超导单光子量子器件

张蜡宝
南京大学电子科学与工程学院

目录

Email: Lzhang@nju.edu.cn

1. 超导体与超导电子学

1908年，荷兰物理学家昂纳斯首次成功地把称为“永久气体”的氦液化，因而获得4.2K 的低温源，为超导发现准备了条件。三年后即1911年，在测试纯金属电阻率的低温特性时，昂纳斯又发现，汞的直流电阻在4.2K时突然消失，多次精密测量表明，汞柱两端压降为零，他认为这时汞进入了一种以零阻值为特征的新物态，并称为“超导态”。

Email: Lzhang@nju.edu.cn

超导体的基本性质

零电阻效应

迈斯纳效应(完全抗磁性)

超导态的临界参数

约瑟夫森效应

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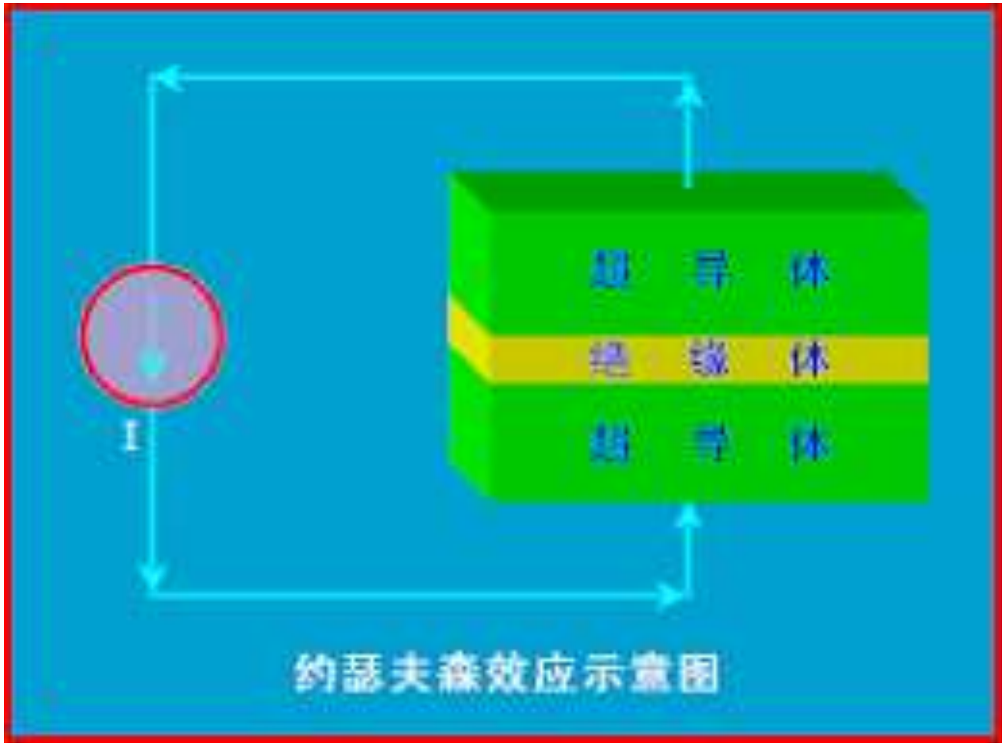
约瑟夫森效应与超导电子学



这种电子对通过超导的约瑟夫森结中势垒而形成超导电流的现象叫超导隧道效应，也叫约瑟夫森效应(Josephson Effect)。

Email: Lzhang@nju.edu.cn

约瑟夫森预言，当绝缘层的厚度只有几十埃时，电子对可以越过绝缘层形成电流，而隧道结两端没有电压，即绝缘层也成了超导体。

约瑟夫森的这一重要发现为超导体中电子对运动提供了证据。约瑟夫森效应成为微弱电磁信号探测和其他电子学应用的基础。诞生了一门新的学科——超导电子学。

B.D. Josephson

1973年，Nobel Prize.

超导电子学

超导电子学(superconductor electronics)是超导体物理与电子技术相结合的一门科学，以超导体的约瑟夫逊效应等为基础，主要研究物体处于超导状态下超导电子所具有一系列效应的理论、技术和应用。

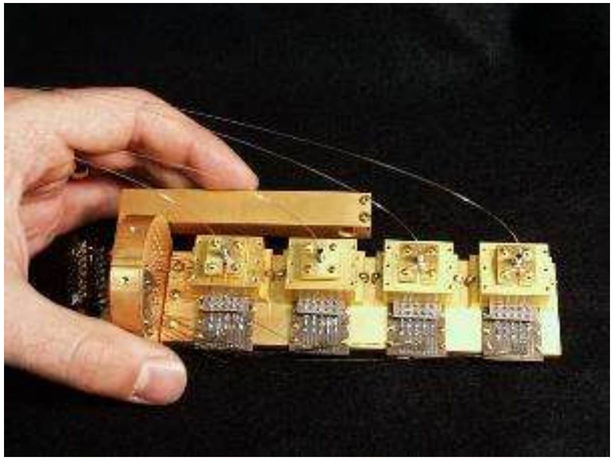
吴培亨 院士

约瑟夫逊效应、超导量子干涉仪、超导数字电路、超导滤波器、超导单光子探测器......

Superconducting nanowire single-photon detector (SNSPD)
Superconducting transition-edge sensor (TES)

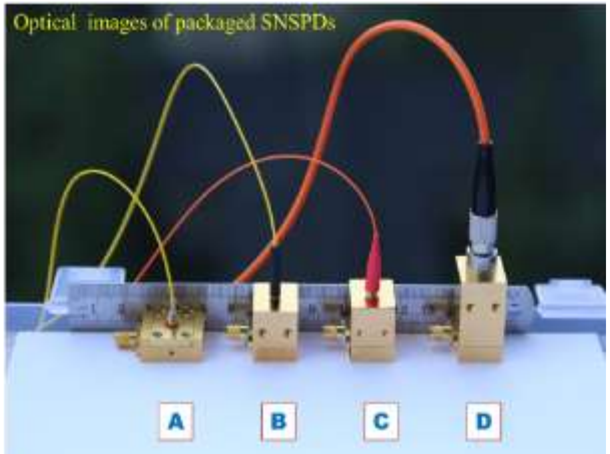
高灵敏光子探测技术

光电倍增管



TES

雪崩二极管



SNSPD

Email: Lzhang@nju.edu.cn

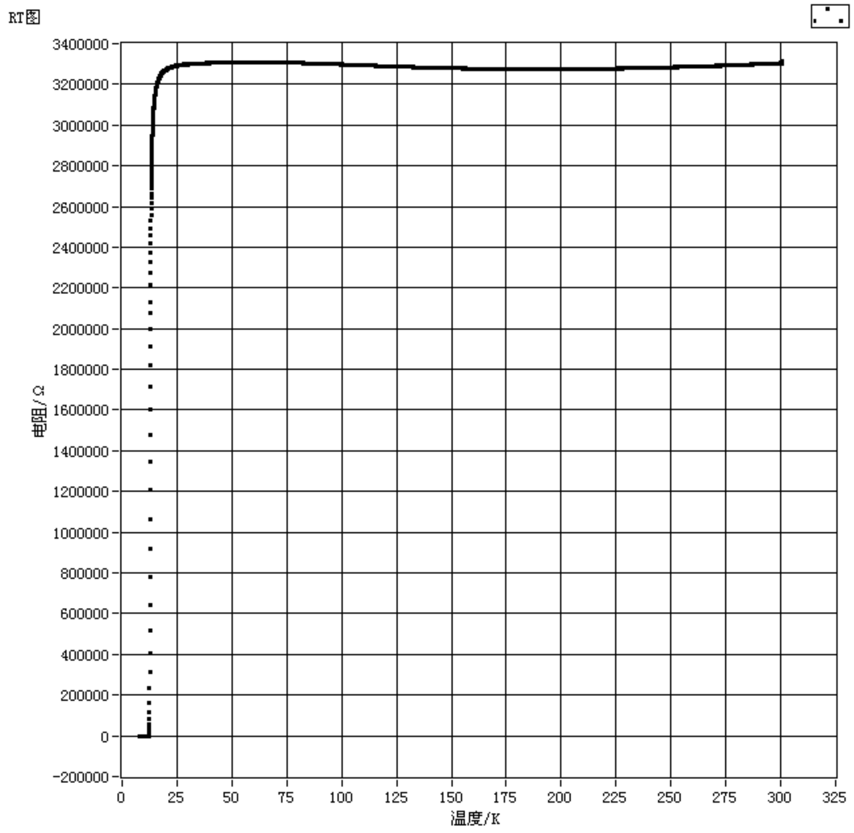
常用单光子探测器

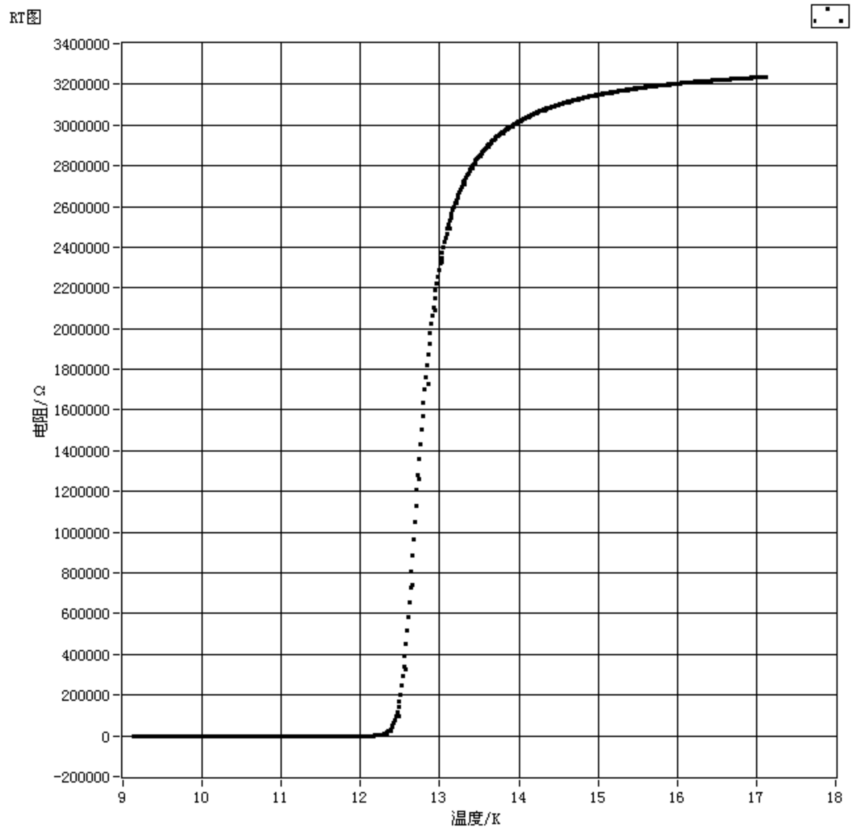
	光电倍增管	雪崩二极管	TES	SNSPD
响应波段			☺	☺
量子效率			☺	☺
暗计数			☺	☺
探测速度		☺		☺
光子数分辨			☺	
时间分辨率				☺
工作温度	☺	☺		
像元数	☺		☺	

2. 超导临界转变单光子探测器(TES)

零电阻效应

将超导体冷却到临界温度（T_C）以下时电阻突然降为零的现象称为超导体的零电阻现象。





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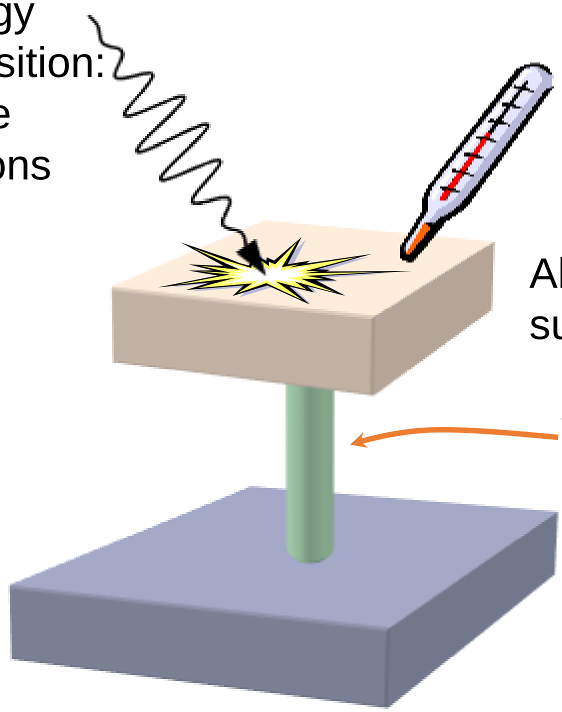
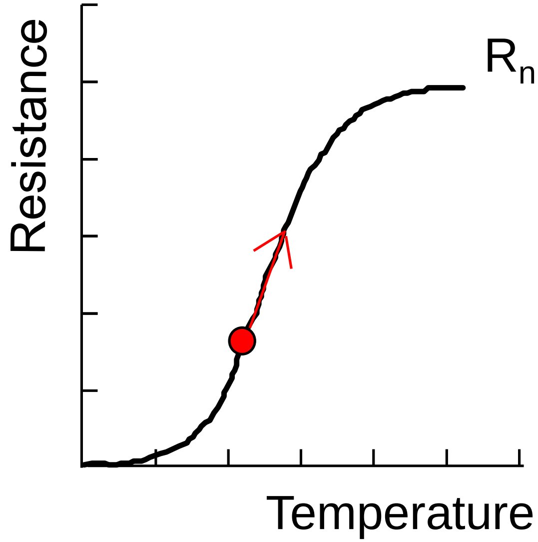
Transition Edge Sensor (TES)



Resistance vs. temperature dependence for W



Calorimetric detection of X-ray/UV/optical/IR photons:
Photon(s) are absorbed by a W ultrathin film, very connected to a thermal sink.

Temperature of the absorber is monitored by an ultra-sensitive thermometer (superconducting-to-normal transition).

Email: Lzhang@nju.edu.cn

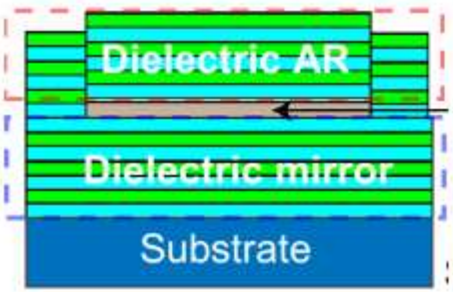
材料与结构

- Relatively high T_c superconductor
  - Improve response time, time jitter and timing resolution
  - Titanium T_c~360 mK

T_c of superconductors

W	100 mK
Ir	112 mK
Hf	165 mK
Ti	360 mK

- Multi-layered optical cavity structure
  - Anti-reflection/TES/High reflection mirror
  - Dielectric films of Ta_2O_5 and SiO_2
  - High absorption and wide bandwidth
  - Optimized at any wavelength



D. Fukuda, Proc. SPIE 7236C(2009)

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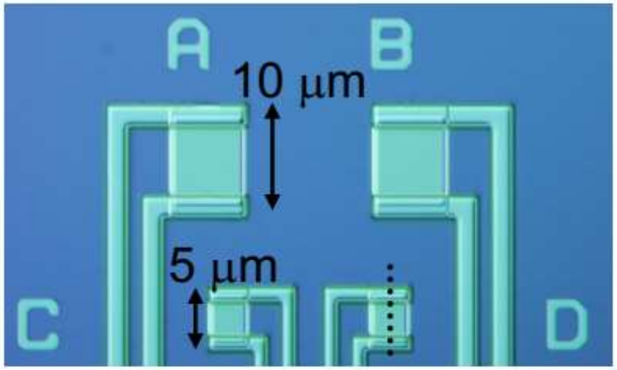
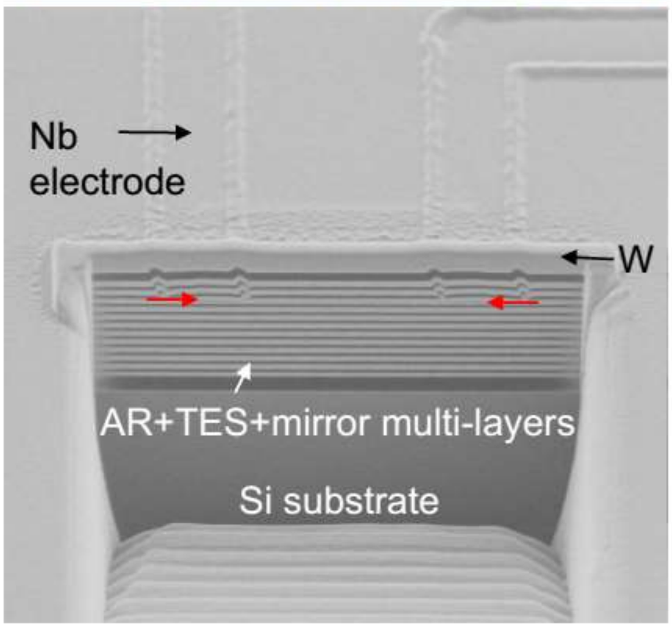
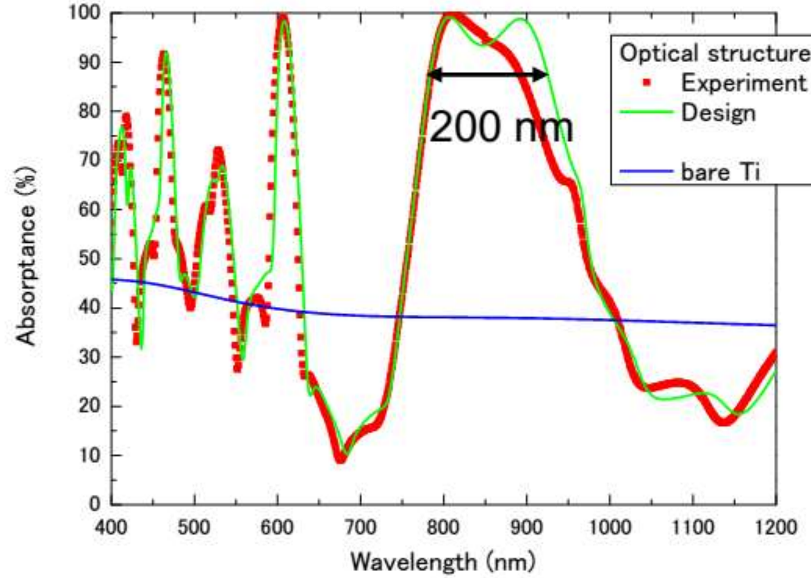
Ti-TES with optical cavity



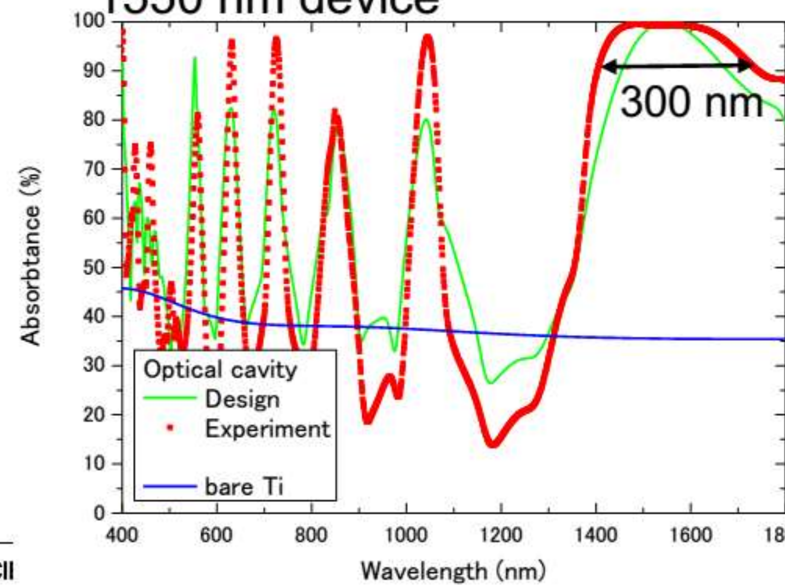


D. Fukuda, *Opt.Express*, **19**, 870, (2011)

850 nm device

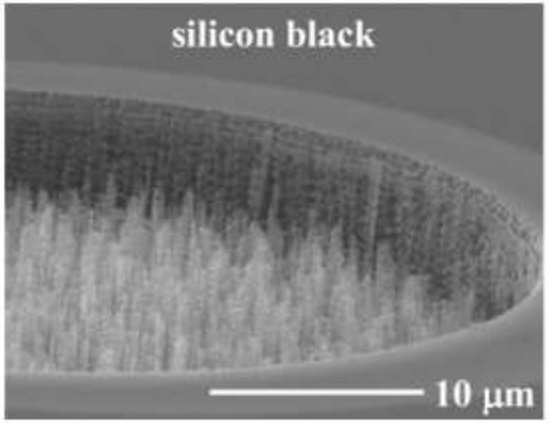


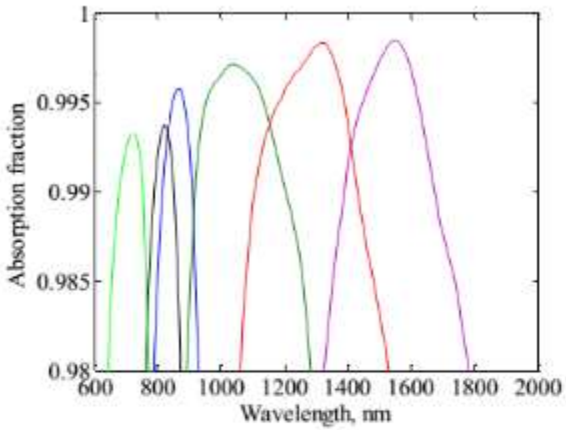
1550 nm device



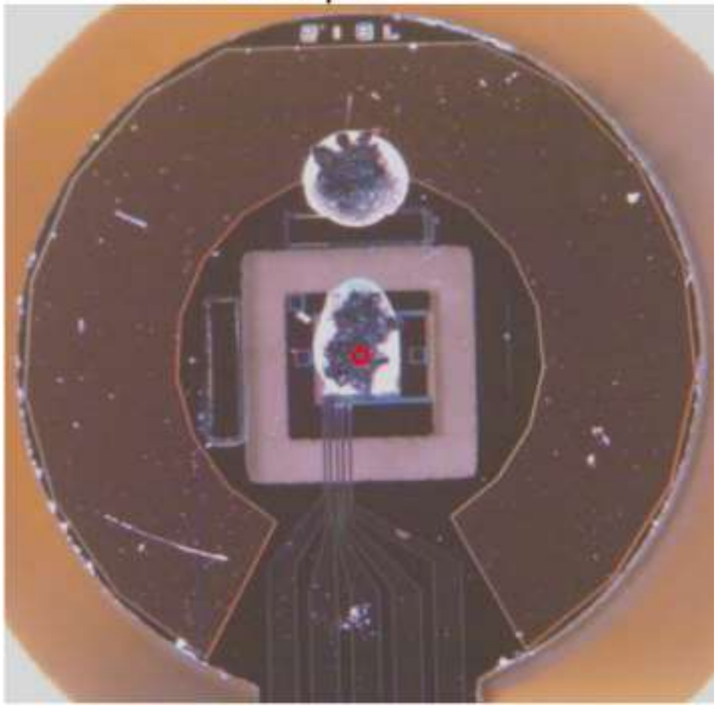
吸收体：

Absorber





- epoxy used to attach multiwall carbon nanotubes over the TES
  - Nanocyl, > 99% absorption from visible to 10 μm



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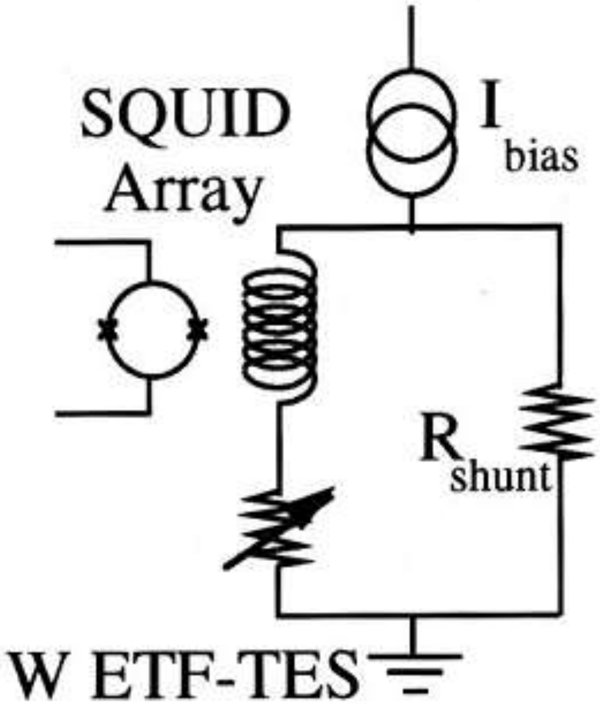
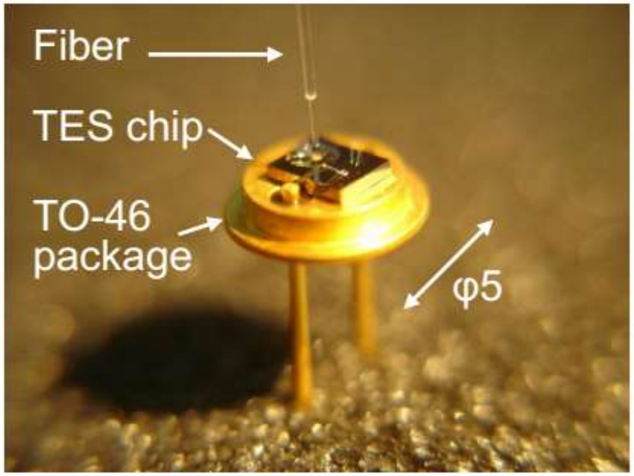
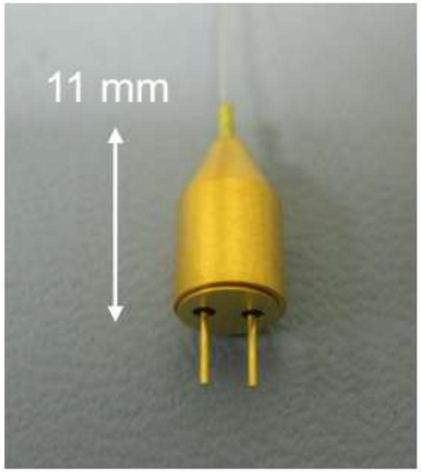
读出电路

