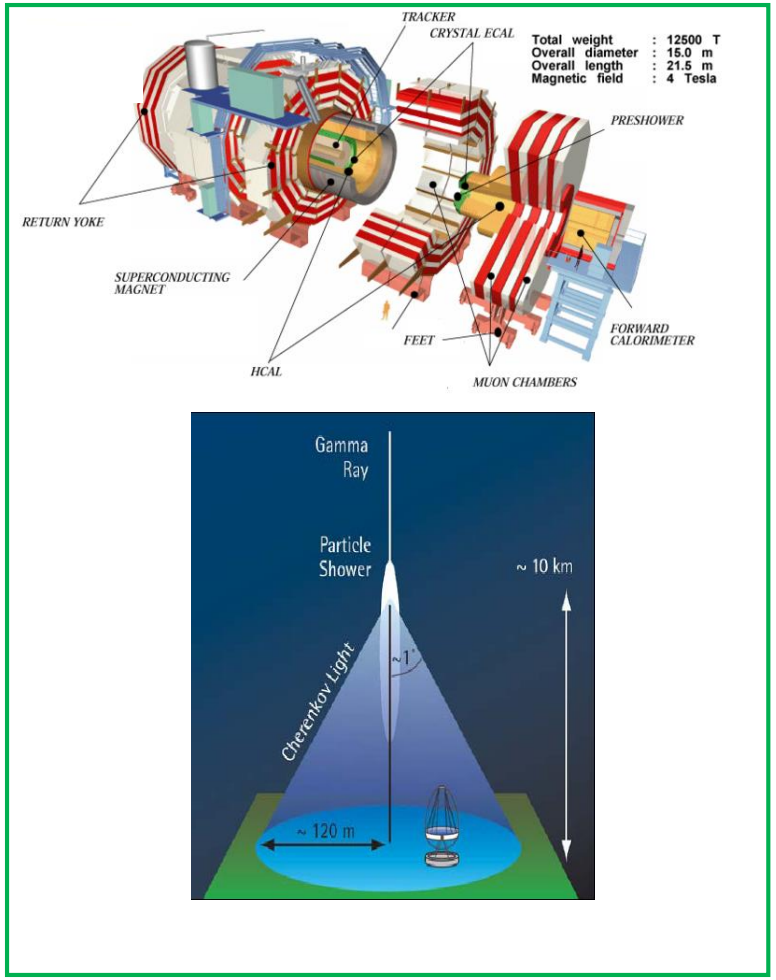
什么是硅光电倍增器（SiPM)

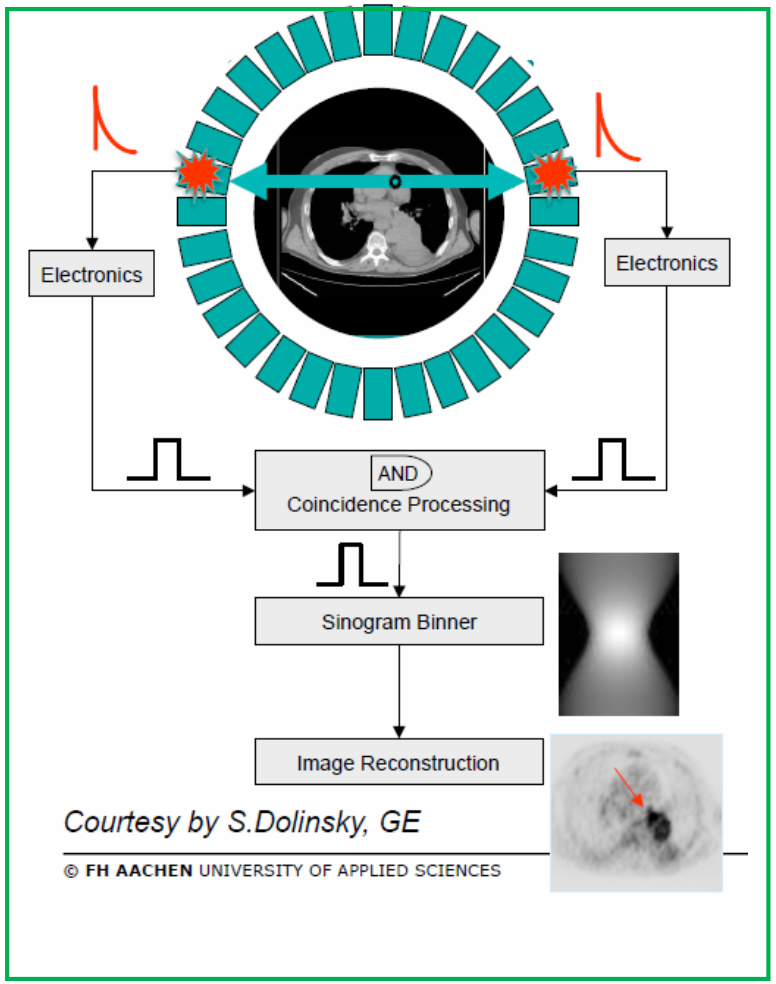
- 硅光电倍增器（SiPM--silicon photomultiplier)是一种由**工作于雪崩击穿电压之上和具有雪崩淬灭机制**的单光子雪崩二极管（SPAD）阵列并联构成的，具有极佳的光子数分辨和单光子探测灵敏度的硅基弱光探测器。

