Pre-production of USTC-IME LGAD for ATLAS HGTD

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半导体辐射探测器研讨会

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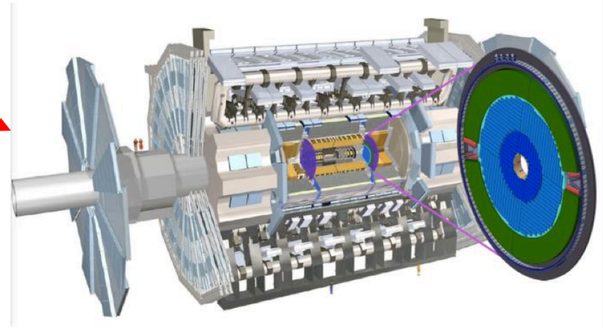
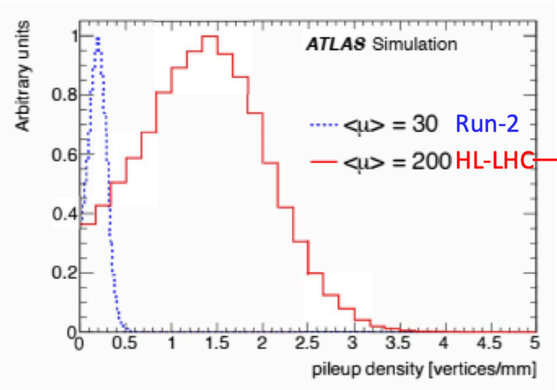
高粒度时间探测器

- 大型强子对撞机（LHC）于2028年升级为高亮度LHC，导致堆积效应上升
- 在高亮度LHC上，时间信息将会被用于区分对撞顶点
- HGTD会被应用于LHC上四个主要探测器之一的ATLAS探测器2期升级上，用以提供时间信息
- 由于具有良好的时间分辨和抗辐照性能，LGAD将作为HGTD的传感器

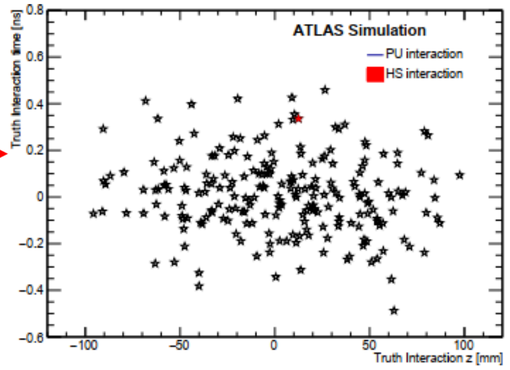
ATLAS Detector in LHC



Position of the HGTD within ATLAS



Local pileup vertex densities at generator level

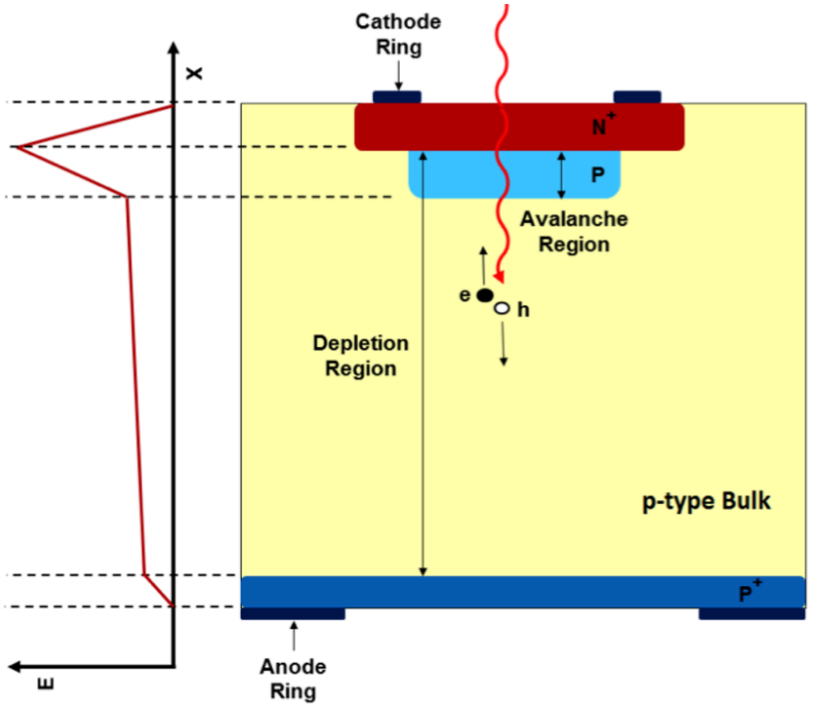


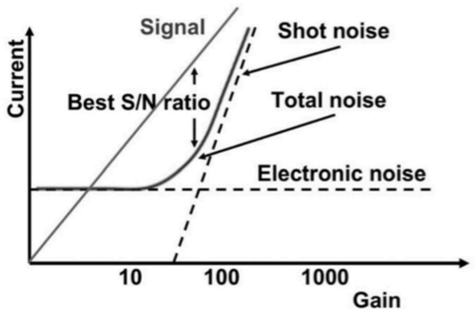
truth interactions in a single bunch crossing in the z–t plane

低增益雪崩探测器

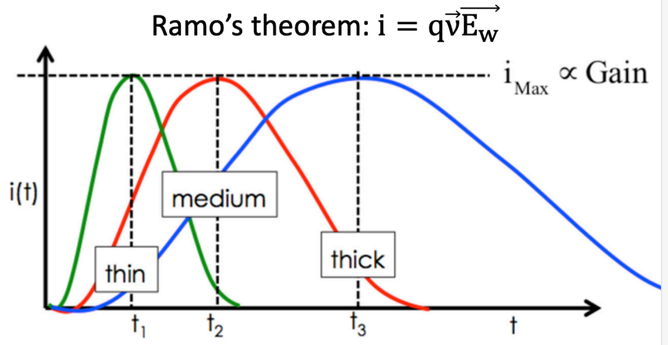
- LGAD工作原理
  - LGAD 是一种包含额外高浓度p掺杂增益层的 n-in-p硅探测器，存在强电场区，电子漂移进入后会产生雪崩
  - 时间分辨：$\sigma_t^2 = \sigma_{Jitter}^2 + \sigma_{timewalk}^2 + \sigma_{Landau}^2$
  - $\sigma_{Jitter} \sim \frac{t_{rise}}{S/N}$，其中$t_{rise}$是上升时间，S/N代表信噪比

