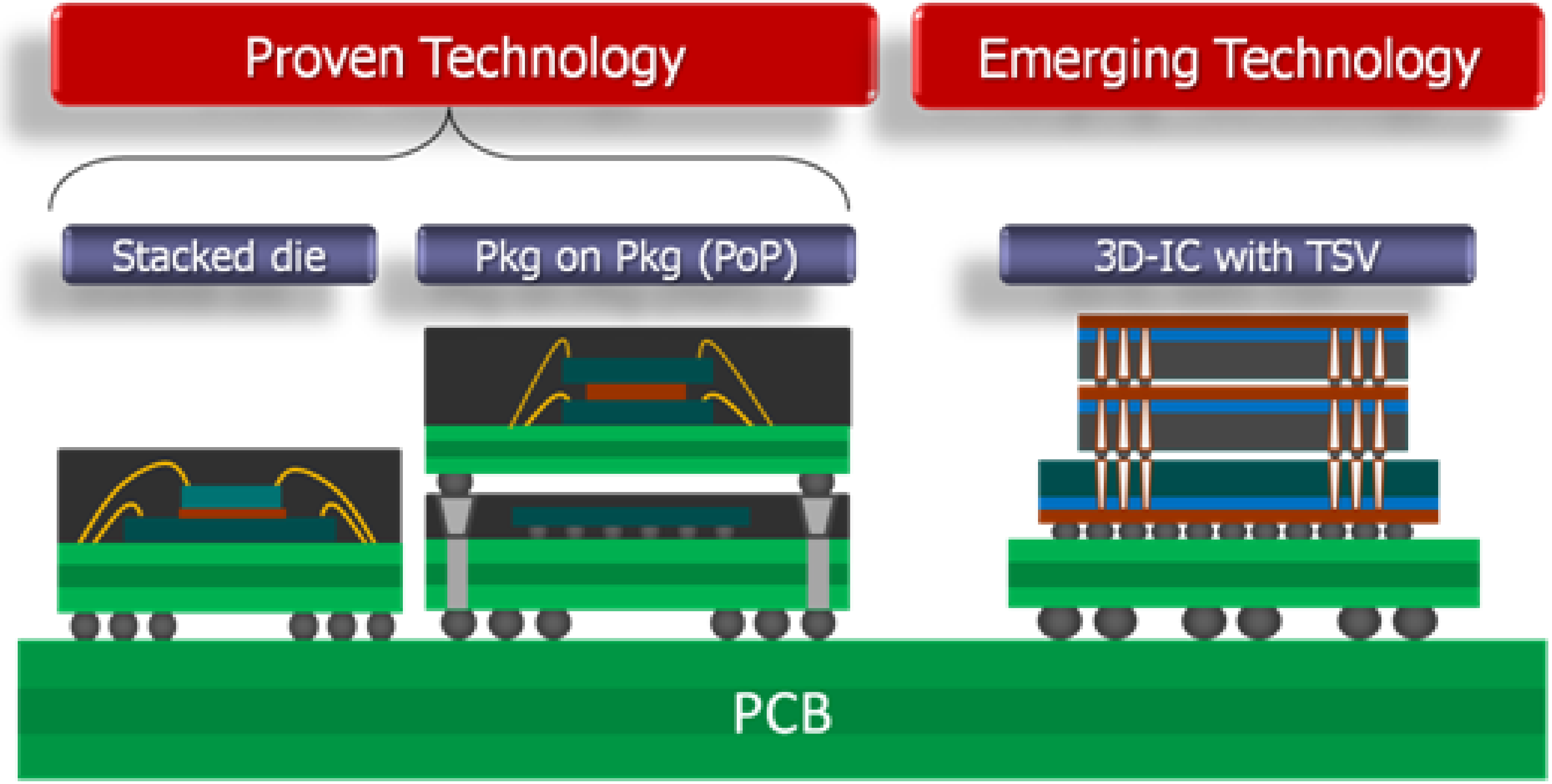
10 micron

analog electronics

digital electronics

Micro-electronics

Present: going vertical!



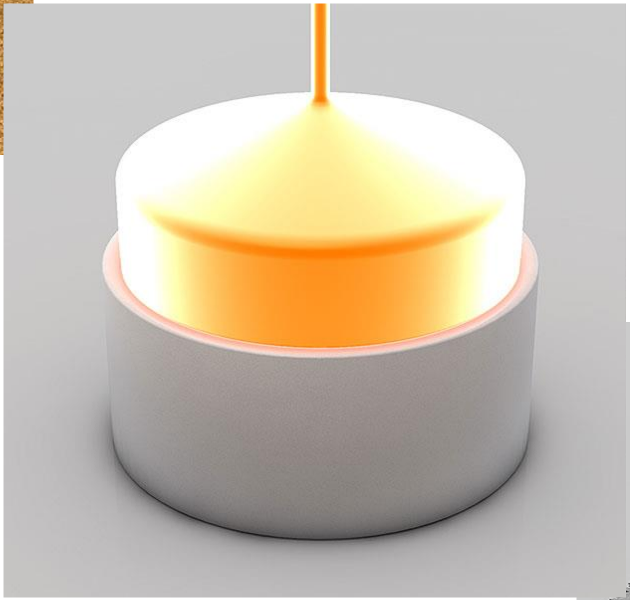
Picture from: https://www.semiwiki.com/forum/content/860-physical-verification-3d-ic-designs-using-tsvs.html

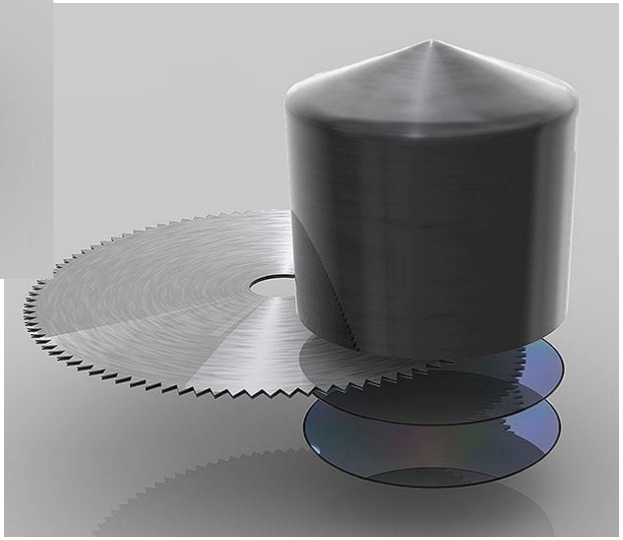
Micro-electronics technology

Starting material: silicon.

Sand: silicon oxide

Growth of silicon ingot



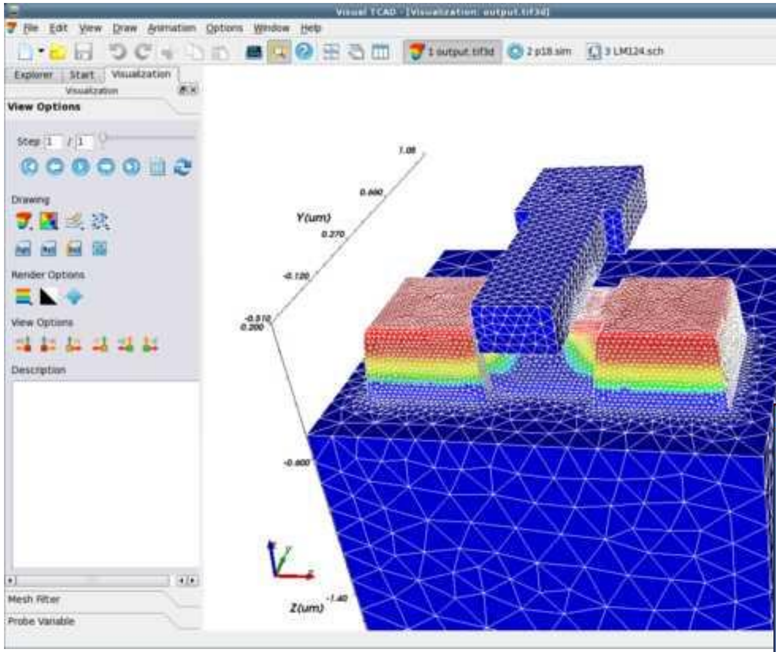


Pictures from: http://apcmag.com/picture-gallery-how-a-chip-is-made.htm/

Silicon wafer

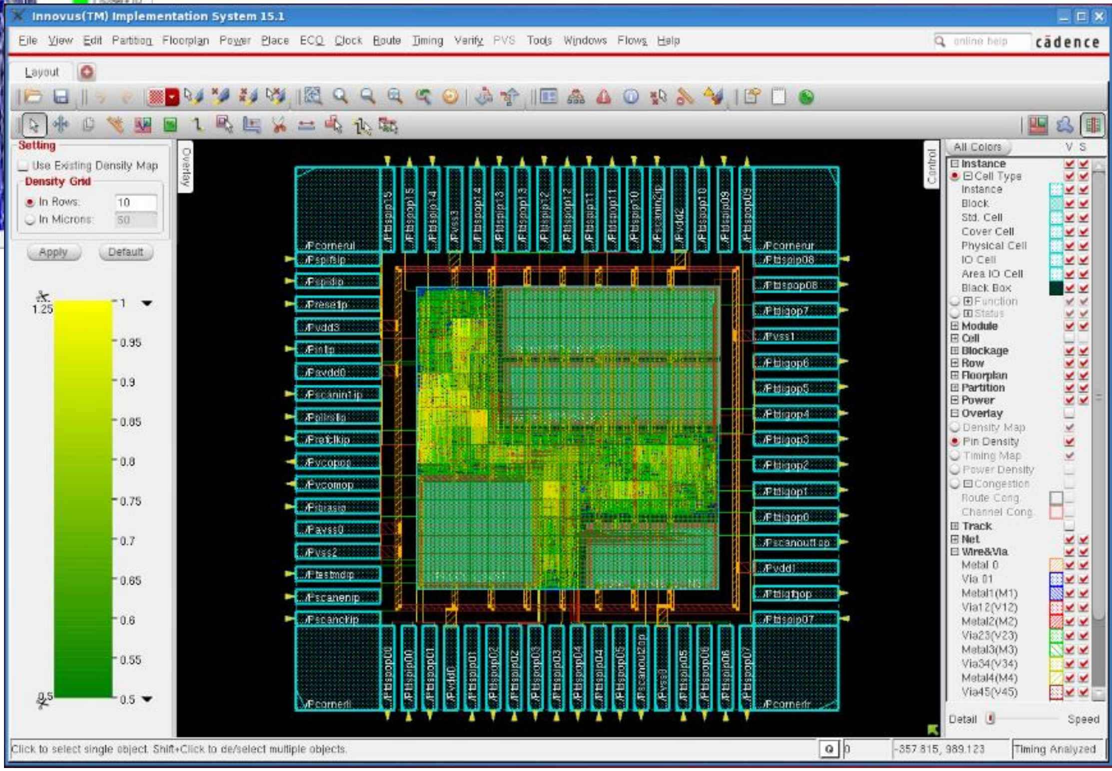
Circuit design

Simulation



Step 1 / 1

CAD design



Setting

☐ Use Existing Density Map

Density Grid

● In Rows: 10

○ In Microns: 50

Click to select single object. Shift+Click to de/select multiple objects.