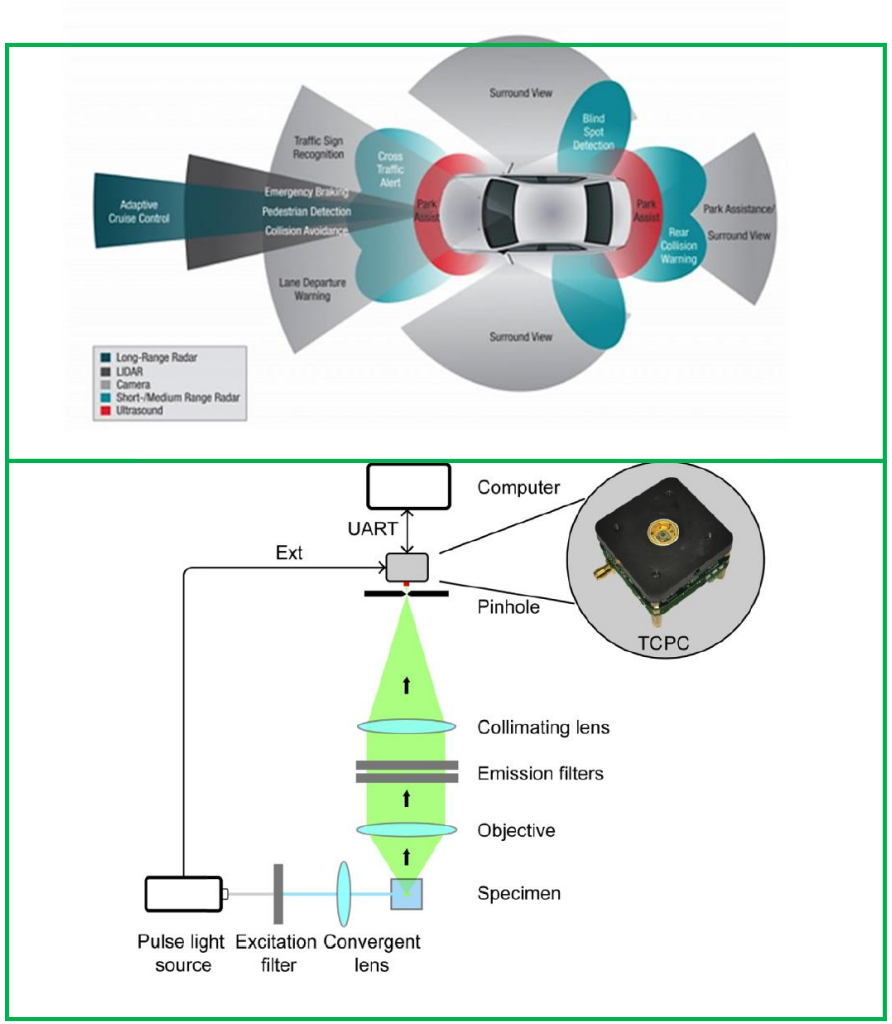
SiPM ≈ SPAD Array

- 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兴起于上个世纪九十年代，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