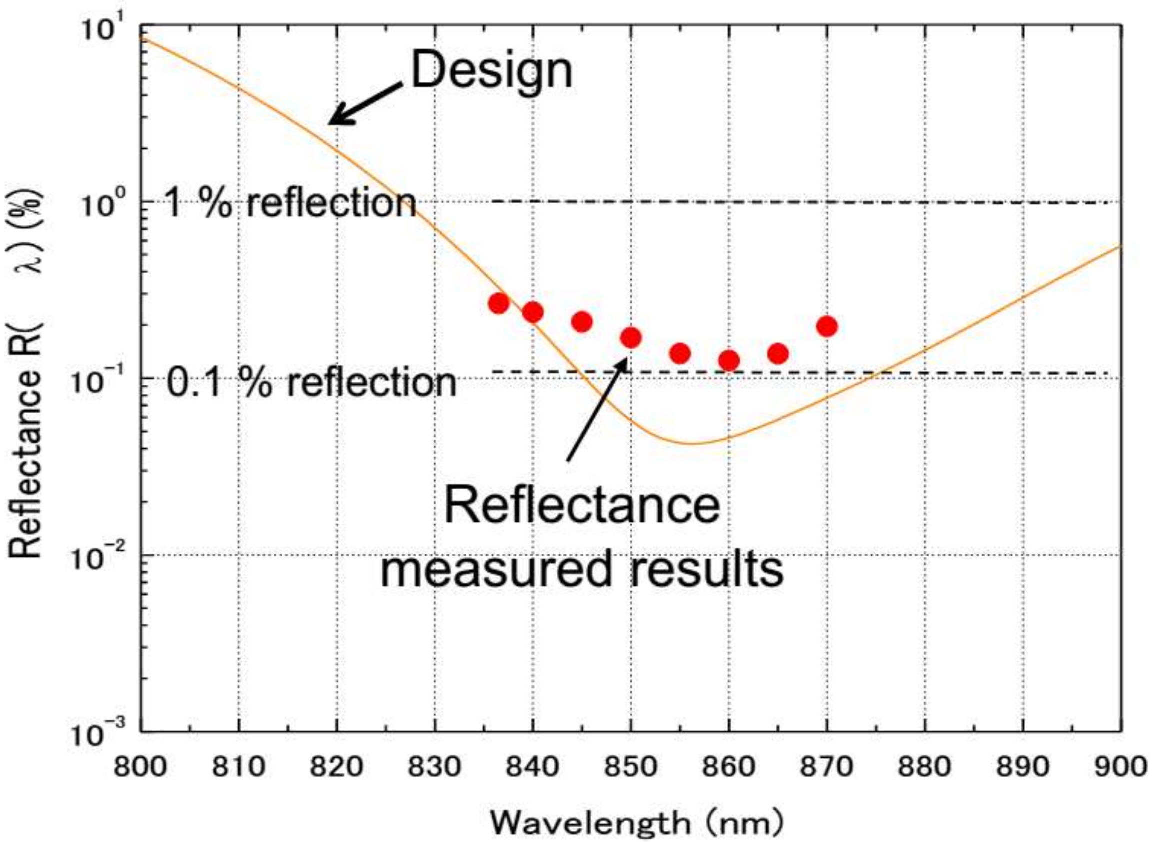


日本产业技术综合研究所(AIST)TES封装与光耦合

Fiber coupled TES device



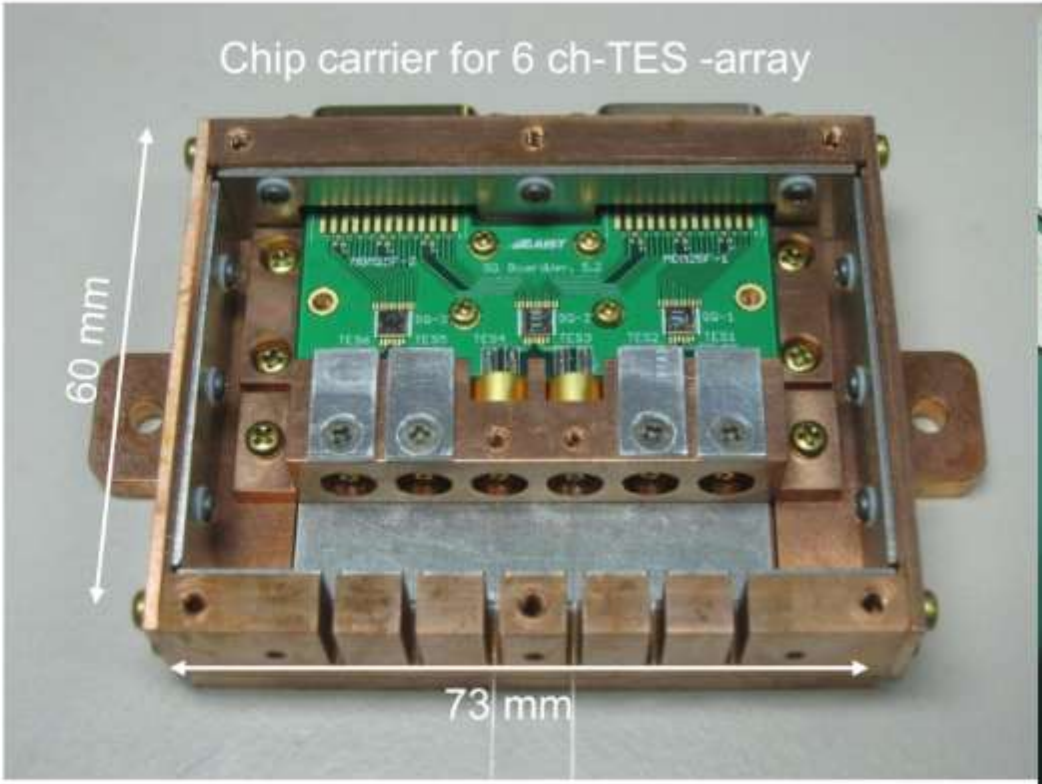




•The reflectance of the fiber coupled device was measured with return loss measurement method (IEC 61300-3-6).

Email: Lzhang@nju.edu.cn

日本产业技术综合研究所(AIST)TES实验测量系统



- A chip carrier for 6-ch TES array is placed in cryogen free ADR(adiabatic demagnetization refrigerator)
- Turn-key operation in ADR, the minimum temperature~50 mK

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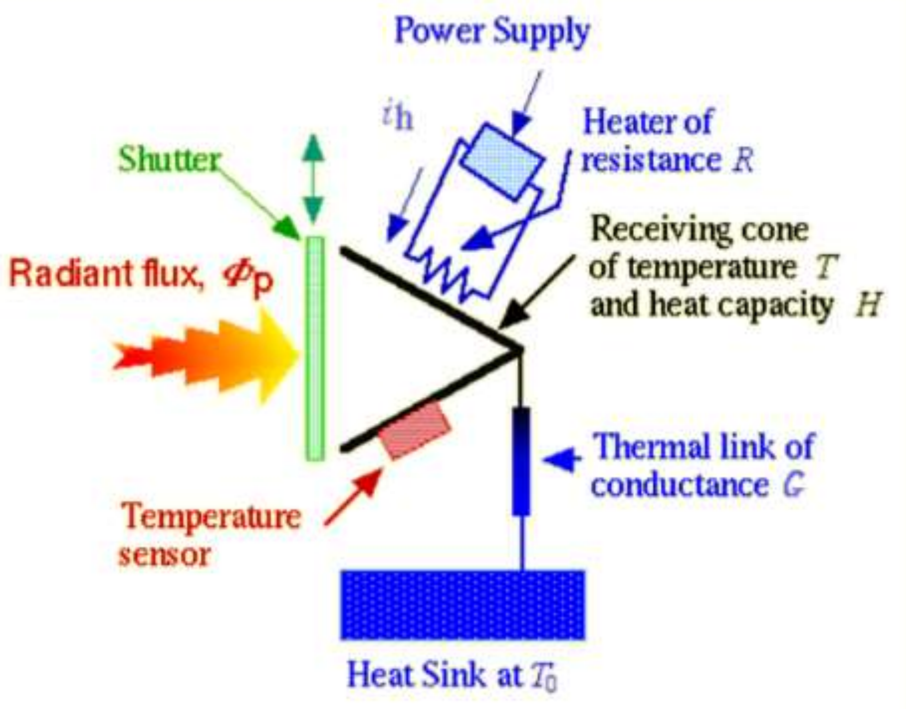
美国国家标准局(NIST)TES实验测量系统

Radiometry

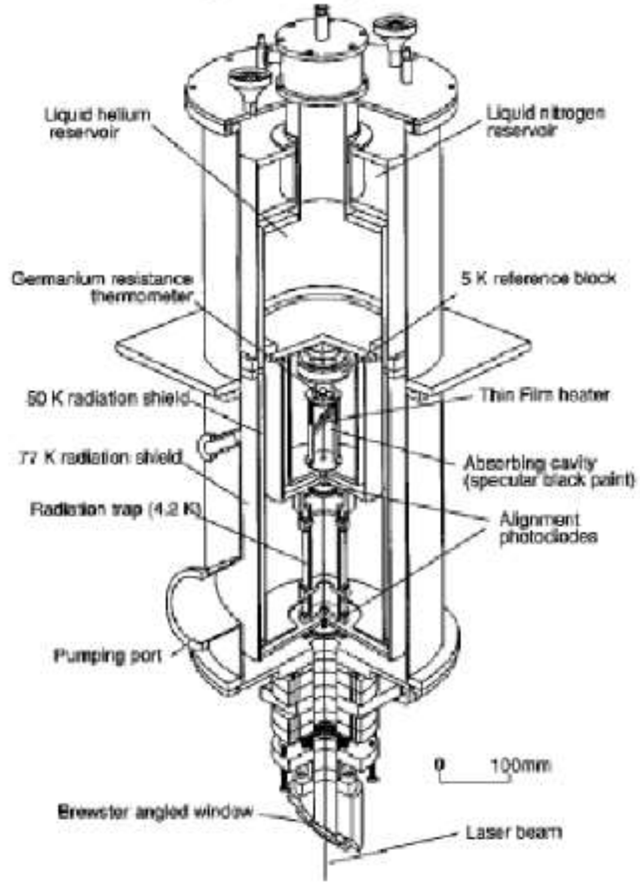
Electrical Substitution Radiometry



From NIST Technical Note 1421, A. Parr

Optical Power = Electrical Power

High-Accuracy Cryogenic Radiometer (HACR) 1980s

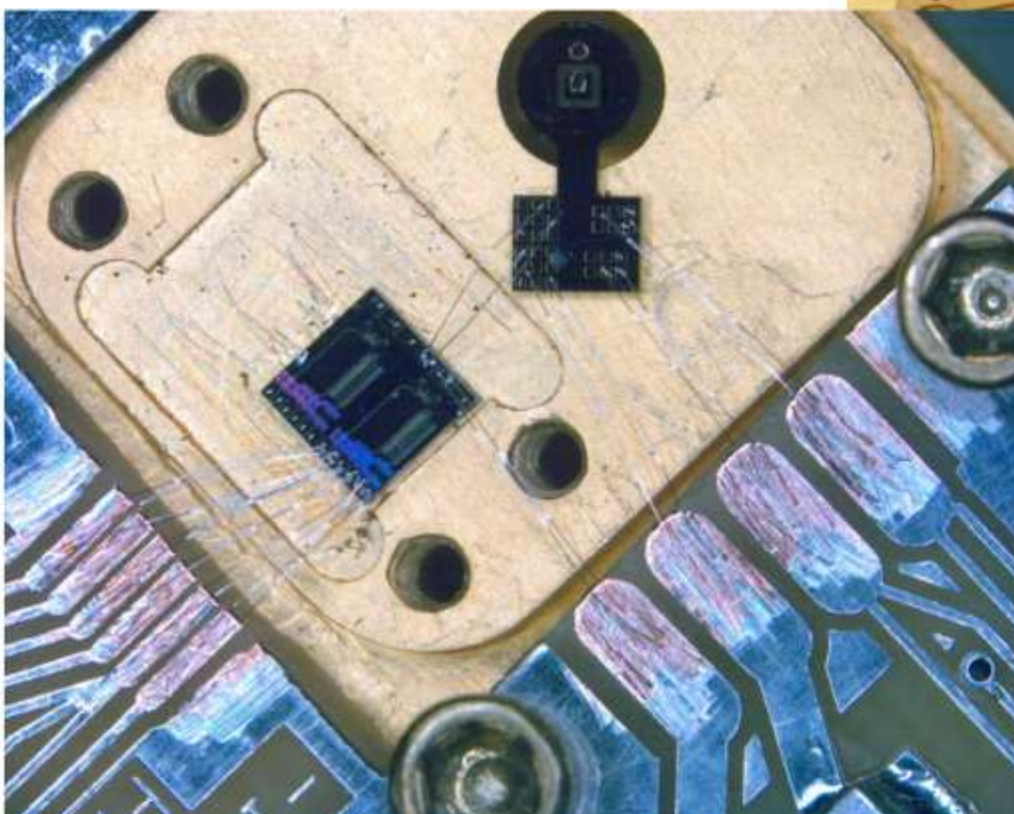


Laser Optimized Cryogenic Radiometer (LOCR) 1990s

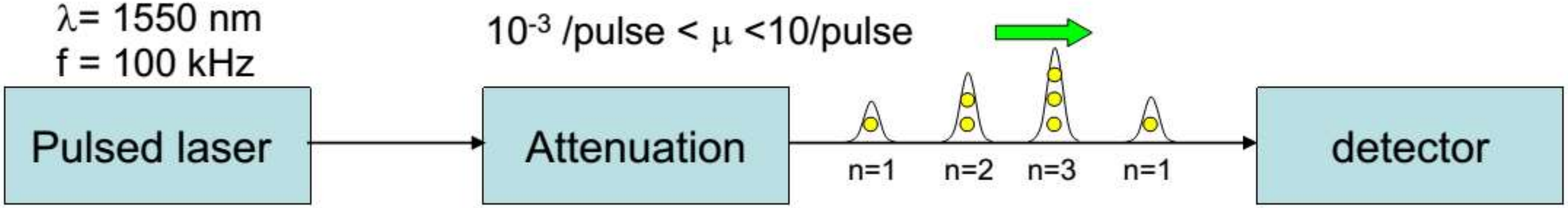
Email: Lzhang@nju.edu.cn

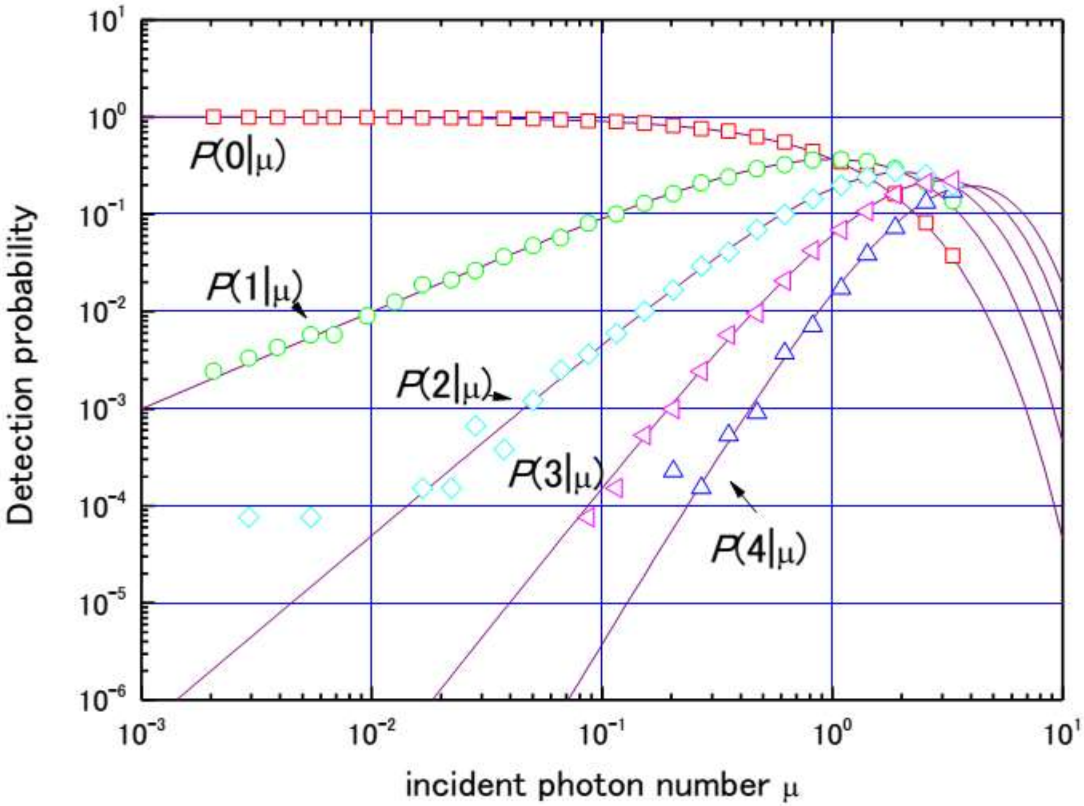
美国国家标准局(NIST)TES封装与光耦合

Complete radiometer



Detection efficiency





Photon detection probability with a free parameter η,

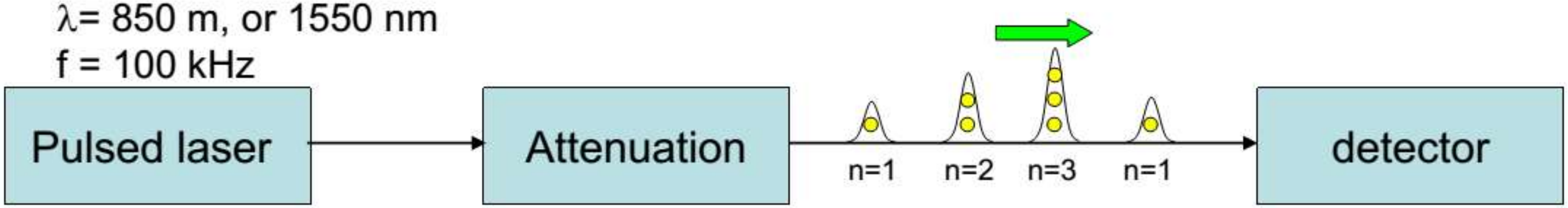
$$P_\eta(n \mid \mu) = \frac{(\eta\mu)^n e^{-\eta\mu}}{n!}$$

μ: Incident average photon number
n: Photon number
η: Detection efficiency

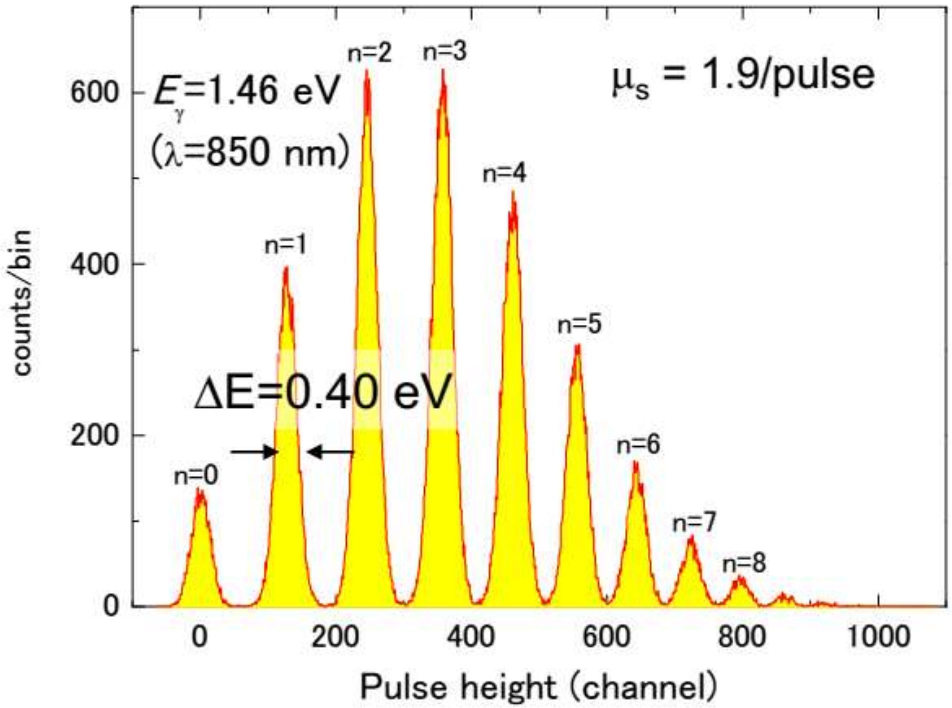
$\eta = 98\,\% \pm 1\,\%$ @ 844 nm (k=1)

Photon number resolving capability

λ= 850 m, or 1550 nm
f = 100 kHz



10 μm size device@ 850 nm(Ti-TES)



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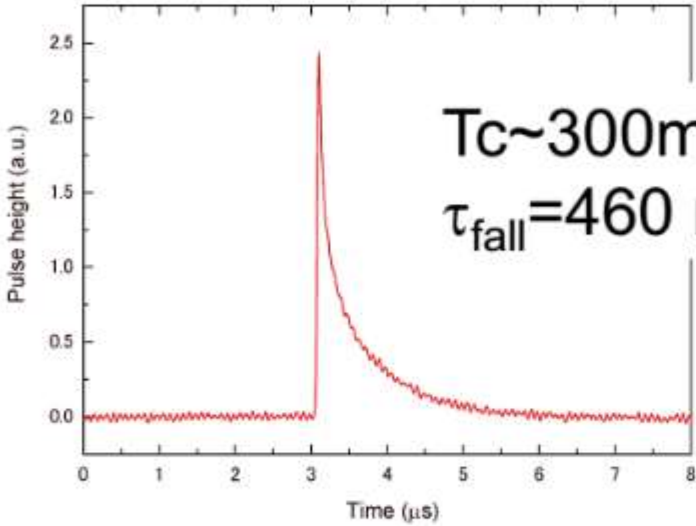
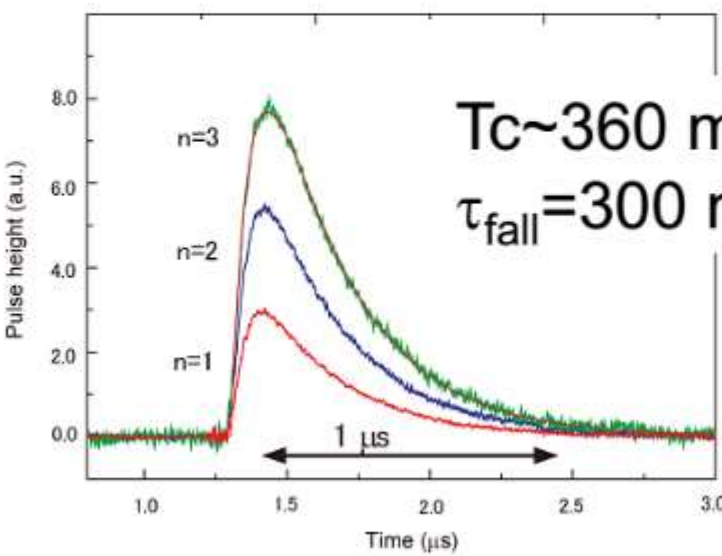
Response speed

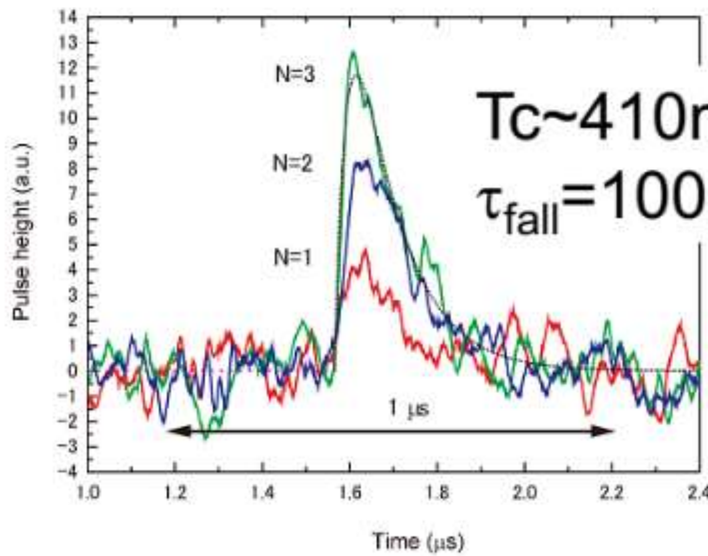


Tc~300mK
τ_{fall}=460 ns

$$\tau_{fall} = \frac{\gamma\rho}{5\Sigma T_c^{\,3}} \frac{1}{1+\alpha/n} \propto T_c^{-3}$$

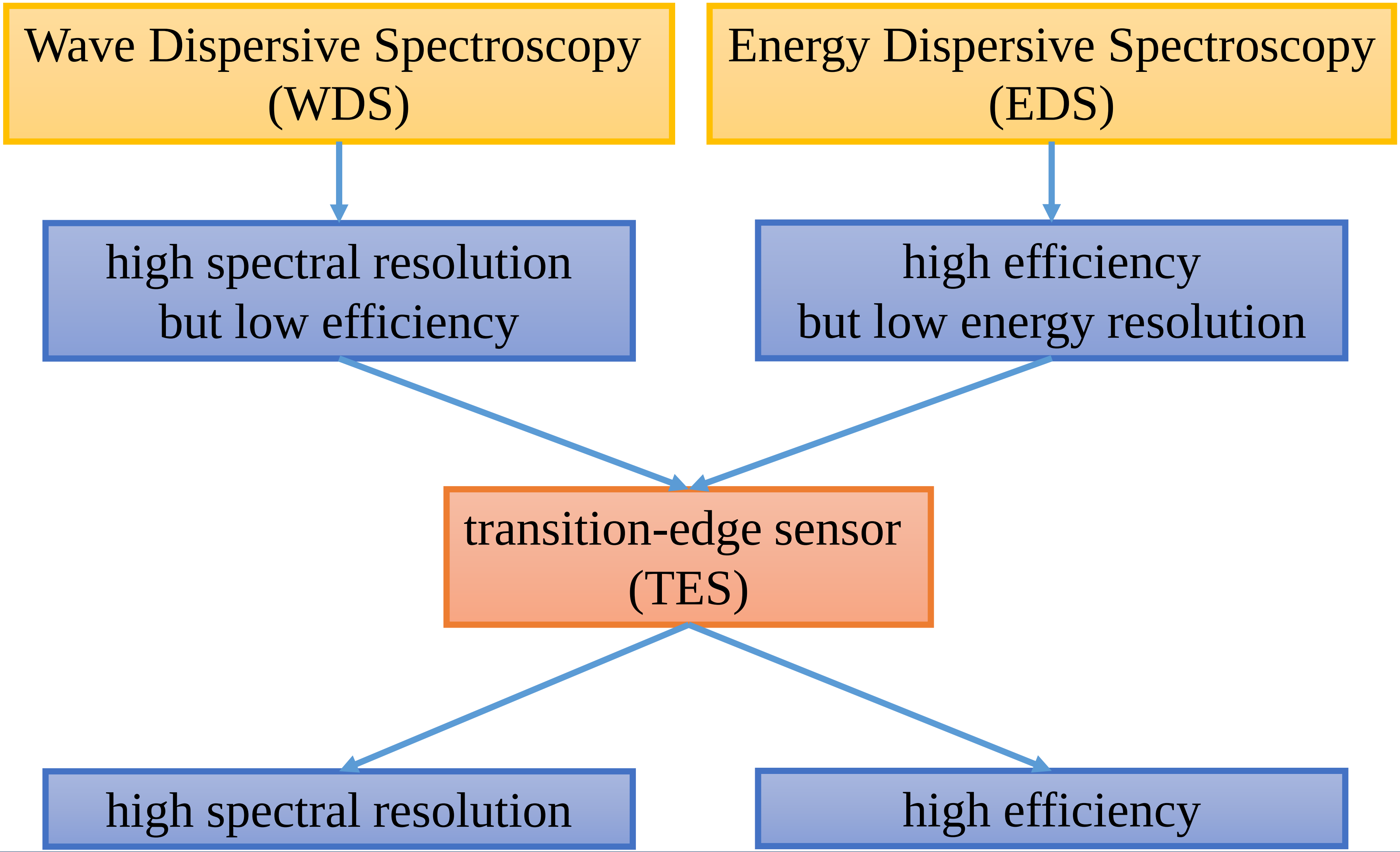


Tc~360 mK
τ_{fall}=300 ns



Tc~410mK
τ_{fall}=100 ns

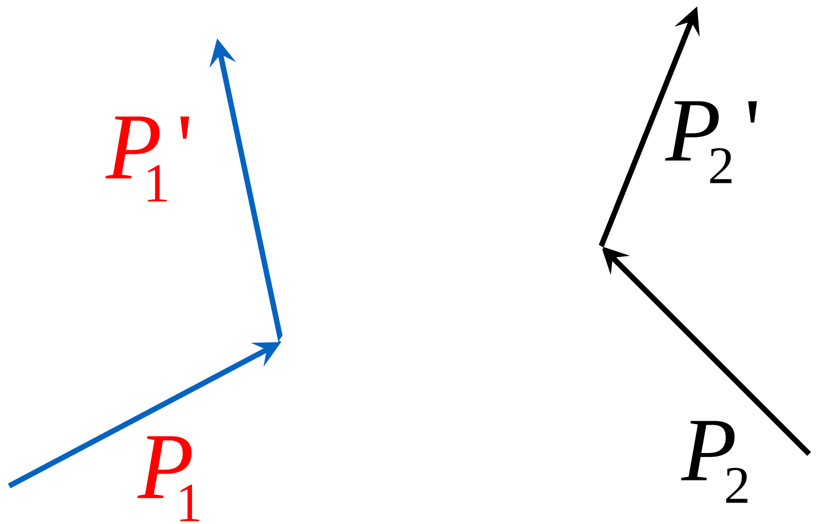
TES 特点


Wave Dispersive Spectroscopy (WDS)
Energy Dispersive Spectroscopy (EDS)
high spectral resolution but low efficiency
high efficiency but low energy resolution
transition-edge sensor (TES)
high spectral resolution
high efficiency

