Superconducting Nanowire Single Photon Detectors Based on MgB_2

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[3]*Kitami Institute of Technology, JPN*
[4]*NTT Basic Research Laboratories, JPN*
[5]*National Institute of Advanced Industrial Science and Technology, JPN*
[6]*National Institute of Standards and Technology, USA*

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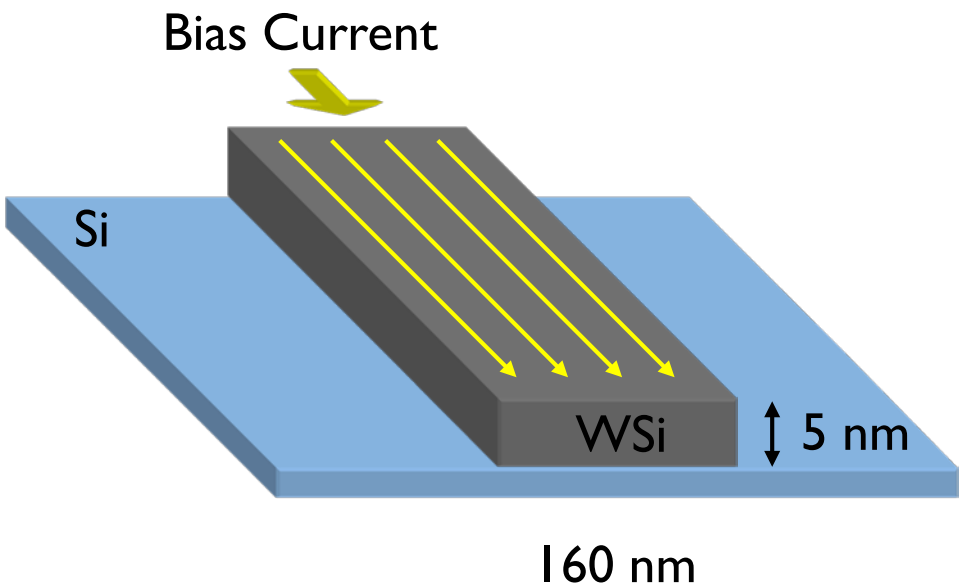
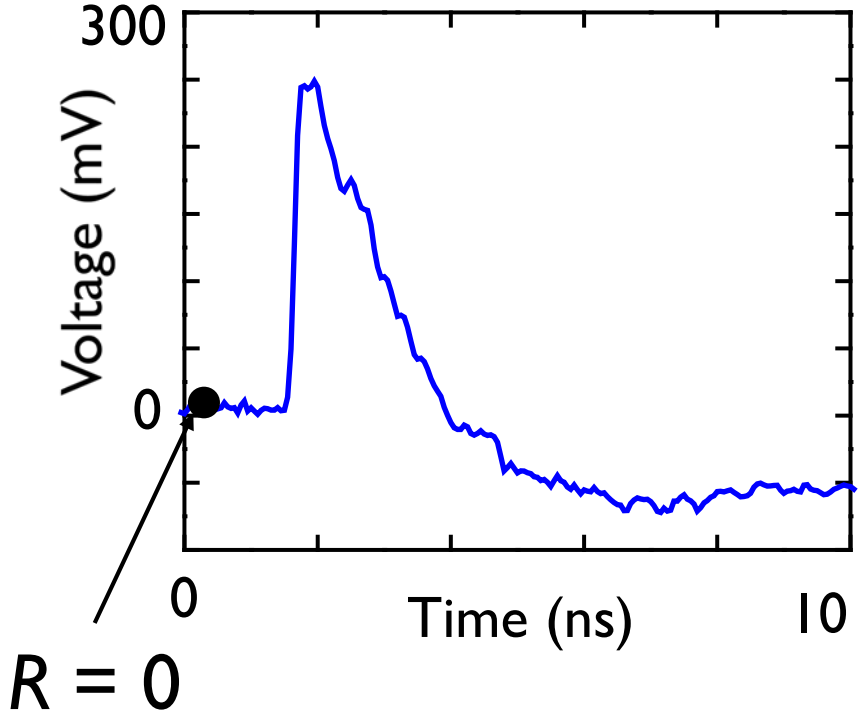
Superconducting Nanowire Single-Photon Detector (SNSPD)





- Temperature < T_C
- Current density < J_C

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

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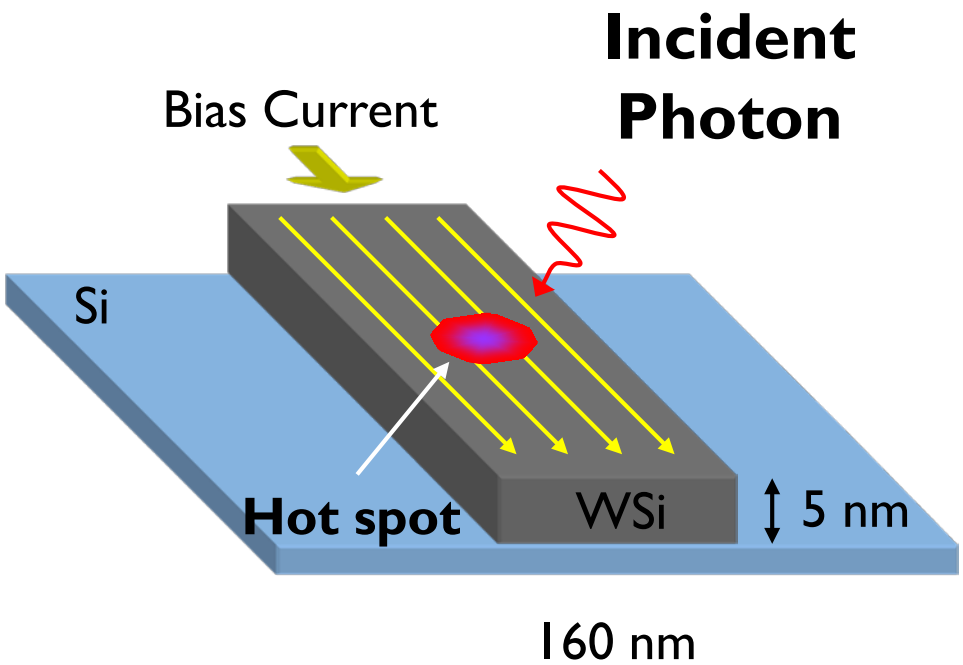

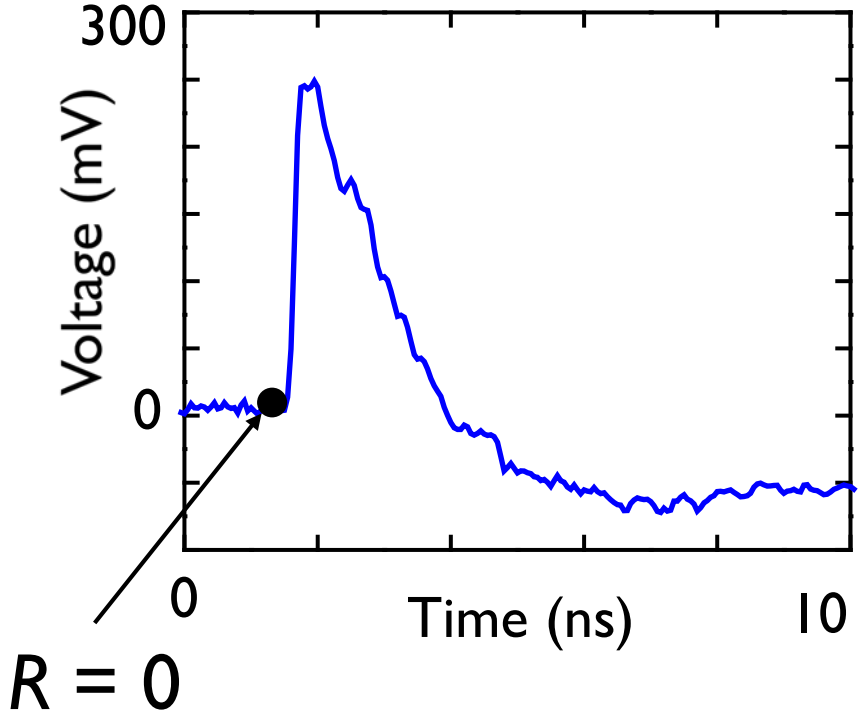

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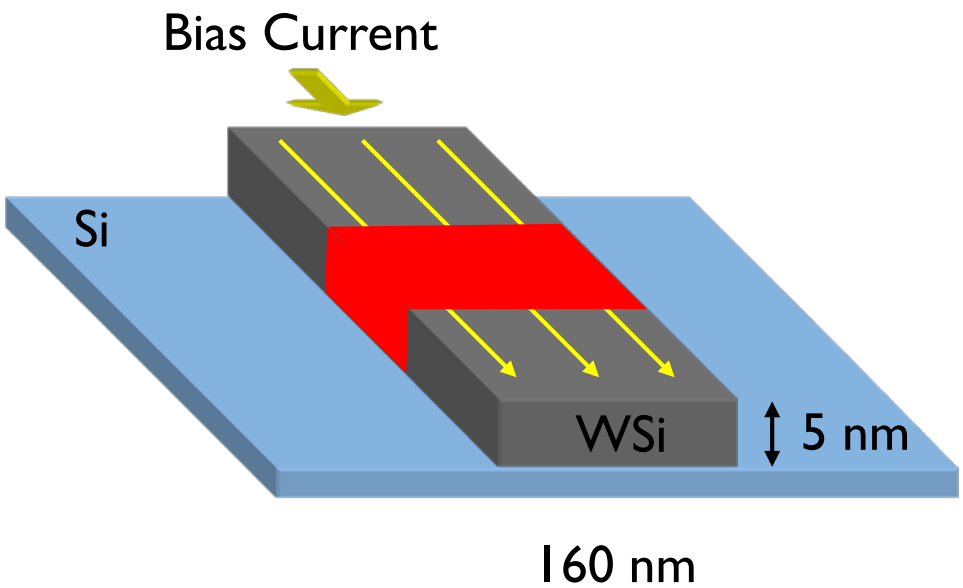

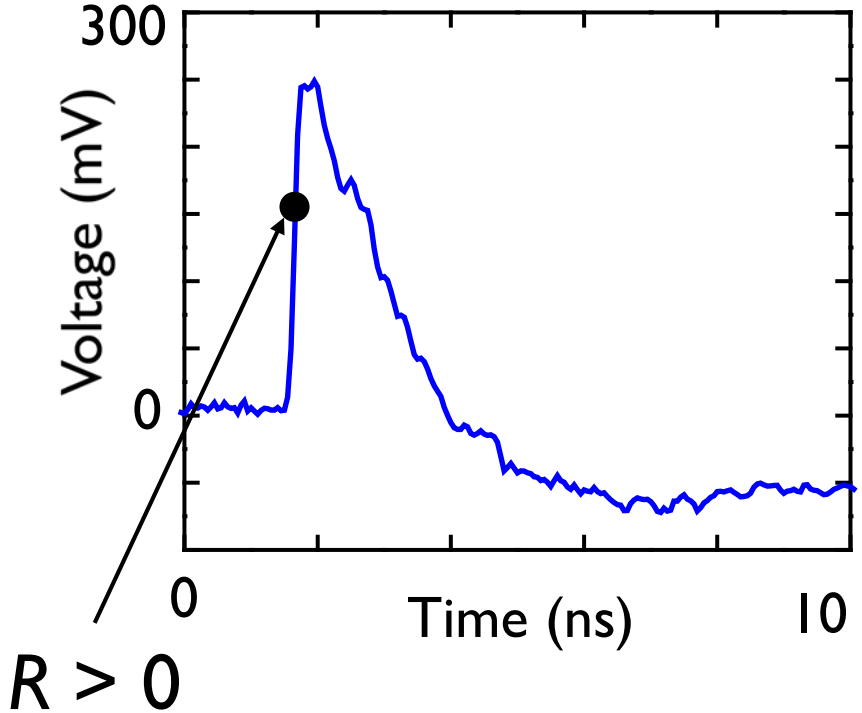

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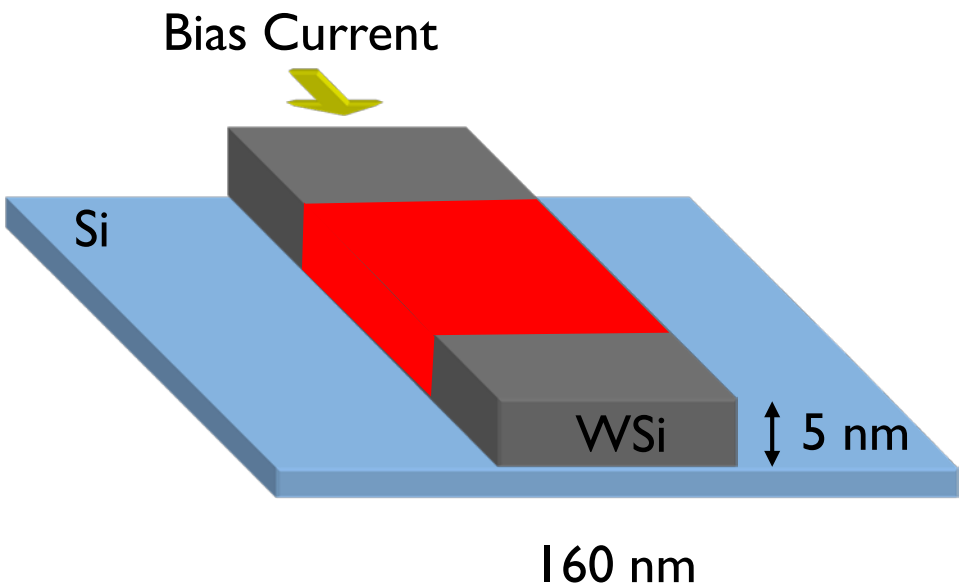

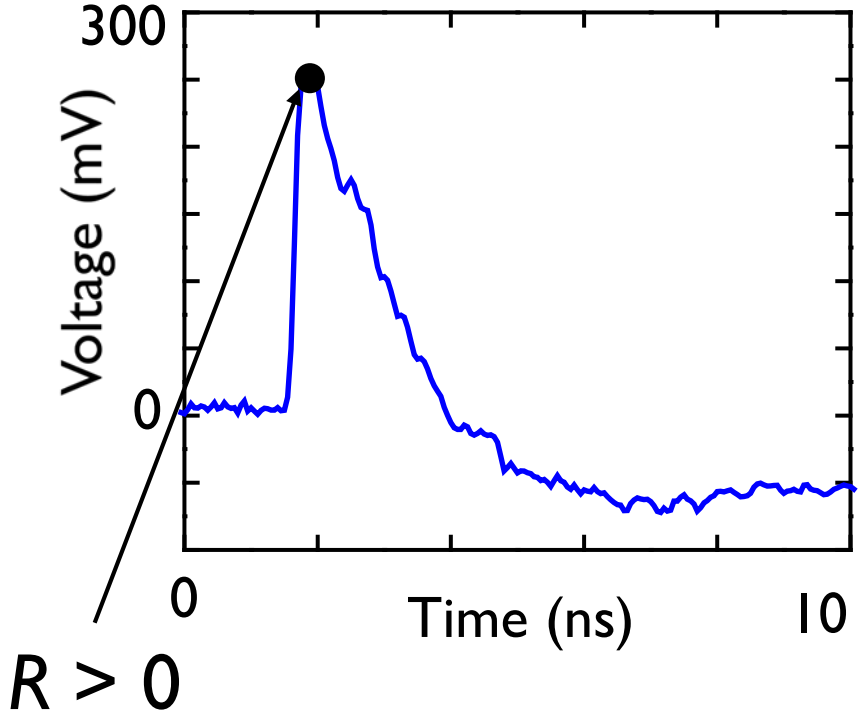

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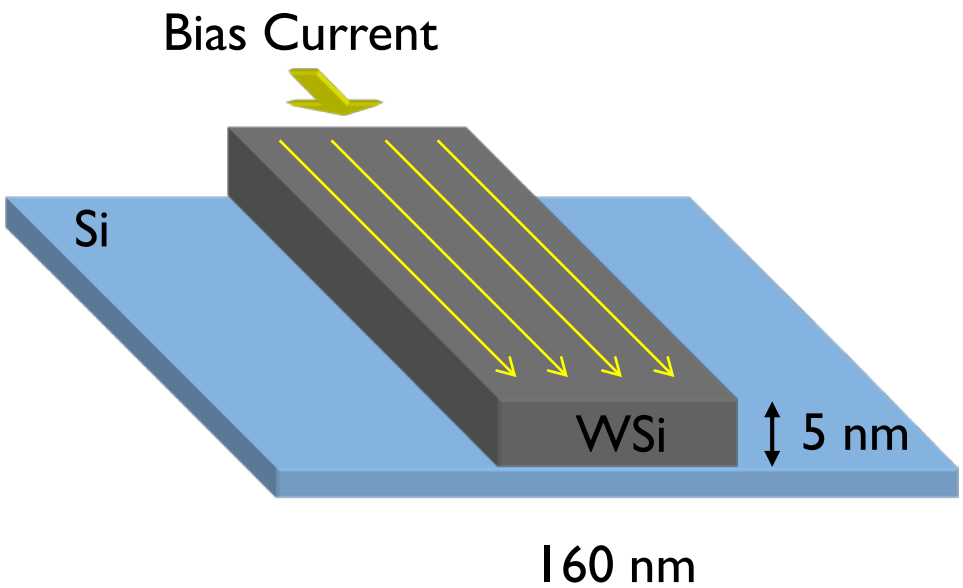
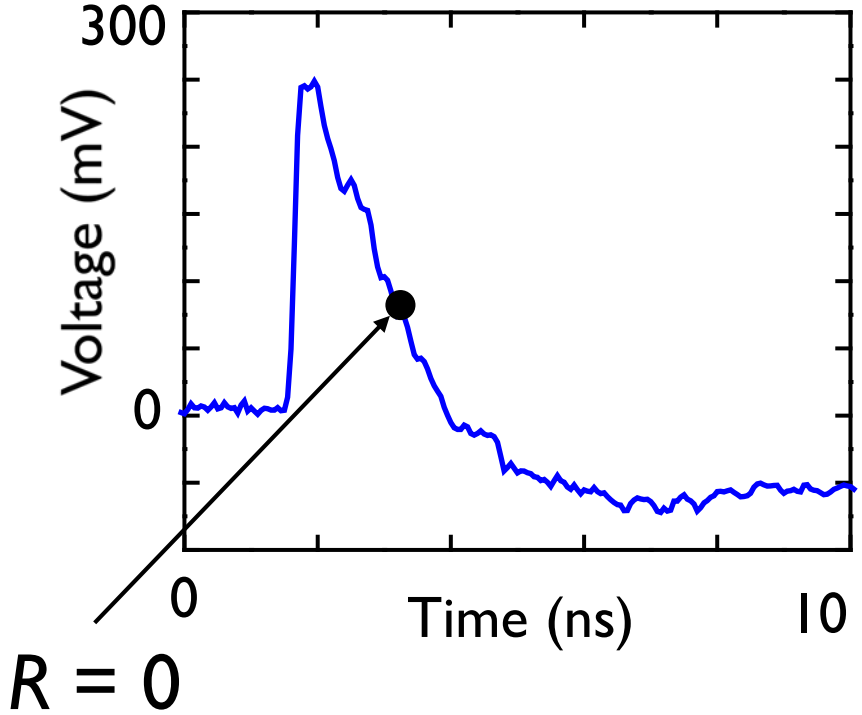




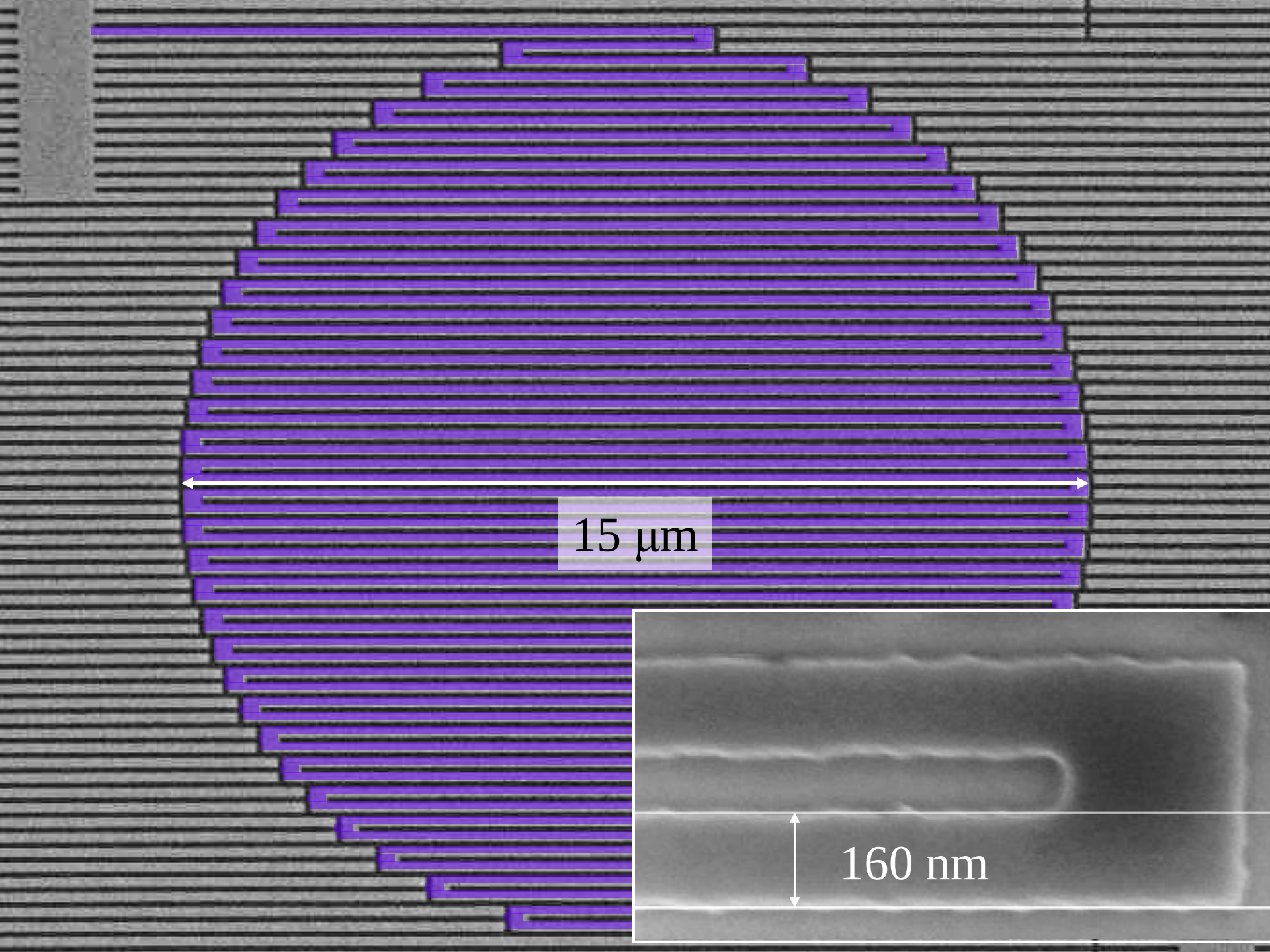
- Temperature < T_C
- Current density < J_C

