国内外硅光电倍增器（SiPM）的现状及发展趋势

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2021年5月16日

主要内容

- 什么是硅光电倍增器（SiPM)
- 有代表性的SiPM结构
- 国内外SiPM的现状
- SiPM的发展趋势—数字SiPM
- 结语

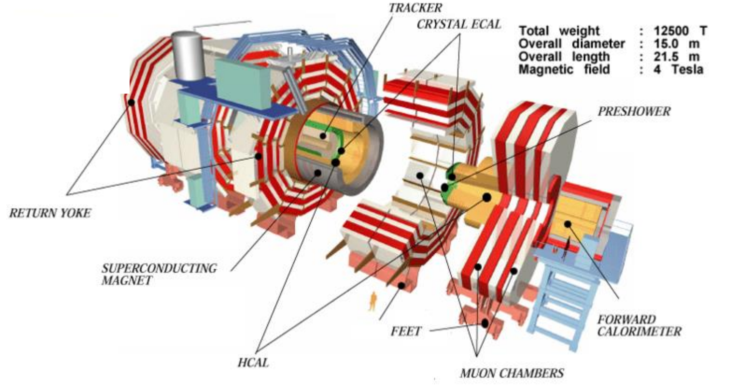
什么是硅光电倍增器（SiPM)

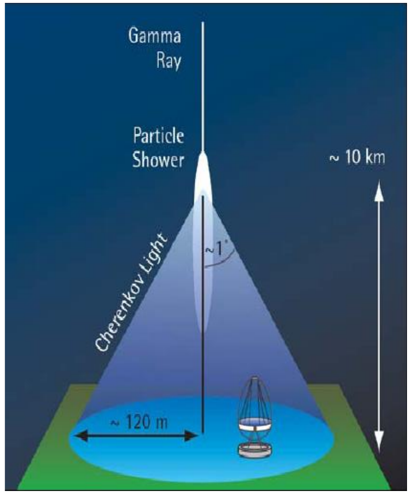
- 硅光电倍增器（SiPM--silicon photomultiplier)是一种由**工作于雪崩击穿电压之上和具有雪崩猝灭机制**的雪崩光电二极管阵列并联构成的，具有极佳的光子数分辨和单光子探测灵敏度的硅基弱光探测器。

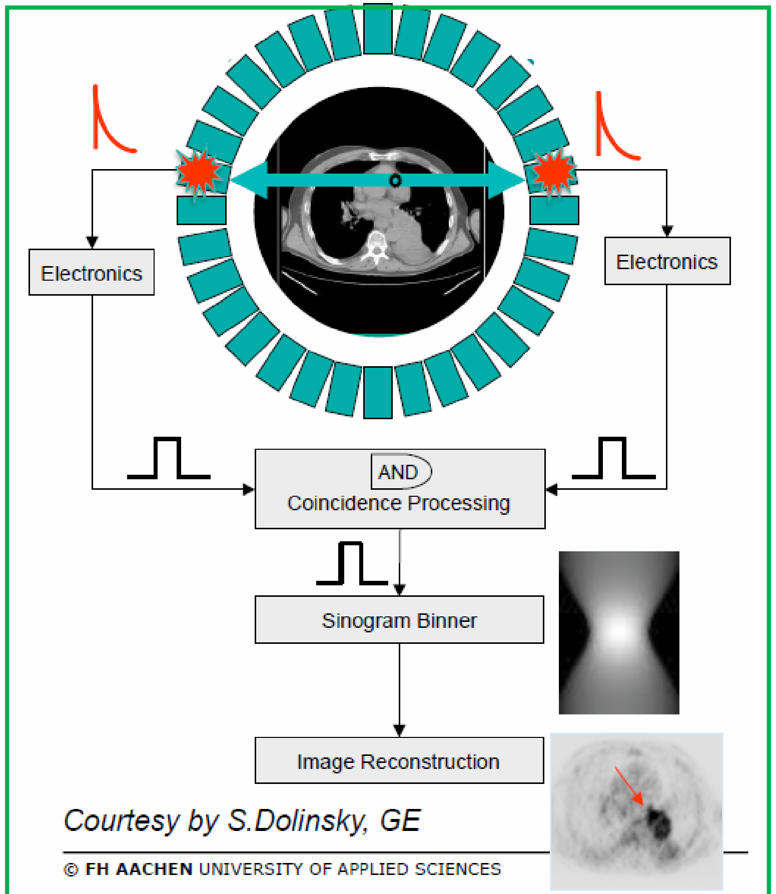
SiPM ≈ G-APD Array

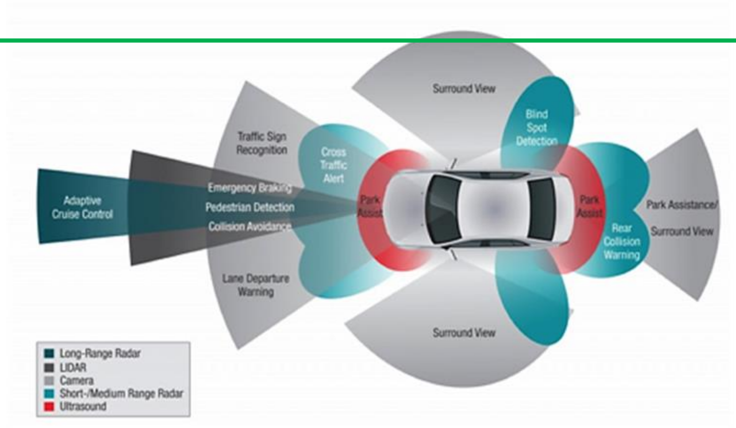
- 关键词：硅光电探测器、雪崩光电二极管（APD）阵列、雪崩淬灭、**"盖革"模式（Geiger mode）**，光子数分辨、单光子探测

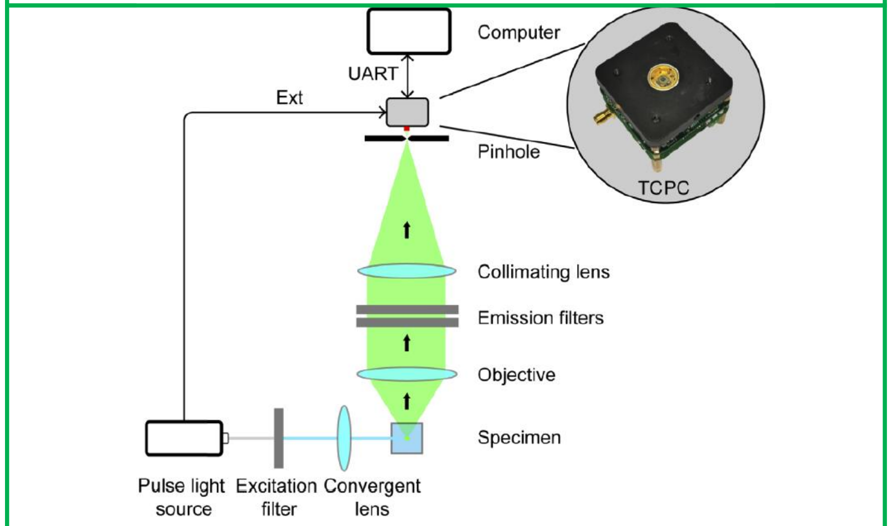
• SiPM是上个世纪九十年代兴起的一种半导体高灵敏（单光子）探测器，在粒子物理与核物理研究、核医学诊疗、激光雷达、荧光检测领域有有非常重要和广泛的应用