3. 超导纳米线单光子探测器(SNSPD)

BCS理论与超导能隙

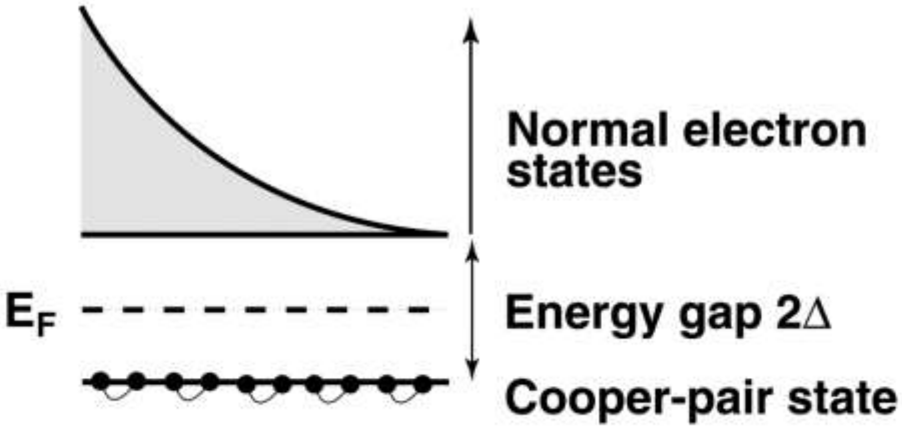
1956年，库柏提出超导态下电子对的形成是产生**能隙**的原因。一对电子通过与声子的相互作用而存在净吸引作用时形成电子对的束缚态。只有两个动量大小相等方向相反的电子才能形成库柏电子对。

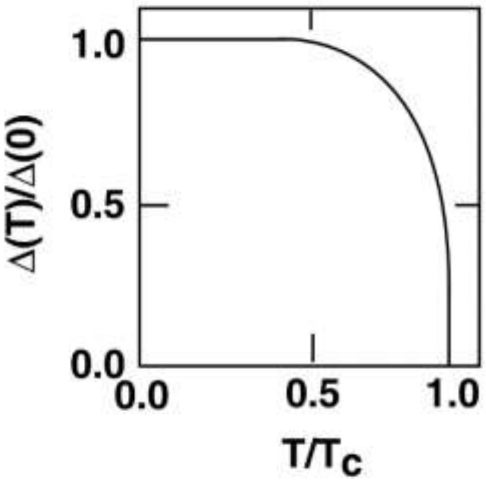


电子–声子相互作用

BCS理论 1972年，Nobel Prize

John Bardeen **Leon N. Cooper** **J. Robert Schrieffer**





$2\Delta(T=0) = 3.52\ k_B\ T_C$

- Superconductivity is an inherently quantum mechanical phenomenon that manifests itself on a macroscopic scale
- Cooper pairs ($\vec{k}\uparrow$, $-\vec{k}\downarrow$) form a single macroscopic wavefunction

Email: Lzhang@nju.edu.cn

一个光子的能量 hf

波长为1550nm的光子1.28 x 10^{-19}焦耳

波长1550nm光子能量：0.8eV
超导NbN能隙(T=0)：5.12 meV

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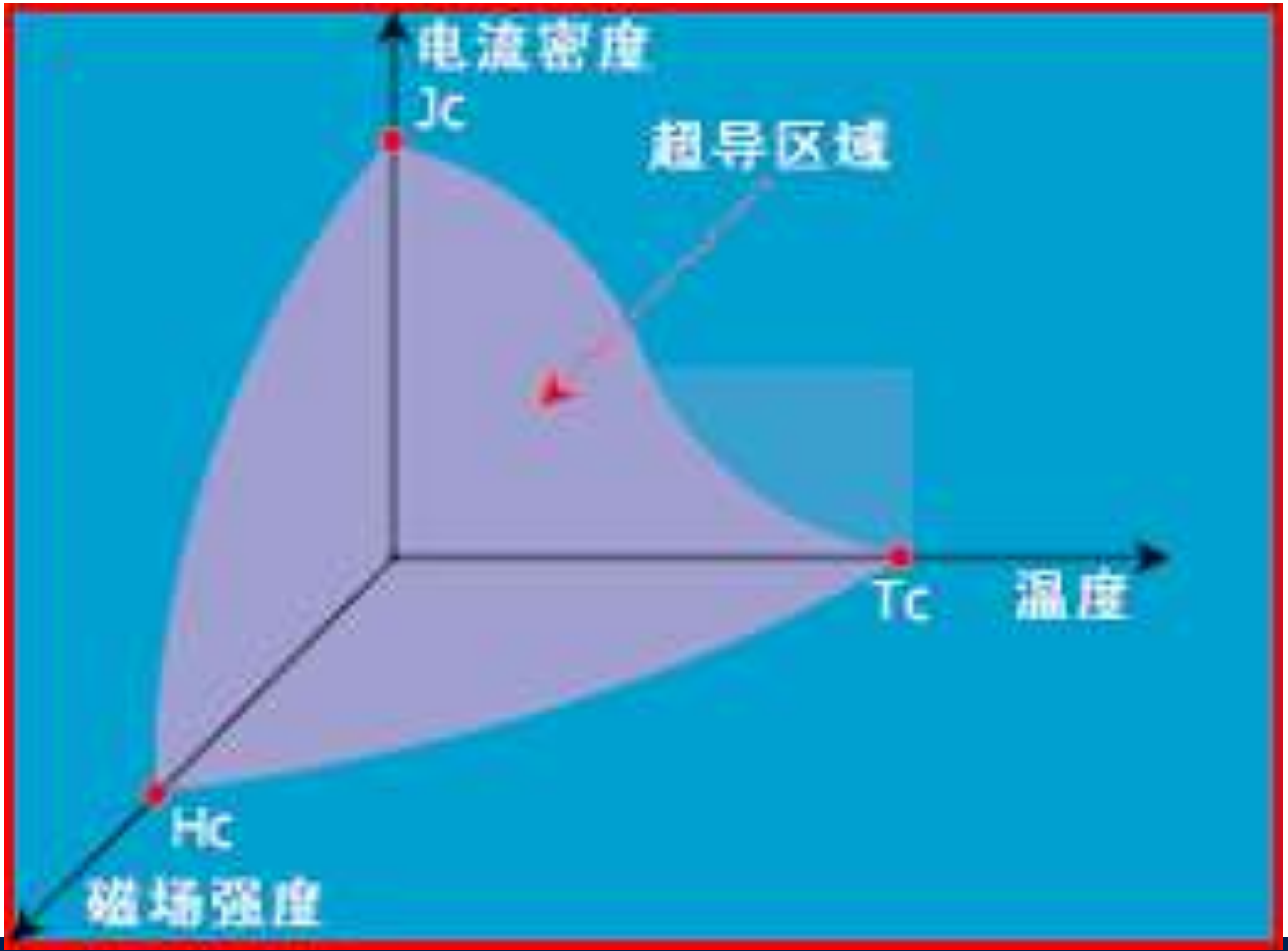
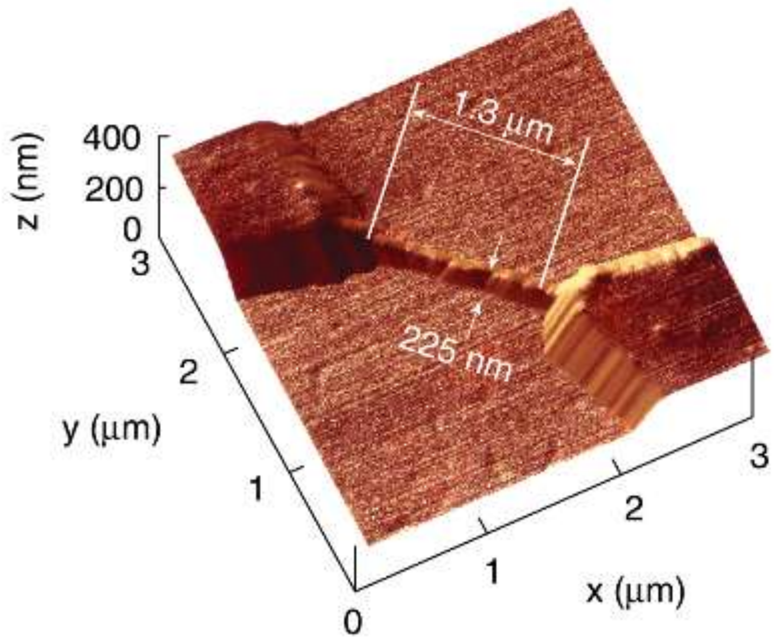
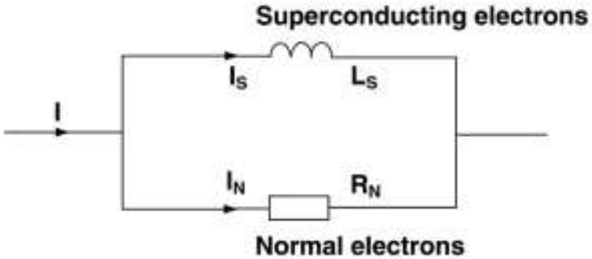
超导态的临界参数



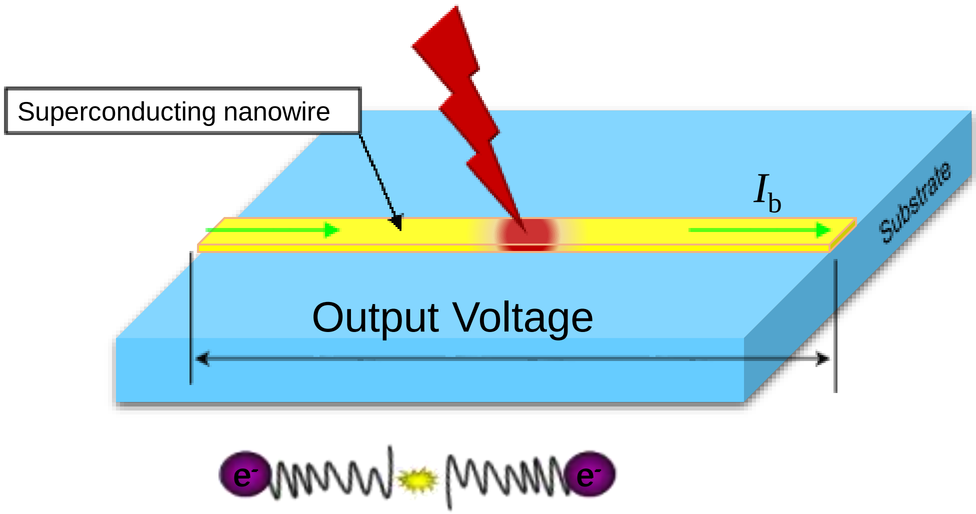


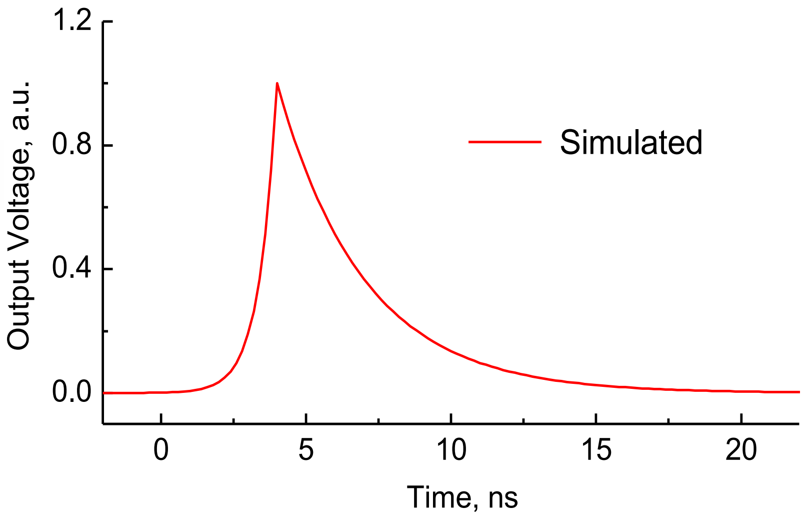
Prof. Gregory N. Goltsman



- Superconductor is truly lossless only for dc currents

Gol'tsman *et al.* APL 79, 705 (2001)





Mechanism: interaction between photons and superconductor

Multi-physical factors: Vortex pairs, Photons, electrons, phonons, superconductor carriers and quasi-particle.

Nano-structure: boundary effect.

Kadin et al, PRL 65, 3193,1990
Gol'tsman et al, *APL* 79, 705-707, 2001
Gol'tsman et al, *APL* 80, 4687-4689, 2002

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Semiconducting vs. superconducting detectors

Semiconductors

a) One optical photon creates only one electron-hole pair (typical bandgap 1-2 eV).

b) Room temperature and cryogenic operation.

c) Large dark counts.

d) Complicated biasing schemes.

Superconductors

a) One optical photon creates ~100–1000 excited electrons (superconducting gap ~ 2 meV for NbN).

b) Relaxation times are picosecond.

c) Extremely low dark counts.

d) No gating required, simple voltage-source biasing.

Low temperature environment reduces background noise and thermal fluctuations responsible for dark counts.

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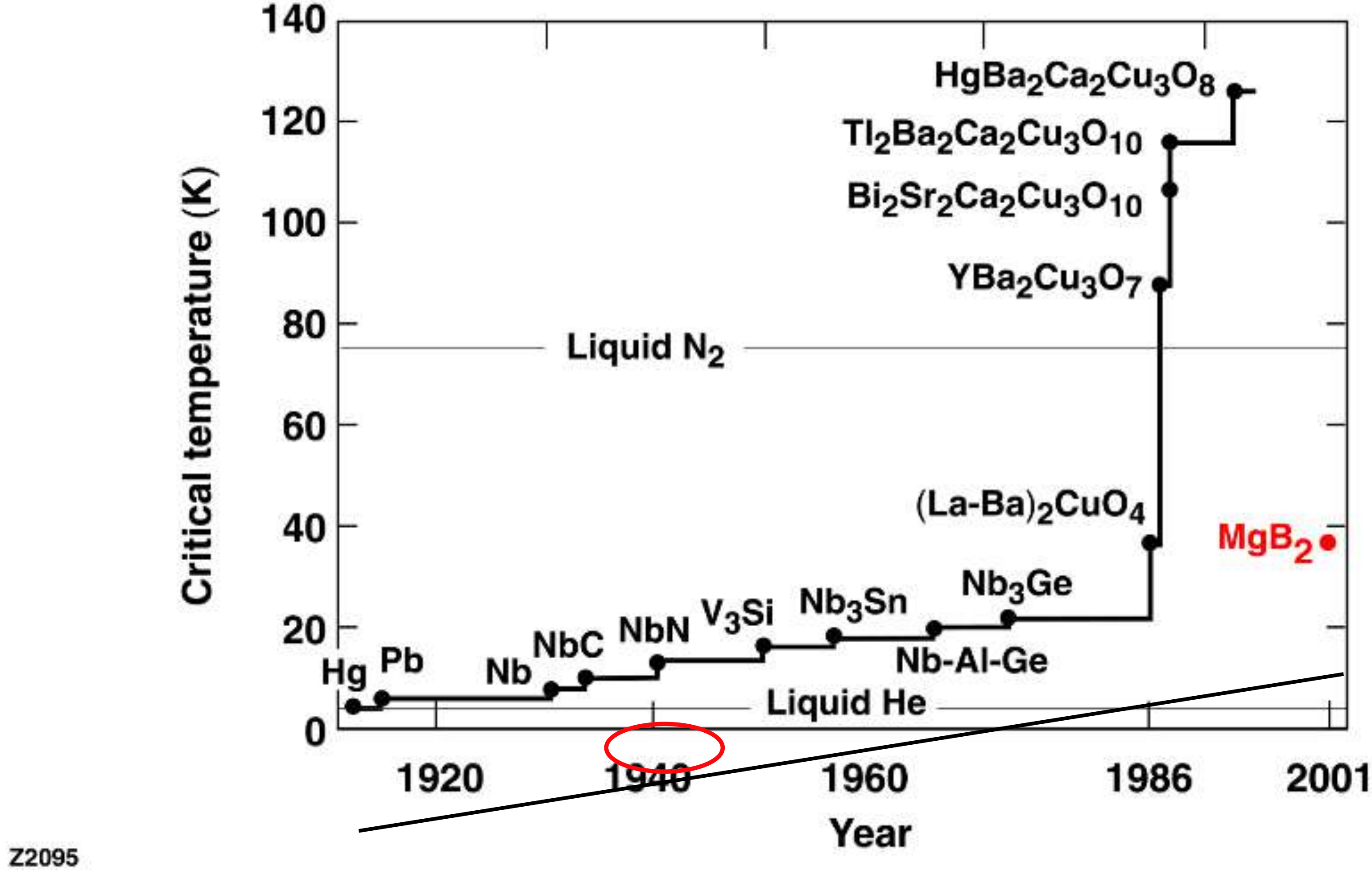

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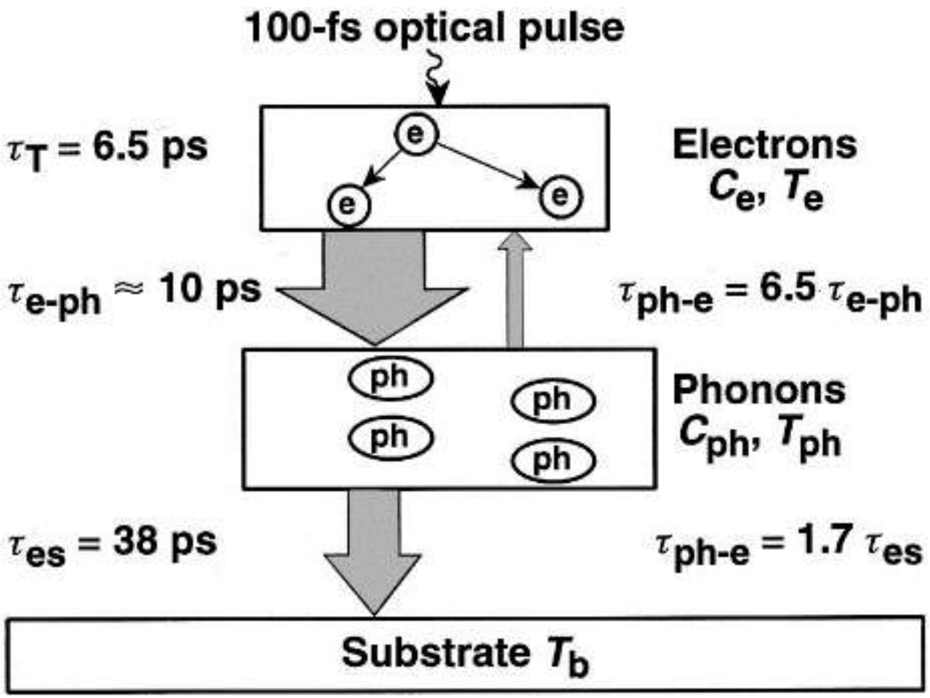
Counting Rate： SSPD >> APD or PMT

Ultra-thin NbN films



InGaAs/InP APD ~ 10^6 Hz

$\tau_e \approx 54.5$ ps   20 GHz

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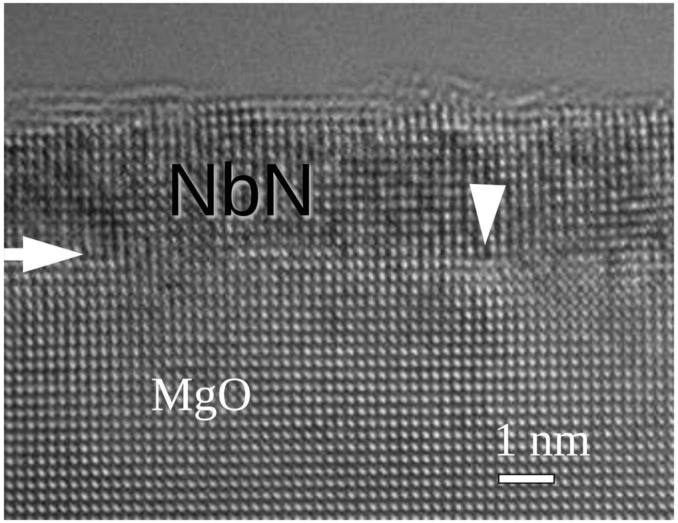
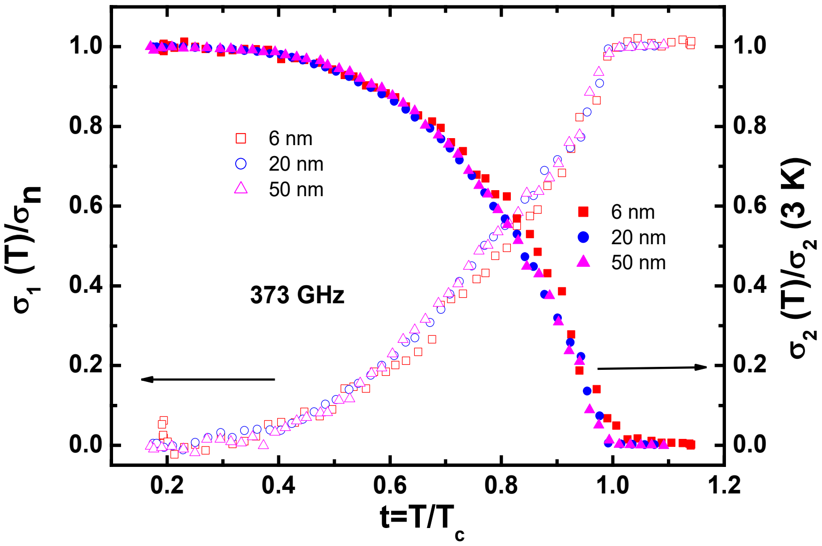
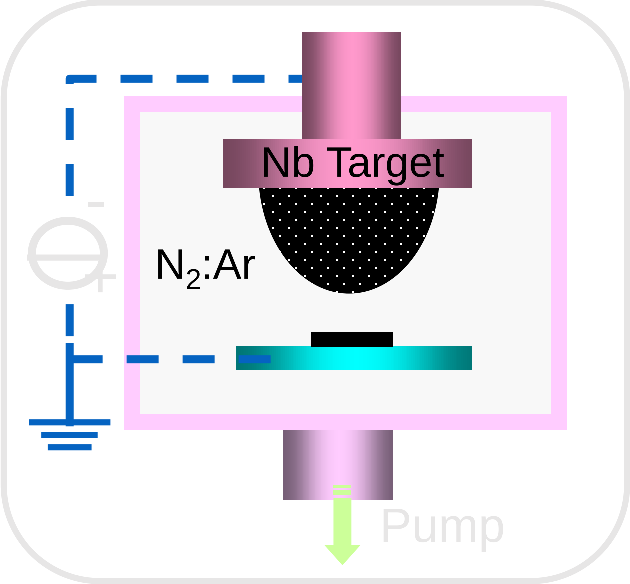
高质量薄膜材料







4 nm

$T_c \approx$ 11 - 12 K

$J_c \approx 4 \times 10^6$ A/cm^2 @ 4.2 K

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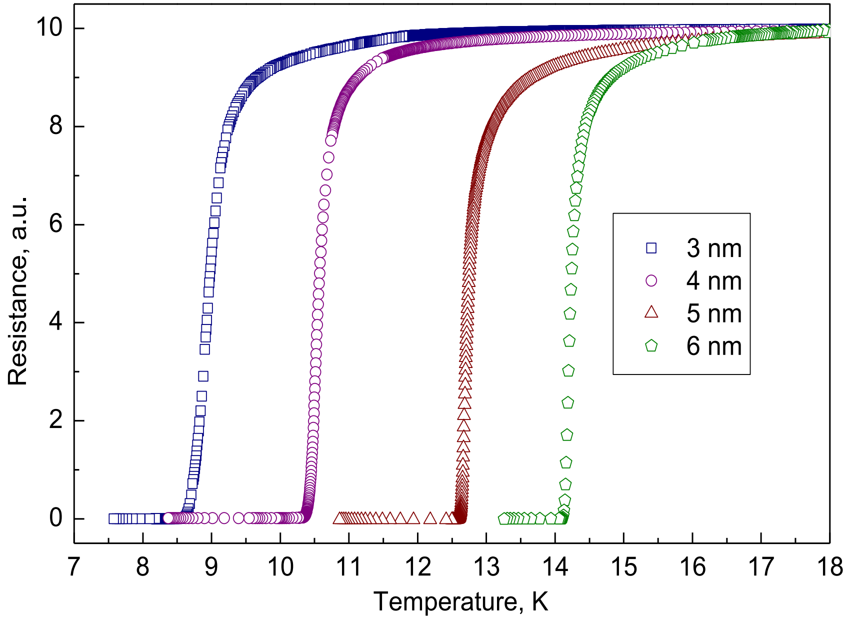
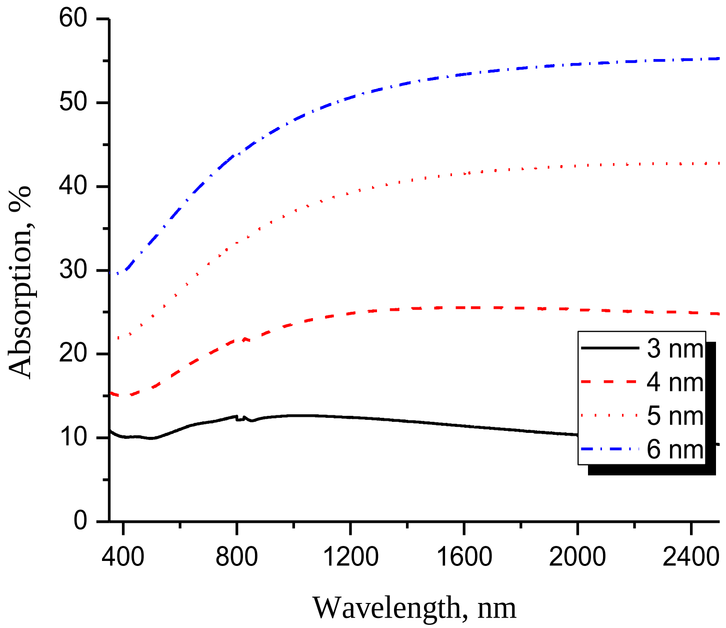
NbN薄膜的R-T曲线　　　薄膜的吸收光谱