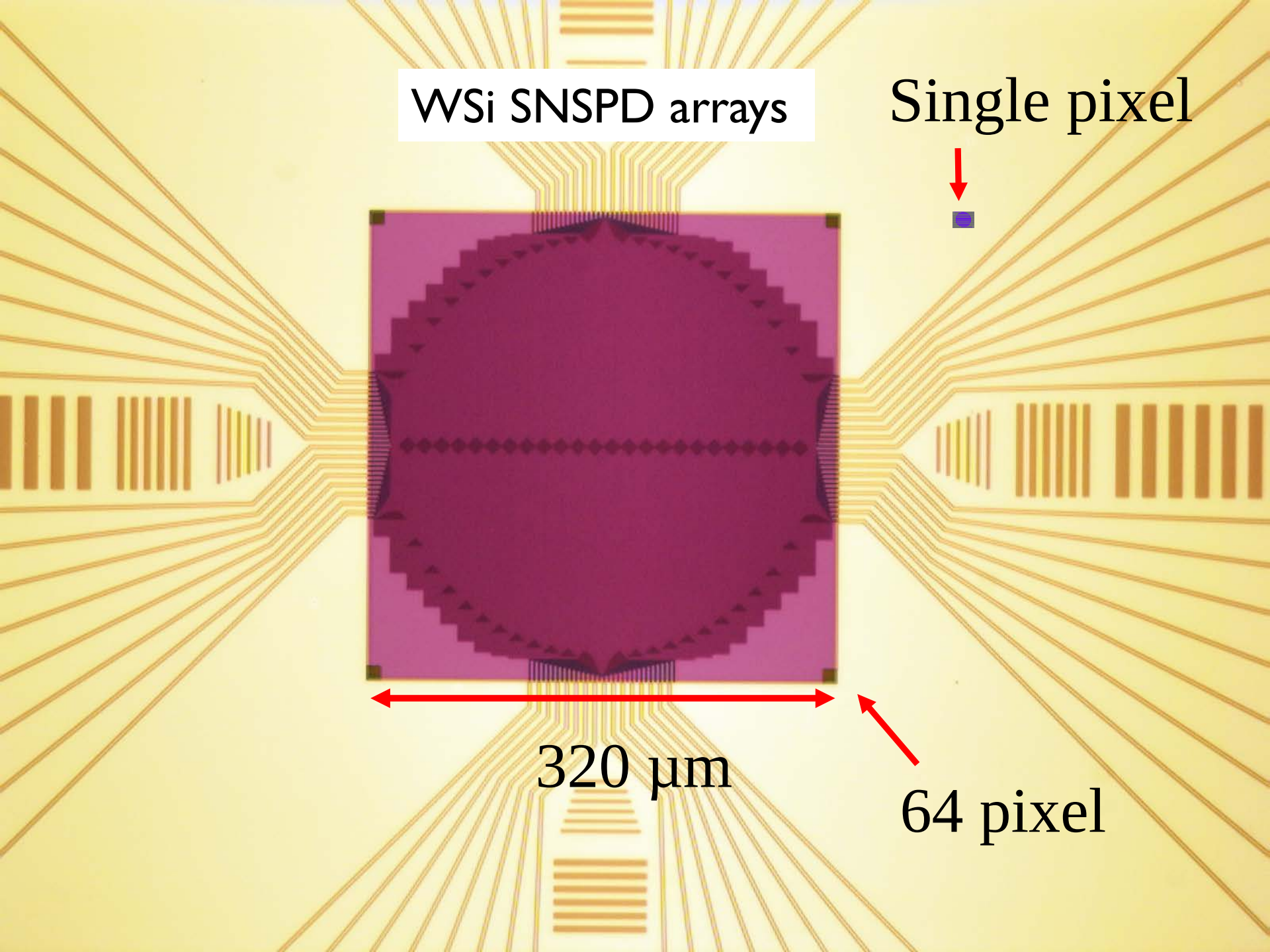
Gol'tsman *et al.*, APL 79, 705 (2001)

Tungsten Silicide (WSi) SNSPDs

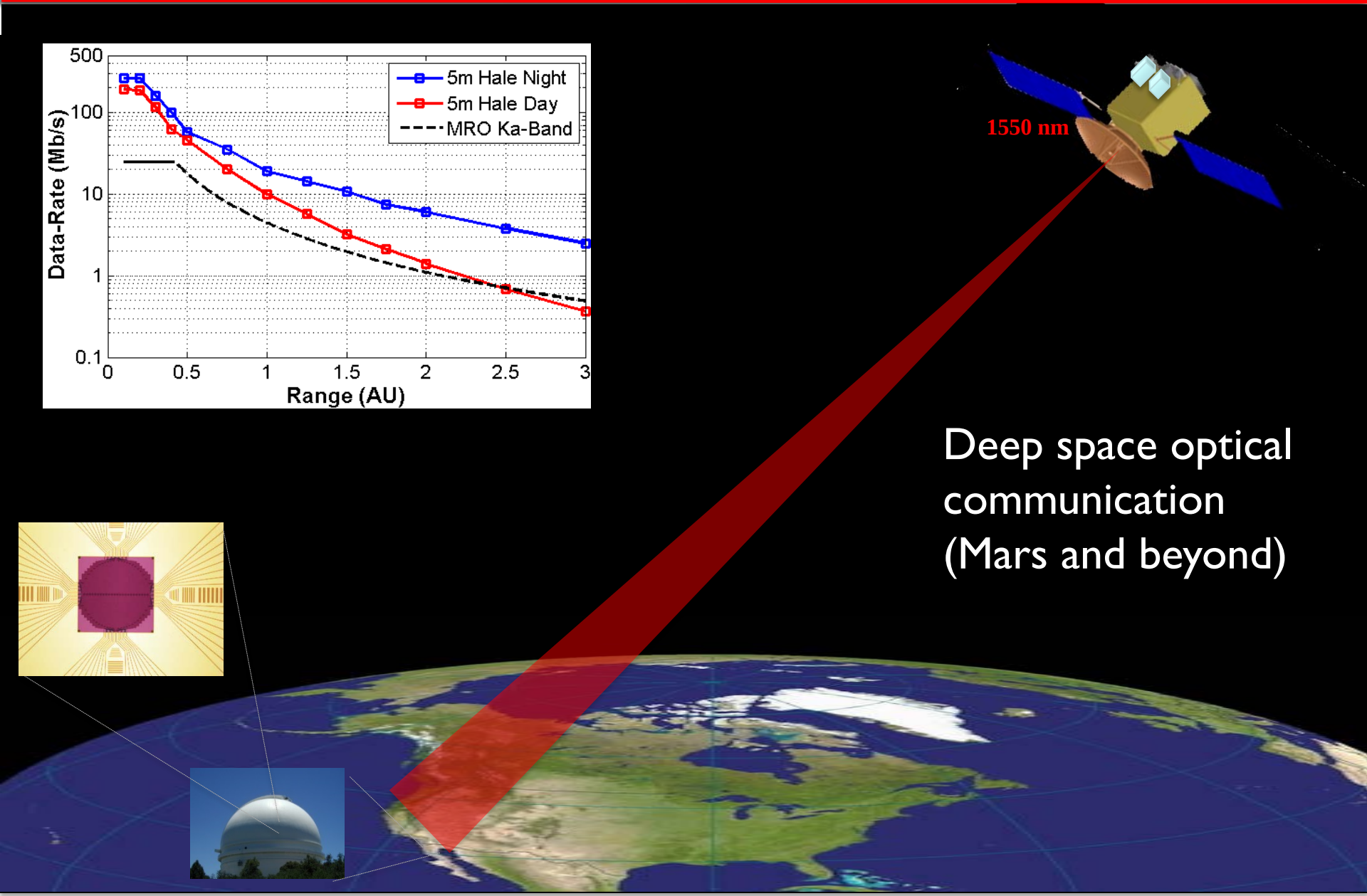
- High system detection efficiency (~ 90% at λ = 1550 nm)
- Low jitter (50 - 150 ps FWHM)
- Low intrinsic dark count rate (~ 1 cps)
- Low reset time (~ 25 ns)
- High maximum count rate (~20 Mcps)
- UV to mid-IR sensitivity

Marsili et al., Nature Photonics 7, 210 (2013)


15 μm
160 nm


WSi SNSPD arrays
Single pixel
320 µm
64 pixel

High T_C SNSPDs: Flight



Deep space optical communication (Mars and beyond)

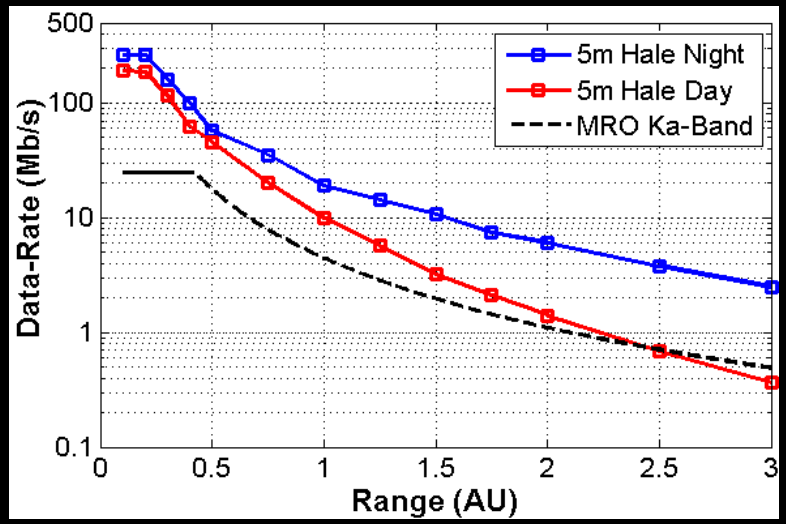
Tungsten Silicide (WSi) SNSPDs

Drawback: Low operating temperature: $T < 1$ K

↓

Complex cryogenics

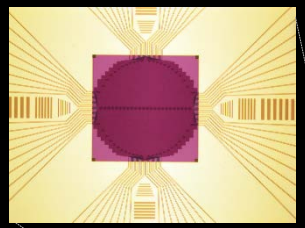
High T_C SNSPDs: Flight Applications



High T_C SNSPDs

1550 nm

Deep space optical communication (Mars and beyond)



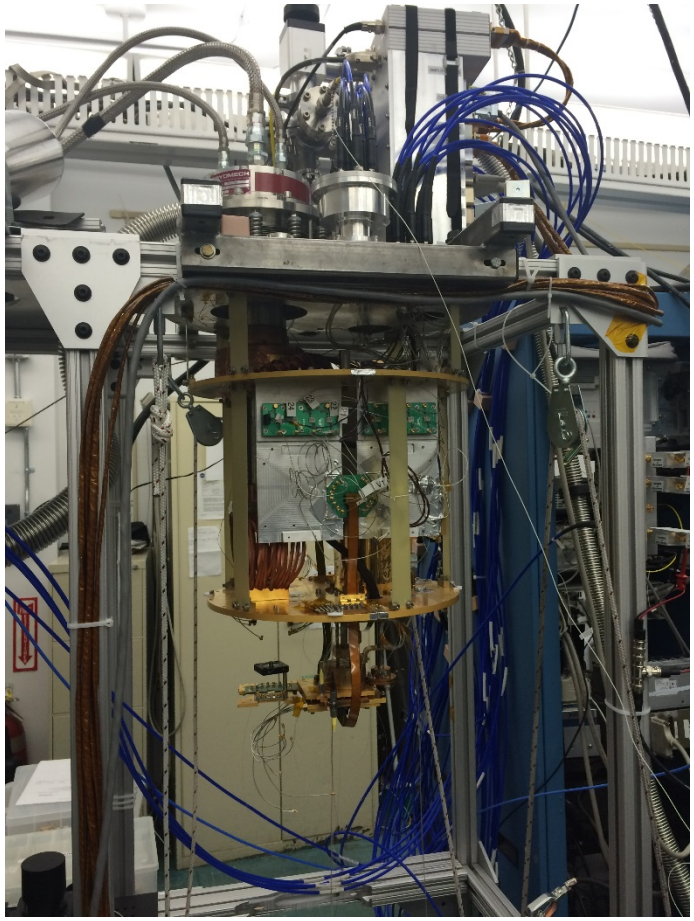
High T_C SNSPDs: Ground

- Quantum optics
- Quantum key distribution (QKD)
- Quantum information
- Ranging (LIDAR)
- Remote sensing (DIAL)

Refrigerator Comparison

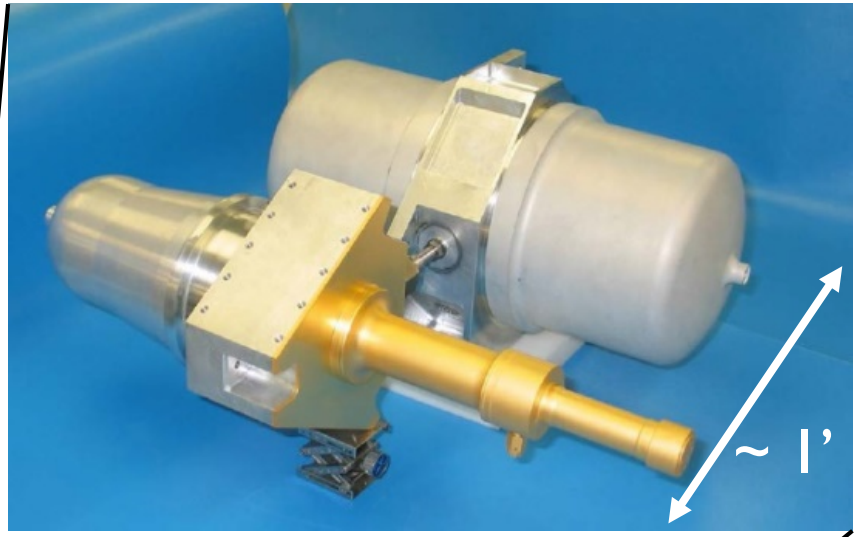
He^3/He^4 Sorption/Pulse Tube

~ 4.5’



T ~ 500 mK

Stirling/Pulse Tube (Raytheon LT-RSP2)

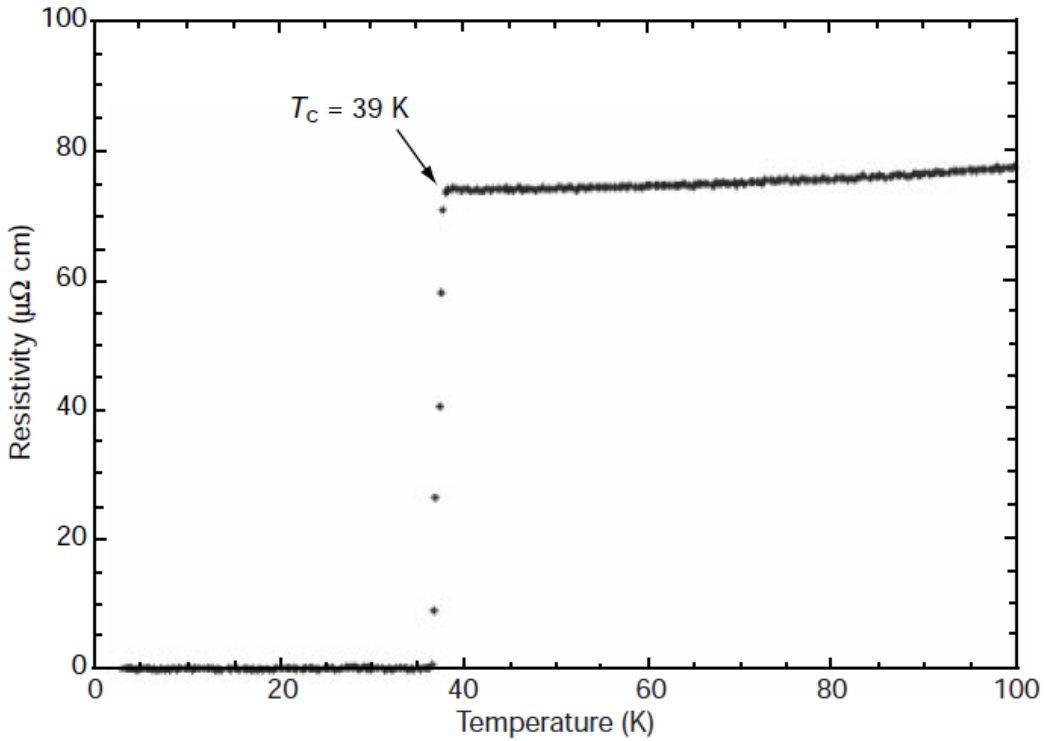


~ 1’

T ~ 10 K

Our Approach: MgB_2 SNSPDs

- Magnesium diboride (MgB_2) has bulk T_C ~ 40 K
- Well behaved, metallic superconductor
- SNSPDs may operate at 20 K where cryogenics is easy, cost effective, reliable, and compact



J. Nagamatsu et al., Nature **410** , 63-64 (2001)

Challenges of MgB_2 SNSPDs

- Difficult to grow high-quality MgB_2 thin films
- MgB_2 nanowire fabrication challenging because:
  i. MgB_2 highly reactive with oxygen
  ii. MgB_2 etch limited to argon ion milling
- Single photon detection at 20 K never demonstrated

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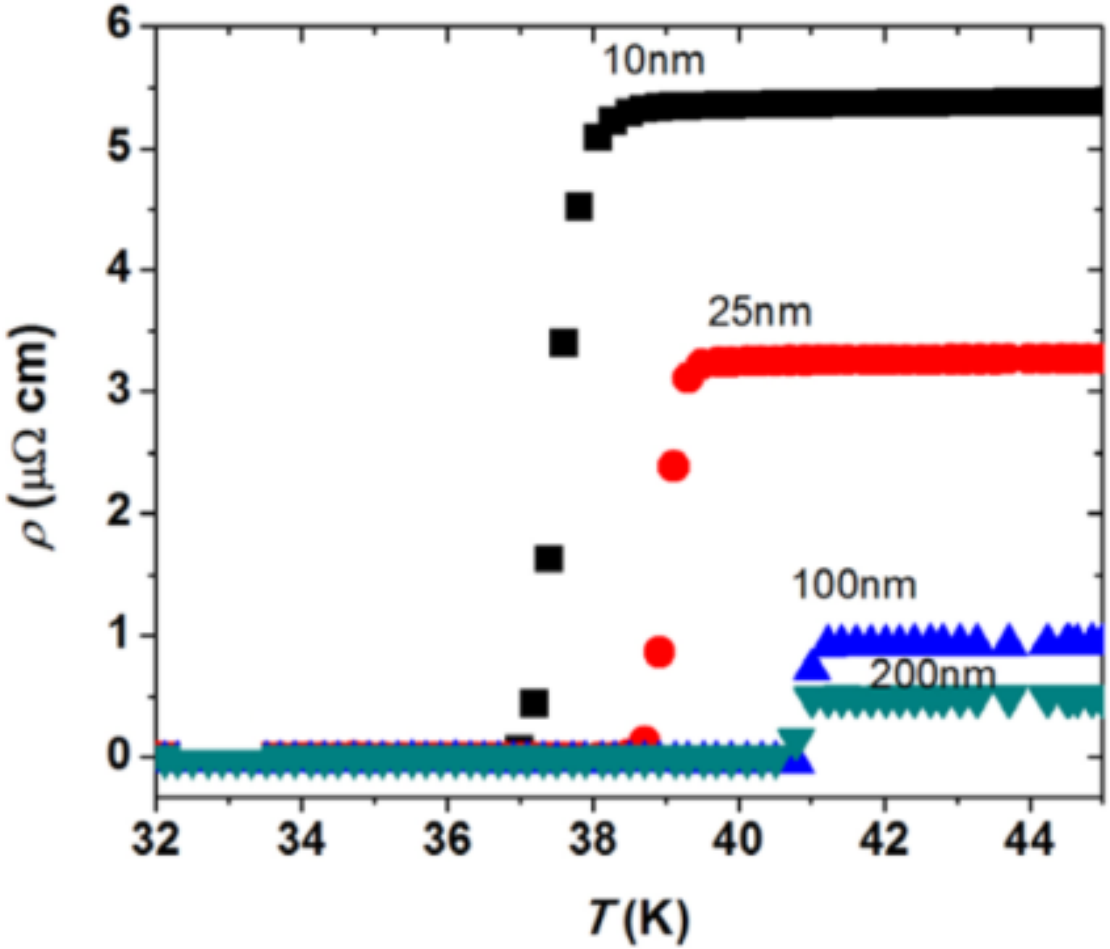
High Quality MgB_2 Thin Films

Hybrid Physical-Chemical Deposition (HPCVD)