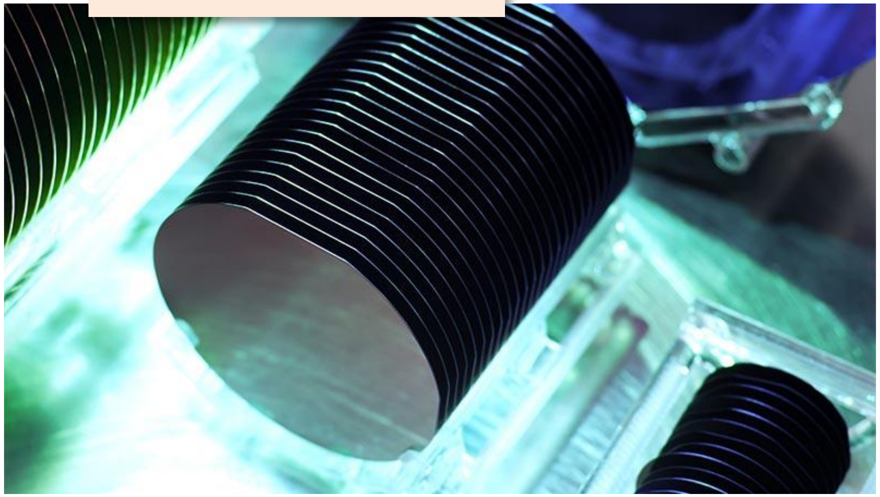
-357.815, 989.123

Timing Analyzed

IC production

Silicon Foundry

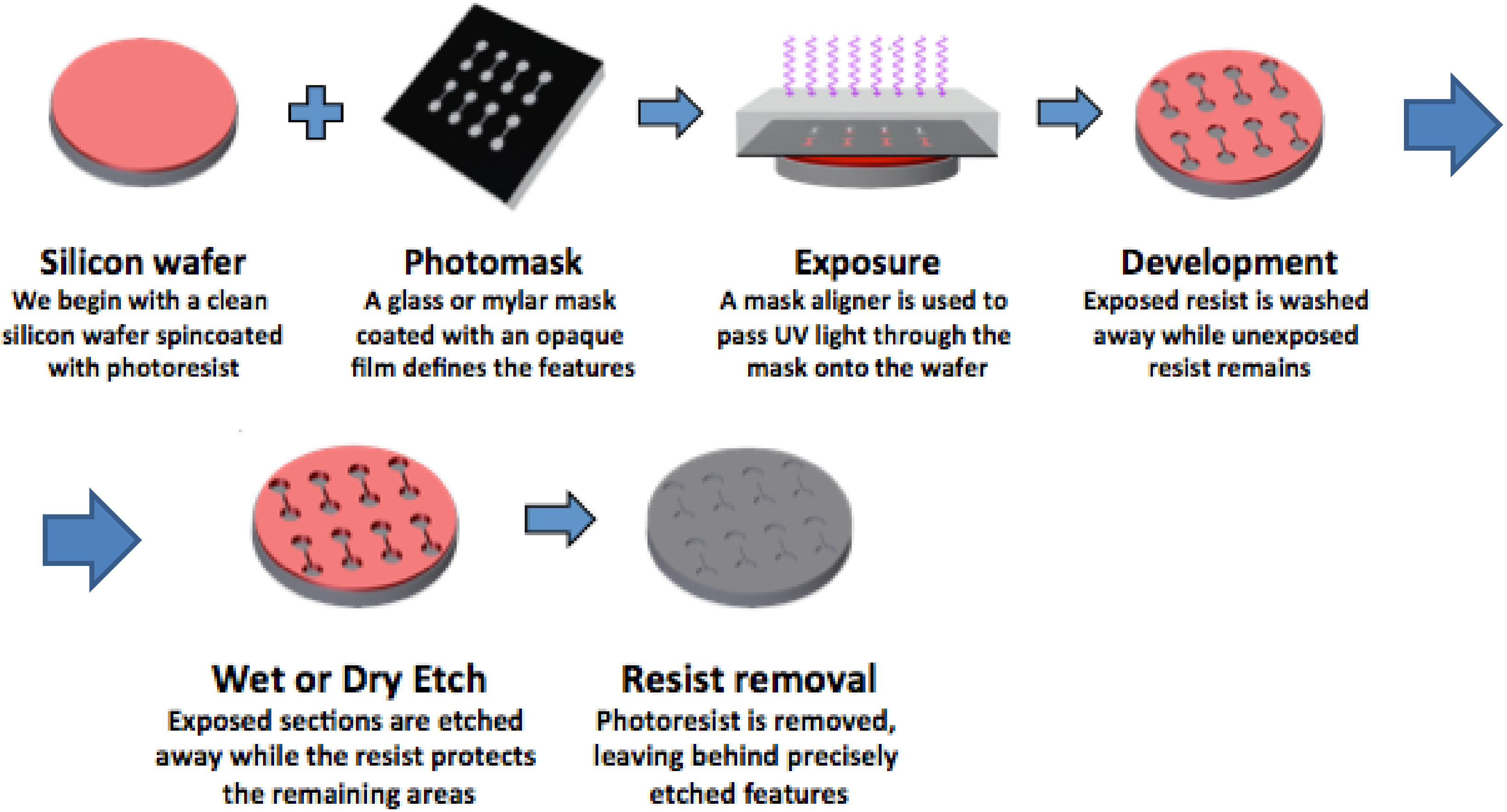
Silicon wafer lot



Silicon wafer with thousands of ICs

IC production

Lithography: core of a foundry



Silicon wafer
We begin with a clean silicon wafer spincoated with photoresist

Photomask
A glass or mylar mask coated with an opaque film defines the features

Exposure
A mask aligner is used to pass UV light through the mask onto the wafer

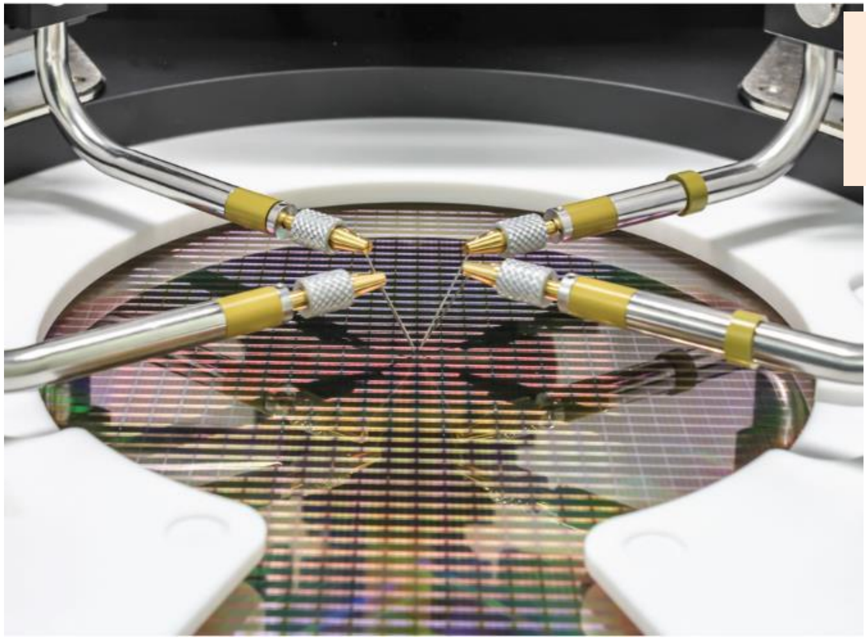
Development
Exposed resist is washed away while unexposed resist remains

Wet or Dry Etch
Exposed sections are etched away while the resist protects the remaining areas

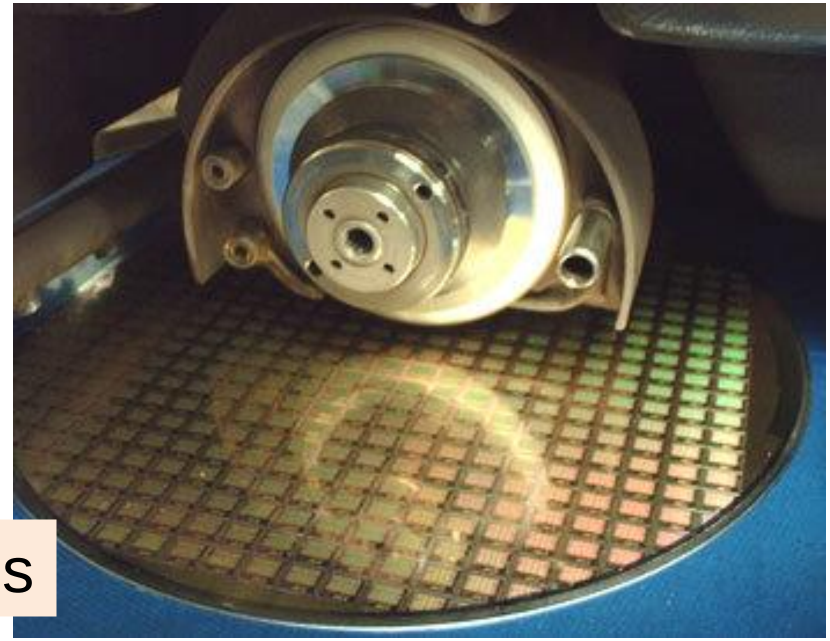
Resist removal
Photoresist is removed, leaving behind precisely etched features

Present CMOS technologies have 30-50 lithos

Wafer testing and dicing

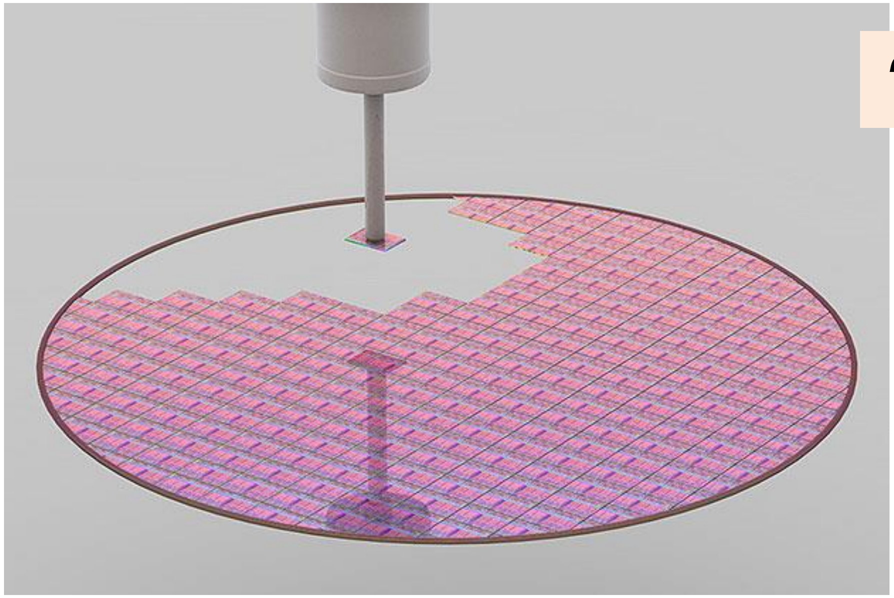


Automatic probers for wafer level testing



Dicing in single ICs

Packaging

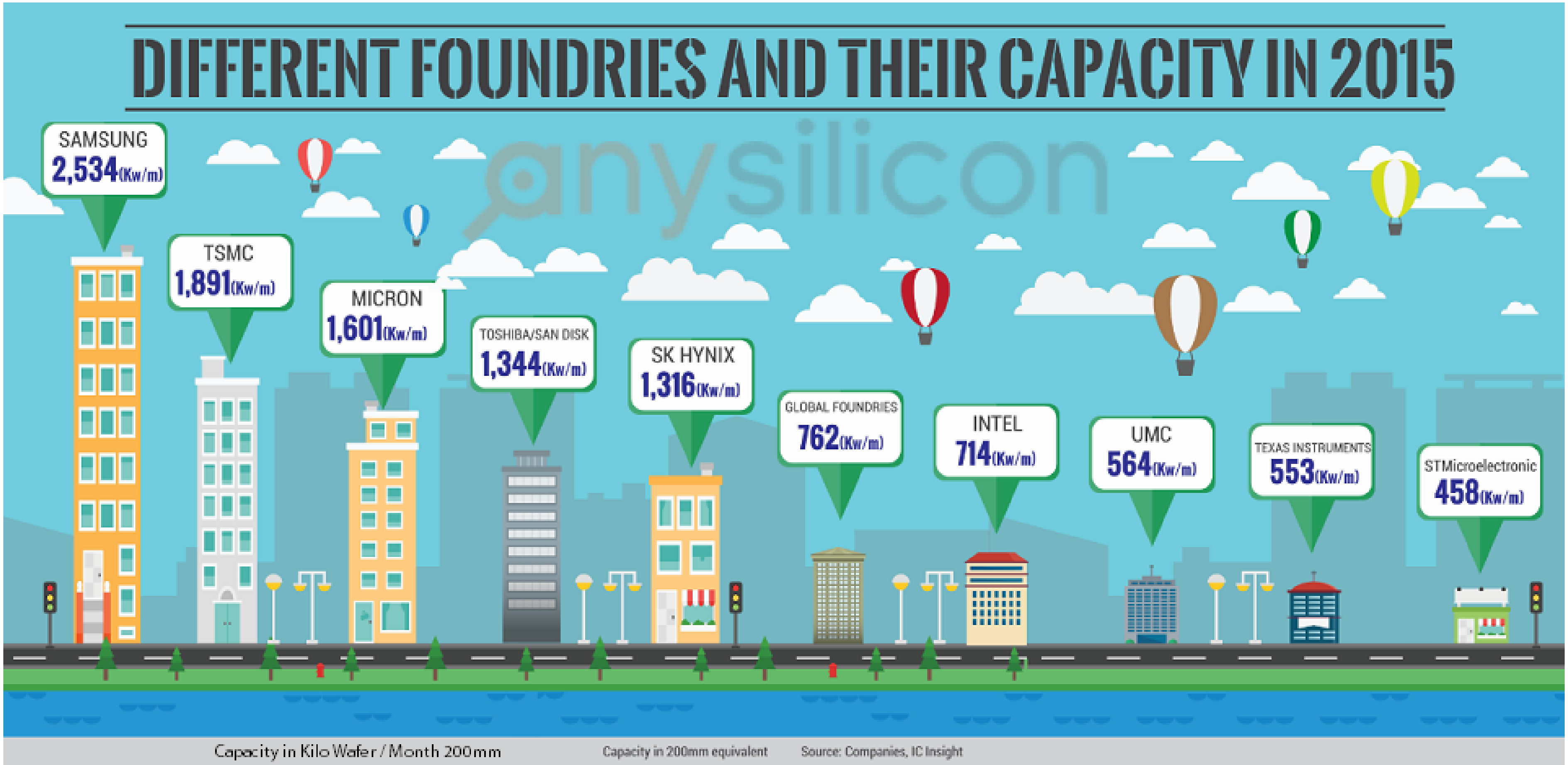


“Pick and place”

IC in package

Pictures from: http://apcmag.com/picture-gallery-how-a-chip-is-made.htm/

Larger IC producers

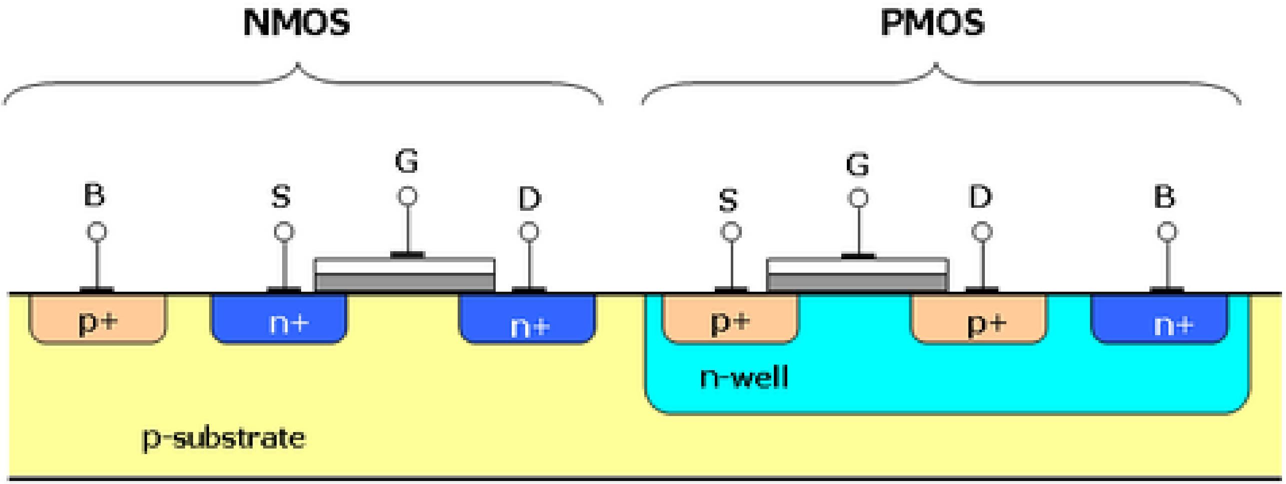


http://anysilicon.com/top-semiconductor-foundries-capacity-2015-2016-infographic/

CMOS technology

Complementary metal–oxide–semiconductor is a technology for constructing integrated circuits.

Typically CMOS designs use complementary and symmetrical pairs of p-type and n-type MOSFETs for logic functions.