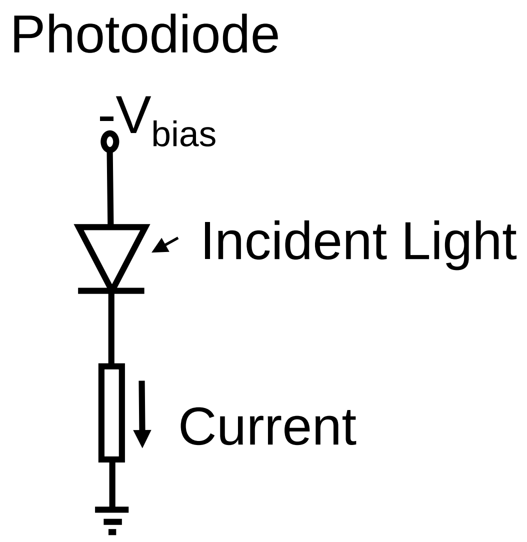


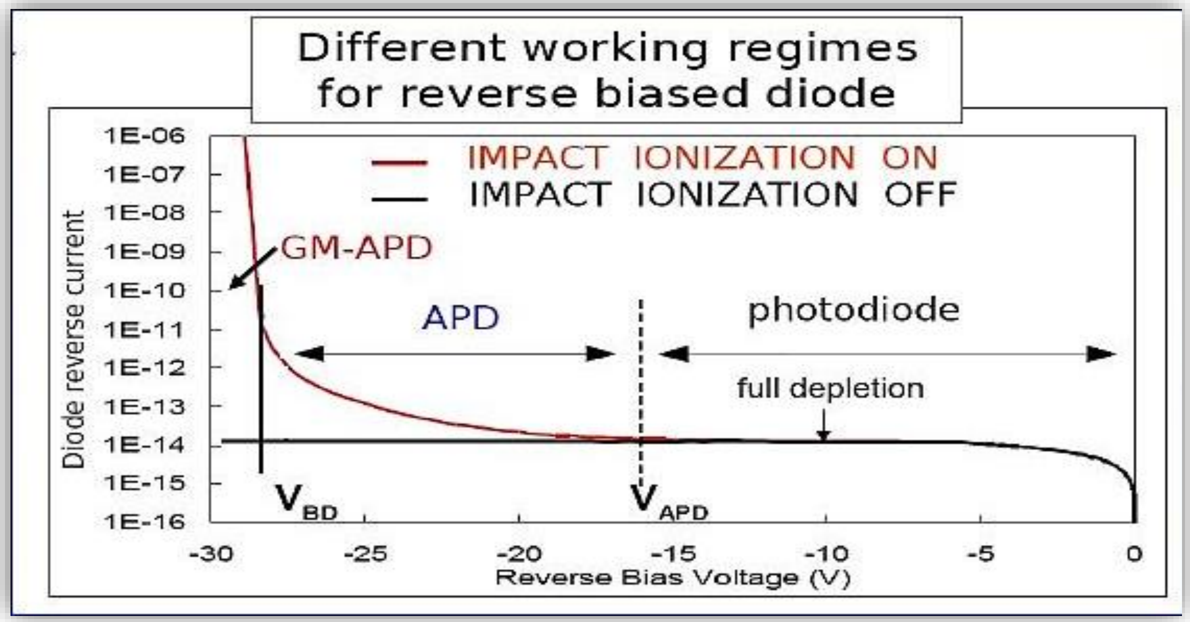






Avalanche Photodiode and Operating Modes





Photodiode

- $0 < V < V_{APD}$
- G=1
- Operate at high light level (hundreds of photons)

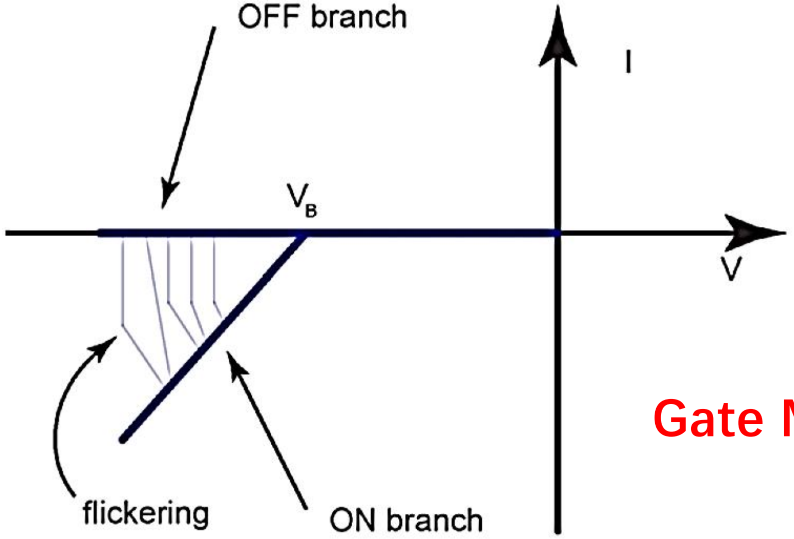
APD

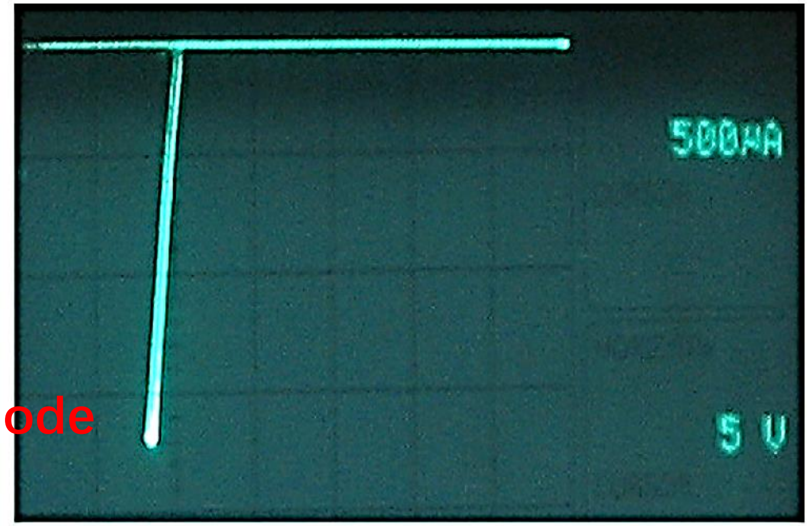
- $V_{APD} < V < V_{BD}$
- G = M (10 - 100)
- Linear mode
- >20 photons detection