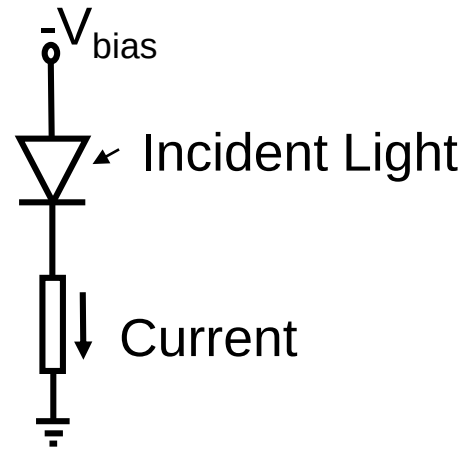


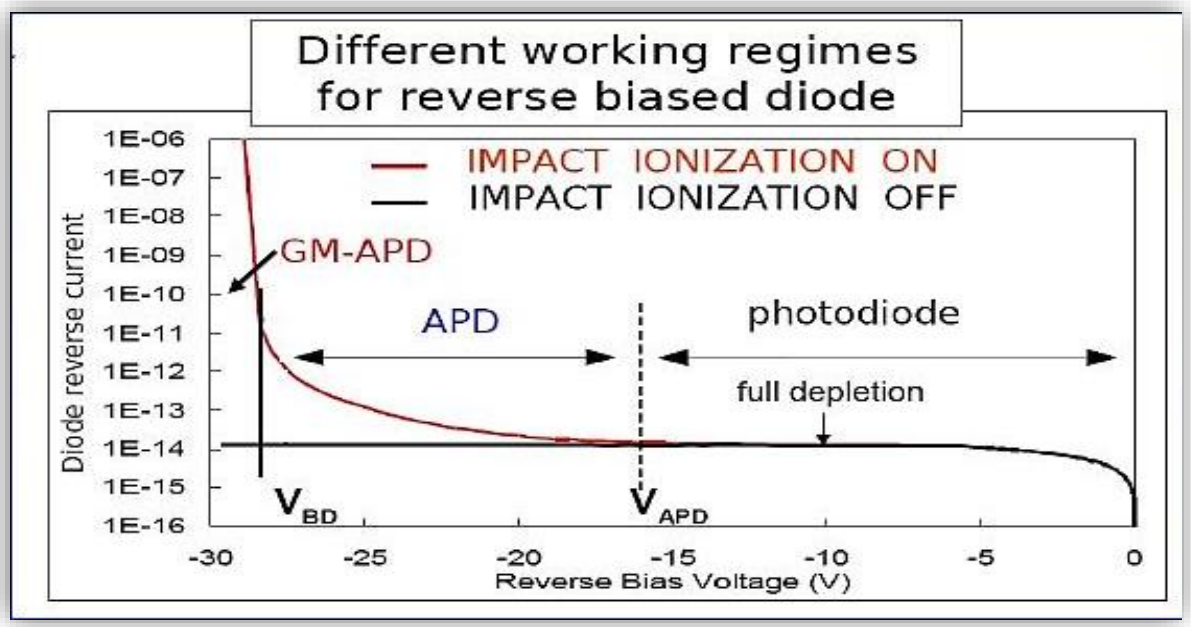




Avalanche Photodiode and Operating Modes

Photodiode





Photodiode

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

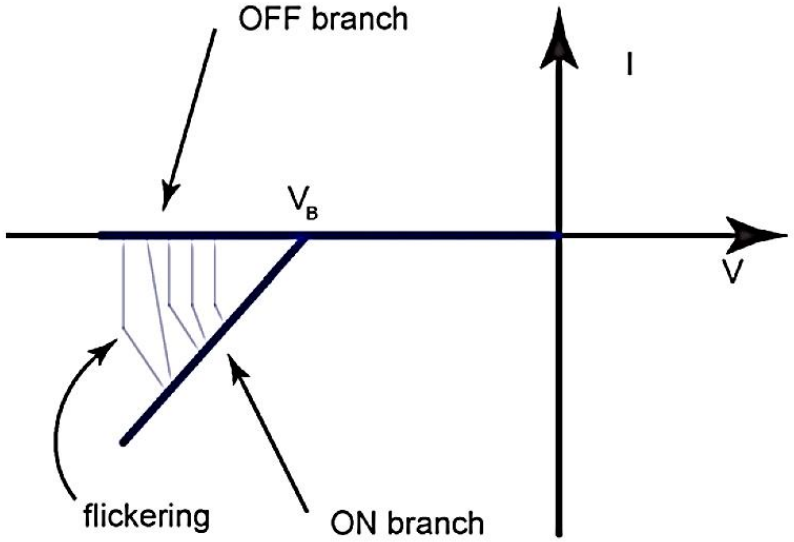
APD

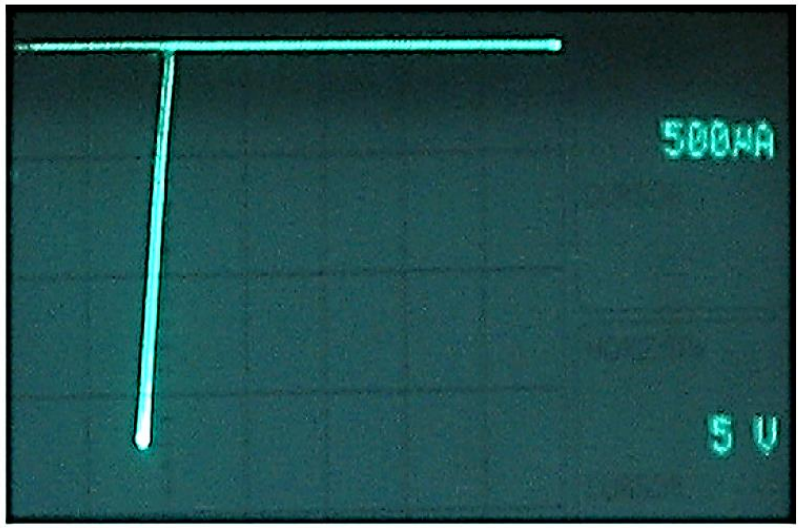
- $V_{APD} < V < V_{BD}$
- G = M (10 - 100)
- Linear mode
- >20 photons detection

G-APD

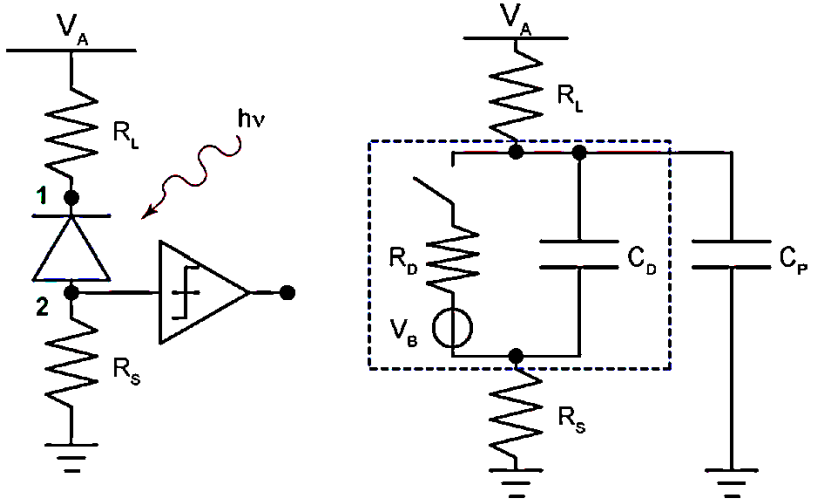
- $V > V_{BD}$
- $G = 10^5$-10^7
- Geiger mode
- Single photon detection

