第十届全国先进气体探测器研讨会

半导体辐射探测器前端读出电子学ASIC芯片研究进展

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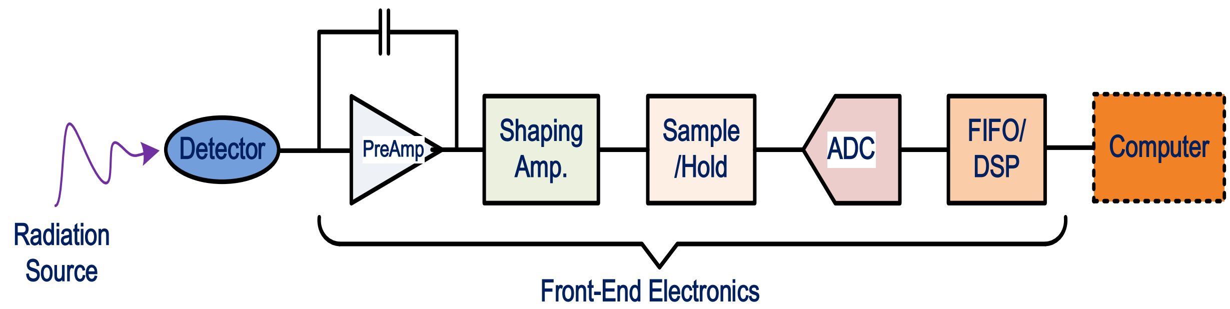
2021年10月22日

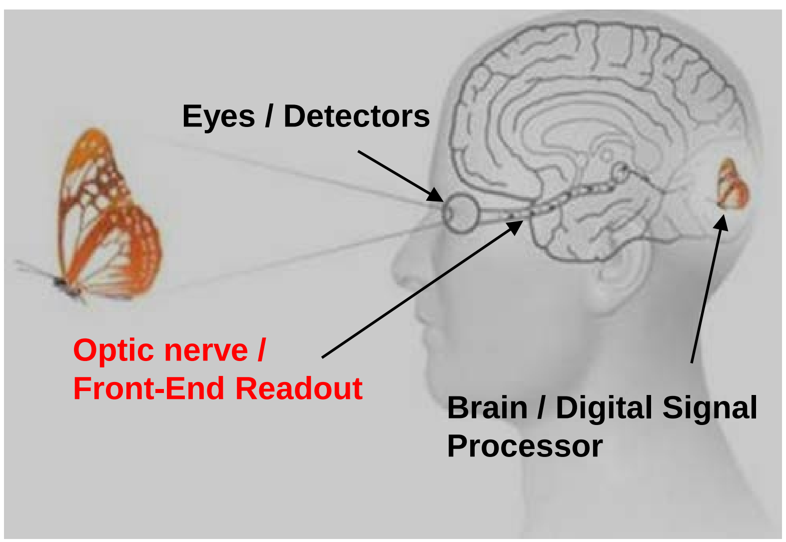
内容安排

探测器前端读出电子学ASIC概述

半导体辐射探测器读出电子学

类似的读出电子学结构

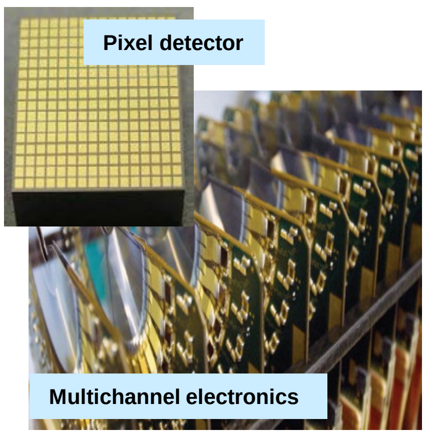


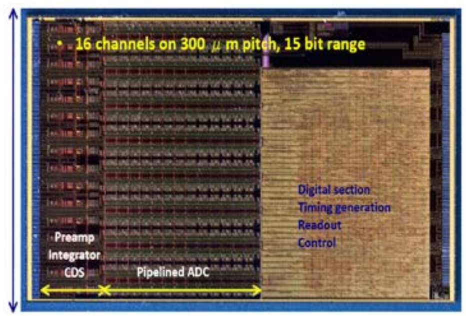


- 主要功能
  - 微弱电流信号读出
  - 多通路信号处理
  - 幅度测量
  - 时间测量
- 解决方案
  - ASIC + 嵌入式

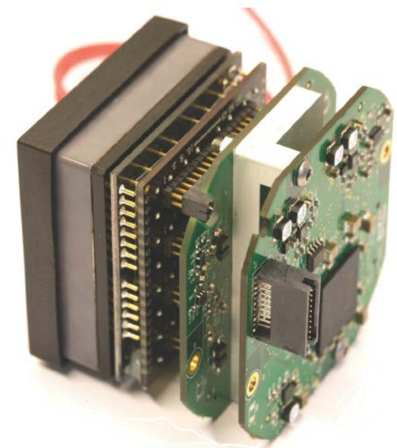
从分立电子学到集成ASIC

- **条状多通路读出ASIC**
  - 电荷灵敏前放、高阶成形主放、峰值采样保持、数据转换器、数据预处理
  - 特点：Big Analog， Small Digital (大A小D)



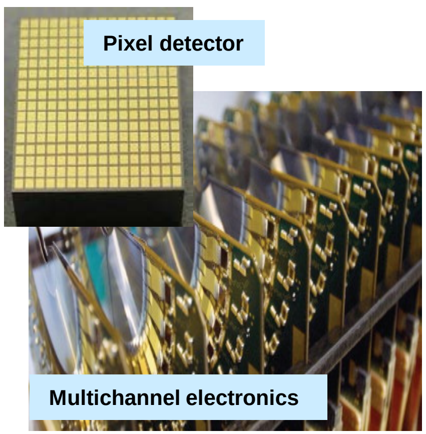


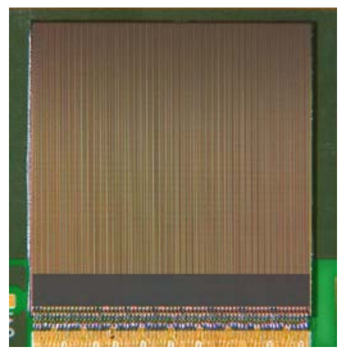
Strip （16/32/64/128）



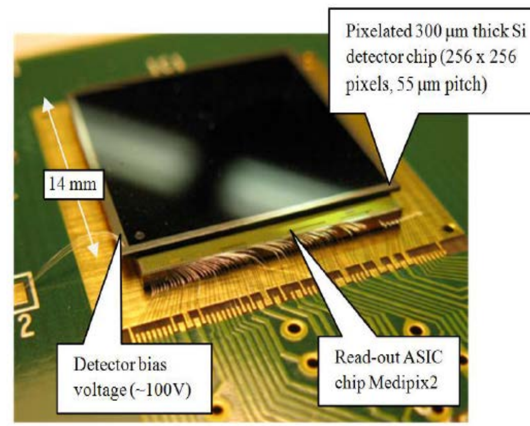
从分立电子学到集成ASIC

➢ **像素型二维读出ASIC**
- **电荷灵敏前放、过域时间甄别器、像素级ADC/计数器、并入串出、高速串行接口**
- **特点：Analog Islands in Digital Sea（数字海、模拟岛）**



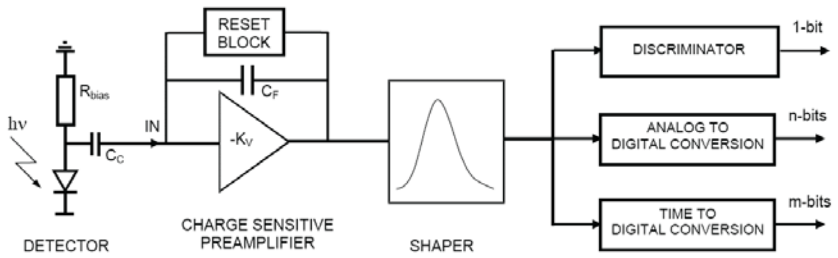


Pixel （256×256）

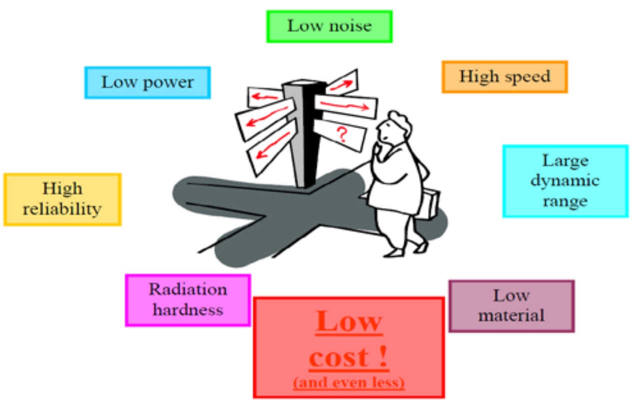


ASIC性能及特点

单路拓扑结构



性能设计

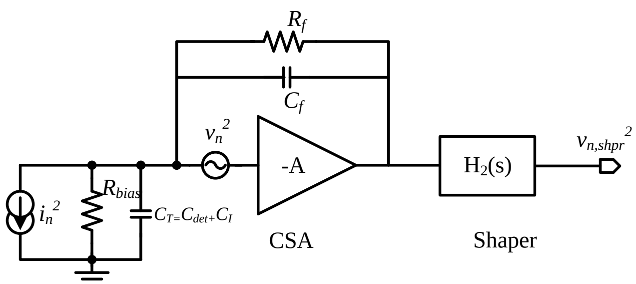


主要特点

- **混合信号ASIC**
  - ✓ 射频/模拟 + 数字 + 抗辐射 → 现代集成电路最尖端技术综合
- **多种性能需求**
  - ✓ 低噪声：~100 e-
  - ✓ 高速并行/串行处理→ 全局/卷帘快门、感兴趣区域、事件驱动
  - ✓ 大动态范围：~100dB
  - ✓ 极低功耗：~ μW/channel
  - ✓ 抗辐射：
    - TID > 10 Mrad(Si);
    - NIEL > 10^{11} Neq/cm^2
    - LET_{th} > 100 MeVcm^2/mg

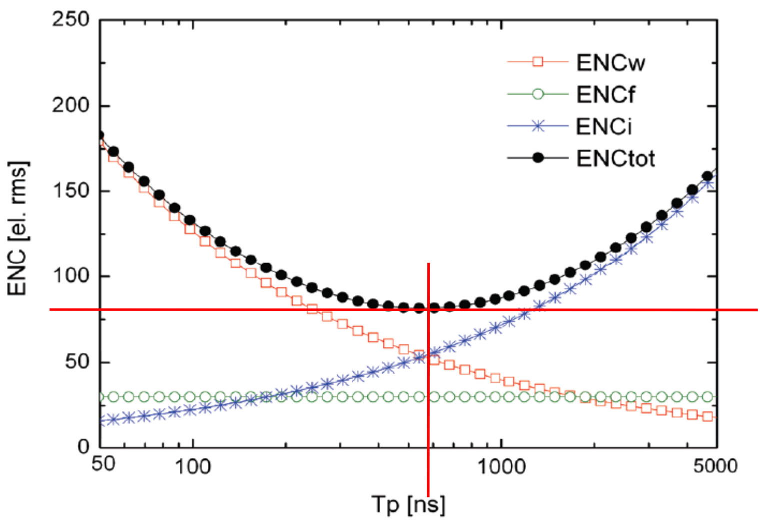
设计挑战一：低噪声设计

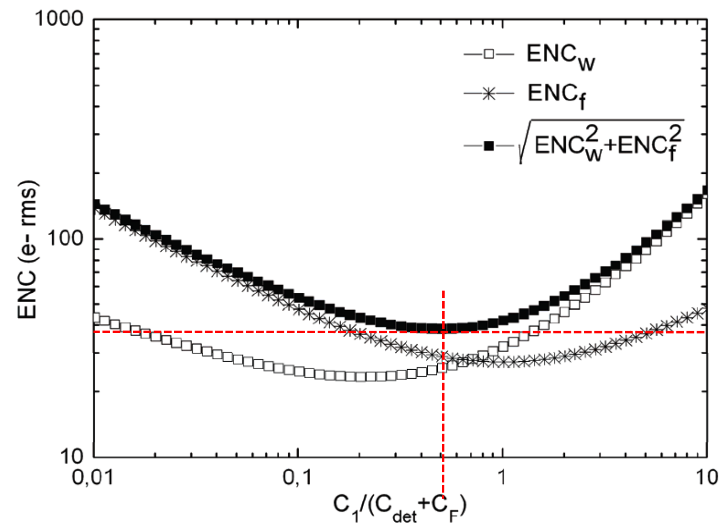
➤ 等效噪声电荷(理想模型)



$$ENC = \frac{\sqrt{\overline{v_{n,shpr}^2}}}{v_{shpr,\max}(Q_{in}=1 \quad electron)}$$

$$= e\sqrt{\frac{t_p}{8}\left(2qI_{det}+\frac{4kT}{R_{bias}}+\frac{4kT}{R_f}\right)+(C_F+C_T)^2\left(\frac{4kT\gamma_n}{8t_p g_{m1}}+\frac{K_f}{2C_{ox}^2}\frac{1}{WL}\right)+N_{const}^2}$$