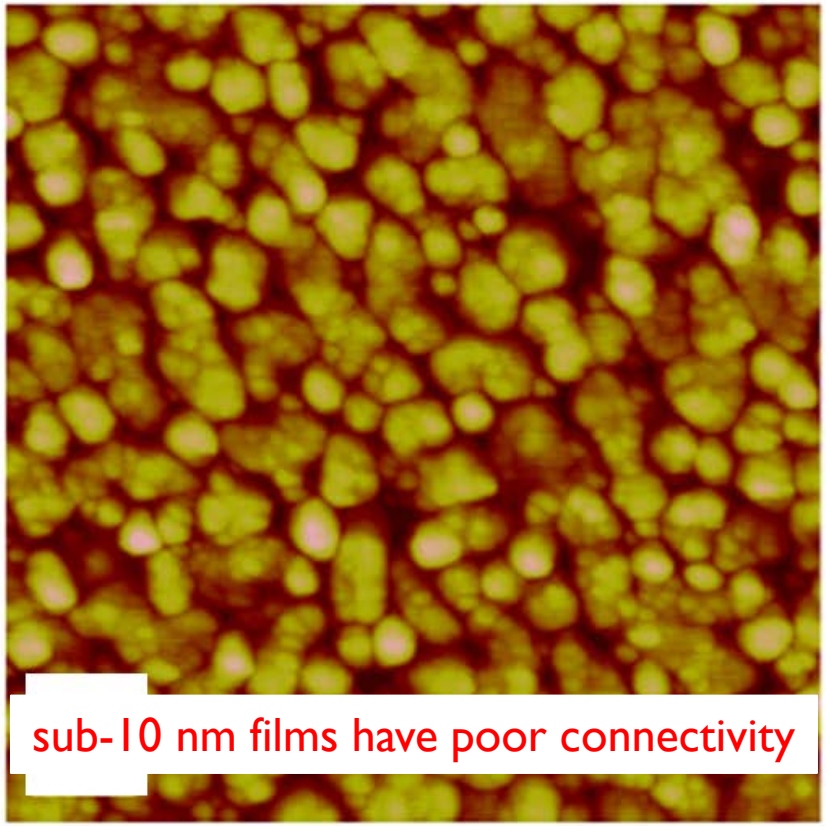


C. Zhuang *et al.*, Supercond. Sci. Technol. **23** (5), 055004 (2010)

Temple University

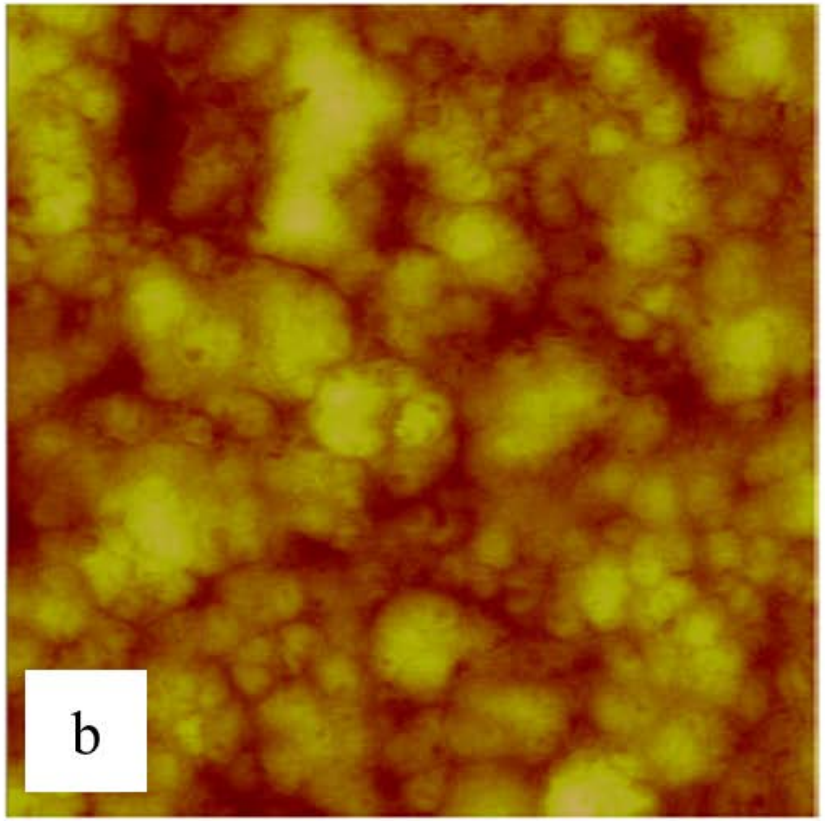
Problem with sub-10 nm films

d = 7.5 nm



1 μm

d = 25 nm

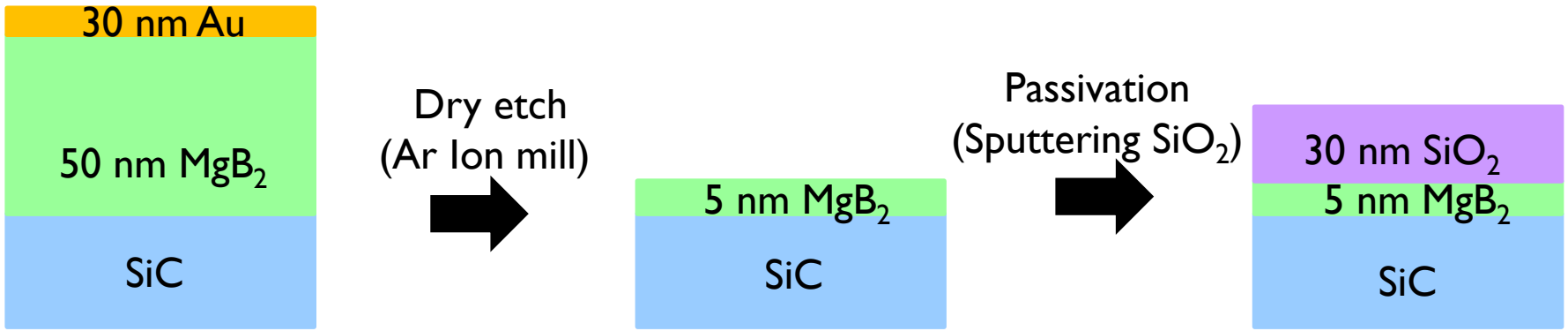


1 μm

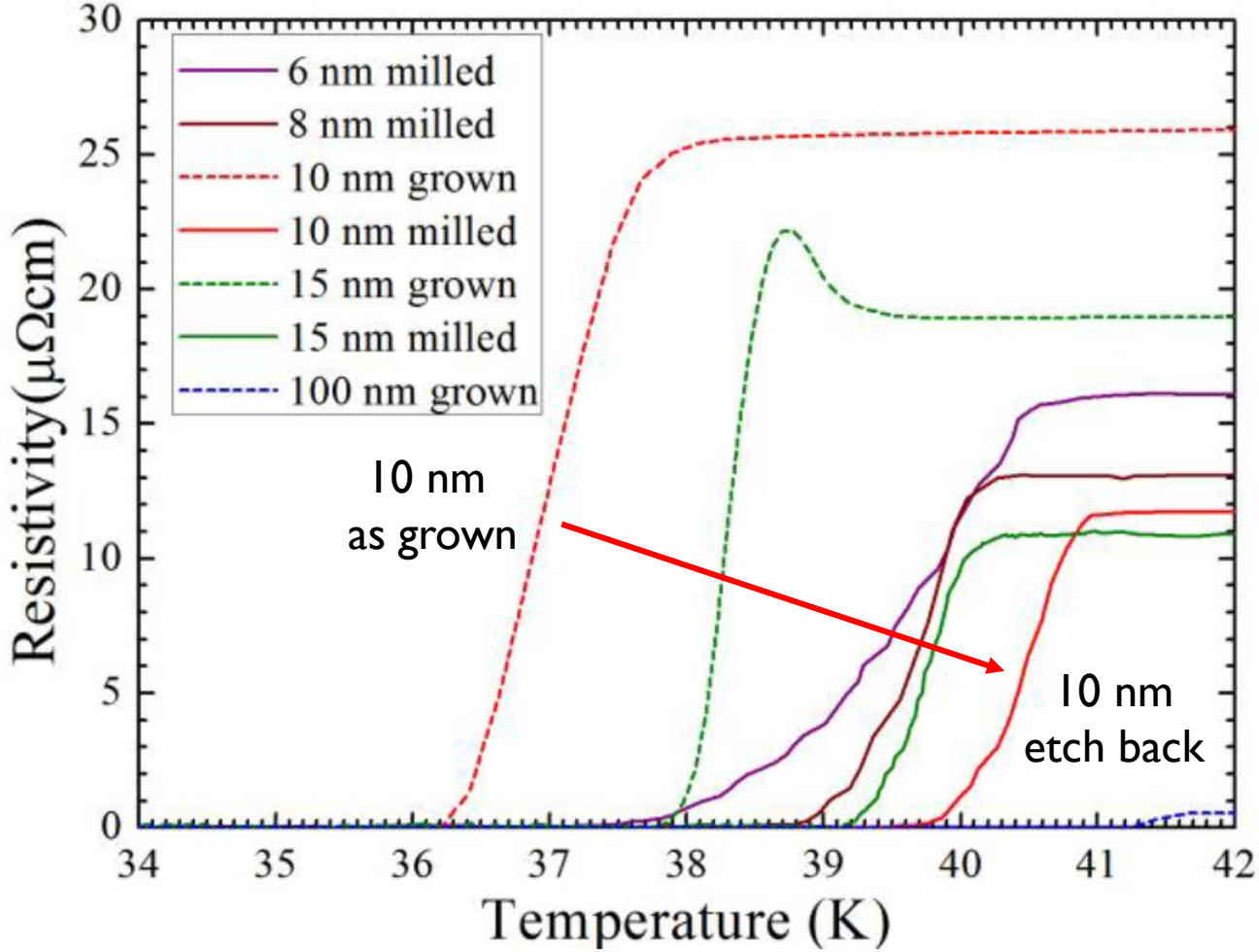
C. Zhuang *et al.*, Supercond. Sci. Technol. **23** (5), 055004 (2010)

Thin Film Fabrication Process

Etch-back technique achieves high-quality sub-10 nm films

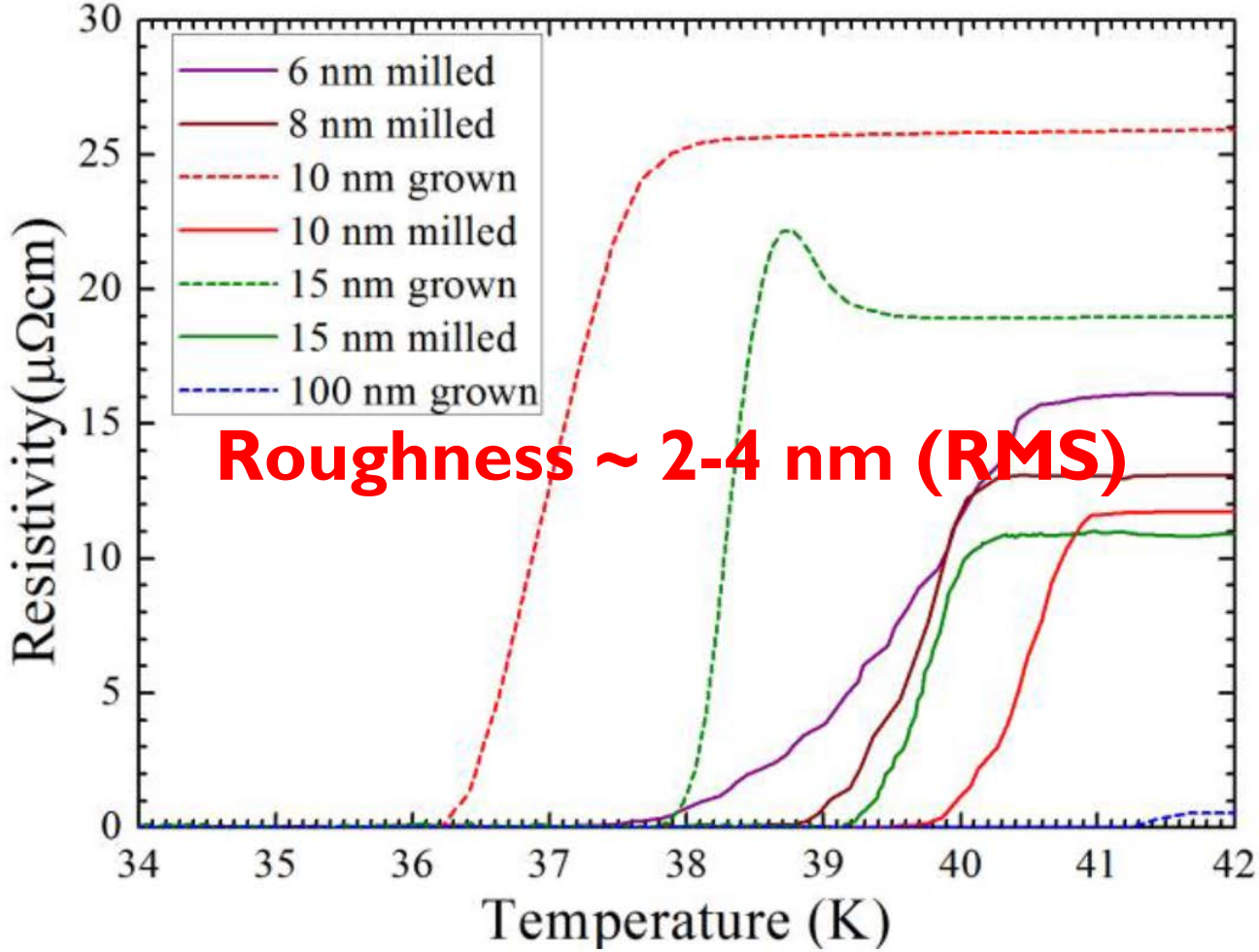


Etch back results



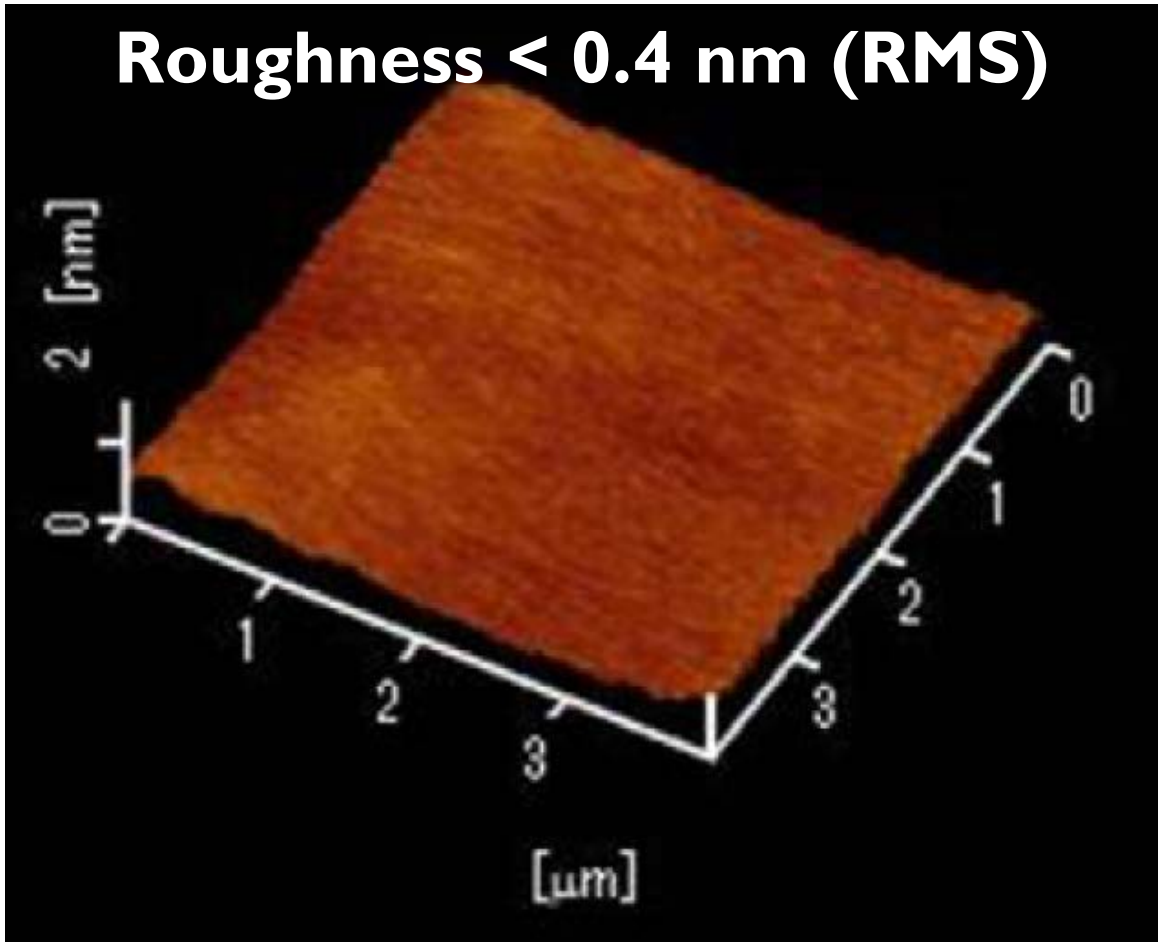
M.A. Wolak et al., IEEE Trans. Appl. Supercond. **25,** 3 7500905 (2015)

Etch back results



M.A. Wolak et al., IEEE Trans. Appl. Supercond. **25,** 3 7500905 (2015)

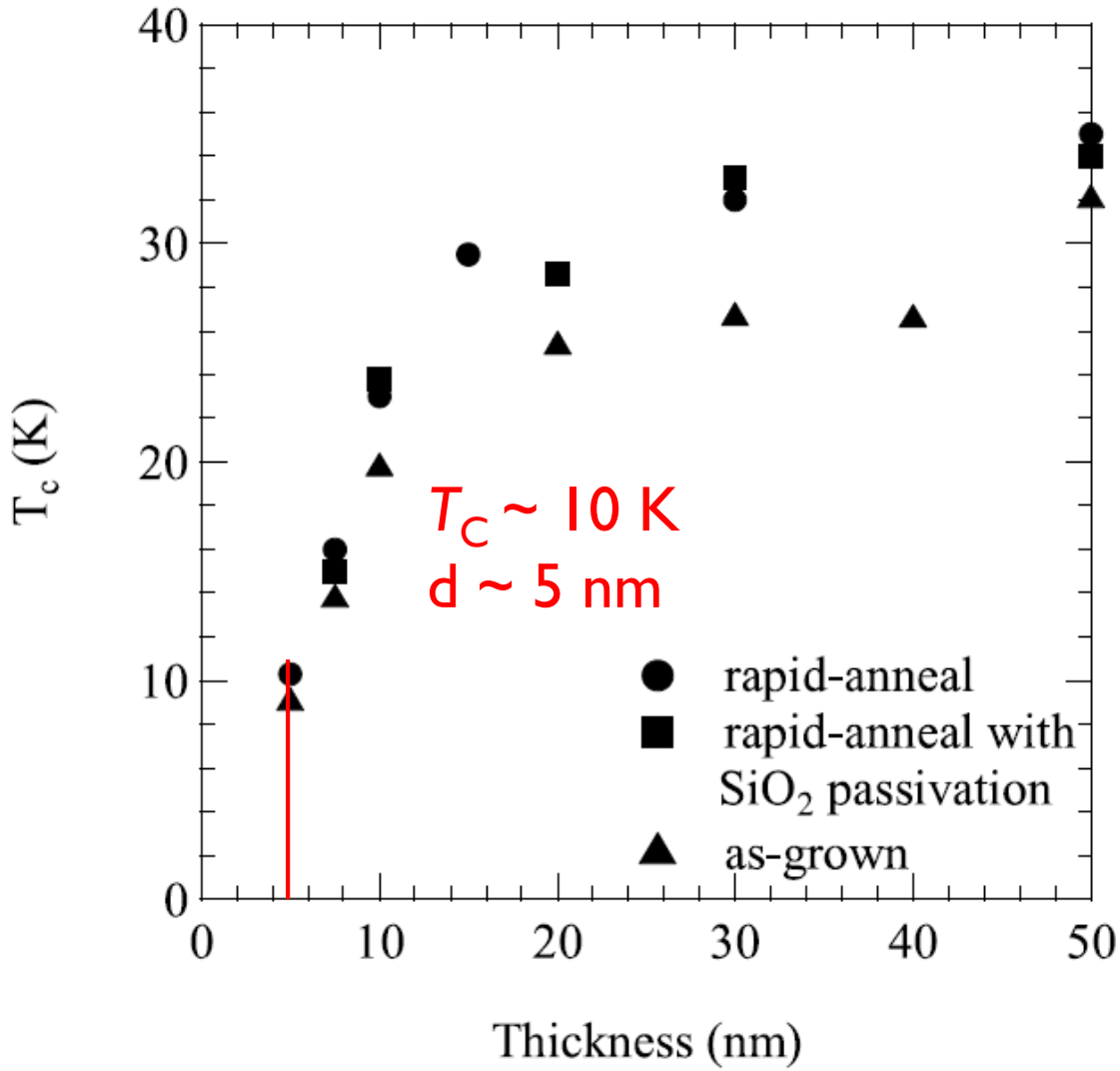
Molecular Beam Epitaxy films



H. Shibata et al., Supercond. Sci. Technol. **26** (2013) 035005

Kitami Institute of Technology

Molecular Beam Epitaxy (MBE) films



H. Shibata et al., Supercond. Sci. Technol. **26** (2013) 035005

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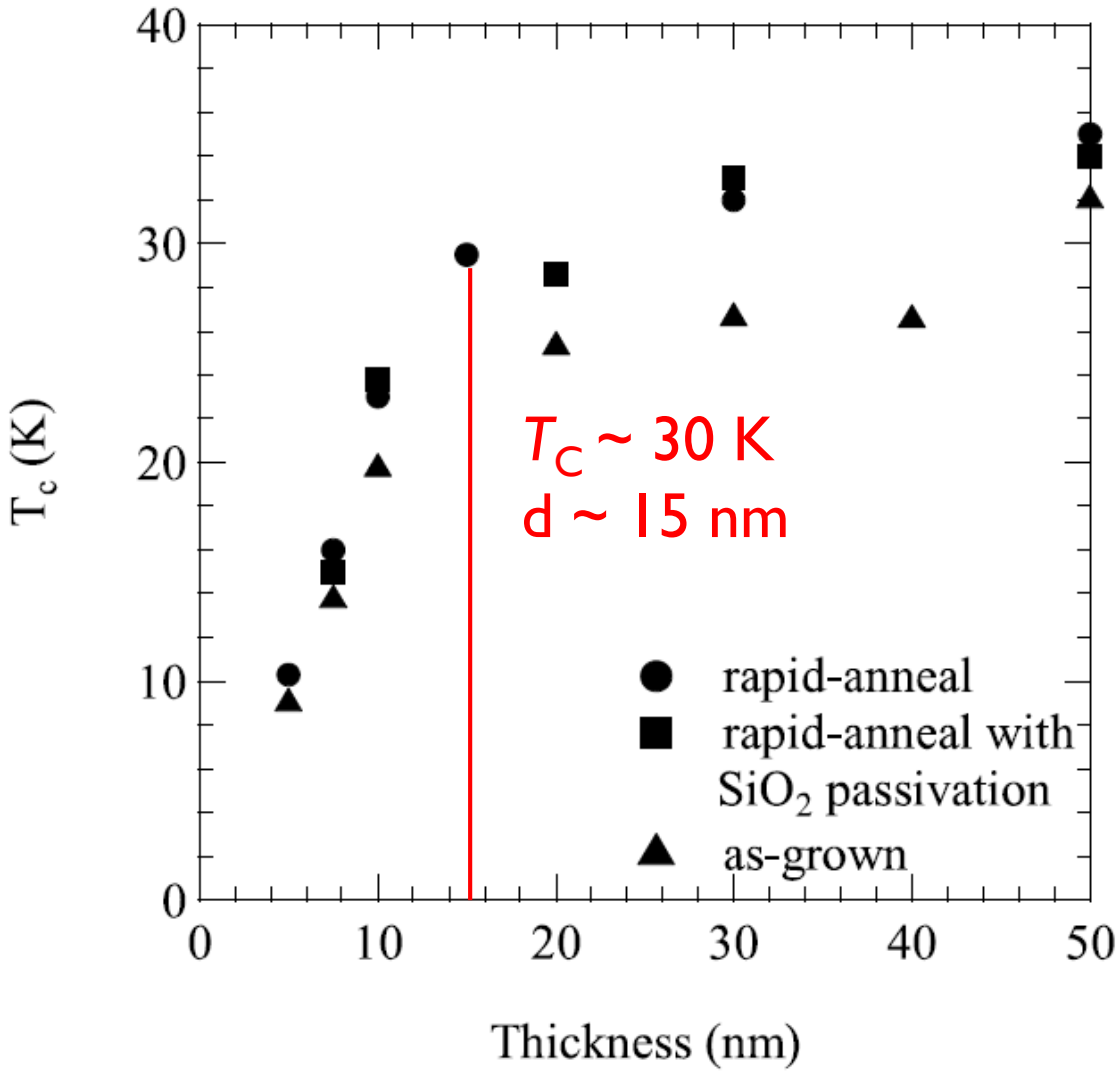