被动淬灭与主动淬灭

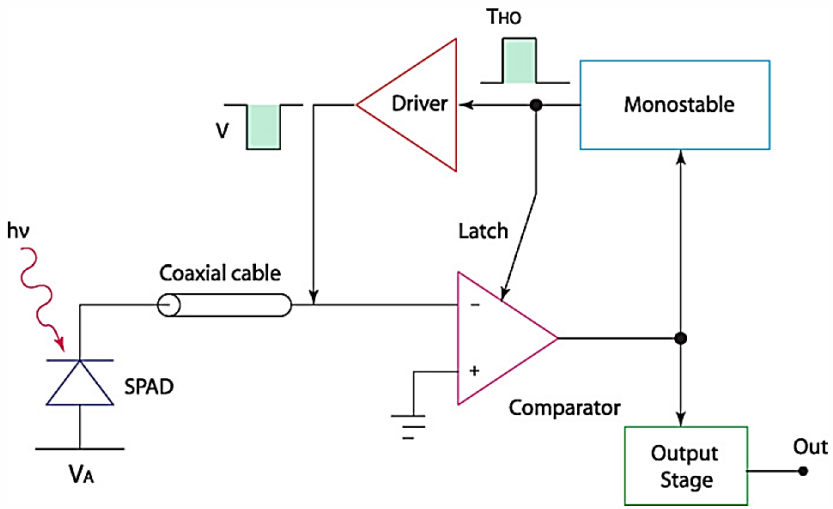




I-V characteristic for a reverse biased SPAD with 10μm diameter and ~25V breakdown voltage, in dark (*F. Zappa et al. / Sensors and Actuators A 140 (2007) 103–112*)



Passive Quenching



Active Quenching

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

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

If R_Q is high enough the internal current is so low that statistical fluctuations may quench the avalanche

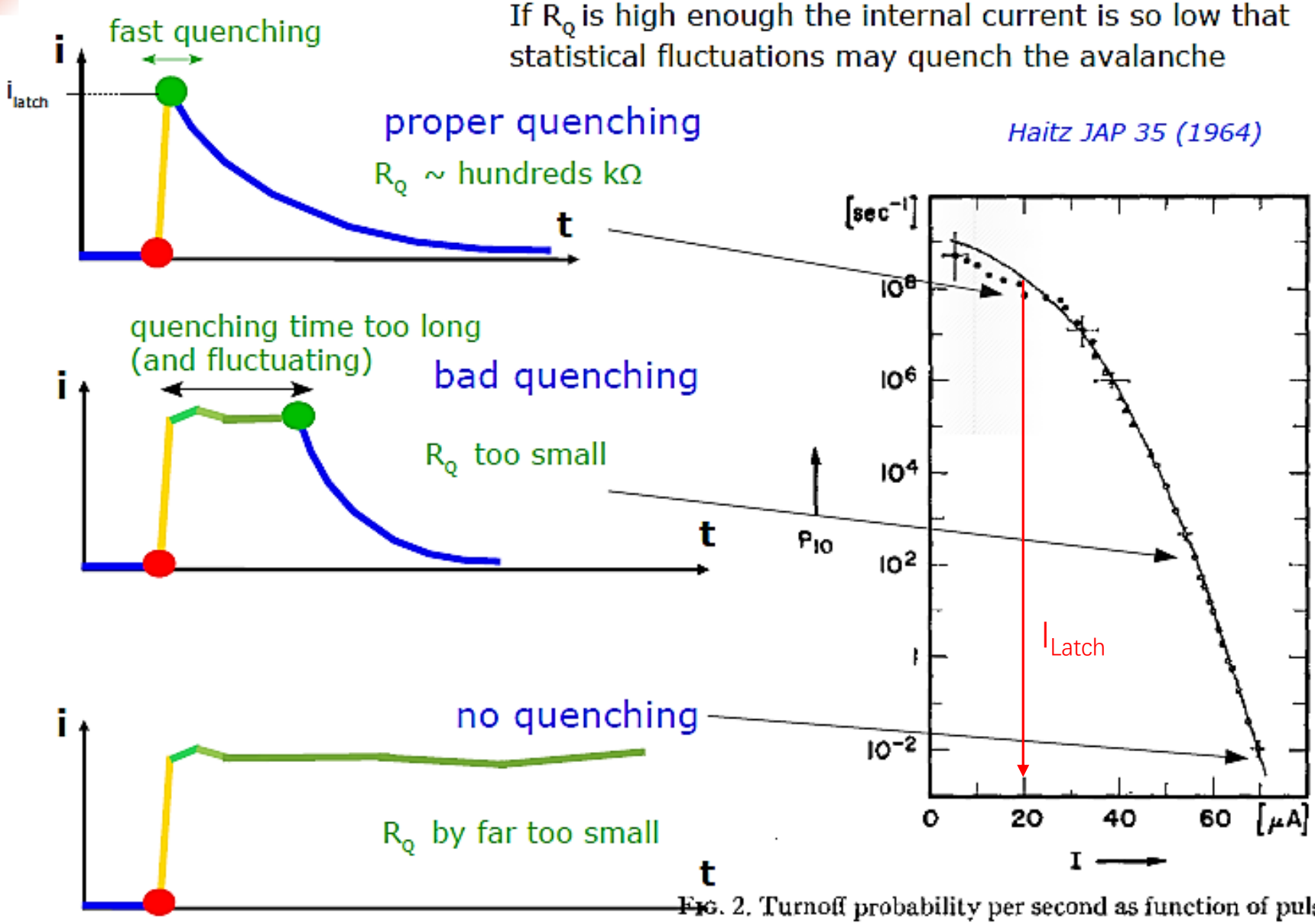
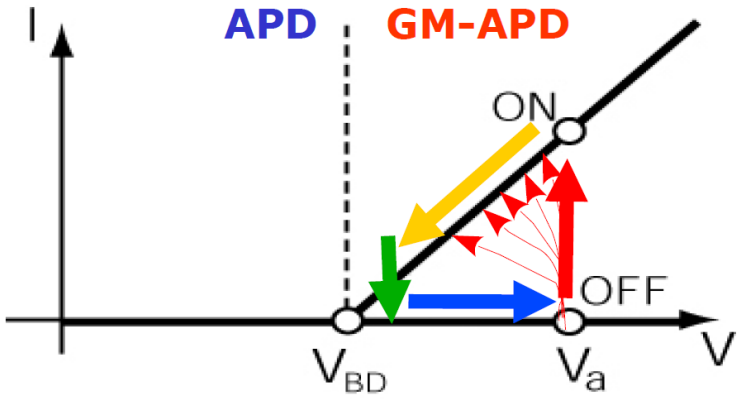
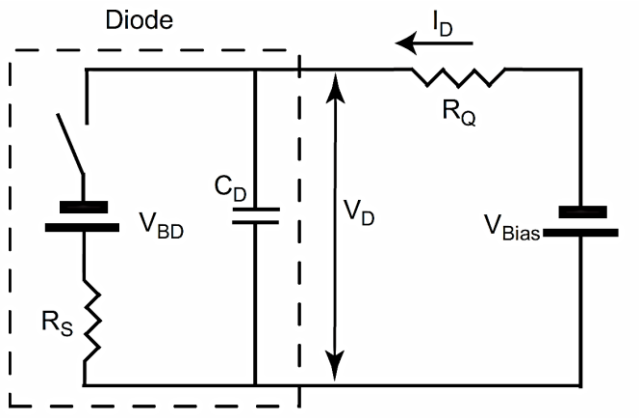