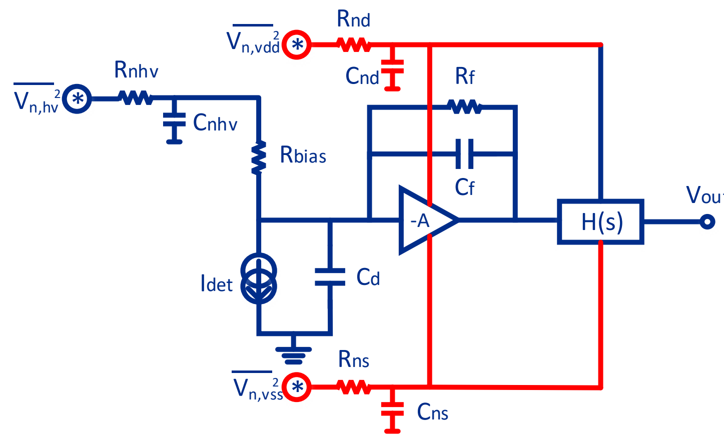
(P. Grybos, 2010)

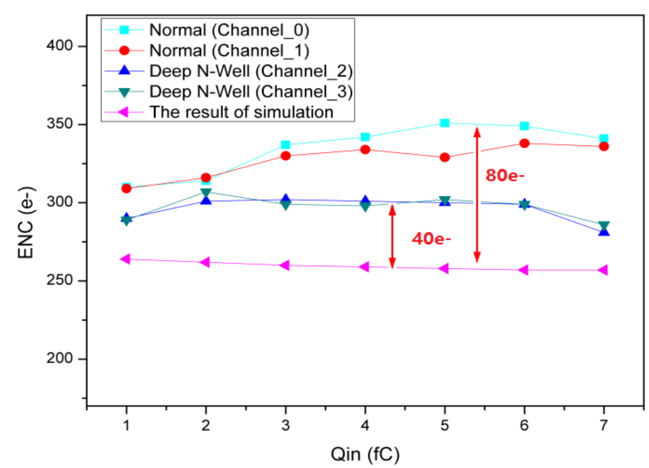
设计挑战一：低噪声设计

➢ **等效噪声电荷 (电源噪声影响)**

$$ENC = \sqrt{ENC_w^2 + ENC_f^2 + ENC_i^2 + ENC_{const}^2}$$

$$ENC_{const}^2 = \frac{0.469 t_p q K T}{R_{n,hv} C_{n,hv} R_{o,hv}} + \frac{K T R_{o,vdd} C_f^2 (g_{m1} + g_{mb1} + g_{ds1} + g_{ds0})^2}{C_{nd} R_{nd} g_{ds0}^2} + \frac{K T R_{o,gnd} C_f^2 g_{ds0}^2}{C_{ns} R_{ns} (g_{m0} + g_{mb0})^2}$$



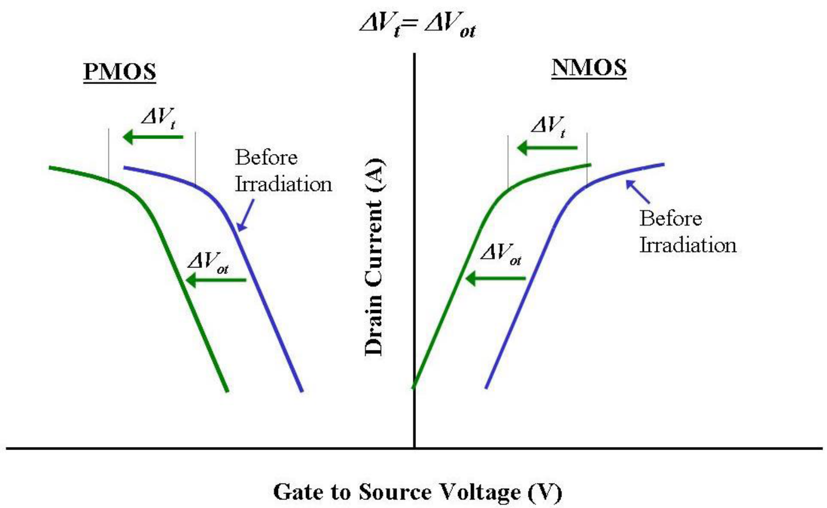


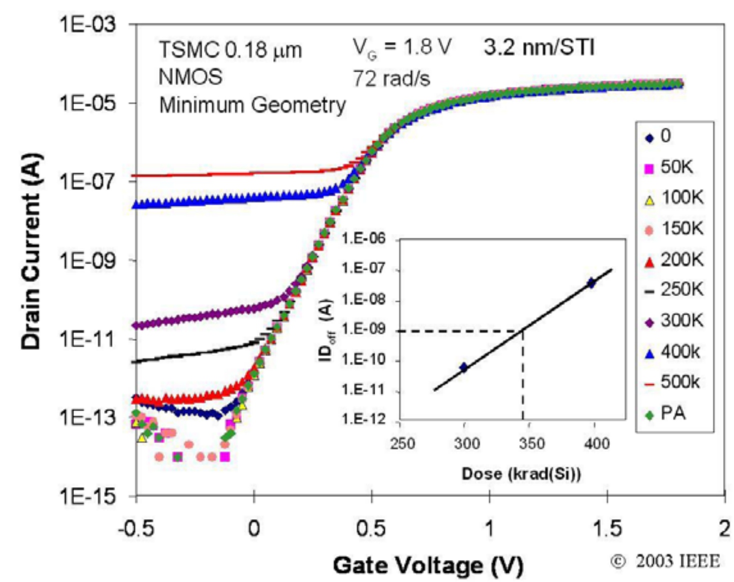
(W. Gao, TNS，2018)