CMOS image sensors

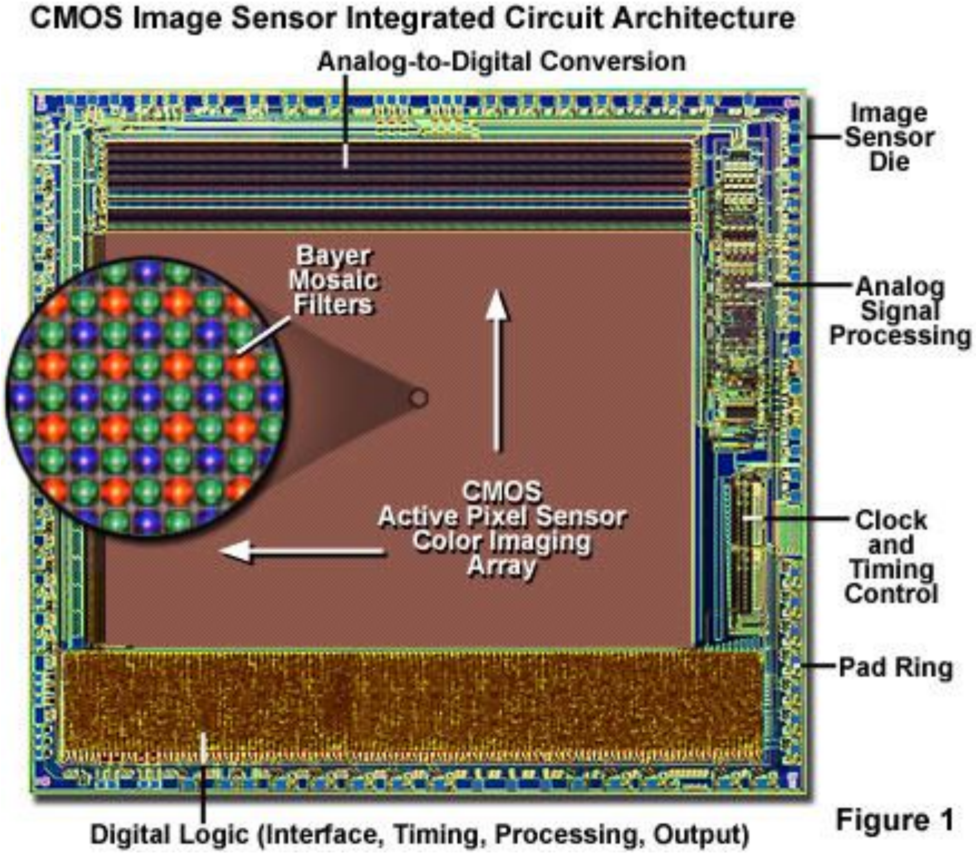


Figure 1

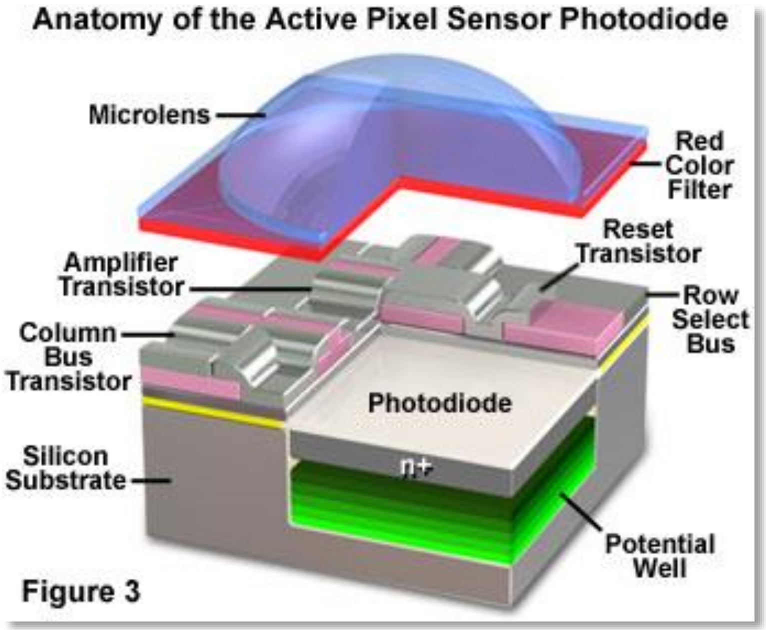
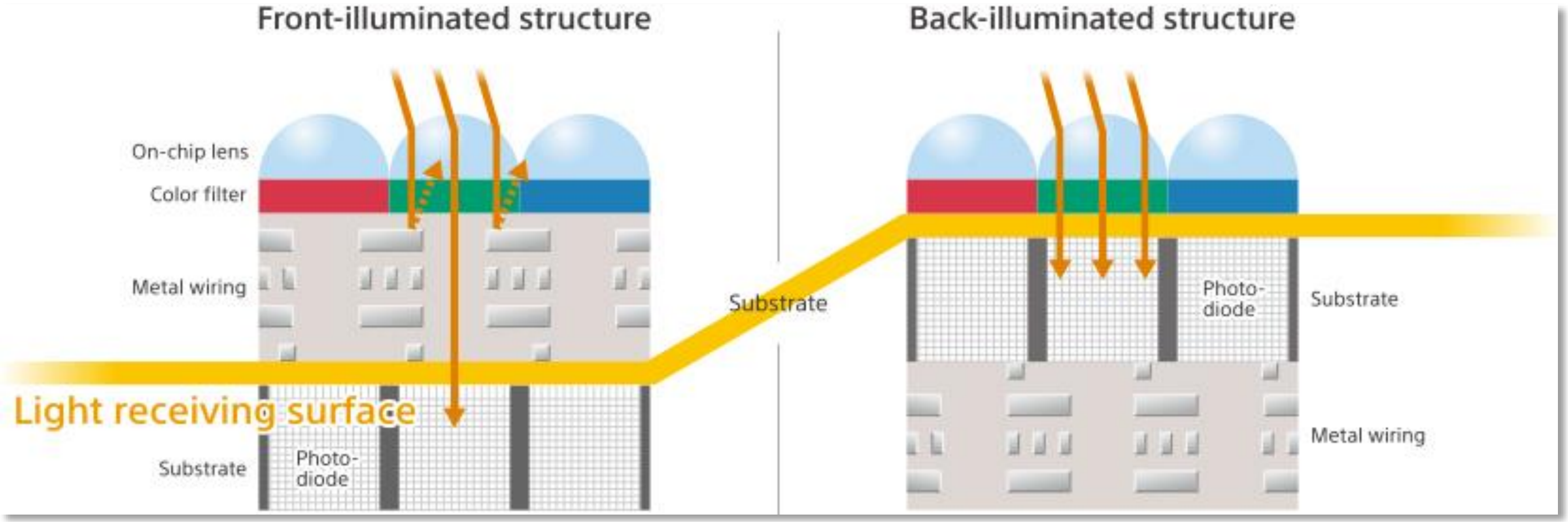


Figure 3

1um

CMOS image sensors: evolution

Backside illumination

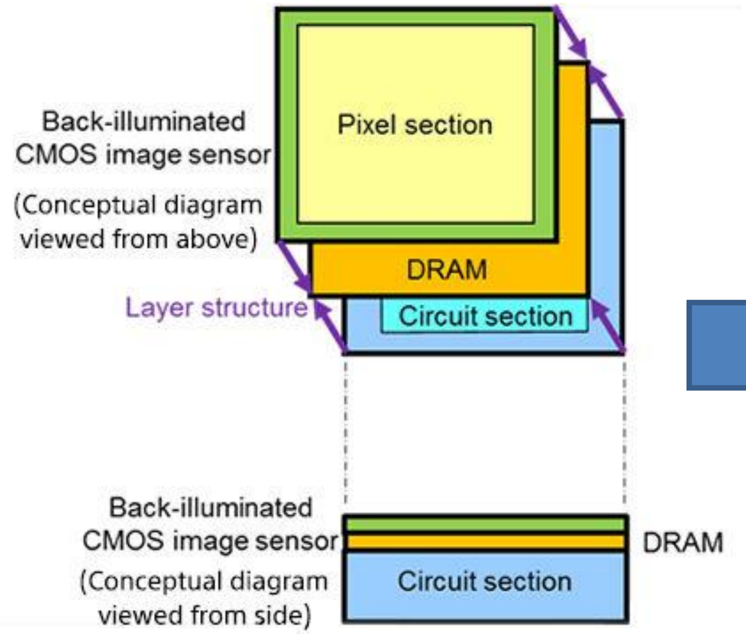


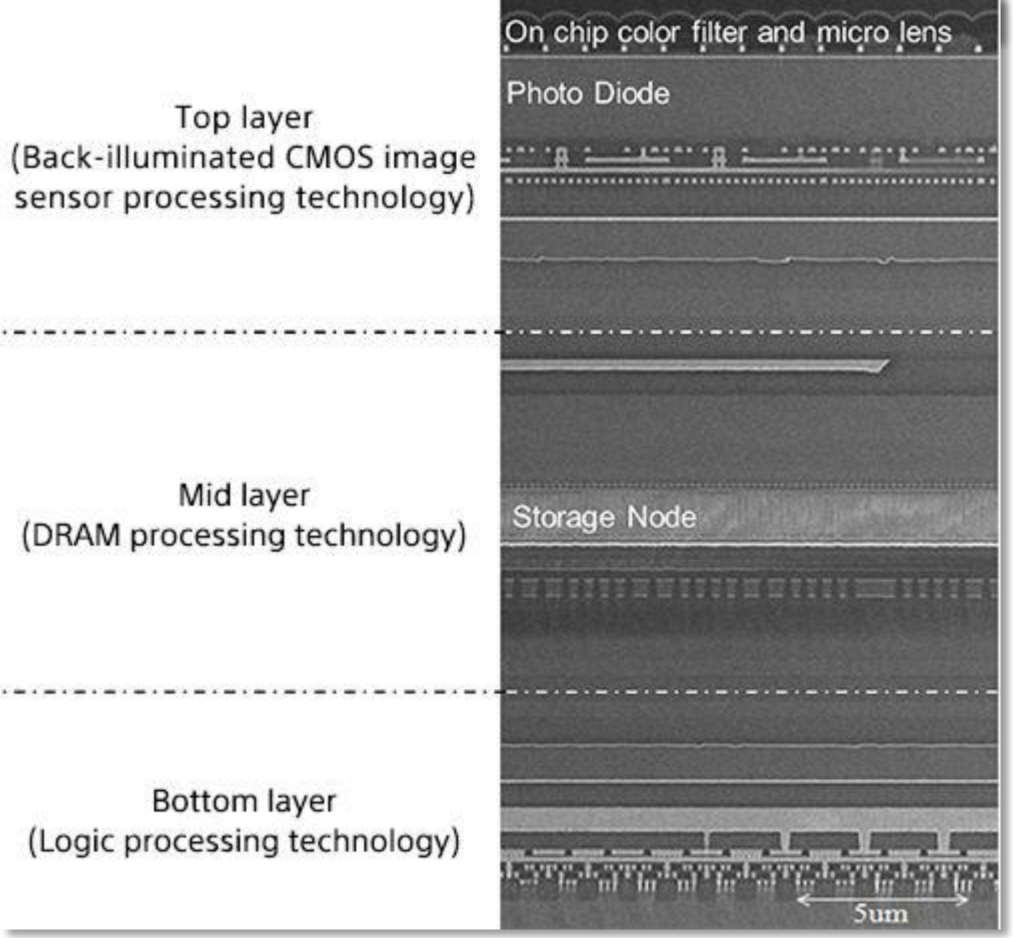
CMOS image sensors

February 07, 2017

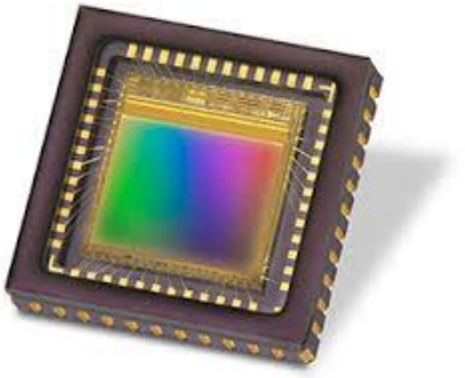
Sony Develops the Industry's First[*1] 3-Layer Stacked CMOS Image Sensor with DRAM for Smartphones

High-Speed Data Readout Minimizes Distortion[*2] in Still Images, and Enables Super Slow Motion Movie Shooting





Main features of the micro-electronics technology

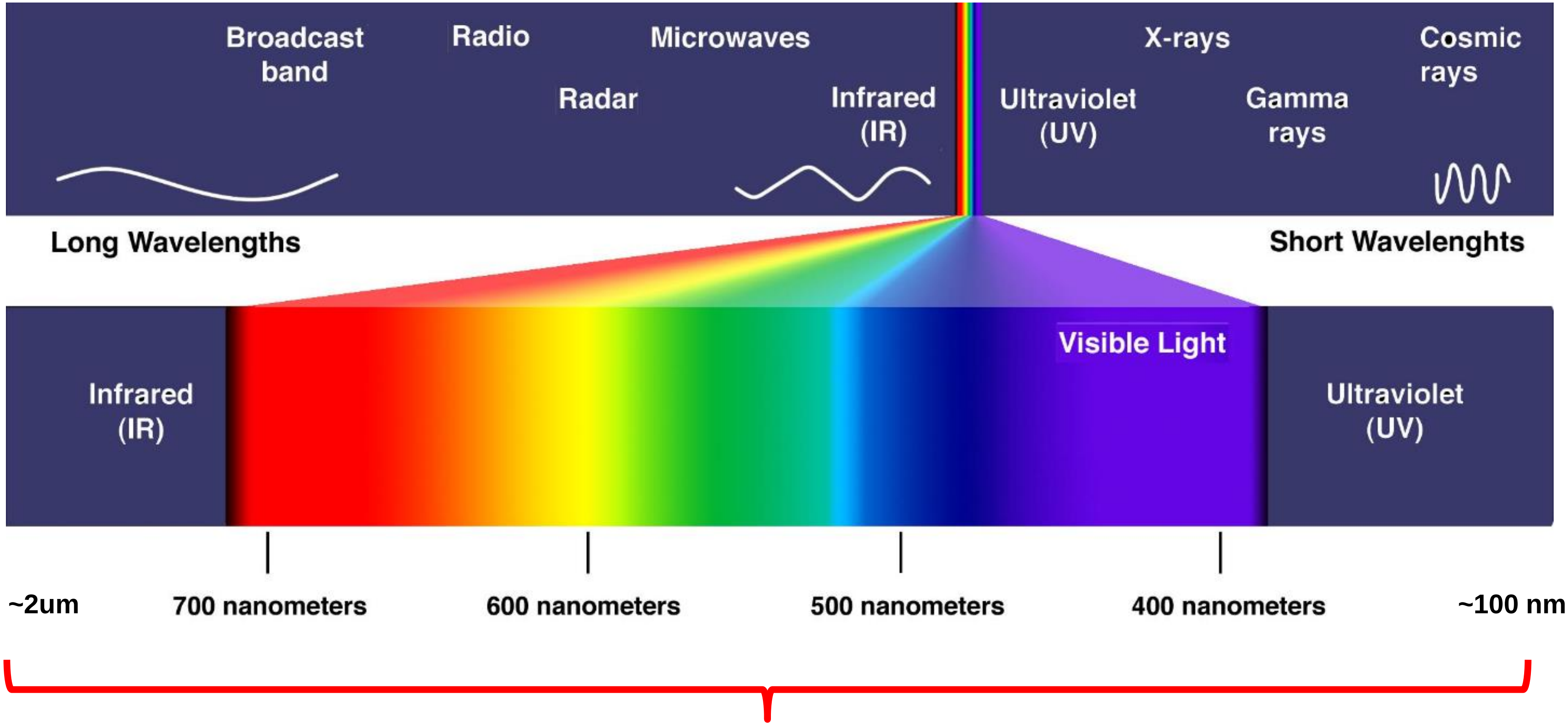


- compact
- rugged
- low power consumption
- **Reliable, reproducible, mass-production**
- **COST**