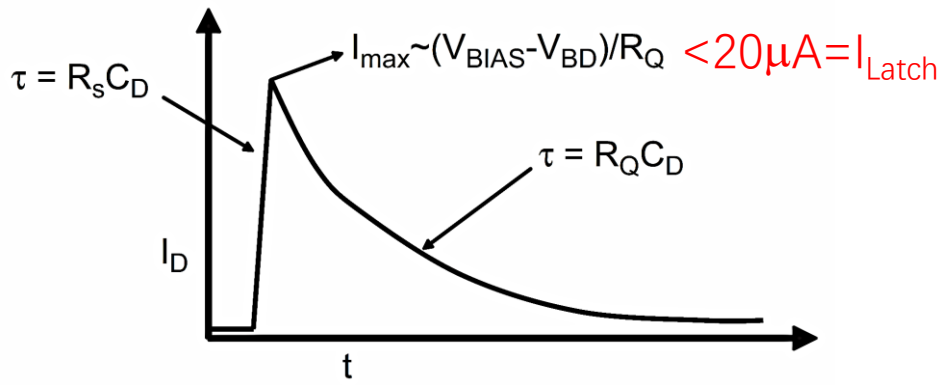
Fig. 2. Turnoff probability per second as function of pulse cu

G.Collazuol - RICH 2013

Passive Quenching G-APD

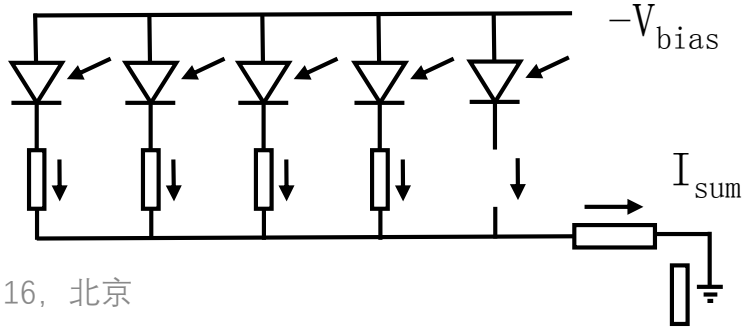


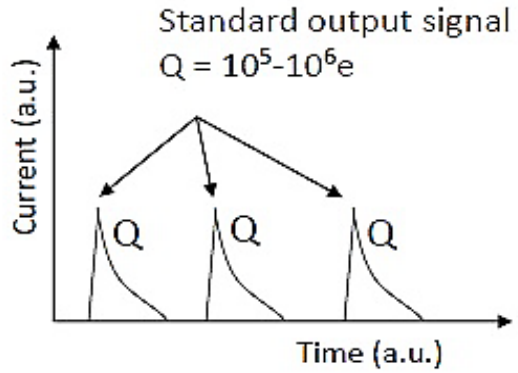




- ON condition: avalanche triggered, switch closed, C_D discharges to V_{BD} with a time constant R_sC_D (discharge time), at the same time the external current asymptotic grows to (Vbias-Vbd)/(Rq+Rd)
- OFF condition: avalanche quenched, switch open, capacitance charged until no current flowing. From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