ENC仿真和测试还是存在差距，如何更精确？

设计挑战二：抗辐射加固设计

- **总剂量效应** → 晶体管阈值电压负向漂移、 漏电流增加

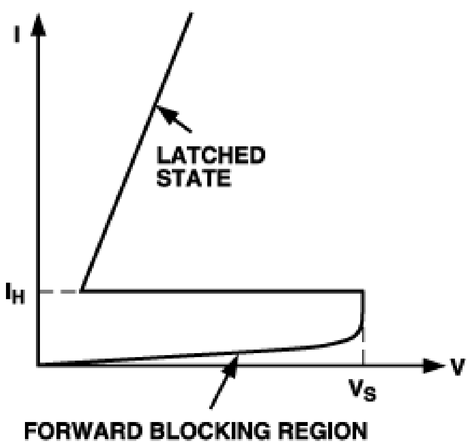


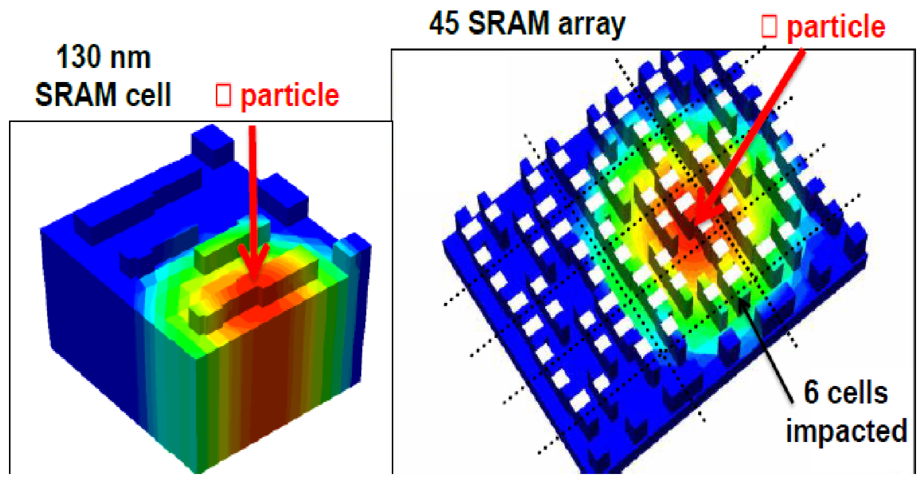


$$-\Delta V_t(N_{ot}) = -\Delta V_{ot} \propto t_{ox}^{\ 2}$$

设计挑战二：抗辐射加固设计

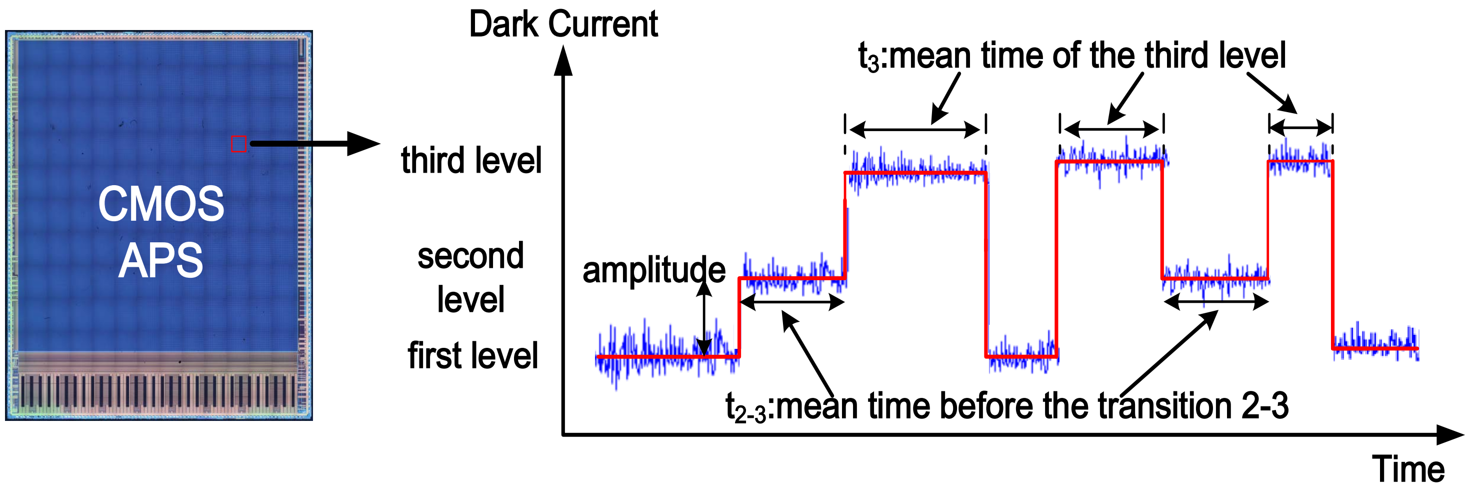
- **单粒子效应 → 单粒子闩锁、单粒子翻转**



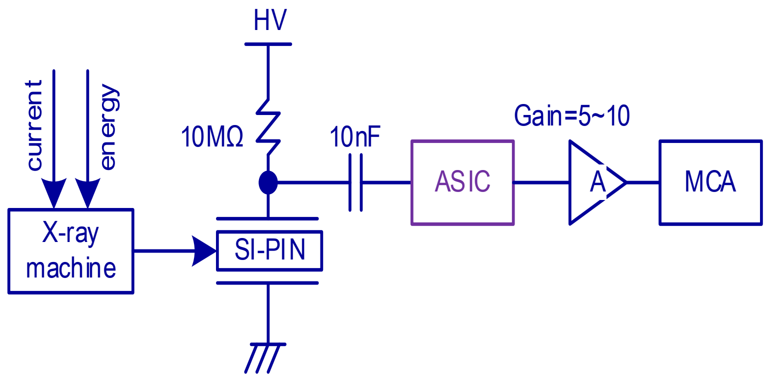


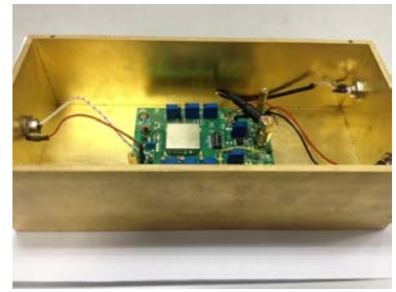
设计挑战二：抗辐射加固设计

- **位移损伤效应** → 二极管、双极型电路 → 随机电报信号噪声



设计挑战三：测试与评估





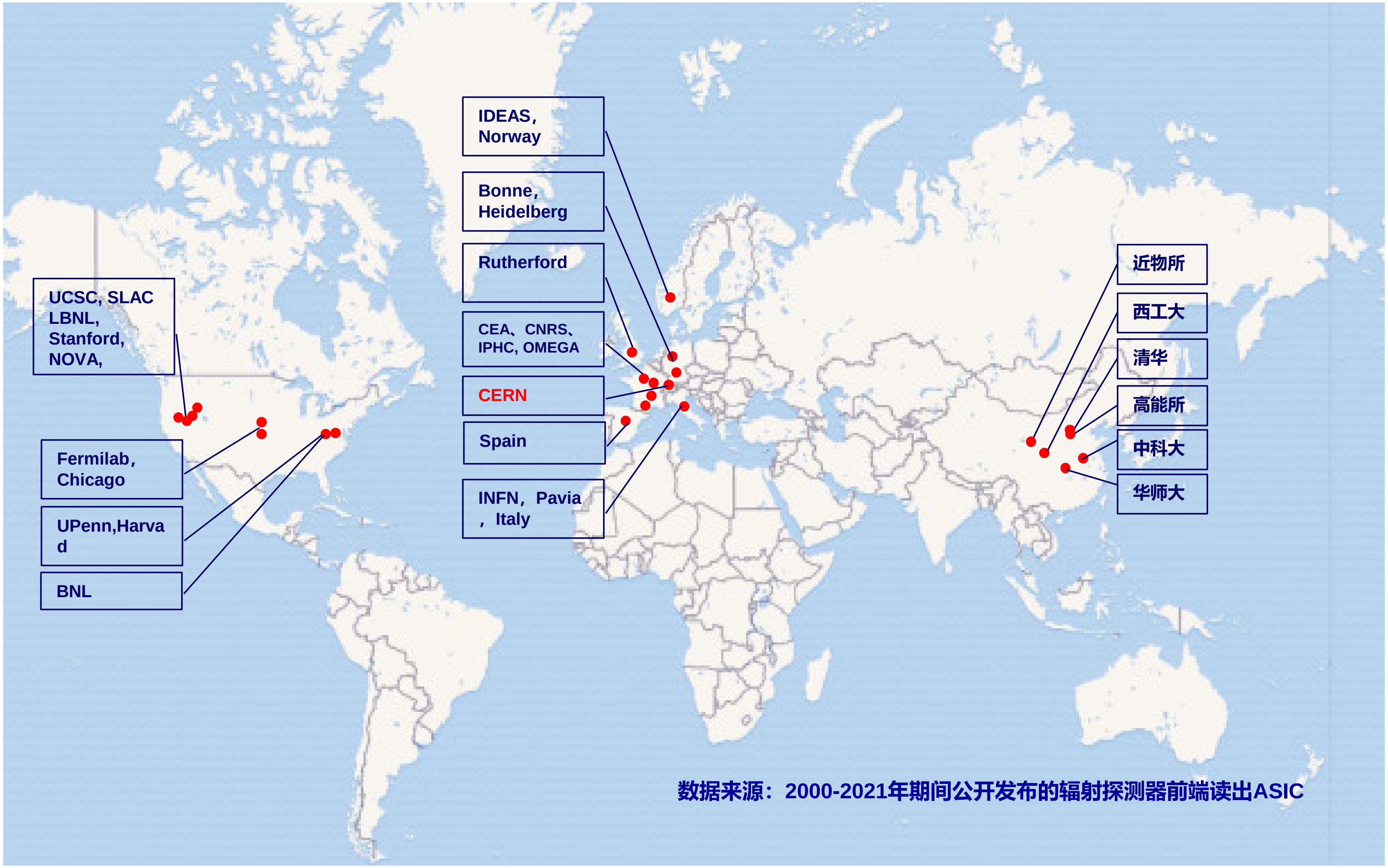
- **电气性能测试**
  - **Q_{max} → T_p → ENC → P_d**
  - **FOM（Figure of Merit）**
- **连探测器能谱测试**
  - **匹配性：一致性、盲像元率**
  - **σ → Energy Resolution**
- **抗辐射能力测试**
  - **TID：Co-60**
  - **SEE：重离子、质子**
  - **DD：中子**

$$FOM_{roc} = \frac{P_d \cdot \tau_p}{Q_{max} / ENC}$$

$$\sigma \approx \frac{A_Q \cdot ENC \times 2.35}{V_{LSB} \cdot \sum_{i=1}^{N} 2^i} \times 100\%$$

国内外现状及动态

国内外主要研究单位



数据来源：2000-2021年期间公开发布的辐射探测器前端读出ASIC

国内外主要研究单位

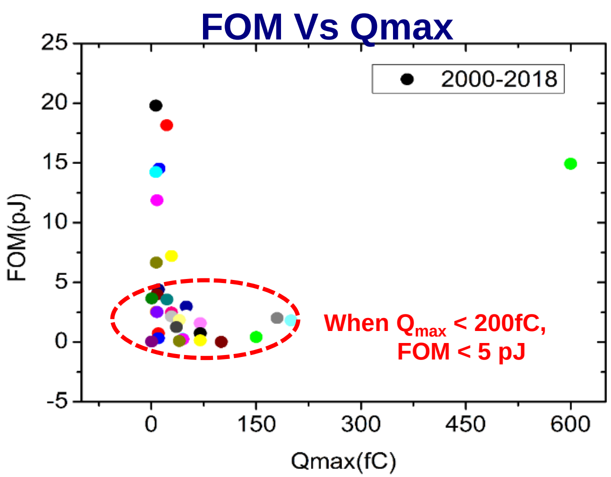
研发现状

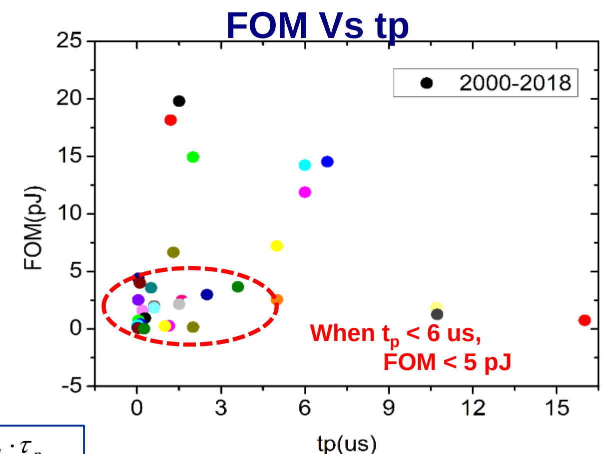
- **国外**
  - ✓**开发始于1980s，芯片设计理论和技术成熟，产品性能高，大规模应用；**
  - ✓**相对于消费类电子芯片，读出ASIC用量少，技术门槛高，开发周期长，研发成本高，一般不在工业界研发，主要集中在欧美国家实验室和相关高校。**
  - ✓**国外提供芯片的公司：IDEAS和NOVA等；**

- **国内**
  - ✓**开发起步于2006年，传统核电子学优势单位开展了ASIC研发，已有少量应用；**
  - ✓**高性能的大通路(>128)、抗辐射ROIC、大阵列像素型ASIC和MAPS等基本上依赖进口。**

