



# Nano-structured superconducting single-photon detector



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## Outline

1. Motivation for development of **IR** Single-Photon Detector
2. Fabrication and design of NbN SPD
3. Mechanism of SSPD photon detection
4. Time constant and jitter of NbN SPD
5. Quantum efficiency and spectral sensitivity
6. Dark counts rate and noise equivalent power
7. Implementation of NbN SPD: Silicon IC Debug
8. Conclusions

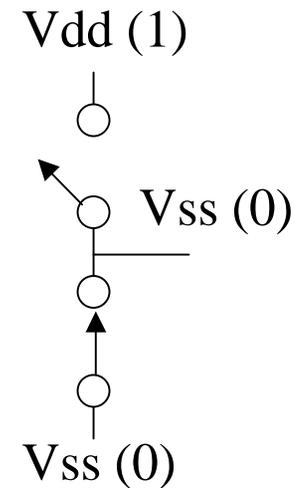
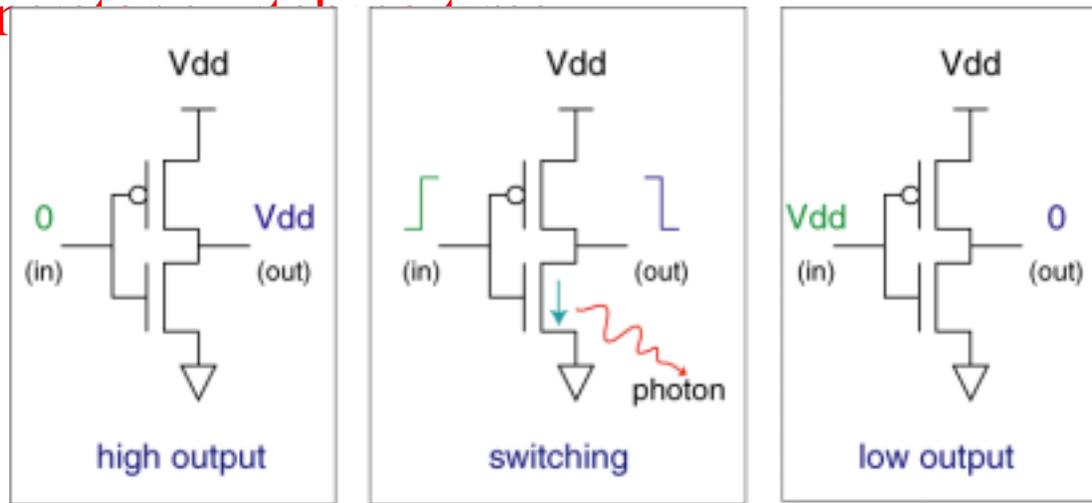
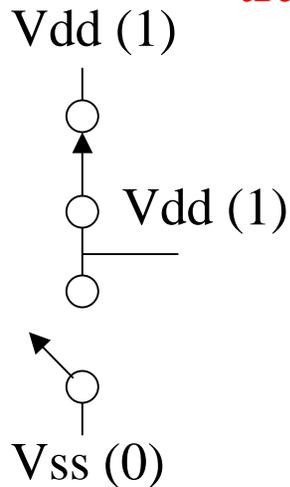




# Motivation: CMOS Device Debug



- Normally operating **nMOS transistor emits near IR photons (0.9-1.4um)** when current passes through the channel
- Time-correlated photon emission detection **measures transition times**



Kash, J. A. and J. C.-H. Tsang (1999). Noninvasive optical method for measuring internal switching and other dynamic parameters of CMOS circuits. USA, International Business Machines Corporation. US Patent # 5,940,545



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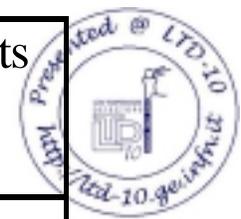




# Specifications for some commercially available single-photon detectors and NbN SSPD at 1.3 micron wavelength



Detector Model	Counting rate (s <sup>-1</sup> )	DE (%)	Jitter (ps)	Dark counts (s <sup>-1</sup> )
<b>FPD5W1KS InGaAs APD</b> (Fujitsu)	<b>5.0x10<sup>6</sup></b>	<b>16</b>	<b>200</b>	<b>500**</b>
<b>R5509-42 STOP PMT</b> (Hamamatsu)	<b>9.0x10<sup>6</sup></b>	<b>0.1</b>	<b>150</b>	<b>2.0x10<sup>4</sup></b>
<b>Si APD SPCM -AQR-16</b> (EG&G)	<b>5.0x10<sup>6</sup></b>	<b>0.01</b>	<b>350</b>	<b>25</b>
<b>Mersicron II PMT</b> (Quantar Tech.Inc)	<b>1.0x10<sup>6***</sup></b>	<b>0.001</b>	<b>100</b>	<b>0.1</b>
<b>Superconducting Tunnel Junction</b>	<b>5.0x10<sup>3</sup></b>	<b>60</b>	<b>N/A</b>	<b>N/A</b>
<b>SSPD (measured)</b>	<b>3x10<sup>9</sup></b>	<b>10</b>	<b>20</b>	<b>&lt;10<sup>-4</sup></b>



\*Gated regime with 0.1% per gate after-count probability.

\*\* Calculated with 10<sup>-4</sup> per gate probability.

\*\*\*Data for a high-speed version; standard devices exhibit 1 ´ 10<sup>5</sup> s<sup>-1</sup>.

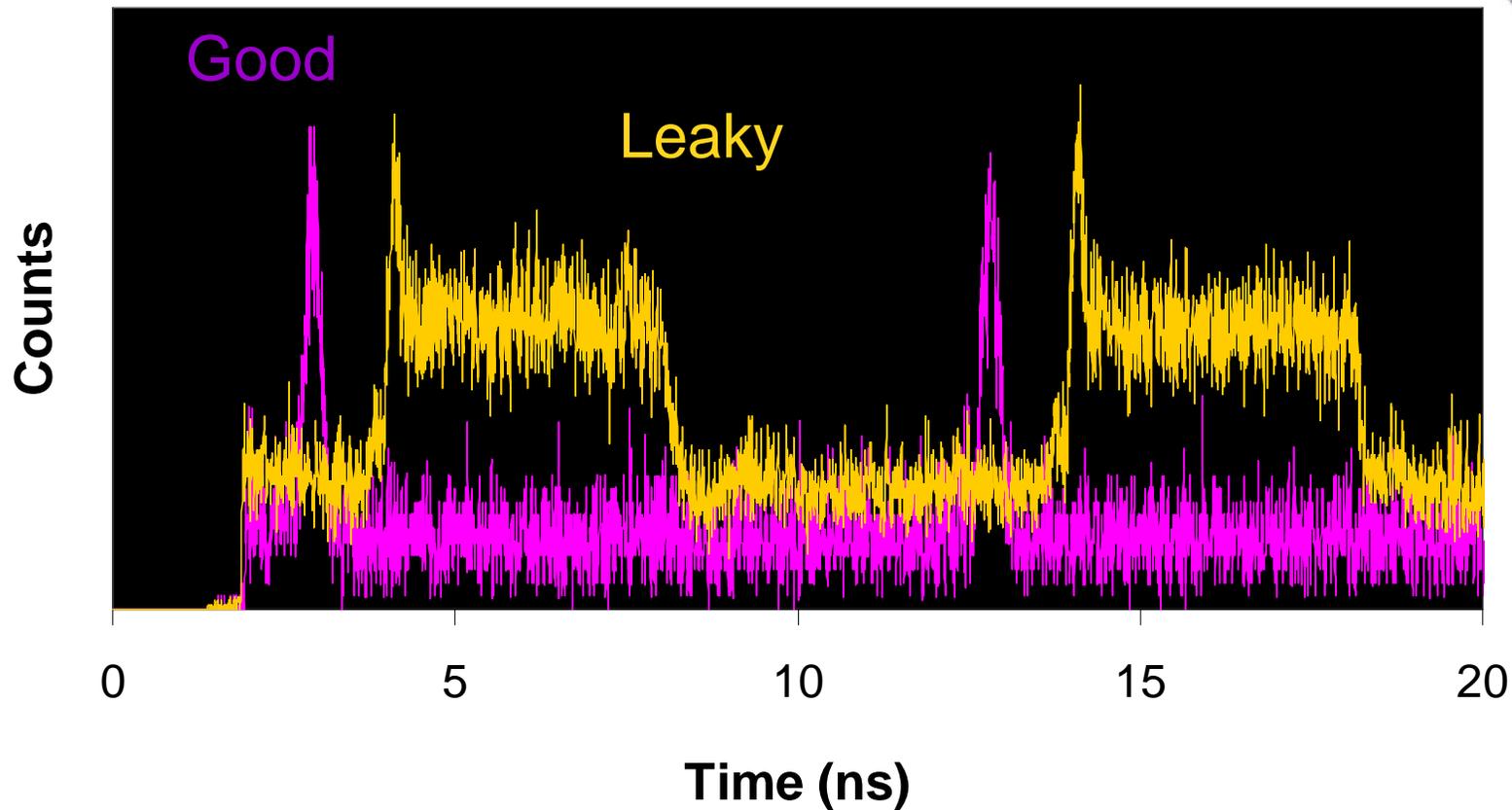




# Emission from Good and Bad Transistors (Mepsicron II detector)



0.35um, 3.3V CMOS device running at 100MHz



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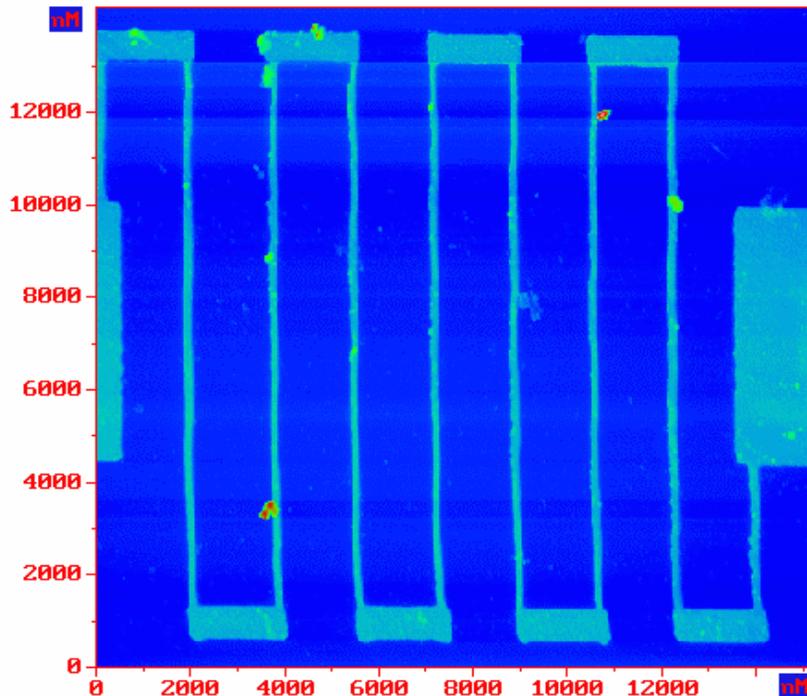
# SSPD Meander Line Fabrication



**Meander used to increase detector active area**

## Structure:

NbN Meander Line Pattern



15um x 15um AFM image of NbN structure

## Fabrication:

- Sputter 3.5 - 10nm thick NbN film on sapphire substrate.
- Form Au contacts with Optical lithography.
- Form 150nm wide meander line pattern with e-beam lithography.