G-APD

- $V > V_{BD}$
- $G = 10^5 \text{-} 10^7$
- Geiger mode
- Single photon detection

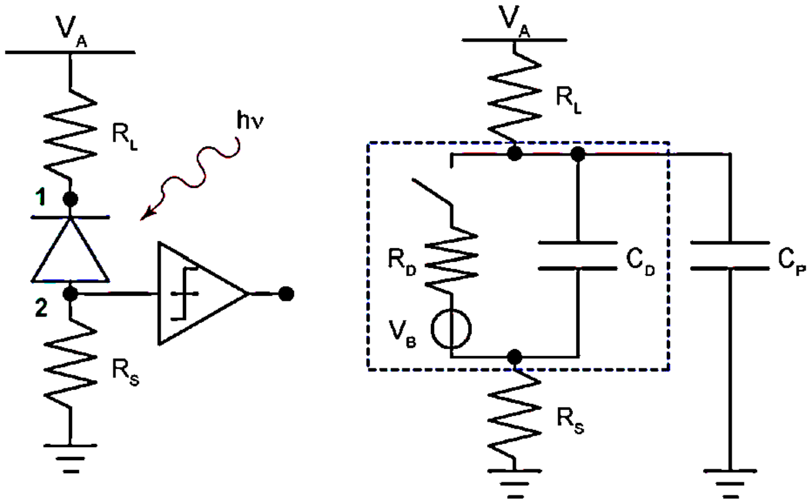
被动淬灭与主动淬灭



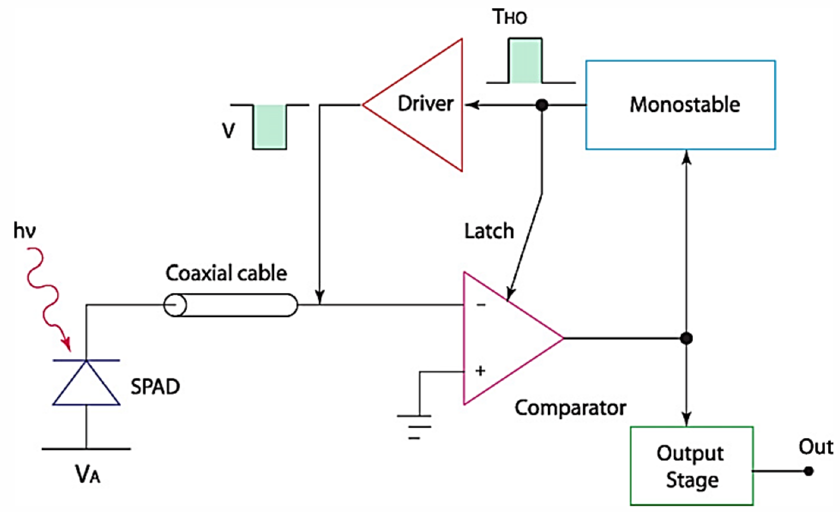


Gate Mode

I-V characteristic for a reverse biased SPAD with 10m diameter and ~25V breakdown voltage, in dark *(F. Zappa et al. / Sensors and Actuators A 140 (2007) 103–112)*



Passive Quenching



Active Quenching

Passive Quenching: tread-off τ_{quench} vs $\tau_{recovery}$

半导体的雪崩击穿与淬灭机理早在上个世纪60年代研究等离子体微区不稳效应时建立起来

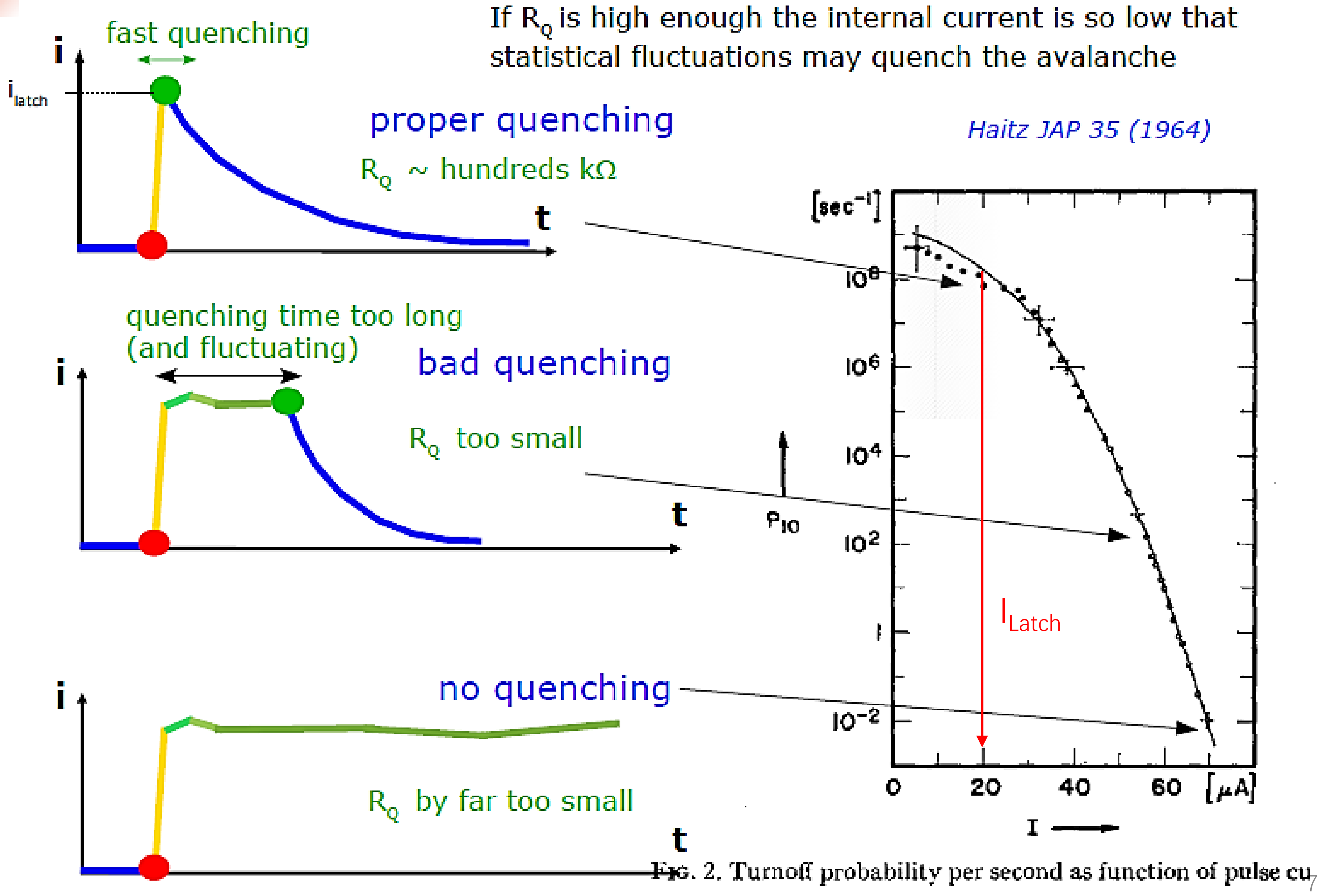
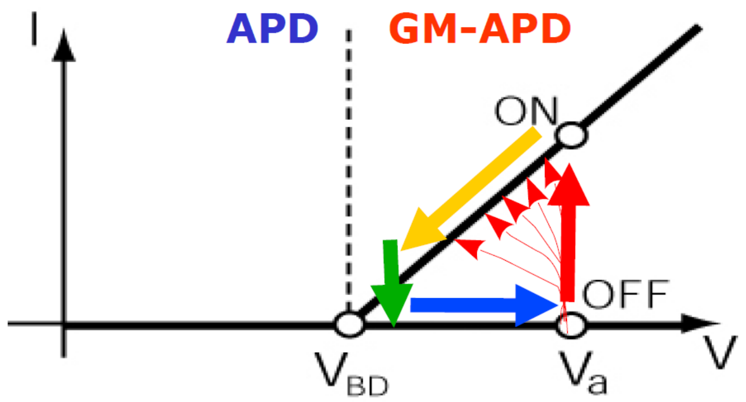
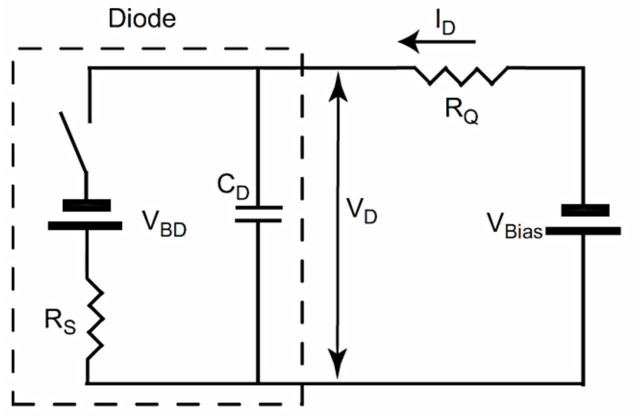