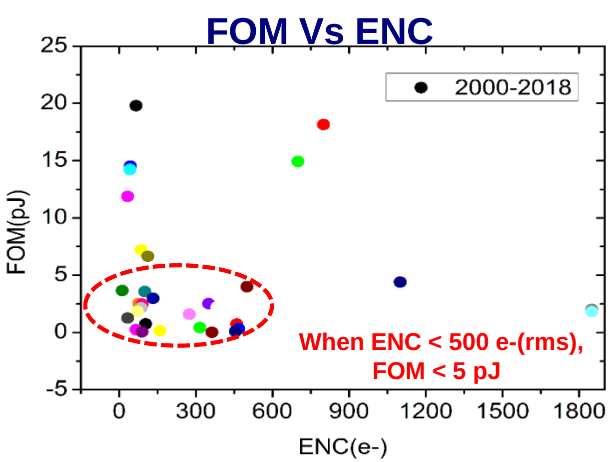
数据来源：2000-2021年期间公开发布的辐射探测器前端读出ASIC

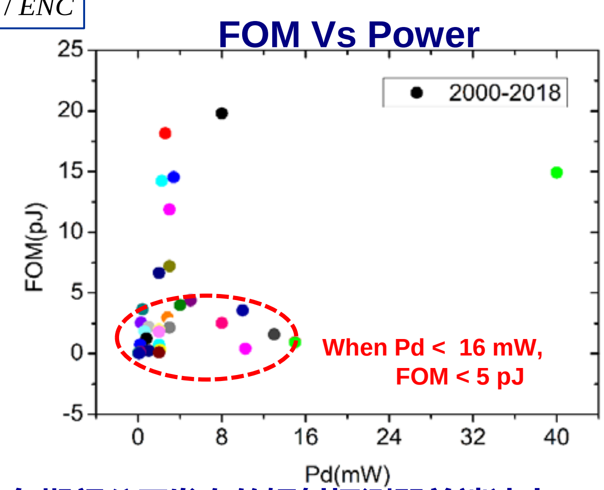
前端读出ASIC性能综述





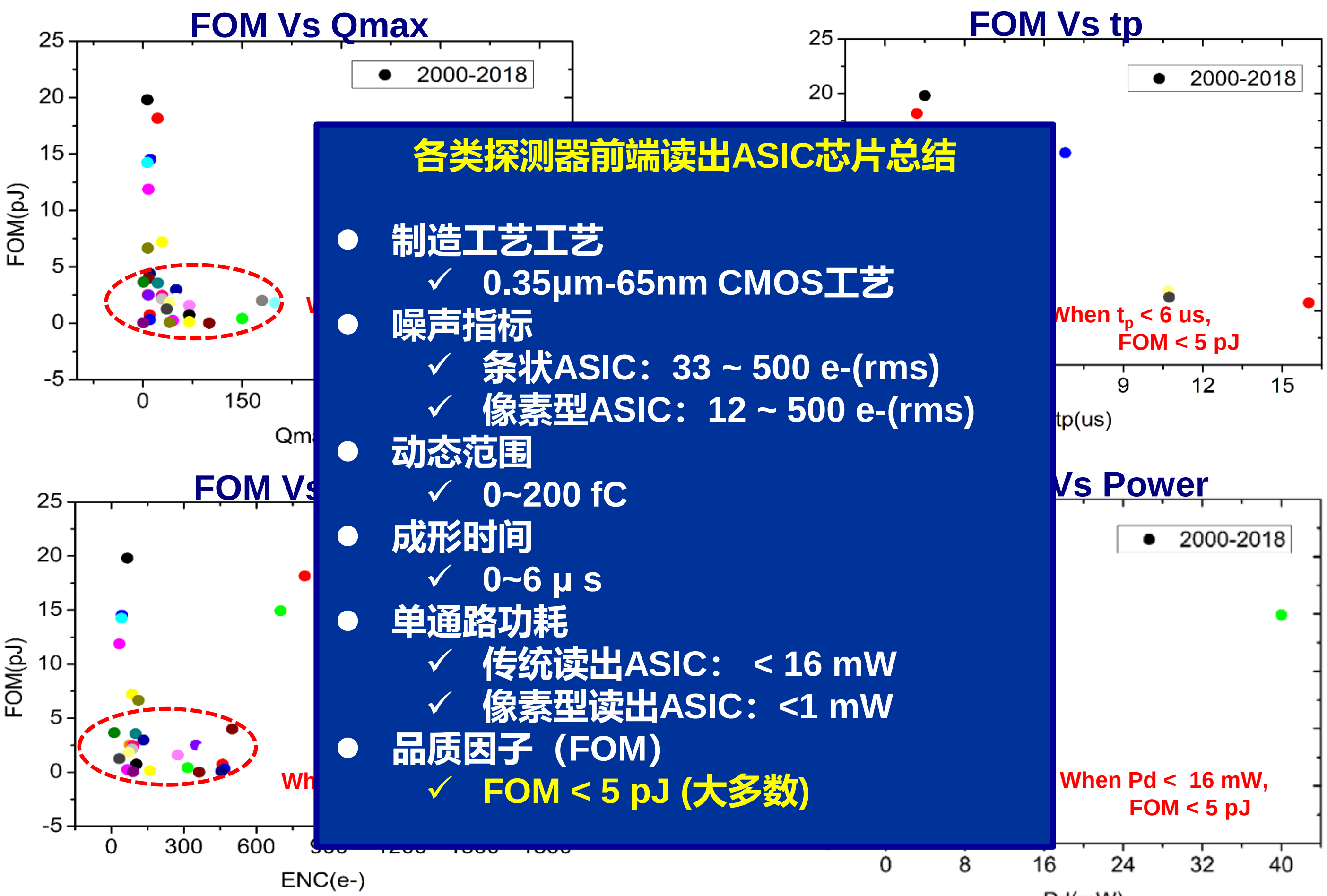
$$FOM_{roc} = \frac{P_d \cdot \tau_p}{Q_{max} / ENC}$$





数据来源：2000-2018年期间公开发布的辐射探测器前端读出ASIC

前端读出ASIC性能综述



各类探测器前端读出ASIC芯片总结

- 制造工艺工艺
  - ✓ 0.35μm-65nm CMOS工艺
- 噪声指标
  - ✓ 条状ASIC：33 ~ 500 e-(rms)
  - ✓ 像素型ASIC：12 ~ 500 e-(rms)
- 动态范围
  - ✓ 0~200 fC
- 成形时间
  - ✓ 0~6 μ s
- 单通路功耗
  - ✓ 传统读出ASIC： < 16 mW
  - ✓ 像素型读出ASIC：<1 mW
- 品质因子（FOM）
  - ✓ FOM < 5 pJ (大多数)

数据来源：2000-2018年期间公开发布的辐射探测器前端读出ASIC

气体探测器前端读出ASIC

典型的气体探测器

□ GEM

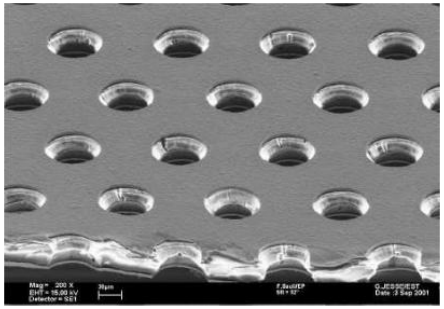
- 特点:高位置分辨率、时间响应快
- 应用：天文射线探测、中子探测

□ Micromegas

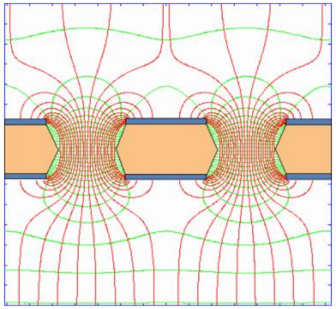
- 特点：良好的空间和时间分辨率、高增益、高计数率
- 应用：粒子物理、核物理和天体物理实验

□ 对前端读出电子学的要求

- 多通路、快速响应、大动态范围、低功耗



- Microscopic picture of a “standard” GEM



- The electric field lines in a hole within the kapton foil

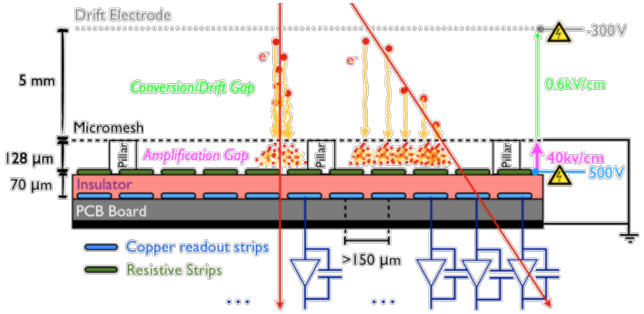
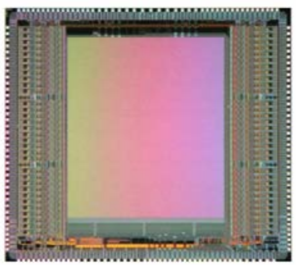


Figure 3. The schematic of the Micromegas detector divided into two regions, the conversion/drift gap and the amplification gap.

GEM探测器ASIC



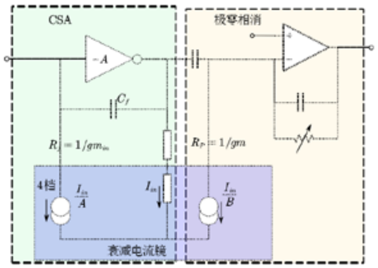


Fig. 5. AGET die photography, size 8.5 x 7.6 mm^2.

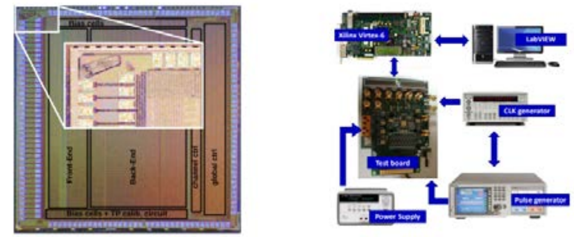


Figure 2: Microphotograph of the TIGER chip (left) and the test bench setup used for the electrical characterization (right).

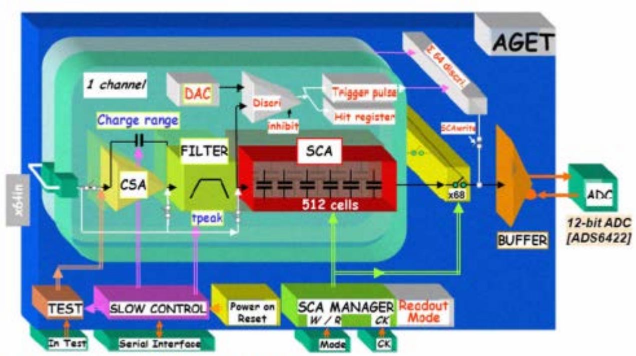


Fig. 3. Architecture of the AGET chip.

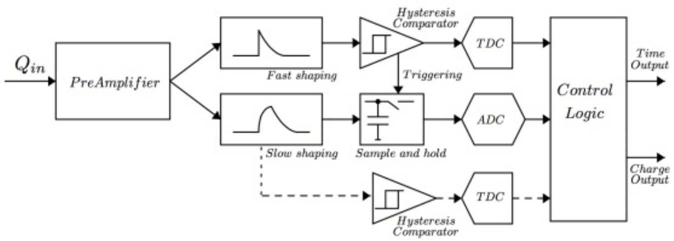


Figure 1: Block diagram of one channel

- **AGET, Saclay, France**
- **TIGER, IHEP, China**

Micromegas探测器ASIC

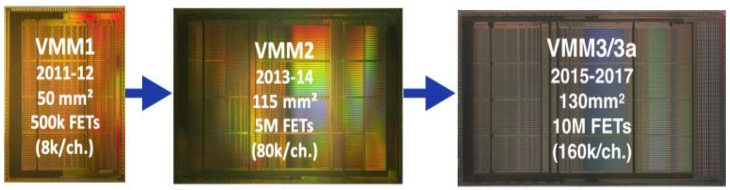


Figure 1. Evolution of the VMM ASIC.

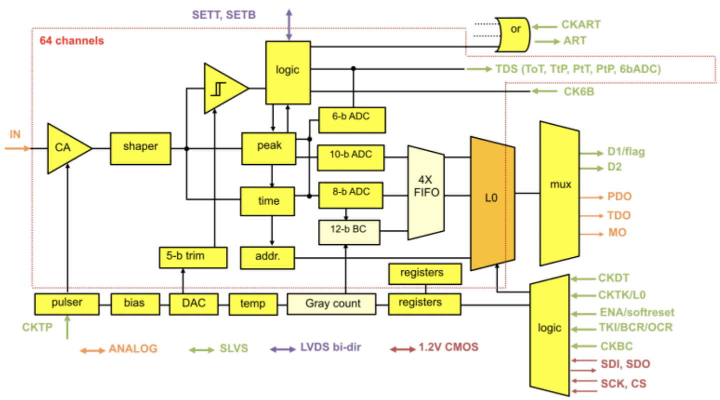


Figure 2. Architecture of the VMM.