Technology	Silicon Low Gain Avalanche Detector (LGAD)
Time resolution	≈ 35 ps (start); ≈ 70 ps (end of lifetime)
Time resolution uniformity	No requirement
Min. gain	20 (start); 8 (end of lifetime)
Min. charge	4 fC
Min. hit efficiency	95%
Granularity	1.3 mm × 1.3 mm
Max. inter-pad gap	100 µm
Max. physical thickness	300 µm
Active thickness	50 µm
Active size	39 mm × 19.5 mm (30 × 15 pads)
Max. inactive edge	500 µm
Radiation tolerance	2.5×10^{15} n_{eq} cm^{-2}, 1.5 MGy
Max. operation temperature on-sensor	−30 °C
Max. leakage current per pad	5 µA
Max. bias voltage	800 V
Max. power density	100 mW/cm^2





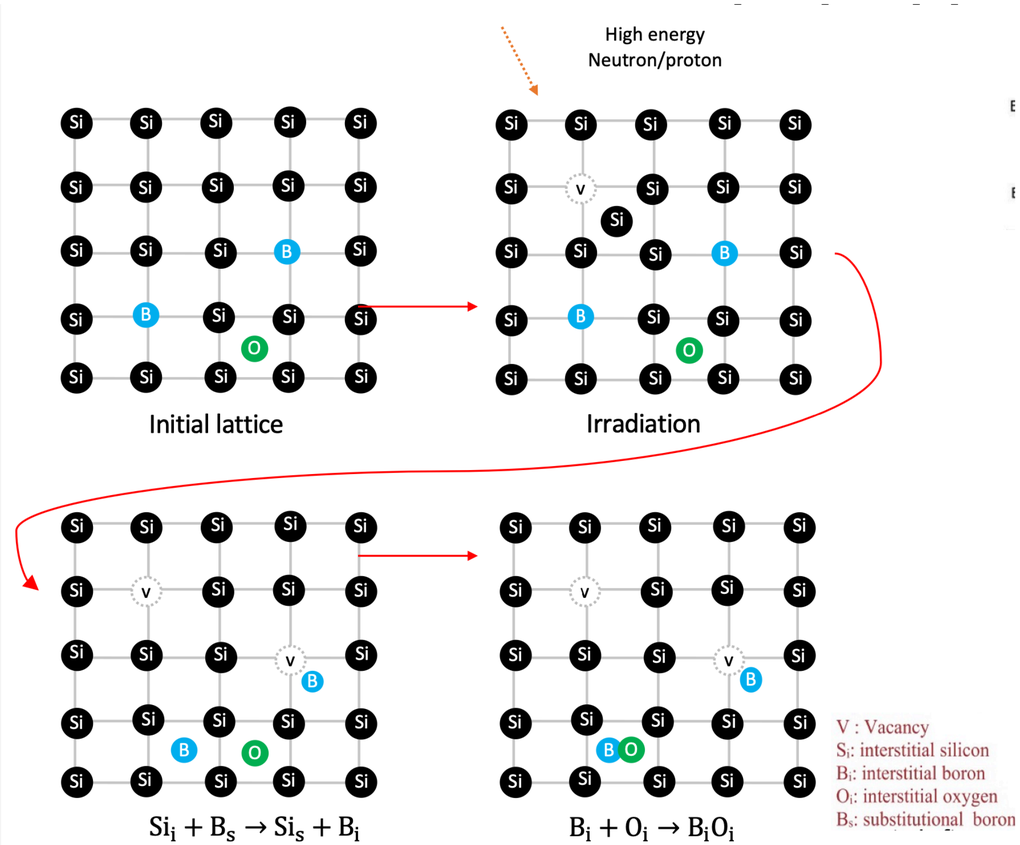
Low gain



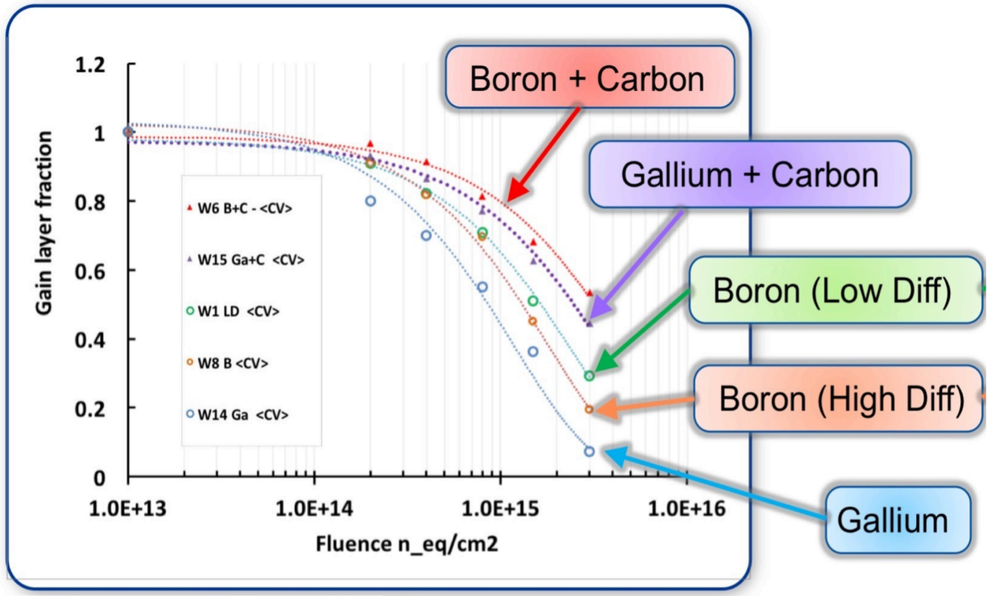
Thin detector

低增益雪崩探测器

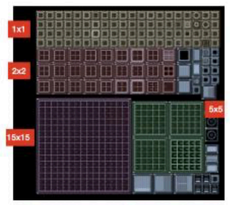
- HGTD 距离对撞点距离z=3.5m，强辐照区域，需要具备良好的抗辐照性能
- 辐照后，由于受体移除过程，增益层中有效参杂浓度减少
- 通过基底掺杂碳，使得$C_i + O_i$与$B_i + O_i$过程竞争，实现辐照后的最大增益