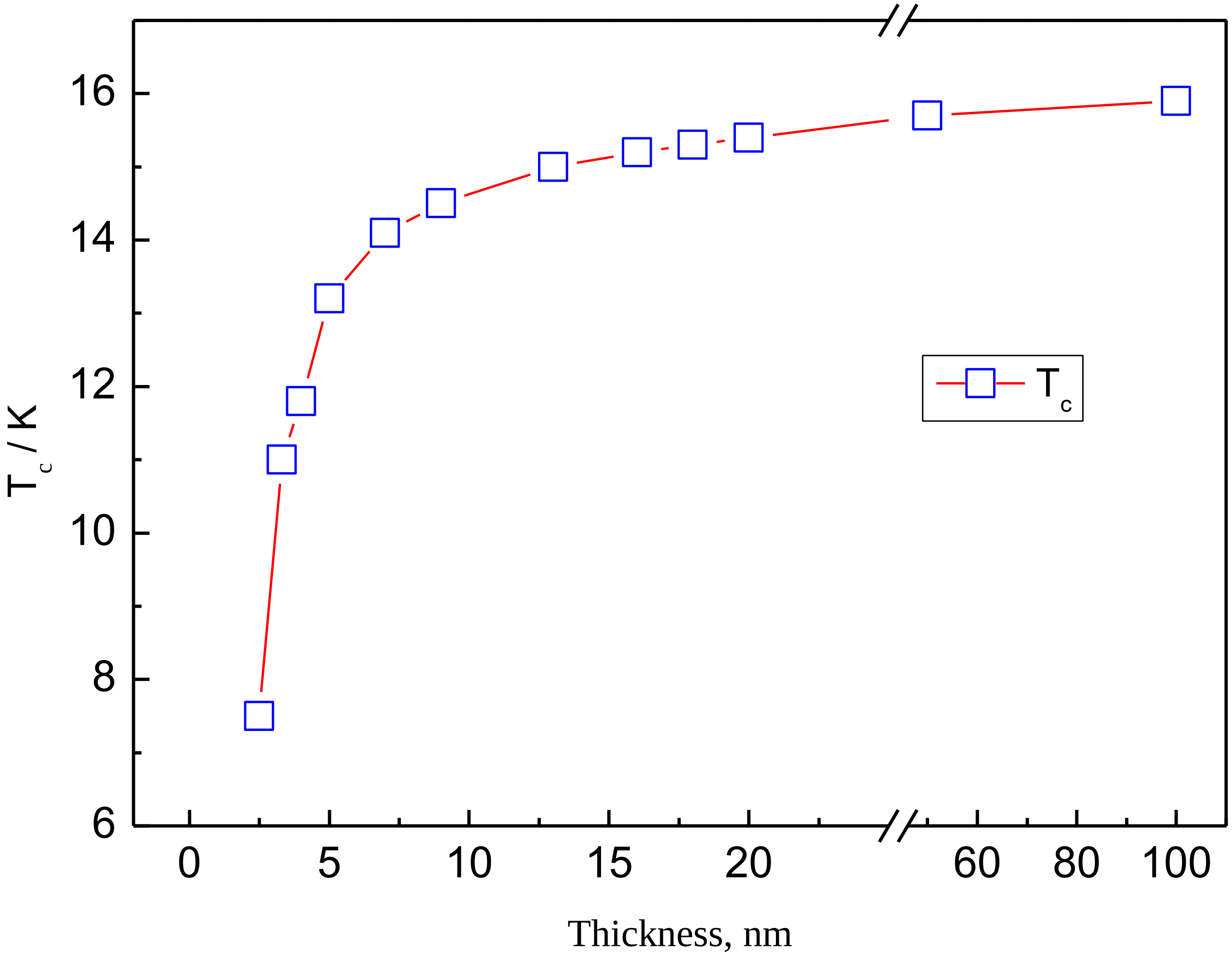
e.g. 4 nm NbN films

Tc= 10.5 K

△Tc=0.4 K

测量温度: 室温

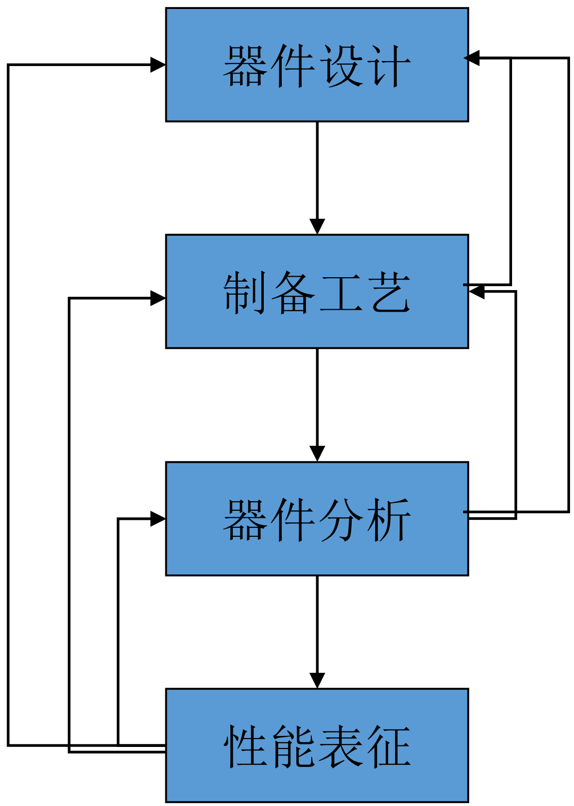
波长范围:
400nm-2500nm



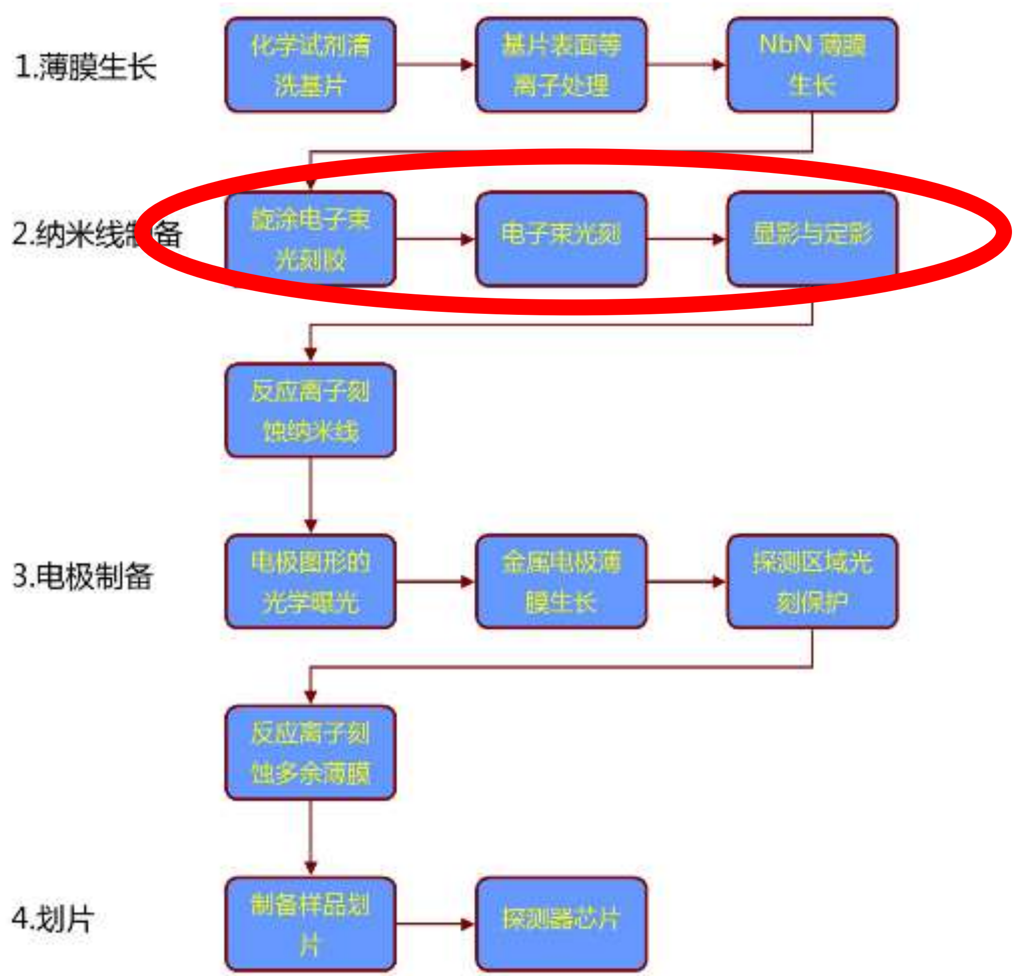
Superconducting transition temperature Tc of NbN films

Email: Lzhang@nju.edu.cn

高质量超导纳米线制备



SNSPD研制流程图



器件制备工艺流程图

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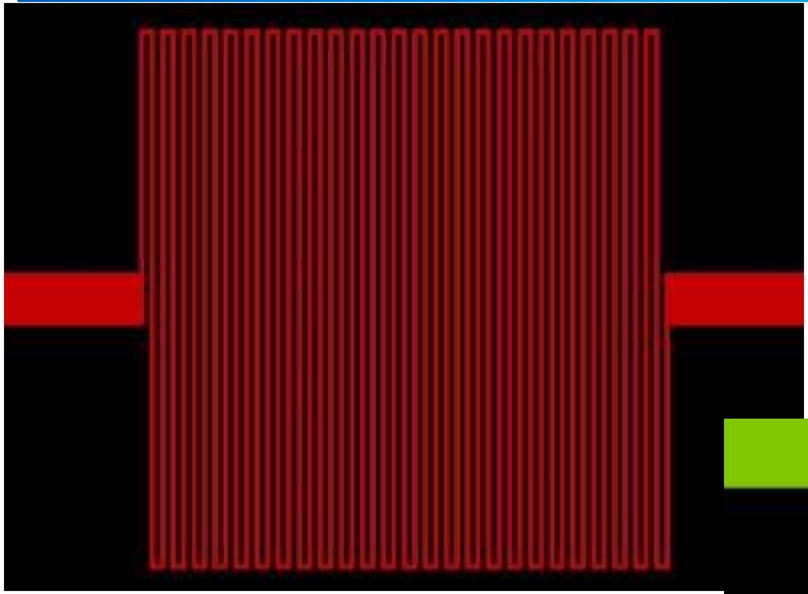
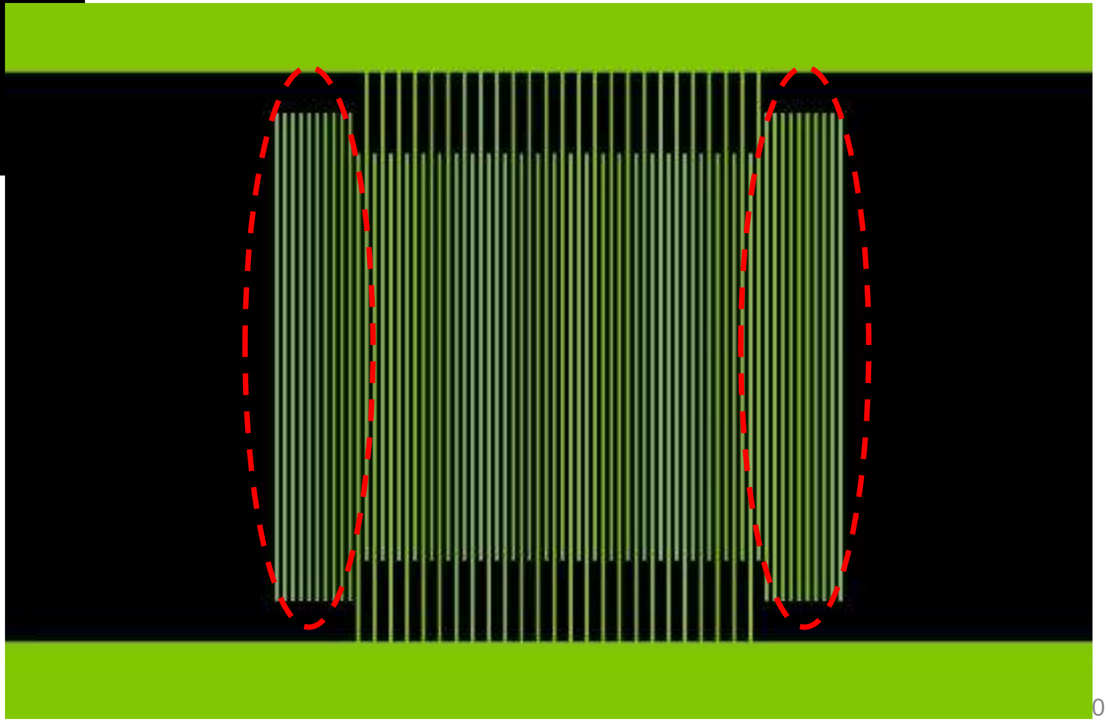
纳米线结构和曝光的图形



纳米线结构

难点：

1. 基片不导电，电荷堆积，临近效应比较严重；
2. 平行结构造成临近效应在中间区域叠加.



光刻图形设计
浅绿色：曝光区域

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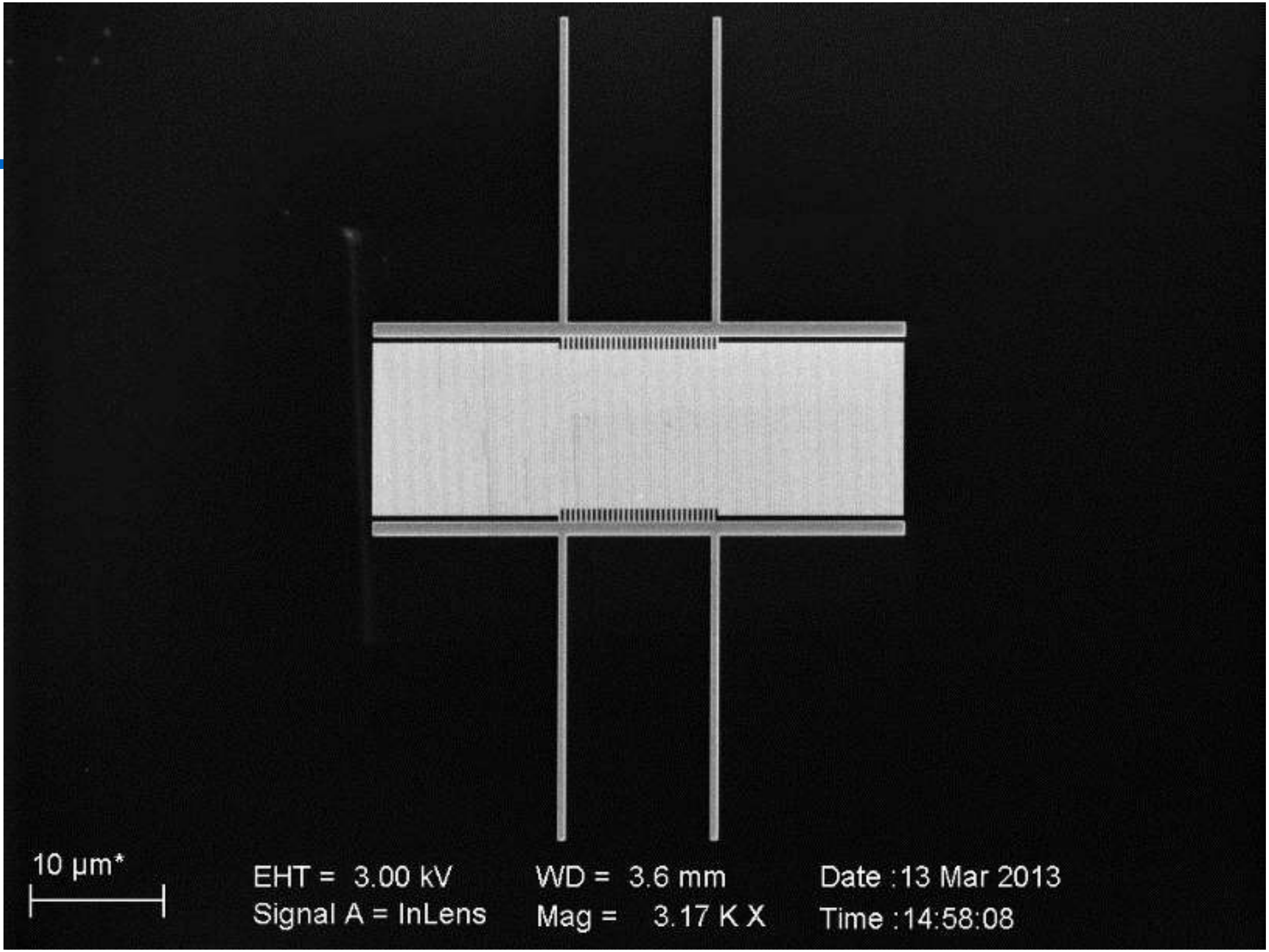

说明：图形为测量测试曝光用图，细节尺寸将进行
具体测量。

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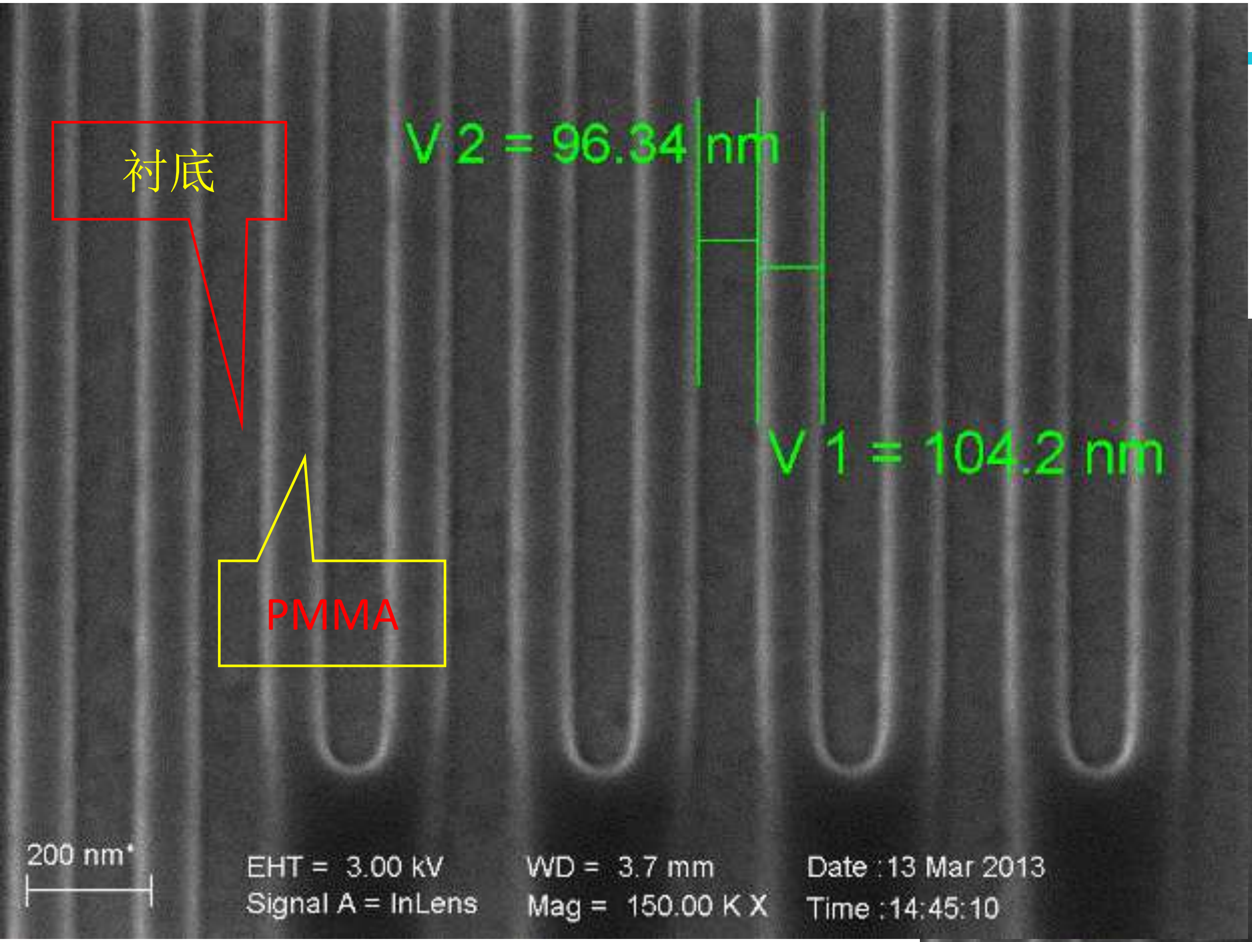
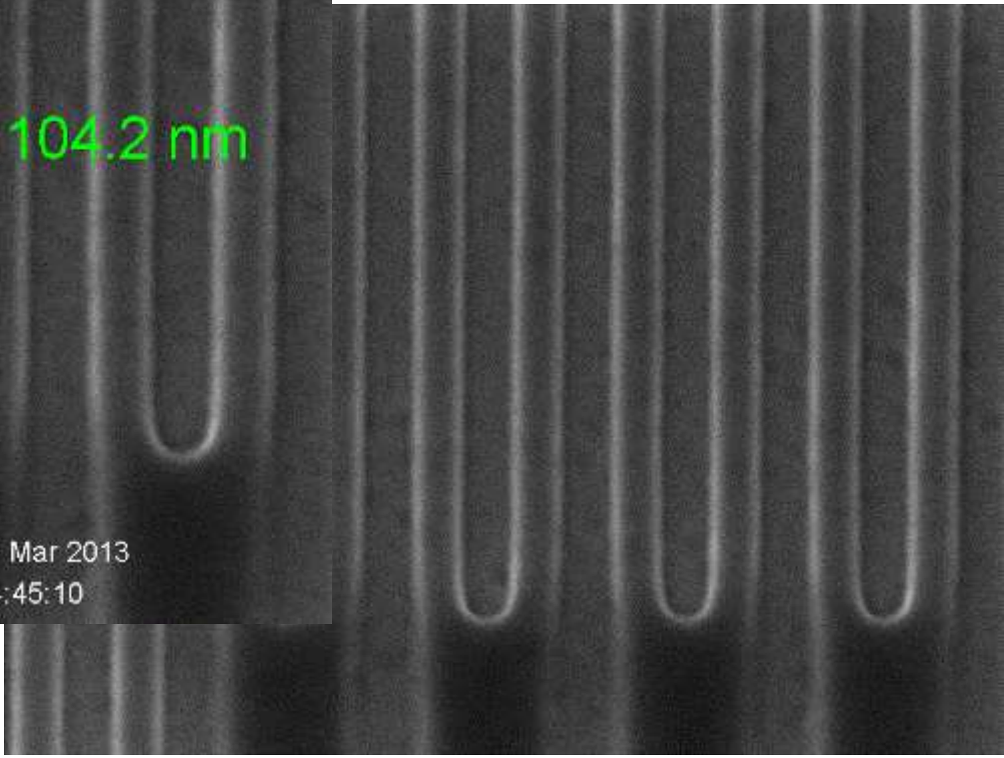
Nb2样品100nm/50%占空比折角处结果





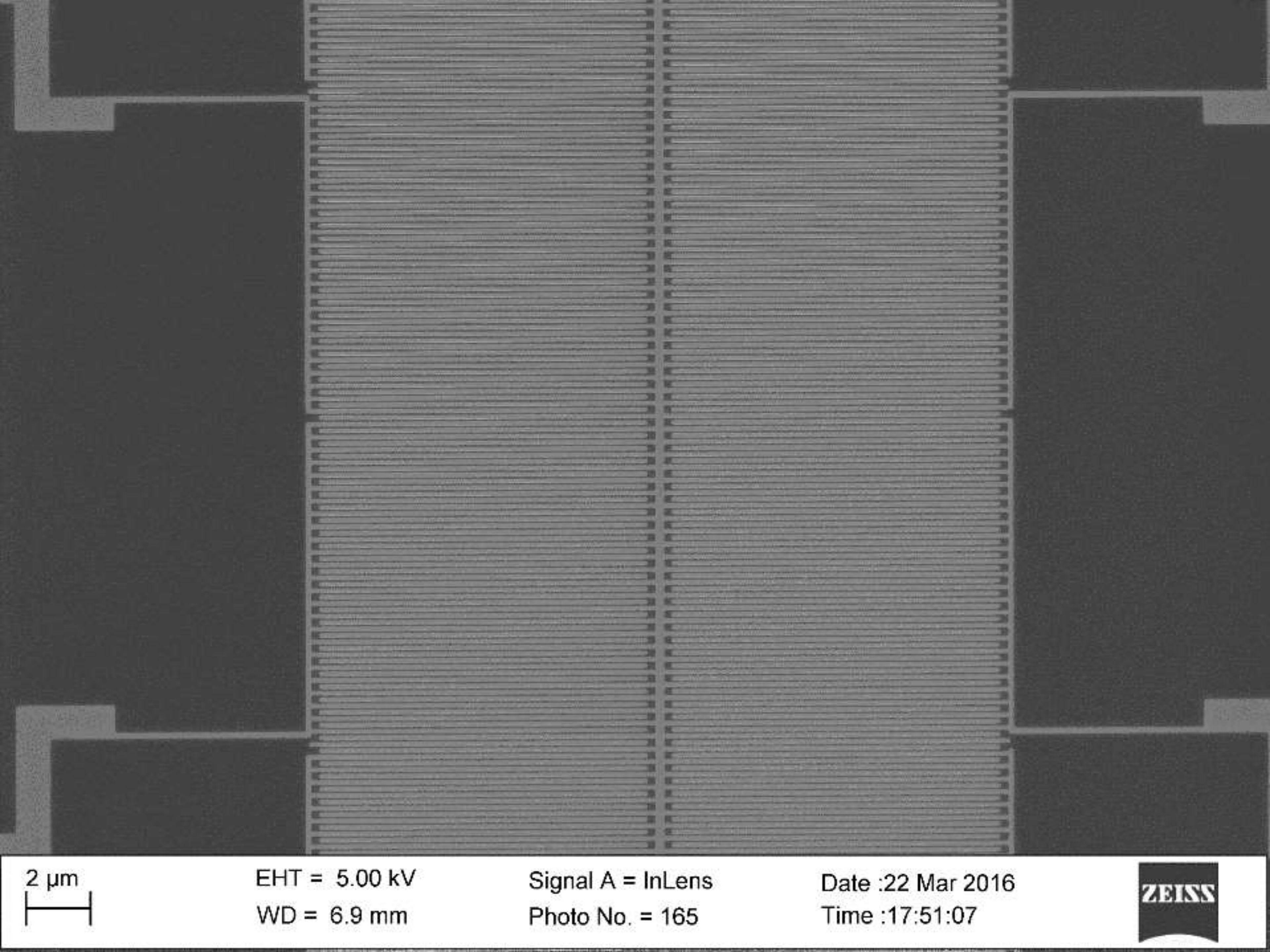
说明：图形为Dose=1100uC/cm^2。尺寸如图中所示。图中所示尺寸测量误差为2nm。原始图片如右下图所示。