- **VMM, BNL, USA**

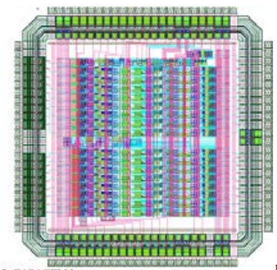


Fig. 3 CASAGEM layout

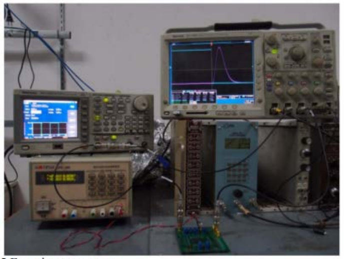


Fig. 5 Function test setup

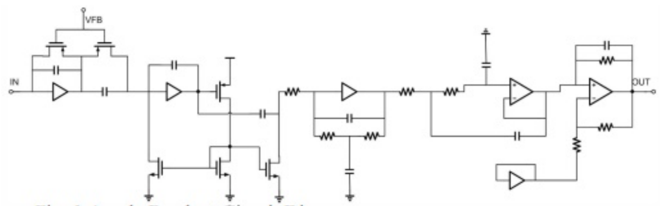


Fig. 1 Anode Readout Circuit Diagram

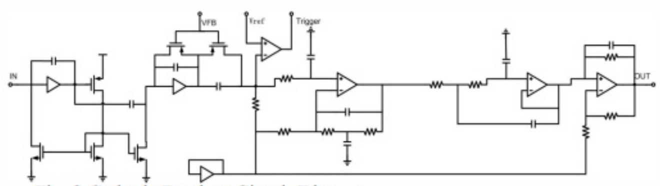
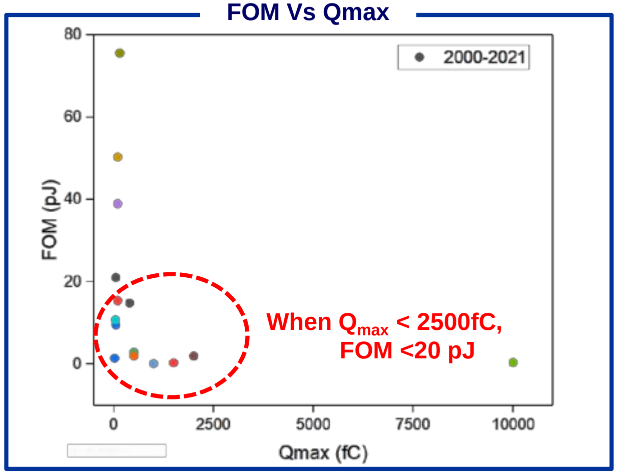


Fig. 2 Cathode Readout Circuit Diagram

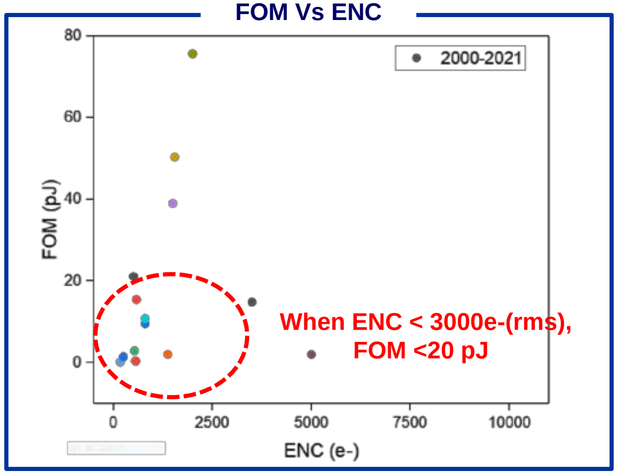
- **CASEGEM, Tsinghua, China**

气体探测器前端读出ASIC性能趋势

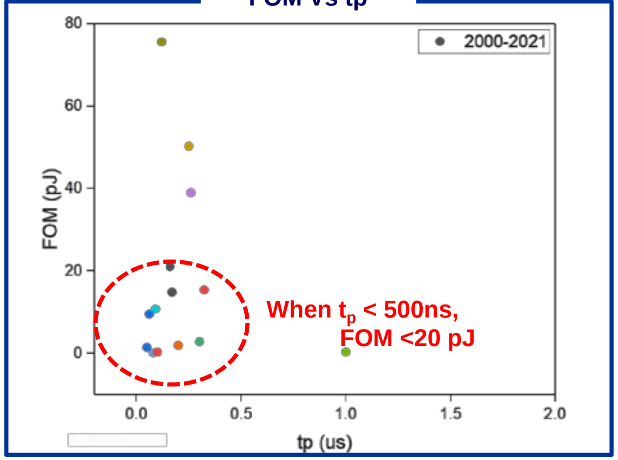
FOM Vs Qmax



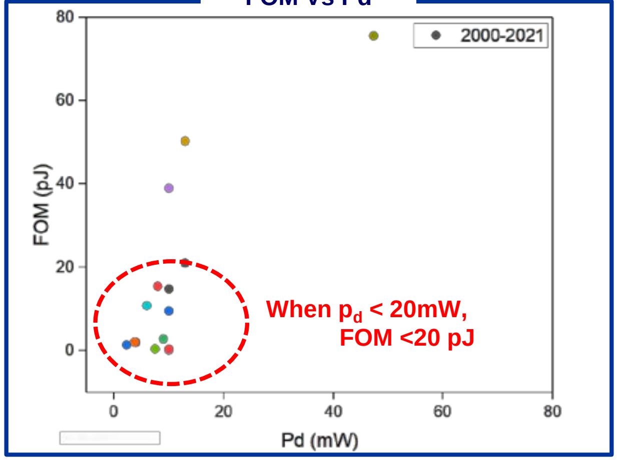
FOM Vs ENC



FOM Vs tp

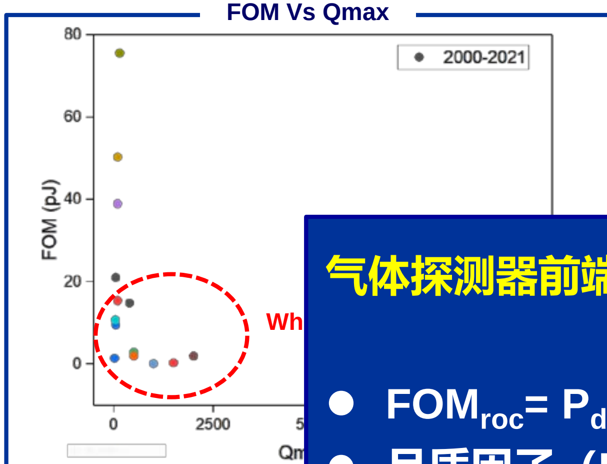


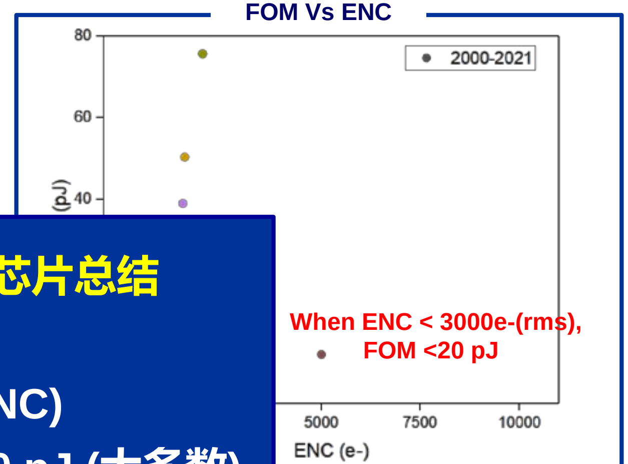
FOM Vs Pd

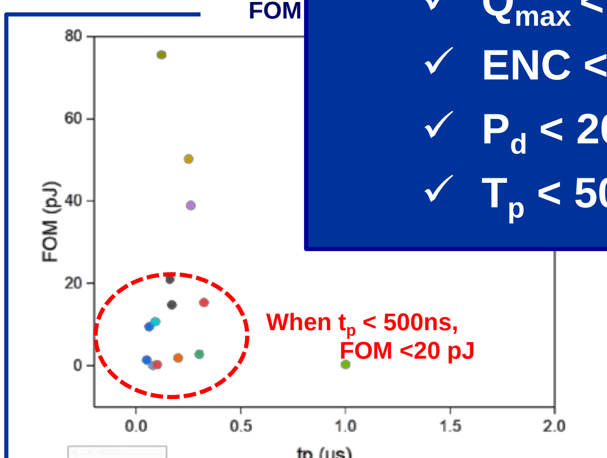


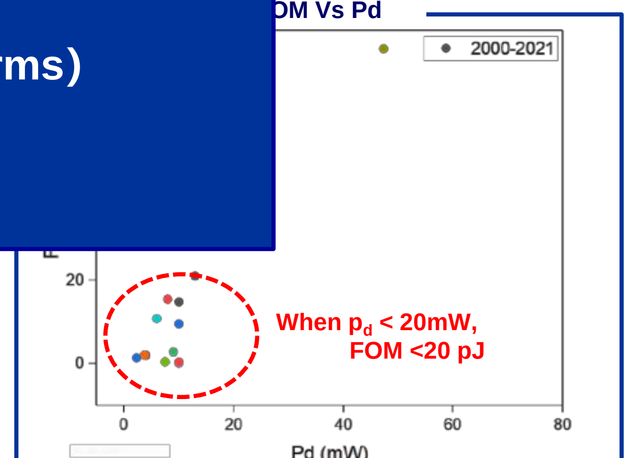
数据来源：2000-2021年期间公开发布的辐射探测器前端读出ASIC

气体探测器前端读出ASIC性能趋势









气体探测器前端读出ASIC芯片总结

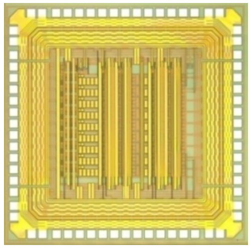
- $FOM_{roc} = P_d \cdot t_p / (Q_{max}/ENC)$
- 品质因子（FOM） < 20 pJ (大多数)
  - ✓ Q_{max} < 2500 fC
  - ✓ ENC < 3000 e-（rms）
  - ✓ P_d < 20 mW/ch
  - ✓ T_p < 500 ns

数据来源：2000-2021年期间公开发布的辐射探测器前端读出ASIC

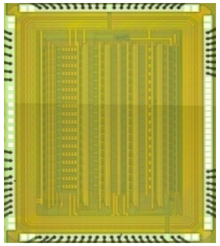
西北工业大学前端读出ASIC研究进展

研发历程

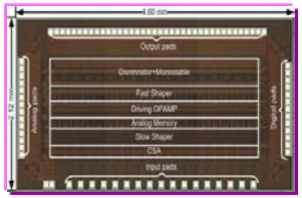
- **国内平台、国内人员、国内工艺、全正向设计**
- **工艺：TSMC 0.35μm, CSMC 0.35μm, TSMC 180nm，SMIC 180nm**
- **探测器：PMT、CZT、APD、Si-PIN、SDD等**
- **关键技术：低噪声、抗辐射**



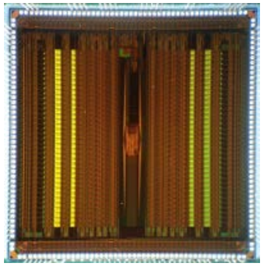
单路前端读出原理样片（2012）



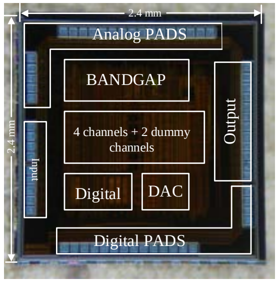
16路模拟读出原理样片（2013）



16路抗辐射前端读出原理样片（2014）



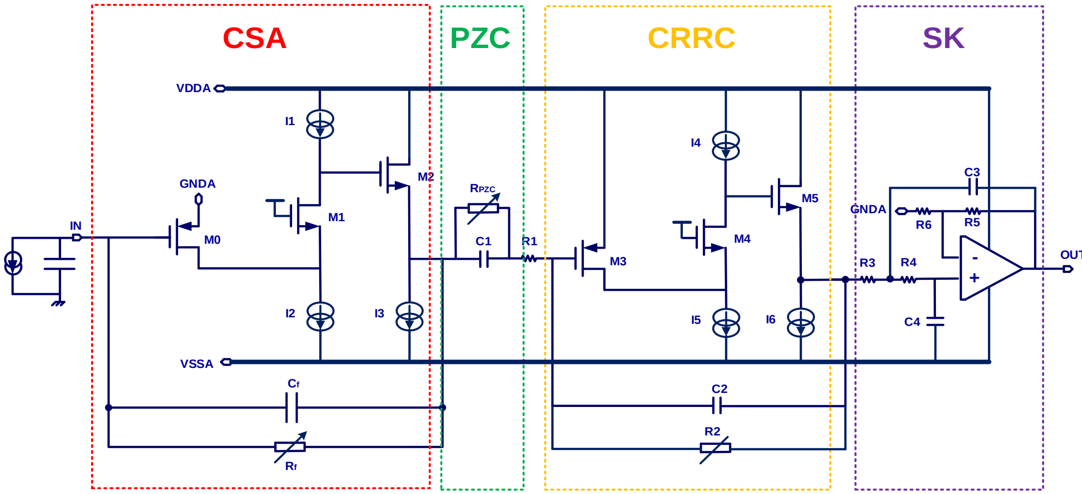
64路前端读出ASIC 工程样片(2017)