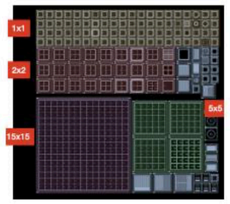
Acceptor (B_s) removal in the gain layer after irradiation



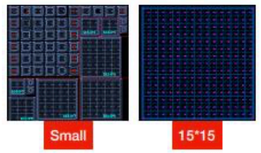
USTC LGAD的预生产



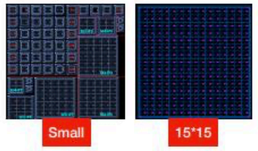
USTC-1.0
Deliver: 2020.7



USTC-1.1
Deliver: 2020.10

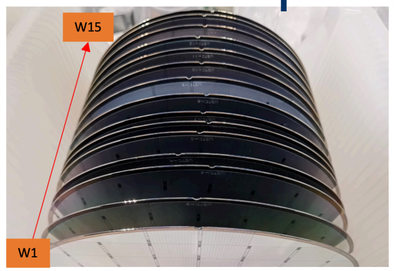


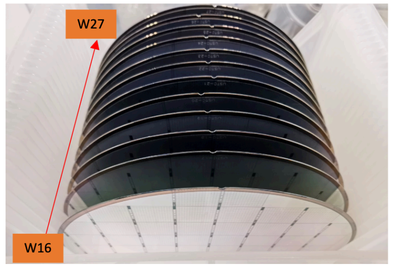
USTC-2.0
Deliver: 2021.4

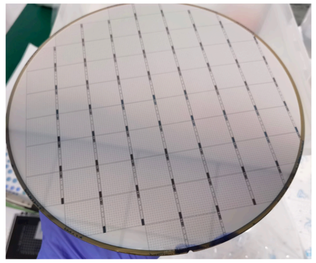


USTC-2.1
Deliver: 2021.10

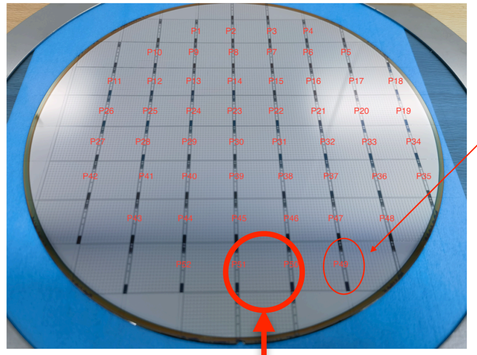
pre-production

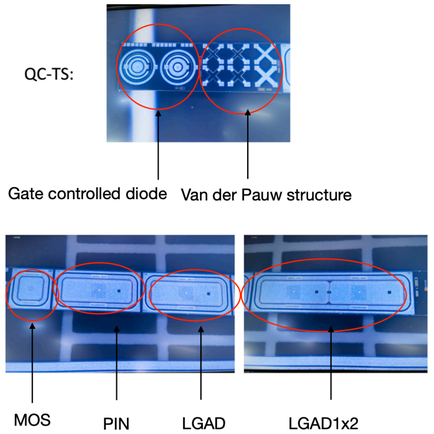




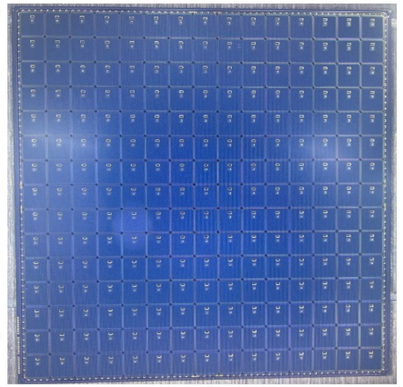


- 预生产以USTC-IME-V2.1-W17样品作为基准
- 27片晶圆，完成背面的减薄和镀金属
- 每片晶圆包含52个15x15 LGAD 阵列，和52个质量检测结构（QCTS）。QCTS用以检测和监控生产工艺和保证生产质量
- 目标至少获得9片合格晶圆，每片上合格传感器阵列数目大于18