Micro-electronics technology is the ideal platform for the development/production of any sensor

Low-level light detection applications

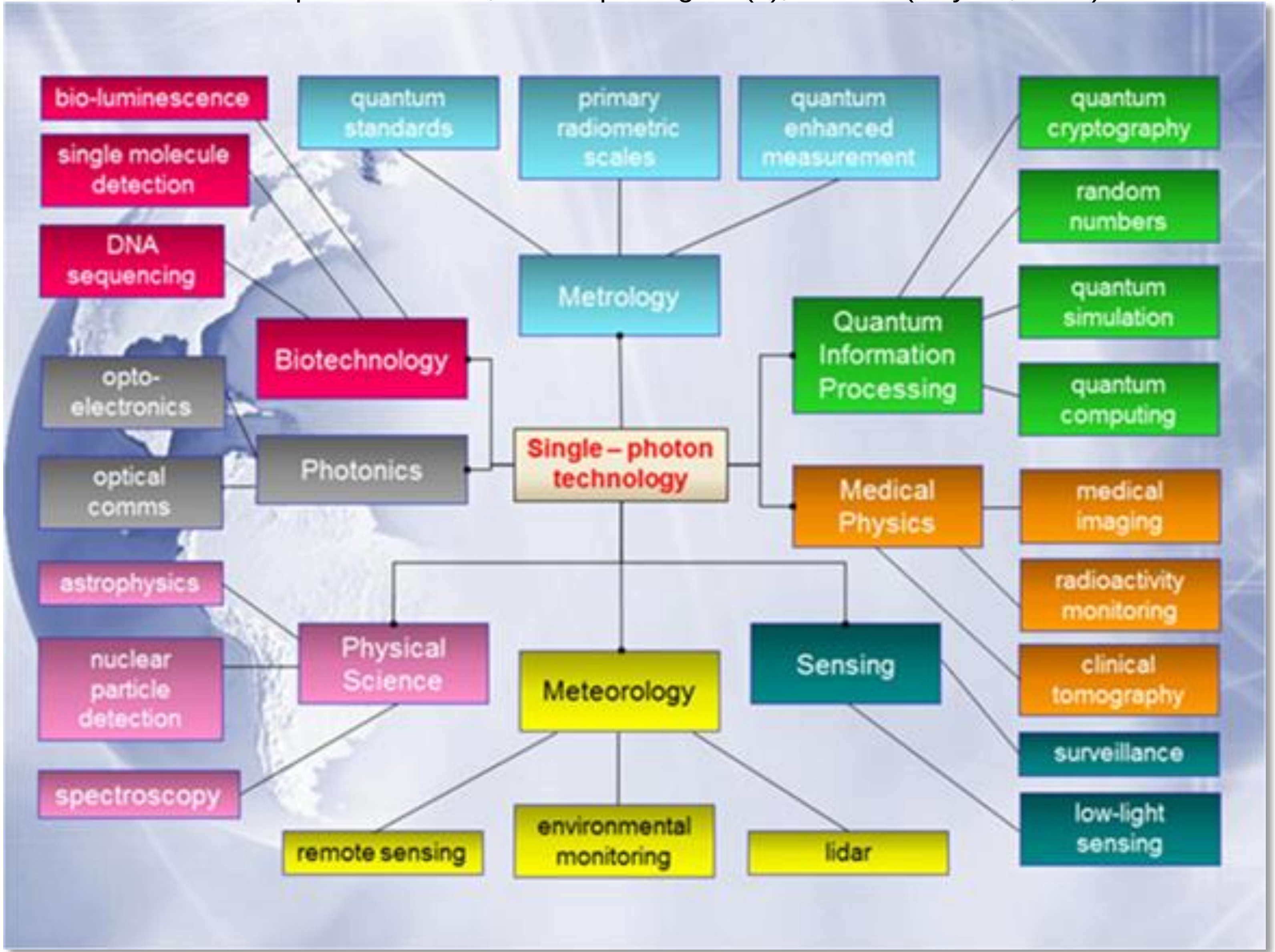
Low-level light detection



we refer to this part
of the spectrum

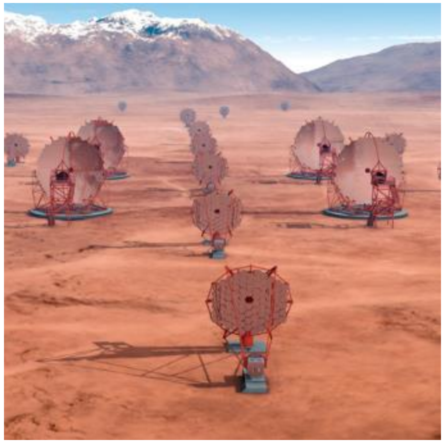
Single-photon applications

Christopher Chunnilal, et al. Opt. Eng. 53(8), 081910 (July 10, 2014).

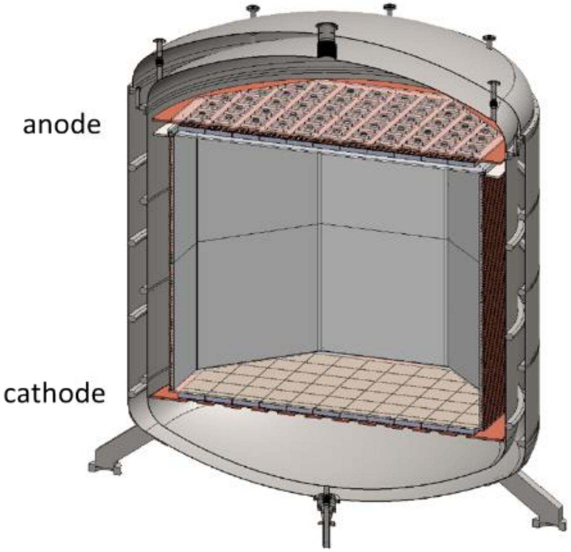


Nuclear Physics

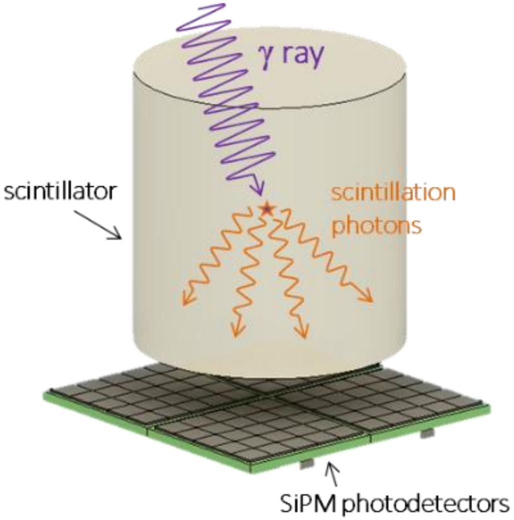
Cherenkov light detection



Noble liquids TPCs



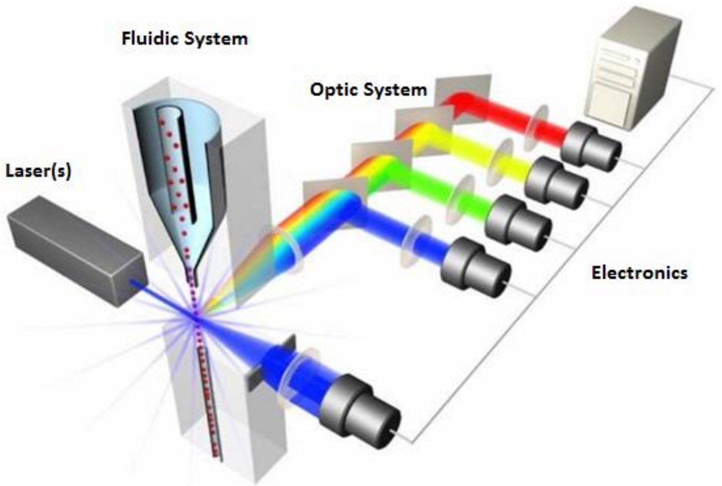
Spectroscopy



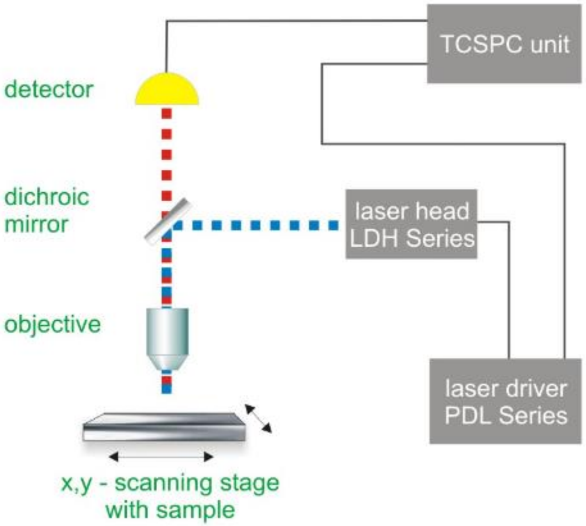
Bio-medical applications

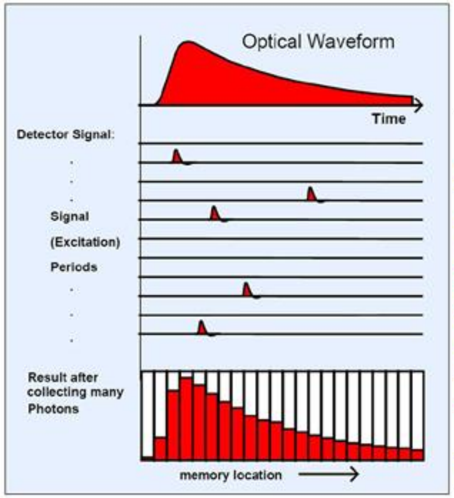
Positron Emission Tomography

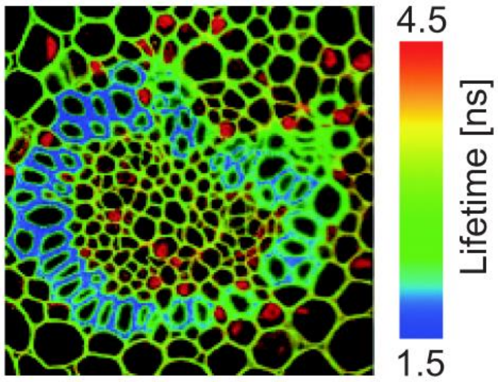
Flow cytometry



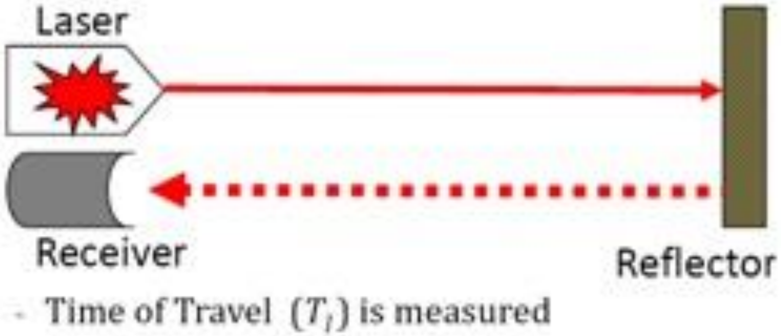
TCSPC





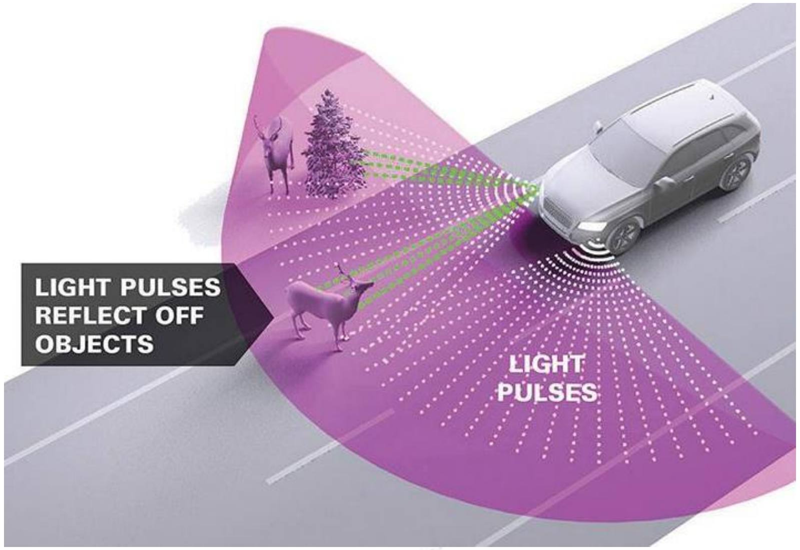


Lidar



- Time of Travel (T_t) is measured

$T_t/2 * c$ = *distance from transmitter to target*



<u>Applications:</u>

Autonomus cruise control

Speed gun

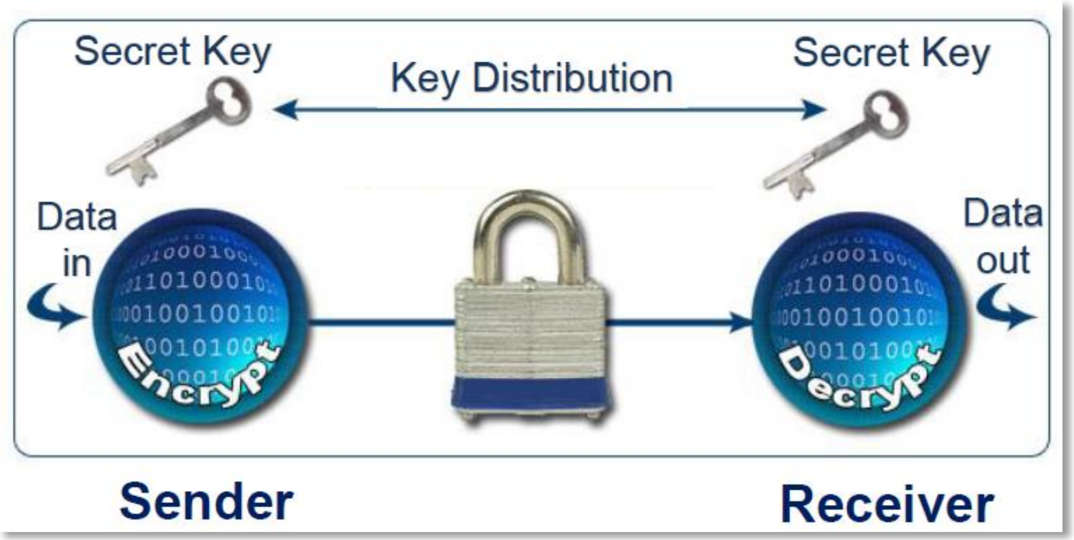
Landing Aid

Rendezvous and docking

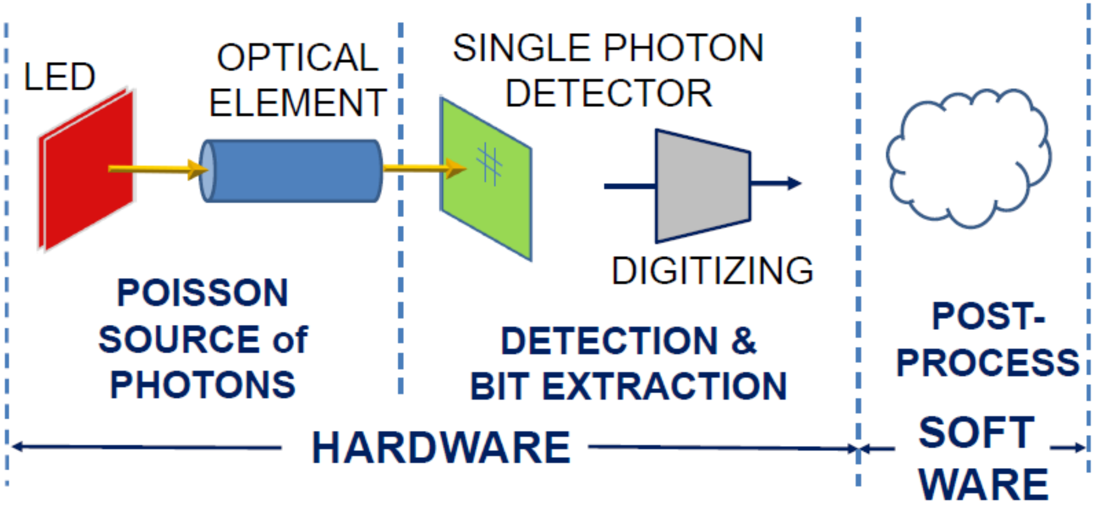
Earth science

….