H. Shibata et al., Supercond. Sci. Technol. **26** (2013) 035005

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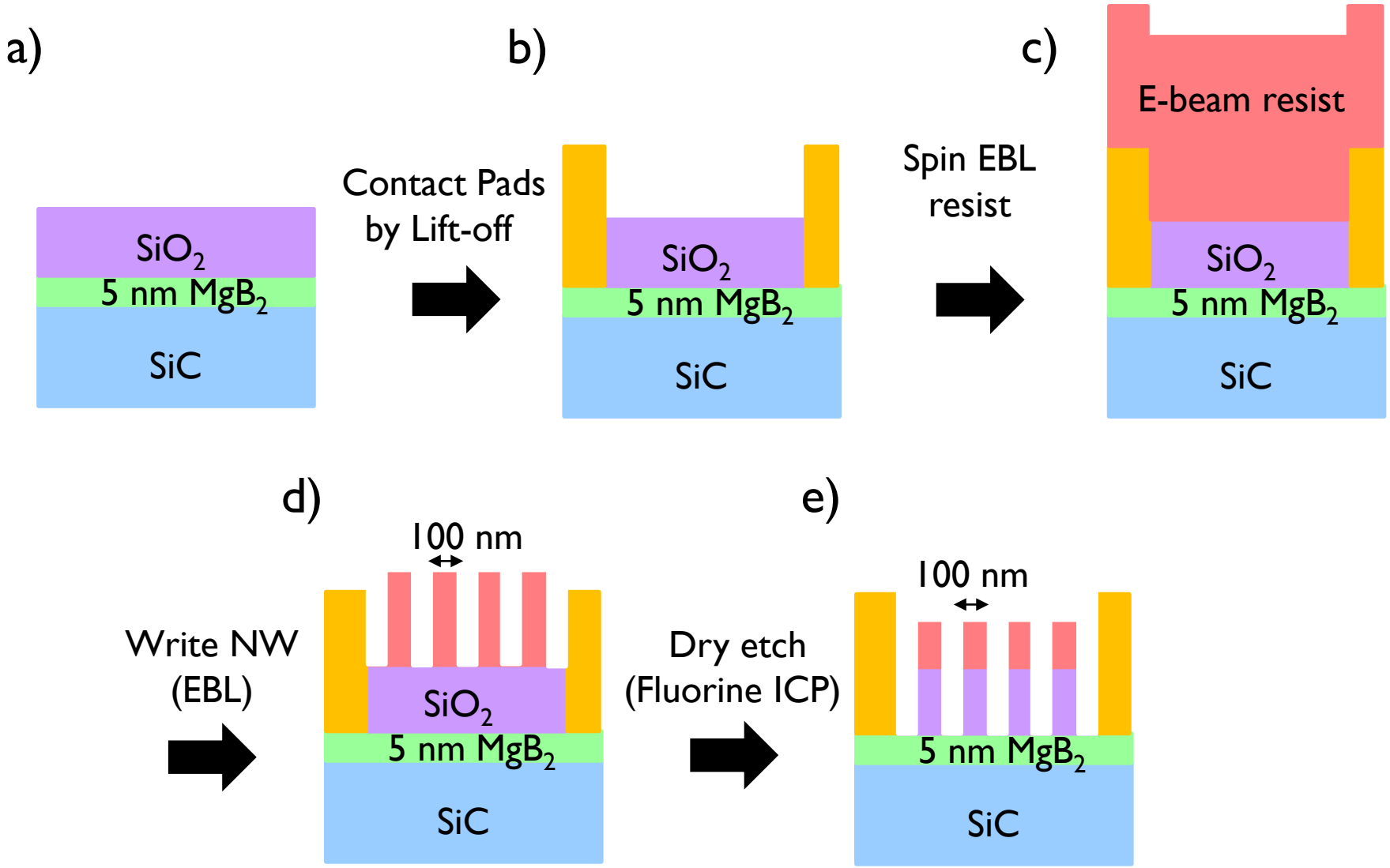
Film comparison

	Roughness (RMS)	T_C	Thickness
Ideal	< 1nm	40 K	5 nm
MBE	<0.35 nm	10 K	5 nm
HPCVD	2-4 nm	39 K	6 nm

Challenges of MgB_2 SNSPDs

- Difficult to grow high-quality MgB_2 thin films
- MgB_2 nanowire fabrication complex because:
  i. MgB_2 highly reactive with oxygen
  ii. MgB_2 etch limited to argon ion milling
- Single photon detection at 20 K never demonstrated

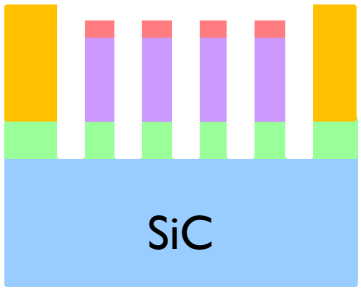
Current fabrication process



Current fabrication process

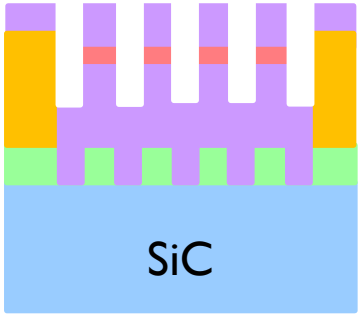
f)

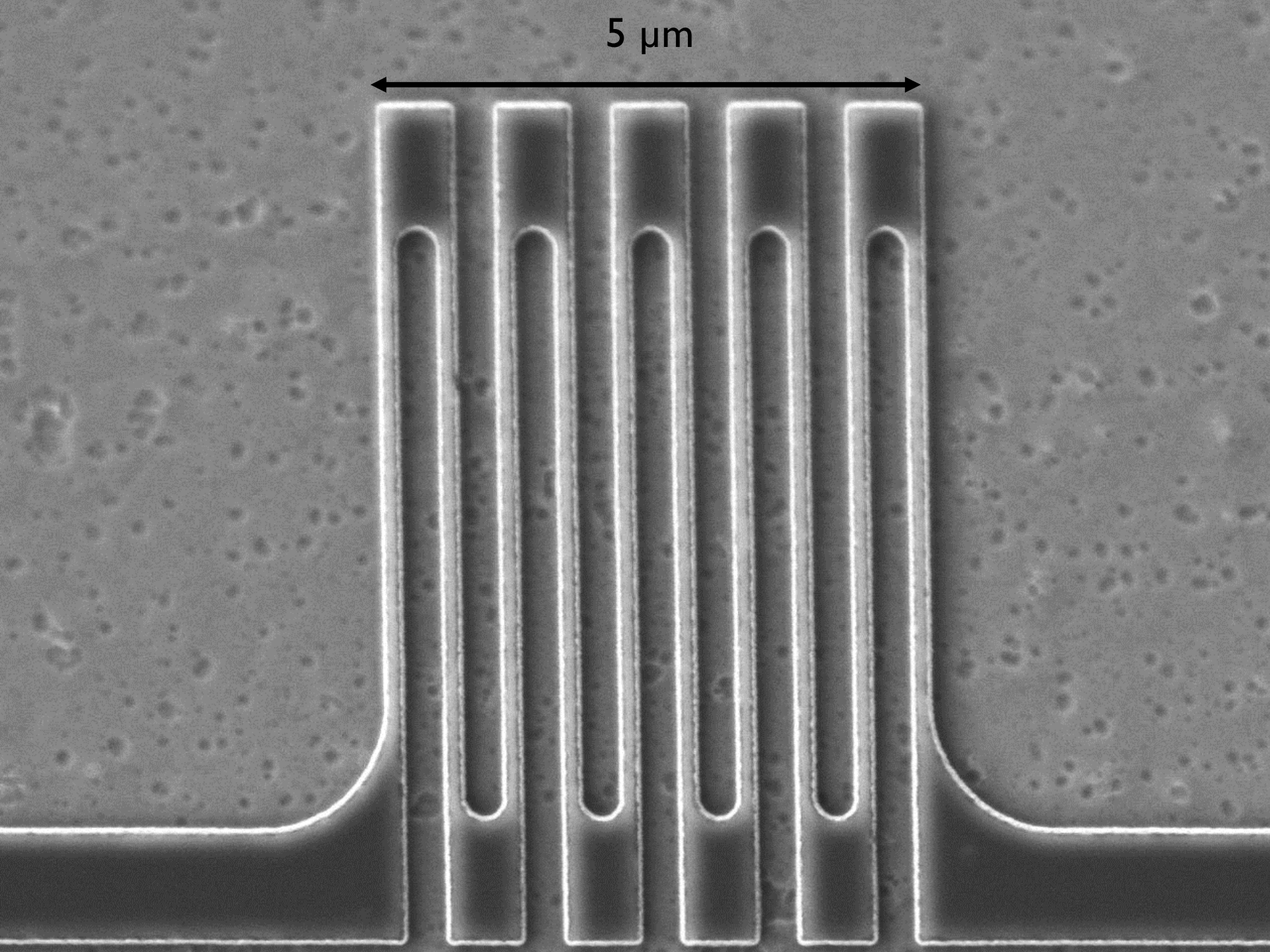
Dry etch
(Ar Ion mill)



g)

Passivation
(SiO_2)




5 µm

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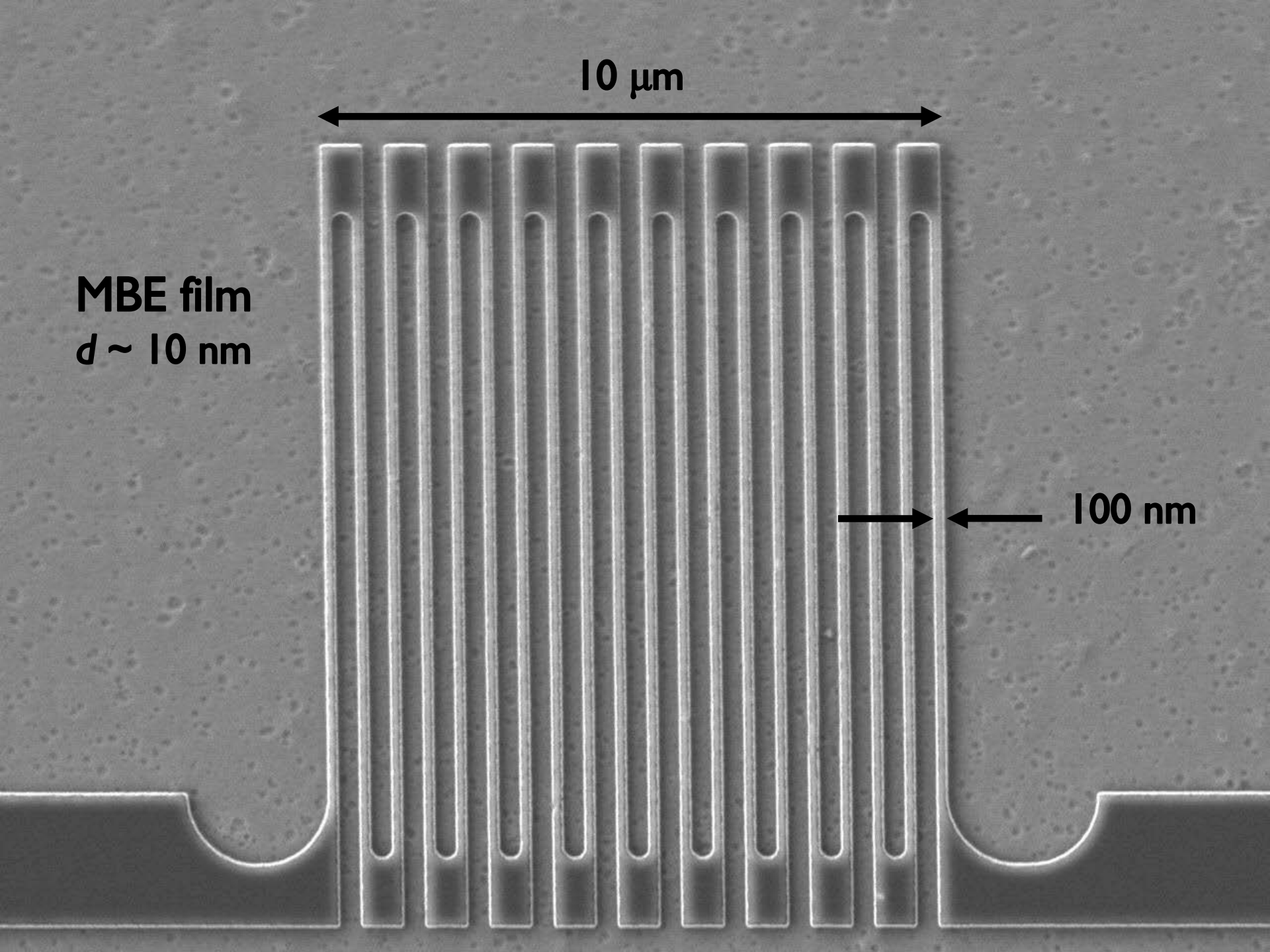
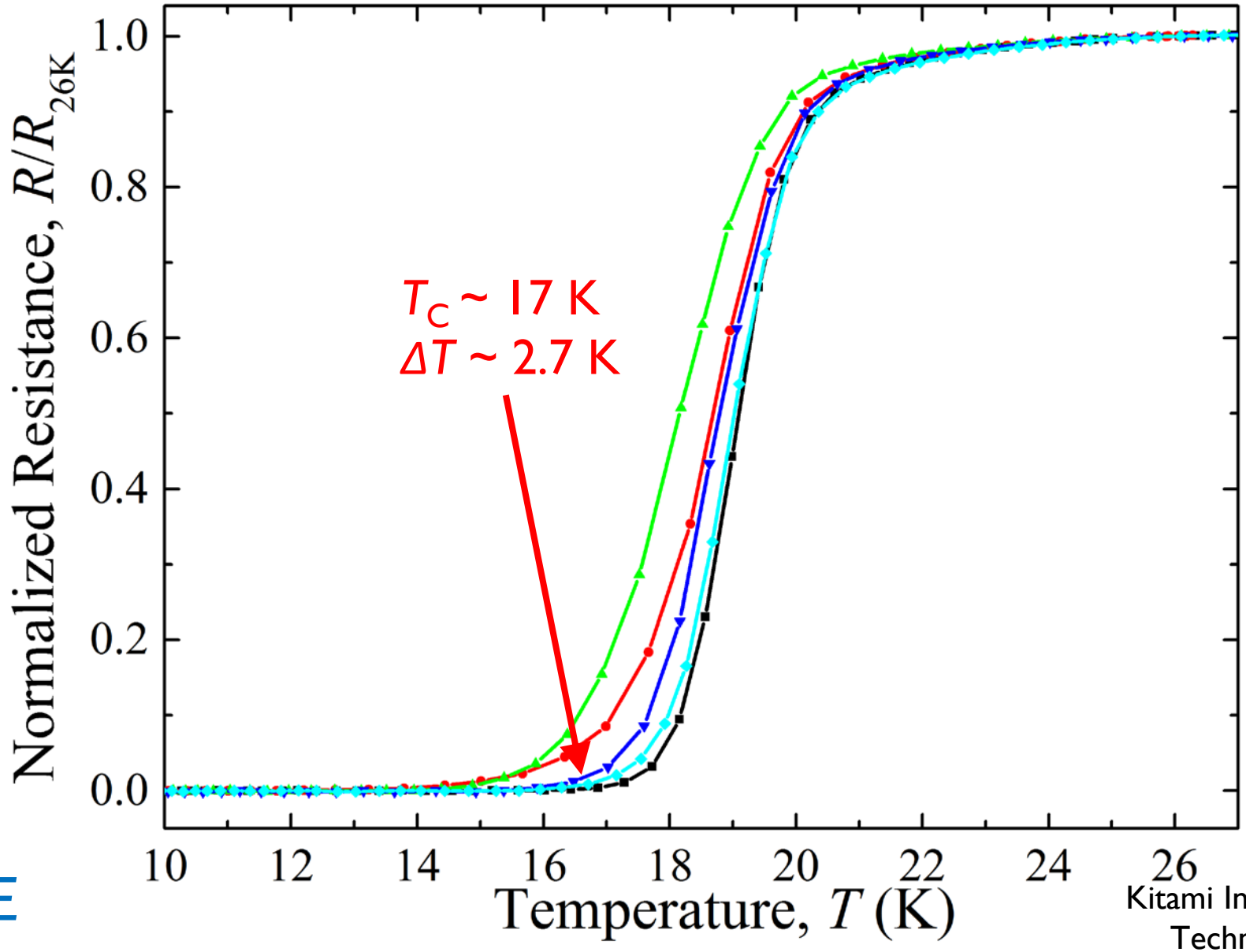

10 μm
MBE film
d ~ 10 nm
100 nm

Transition temperature, T_C



MBE

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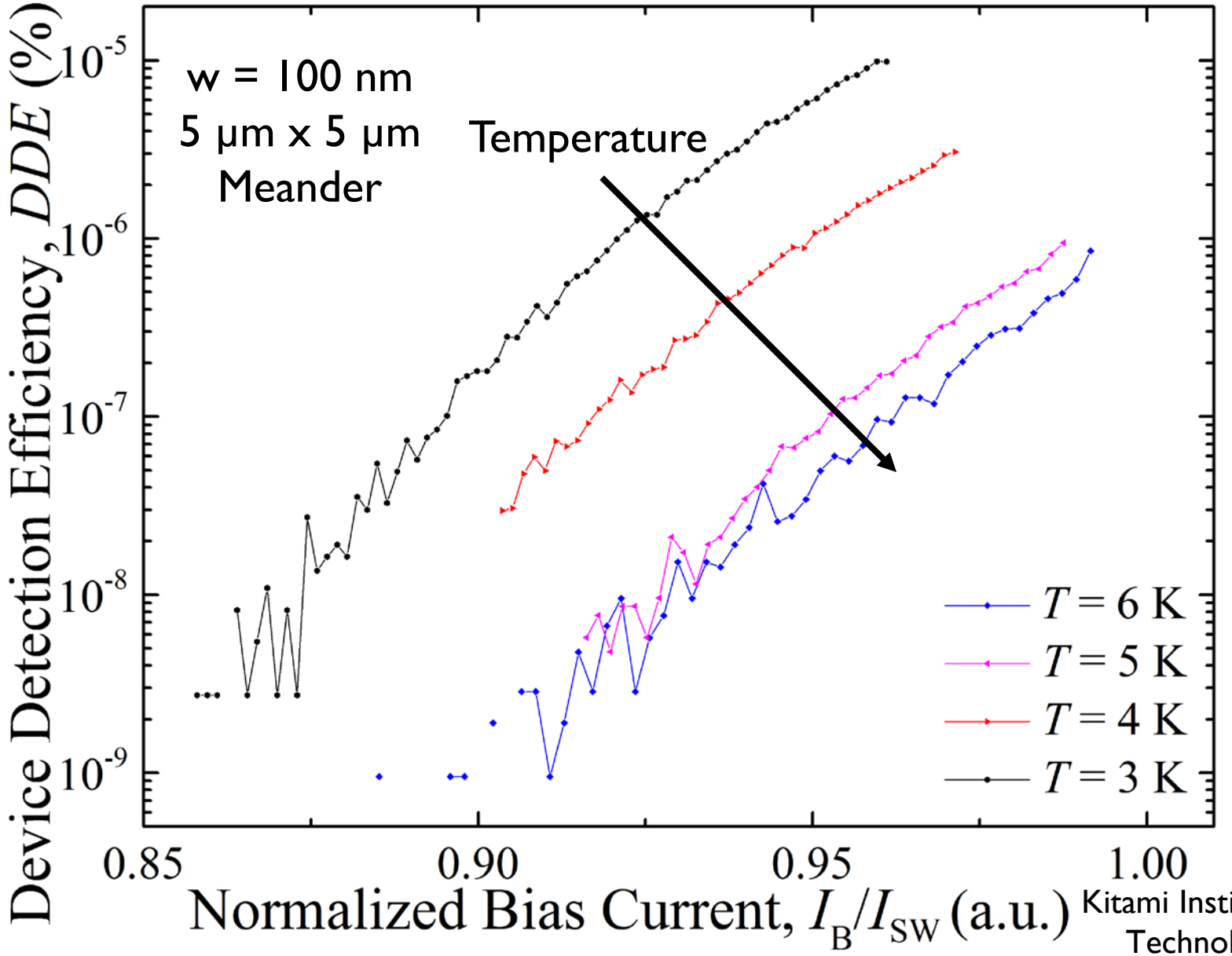
Device detection efficiency at 1550 nm