15x15 LGAD array

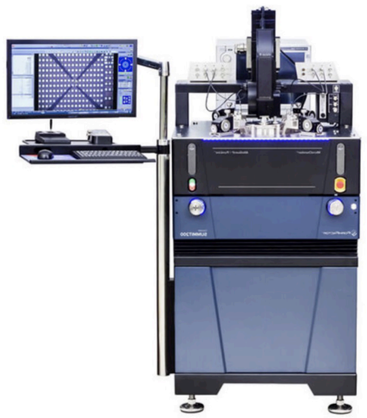


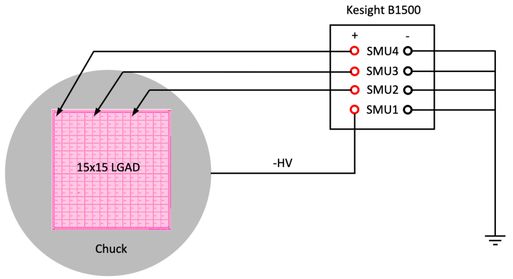
USTC LGAD的预生产

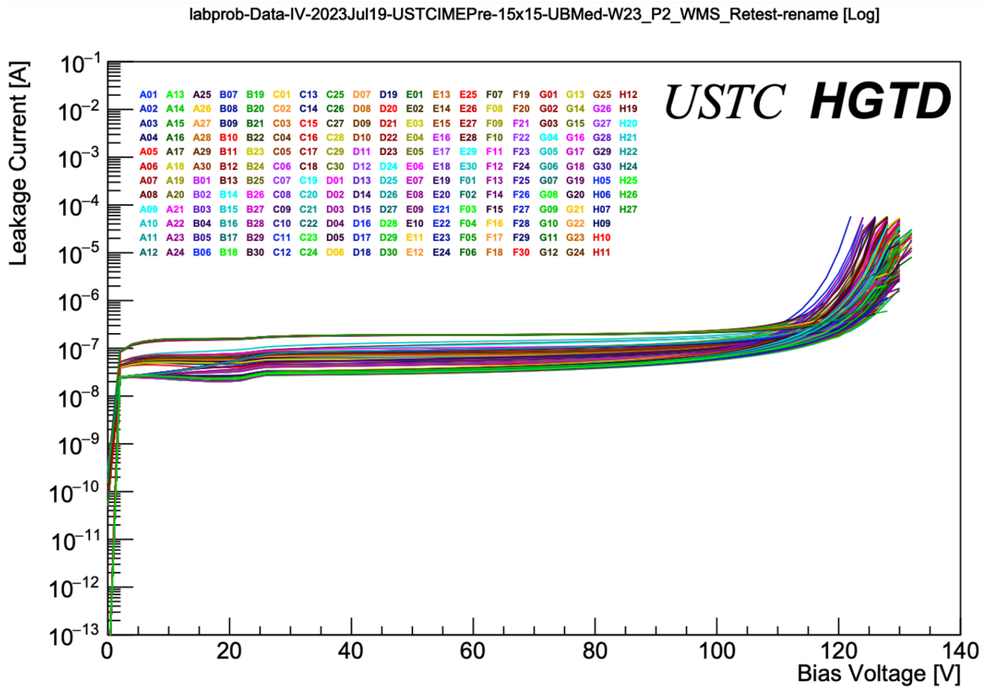
	指标	测试方法
均匀性	单个pad击穿电压不同位置差异小于5%，不同位置pad平均击穿电压差异小于8%	LGAD电压电流测试
时间分辨和电荷收集	收集电荷大于15fC 时间分辨小于40ps	放射源Beta谱测试
抗辐照性能 $2.5 \times 10^{15} n_{eq} cm^{-2}$	收集电荷大于4fC 时间分辨小于70ps	放射源Beta谱测试
生产工艺质量	质量检测结构测试结果与设计值一致	电压电流，电压电容测试

LGAD电流电压测试

- LGAD上正面pad和guard ring接地，背面接负高压，测试通过pad上电流
- 使用探针测试平台，一次同时测量3个LGAD
- 通过LGAD电压电流曲线，计算出击穿电压Vbd(pad上电流大于500nA)
- 对15x15的LGAD阵列Vbd进行数据统计分析

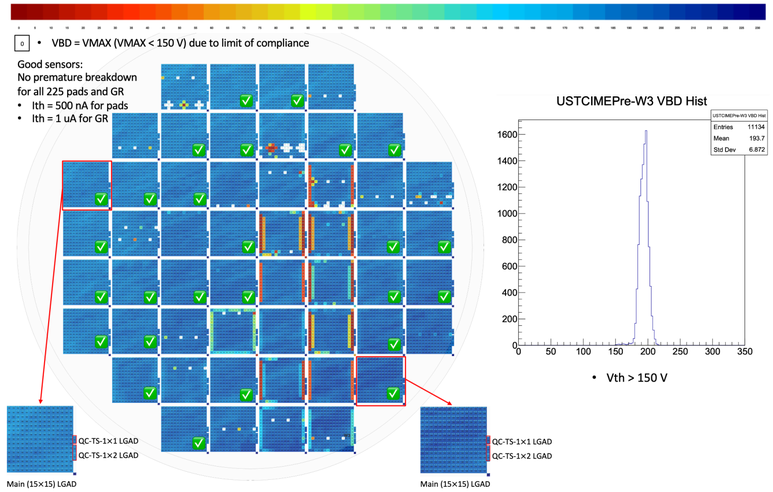






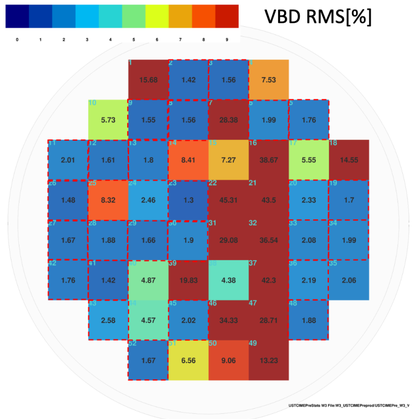
LGAD电流电压测试结果

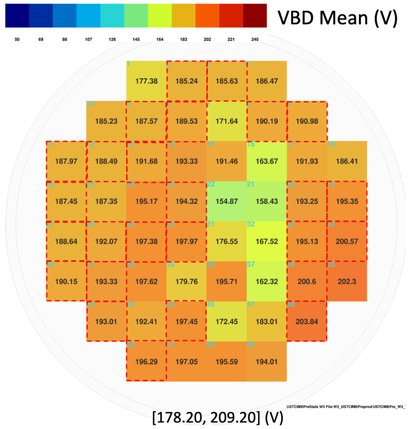
W3 – V_{BD} Histogram



• Vth > 150 V

W3 – V_{BD} RMS and Mean





$V_{bd,pad}$ spread over the Sensor*,○ | RMS($V_{bd,pad}$)/<$V_{bd,pad}$> <0.05

Good/Total: 26/52 ~ 50 %

[178.20, 209.20] (V)