4通路前端读出ASIC 芯片产品(2019~2020)

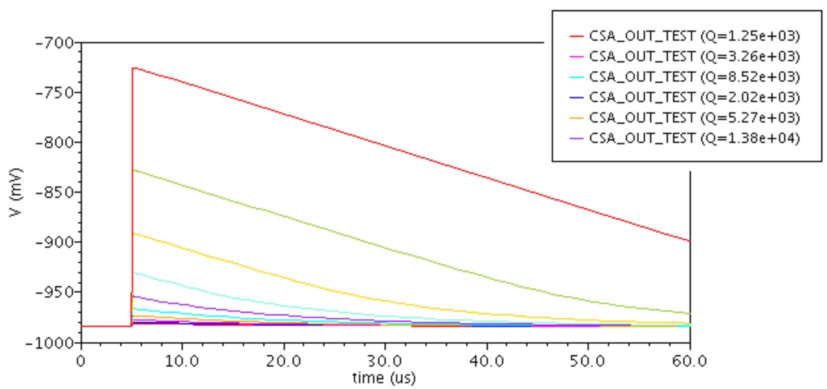
西北工業大學 NORTHWESTERN POLYTECHNICAL UNIVERSITY

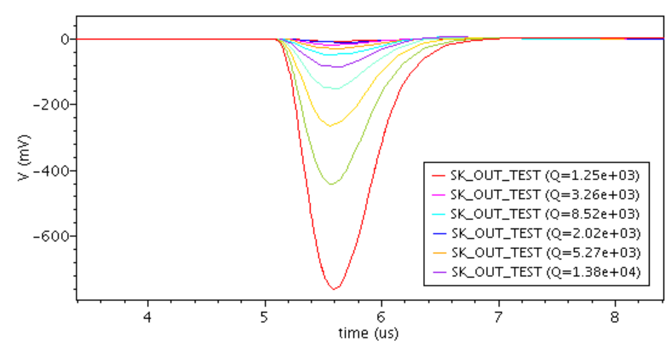
解决方案：低噪声模拟前端



- 电路结构
  - ✓电荷灵敏前放
  - ✓CR-RC3成形主放
  - ✓零极相消电路
  - ✓可变电阻电路
- 电压源(VDDA, VSSA, GNDA)

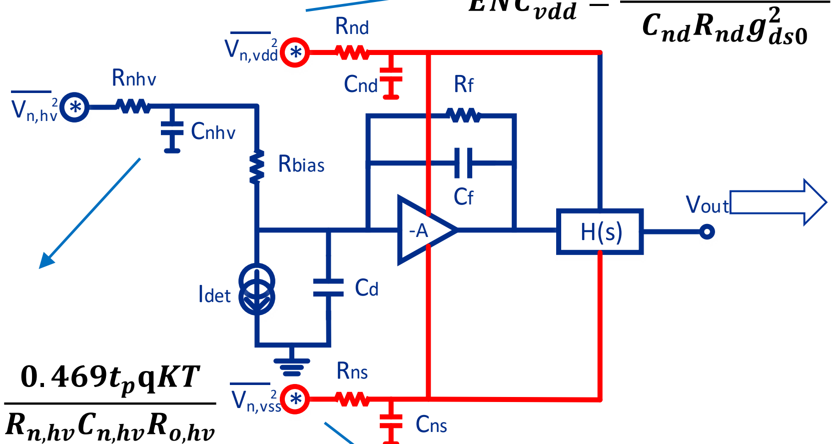
$$H(s) = -\frac{R_f}{1+sC_fR_f} \cdot \frac{1+sC_1R_{pzc}}{R_{pzc}} \cdot \frac{sA_{v0}}{(1+s\tau)^4}$$





噪声建模及优化方案

$$ENC_{vdd}^2 = \frac{KTR_{LDO}C_f^2 g_{m1}^2}{C_{nd}R_{nd}g_{ds0}^2}$$



$$ENC_{hv}^2 = \frac{0.469 t_p qKT}{R_{n,hv}C_{n,hv}R_{o,hv}}$$

$$ENC_{vss}^2 = \frac{KTR_{o,vss}C_f^2 g_{ds0}^2}{C_{ns}R_{ns}(g_{m0}+g_{mb0})^2}$$

$$ENC^2 = ENC_i^2 + ENC_v^2 + ENC_f^2 + ENC_{const}^2$$

$$ENC_i^2 = 0.462 t_p\left[qI_{det} + 2kT\left(\frac{1}{R_{bias}} + \frac{1}{R_f}\right)\right]$$

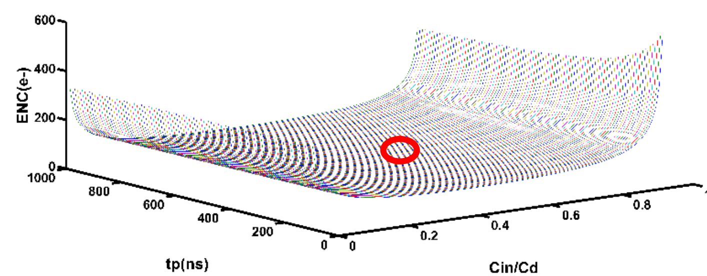
$$ENC_v^2 = 3.696\frac{(C_F + C_T)^2}{t_p}\frac{kT\gamma_n}{g_{m1}}$$

$$ENC_f^2 = 3.696(C_F + C_T)^2\frac{K_f}{C_{ox}^2}\frac{1}{WL}$$

$$ENC_{const}^2 = ENC_{pwr,hv}^2 + ENC_{pwr,asic}^2 + ENC_{gnd,asic}^2$$

Optimized parameters

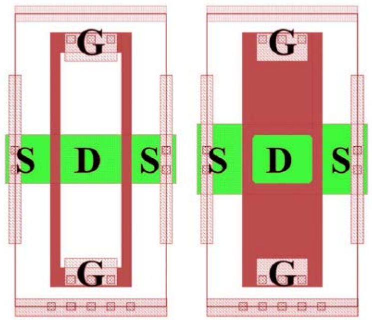
- ✓ C_f = 50 fF
- ✓ W = 1200 μm
- ✓ L = 400 nm
- ✓ $I_{D,CSA}$ = 400 μA
- ✓ T_p = 250 ns

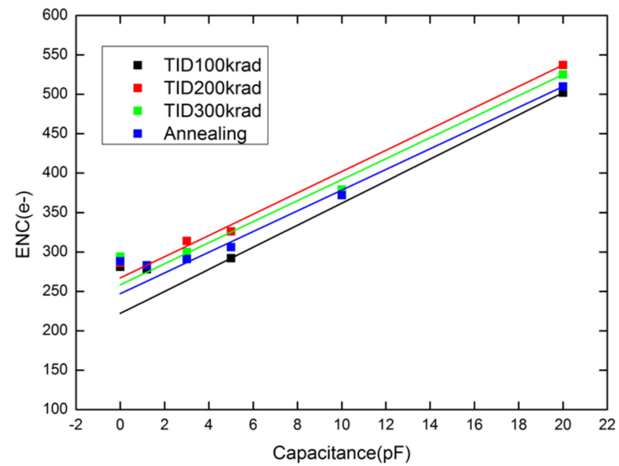


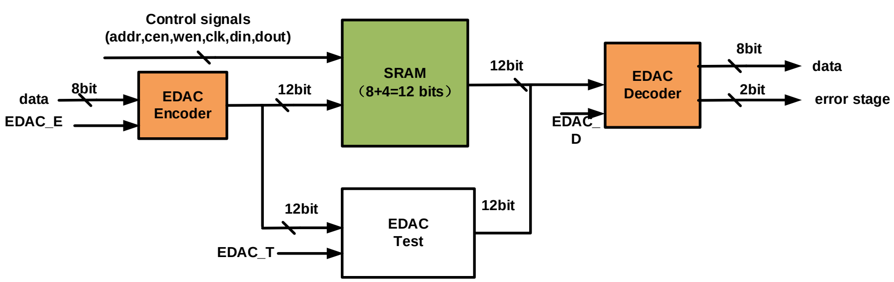
ENC calculation

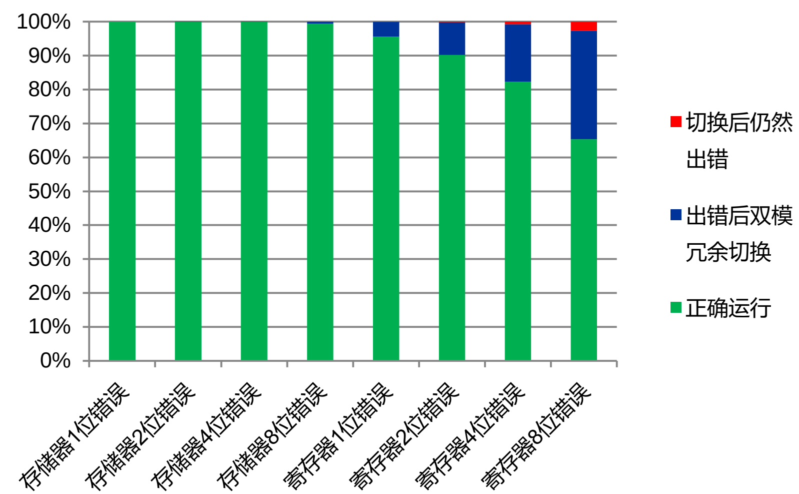
抗辐射加固设计方案

- □ 版图级加固
- □ 硬件检错纠错

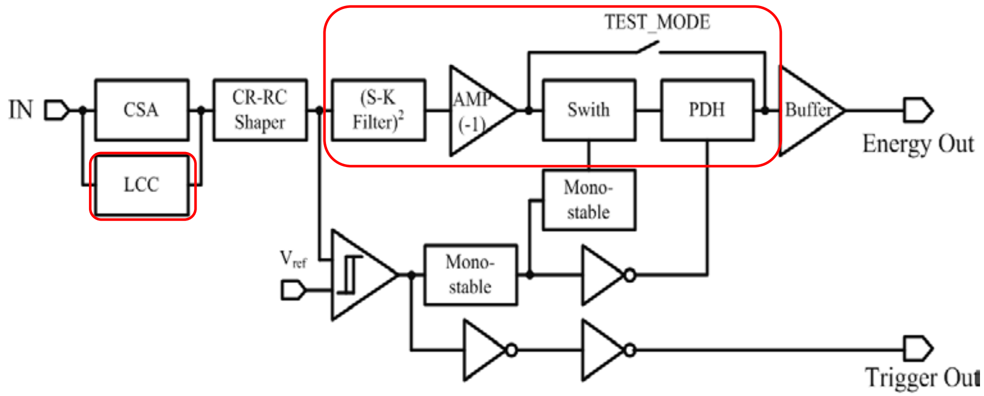


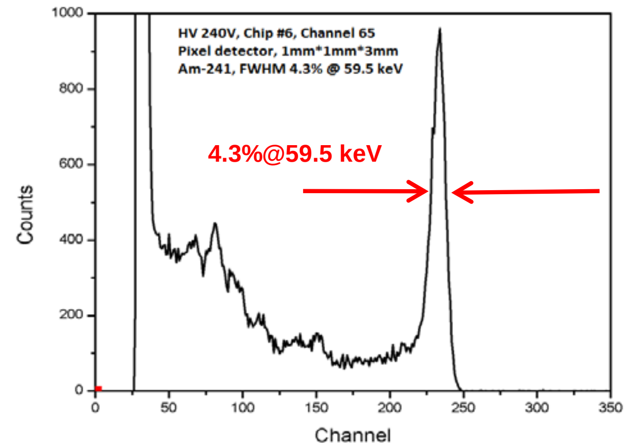


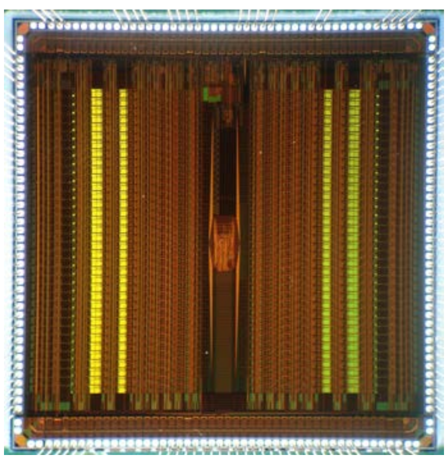




低噪声多通路前端读出ASIC





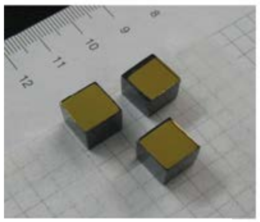


FOM=2.4 pJ

参数	性能指标(SENSROC8)
Detector	8×8阵列CZT晶体（Pixel size：1mm × 1mm× 3mm）
Process(μm)	CMOS 0.35um 3.3V MS
Channel No.	64
Input range(e-)	2k~247k
ENC (rms)	66 e-+14e-/pF (tested)
Consistency	< 3 %
Radiation Hardness	200 krad(Si)