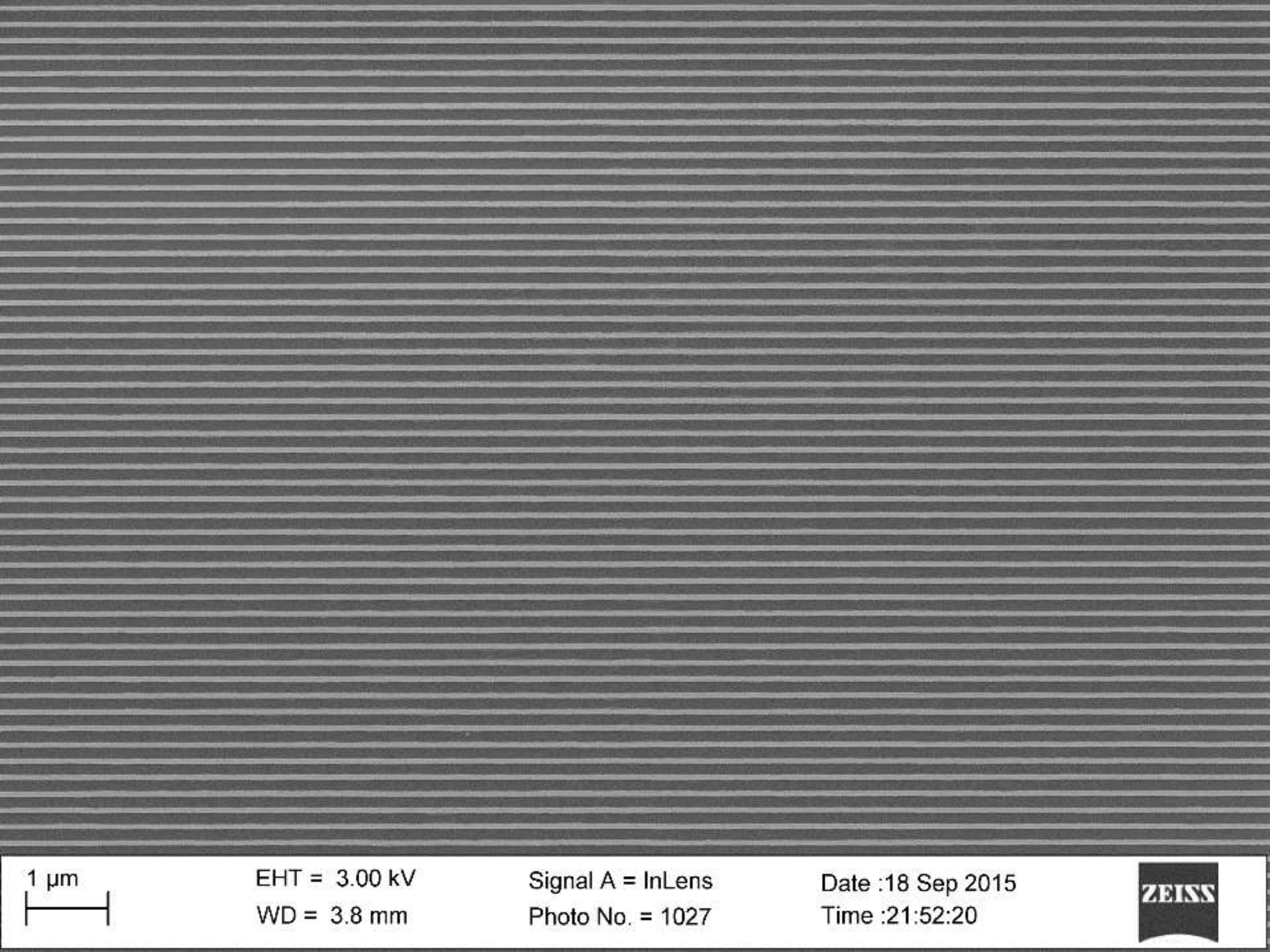
Email: Lzhang@nju.edu.cn

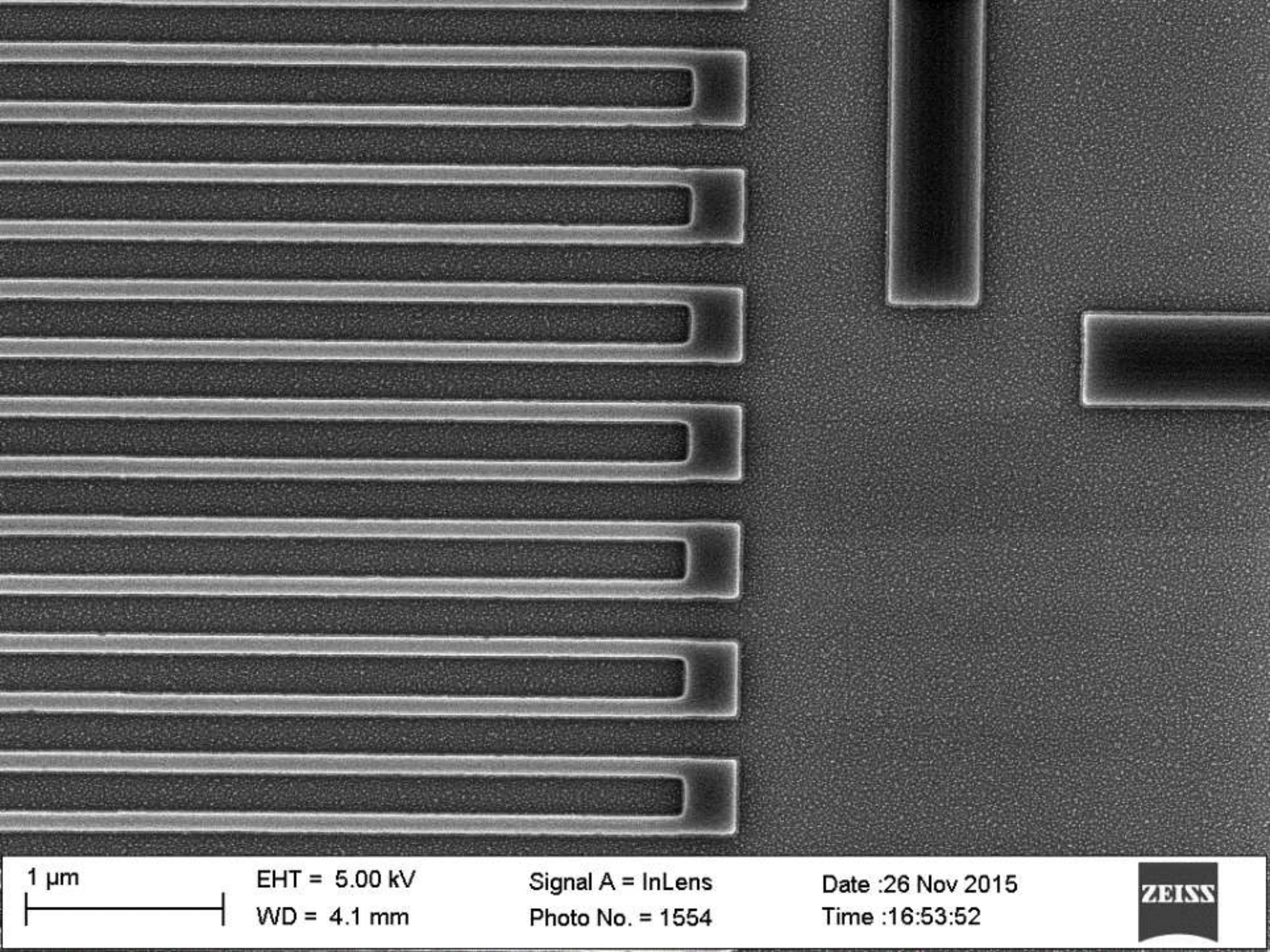
EBPG 5200 电子束光刻系统

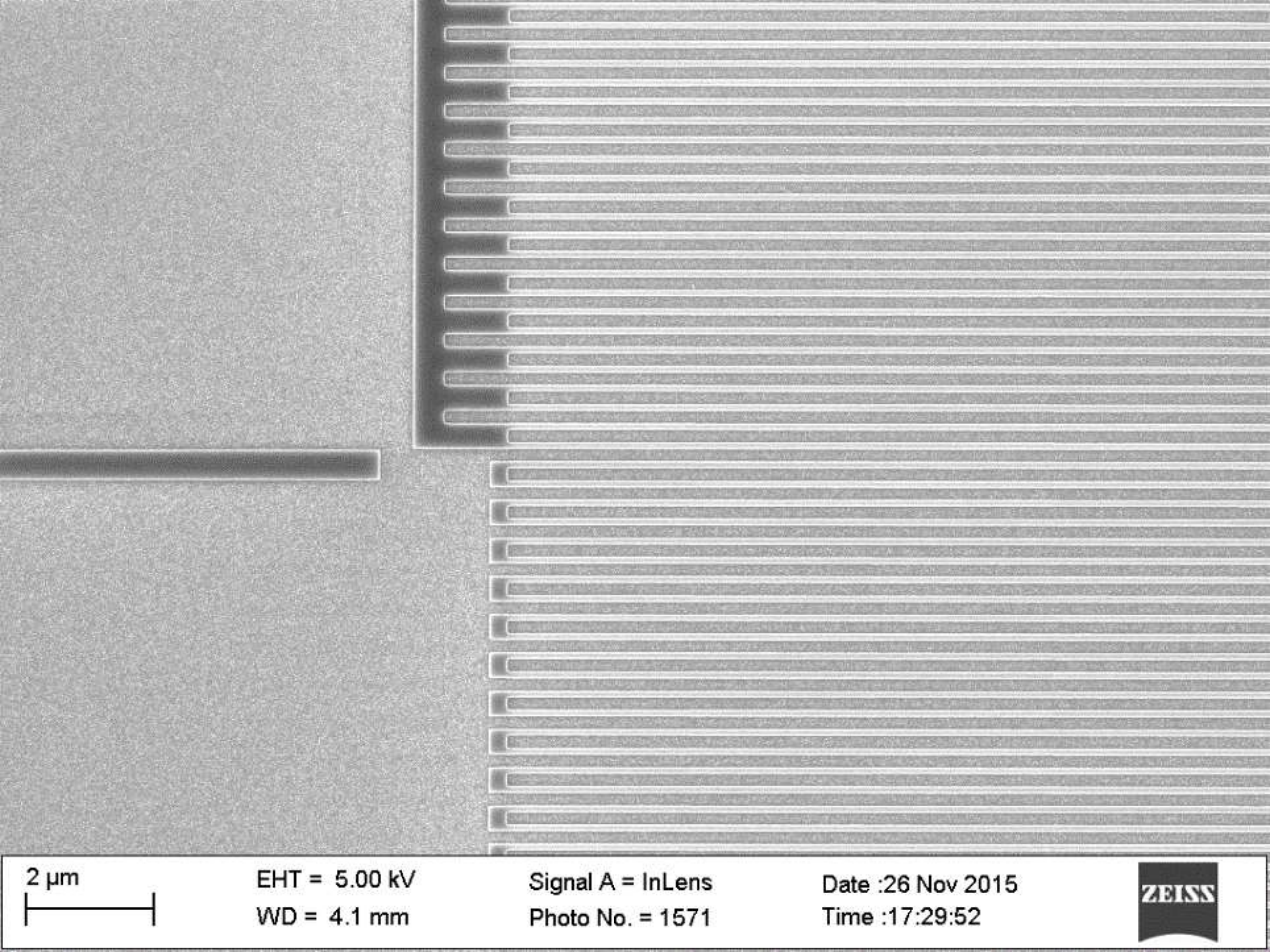
蔡斯MERLIN Compact SEM

Email: Lzhang@nju.edu.cn

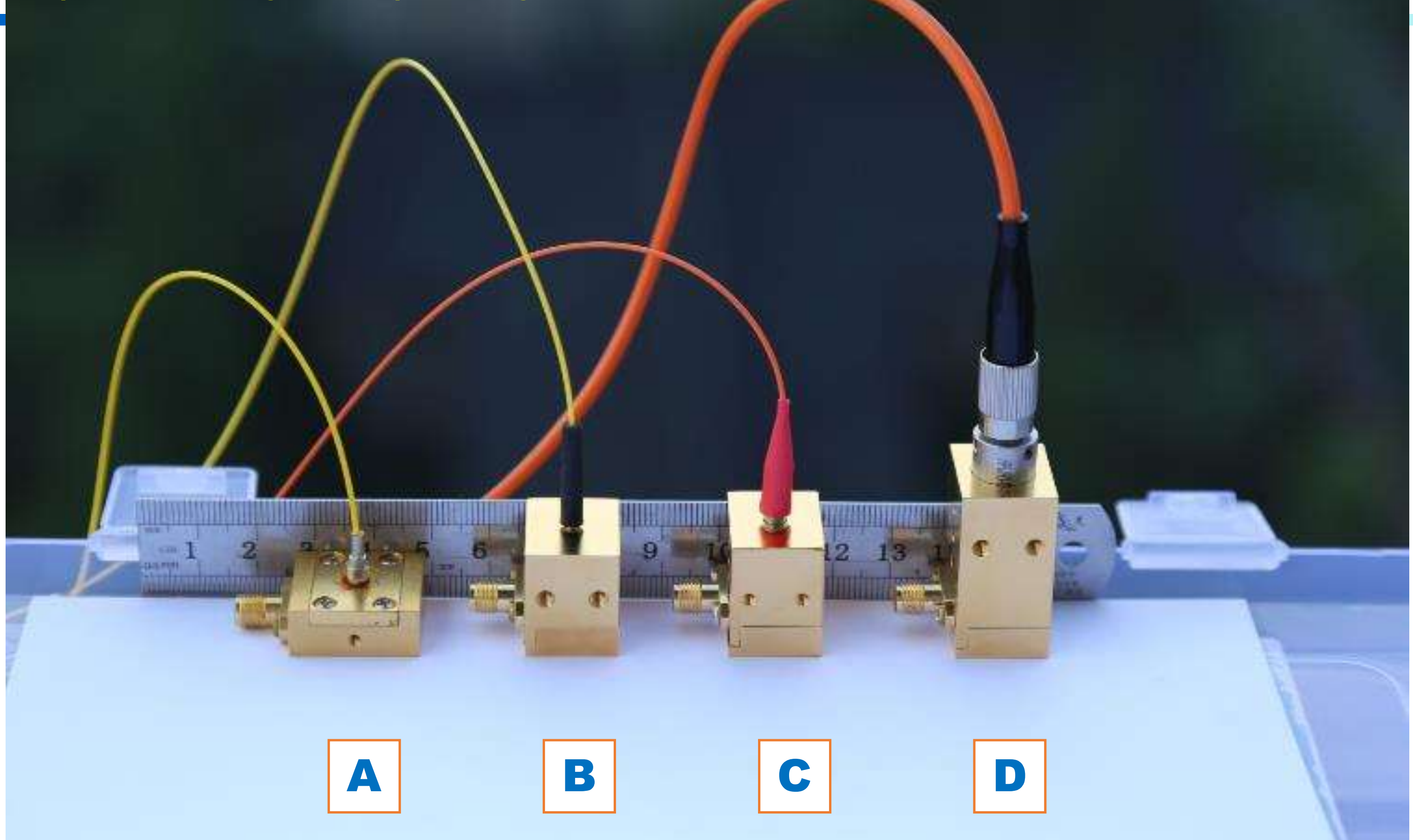

2 µm
EHT = 5.00 kV
WD = 6.9 mm
Signal A = InLens
Photo No. = 165
Date :22 Mar 2016
Time :17:51:07


1 µm
EHT = 3.00 kV
WD = 3.8 mm
Signal A = InLens
Photo No. = 1027
Date :18 Sep 2015
Time :21:52:20
ZEISS


1 µm
EHT = 5.00 kV
WD = 4.1 mm
Signal A = InLens
Photo No. = 1554
Date :26 Nov 2015
Time :16:53:52
ZEISS


2 µm
EHT = 5.00 kV
WD = 4.1 mm
Signal A = InLens
Photo No. = 1571
Date :26 Nov 2015
Time :17:29:52
ZEISS

Optical images of packaged SNSPDs



	A	B	C	D
Detection area	≧10μm×10μm	≧10μm×10μm	≧15μm×15μm	≧10μm×10μm
Fiber type	Single mode	Single mode	Multi-mode (50 μm)	Multi-mode (62.5 μm)

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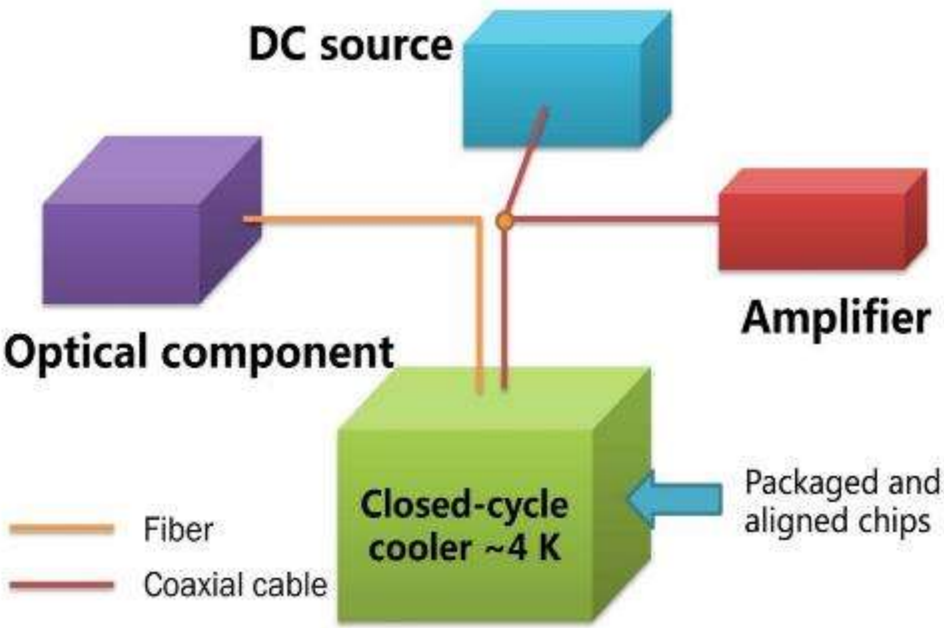
系统结构简图



System structure of SNSPD

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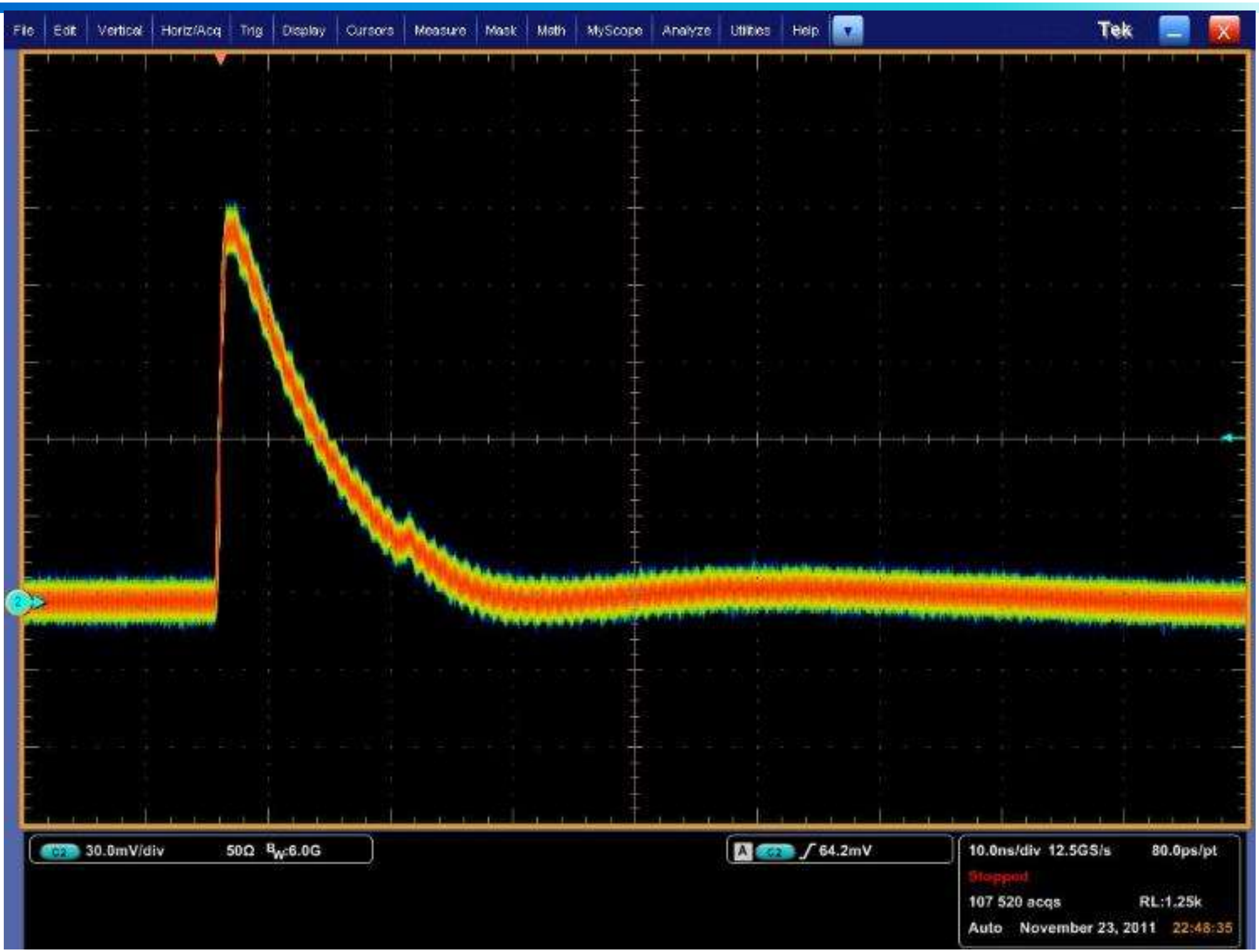
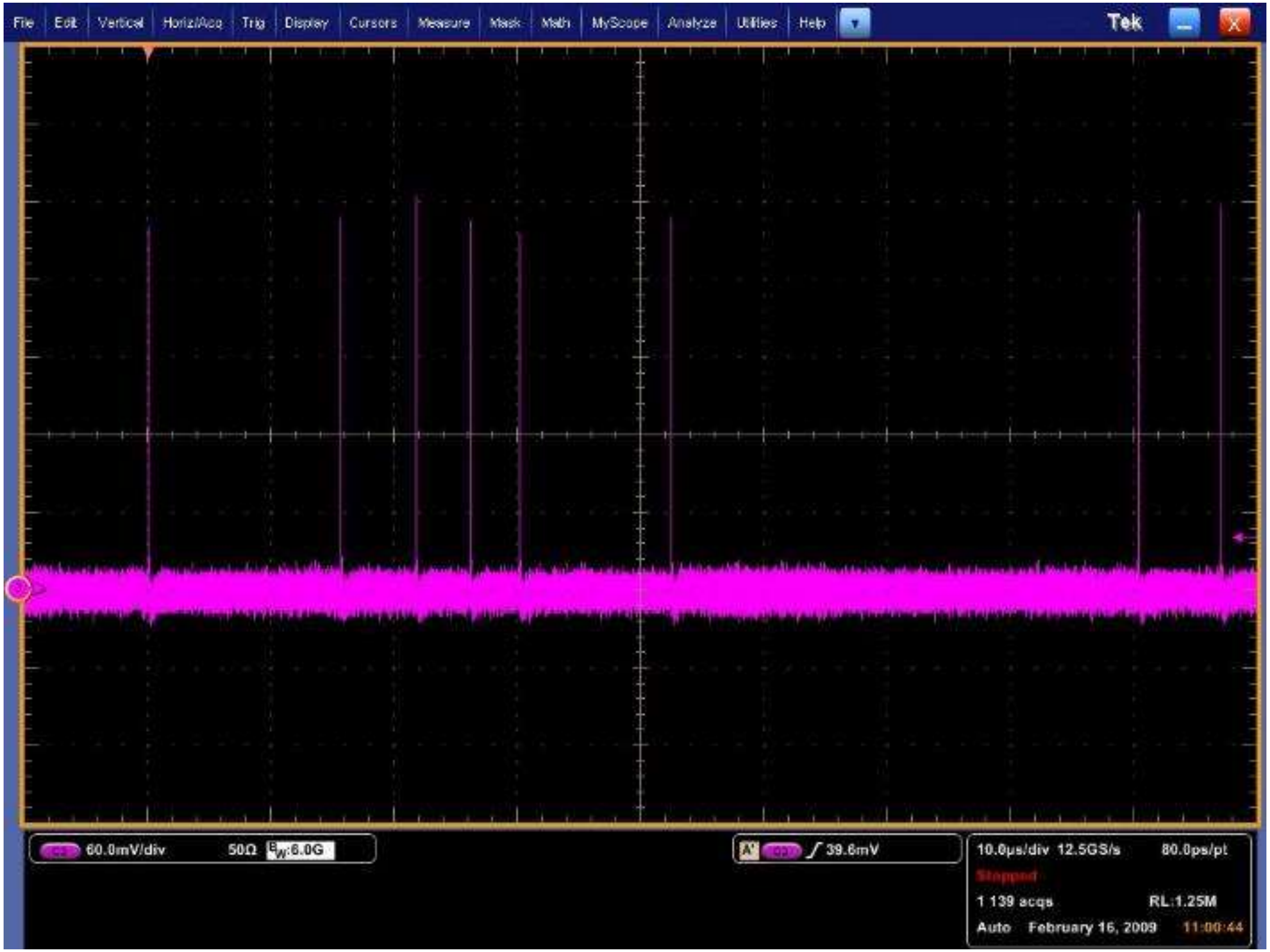
探测器输出光子响应脉冲信号