Variation of the V_{bd} between different sensors | ±8% from the average V_{bd}

Good/Total: 26/52 ~ 50 %

• Combined results: yield ~ 50 %

Overview of USTC-IME Preproduction

Production version	Wafer No.	GL.Dose	Implantation	LGADs	VBD mean	Labelled	Thinned	Backside (Al)	UBMed	Diced	Yield	Quality
USTC-IME Pre-production	W1	Medimum	**B+1C**	15x15	**~ 182.8 V**	Done					17/52 ~ 33 %	
	W2	Medimum	**B+1C**	15x15	**~ 186.5 V**	Done	Done	Done		Done	2/52 ~ 4 %	
	W3	Medimum	**B+1C**	15x15	**~ 193.7 V**	Done	**Done**	**Done**	**Done**		**26/52 ~ 50 %**	**Good**
	W4	Medimum	**B+1C**	15x15	**~ 190.8 V**	Done	**Done**	**Done**	**Done**		**24/52 ~ 46 %**	**Good**
	W5	Medimum	**B+1C**	15x15	**~ 191.7 V**	Done	**Done**	**Done**	**Done**		**24/52 ~ 46 %**	**Good**
	W6	Medimum	**B+1C**	15x15	**~ 188.5 V**	Done	**Done**	**Done**	**Done**		**22/52 ~ 42 %**	**Good**
	W7	Medimum	**B+1C**	15x15	**~ 184.9 V**	Done	**Done**	**Done**	**Done**		**22/52 ~ 42 %**	**Good**
	W8	Medimum	**B+1C**	15x15	**~ 186.2 V**	Done	**Done**	**Done**	**Ready**		**22/52 ~ 42 %**	**Good**
	W9	Medimum	**B+1C**	15x15	**~ 195.6 V**	Done					13/52 ~ 25 %	
	W10	Medimum	**B+1C**	15x15	**~ 193.6 V**	Done					16/52 ~ 31 %	
	W11	Medimum	**B+1C**	15x15	**~ 192.3 V**	Done	**Done**	**Done**	**Ready**		**26/52 ~ 50 %**	**Good**
	W12	Medimum	**B+1C**	15x15	**~ 193.1 V**	Done	Done	Done		Done	13/52 ~ 25 %	
	W13	Medimum	**B+1C**	15x15	**~ 188.8 V**	Done	**Done**	**Done**	**Ready**		**21/52 ~ 40 %**	**Good**
	W14	Medimum	**B+1C**	15x15	**~ 191.6 V**	Done	**Done**	**Done**	**Ready**		**18/52 ~ 35 %**	**Good**
	W15	Medimum	**B+1C**	15x15	**~ 193.0 V**	Done			Done	Done	12/52 ~ 23 %	
	W16	Medimum	**B+1C**	15x15	~ 152.4 V	Done					23/52 ~ 44 %	
	W17	Medimum	**B+1C**	15x15	~ 150.4 V	Done					27/52 ~ 52 %	
	W18	Medimum	**B+1C**	15x15	~ 137.7 V	Done					25/52 ~ 48 %	
	W19	Medimum	**B+1C**	15x15	~ 146.5 V	Done					26/52 ~ 50 %	
	W20	Medimum	**B+1C**	15x15	~ 138.9 V	Done					20/52 ~ 36 %	
	W21	Medimum	**B+1C**	15x15	~ 127.5 V	Done					17/52 ~ 33 %	
	W22	Medimum	**B+1C**	15x15	~ 143.6 V	Done					18/52 ~ 35 %	
	W23	Medimum	**B+1C**	15x15	~ 130.6 V	Done			Done	Done	15/52 ~ 29 %	
	W24	Medimum	**B+1C**	15x15	~ 151.8 V	Done	Done	Done		Done	21/52 ~ 40 %	
	W25	Medimum	**B+1.3C**	15x15	~ 116.9 V	Done	Done	Done		Done	10/52 ~ 18 %	
	W26	Medimum	**B+1.5C**	15x15	~ 111.8 V	Done	Done	Done		Done	13/52 ~ 25 %	
	W27	Medimum	**B+0.7C**	15x15	~ 158.1 V	Done	Done	Done		Done	25/52 ~ 48 %	

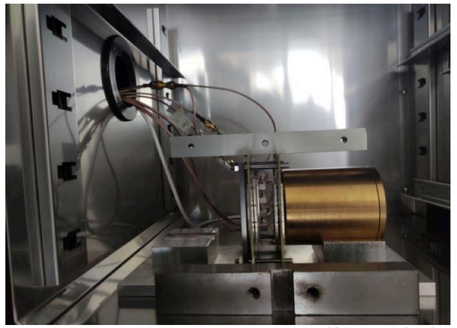
Normal VBD

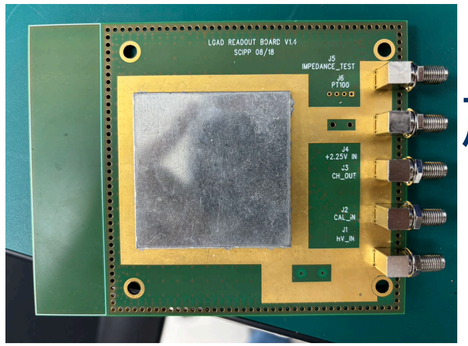
Low VBD

*VBD: the voltage where the pad's leakage current is 500 nA. The "Good" quality means the yield isn't smaller than 18/52 (~35%)

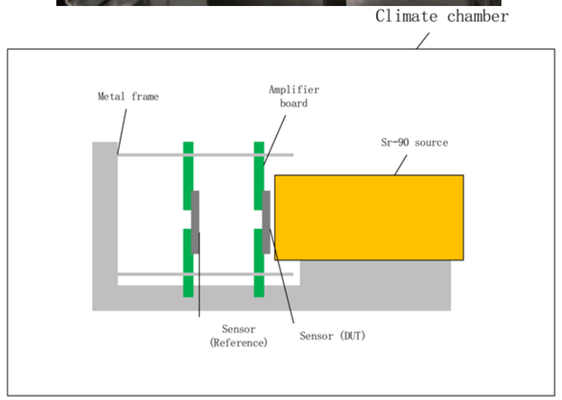
收集电荷和时间分辨测试

- 测试设备： Sr-90放射源，电压源，示波器，触发器
- 测试温度：-30摄氏度
- 未辐照前时间分辨和电荷收集的结果和基准样品一致(USTC-IME-v2.1-W17)
- 满足设计要求时间分辨率小于40ps，收集电荷大于15fC