## Requirements:

- Uniform film material and thickness.
- Uniform line width.
- High substrate surface quality.





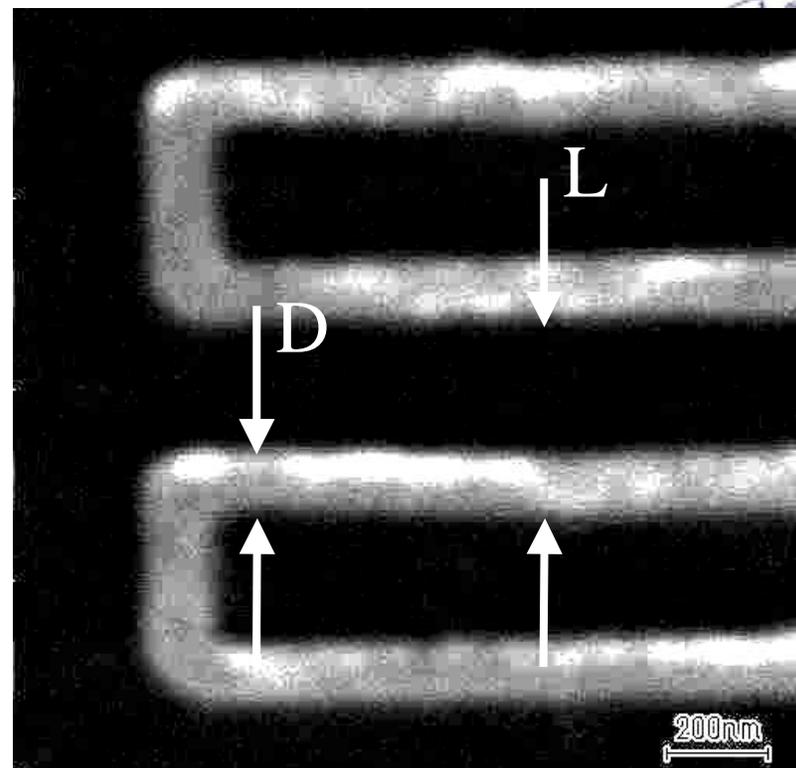
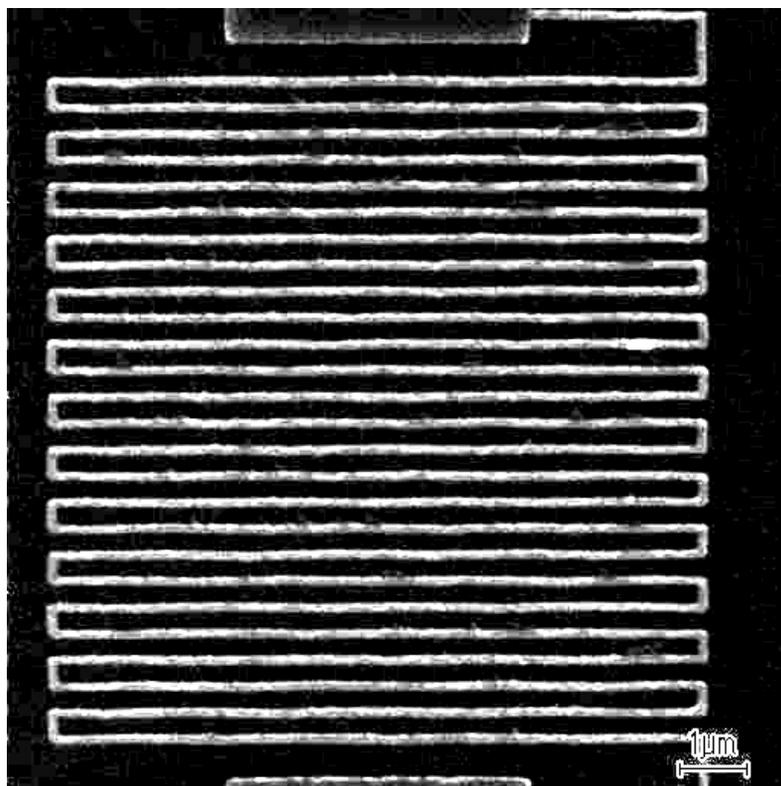
# SSPD Requirements



N	SSPD Requirement	Our option
1	Superconducting material	NbN
2	thin and narrow strips	Thickness of NbN film – 3.5 nm Width of strip ~100 nm
3	Covered area and filling factor	Meander type device with $4 \times 4$ or $10 \times 10 \mu\text{m}^2$ area Filling factor up to 0.5



# SSPD Requirements



filling factor:  
 $D/L$



# Fabrication of SSPD Using Direct Electron Beam Lithography and Reactive Ion Etching Process

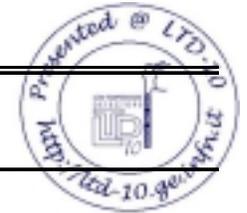


ID#	Sketch	Comments
1. Deposition of a NbN film by dc reactive magnetron sputtering.		Substrate: double-side-polished, 300- $\mu\text{m}$ -thick sapphire. Residual pressure $1.5 \times 10^{-6}$ mbar. Substrate temperature $850^{\circ}\text{C}$ . $\text{N}_2$ partial pressure $10^{-4}$ mbar. Ar partial pressure $5 \times 10^{-3}$ mbar.
2. Patterning of alignment marks.		Lift-off process. Ti/Au 5/100 nm alignment marks. Vacuum resistive evaporation at room temperature. Optical lithography process with AZ1512 photoresist.
3. Patterning of stripe windows in preparation for a meander structure.		Direct electron beam lithography process with PMMA 950K (2%, 0.08 $\mu\text{m}$ ) electron resist. Process parameters: $I = 25$ pA, $U = 25\text{kV}$ . The developer: toluene and isopropanol 1:10 mixture. Reactive ion etching of NbN film in $\text{SF}_6$ . Removal of electron resist layer.





# Fabrication of SSPD Using Direct Electron Beam Lithography and Reactive Ion Etching Process

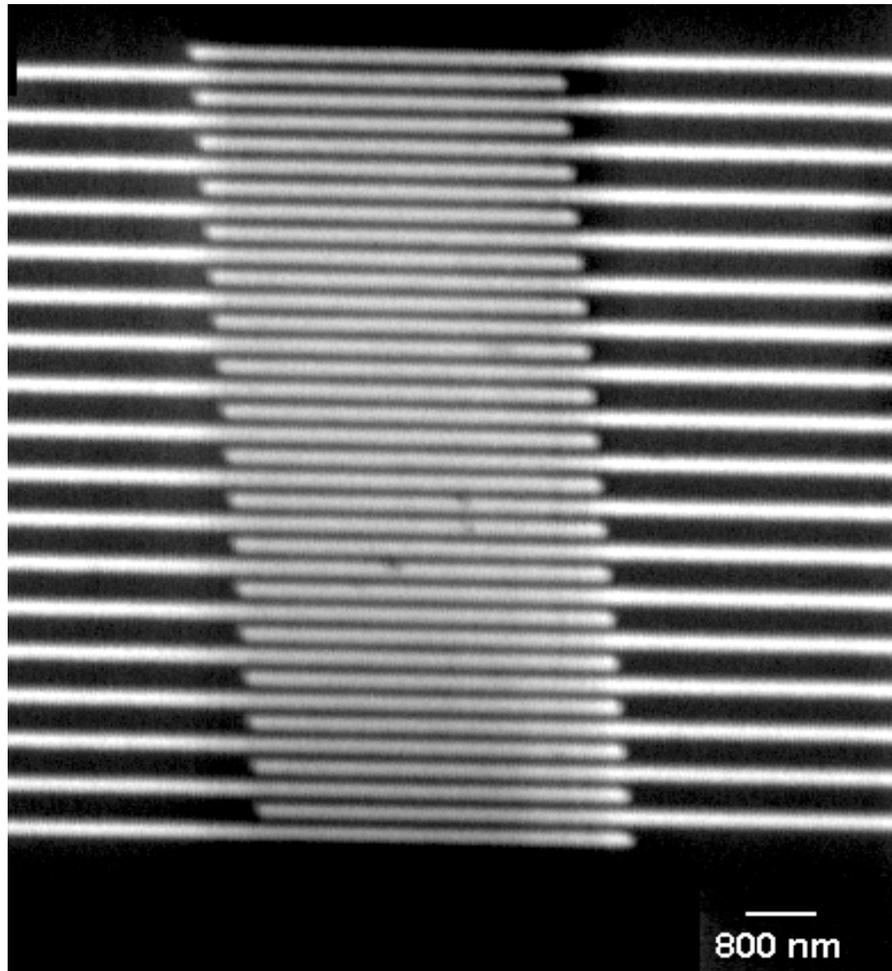


ID#	Sketch	Comments
4. Patterning of outer contact pads.		Lift-off process. Ti/Au 5/200 nm contact pads. Vacuum resistive evaporation at room temperature. Optical lithography process with AZ1512 photoresist.
5. Final patterning of meander structure.		Photolithography process with AZ1512 photoresist. Chemical etching of unprotected areas of NbN film in CP-4 (HNO <sub>3</sub> /HF/CH <sub>3</sub> COOH (5:3:3)). Removal of electron resist layer.