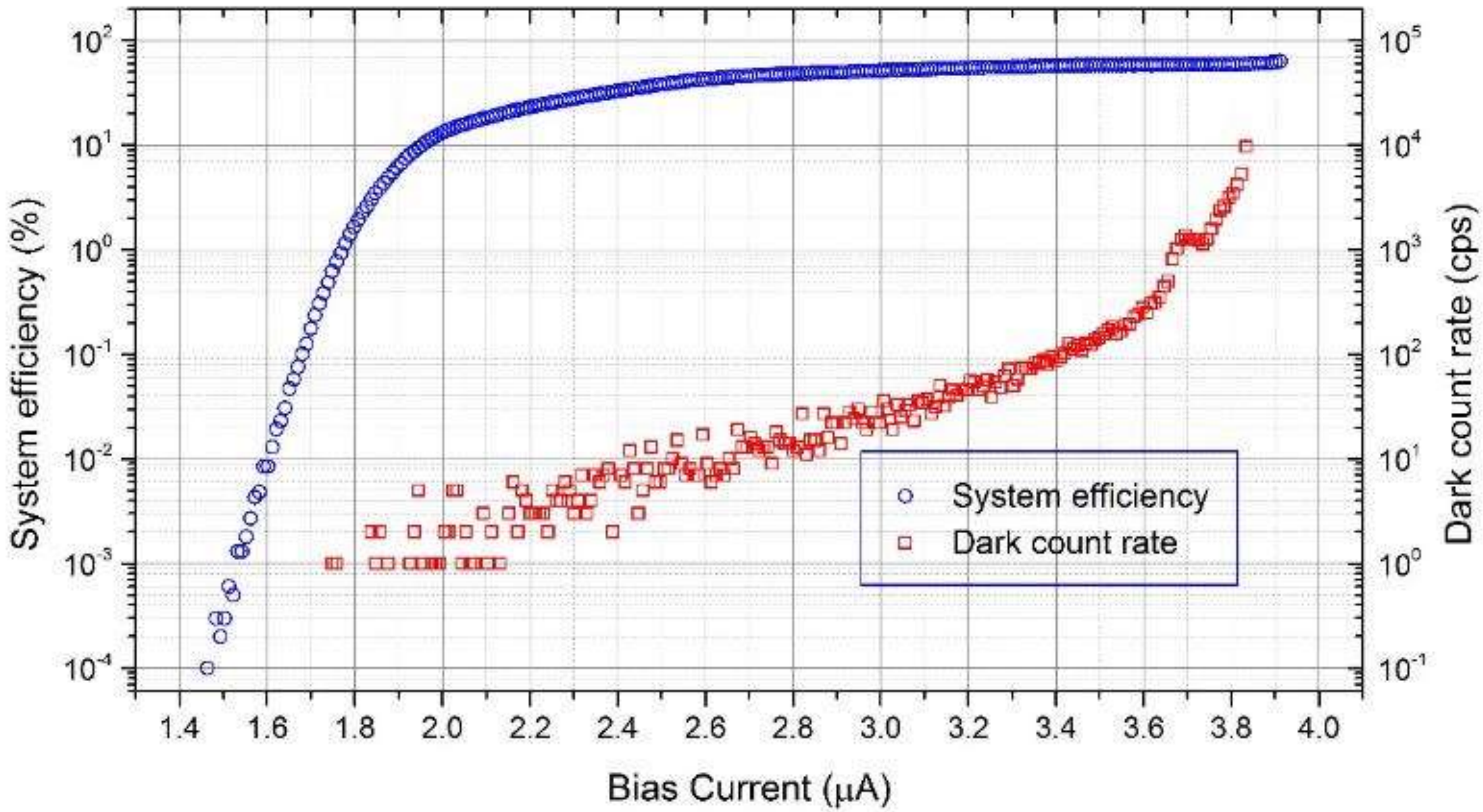


Email: Lzhang@nju.edu.cn



Email: Lzhang@nju.edu.cn

探测效率与暗计数



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南京大学2015. 12达到指标

性能与国际相应研究的最好水平相当

暗计数：100 cps，温度2.3K

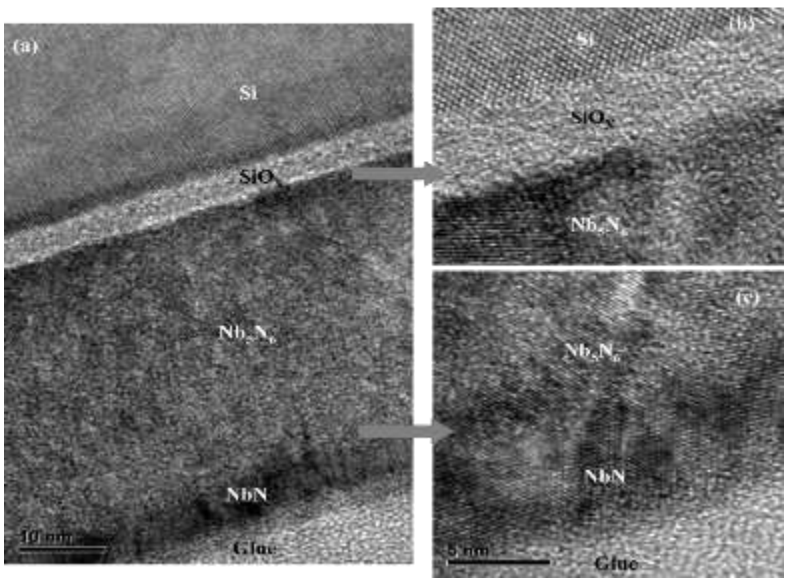
探测器类型	波长（nm）	效率(%)	时间抖动(ps)	速率(Hz)	尺寸（μm^2）	光纤
SNSPD/Si	1550	60 %	< 50	100 M	10×10	单/多模
SNSPD/Si	1550	60 %	< 50	50 M	15×15	单/多模
SNSPD/Si	1650/ 1550	80 / 72%	~ 70	10 M	30×30	单/多模
SNSPD/MgF_2	532-1550 - 2700	> 30% > 1.6 %		40M	10×10	单/多模 红外
1×6 SNSPD	1550	> 40%				单模

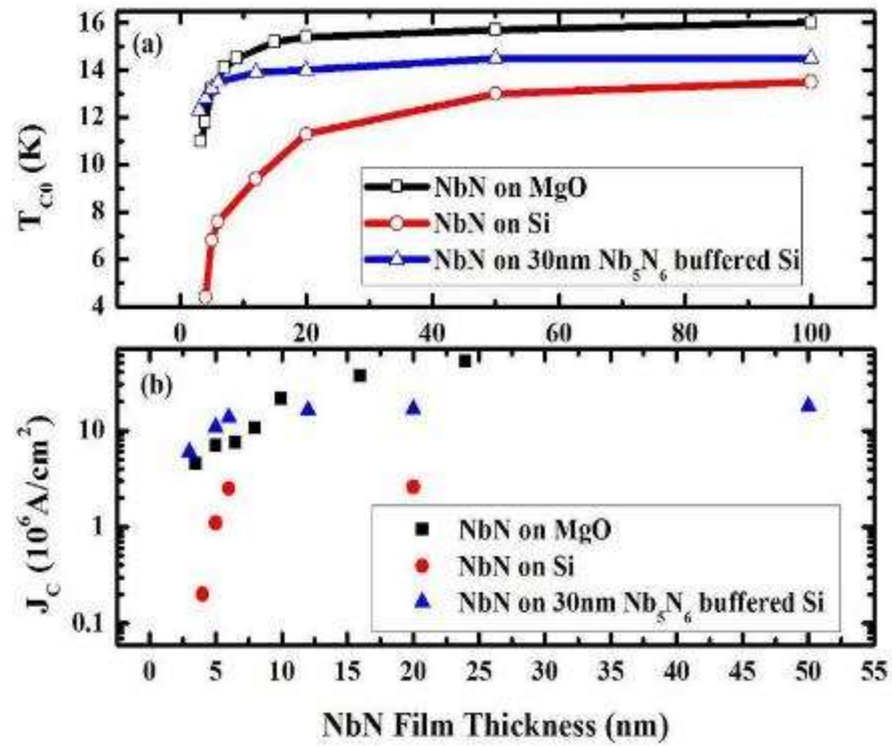
4. 研究进展与应用举例

Nb_5N_6为缓冲层，NbN超薄膜的Tc 提升5-8 K，Jc提高1个量级。

6nm NbN/30 nm Nb_5N_6/Si，T_{C0} 13.5 K， J_C 13.6×10^6 A/cm^2

是目前报道的最好结果，利于提高器件信噪比

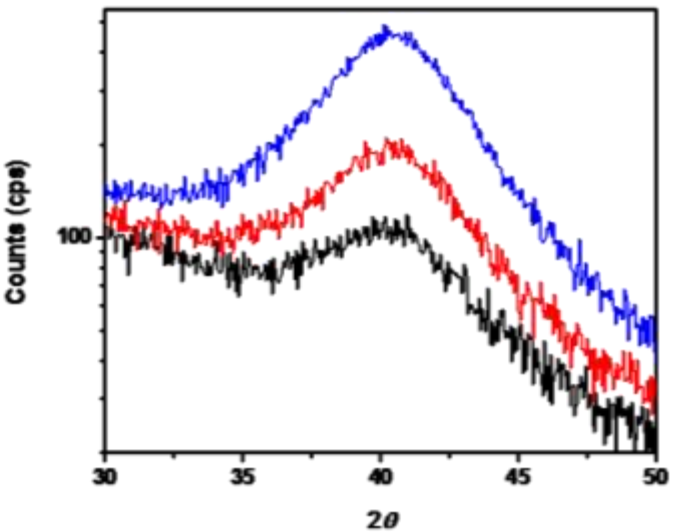




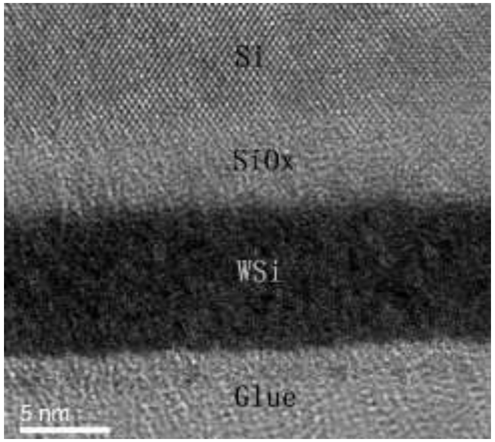
Email: Lzhang@nju.edu.cn

WSi 超薄薄膜，有望工作于2.3K温区

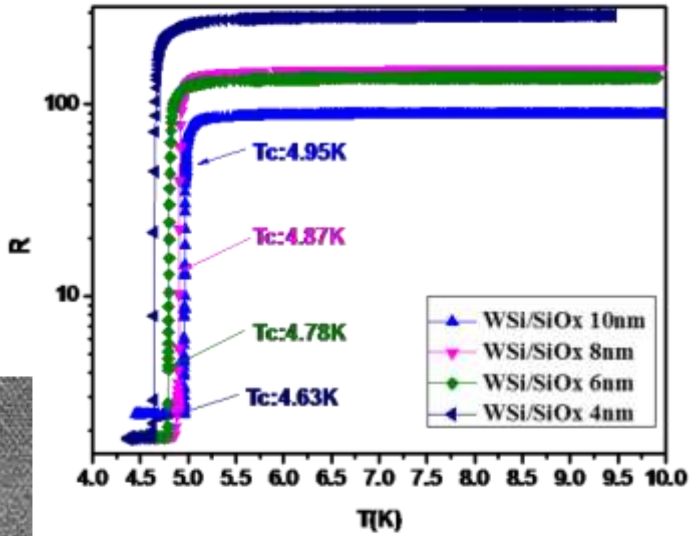
提高检测效率，扩展工作波长

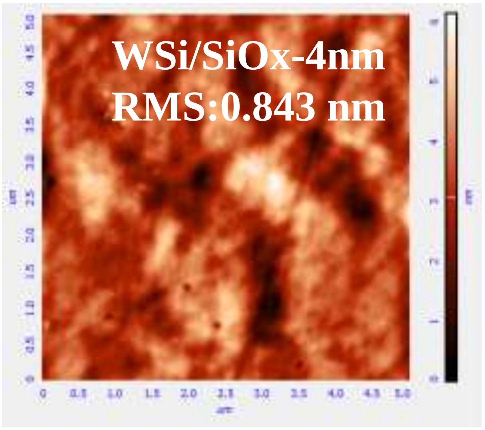


6nm WSi薄膜, 掠入射XRD，
衍射峰在40.2° 附近



TEM



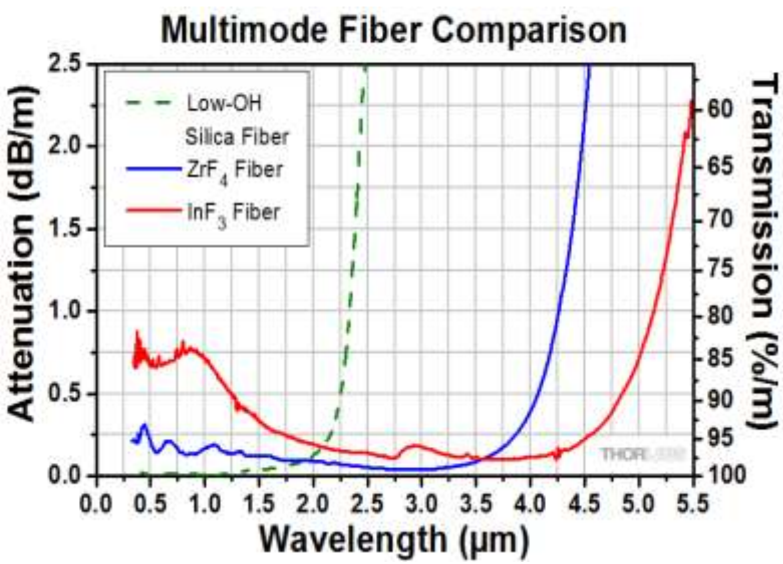


AFM

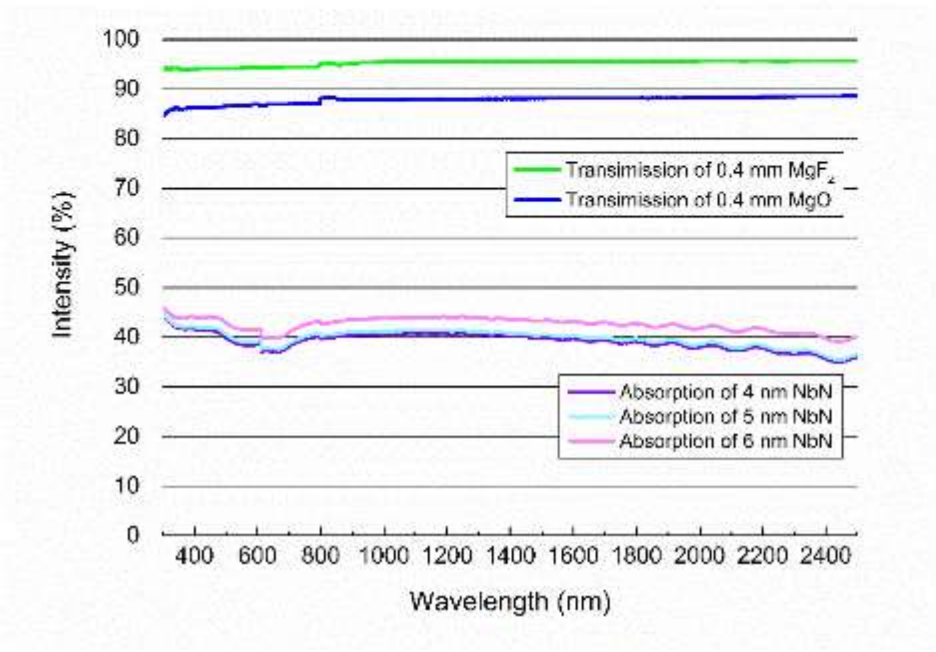
MgF2基中红外SNSPD

工作波段：0.532-2.7 μm　　DE:　2.0 μm：26.8 %

中红外光纤透射谱



衬底和氮化铌薄膜吸收/透射谱



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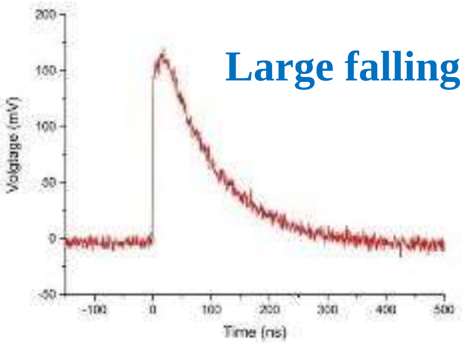
大面积 SNSPD

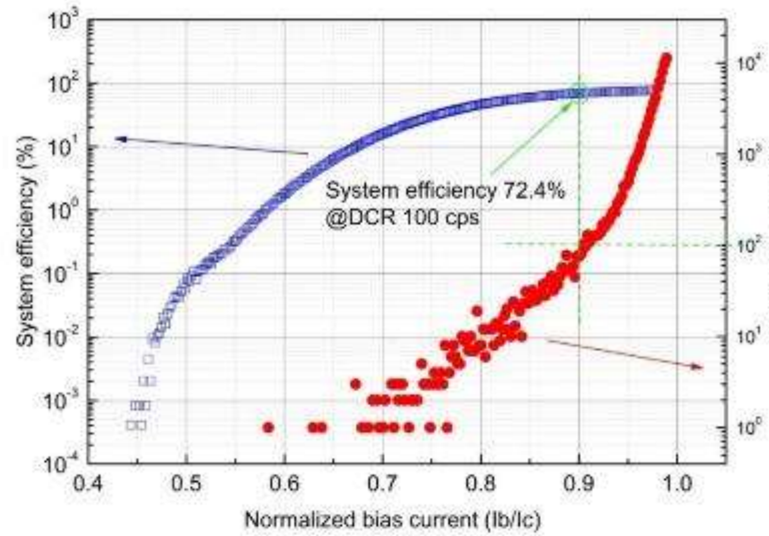
探测区尺寸：30μm×30μm



Large falling time: ~100 ns

1550 nm

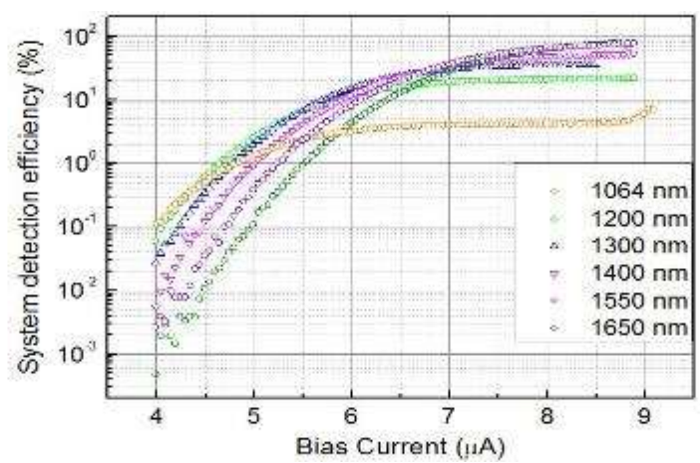
系统效率	72%	40%
暗计数(cps)	100	1
速率（MHz）	10	10

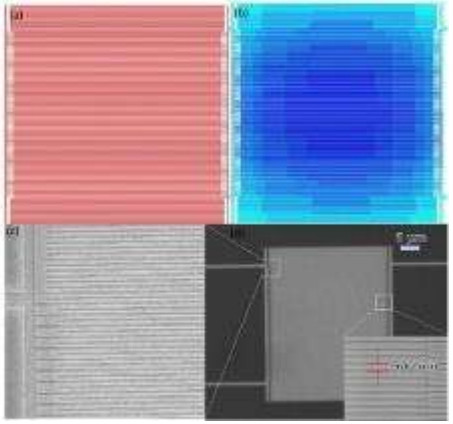


波长：1650nm

效率：   80%

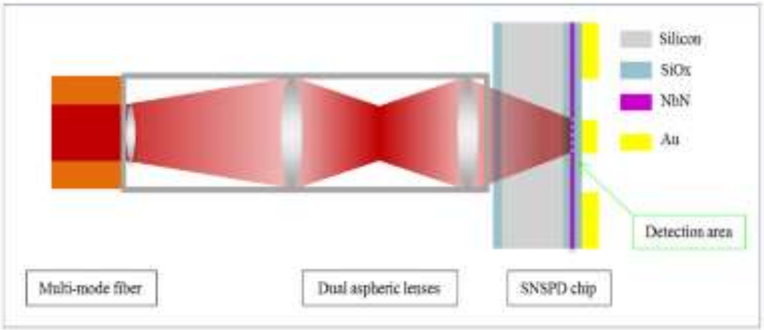
时间抖动： ~ 70 ps





光束压缩与多模光纤耦合

光纤内径：**62.5μm**



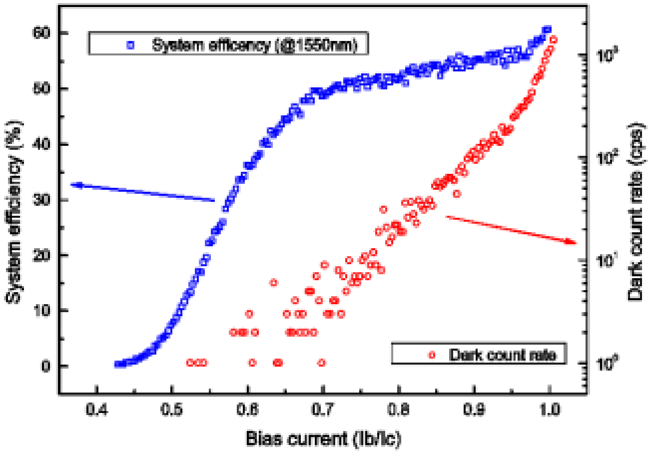
两个微透镜。第一个增大发散角和物距，第二个具备较小的焦距

耦合效率 95%

$$\omega_0' = \frac{\lambda f}{\pi\sqrt{\omega_0^2 + (\theta s)^2}}$$

工作波长：1550 nm
系统效率：60%
暗计数： 100 cps

xy 平面对称设计，
抵消热/冷偏移
Z轴 束腰附近，抛物线顶点，变化慢



探测区尺寸：15μm×15μm

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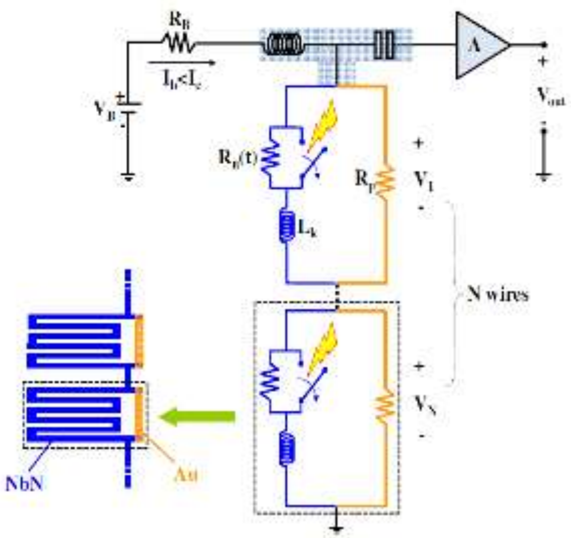
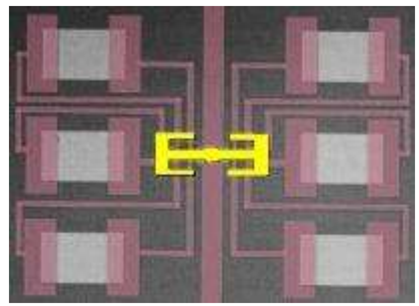
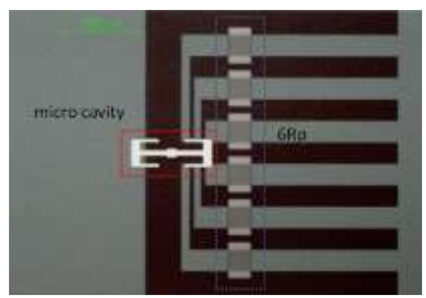
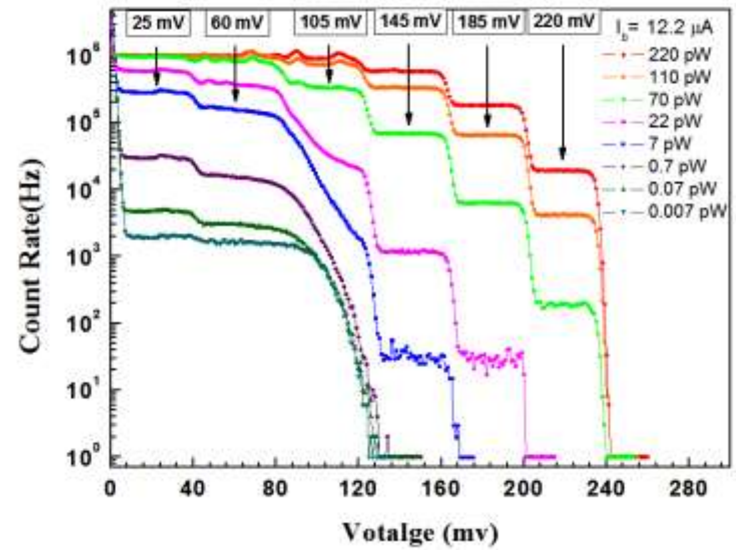
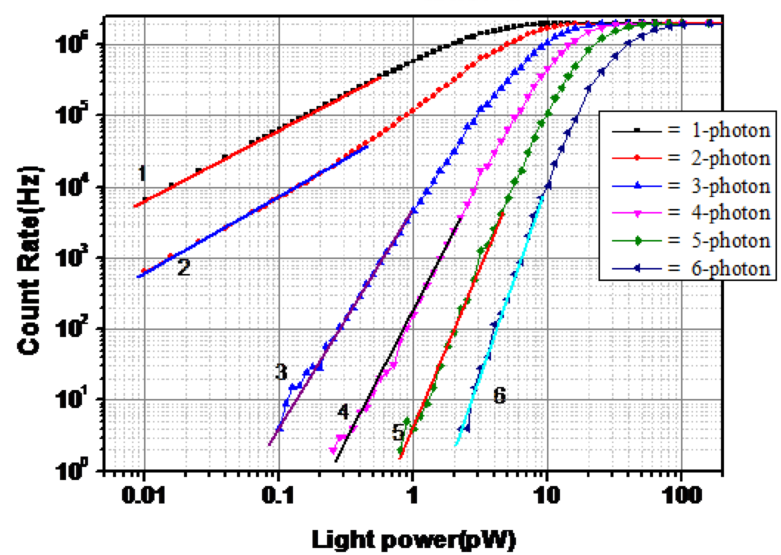
光子数分辨 SNSPD