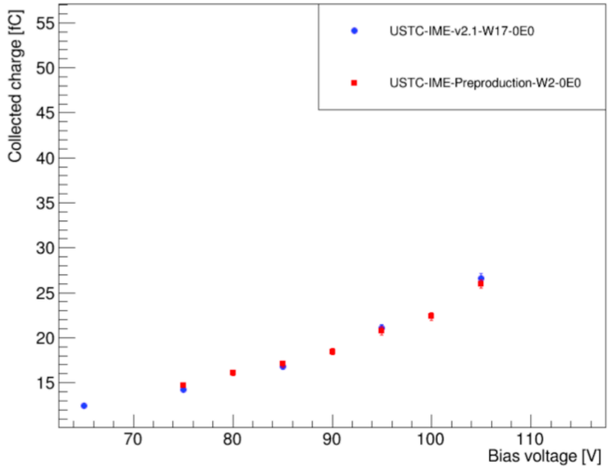


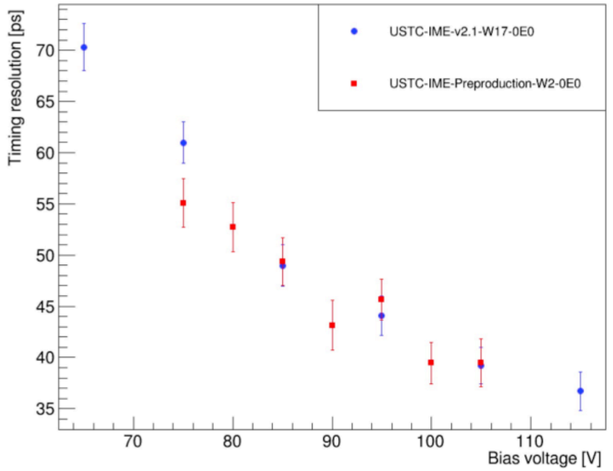


放大板



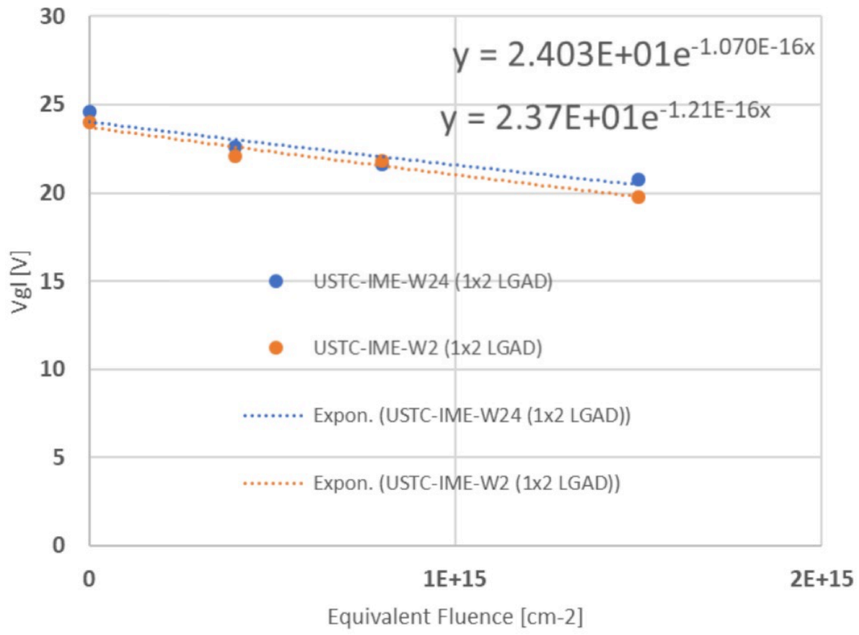
温控箱

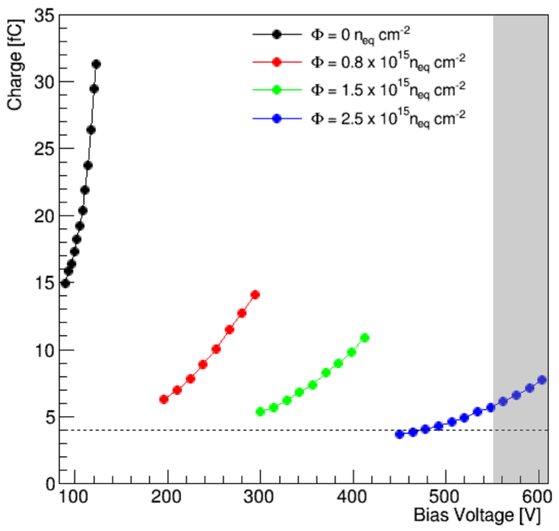


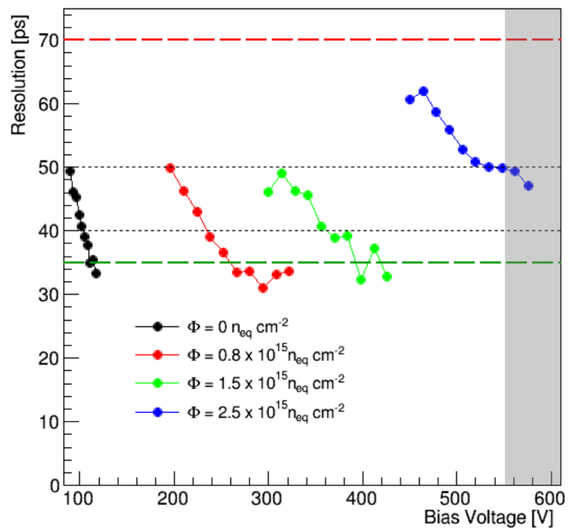


LGAD抗辐照性能测试

- 对传感器进行了辐照强度为 4×10^{14}，8×10^{14}，1.5×10^{15}，2.5×10^{15} n_{eq}/cm^2的中子辐照
- C-factor可以通过耗尽电压获得 $V_{gl}(\Phi_{eq})/V_{gl}(0)=e^{-c\Phi_{eq}}$，在预生产中的样品C-factor 为 $1.21\times10^{-16}cm^2$，与基准值 $1.23\times10^{-16}cm^2$一致（测试结果来自JSI）
- 在2.5×10^{15} n_{eq}/cm^2的辐照强度下，收集电荷大于4fC，时间分辨好于70ps