# Images of SSPD

(direct electron beam lithography and reactive ion etching process)



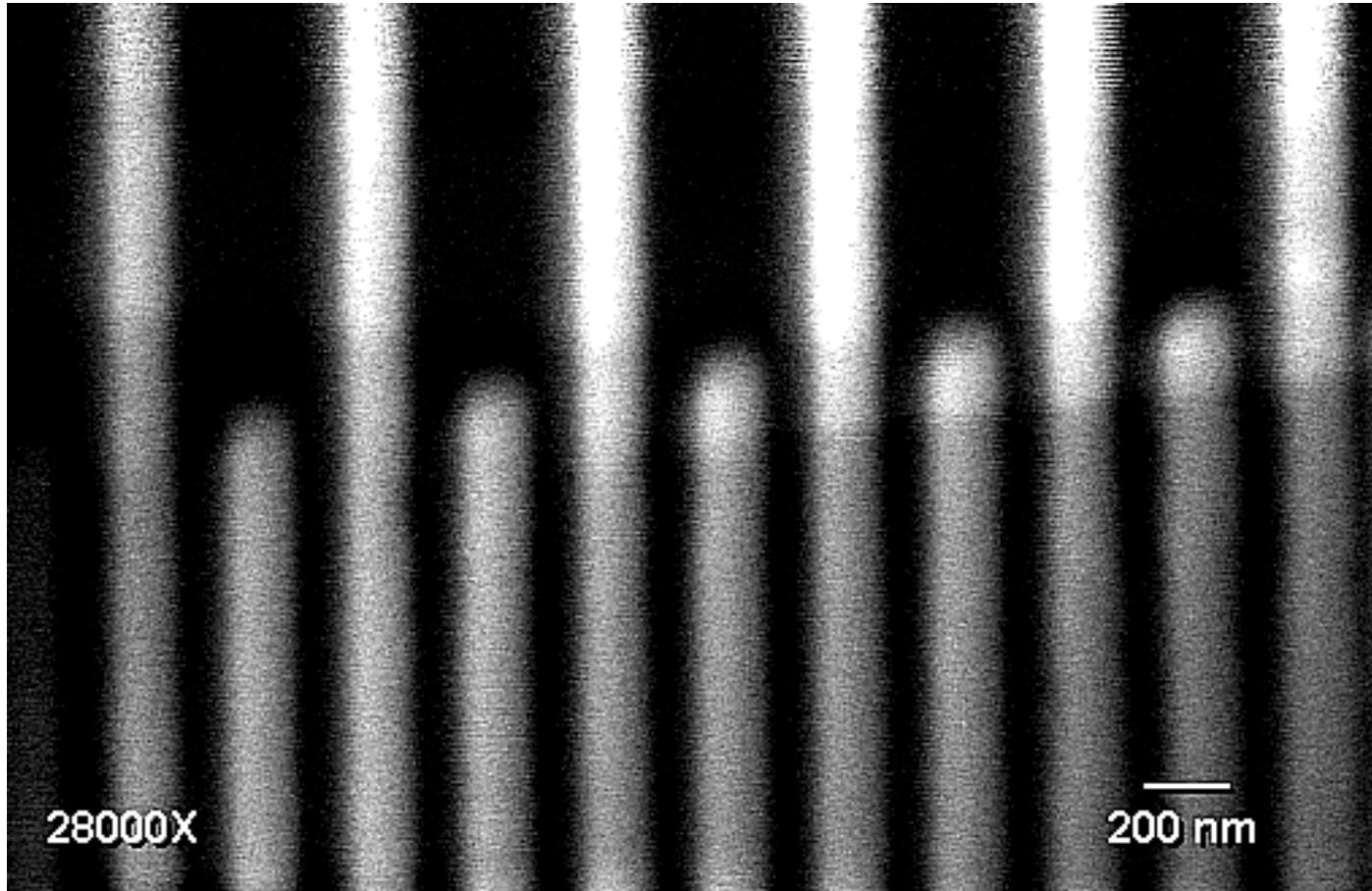
Scanning Electron  
microscope image



filling factor  
 $1/2$



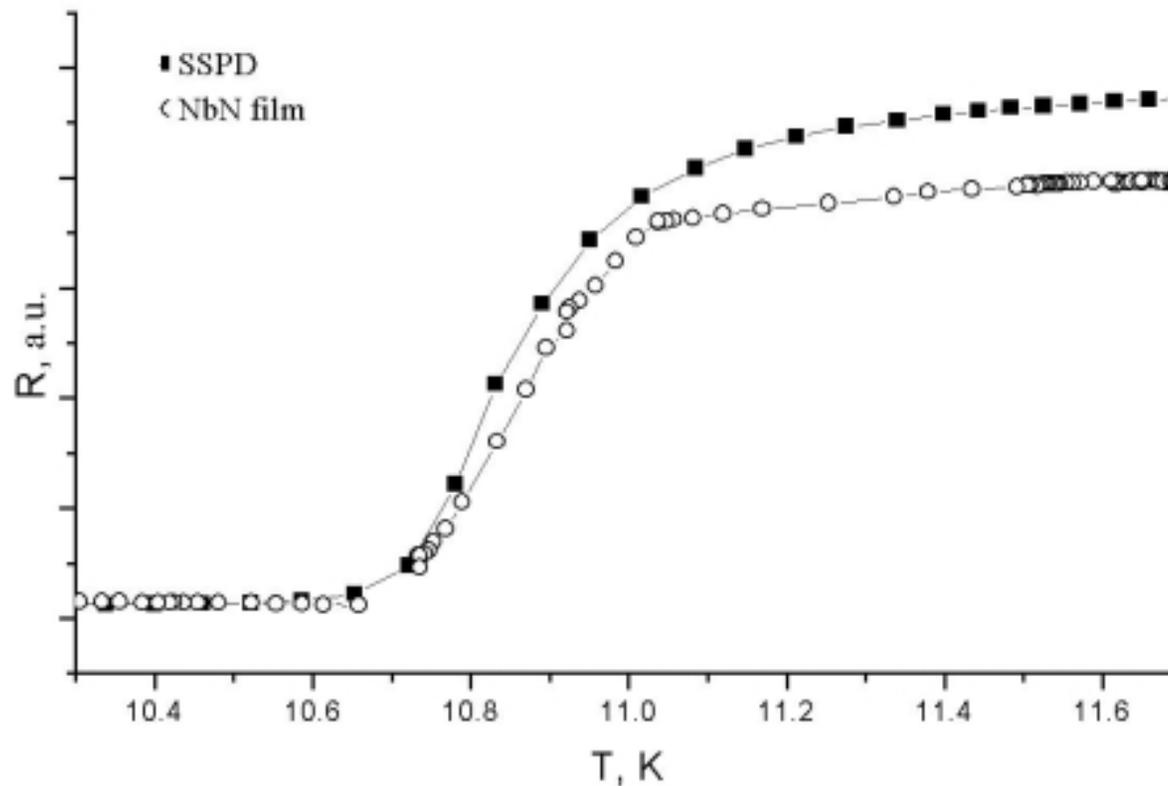
# Scanning Electron microscope image.





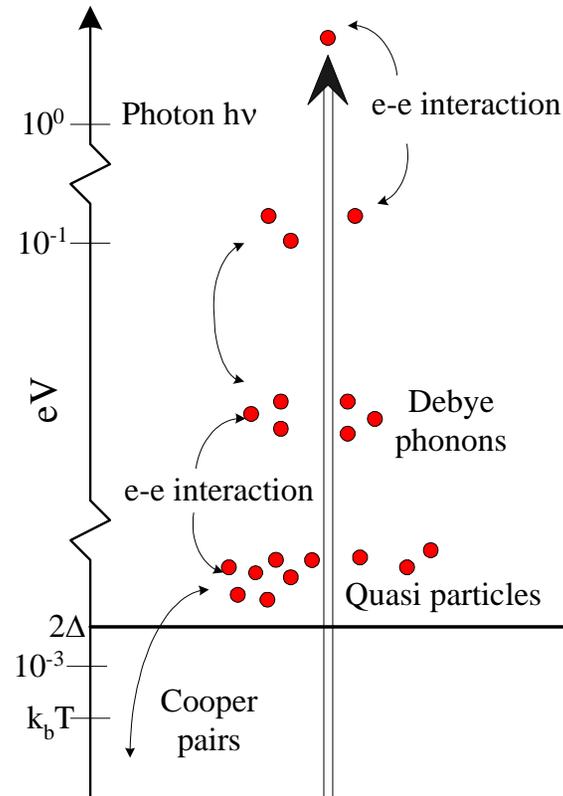
# Resistance vs Temperature Curves for Sputtered NbN Film 3.5 nm Thick and for SSPD Device

Direct electron beam lithography and reactive ion etching process





# Energy Relaxation Process



Schematic description of relaxation process in an optically excited superconducting thin film.