串联结构SNPD（6-SND），实现1- 6个光子数的识别，系统效率大于40%

The count rates at different counting level and input light power

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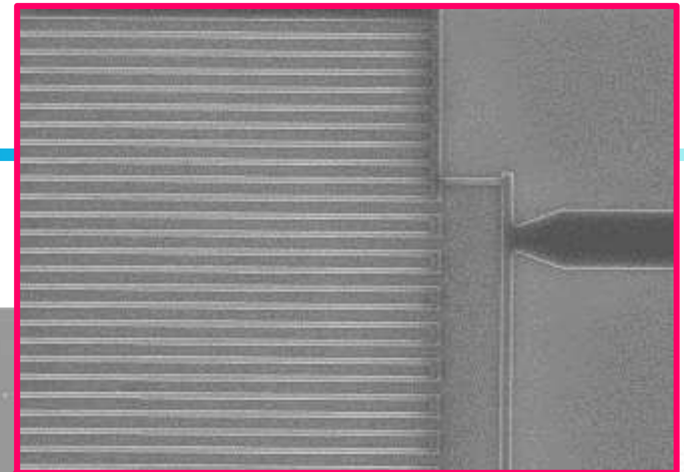
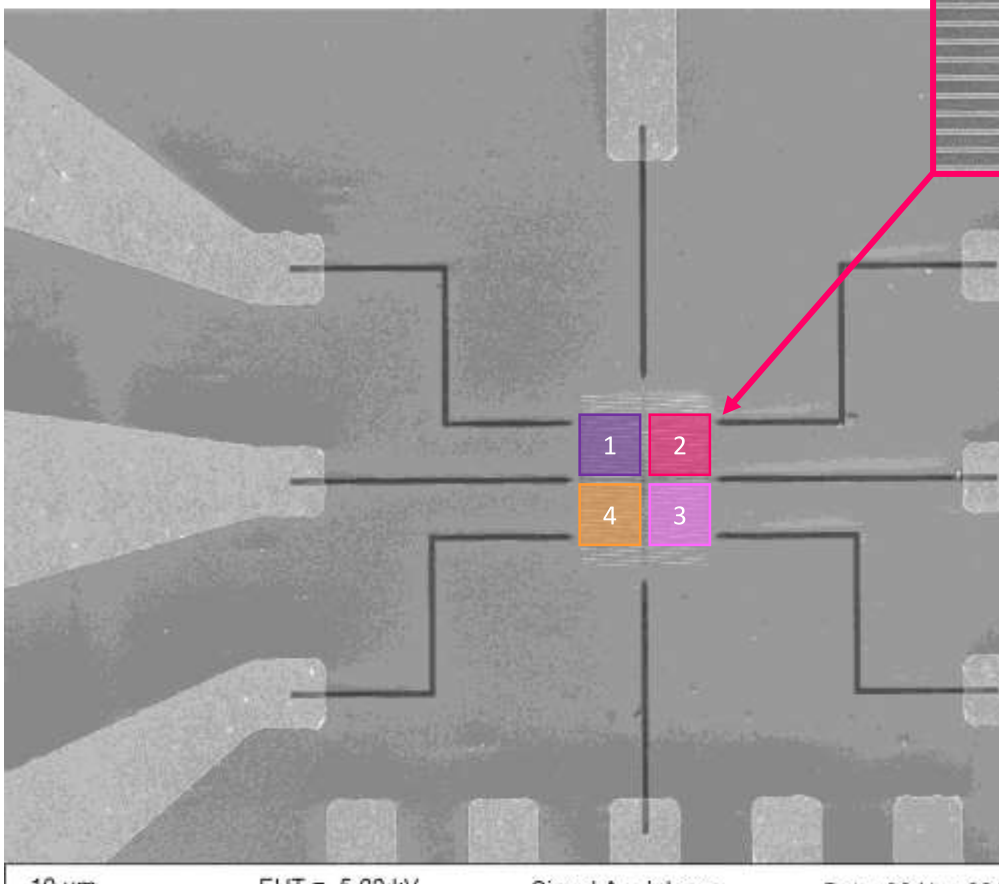
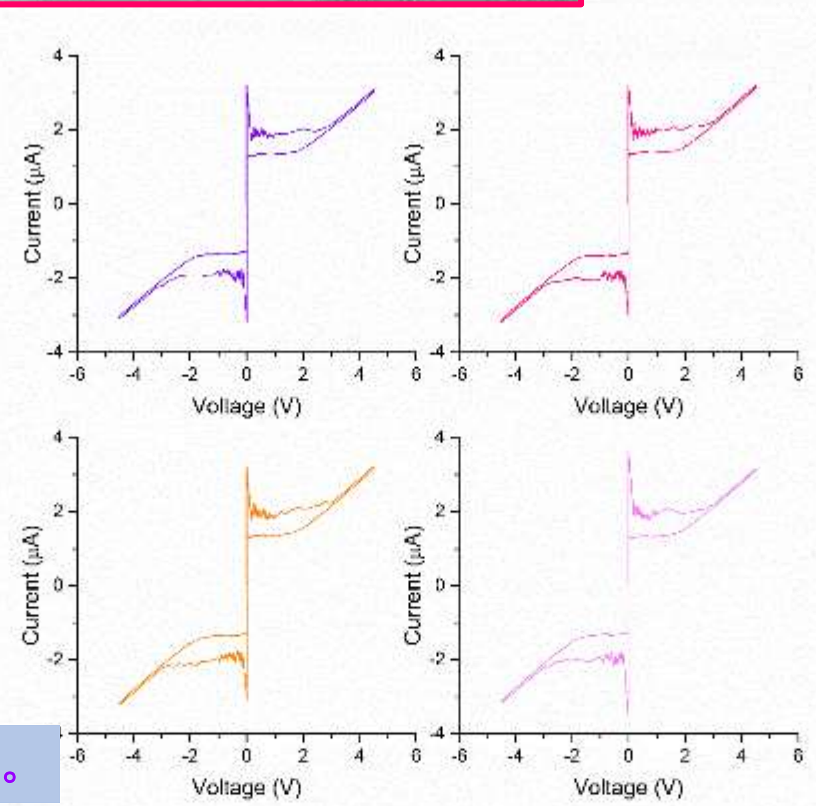
2×2 SNSPD

器件SEM图形和IV曲线(4.2K)



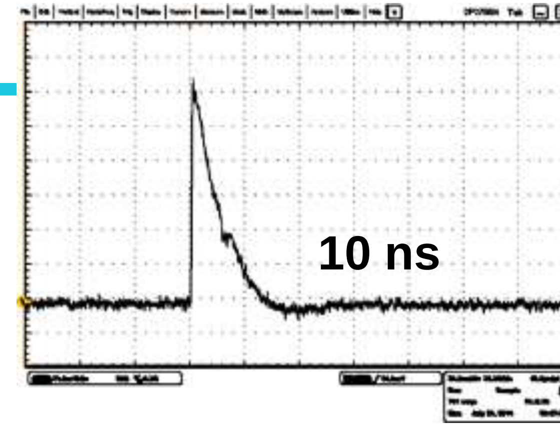


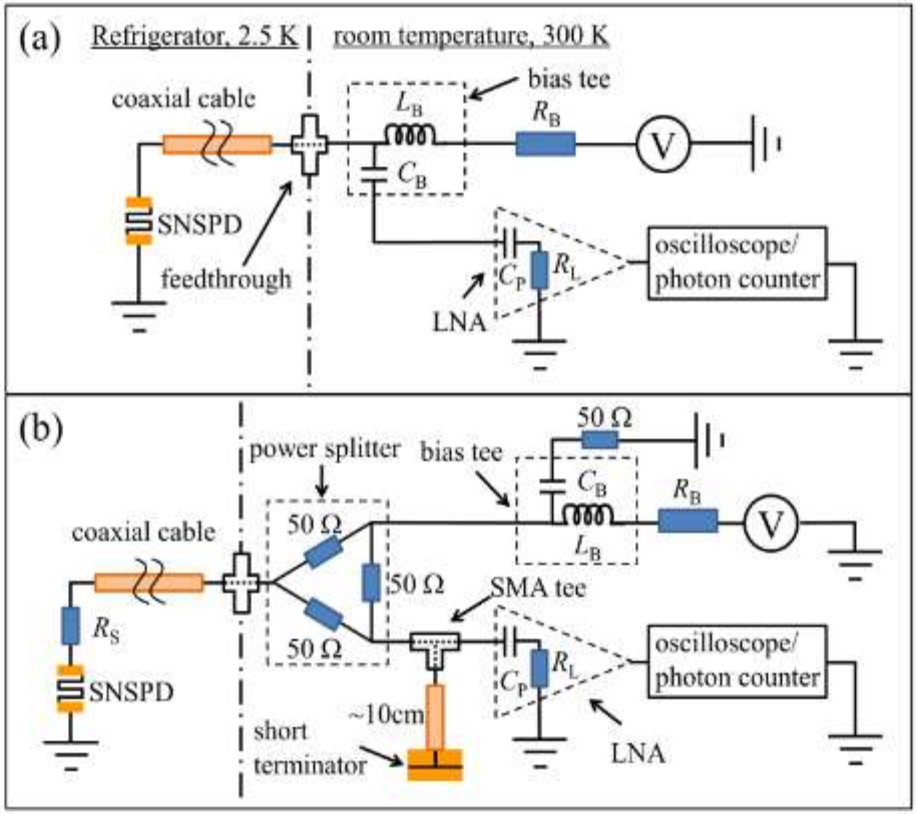


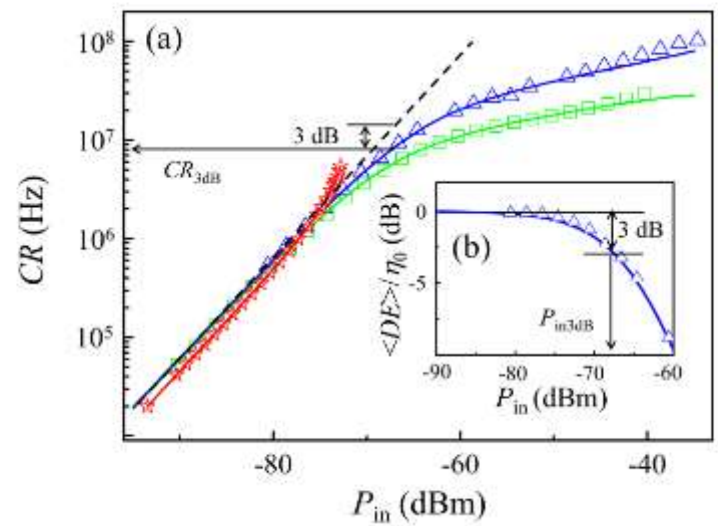
纳米线结构分析和电学性能分析表明各像元一致。

Email: Lzhang@nju.edu.cn

常温读出电路改进
提高探测速率







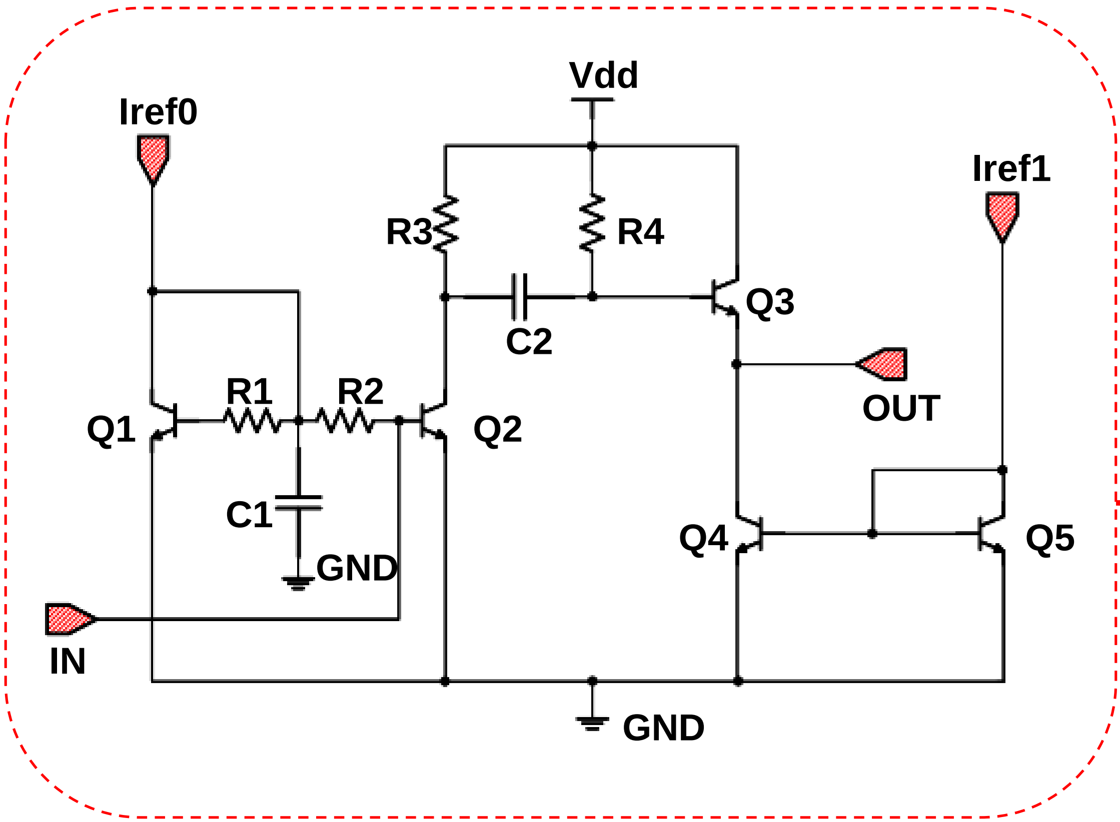
消除C_P上电势

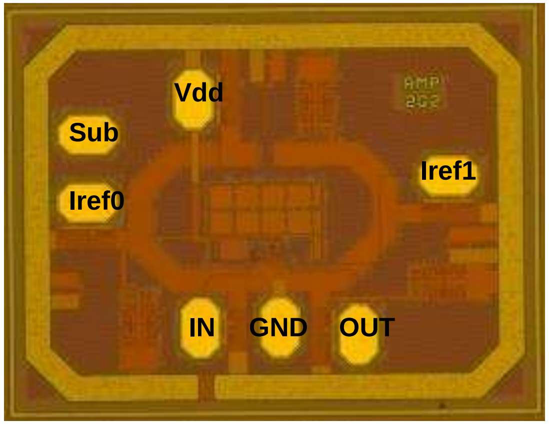
计数率可以达到100 MHz

Q. Y. Zhao et. al, Optics Letters, vol. 39, 1869, 2014

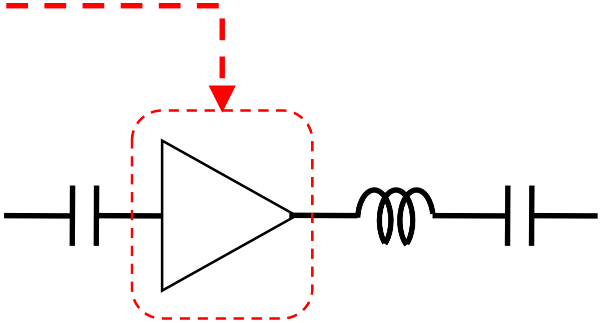
Email: Lzhang@nju.edu.cn

低温 SiGe 读出电路





Chip



整体结构

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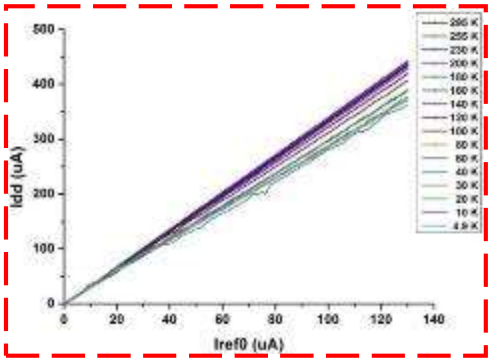
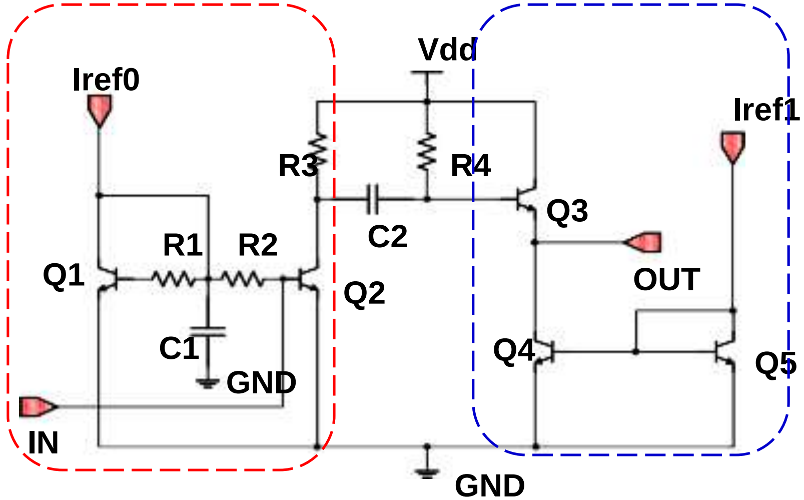
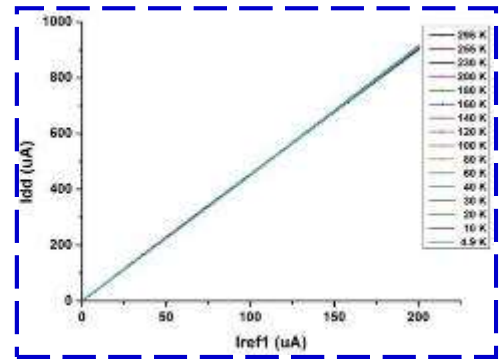
SiGe HBT 温度特性

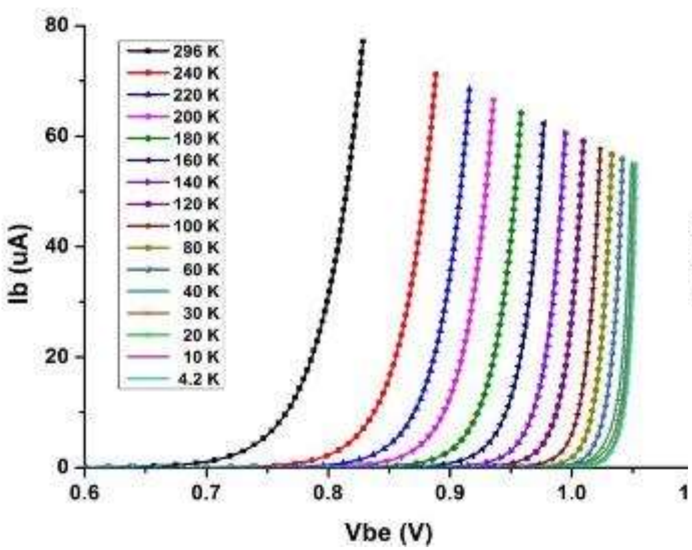




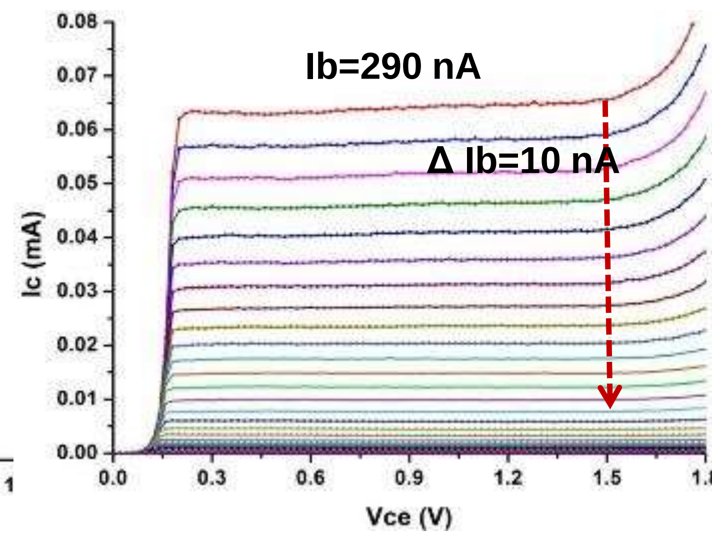


Q1:Q2=1:4

Q4:Q5=6:1



I_b as a function of Vbe from 300K to 4.2K



I_c vs Vce at 4.2 K

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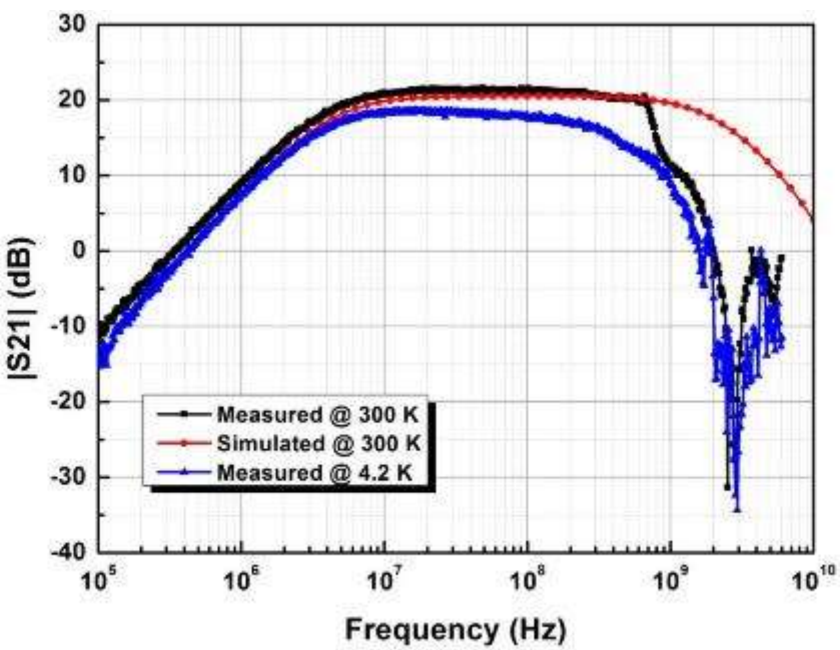
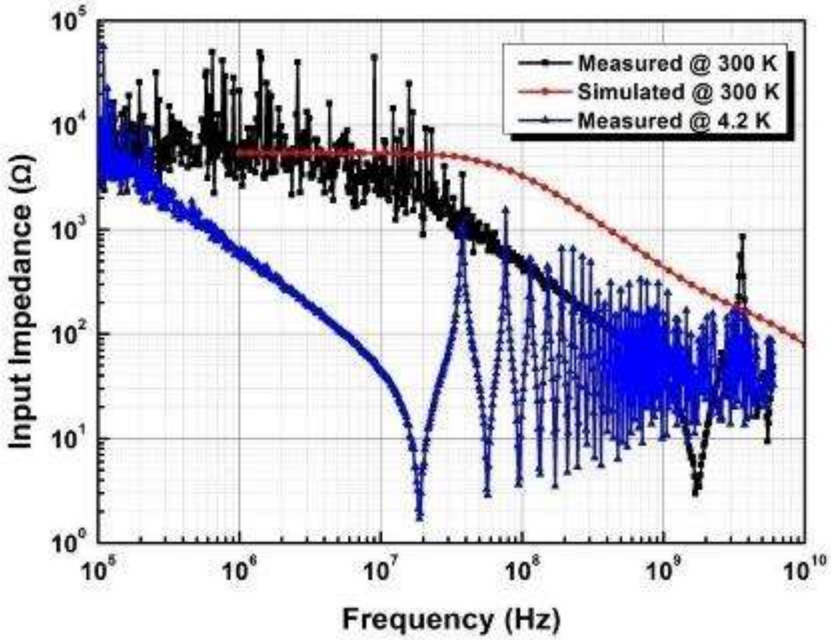
Measurement Result

	Iref0 (uA) / Vref0 (V)	Iref1 (uA) / Vref1(V)	Vin (V)	Vout (V)
Simulated	130 / 1.064	200 / 0.887	0.843	0.921
Measured(300K)	130 / 1.060	200 / 0.918	0.875	0.884
Measured(4.2K)	15 / 1.049	85 / 1.071	1.052	1.071



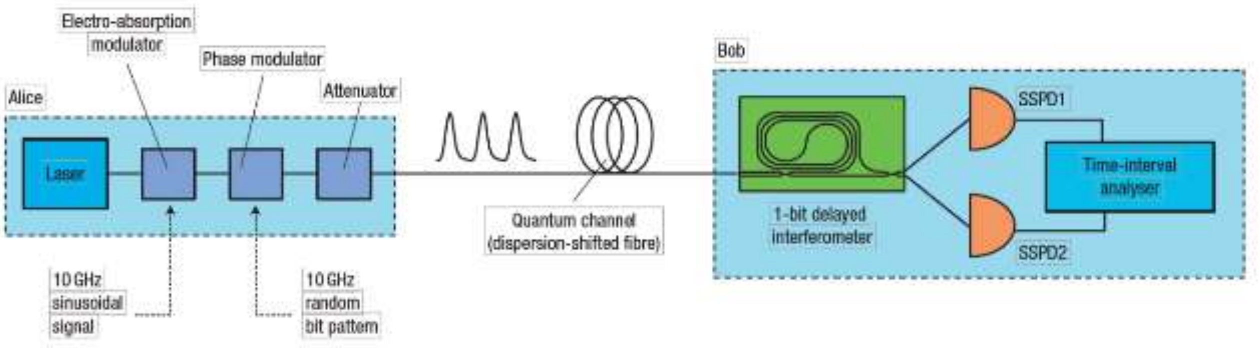


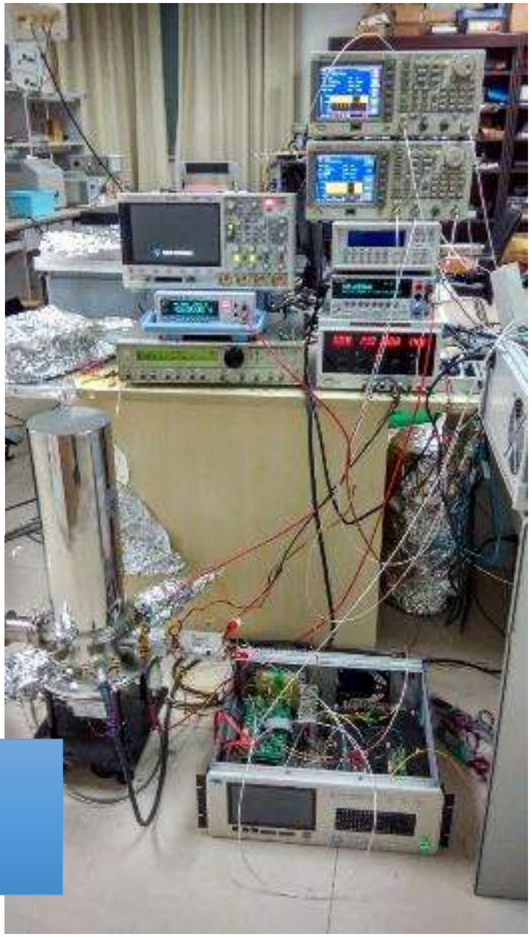
4.2 K时，功耗~ 0.9 mW

Email: Lzhang@nju.edu.cn

量子信息：量子通信，量子光学。

量子密钥分发

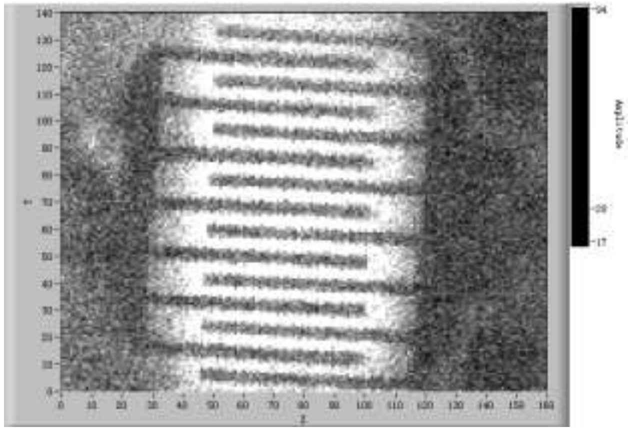




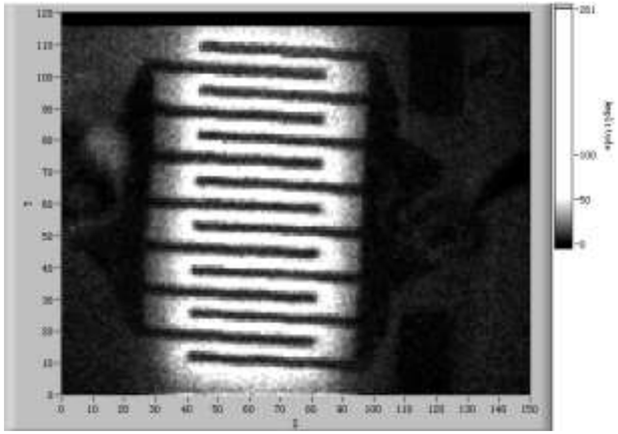
用户单位：中国科学技术大学
使用结果：将通信距离从150公里提高到了250公里。