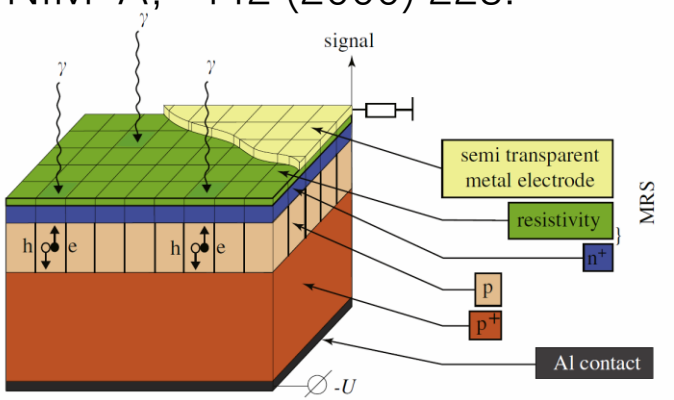
GAPD Array – SiPM
Sum Individual Pixels





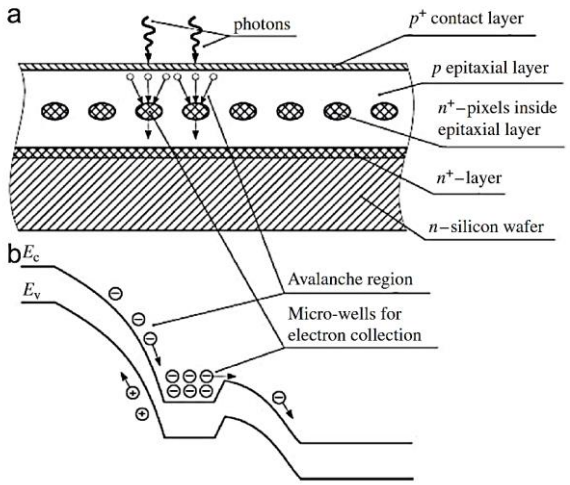
有代表性的SiPM结构（1）

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.



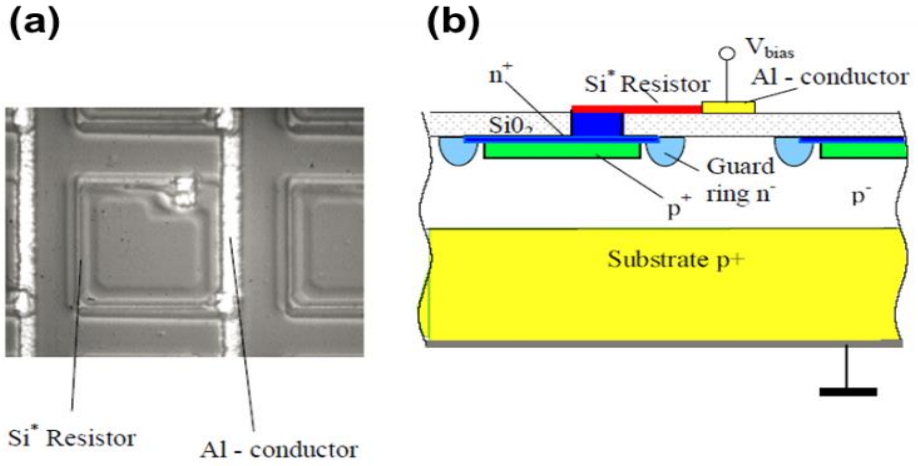
1989-1990 MRS结构，采用SiC或者SiXOY做淬灭电阻，半透明金属Ti做电极

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



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

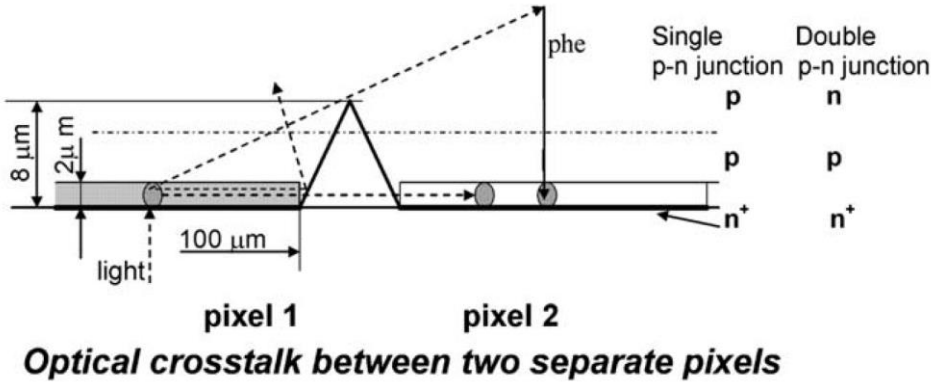
Russian MePhi/Pulsar, Dolgoshein, NIMA 563 (2006)