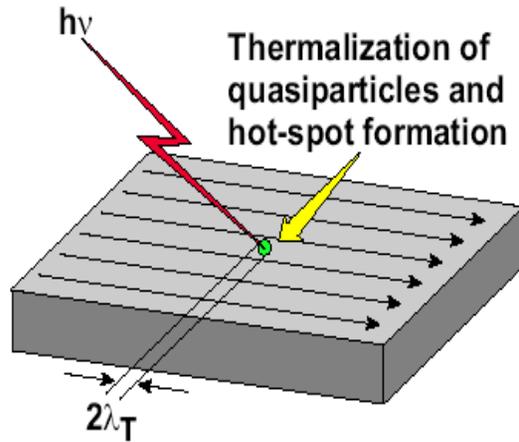


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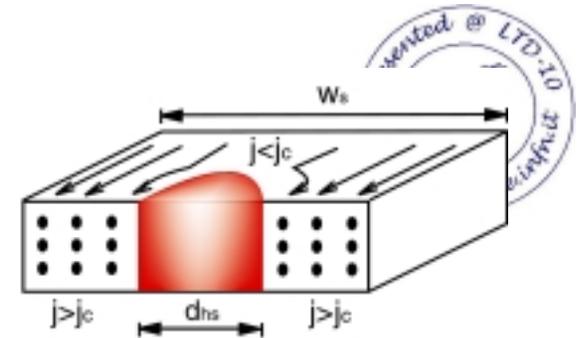
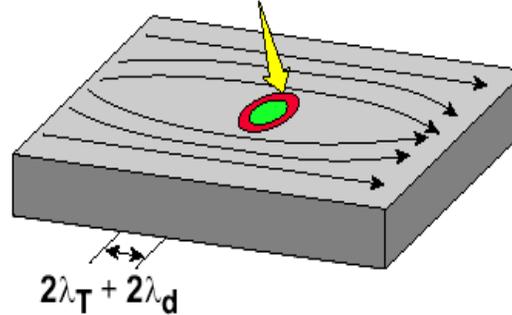