MBE

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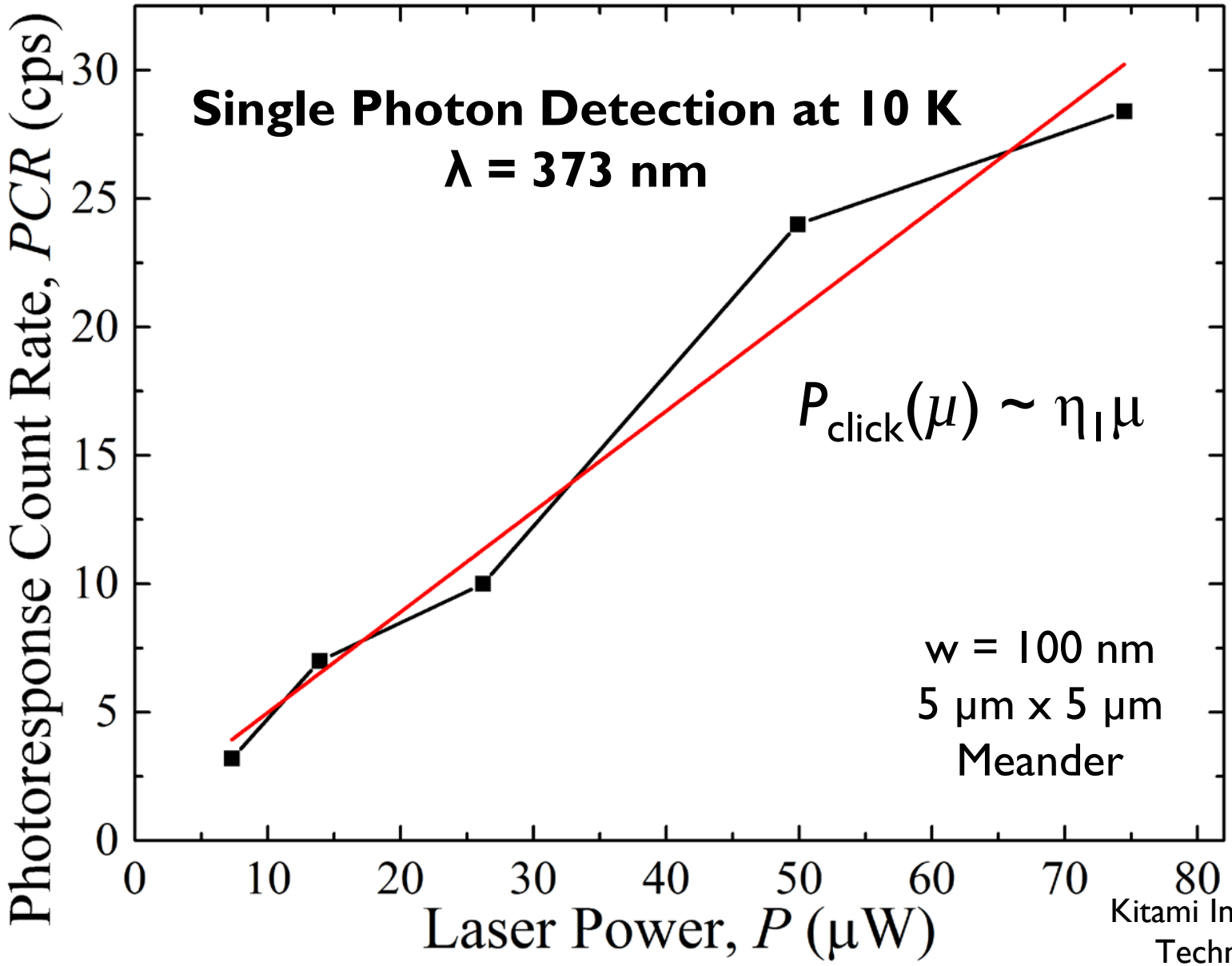
Single photon sensitive at T = 10 K



MBE

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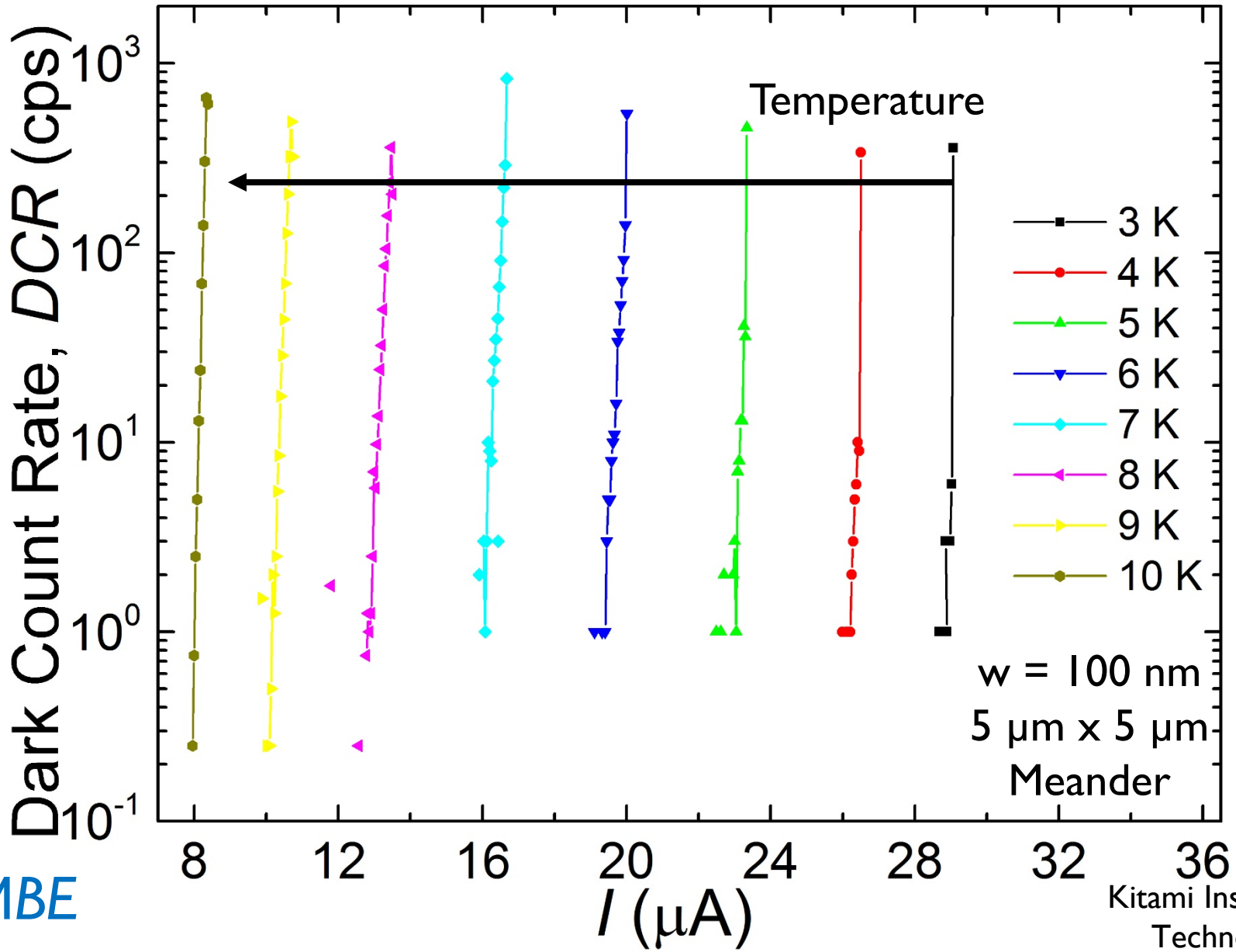
Dark count rate, *DCR*



MBE

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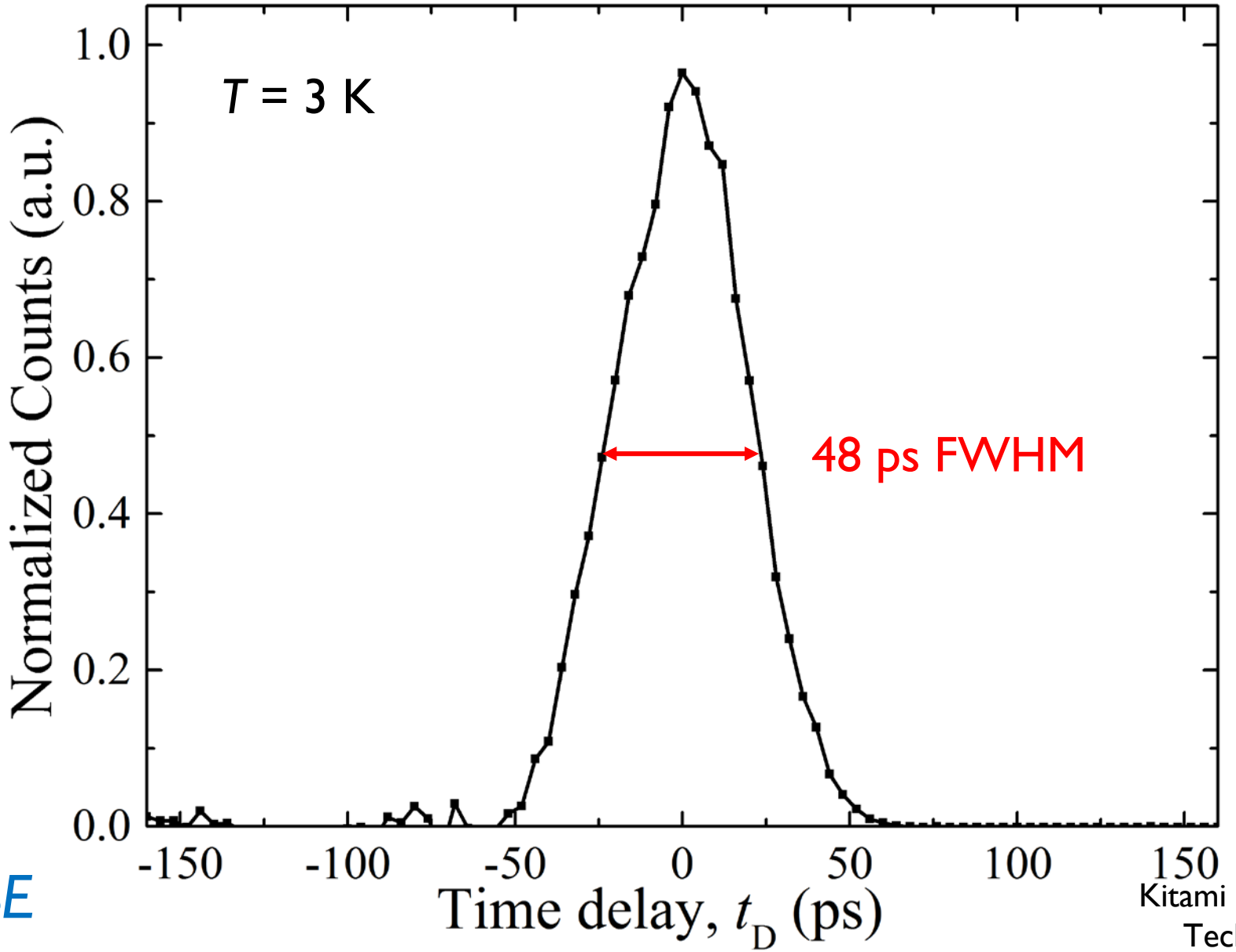
Instrument response function



MBE

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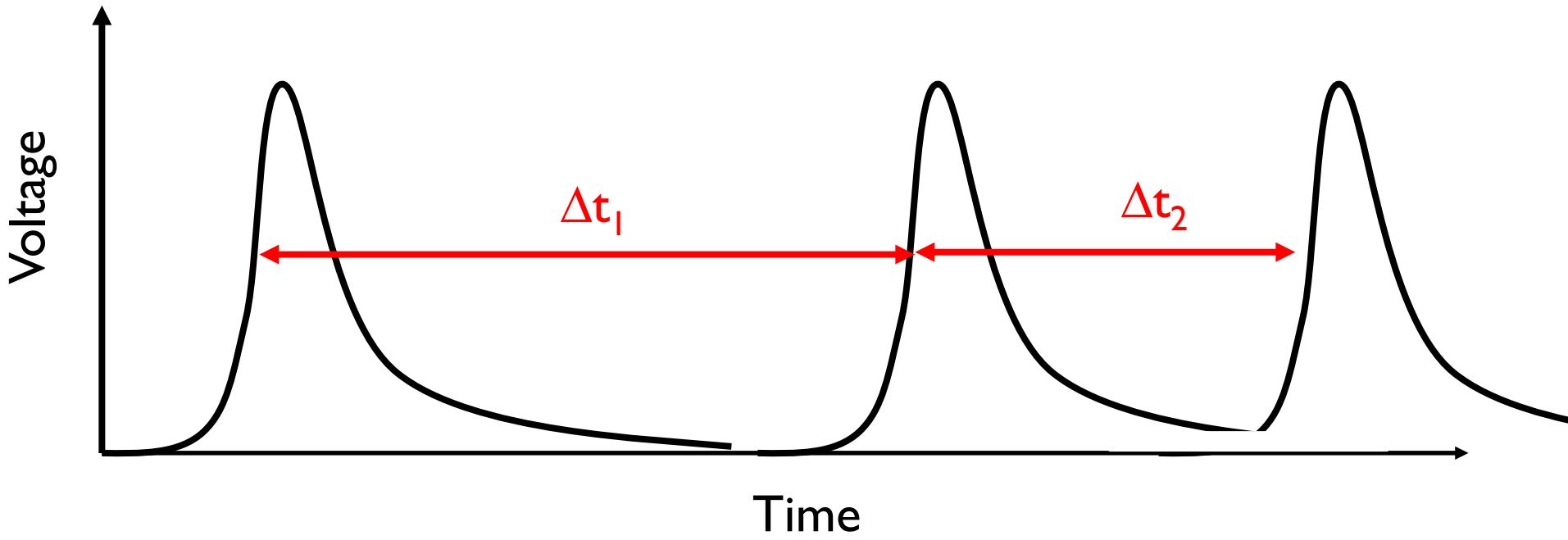
Inter-arrival time measurement



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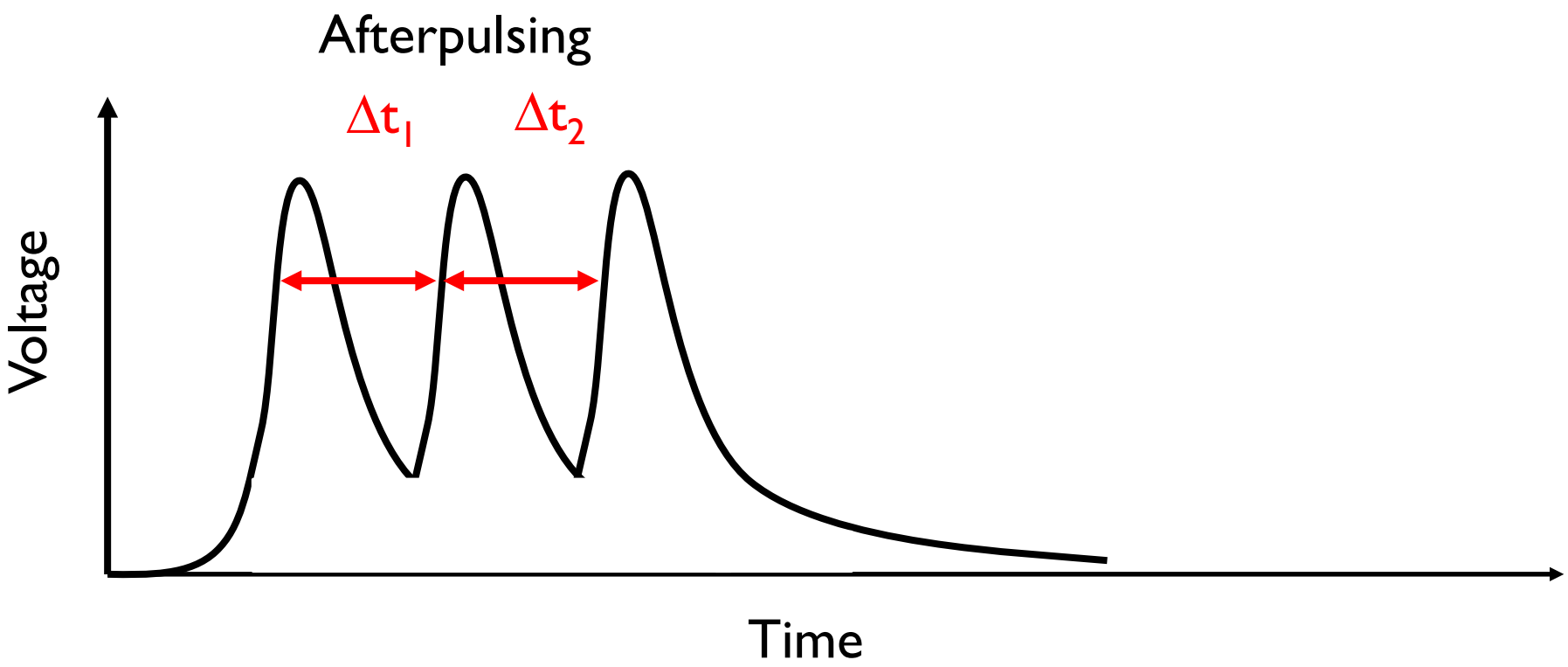
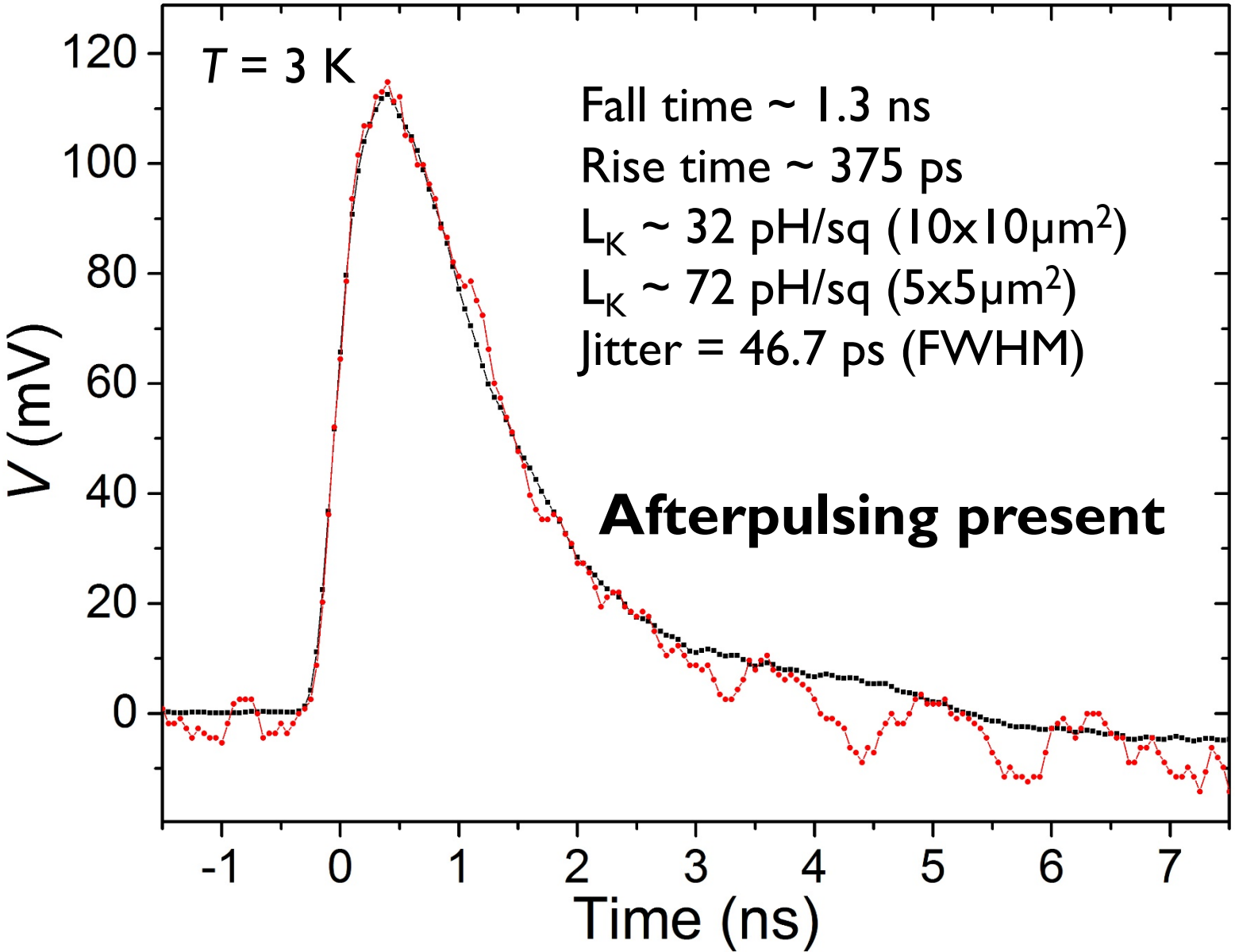
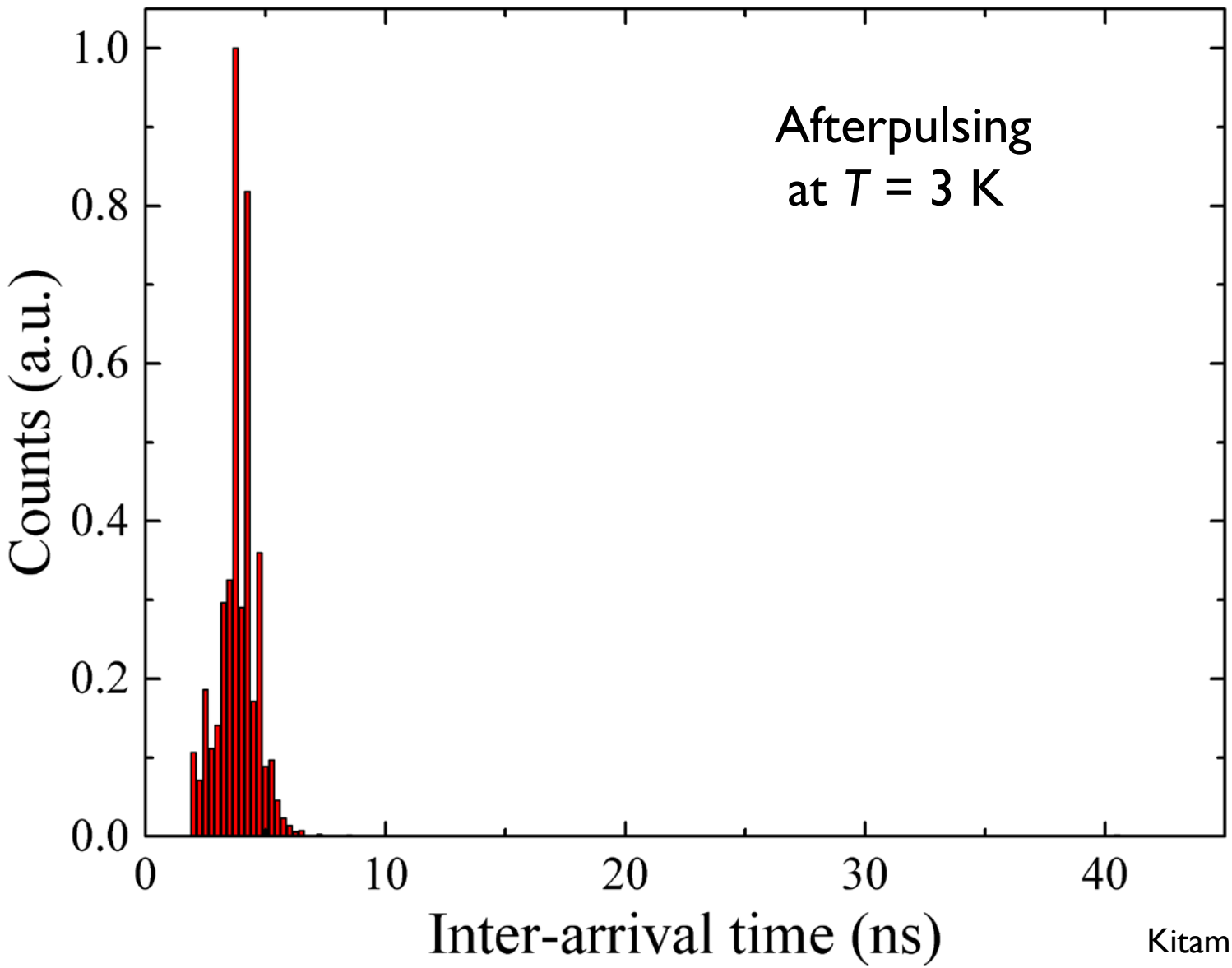