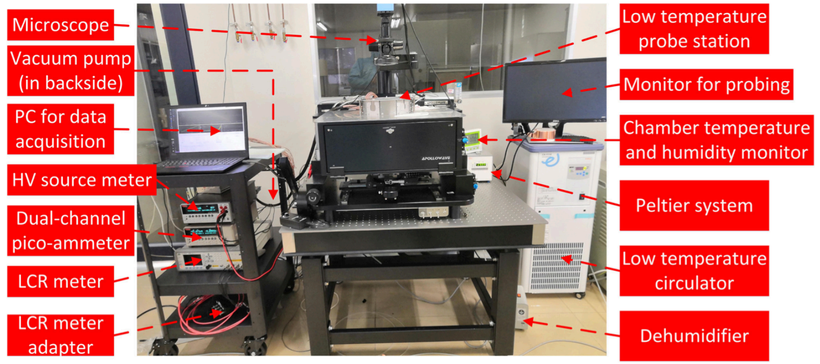




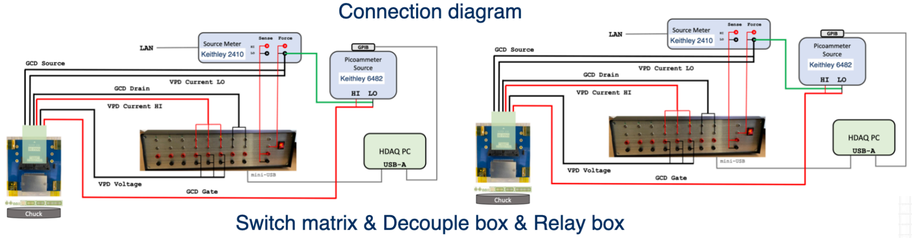


质量检测结构（QCTS）

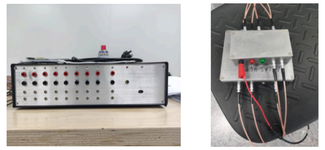
- QCTS用以检测晶圆的生产工艺和监控生产过程，对预生产起到指导作用
- QCTS结构
  - LGAD
  - PIN二极管
  - MOS 电容
  - 范德堡结构
  - 栅控二极管
- QCTS测试
  - LGAD, PIN, 栅控二极管的电流电压测试
  - LGAD, MOS的电容电压测试
  - 范德堡结构电阻测试

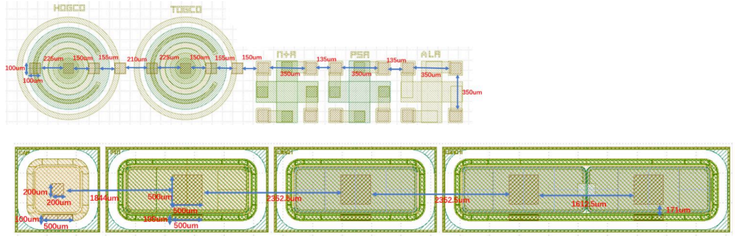


Connection diagram



Switch matrix & Decouple box & Relay box



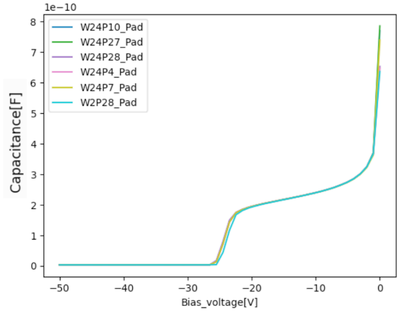


质量检测结构测试结果

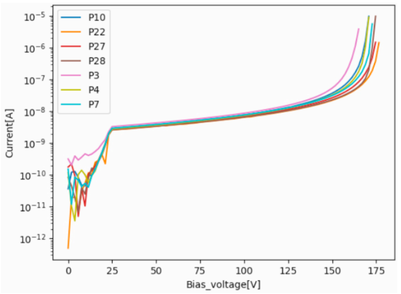
参数	结果
MOS氧化层厚度	～1微米
PIN电流	1E-10安培
N+ vdp 电阻	37欧姆
P-stop 电阻	34欧姆
AL电阻	0.002欧姆