# Mechanism of SSPD Photon Detection

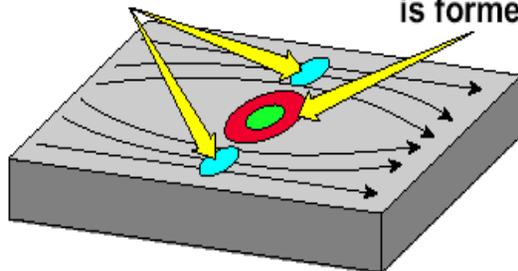


Hot-spot diffusion and superconductivity suppression

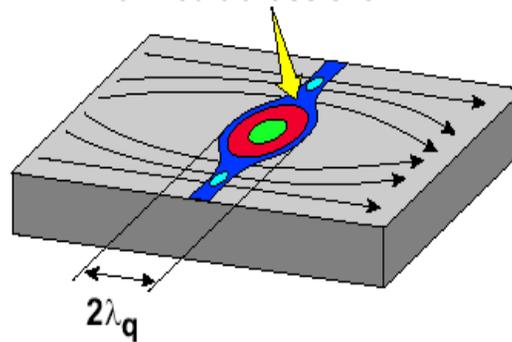


Current density is above the critical

Normal region is formed



Resistive region is formed across the film

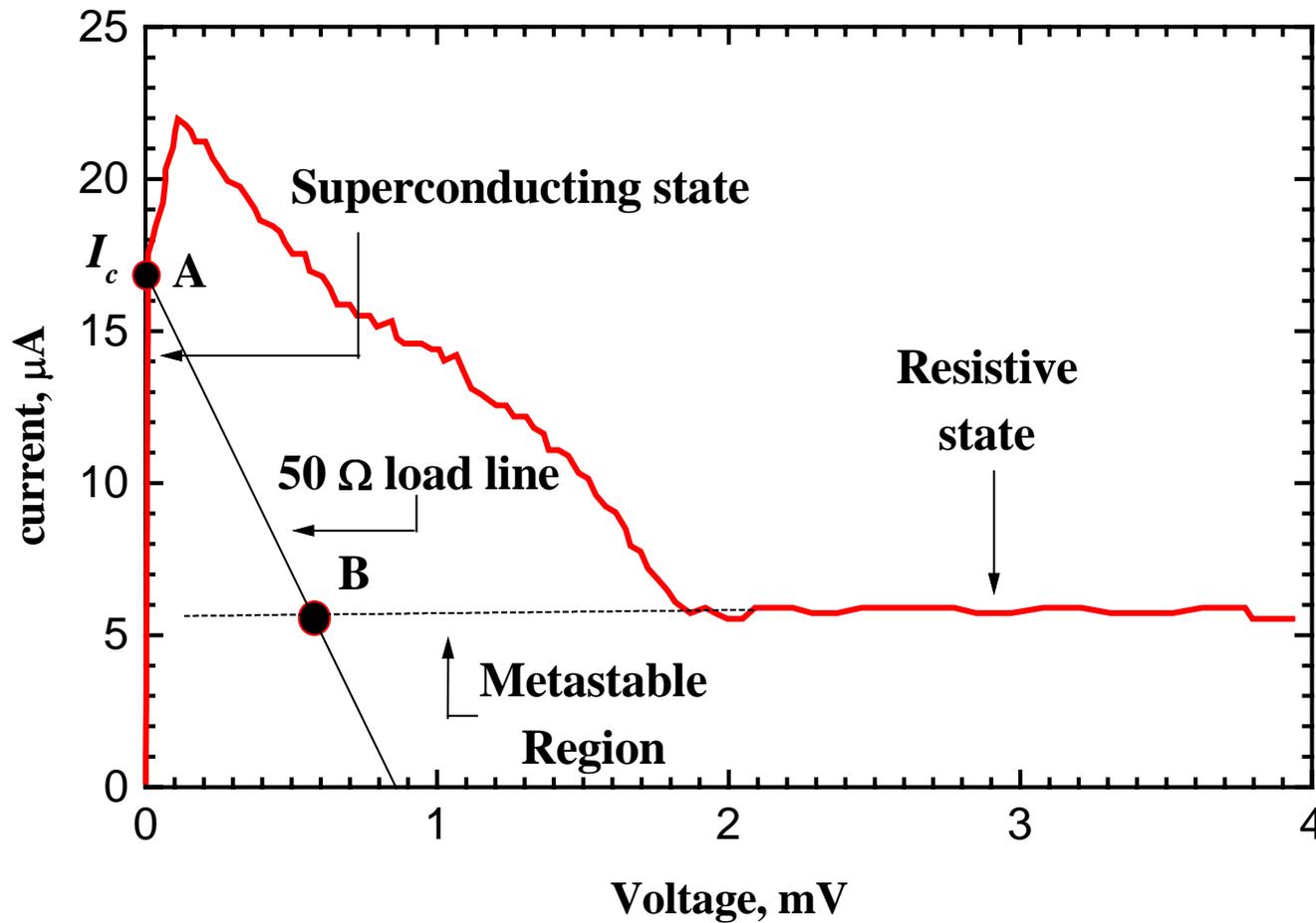


Z2509



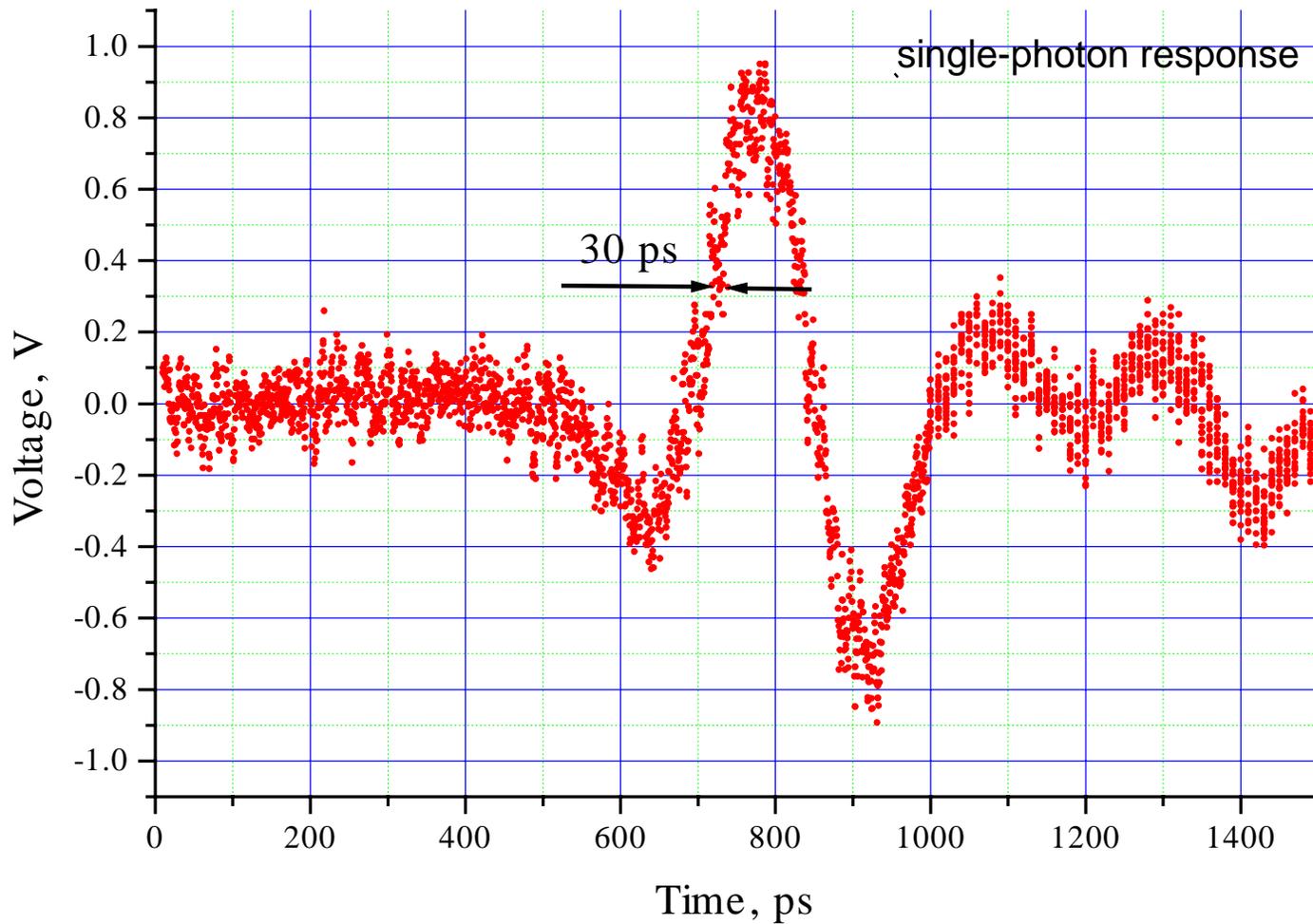


# IV-curves of the 3.5-nm thick film devices at 4.5 K





# Response of NbN SPD with 3.5 nm film thickness

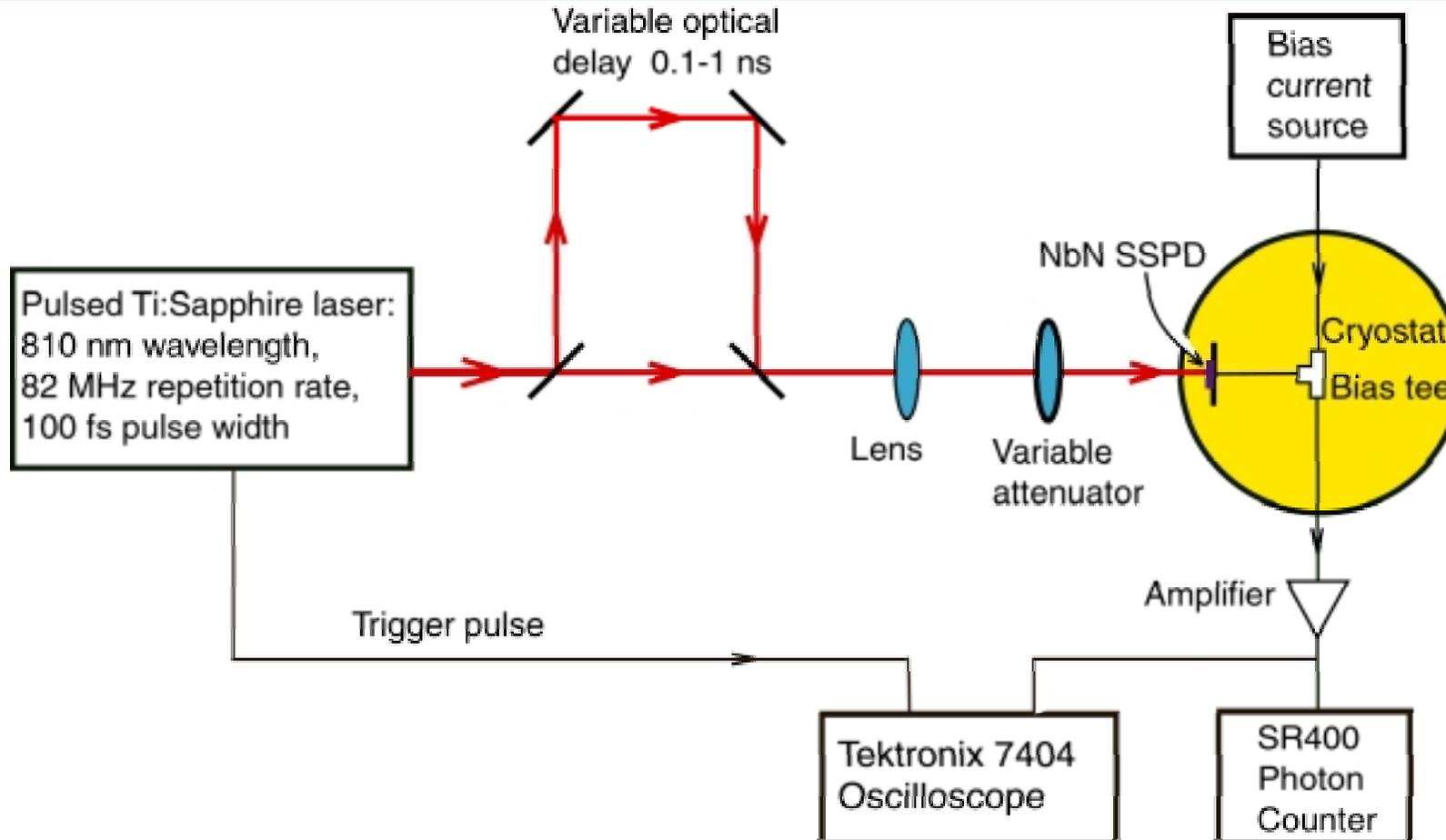


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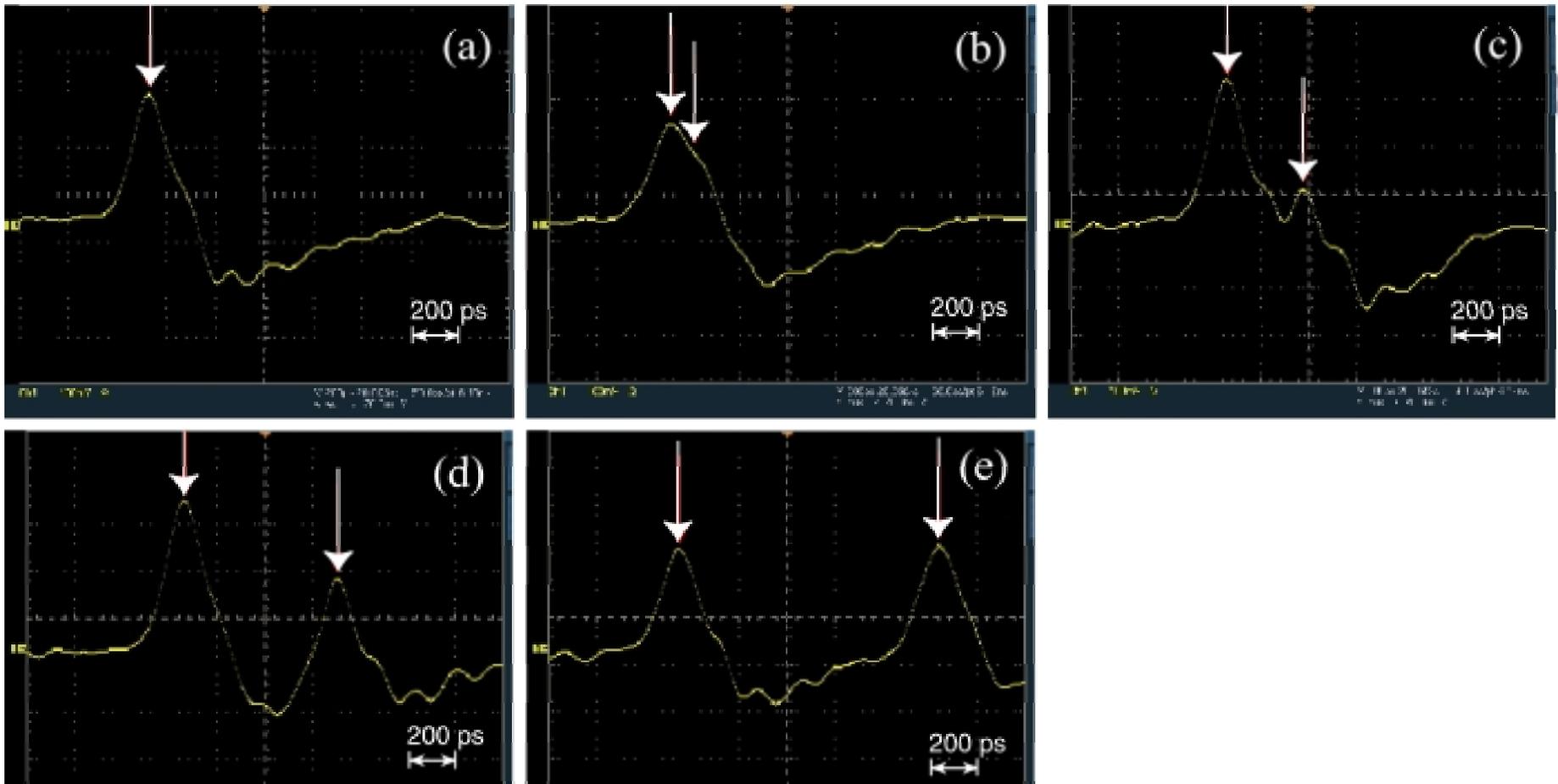


# Experimental setup with variable optical delay





Pulse patterns at different optical delays. (a) delay = 0;  
(b) delay = 100ps, we can see the signature of the  
delayed pulse; (c) delay = 330ps; (d) delay = 650ps; (e)  
delay = 1080ps.

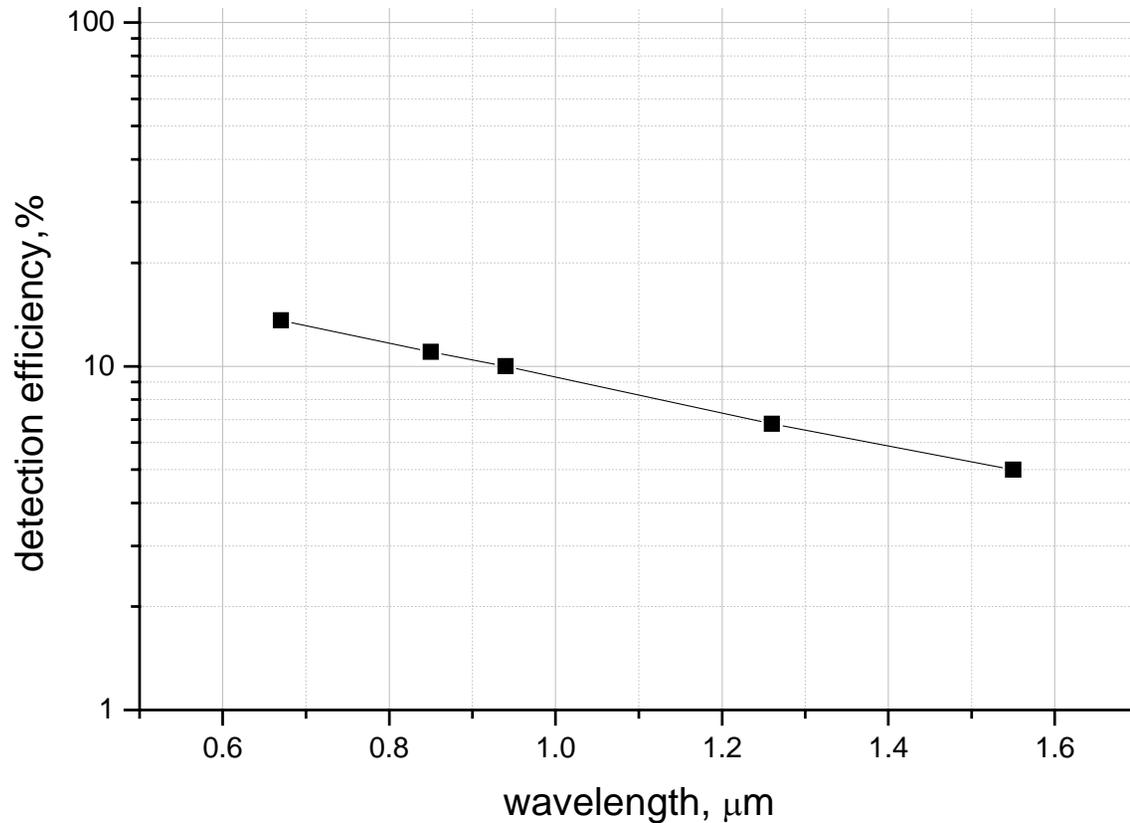


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# SPD's Spectral Sensitivity