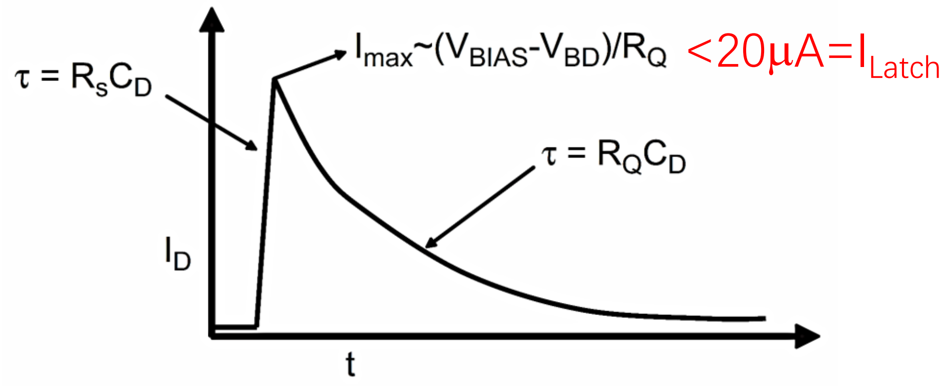
Fig. 2. Turnoff probability per second as function of pulse cu

G.Collazuol - RICH 2013

Passive Quenching G-APD

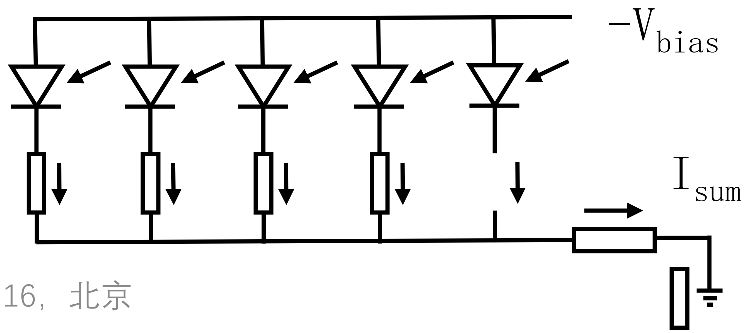


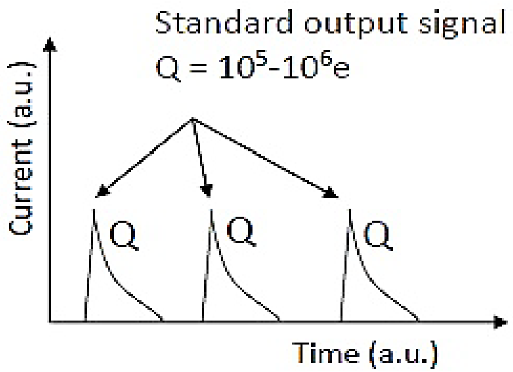




- ON condition: avalanche triggered, switch closed, C_D discharges to V_{BD} with a time constant R_sC_D (discharge time), at the same time the external current asymptotic grows to (Vbias-Vbd)/(Rq+Rd
- OFF condition: avalanche quenched, switch open, capacitance charged until no current flowing. From V_{BD} to V_{Bias} with time constant R_QC_D (recovery time)