Optical response at 1550 nm



Increasing device speed with temperature



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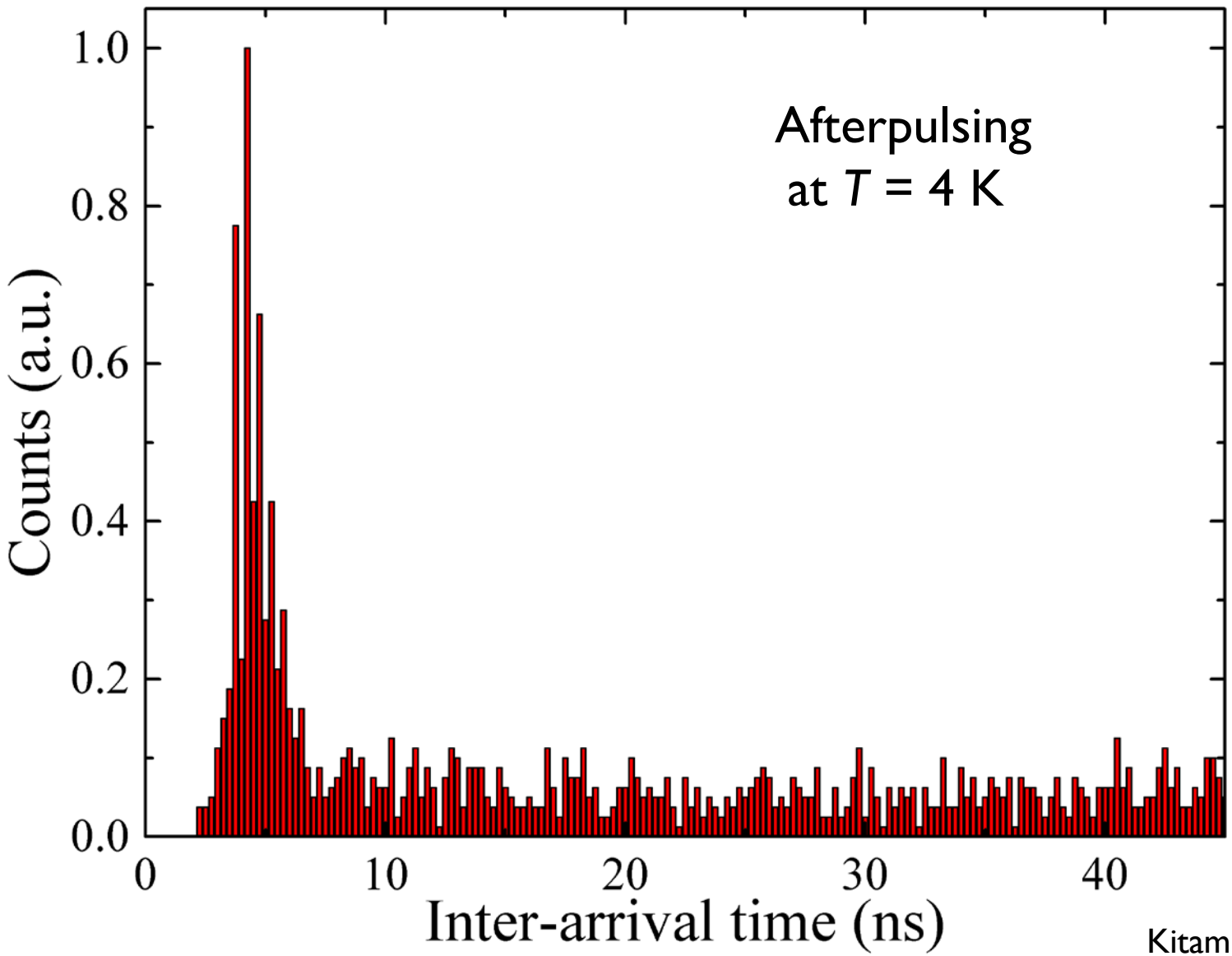

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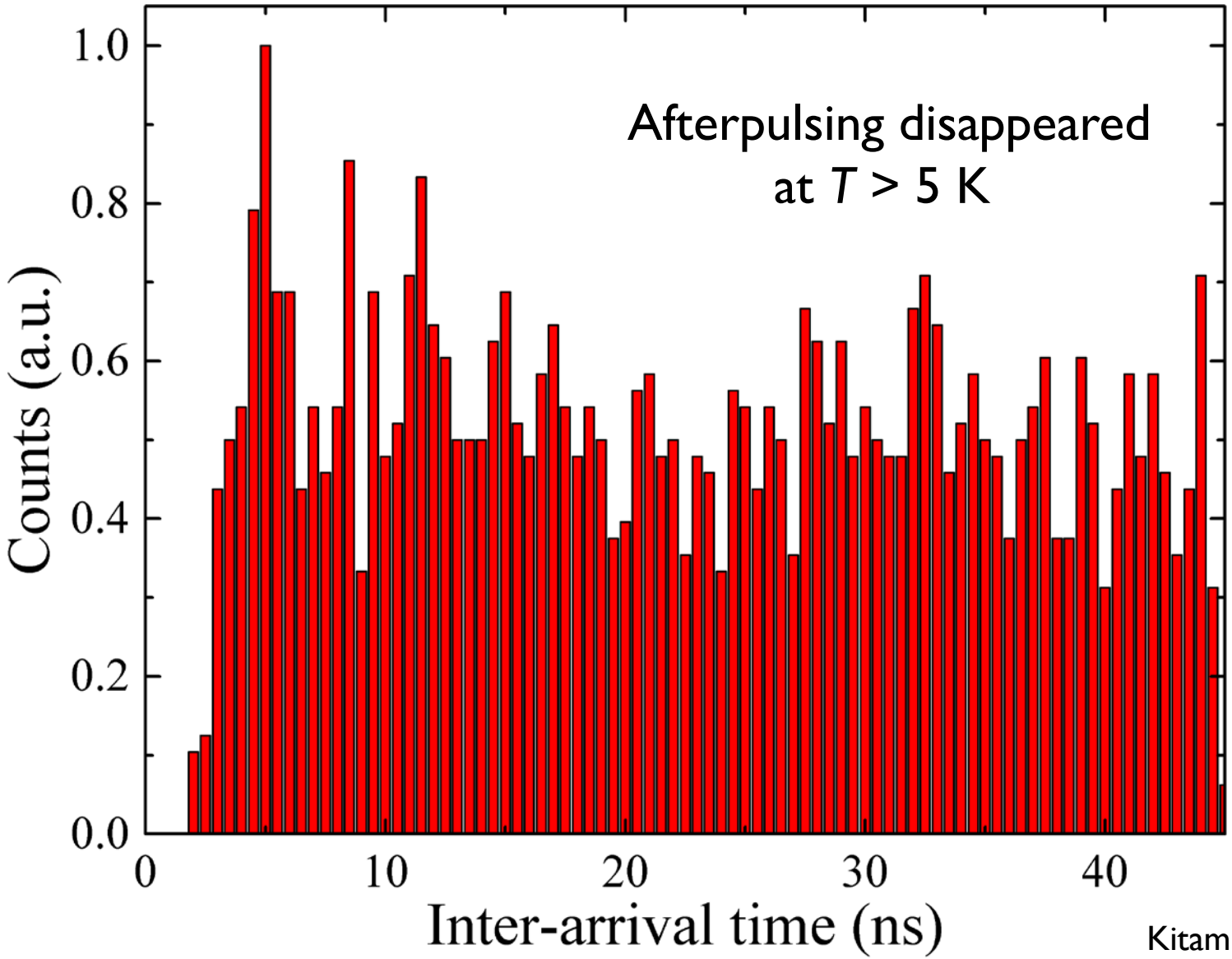

MBE

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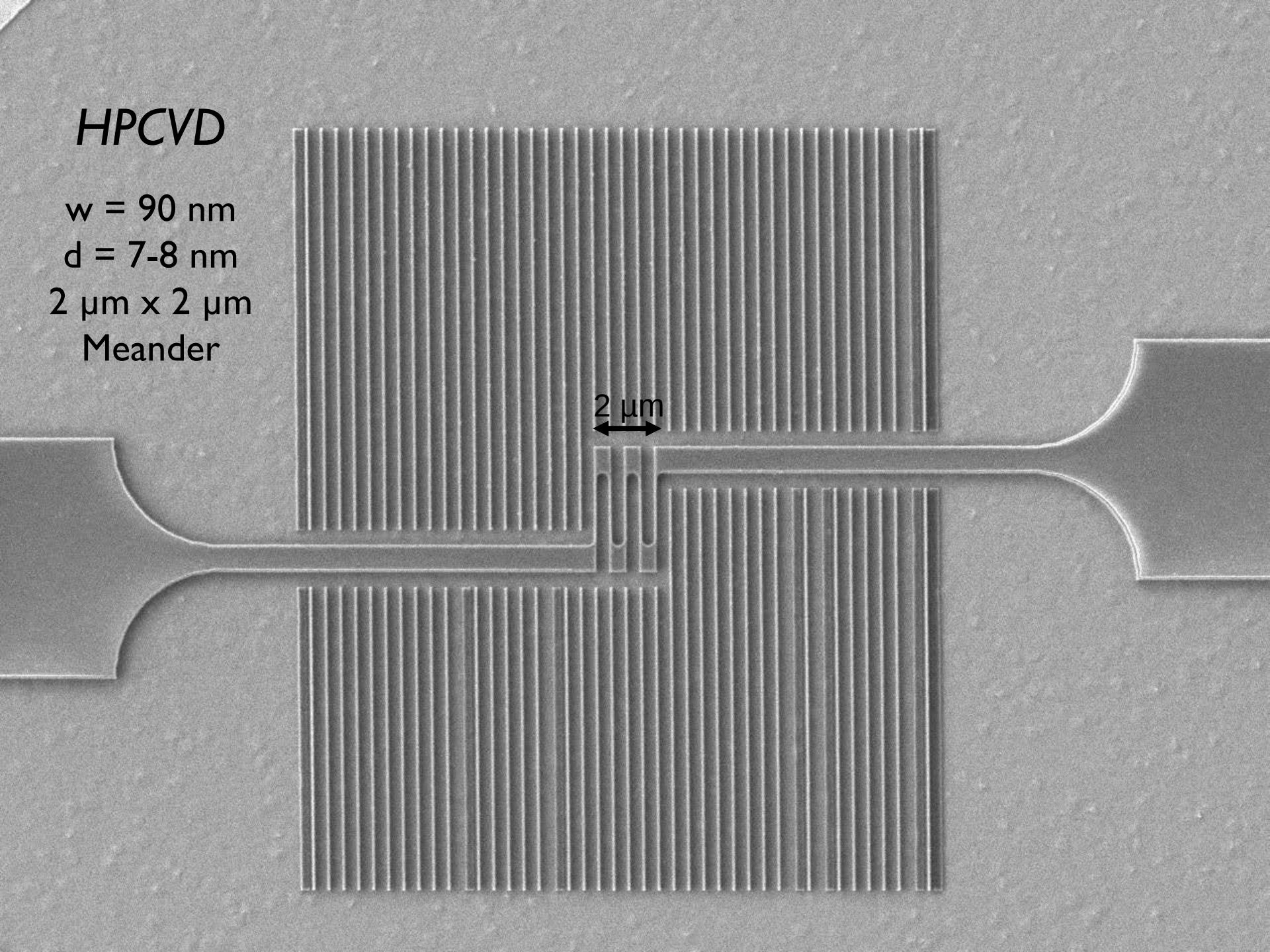
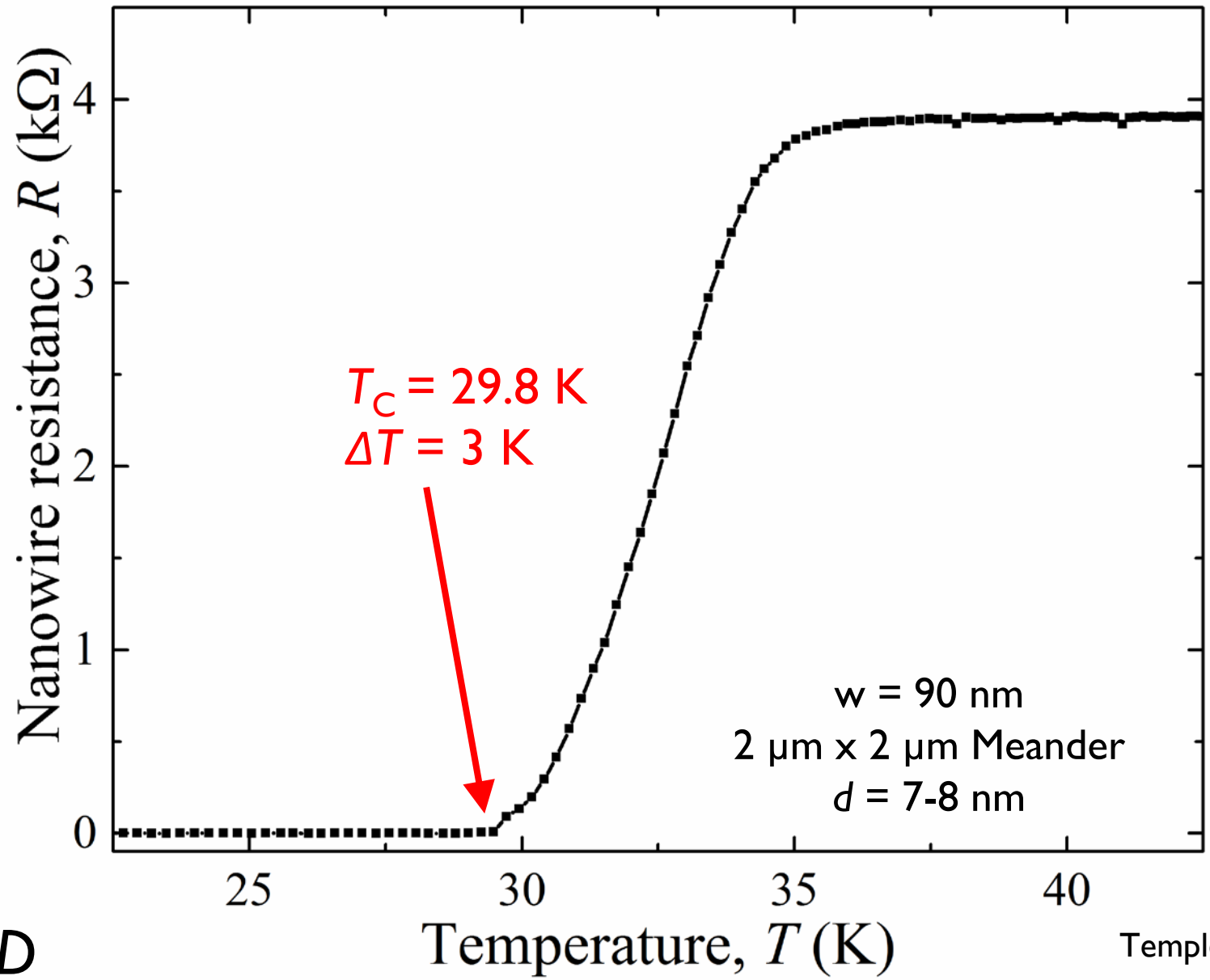
HPCVD