2002 表面多晶硅淬灭电阻条结构

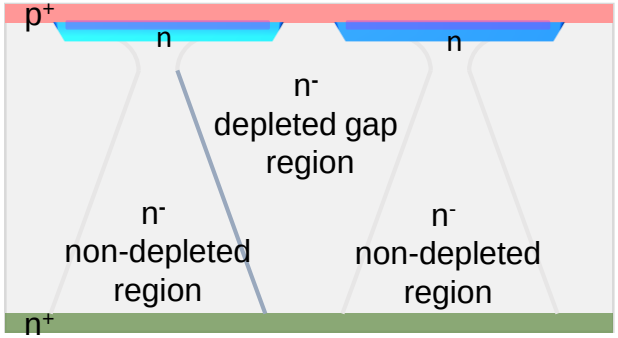
有代表性的SiPM结构（2）

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

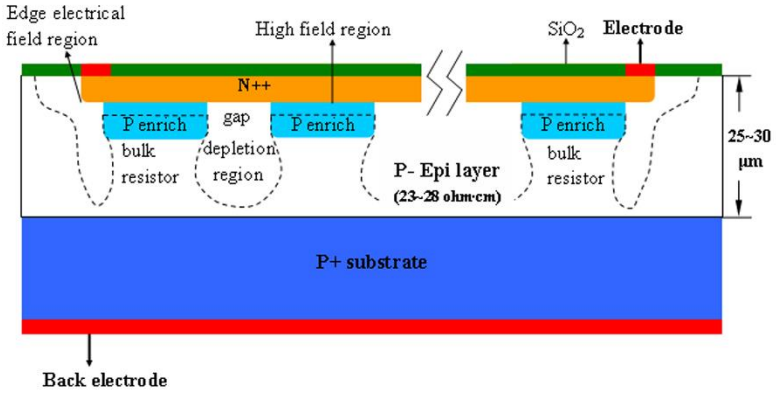


Optical crosstalk between two separate pixels

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



中国 NDL, NIM A621 (2010) 116-120



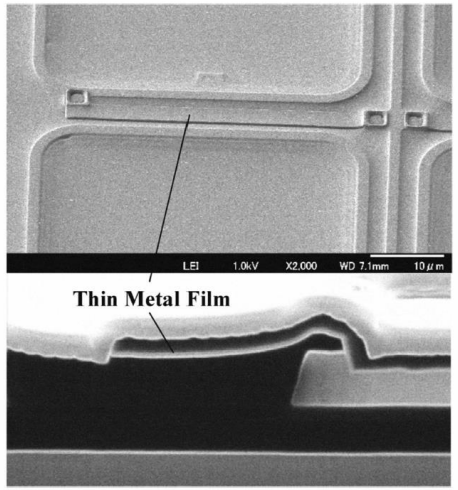
2009 微单元间采用沟槽隔离结构，

2009 体硅电阻淬灭SiPM

2010 外延电阻淬灭（EQR）SiPM，兼顾高探测效率和大动态范围

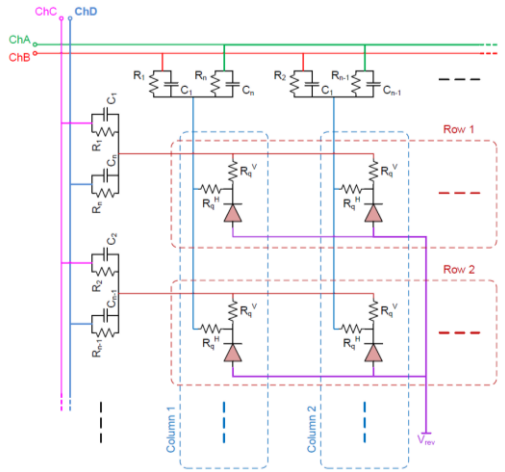
有代表性的SiPM结构（3）

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



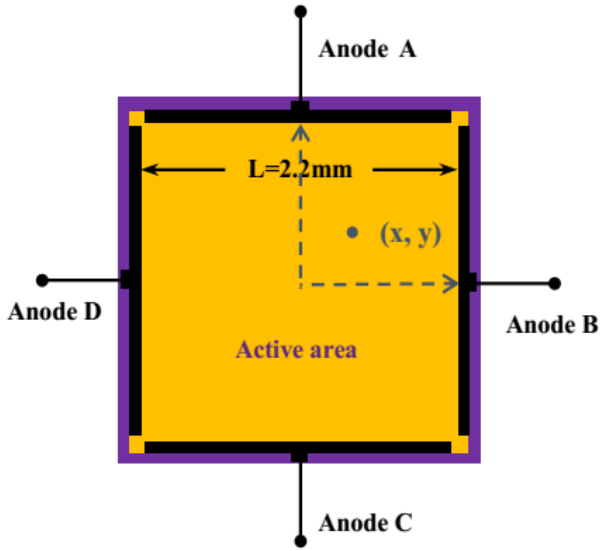
2011 用金属条做淬灭电阻，

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

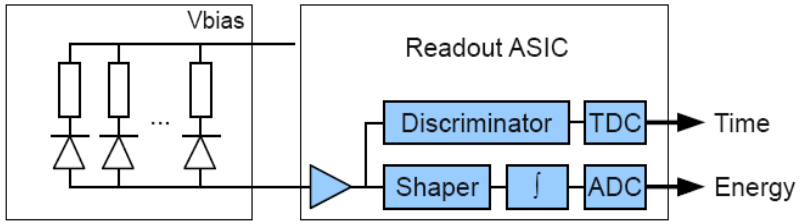


2014 位置灵敏SiPM，结构简单，位置和时间分辨率高、读出通道少

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