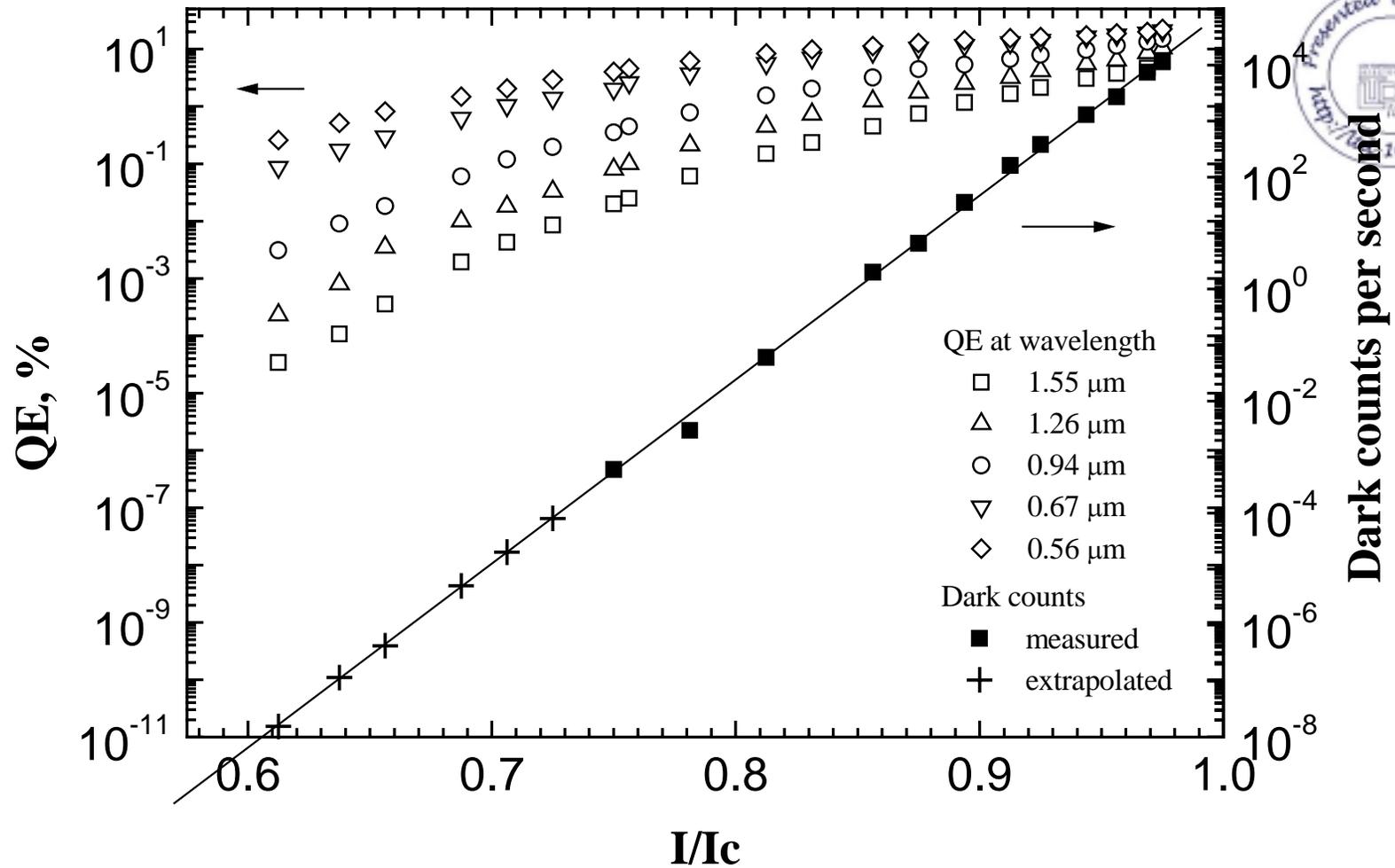


Detection efficiency vs radiation wavelength for the devices made from 3.5 nm-thick NbN films.



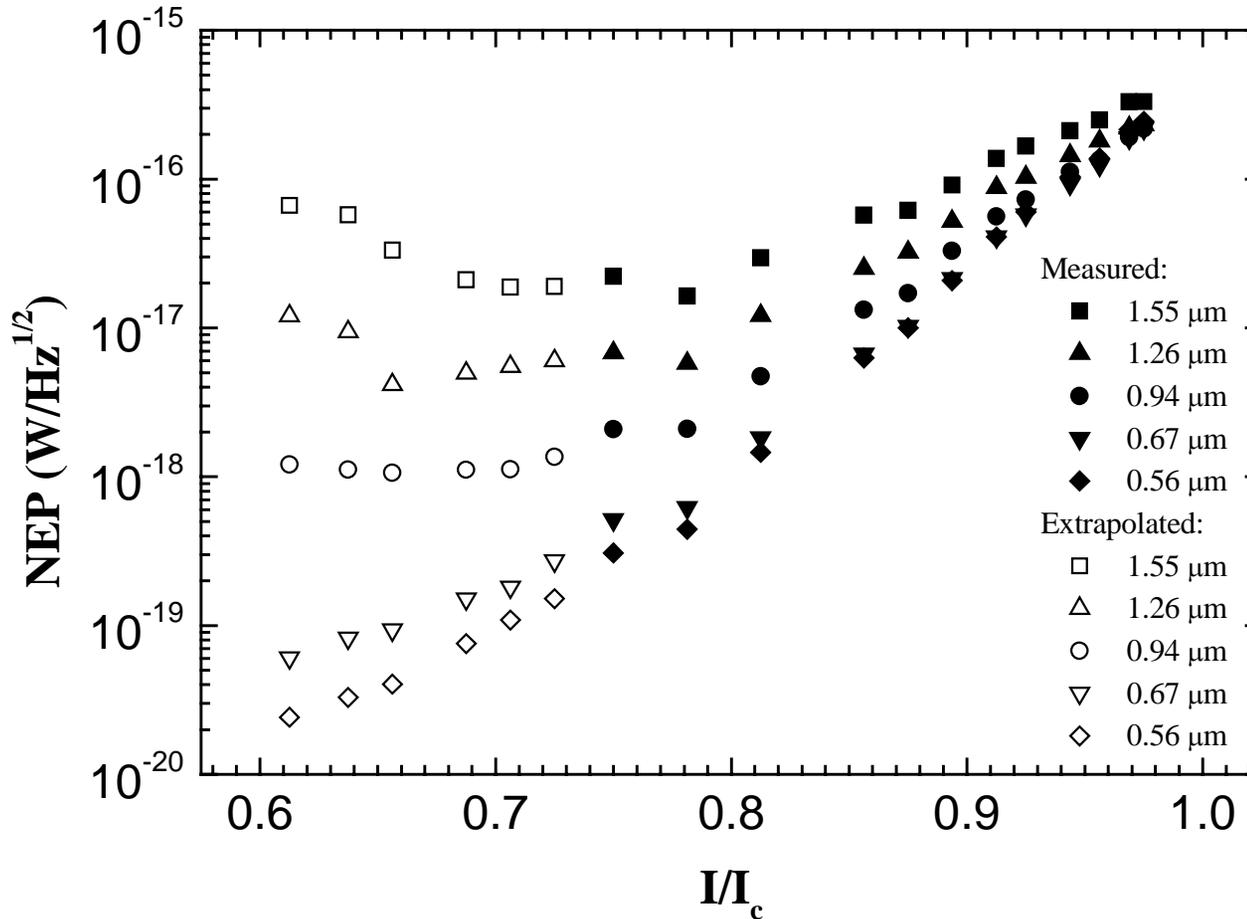


# Quantum efficiency and dark counts rate vs bias current.





# NEP as a function of the bias current in the visible and IR ranges.



Noise Equivalent Power (NEP)