Quantum Random Number Gen.

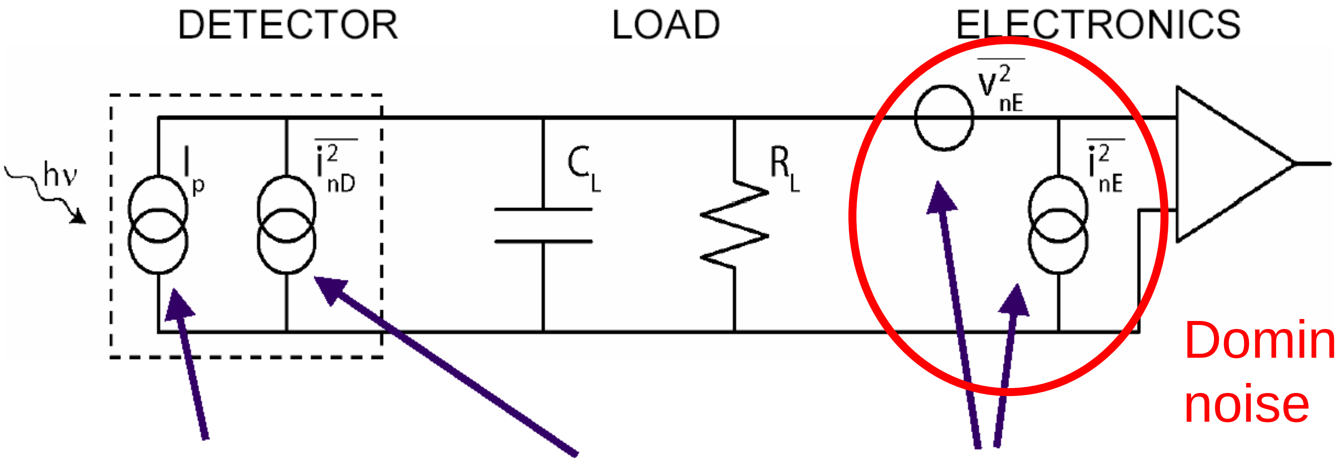


The problem
of secure
communication



Low-level light detection technologies

The problem: processing of extremely weak signals



Dominating noise

Current signal: 1 pair/photon

Detector noise: fluctuation of leakage current

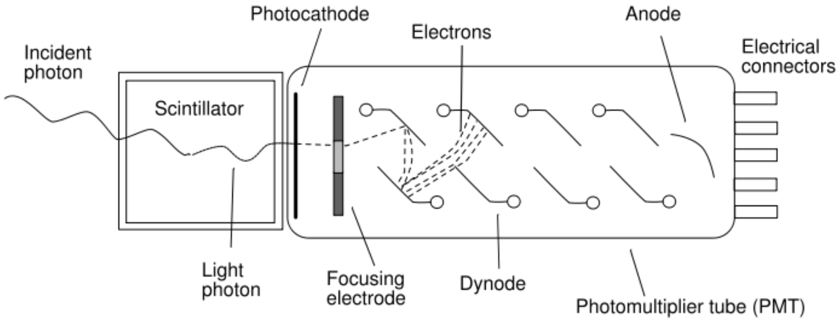
Electronics noise: shot + thermal noise

Need of a detector with internal amplification to reduce the impact of electronic noise!

Vacuum-based photodetectors with internal gain.

Vacuum technologies

PMT (photomultiplier tube)



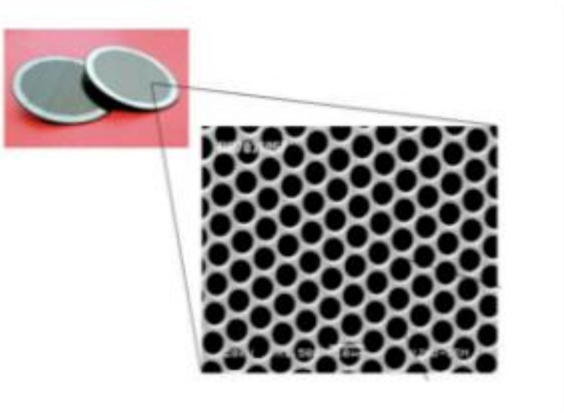
MOST USED for low level light detection!

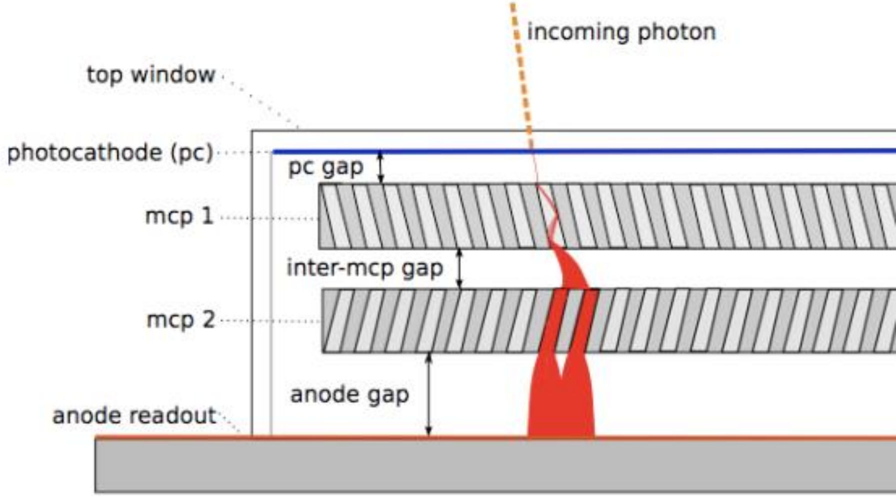
Pros:
- very mature technology
- low dark noise
- good QE in the whole light spectrum

Cons:
- sensible and bulky (vacuum-based)
- requires high voltage
- sensitivity to magnetic fields
- damaged with high light levels

Vacuum technologies

MCP (micro-channel plate)



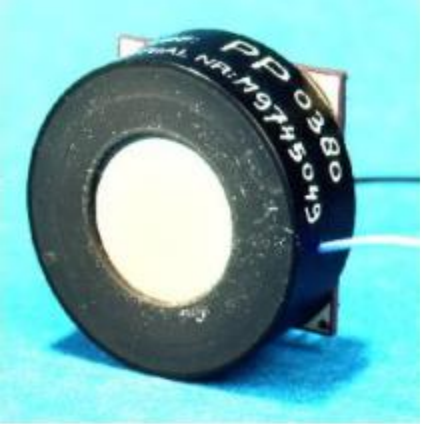


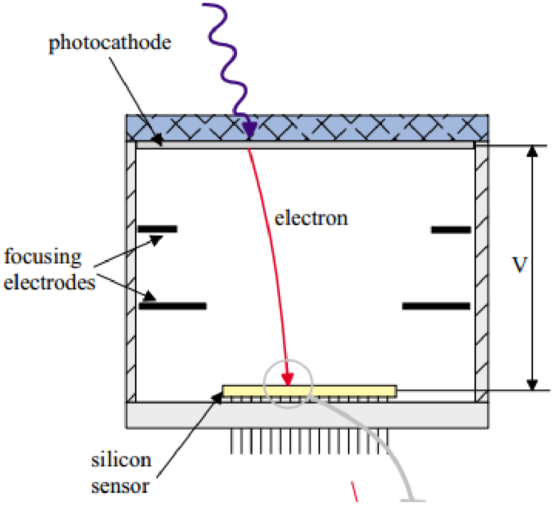
Pros:
- low dark noise
- very fast
- large size possible

Cons:
- sensible and bulky (vacuum-based)
- requires high voltage
- damaged with high light levels

Vacuum technologies

HPD (hybrid photodetector)



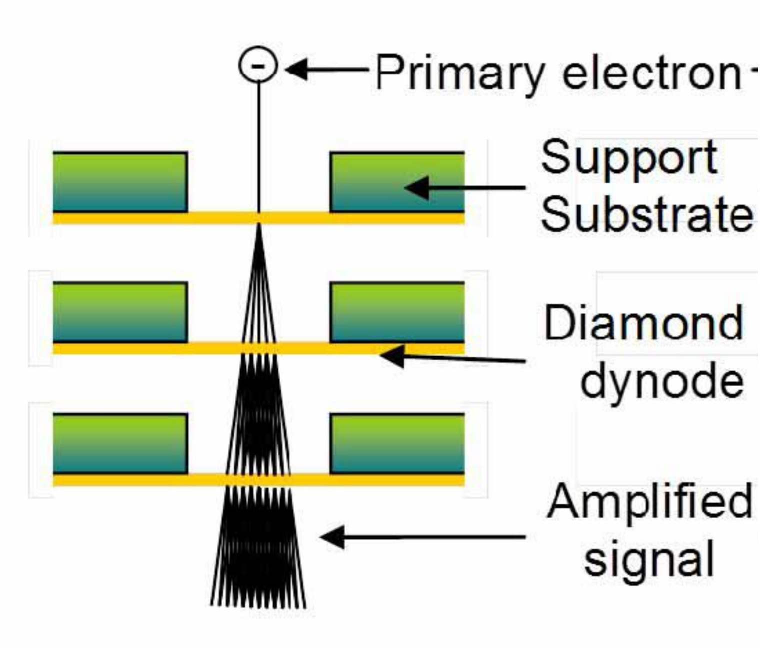


Pros:
- good photon resolution
- fast
- can be operated in magnetic field

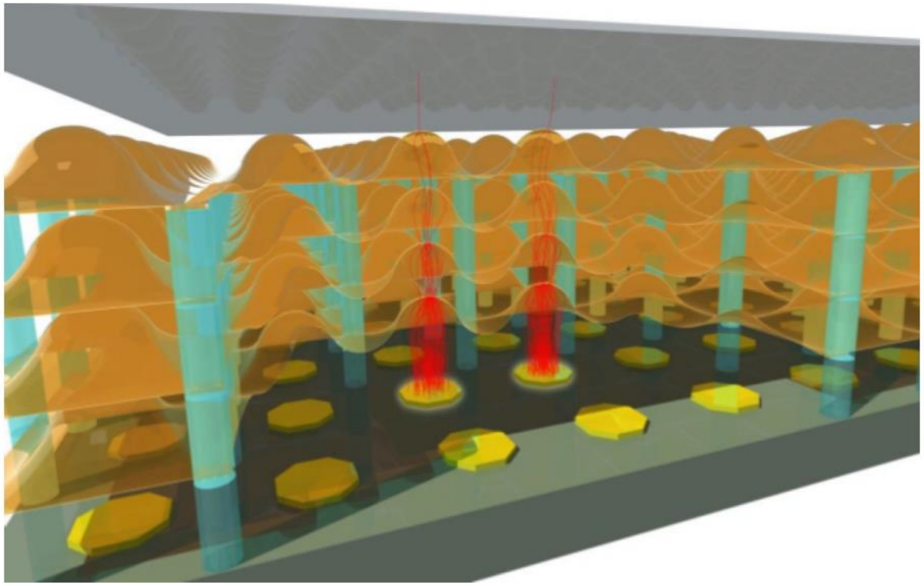
Cons:
- sensible and bulky (vacuum-based)
- requires high voltage
- damaged with high light levels

Vacuum technologies

Transmission dynode (Tynode/Trynode)



TiN + Al2O3



Patent US6657385

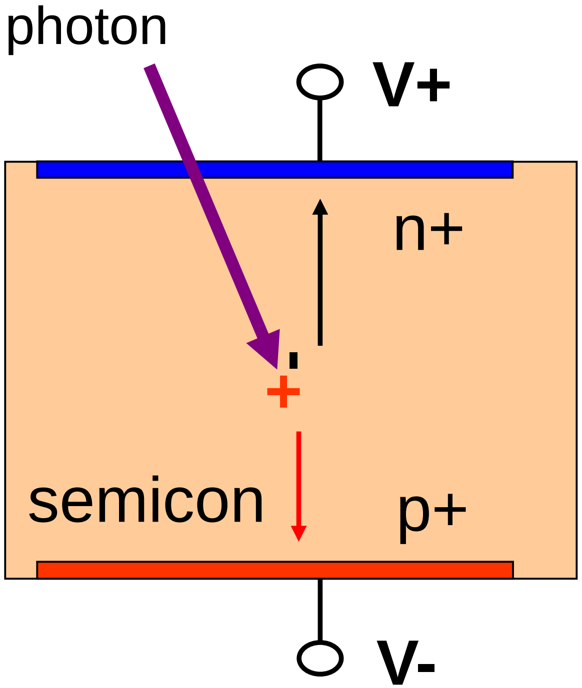
ERC Membrane project
(H. Van Der Graaf)

Solid-state photodetectors with internal gain.