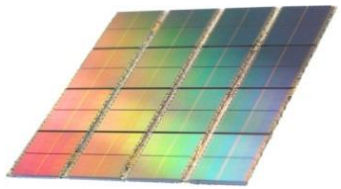
Analog SiPM

Analog Silicon Photomultiplier Detector

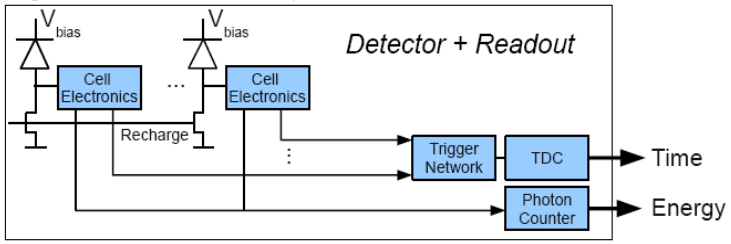


- discrete, limited integration
- analog signals to be digitized
- dedicated ASIC needed
- not scalable

Digital SiPM



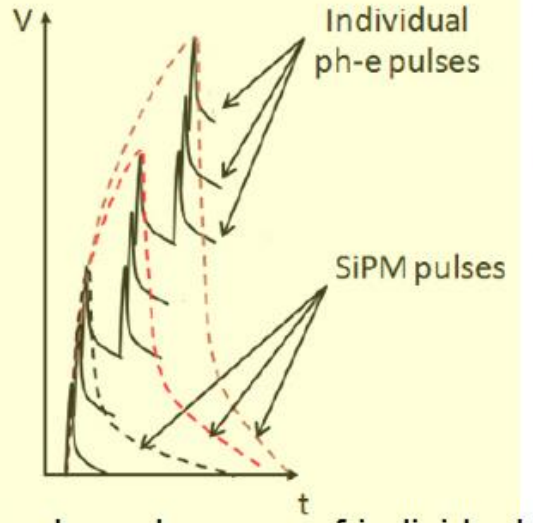
Digital Silicon Photomultiplier Detector



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

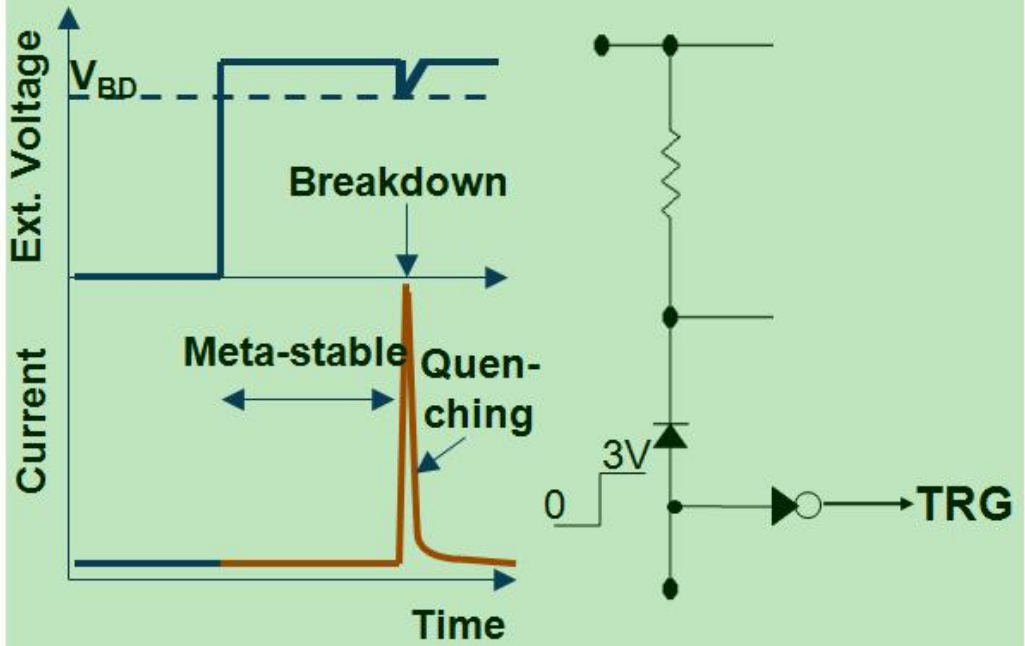
The dSiPM Takes Advantage of the Binary Nature

Analog SiPM



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

Digital SiPM



- 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)*

研发SiPM的主要机构

Fabio Acerbi, “SiPM overview: status and trends”, 2018 International Workshop on New Photon-Detectors PD18