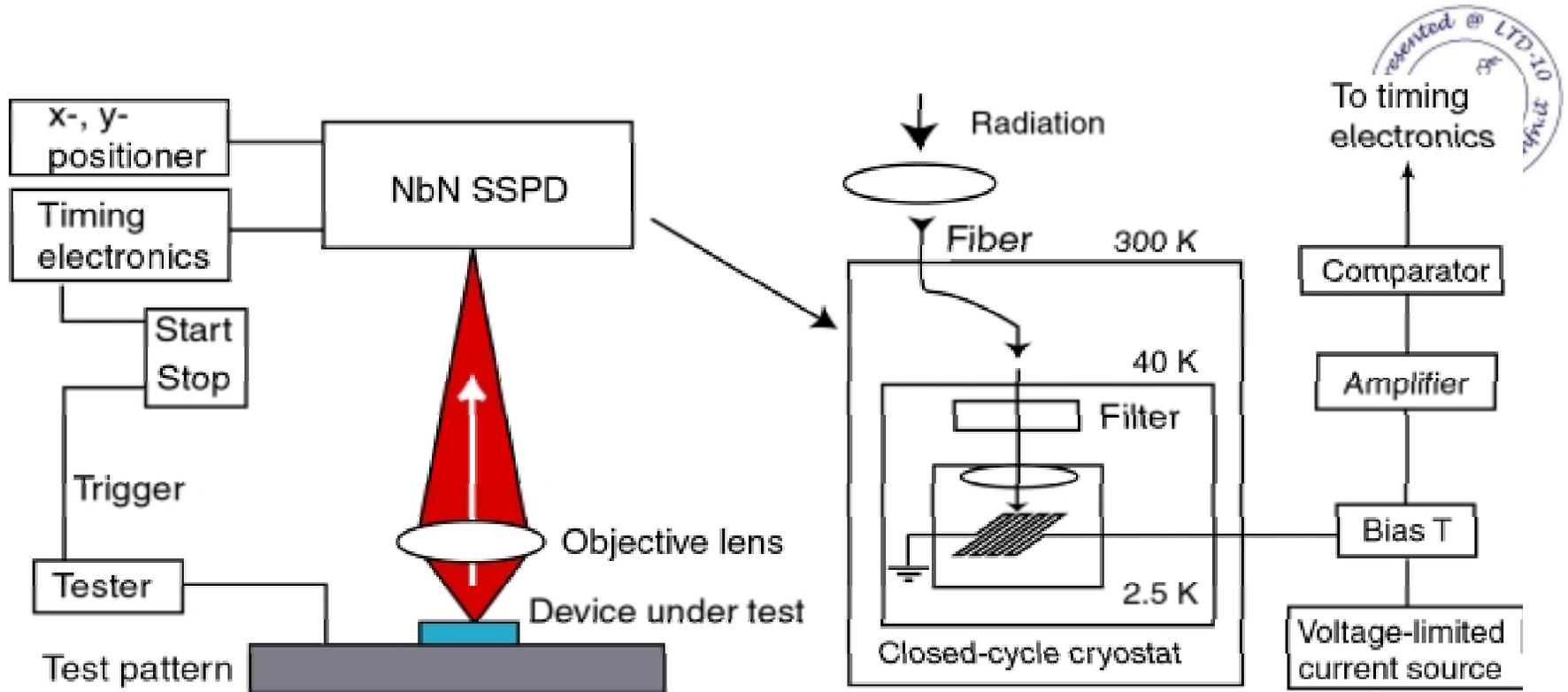


$$NEP = \frac{h\nu}{DE} \sqrt{2R}$$





# Time-Resolved Photon Emission (TRPE) System Setup with Internal-Optical Fiber Alignment



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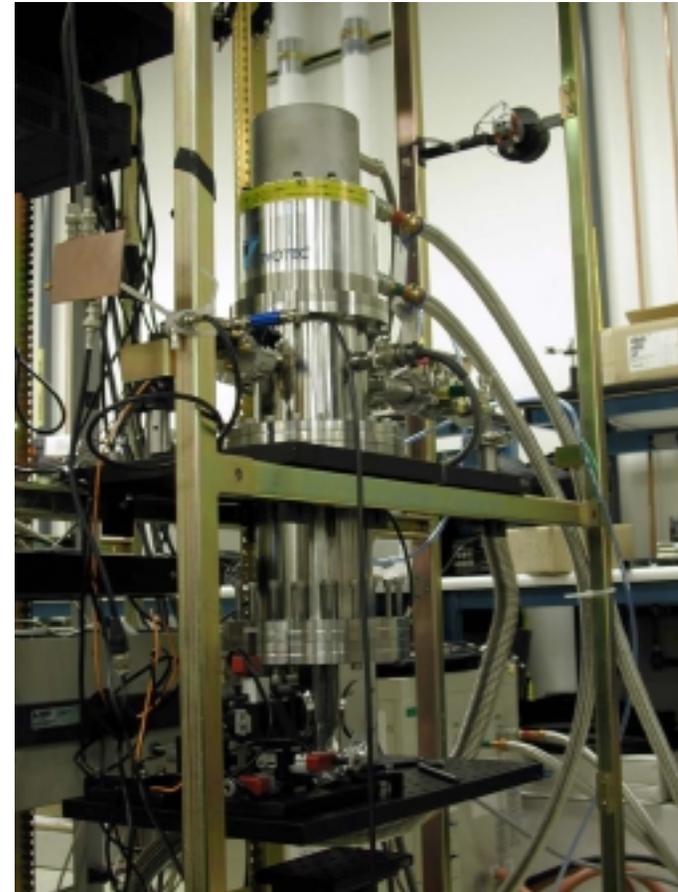


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# Closed-cycle Cryostat



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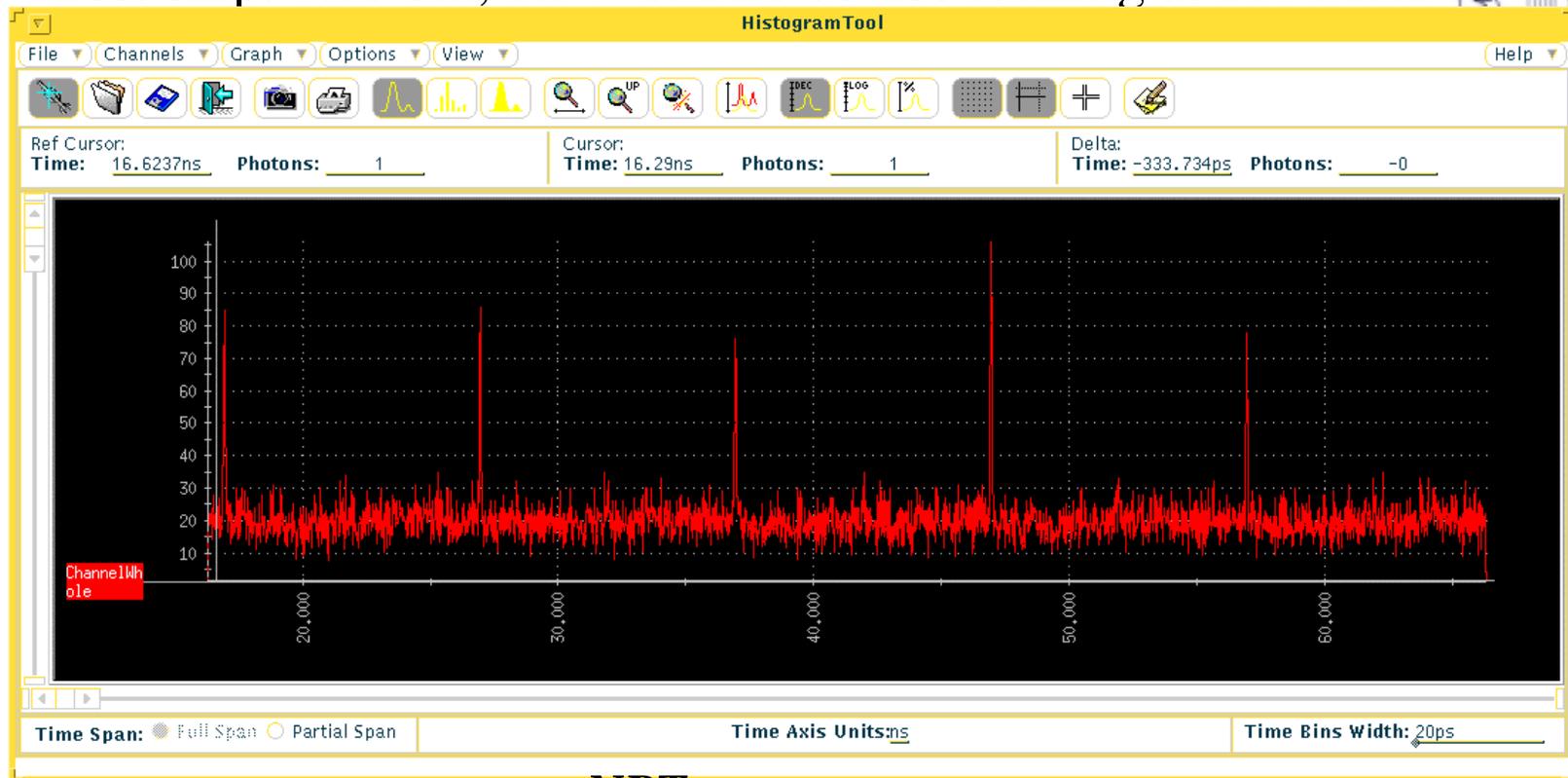




# Application: Silicon IC Debug



- Photon emission correlated with transistor switching event
- Test chip: 0.13  $\mu\text{m}$ , 1.3V CMOS device running at 100 MHz



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**Emission detected by SPD ('Speedy') from nMOS transistor**