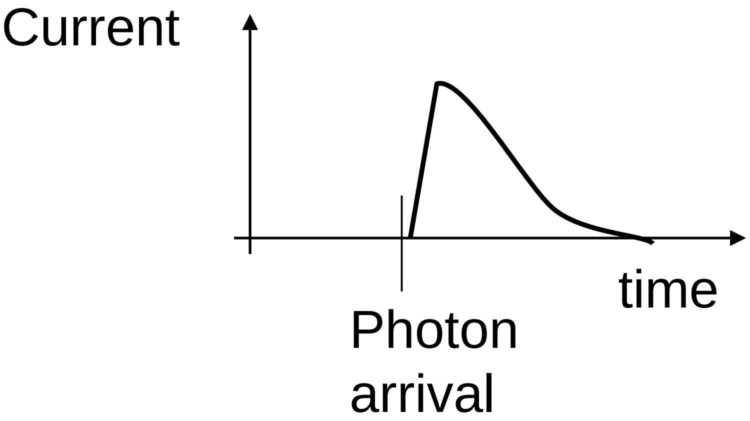
(produced with micro-electronic technologies)

The photodiode

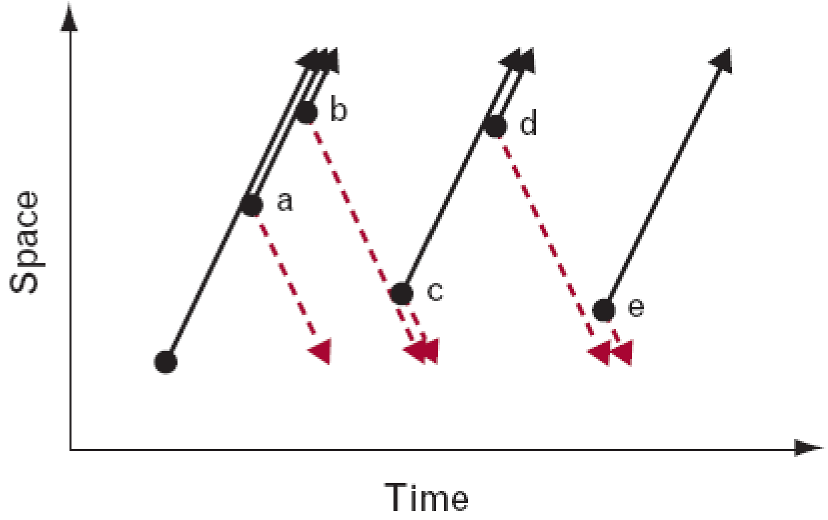
Photodiode (cross-section)



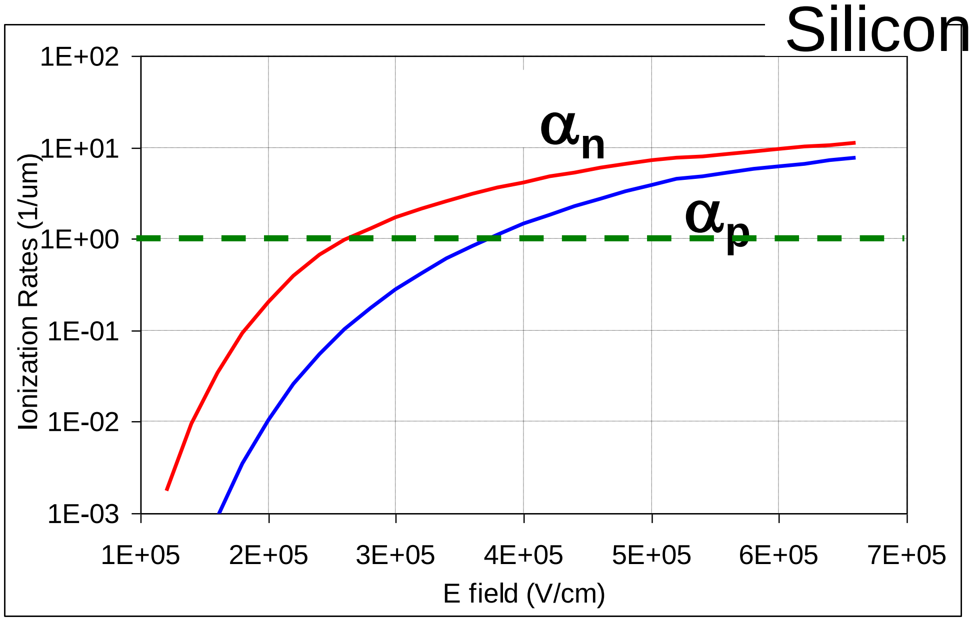
Movement of carriers induces a current at the electrodes according to the Ramo theorem.



Impact ionization



Impact ionization:
carrier has enough kinetic energy to break a bond, i.e. to move an electron from valence to conduction band



Ionization rates:
number of pairs created by a carrier per unit distance travelled

$\Rightarrow$ a field of ~3x10^{5}V/cm is needed to create on average a pair in 1μm travelled.

Reverse current in a diode

Low field region ($V<V_{APD}$)

Leakage current is given by thermal generation
in the depletion region:

$$I = q * G * W_{dep} = q * ni * 1/T_g *W_{dep}$$

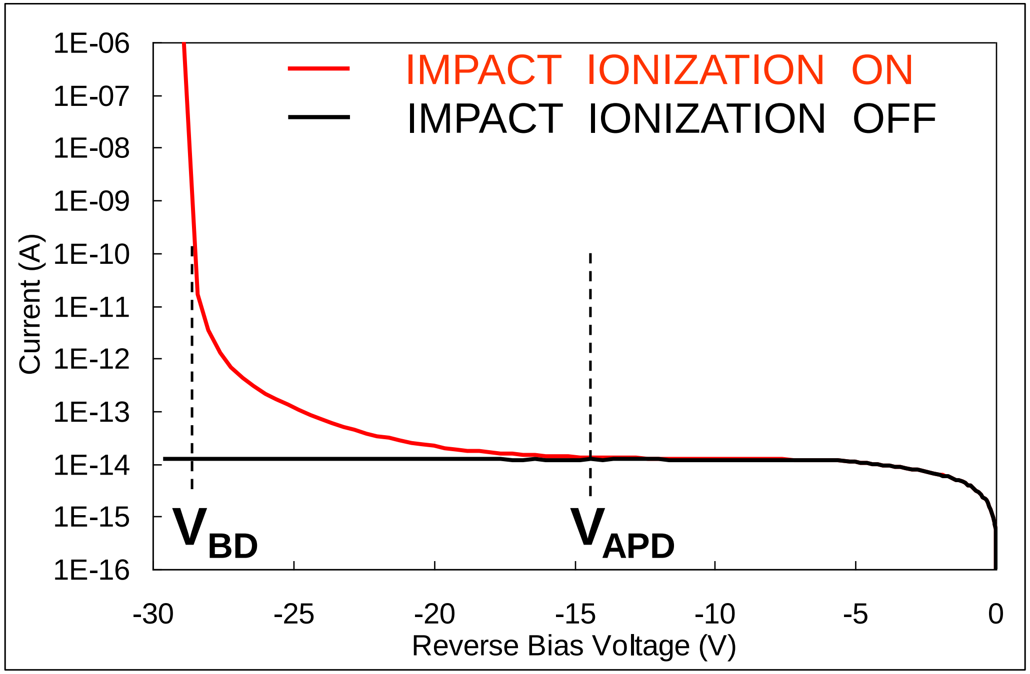
High field region ($V>V_{APD}$)

Leakage current deviates from the expected constant value because some carriers "impact ionize"
A sort of "*GAIN*" could be defined

Very high field region ($V>V_{BD}$)

the current rises indefinetly
"*avalanche*"

Simulated diode reverse current

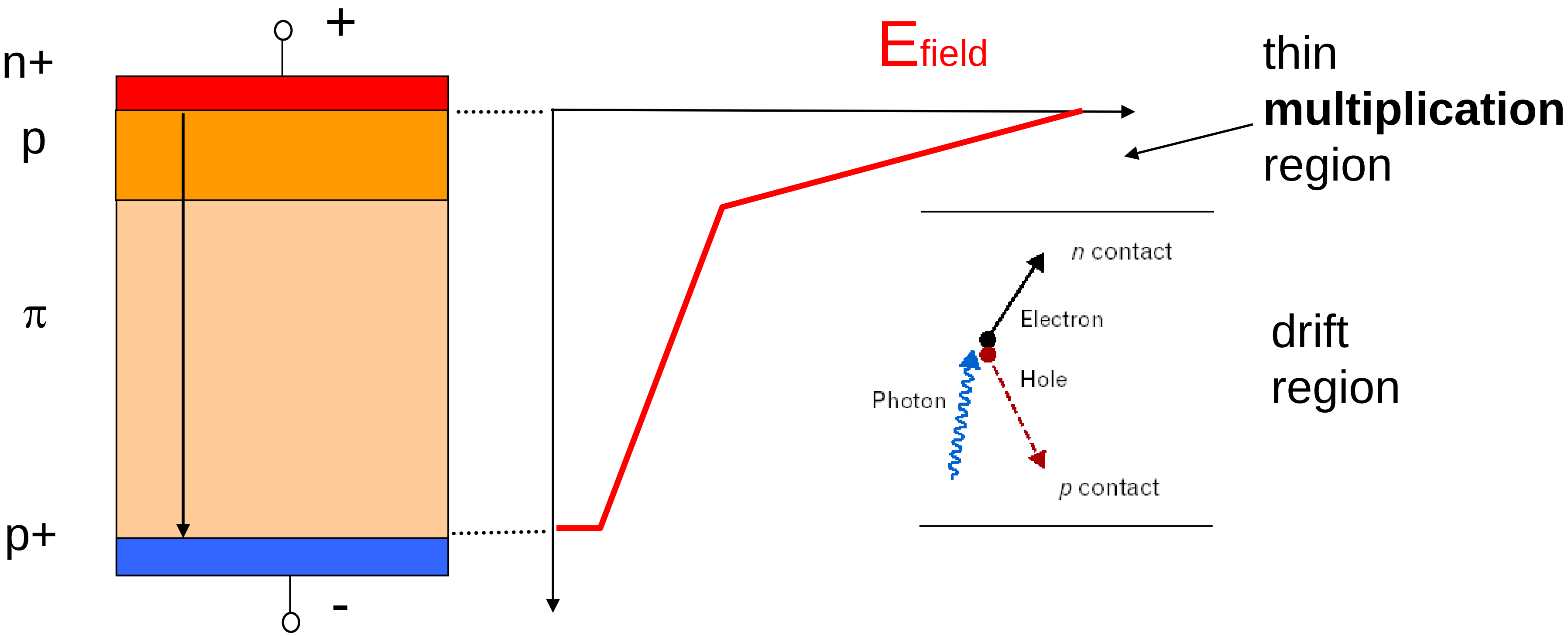


Impact ionization

Avalanche Photo-Diode

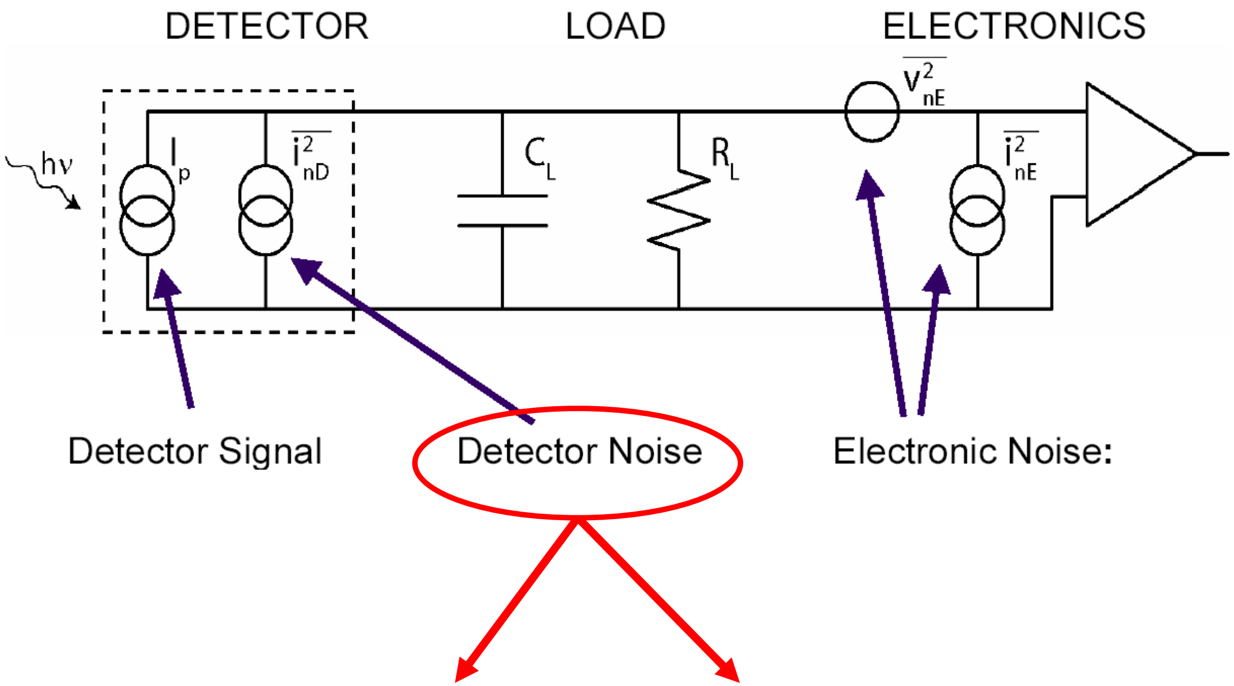
Geiger-Mode Avalanche Photo-Diode/
Single-Photon Avalanche Diode

Avalanche photodiode (APD)



Electrons photo-generated in the drift region are multiplied (on average) by the same factor!

Noise in an APD



DETECTOR

LOAD

ELECTRONICS

Detector Signal

Detector Noise

Electronic Noise:

Fluctuation of leakage current

→ SHOT NOISE

Statistical fluctuation of gain (additional noise vs PD)

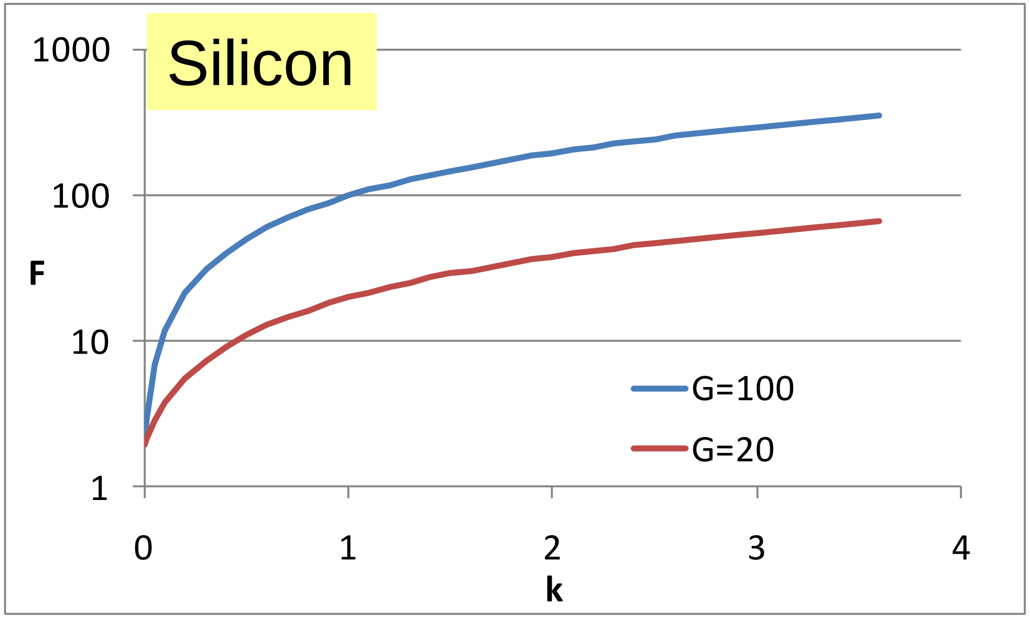
→ EXCESS NOISE

It deterioratess with gain

Excess Noise Factor (F) in an APD

$$\boxed{F = M{*}k + (2-1/M)(1-k)}$$

$k = \alpha_h/\alpha_e$ for electron injection



K must be as small as possible to minimize F.