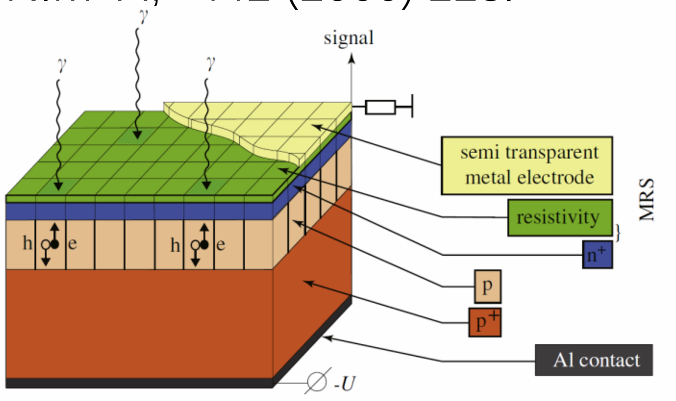
GAPD Array – SiPM
Sum Individual Pixels





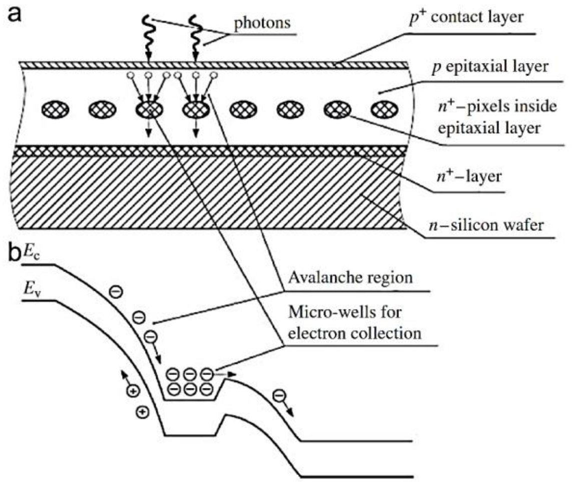
有代表性的SiPM结构（1）

Russian CPTA, V. Golovin, Patent No. RU 2142175, 1998.；Z. Sadygov, Patent No. RU 2102820, 1998；V. Saveliev, V. Golovin, NIM-A, 442 (2000) 223.



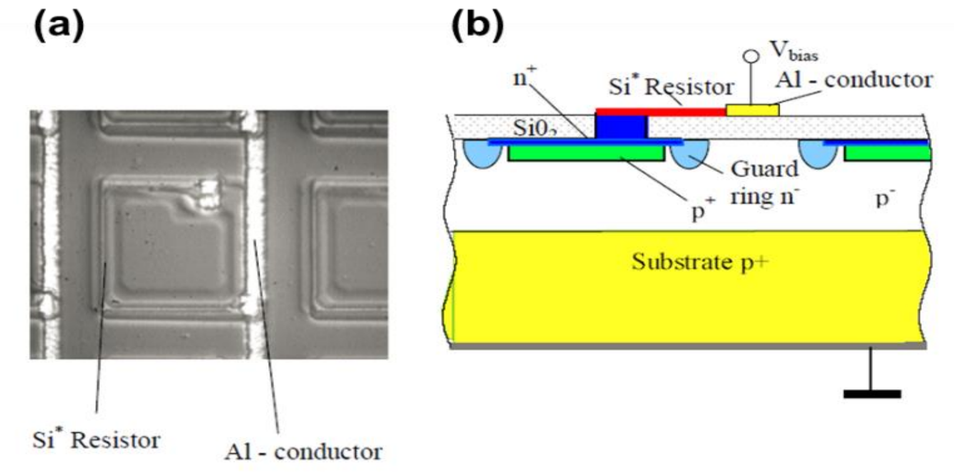
1989-1990 MRS结构，采用SiC或者SiXOY做淬灭电阻，半透明金属Ti做电极

Z. Sadygov – JINR/Micron (Dubna)-*NIMA 567 (2006)70*



2002 Avalanche Micro-channel/pixel
Photo Diodes (AMPD),

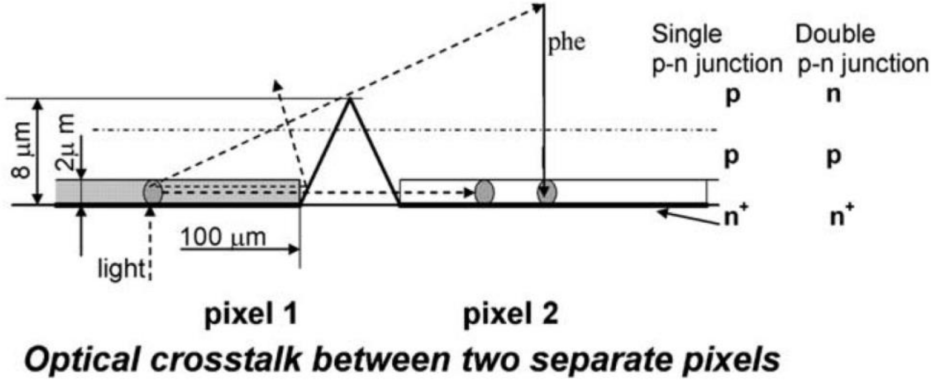
Russian MePhi/Pulsar, Dolgoshein, NIMA 563 (2006)