- 对QCTS结构进行了测试，得到多个参数均符合预期值
- 为后续正式大规模生产提供指导，并且为其他机构提供数据参考

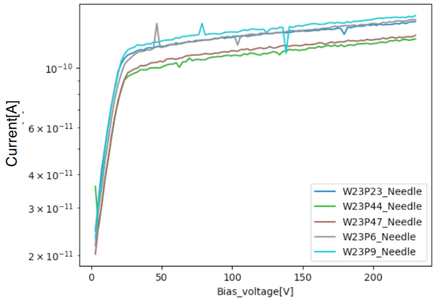
LGAD CV



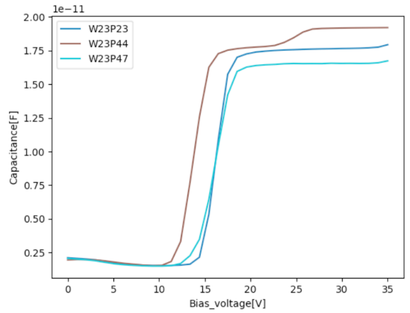
LGAD IV



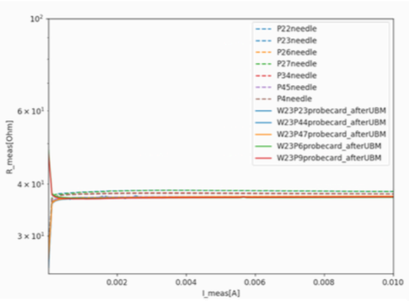
PIN_IV



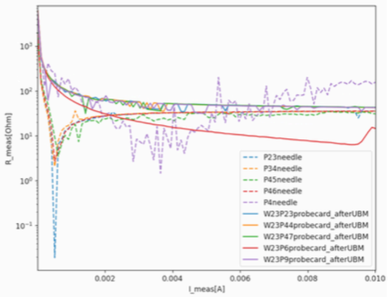
MOS_CV



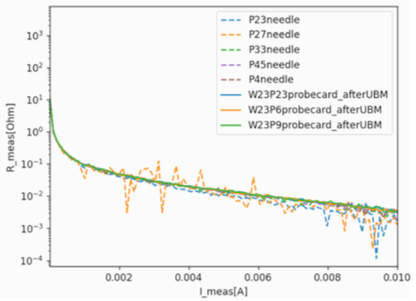
N+A



PSA



ALA

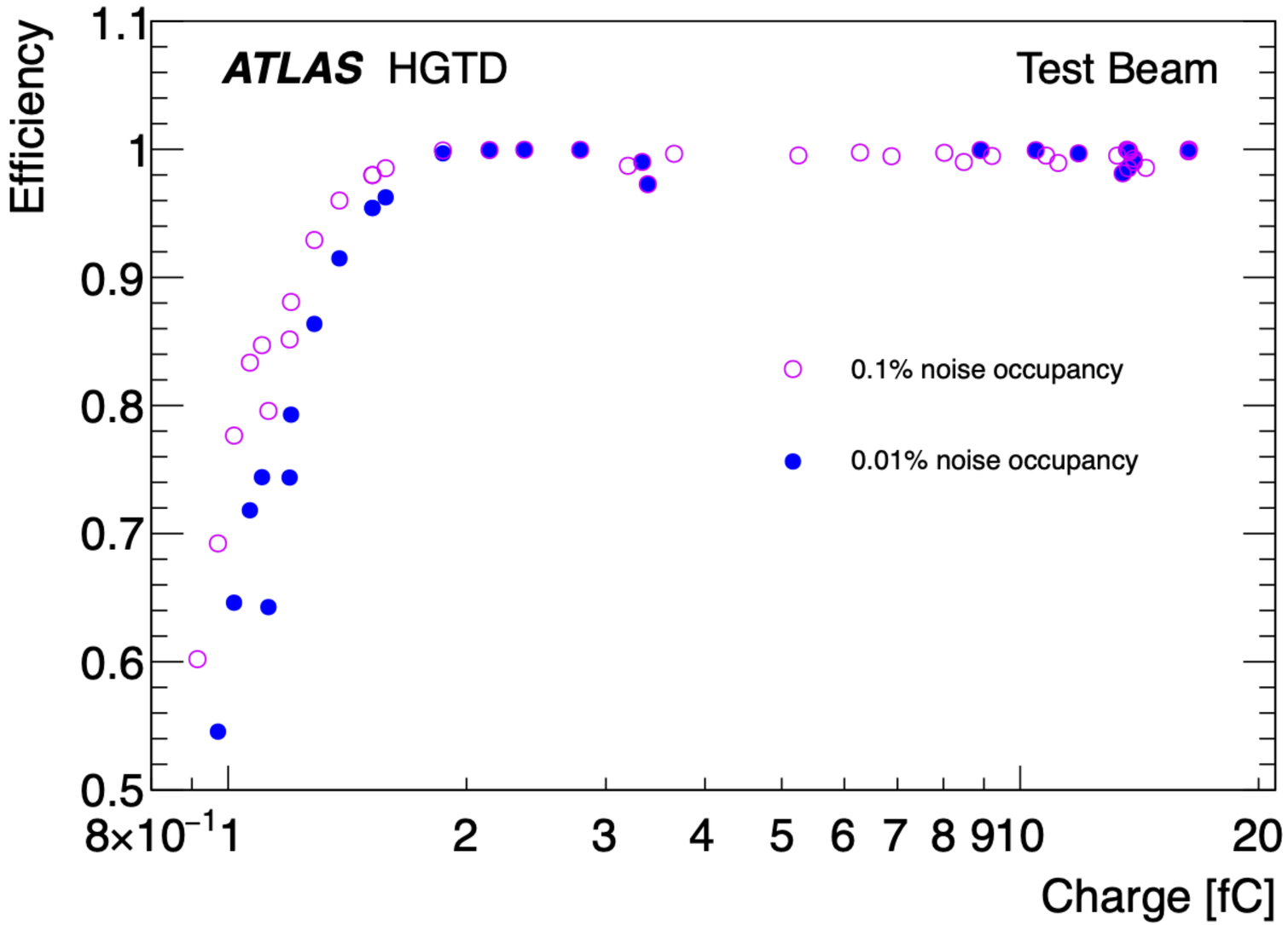


总结

- 总结
  - 具有良好时间分辨和抗辐照性能的LGAD将作为传感器用于ATLAS实验第二阶段升级中
  - USTC HGTD 课题组对预生产阶段的晶圆进行了全面测试，选择出了九片合格晶圆
  - 在未辐照前，LGAD的时间分辨好于40ps，收集电荷大于15fC ，满足要求
  - 在辐照后，LGAD C-factor为1.21×10^{-16}cm^2 ，时间分辨好于70ps，收集电荷大于4fC ，证明了LGAD具有良好的抗辐照性能
  - 对QCTS结构进行了测试，参数均在预期范围内，对预生产起到了监控作用
  - 目前科大已经完成了LGAD预生产的全部工作，符合要求的LGAD已交付ATLAS

Thanks

Efficiency


ATLAS HGTD
Test Beam
Efficiency
1.1
1
0.9
0.8
0.7
0.6
0.5
0.1% noise occupancy
0.01% noise occupancy
8×10⁻¹
1
2
3
4
5
6
7
8
9
10
20
Charge [fC]