Email: Lzhang@nju.edu.cn

集成电路无损检测



APD成像原始图像及数据　（未去本底处理）

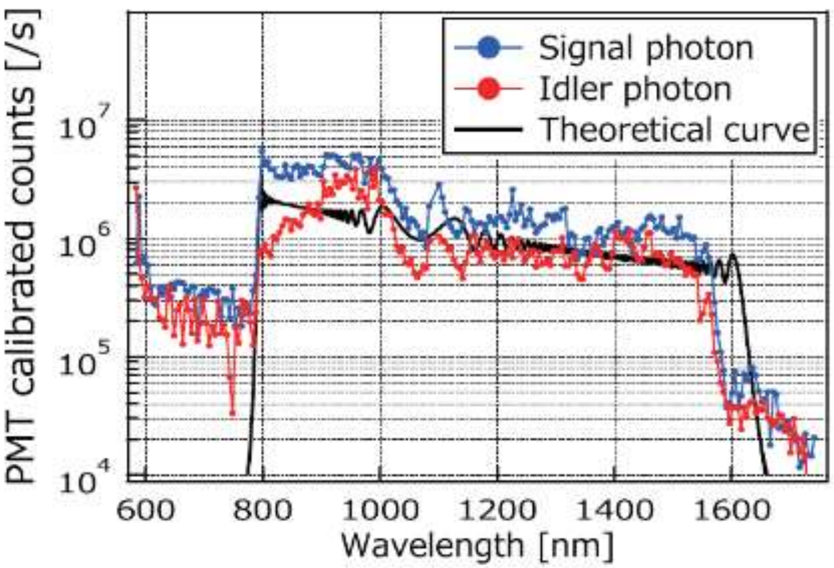


SNSPD成像原始图像及数据（未去本底处理）

用户单位：华南师范大学
使用结果：大幅度提高了成像质量。

Email: Lzhang@nju.edu.cn

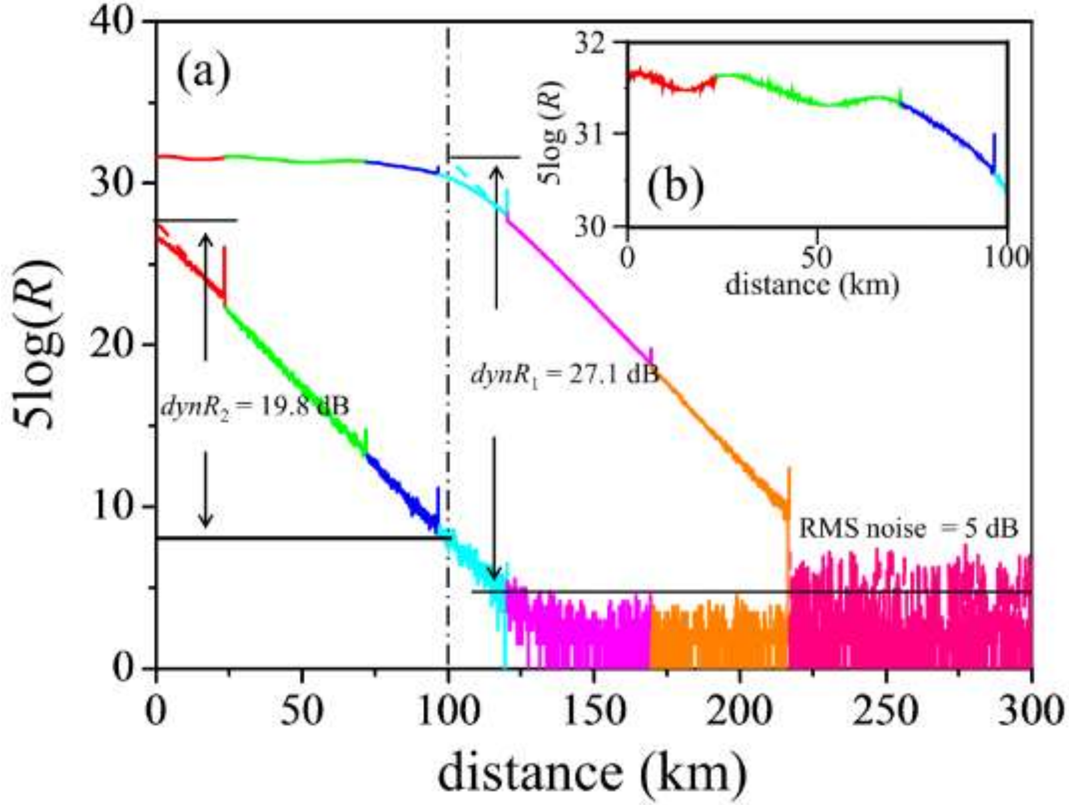
单周期纠缠荧光检测



用户单位：日本大阪大学
使用结果：首次观测到了单周期纠缠荧光谱。

Email: Lzhang@nju.edu.cn

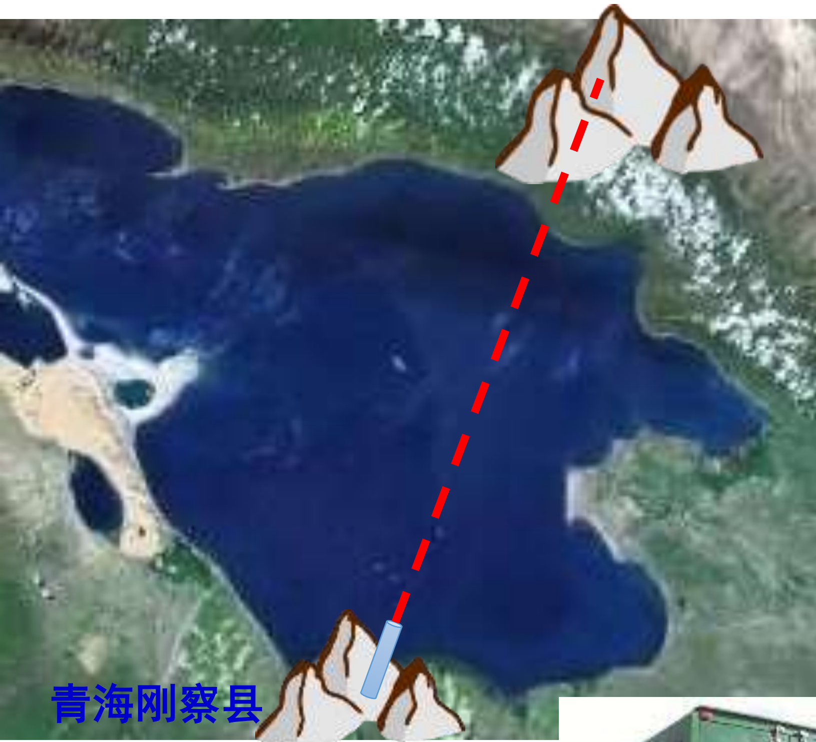
OTDR



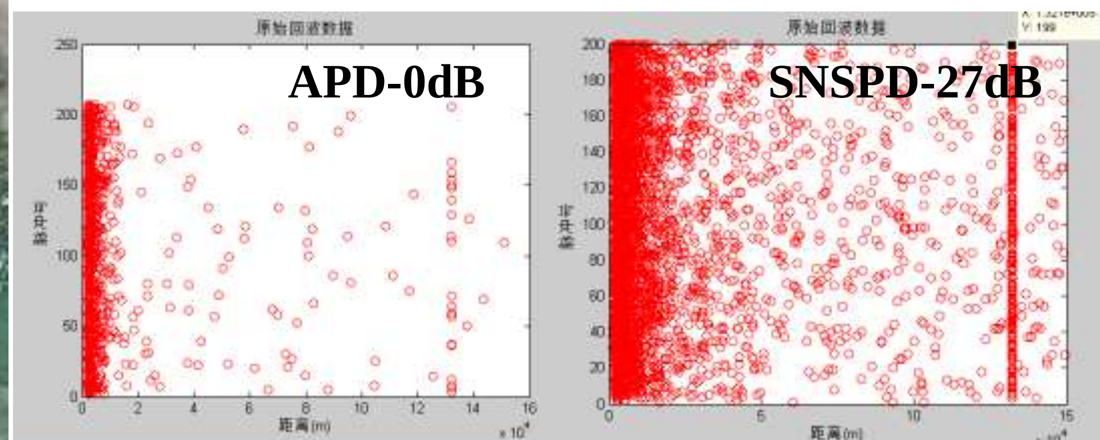
用户单位：南大光通信中心
使用结果：长距离(200km)和高精度(6cm)OTDR。

Email: Lzhang@nju.edu.cn

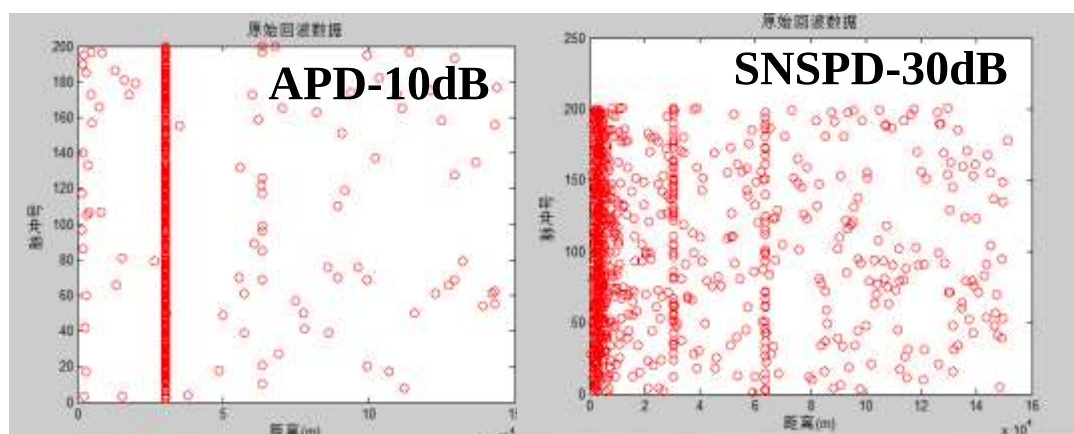
激光雷达 非合作目标(漫反射)



132km大山:夜间



30km小目标:夜间



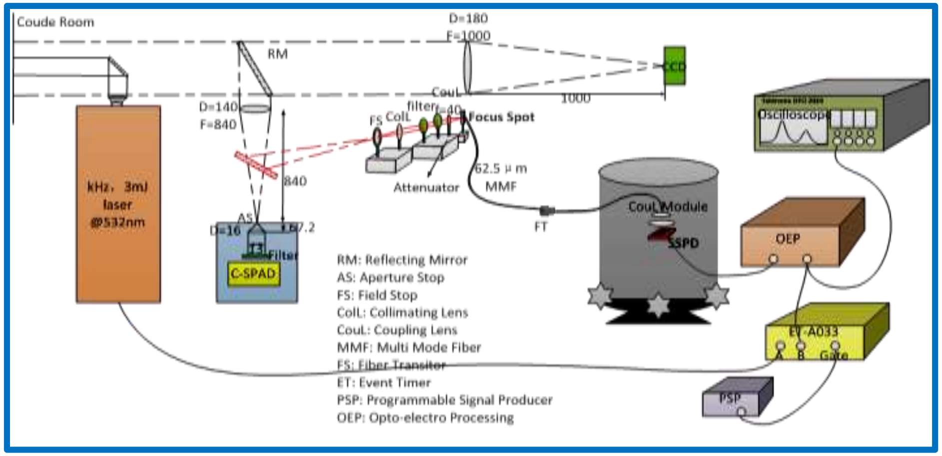
波长　1064 nm
重复频率　5 Hz
脉冲宽度：　10 ns
单脉冲能量　150 mJ

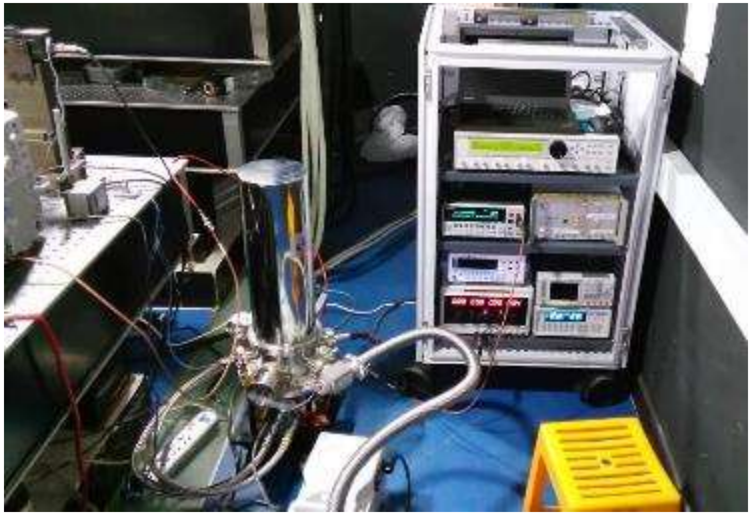
Email: Lzhang@nju.edu.cn

空间目标

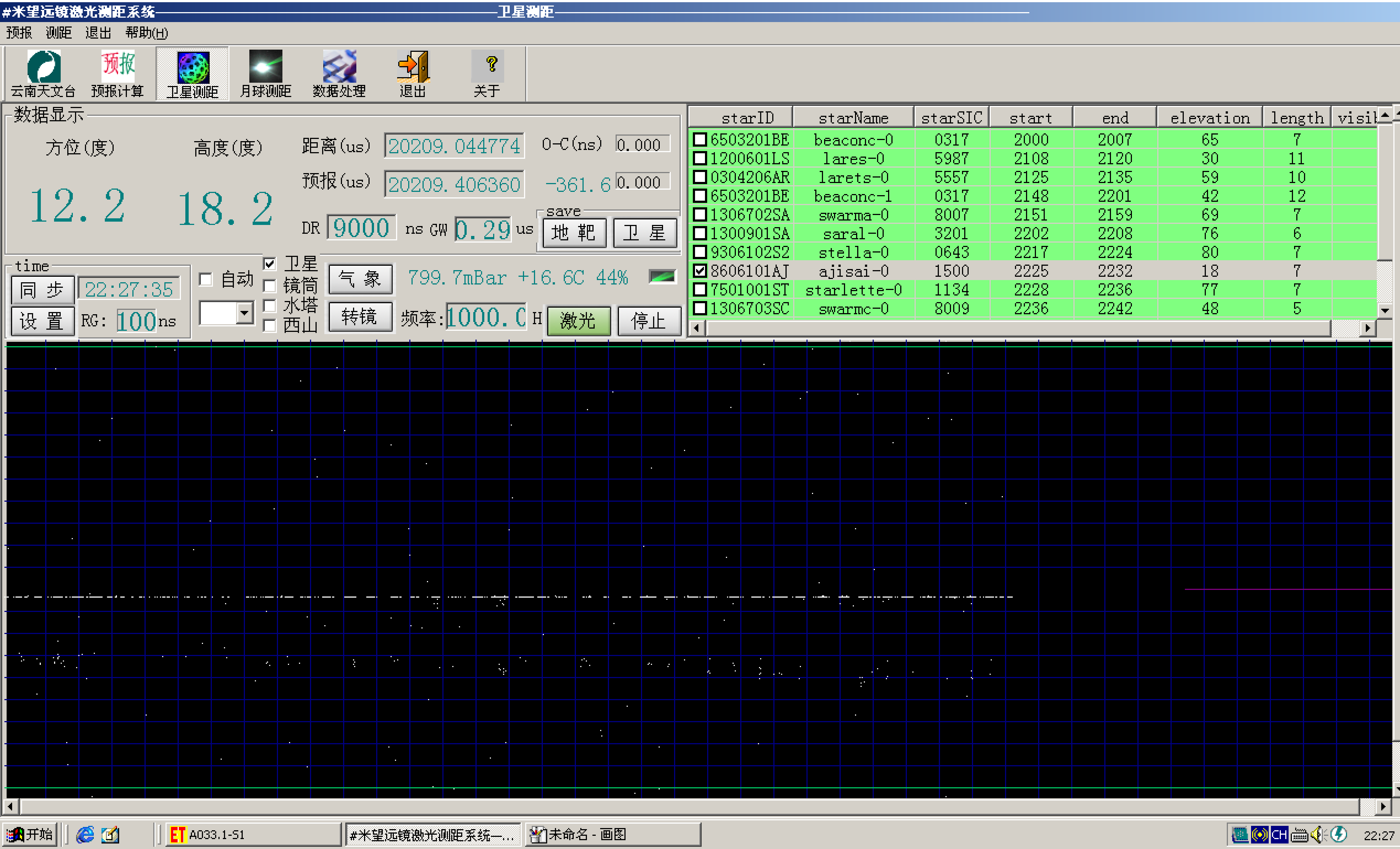
采用长焦距接收光路，

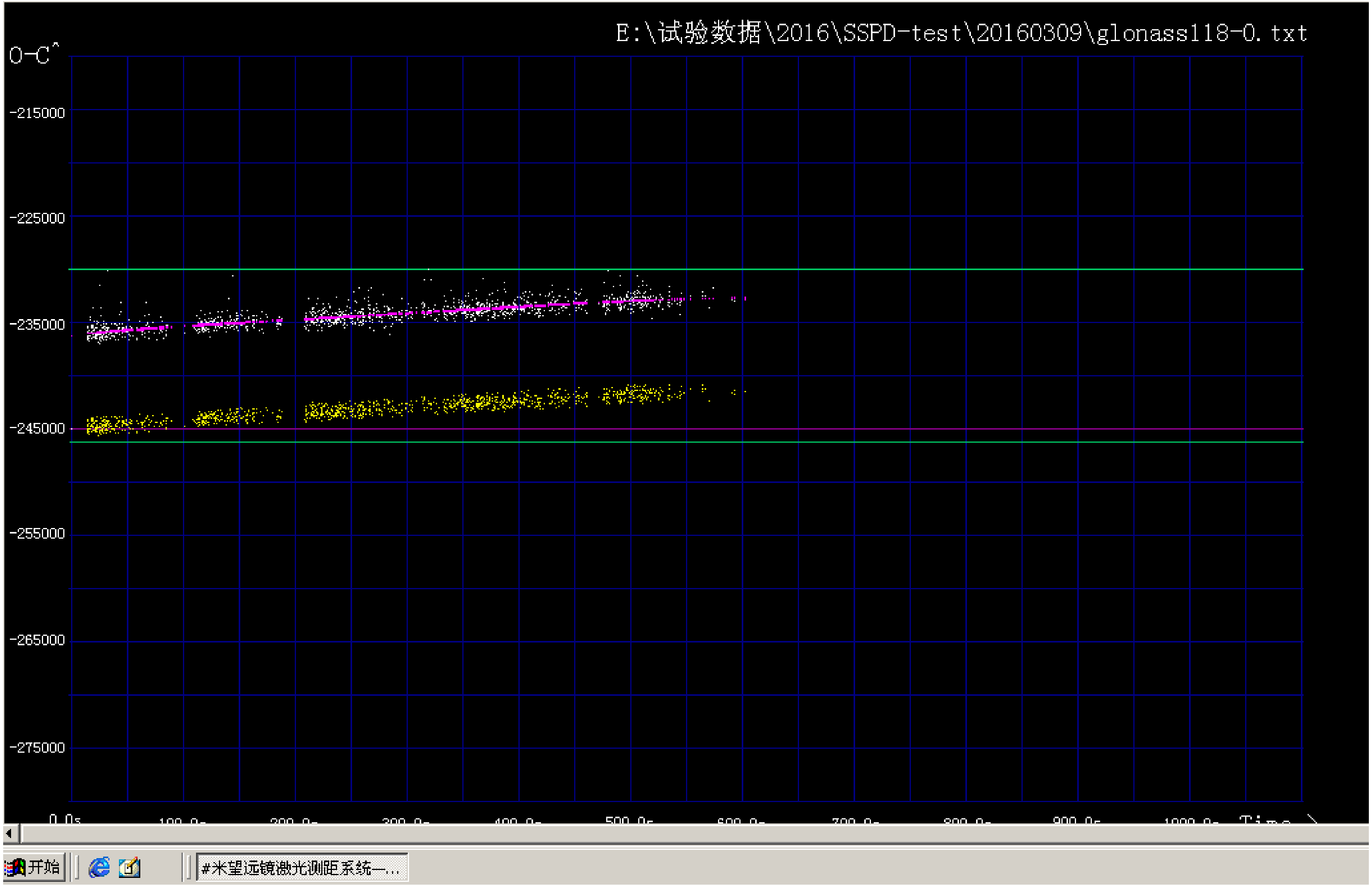
实现了与望远镜系统的工程对接。



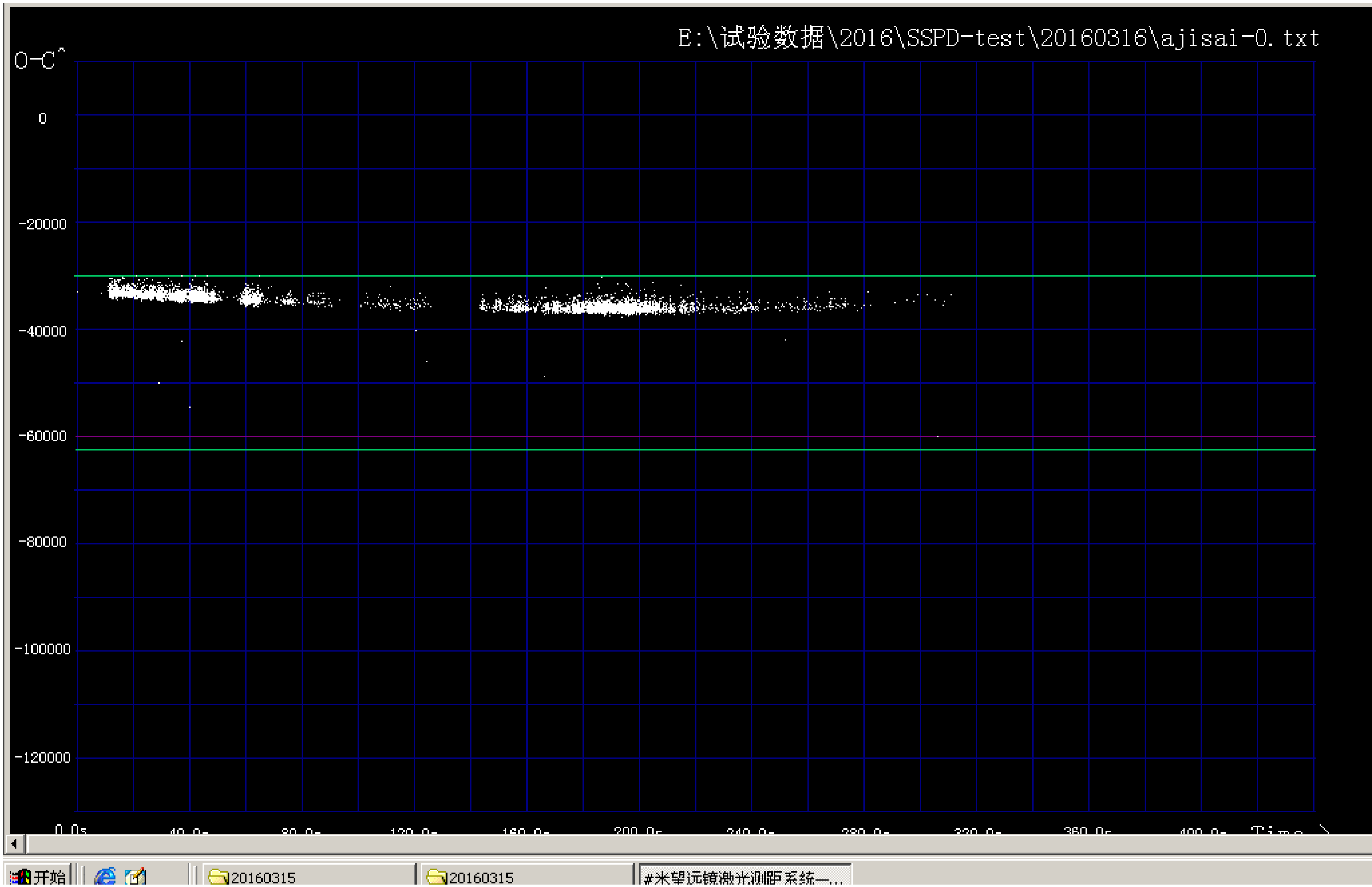


Email: Lzhang@nju.edu.cn


#米望远镜激光测距系统
卫星测距
预报 测距 退出 帮助(H)
云南天文台
预报计算
卫星测距
月球测距
数据处理
退出
关于
数据显示
方位(度)
高度(度)
12.2
18.2
距离(us)
20209.044774
O-C(ns)
0.000
预报(us)
20209.406360
-361.6
0.000
DR 9000 ns GW 0.29 us
save
地 靶
卫 星
time
同 步
22:27:35
设 置
RG: 100ns
自动
卫星
镜筒
水塔
西山
气 象
799.7mBar +16.6C 44%
转镜
频率:1000.0 H
激光
停止
starID starName starSIC start end elevation length
6503201BE beaconc-0 0317 2000 2007 65 7
1200601LS lares-0 5987 2108 2120 30 11
0304206AR larets-0 5557 2125 2135 59 10
6503201BE beaconc-1 0317 2148 2201 42 12
1306702SA swarma-0 8007 2151 2159 69 7
1300901SA saral-0 3201 2202 2208 76 6
9306102S2 stella-0 0643 2217 2224 80 7
8606101AJ ajisai-0 1500 2225 2232 18 7
7501001ST starlette-0 1134 2228 2236 77 7
1306703SC swarmc-0 8009 2236 2242 48 5
开始
A033.1-S1
#米望远镜激光测距系统—...
未命名 - 画图
CH
22:27



Email: Lzhang@nju.edu.cn


E:\试验数据\2016\SSPD-test\20160316\ajisai-0.txt
O-C
0
-20000
-40000
-60000
-80000
-100000
-120000
开始
20160315
20160315

5. 结论与展望

- 介绍了TES和SNSPD两种超导单光子探测器.

超导探测器特点: 性能好, 成本和体积略大.

发展前景:

性能: 效率 速度 等

实用: 光敏面 成本 体积

预计在极限性能检测和大型工程/国防项目应用。

Email: Lzhang@nju.edu.cn