2002 表面多晶硅淬灭电阻条结构

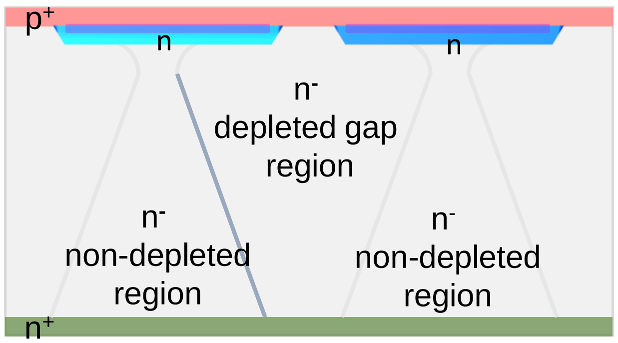
有代表性的SiPM结构（2）

Russian MePhi/Pulsar ,P.Buzhan, B.Dolgoshein, NIM-A610 (2009)131–134



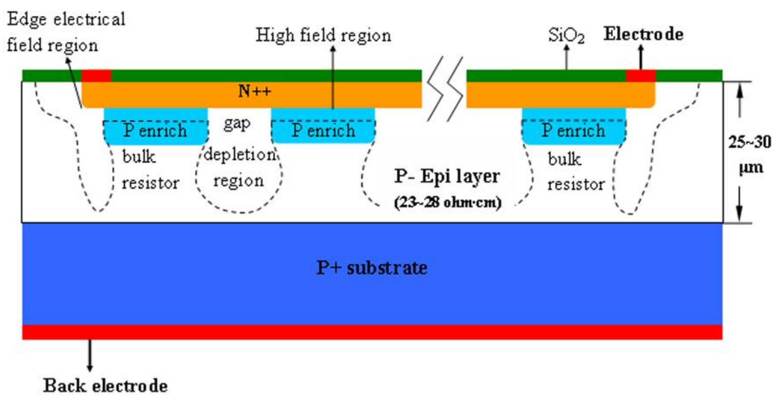
2009 微单元间采用沟槽隔离结构，

Germany MPI, Ninkovic et al NIM A610 (2009) 142



2009 体硅电阻淬灭SiPM

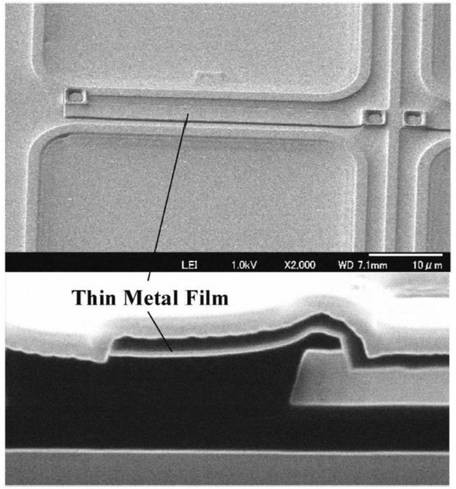
中国 NDL, NIM A621 (2010) 116-120



2010 外延电阻淬灭（EQR）SiPM，兼顾高探测效率和大动态范围

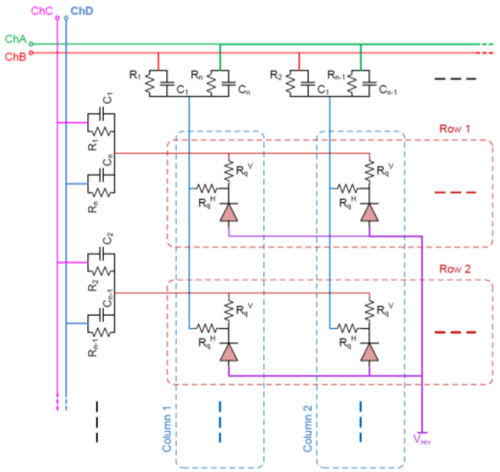
有代表性的SiPM结构（3）

日本滨松，T. Nagano, et al., 2011 IEEE Nuclear Science Symposium, NP5.S-130



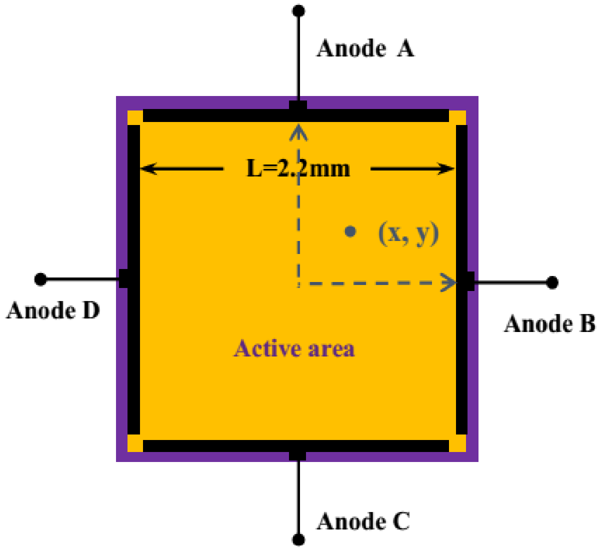
2011 用金属条做淬灭电阻，

Gola A, et al., 2013 IEEE Nuclear Science Symposium Conference Record



2013 位 置 灵 敏 SiPM （LG-SiPM）

中国 NDL, IEEE TRANS. ON ELECTRON DEVICES, 61(2014)3229-3232



2014 位置灵敏SiPM，结构简单，位置和时间分辨率高、读出通道少

国内外SiPM的现状

研发SiPM的主要机构 [Fabio Acerbi, “SiPM overview: status and trends”， 2018 International Workshop on New Photon-Detectors PD18]

Hamamatsu VS NDL

	Hamamatsu MPPC			NDL SiPM		
Active Area	S14160-3010	S14160-3015	S14160-3050	EQR06 3030D	EQR10 3030D	EQR15 3030D
	3.0×3.0 mm^2	3.0×3.0 mm^2	3.0×3.0 mm^2	3.0×3.0 mm^2	3.0×3.0 mm^2	3.0×3.0 mm^2
Effective Pitch	10	15	50	6 μm	10 μm	15 μm
Microcell NO.	89984	39984	3531	244720	90000	40000
Breakdown Voltage	38±3 V	38±3 V	38±3 V	24.5±0.5V	28.5±0.5V	28±0.2V
Peak PDE	18%@460nm	32%@460nm	50%@450nm	30%@420nm	36%@420nm	45%@420nm
DCR (kHz)	700-2100	700-2100	0.6-1.8 μA	2500	3600	2400
Gain	1.8×10^5	3.6×10^5	2.5×10^6	8×10^4	1.7×10^5	4×10^5
Terminal C(pF)	530	530	500	45.8	31	48
Temp. Coef. For V_b	34mv/°C	34mv/°C	34mv/°C	20mv/°C	19mv/°C	28 mV/℃

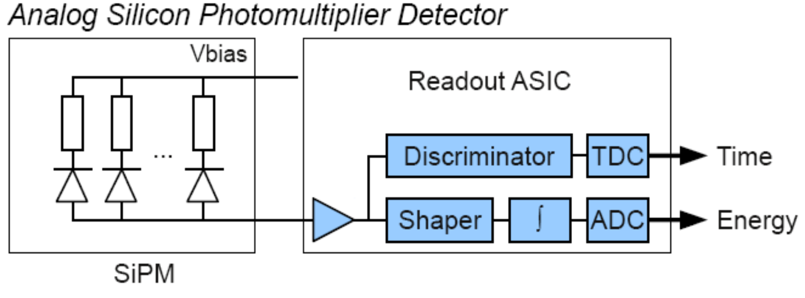
SensL VS NDL

	SensL SiPM			NDL SiPM		
Active Area	C10010	J30020	J30035	EQR06 3030D	EQR10 3030D	EQR15 3030D
	1.0×1.0 mm²	3.0×3.0 mm²	3.0×3.0 mm²	3.0×3.0 mm²	3.0×3.0 mm²	3.0×3.0 mm²
Effective Pitch	10 μm	20 μm	35 μm	6 μm	10 μm	15 μm
Microcell NO.	2880	14410	5676	244720	90000	40000
Breakdown Voltage	24.2-24.7 V	24.2-24.7 V	24.2-24.7 V	24.5±0.5V	28.5±0.5V	28±0.2V
Peak PDE	14%@420nm	30%@+2.5 V 38%@+5.0 V	38%@+2.5 V 50%@+6.0 V	30%@420nm	36%@420nm	45%@420nm
DCR (kHz/mm²)	30-96	50@+2.5 V 125@+5.0 V	50@+2.5 V 150@+6.0 V	278@+8V	400@+12V	267@+8V
Gain	2×10^5	1.0×10^6@+2.5 V 1.9×10^6@+5.0 V	2.9×10^6@+2.5 V 6.3×10^6@+6.0 V	8×10^4@+8V	1.7×10^5@+12V	4×10^5@+8V
Terminal C(pF)	50	1040	1070	45.8	31	48
Temp. Coef. For V_b	21.5 mv/°C	21.5 mv/°C	21.5 mv/°C	20mv/°C	19mv/°C	28 mV/℃

SiPM的发展趋势—数字SiPM

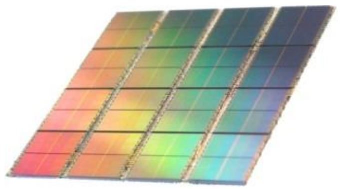
Philips, dSiPM, IEEE Nuclear Science Symposium/Medical Imaging Conference, Orlando, FL, Oct.28, **2009**