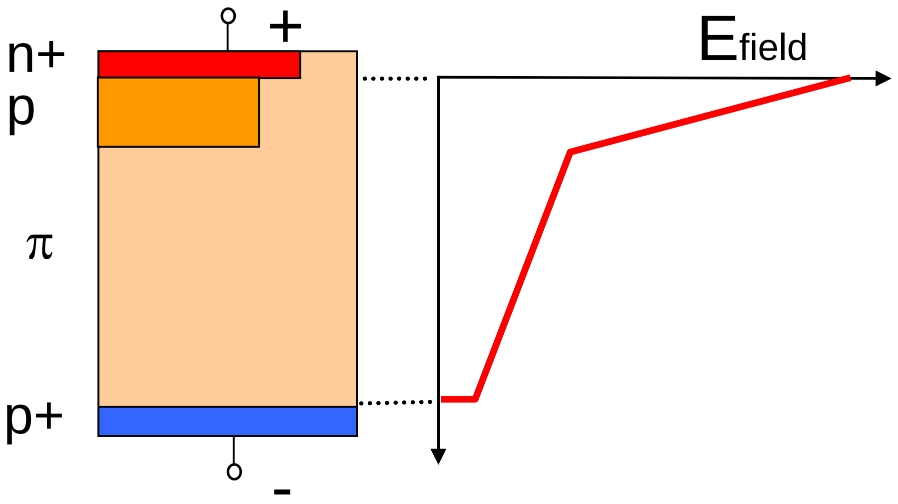
Ideally = 0 => holes do not ionize

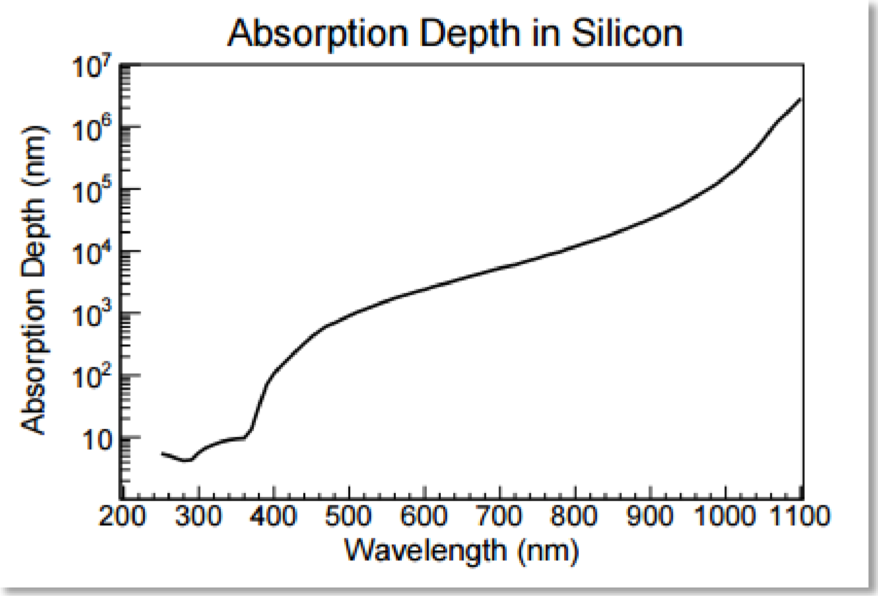
In silicon, k depends strongly on the field, at low fields (~$2\text{x}10^5$V/cm) k<<1

Reach-through APD

photon

front-side illumination
suitable for red/IR light





photon

The structure can be designed for backside illumination to allow usage also at short wavelengths.

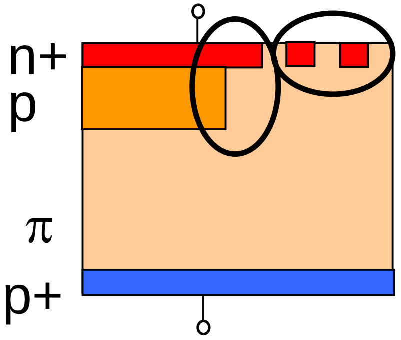
Features of an APD

1. Spatially uniform avalanche multiplication

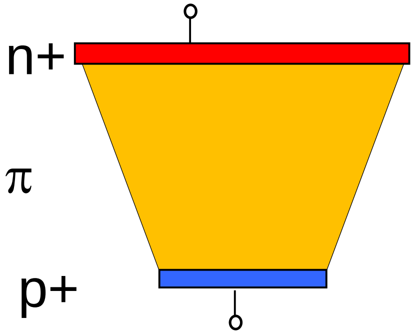
No micro-plasmas → dislocation-free process

2. Reduction of the field along the edges

⇒ guard-ring



⇒ beveled structure



Features of an APD

3. Choice of semiconductor material based on:

- quantum efficiency at particular wavelength
- response speed
- noise

Germanium:	*Sensitivity from 1 to 1.6um* *k~1 → high F* *High speed*
Silicon:	*Sensitivity from 0.1 to 1um* *k~0.1 → low F*
Hetero-junct.:	*sensitivity from 1 to 1.7um* *k depends on materials* *high speed*

GM-APD/SPAD: principle (i)

$t = 0$ ……..let's bias the diode at $V>V_{BD}$

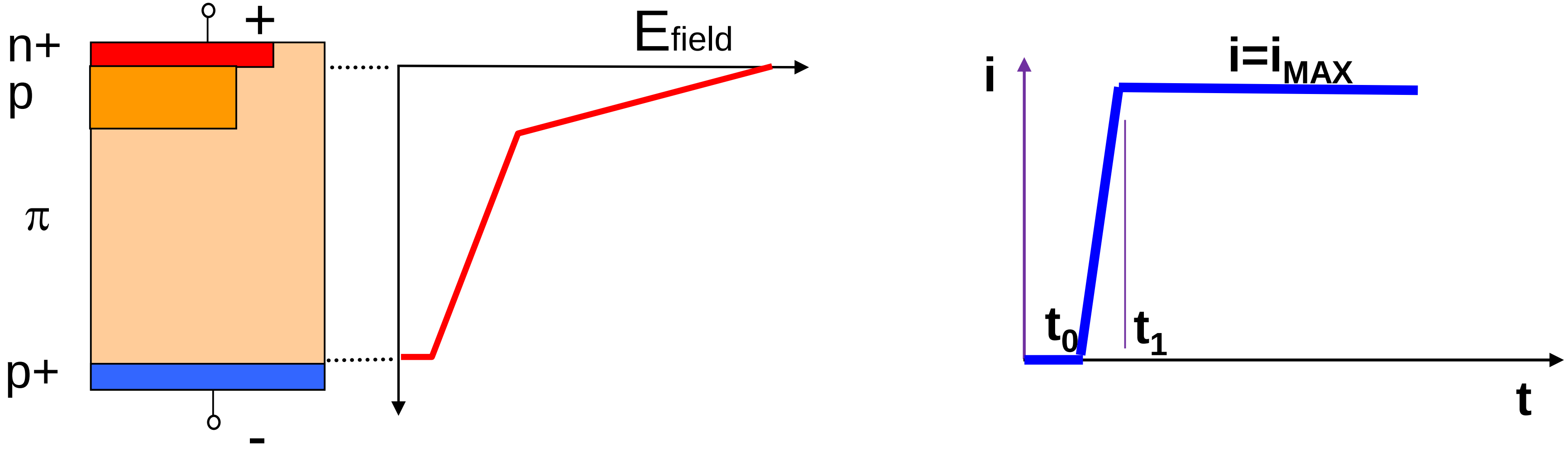
$t < t_0$ ……..i=0 (if no free carriers in the high field region)

$t = t_0$ ……….photo**carrier initiates the avalanche**

$t_0 < t < t_1$….avalanche spreading

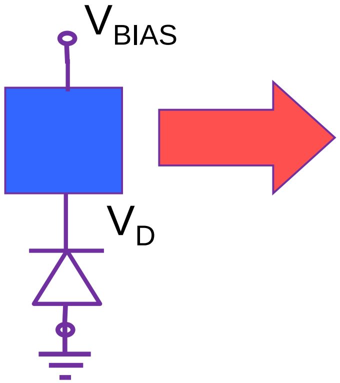
$t > t_1$ ……..self-sustaining current

(limited by series resistances)

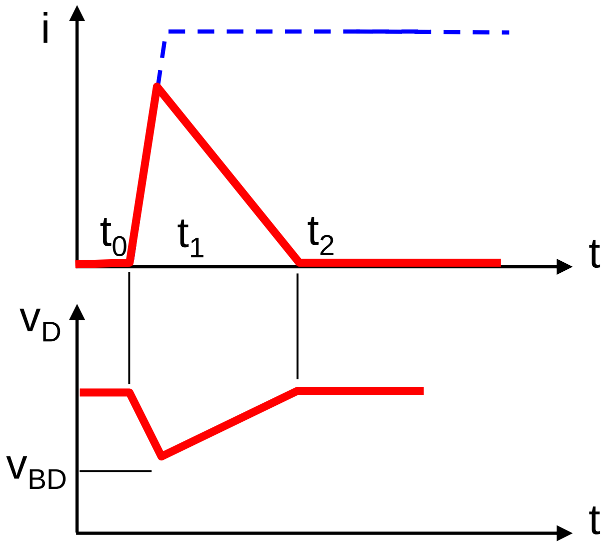


GM-APD/SPAD: principle (ii)

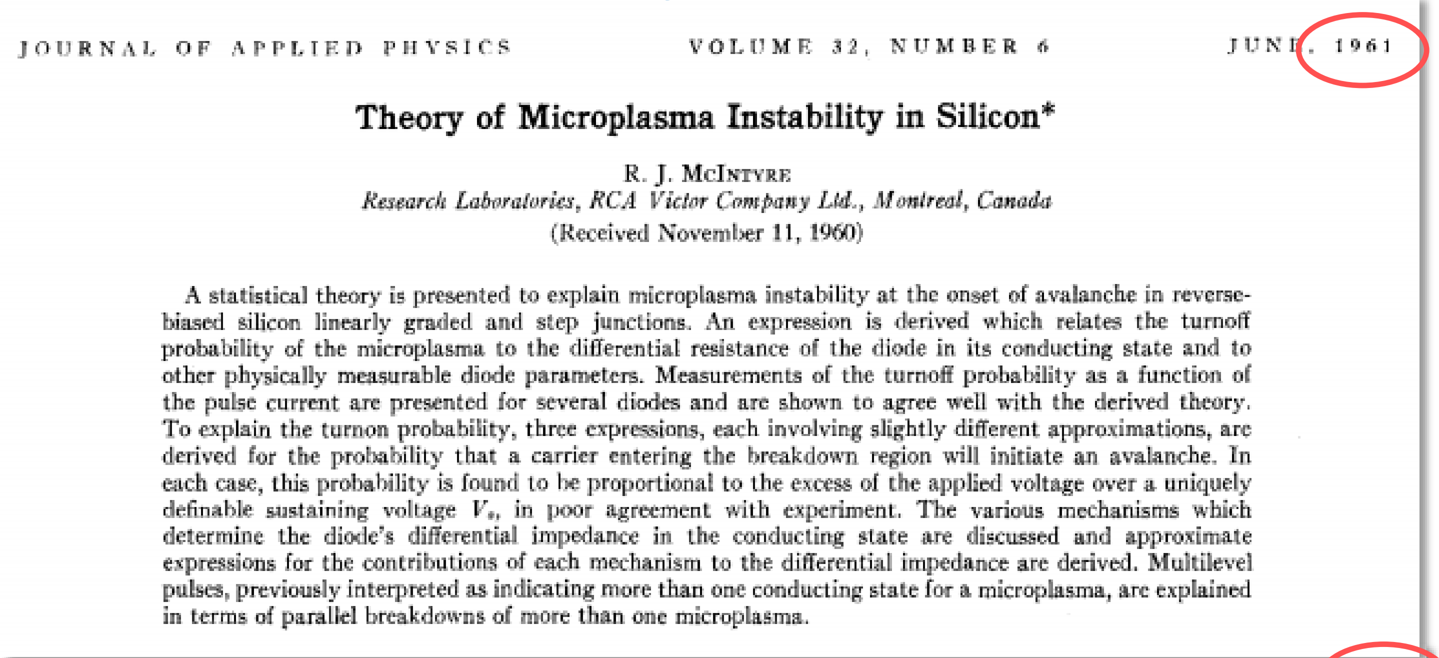
We need to quench the avalanche to detect another photon