w = 90 nm
d = 7-8 nm
2 μm x 2 μm
Meander



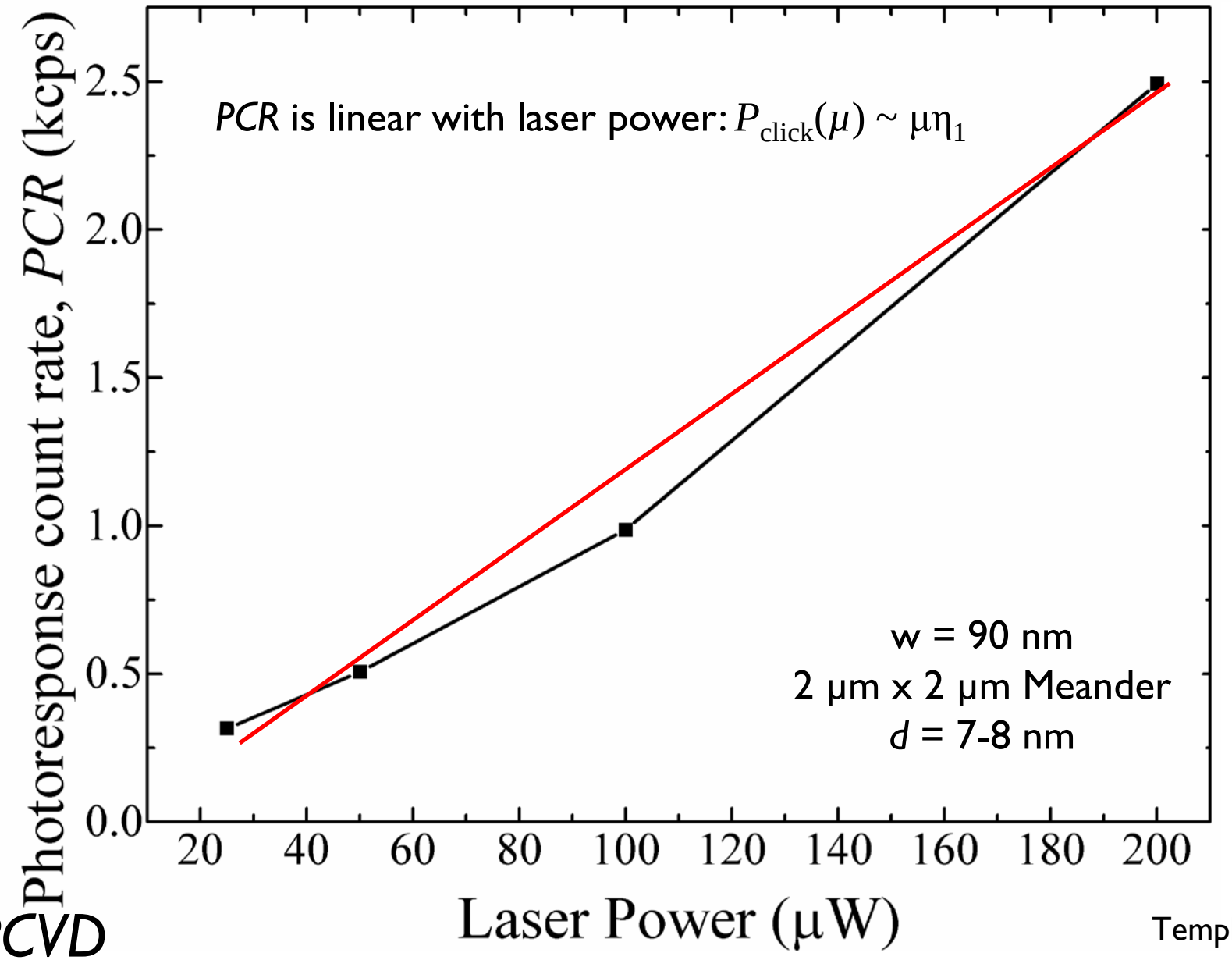
Transition temperature, T_C



HPCVD

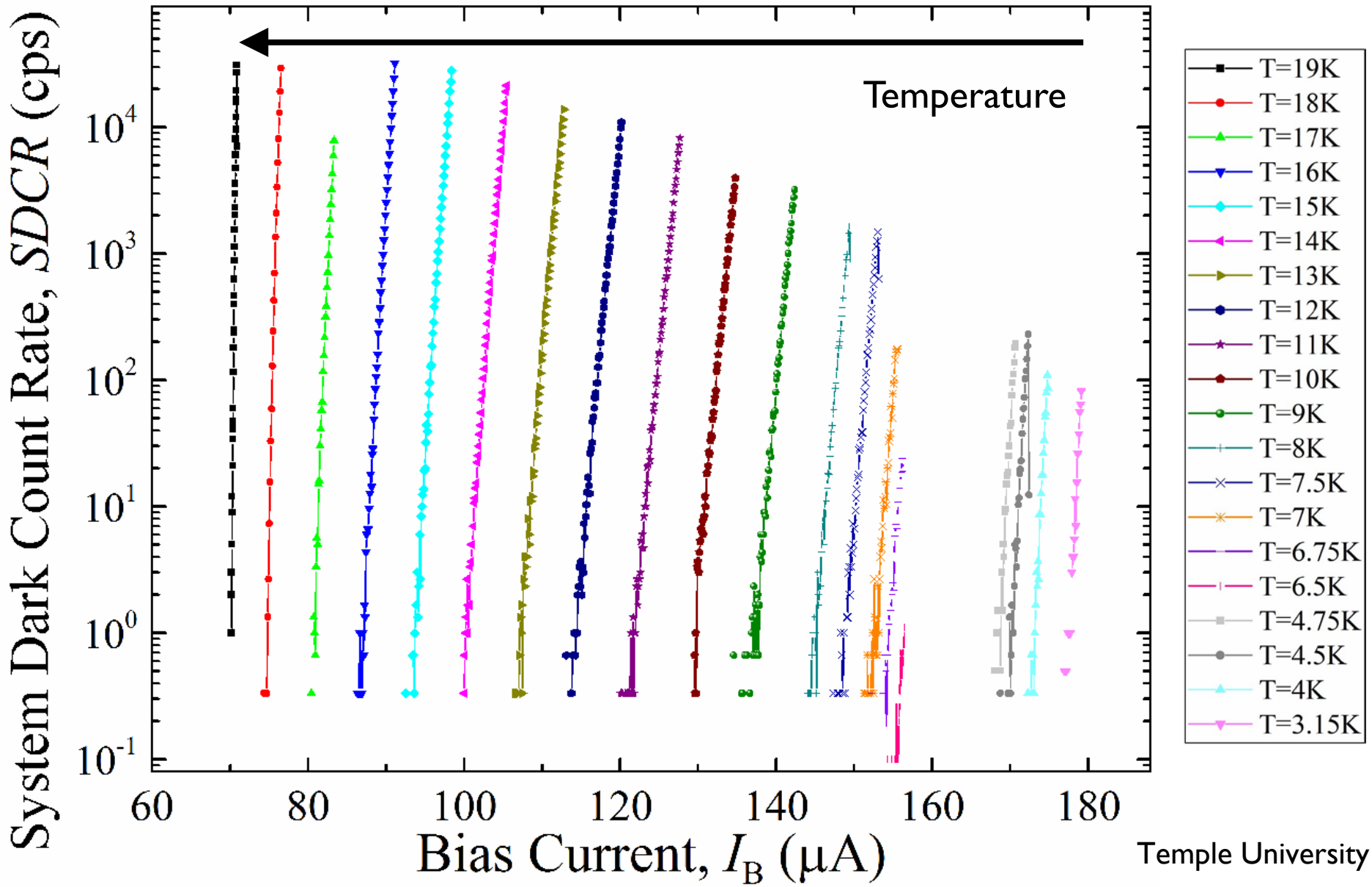
Temple University

Single Photon Detection at 18 K

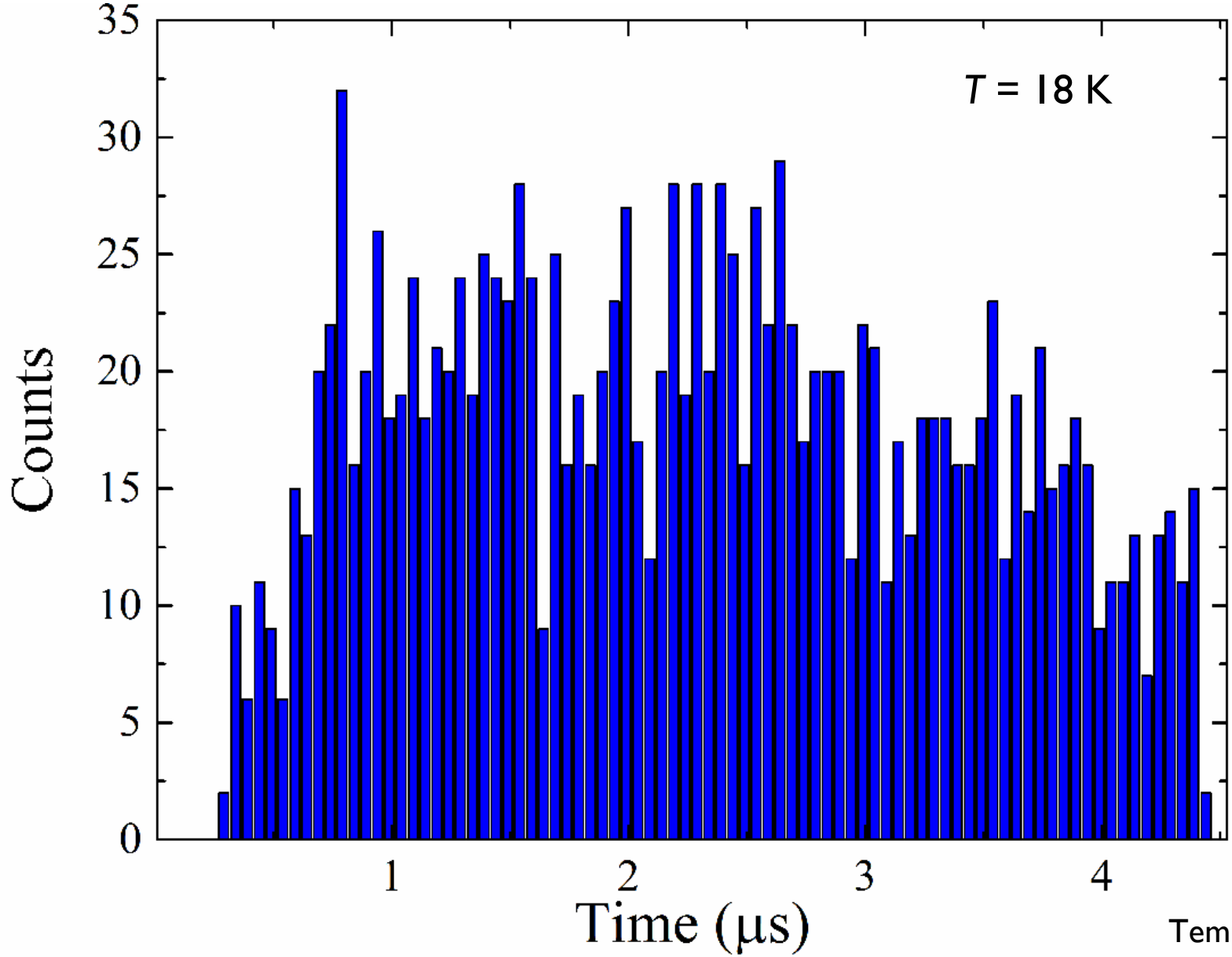


HPCVD

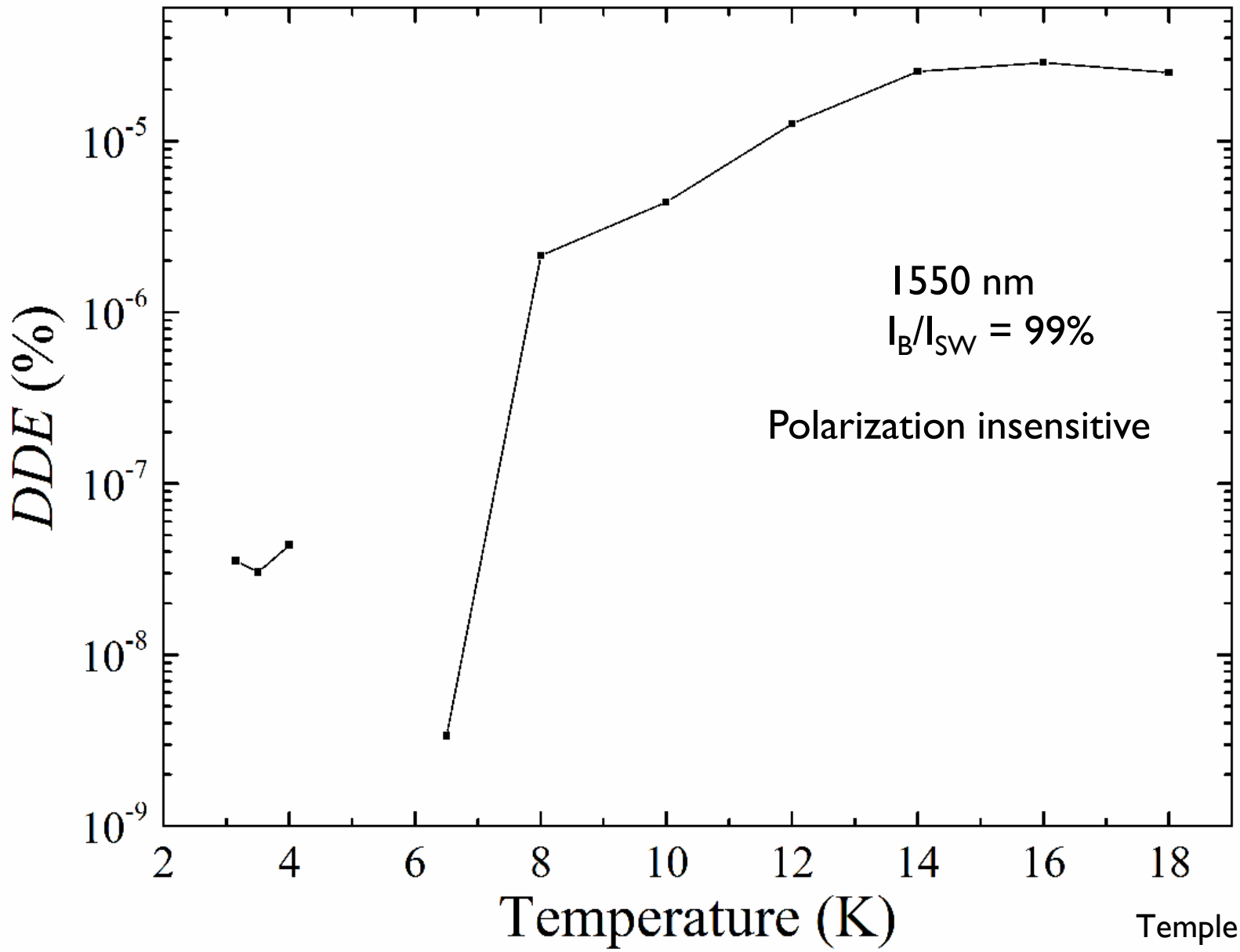
System Dark Count Rate vs Temperature



Inter-arrival time measurement



Device detection efficiency (*DDE*) vs Temperature



Temple University

Summary

- Single-photon response with MBE film
  a) λ = 373 nm
  b) Up to T = 10 K
  c) Timing jitter ~ 50 ps (T = 3 K)
  d) Large active area (10 μm × 10 μm)
- Single-photon response with HPCVD film
  a) λ = 1550 nm
  b) Up to T = 18 K

Future work

- Increase operating temperature
  a) Reducing roughness of thin HPCVD films
  b) Narrower nanowires for thick MBE films
- Increase detection efficiency by decreasing nanowire cross section

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End of Presentation

Single photon sensitivity

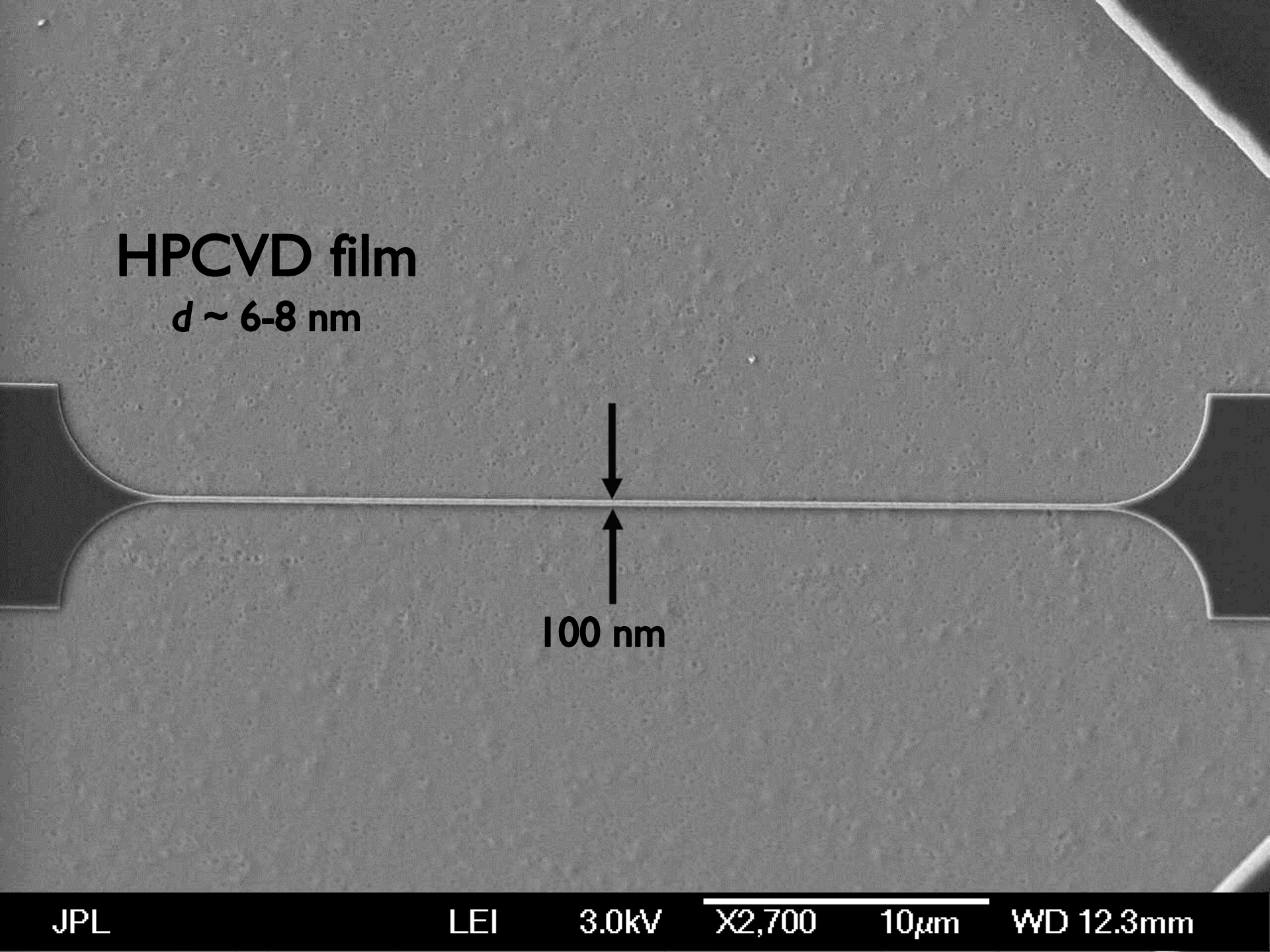
$$P_{\text{click}}(\mu) = 1 - e^{-\mu} \sum_{n=0}^{\infty} \frac{\mu^n}{n!} (1-\eta_1)^n (1-\eta_2)^{n(n-1)/2}$$

$$\eta_2 = 0,\ \mu\eta_1 << 1$$

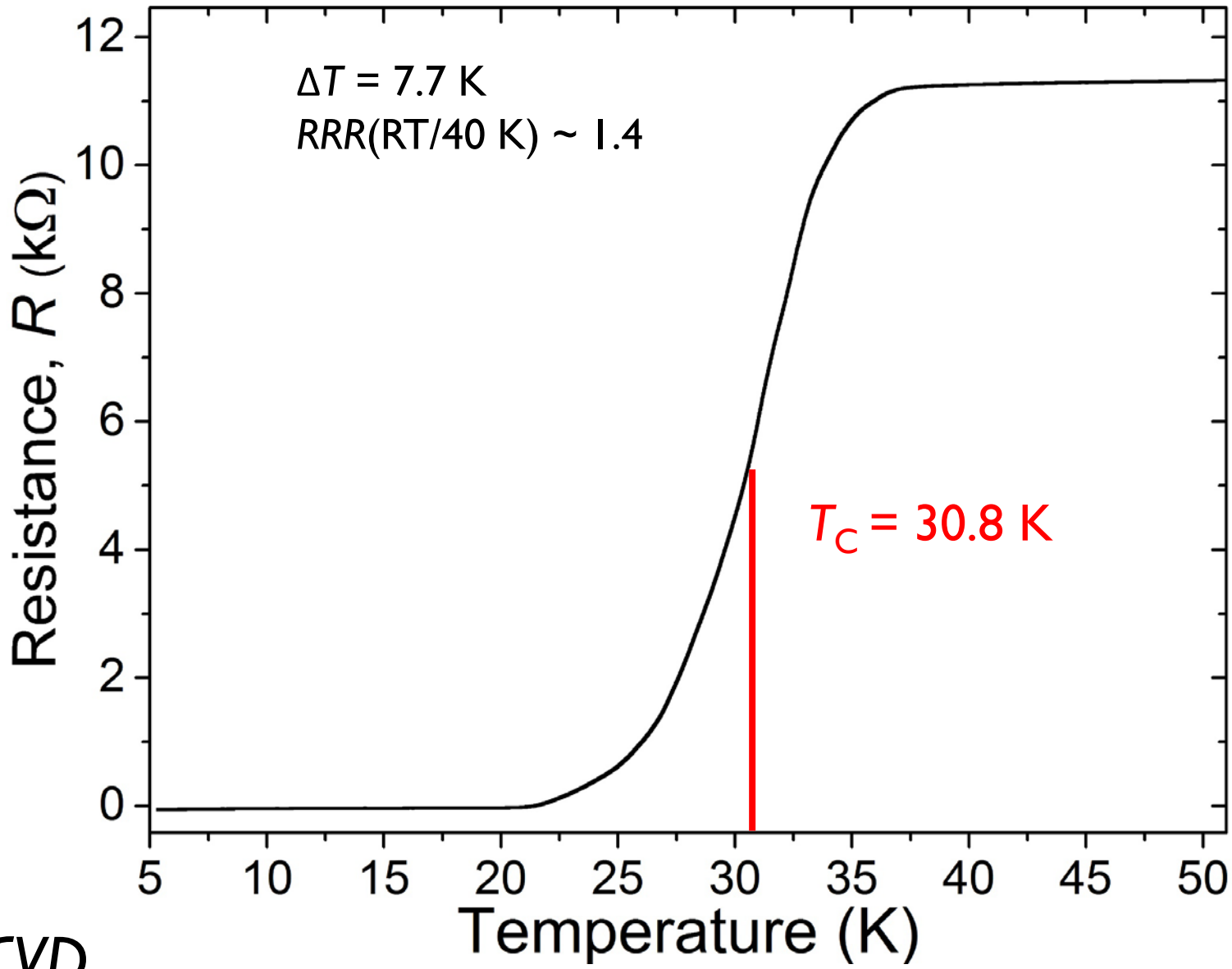
$$P_{\text{click}}(\mu) \sim \mu\eta_1$$

μ = mean photon flux
η_1 = single photon detection efficiency
η_2 = two photon detection efficiency