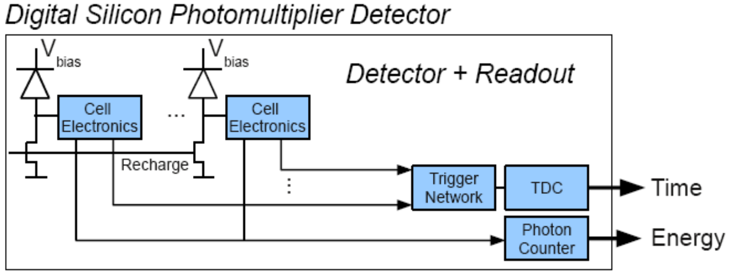
Analog SiPM



- discrete, limited integration
- analog signals to be digitized
- dedicated ASIC needed
- not scalable

Digital SiPM

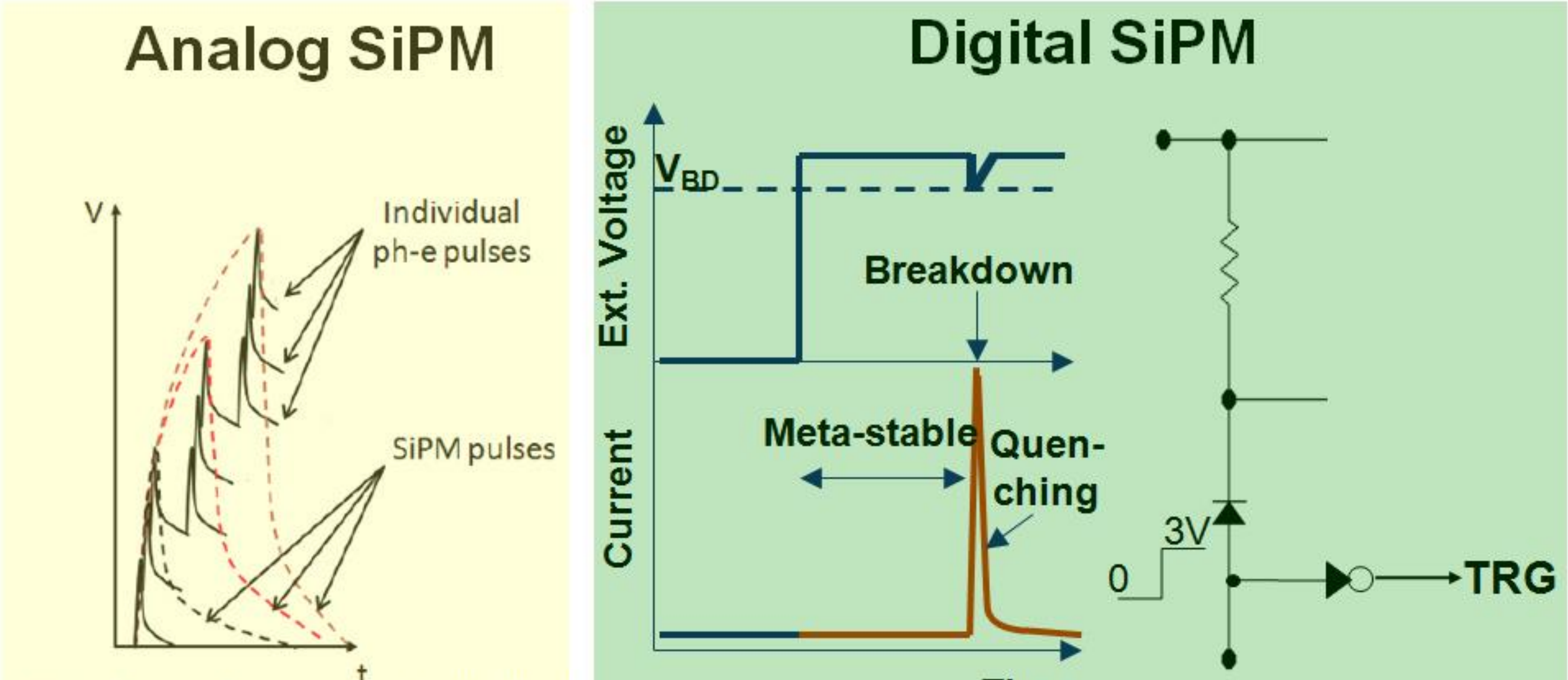




- fully integrated
- fully digital signals
- no ASIC needed
- fully scalable

韩德俊，中国高能物理非加速器战略研讨会，2021-5-16，北京

The dSiPM Takes Advantage of the Binary Nature



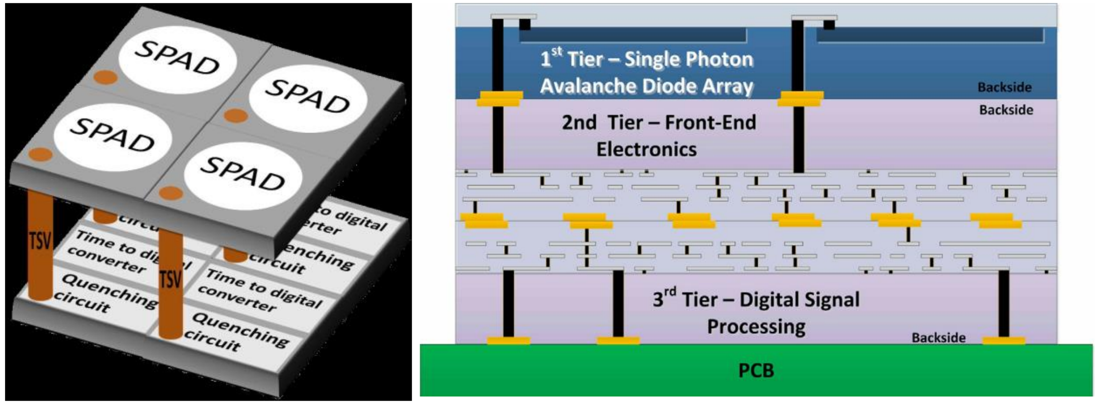
- Signal: analog sum of individual pulse amplitudes
- amplitudes depend on gain
- gains depend on temperature
- temperature drifts: 2-8%/K

- Signal: digital sum of trigger bins & digital time stamp from TDC
- amplitudes are not relevant
- no gain dependency, reduced temp. drift: 0.33%/K

“Therefore, while the APD is a linear amplifier for the input optical signal with limited gain, the SPAD is a trigger device so the gain concept is meaningless.” *(source: Wikipedia)*