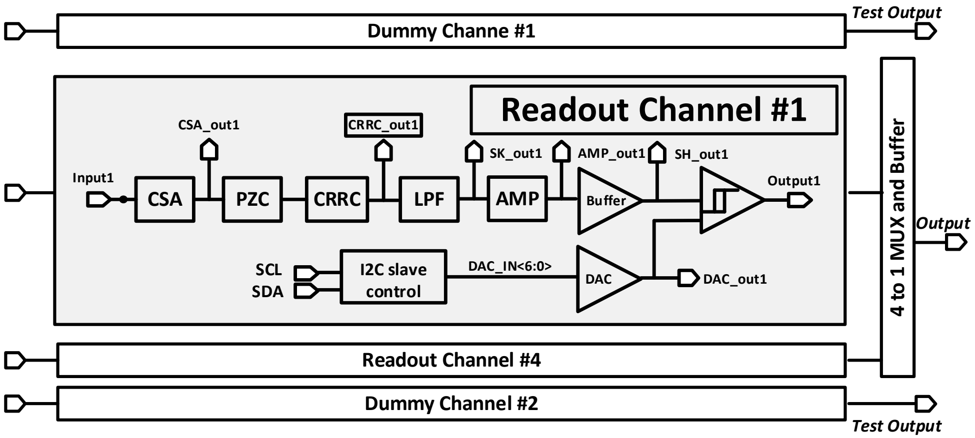
(NIM A, 2014, MEJ 2016)

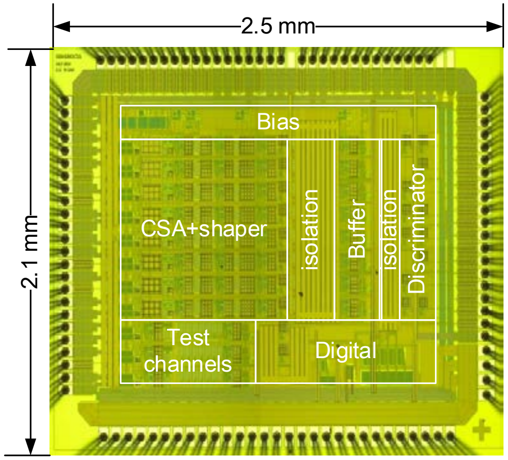
低功耗前端读出ASIC



探测器
(CZT)

个人剂量仪





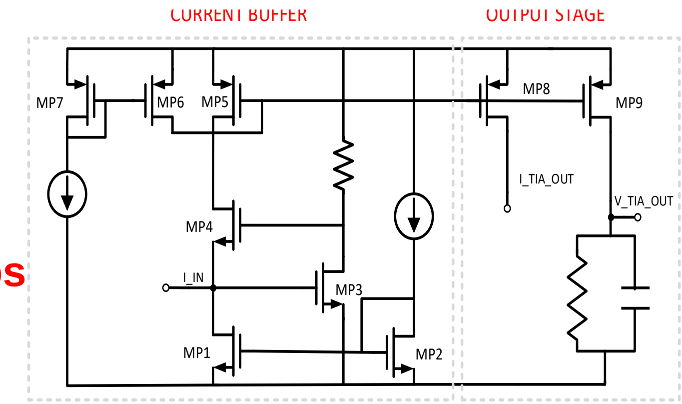
FOM=0.5 pJ

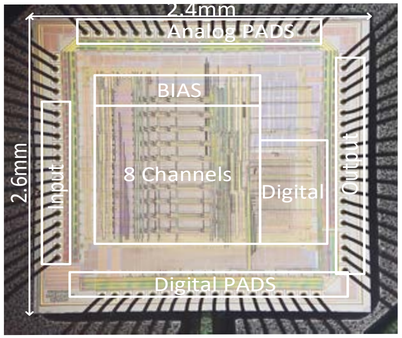
参数	性能指标
探测器	CZT探测器（3mm×7mm×3mm）
Process	CMOS 0.18μm 1.8/3.3V MS
die size	2.1 mm× 2.5 mm
Input Range	0.2 fC -15 fC
Linearity	< 3%
Gain	>100 mV/fC
ENC	112 e- + 17 e-/pF
Count rate	10^5(100 kCPS)
Power Diss.	1.74 mW/channel
Application	Electronic Personal Dosimeter

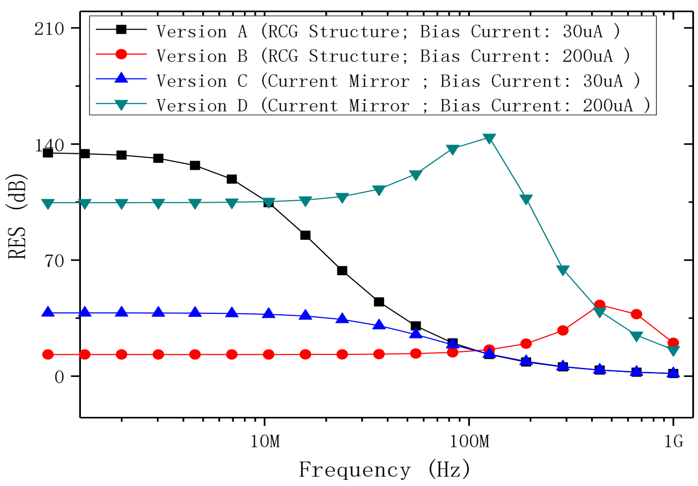
(TNS, 2018)

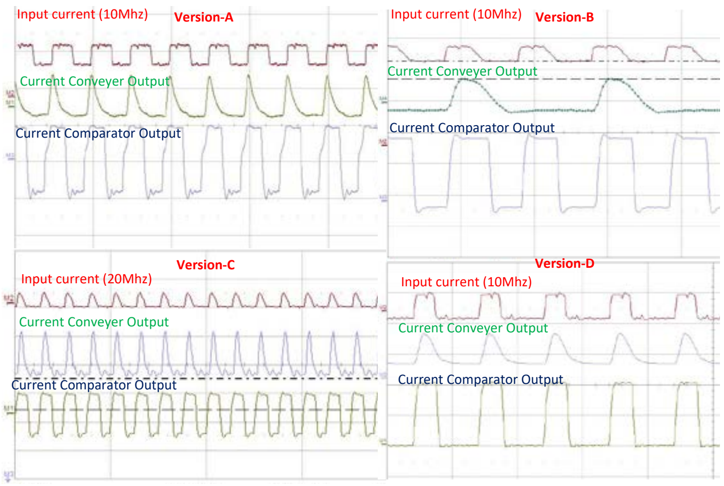
高计数率前端读出ASIC

- □ **电路结构**
  - ✓RGC跨阻放大器
  - ✓电流比较器
- □ **主要特点**
  - ✓高计数率：**20 Mcps**
  - ✓低输入阻抗，**20 Ω**



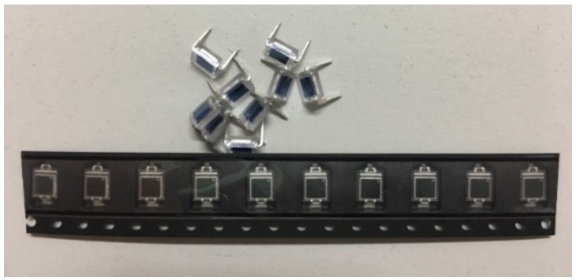




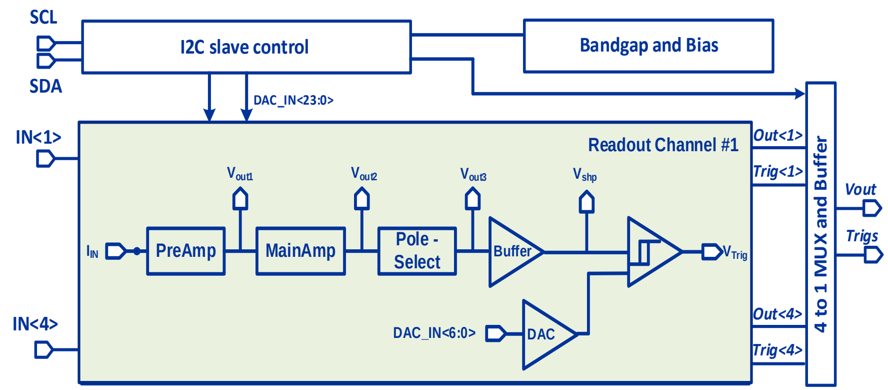


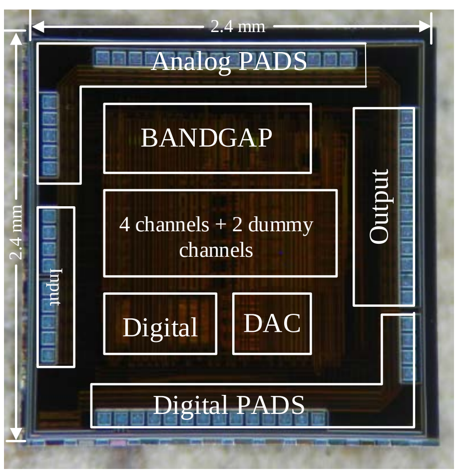
(NSS-MIC, 2021)

低功耗前端读出ASIC



探测器
(Si-PIN)



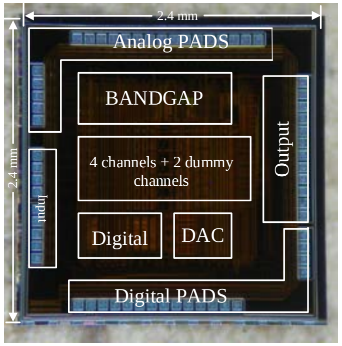


参数	性能指标
探测器	Si-PIN探测器（2.7mm×2.7mm×3mm）
Process	CMOS 0.35μm 3.3V MS
die size	2.4 mm× 2.4 mm
Input Range	0.2 fC -15 fC
Linearity	< 3%
Gain	>60 mV/fC
ENC	119 e- + 5 e-/pF
Count rate	150 kCPS
Power Diss.	1.25 mW/channel
Application	Electronic Personal Dosimeter