- large resistance: passive quenching
- analog circuit: active quenching



GM-APD/SPAD: model



JOURNAL OF APPLIED PHYSICS VOLUME 32, NUMBER 6 JUNE, 1961

Theory of Microplasma Instability in Silicon*

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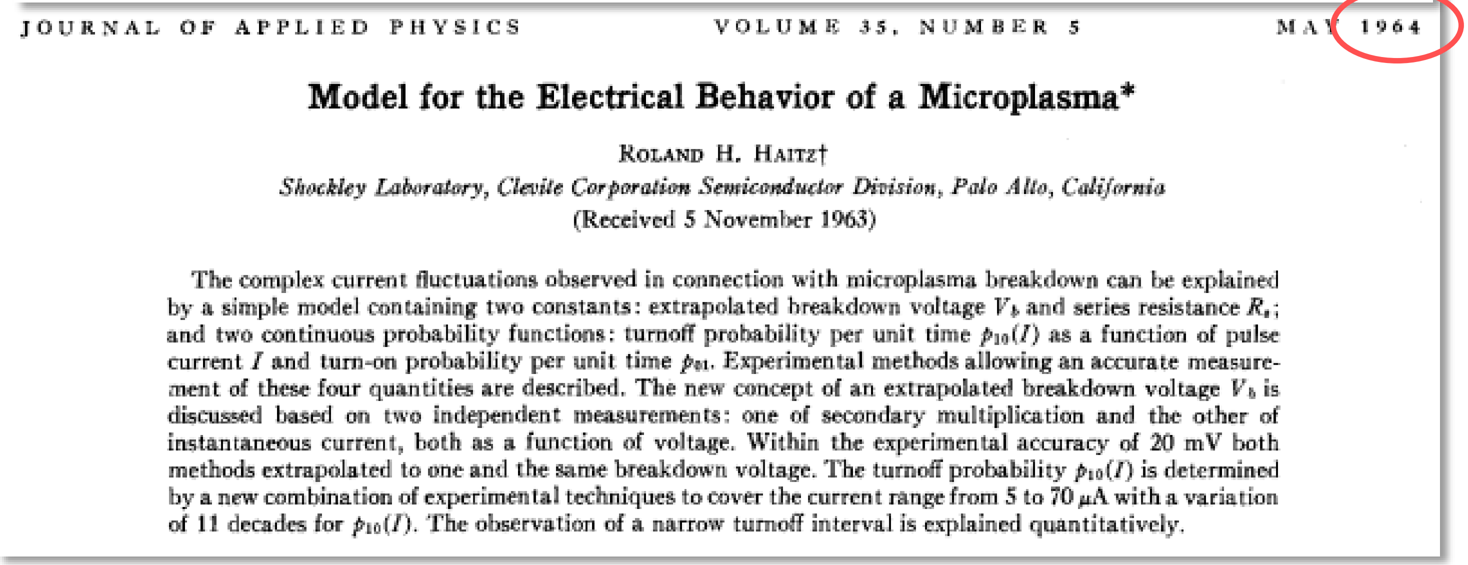
(Received November 11, 1960)

A statistical theory is presented to explain microplasma instability at the onset of avalanche in reverse-biased silicon linearly graded and step junctions. An expression is derived which relates the turnoff probability of the microplasma to the differential resistance of the diode in its conducting state and to other physically measurable diode parameters. Measurements of the turnoff probability as a function of the pulse current are presented for several diodes and are shown to agree well with the derived theory. To explain the turnon probability, three expressions, each involving slightly different approximations, are derived for the probability that a carrier entering the breakdown region will initiate an avalanche. In each case, this probability is found to be proportional to the excess of the applied voltage over a uniquely definable sustaining voltage V_s, in poor agreement with experiment. The various mechanisms which determine the diode's differential impedance in the conducting state are discussed and approximate expressions for the contributions of each mechanism to the differential impedance are derived. Multilevel pulses, previously interpreted as indicating more than one conducting state for a microplasma, are explained in terms of parallel breakdowns of more than one microplasma.



JOURNAL OF APPLIED PHYSICS VOLUME 35, NUMBER 5 MAY 1964

Model for the Electrical Behavior of a Microplasma*

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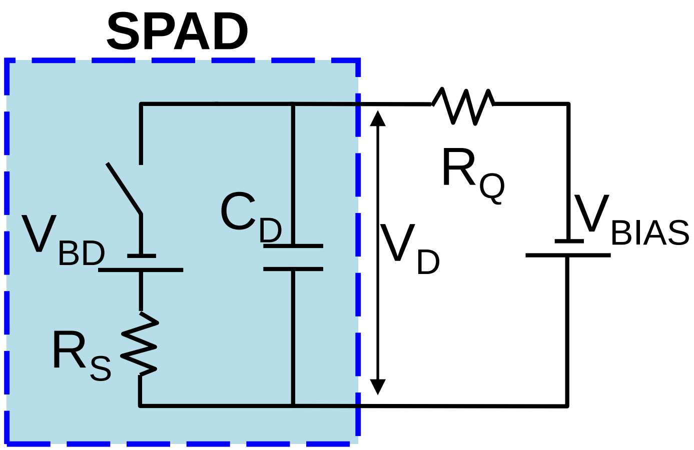
(Received 5 November 1963)

The complex current fluctuations observed in connection with microplasma breakdown can be explained by a simple model containing two constants: extrapolated breakdown voltage V_b and series resistance R_s; and two continuous probability functions: turnoff probability per unit time $p_{10}(I)$ as a function of pulse current I and turn-on probability per unit time p_{01}. Experimental methods allowing an accurate measurement of these four quantities are described. The new concept of an extrapolated breakdown voltage V_b is discussed based on two independent measurements: one of secondary multiplication and the other of instantaneous current, both as a function of voltage. Within the experimental accuracy of 20 mV both methods extrapolated to one and the same breakdown voltage. The turnoff probability $p_{10}(I)$ is determined by a new combination of experimental techniques to cover the current range from 5 to 70 μA with a variation of 11 decades for $p_{10}(I)$. The observation of a narrow turnoff interval is explained quantitatively.

GM-APD/SPAD: model

The GM-APD can be modeled with **an electrical circuit and two probabilities**:

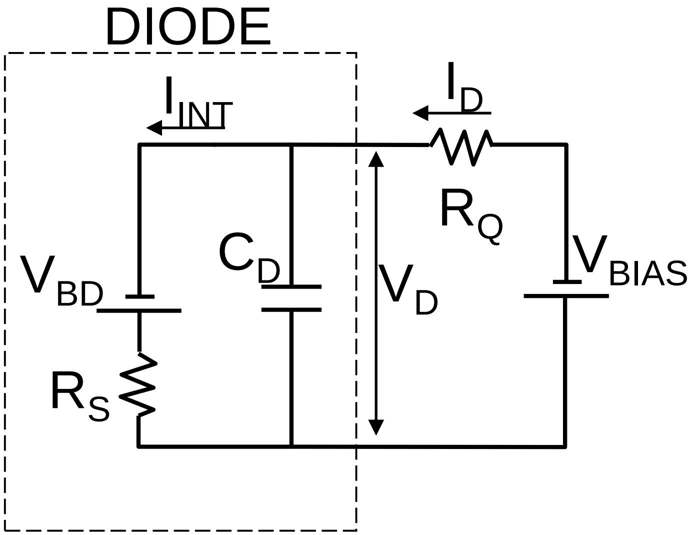


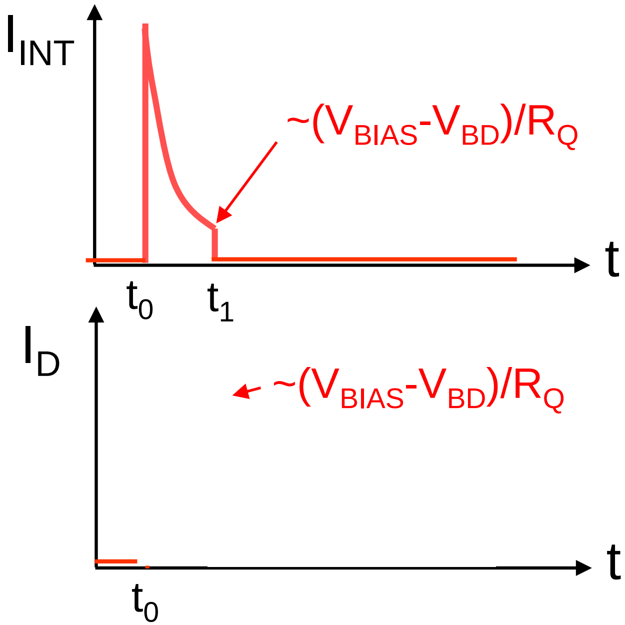
- C_D = diode capacitance
- R_s = series resistance (~1kΩ)
- V_{BD} = breakdown voltage

- R_Q = quenching resistance (>300kΩ)
- $V_{BIAS} > V_{BD}$

- P_{01} = Triggering probability
- P_{10} = turn-off probability

which govern the switch transition





OFF condition: switch open, (capacitance charged to V_{BIAS}, no current flowing)

Avalanche triggering (P_{01}) $[t_0]$

ON condition: switch closed

$\Rightarrow$ C_D discharges to V_{BD} with a time constant R_SxC_D, at the same time the external current grows to $(V_{BIAS}$-$V_{BD})/R_Q$

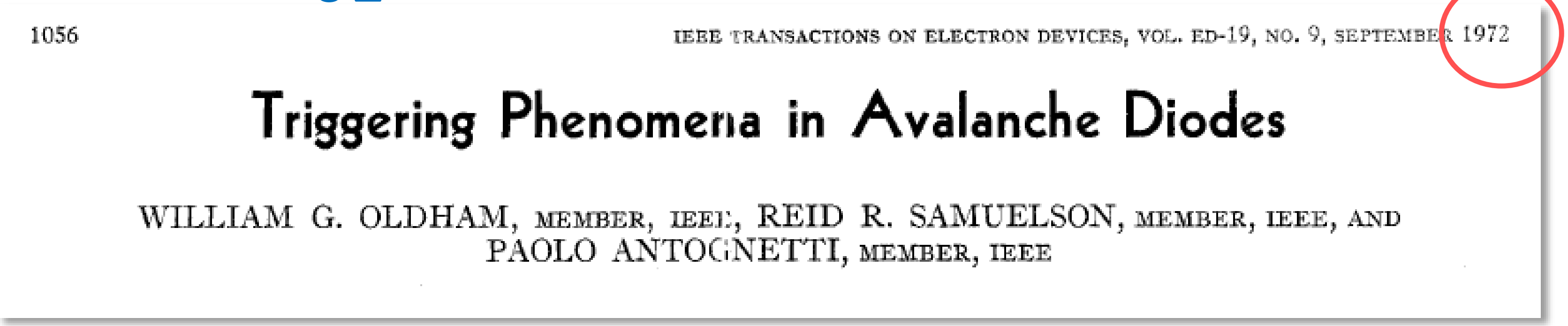
Avalanche quenching (P_{10}) $[t_1]$

OFF condition: switch open

$\Rightarrow$ diode capacitance recharghes from V_{BD} to V_{BIAS} with a time constant R_QxC_D

Ready for new detection $[t_2]$

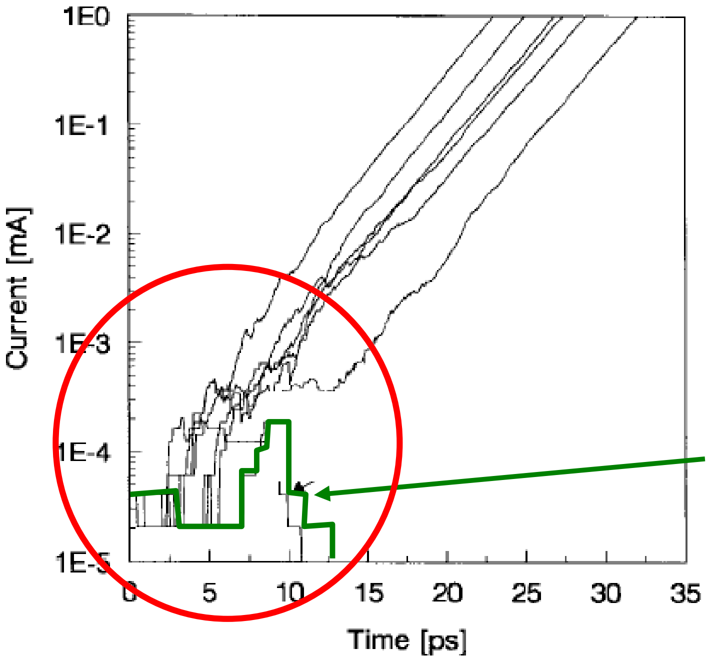
P_{01} – Triggering probability



1056 IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. ED-19, NO. 9, SEPTEMBER 1972

Triggering Phenomena in Avalanche Diodes

WILLIAM G. OLDHAM, MEMBER, IEEE, REID R. SAMUELSON, MEMBER, IEEE, AND
PAOLO ANTOGNETTI, MEMBER, IEEE



MC simulations of the current growth during an avalanche build-up process

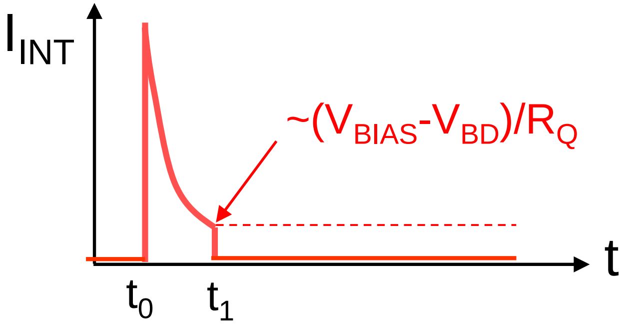
[Spinelli, IEEE TED, vol. 44, n. 11, 1997]

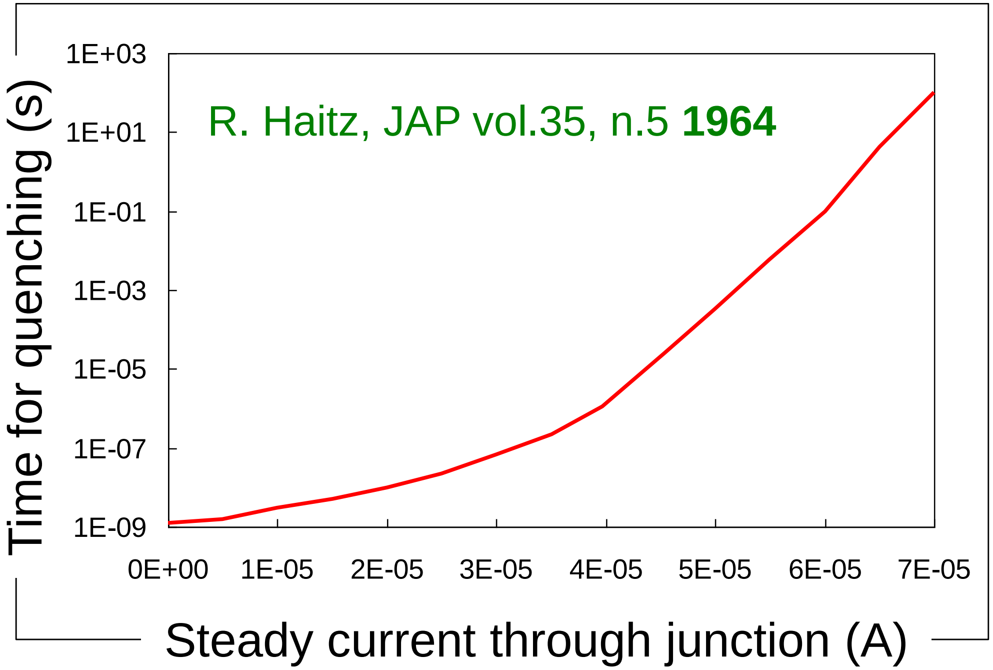
avalanche failed
=> no photon detection

→ Triggering probability depends on the ionization rates.
→ Important factor in the photo-detection efficiency.

P_{10} – Turn-off probability

probability to quench the avalanche by a fluctuation to zero of the number of carriers crossing the HF





➡ Quenching resistance must be high enough!!