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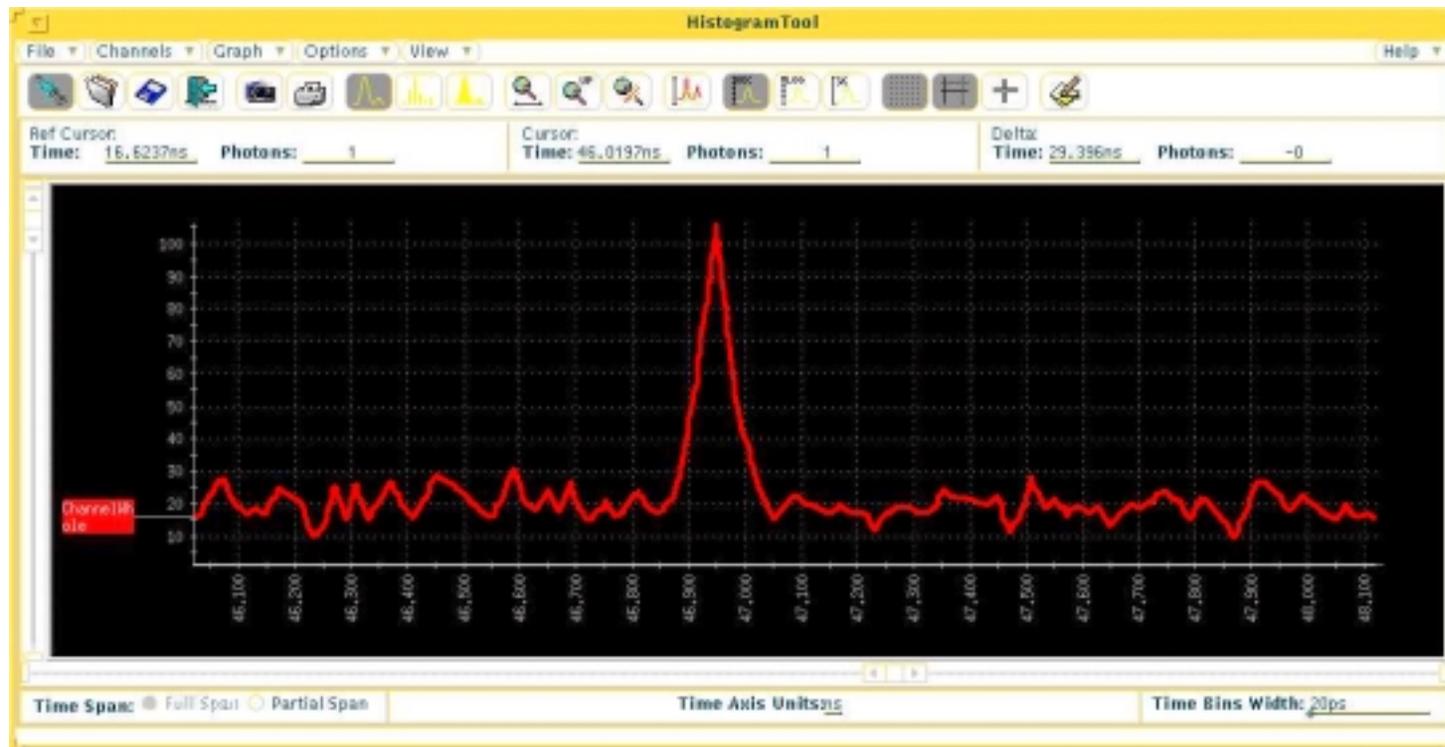




# Precise Timing Analysis with SPD



- Pulse position measures transistor switching timing
  - $< 10$  ps edge timing accuracy
- Pulse width related to transistor switching time



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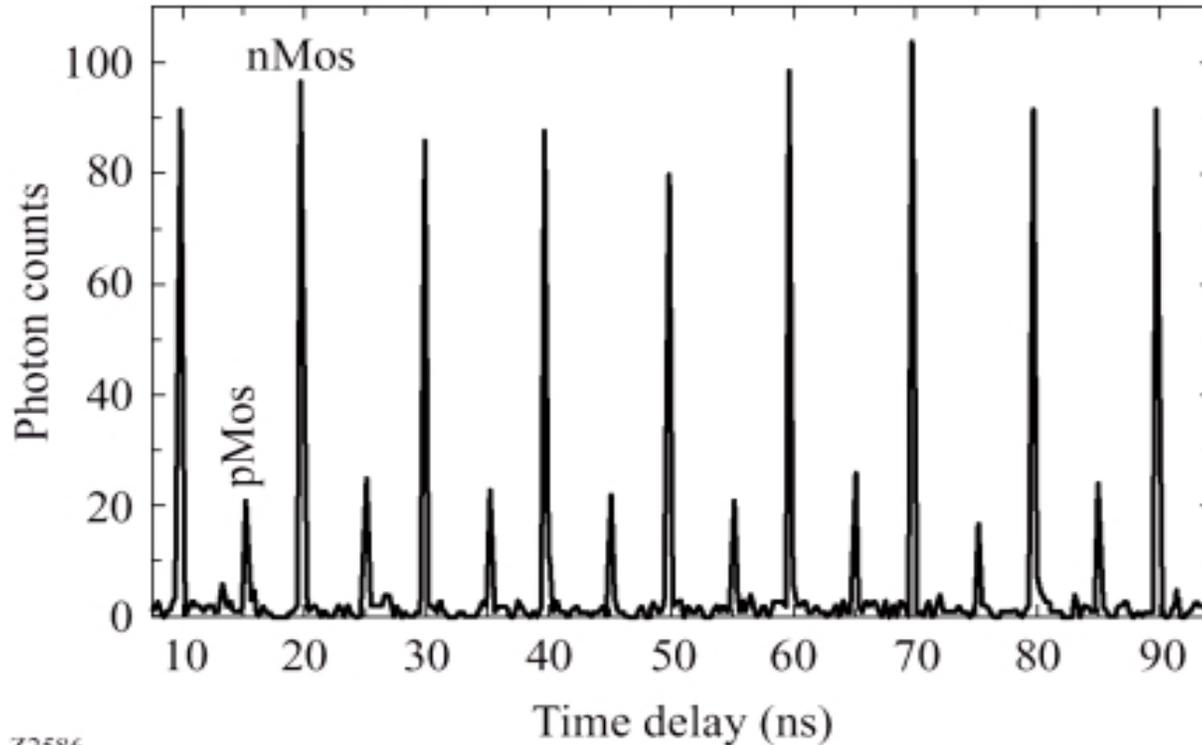


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# Single-photon emission from a CMOS VLSI chip



Z2586

Photon counting histogram from a  $0.13 \mu\text{m}$ ,  $1.3 \text{ V}$  CMOS chip running at  $100 \text{ MHz}$  measured with  $3.5\text{-nm}$ -thick NbN SSPD with bias current of  $0.85 I_c$ .

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# The relationship of $T_{acq}$ versus $1/(kQE)$ for TRPE system



$$T_{acq} = T_{loop} \cdot \left(\frac{\Delta t_{tts}}{\Delta t}\right)^2 \cdot \frac{kQE + \Delta t_{tts} \cdot R_{dk}}{(kQE)^2},$$

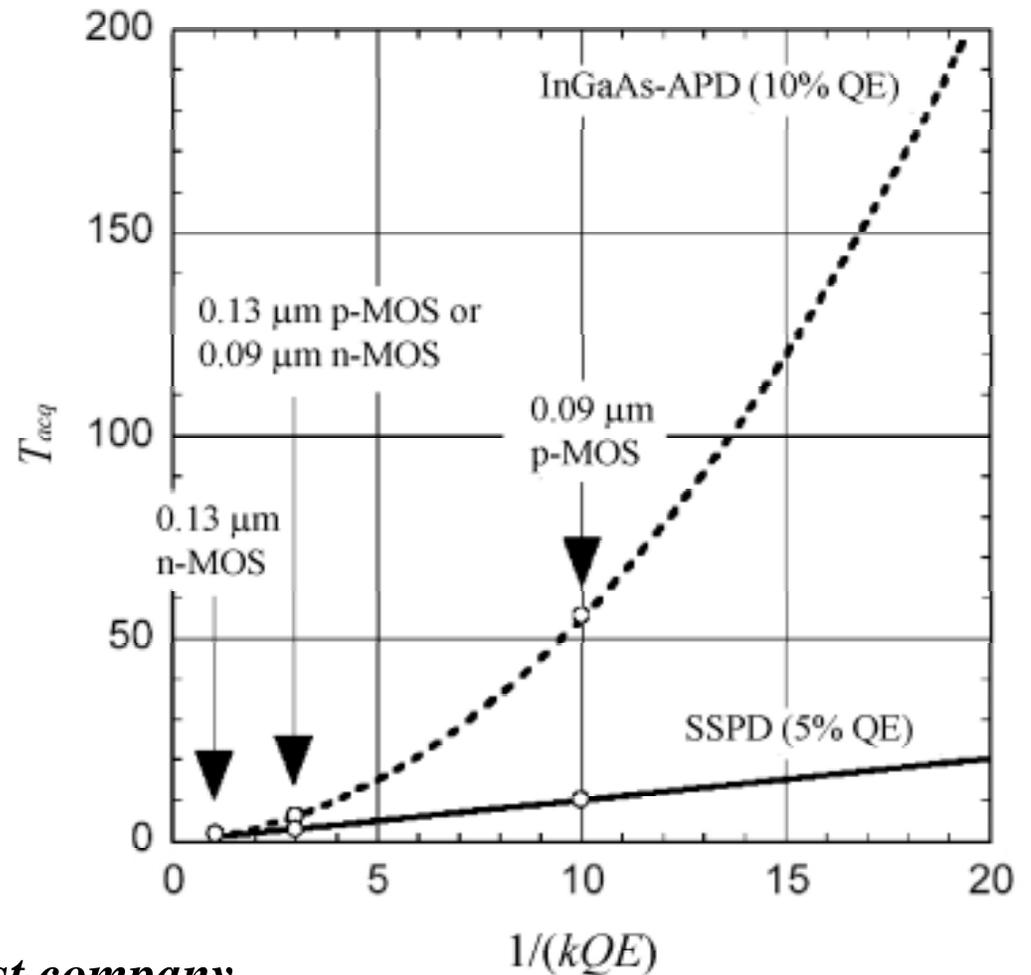
$T_{loop}$  is the loop length of the test

$\Delta t_{tts}$  is the jitter of the detector system

$\Delta t$  is the timing accuracy required

$R_{dk}$  is the dark counting rate

$k$  is a factor dependent on the strength of photon emission from the transistor and the photon collection efficiency of the optical system



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# Conclusions



- NbN SSPDs are sensitive to radiation from UV to mid-IR.
- 3.5-nm-thick devices approach detection efficiency  $DE = 10\%$  at  $\sim 1.3 - 1.5 \mu\text{m}$ , related to intrinsic QE close to 100 %.
- Voltage pulse has FWHM and risetime of about 150 ps and 100 ps, respectively, limited by read-out electronics; experimentally measured repetition rate in single-photon regime is 3 GHz.
- Jitter is about 20 ps ; significantly lower comparing with any semiconductor detectors.
- Dark counting rate is extremely low  $10^{-4}$  counts per second and less. Dynamic range is about 130 dB.
- Measured NEP is about  $10^{-18} \text{ W/Hz}^{1/2}$  at 1.3 micron wavelength and less than  $10^{-19} \text{ W/Hz}^{1/2}$  in the visible range.
- NbN SSPD is practical device for non-invasive optical analysis of Si CMOS circuits.