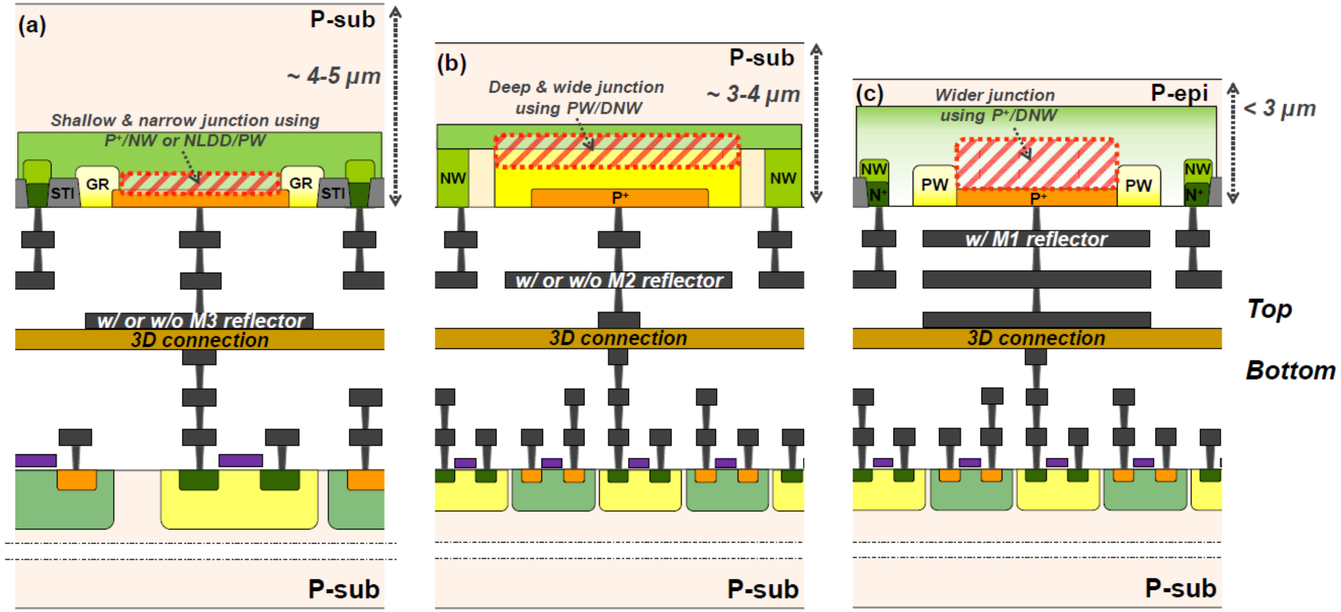
其它dSiPM概念

B.L. Berube, et al., , IEEE Transactions on Nuclear Science， 62 (2015)710.

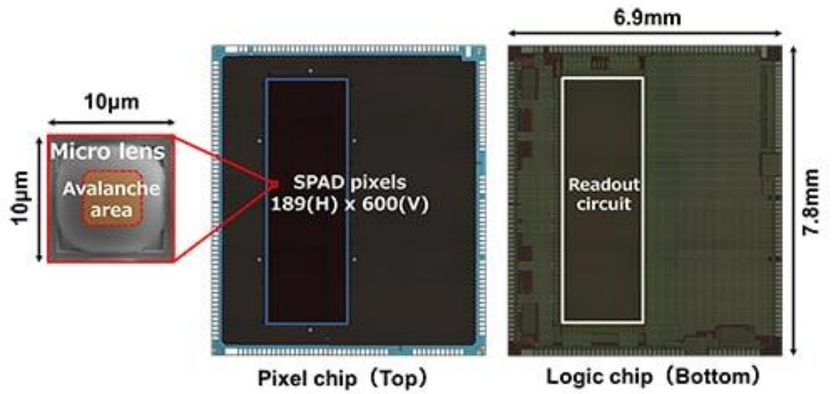


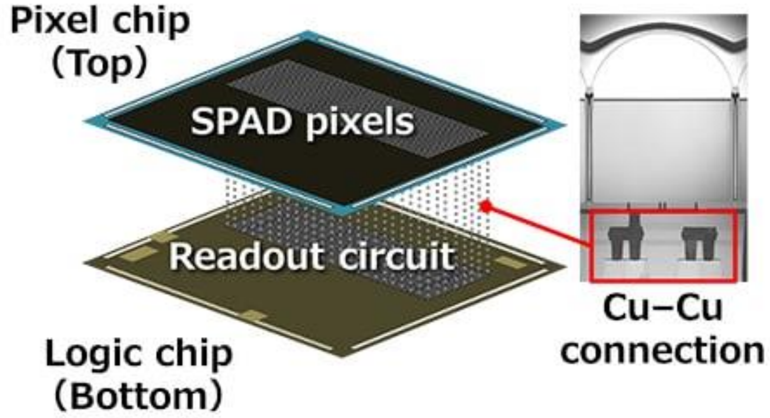
正面入射3D叠层数字SiPM的结构

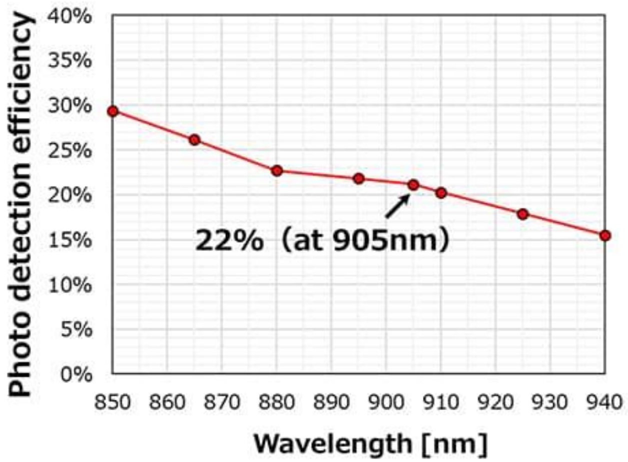
M.-J. Lee, et al., IEDM Tech. Dig., 2017, 16.6.1.



背面入射3D叠层SPAD阵列结构示意图







Total number of SPAD pixels	189 x 600 pixels (H x V), approx. 110,000 pixels
Image size	Diagonal 6.25 mm (1/2.9-type)
Recommended light source wavelength	905 nm
SPAD unit cell size	10 μm x 10 μm
Element size (ToF pixel unit)	3 x 3 pixels (H x V)
Power consumption	1,192 mW
Photon detection efficiency	22%
Response speed	6 ns
Saturation signal amount (max. count rate)	60,000,000 cps
Max. detection distance	300 m
Distance precision at 300 m	3 x 3 pixels (H x V) additive mode: 30 cm 6 x 6 pixels (H x V) additive mode: 15 cm

结语

- 模拟SiPM的基本器件结构在2010年前后已基本建立起来
- 数字SiPM是大势所趋
- SiPM的应用方兴未艾
- NDL SiPM在兼顾大动态范围与高探测效率、快时间响应和高计数率、抗辐射等方面有优势
- SiPM不大可能像PMT那样出现少数寡头企业垄断局面