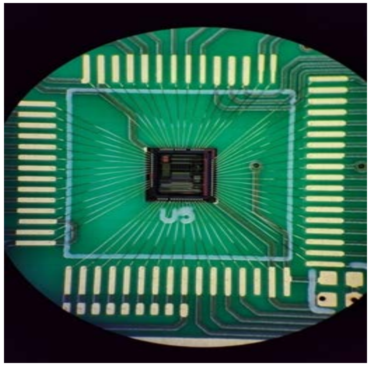
FOM=0.59 pJ

(TNS, 2019)

前端读出ASIC应用

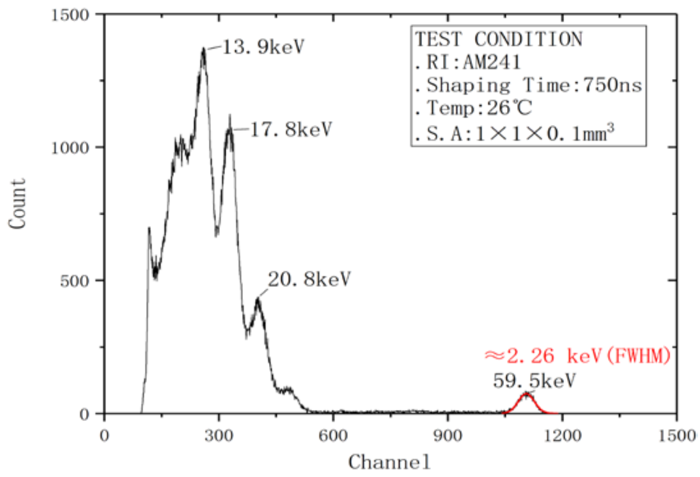


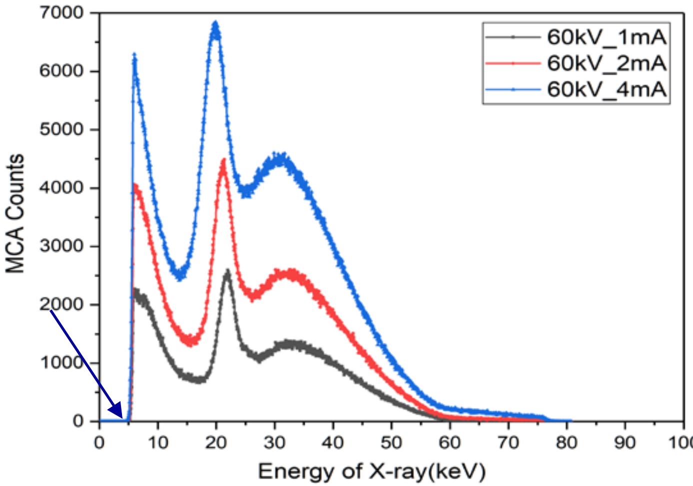
芯片照片



芯片封装

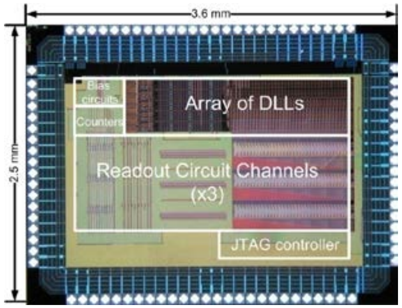
芯片应用



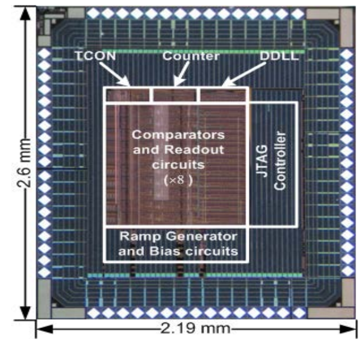


(NSS/MIC, 2020)

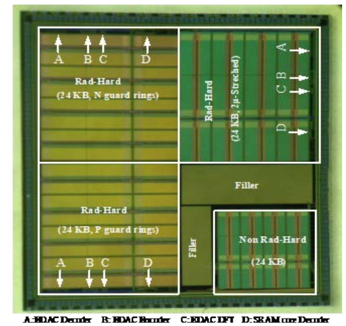
西工大研发的其他芯片



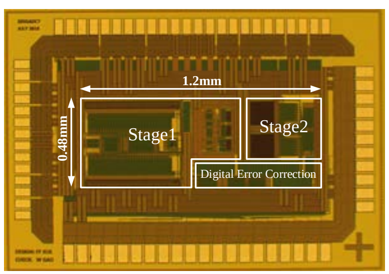
高分辨率TDC(2011)
AMS 0.35μm CMOS



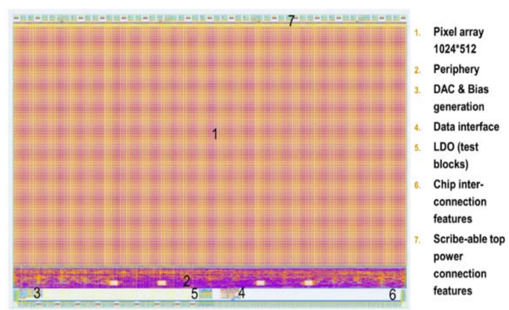
12位单斜坡ADC(2012)
AMS 0.35μm CMOS



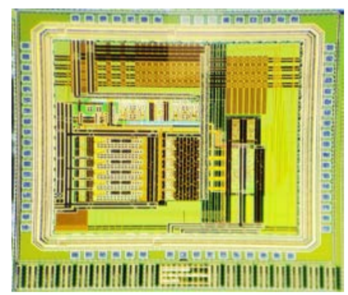
抗辐射SRAM(2014)
SMIC 0.18μm CMOS



12位流水式逐次逼近ADC(2017)
TSMC 0.18μm CMOS



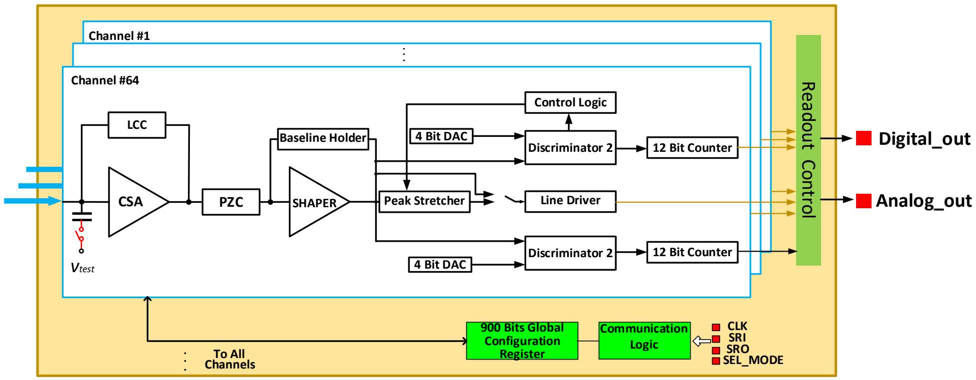
MAPS高速数字读出(2020)
TJ 0.18μm CMOS

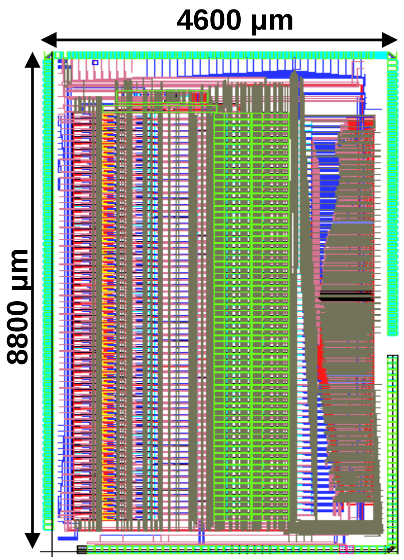


14位单斜坡ADC(2021)
GF 0.18μm CMOS

下一步工作1：超低噪声计数型多路读出ASIC

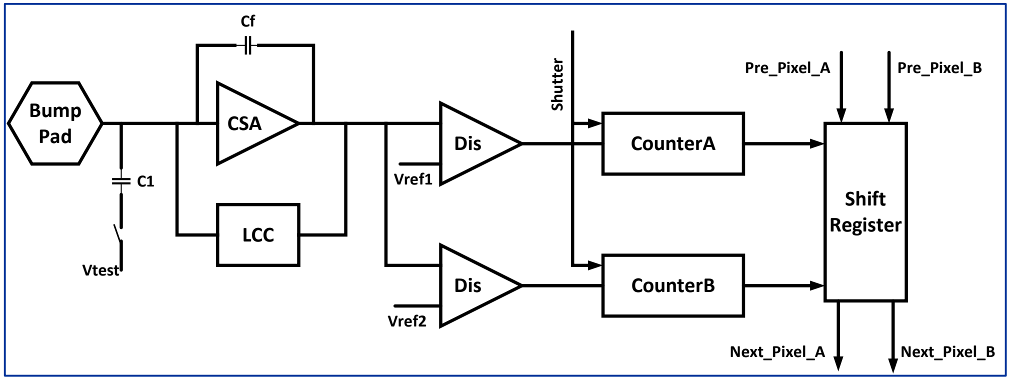
- **电路结构**
  - ✓电荷积分式模拟前端
  - ✓高分辨计数器
- **主要特点**
  - ✓超低噪声：29 e- + 5 e-/pF
  - ✓双计数器：12 位
  - ✓事件驱动读出

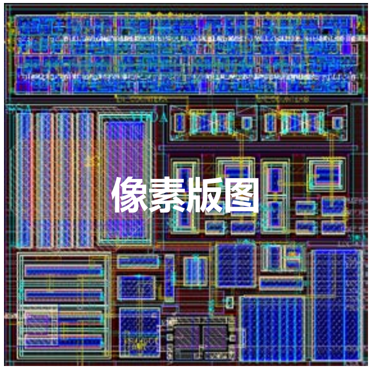


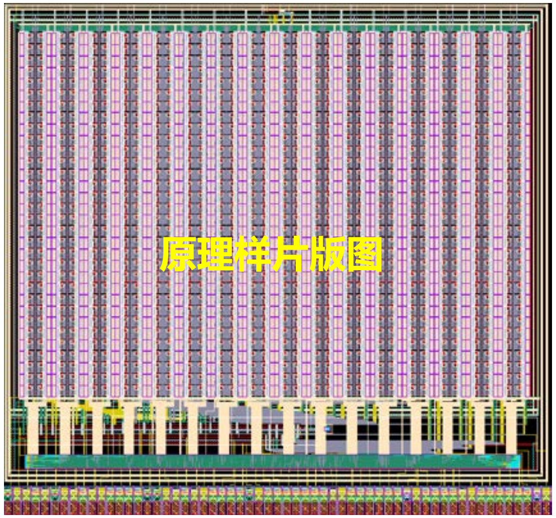


参数	仿真结果
Process	CMOS 0.35μm
Detectors	Si-PIN Detector
Power supply	3.3 V
Die size	4.6 mm×8.8 mm
Energy range	0.08~1 fC
Shaping time	0.1,0.2,0.4, 0.7 μS
Linearity	<2.5%
Count rate	>1 Mcps
ENC	29 e- + 5 e-/pF
Power dissipation	<4.5 mW/channel
Application	X-Ray Diffractometer

下一步工作2：像素型读出ASIC







参数指标	仿真结果
像素尺寸	75 μm × 75 μm
阵列大小	32×32
输入范围	0 ~ 10 fC
增益	60 mV/fC
等效输入噪声电荷	113 e-
计数范围	2×6 bits
功耗	42 μW/pixel
计数率	> 500 k/pixel
应用	彩色CT成像、天文望远镜

总结语

1. 探测器前端读出电子学ASIC概述
2. 国内外现状及动态
3. 气体探测器前端读出ASIC
4. 西北工业大学前端读出ASIC研究进展
5. 下一步工作：超低噪声、数字像素型

请各位专家批评指正

谢 谢 ！