F. Marsili et al., arXiv: 1506.03129 (2015).

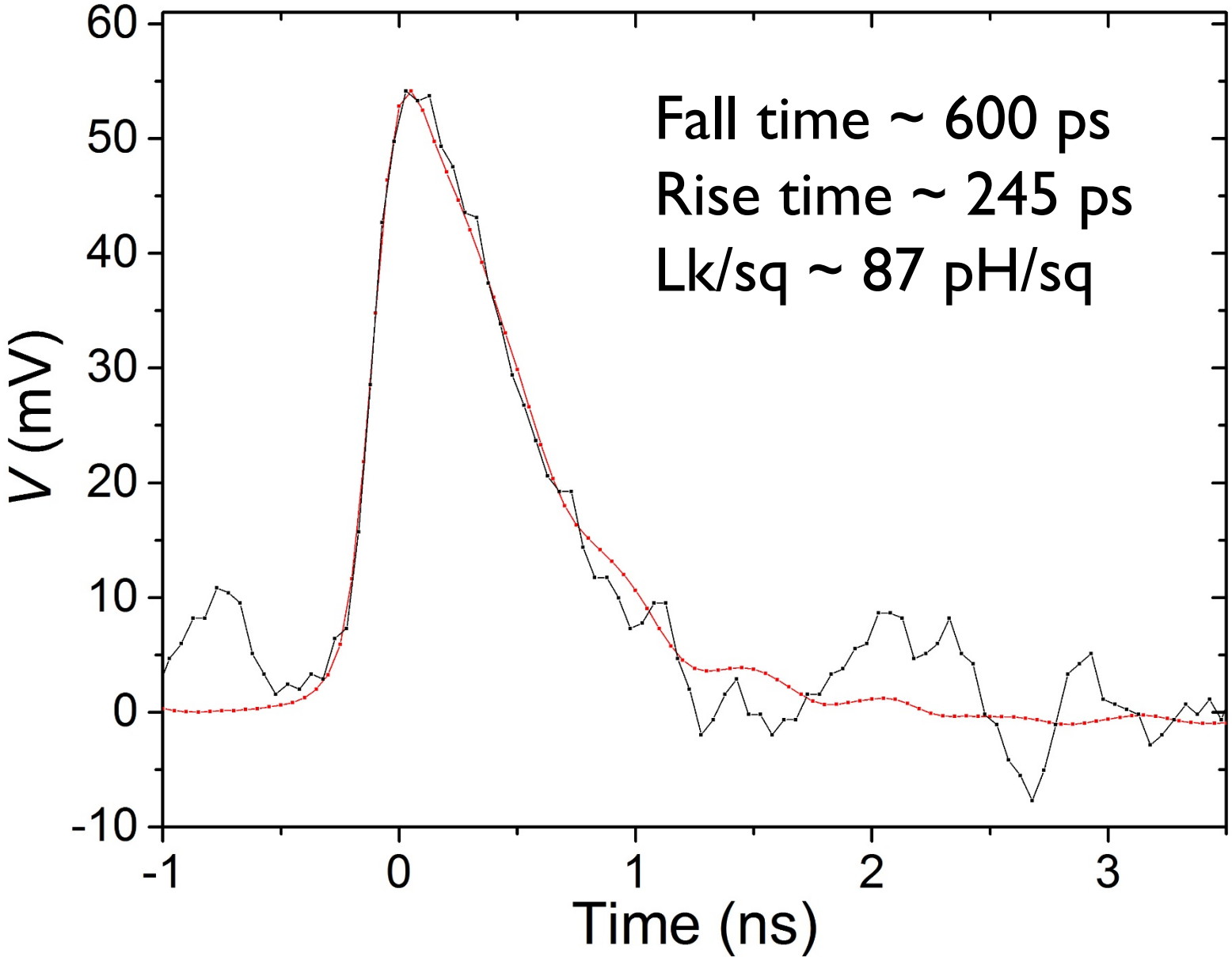

HPCVD film
d ~ 6-8 nm
100 nm
JPL
LEI
3.0kV
X2,700
10μm
WD 12.3mm

Transition Temperature, T_C

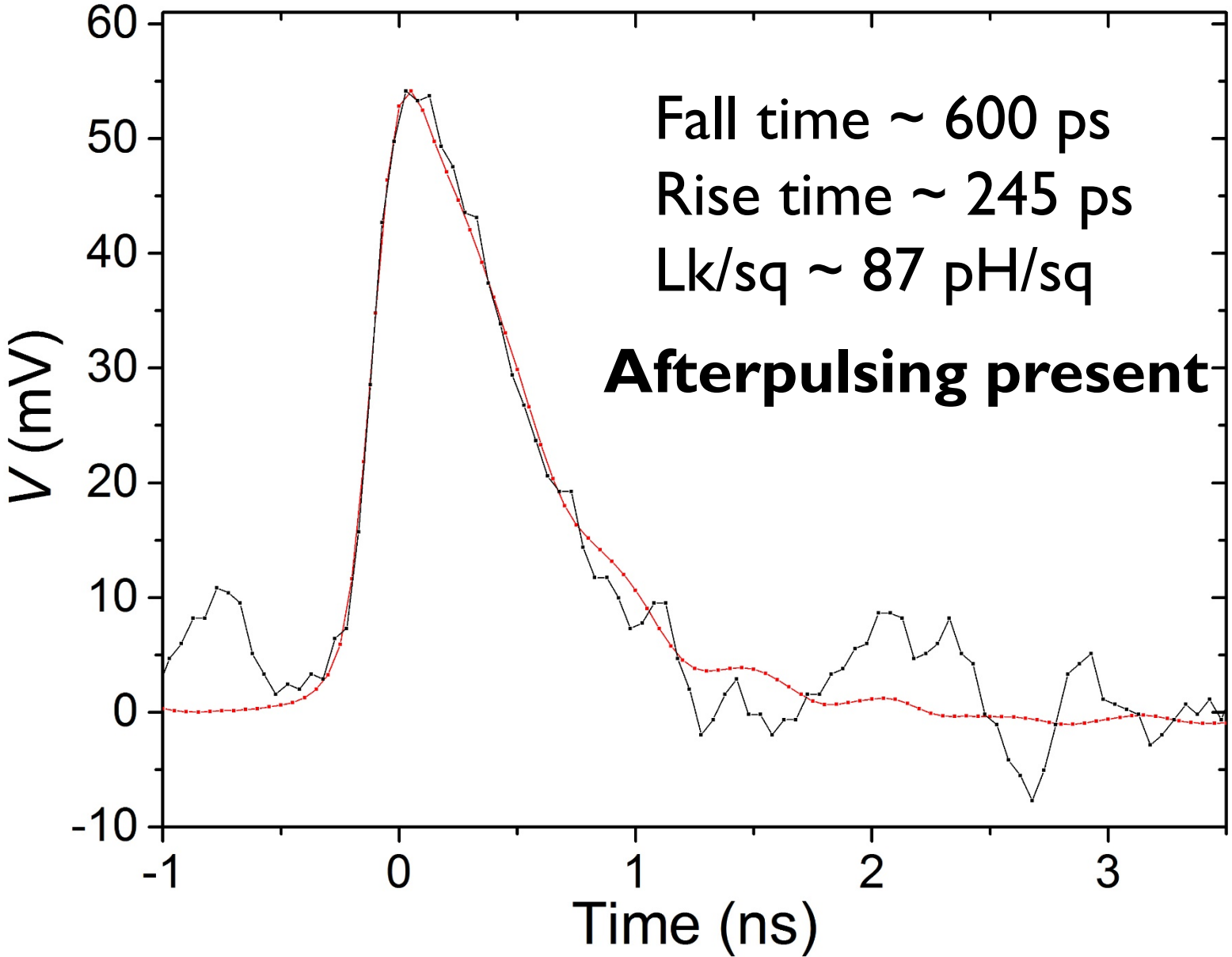


HPCVD

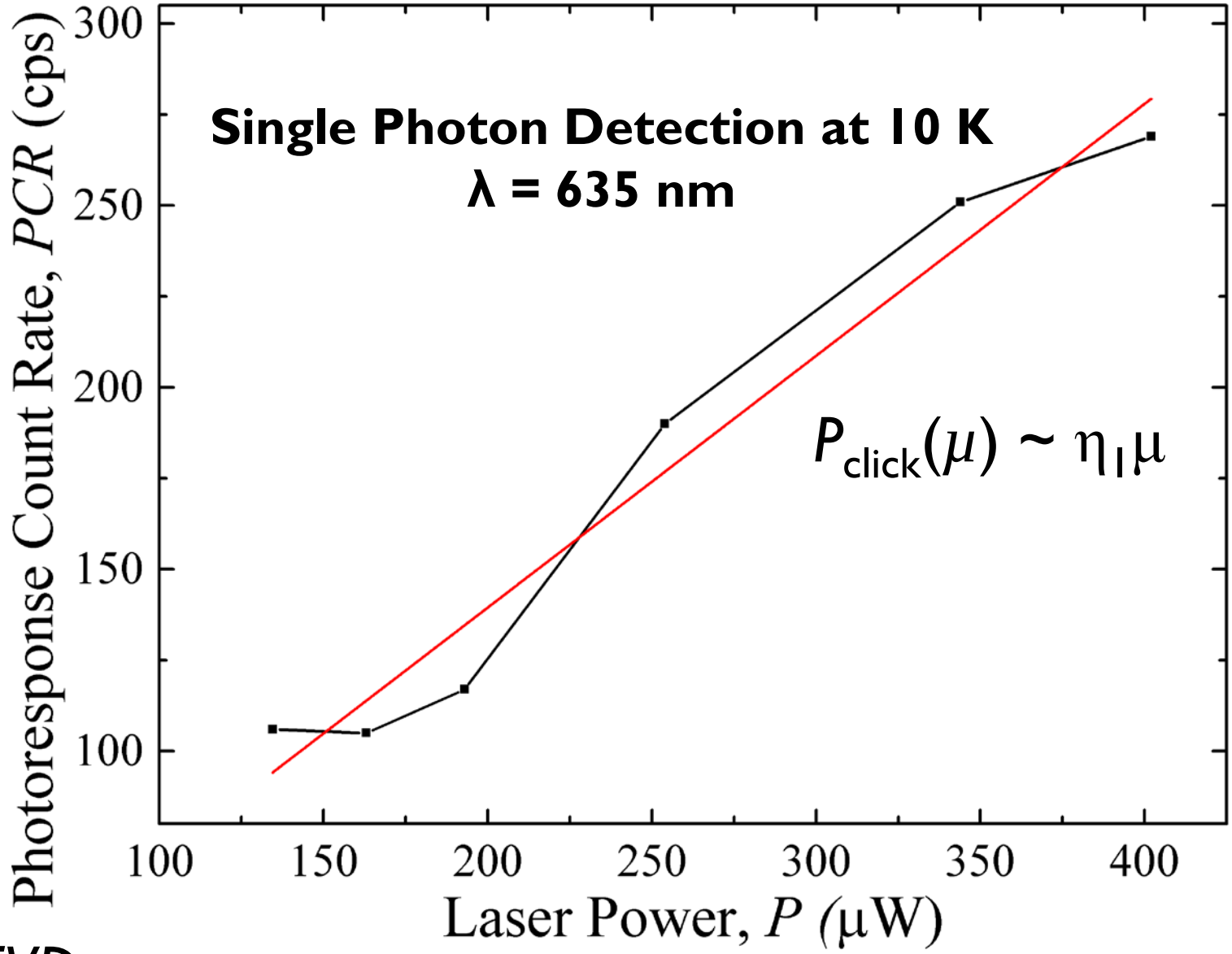
Optical pulse at 635 nm



Optical pulse at 635 nm

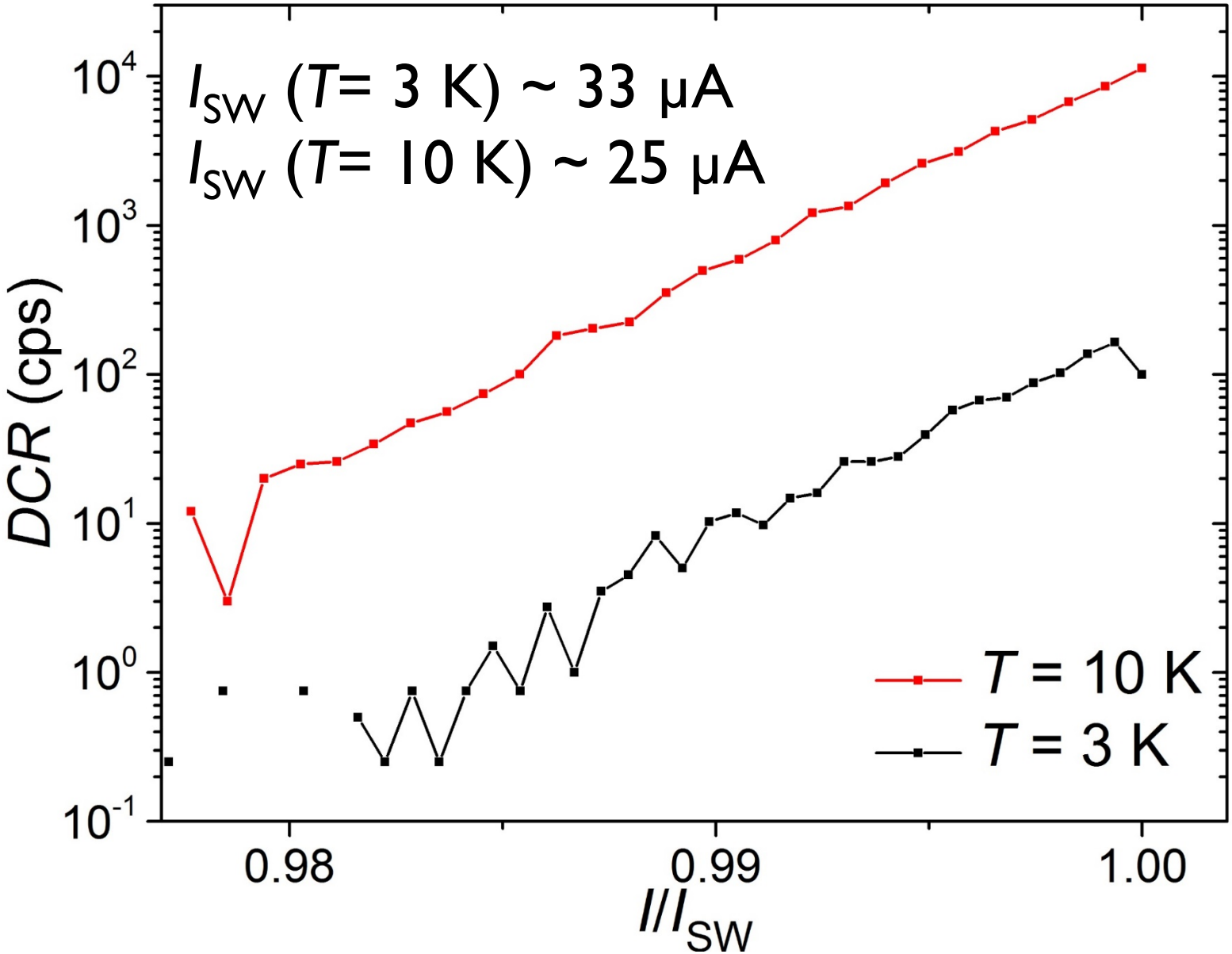


Single Photon Detection at 10 K



HPCVD

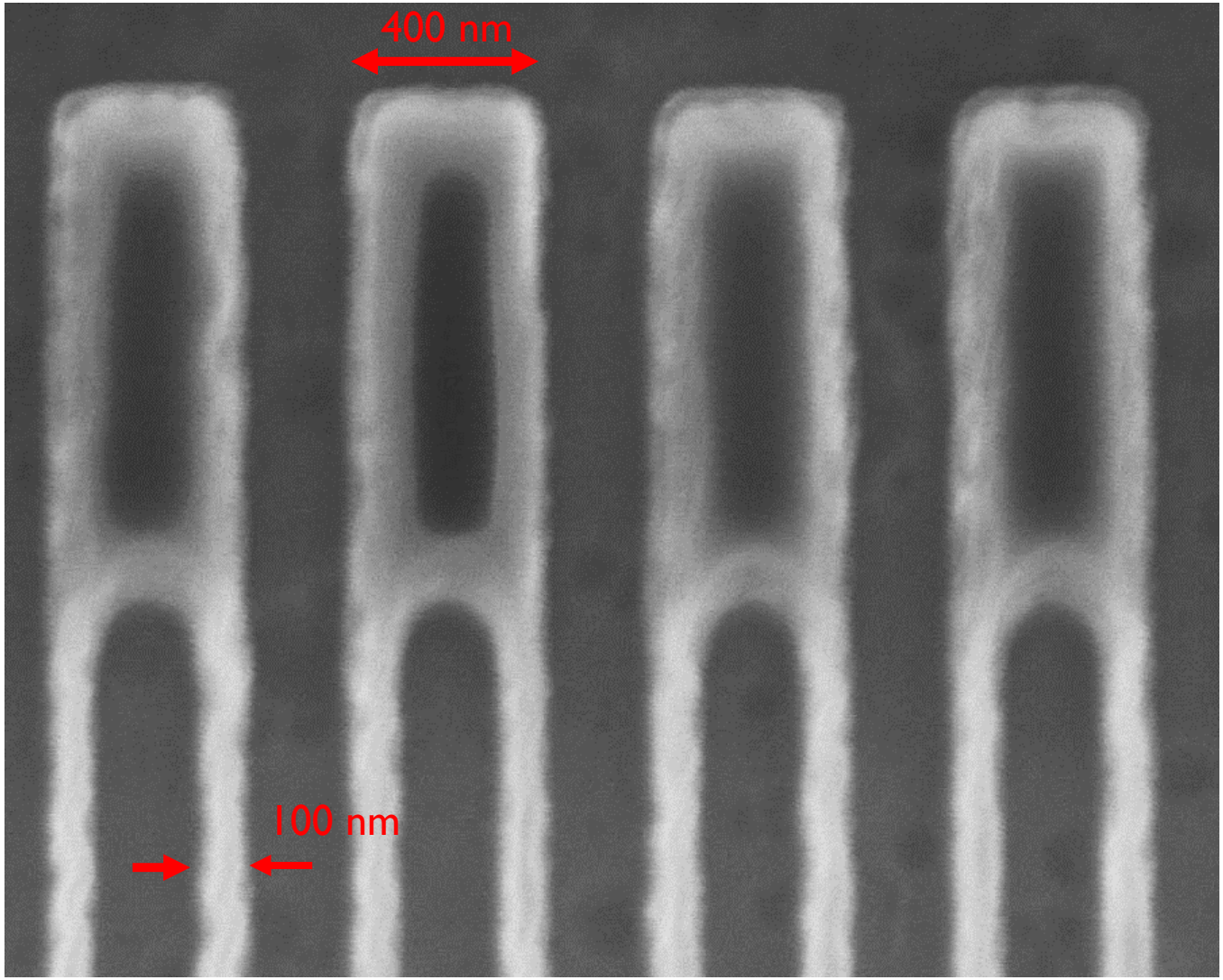
Dark count rate, *DCR*



Challenges of MgB_2 SNSPDs

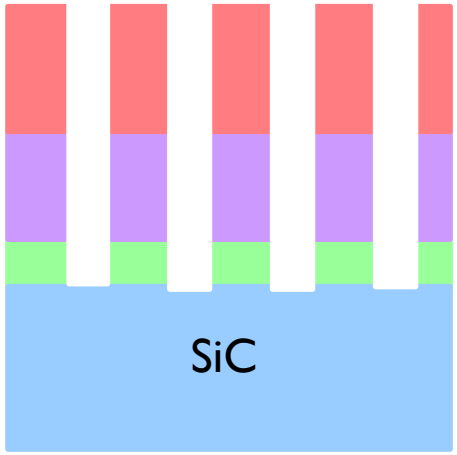
- Fabrication issues:
  i. MgB_2 highly reactive with oxygen
  ii. MgB_2 etch limited to argon ion milling

SEM after ion mill:100 nm meander

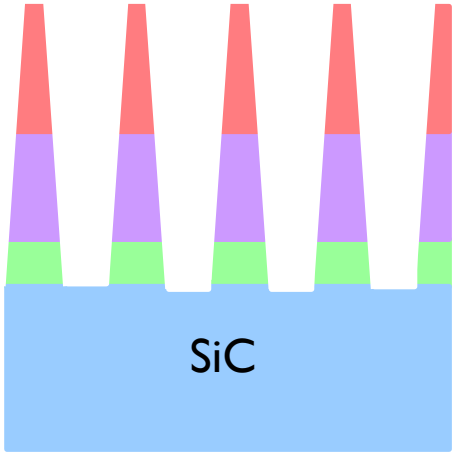


Low yield: Dry etch (Ar ion mill)

Ideal

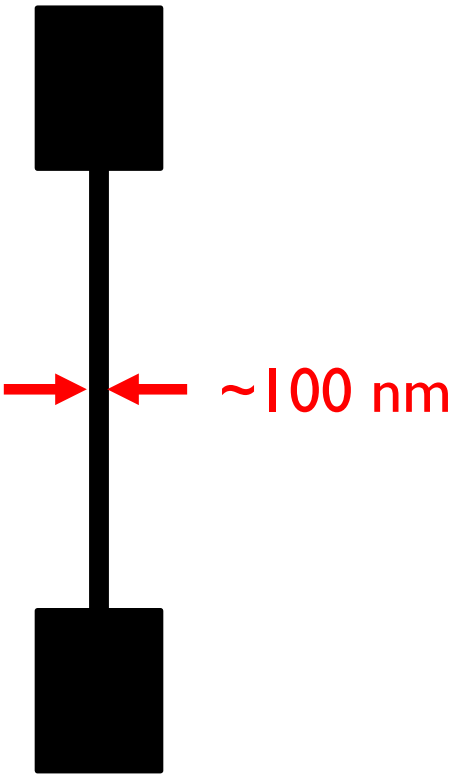


Reality

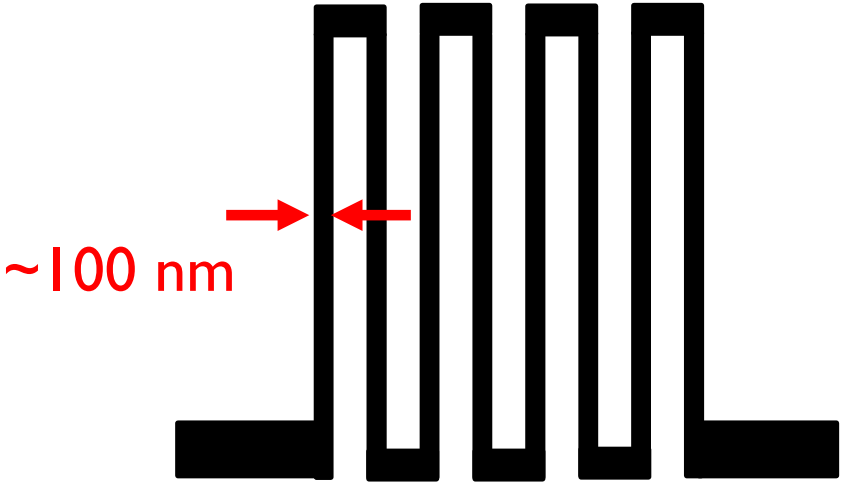


Etching: Bridges and Meanders

Bridges



Meander

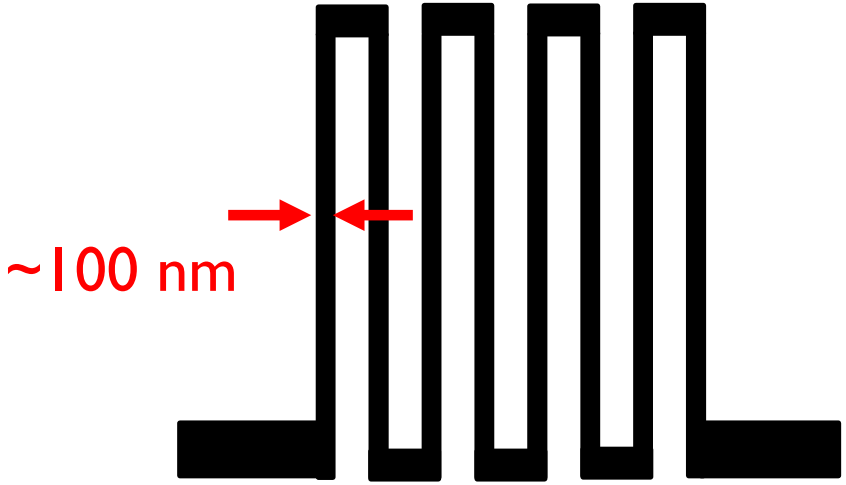


Etching: Bridges and Meanders

Bridges

Etched first

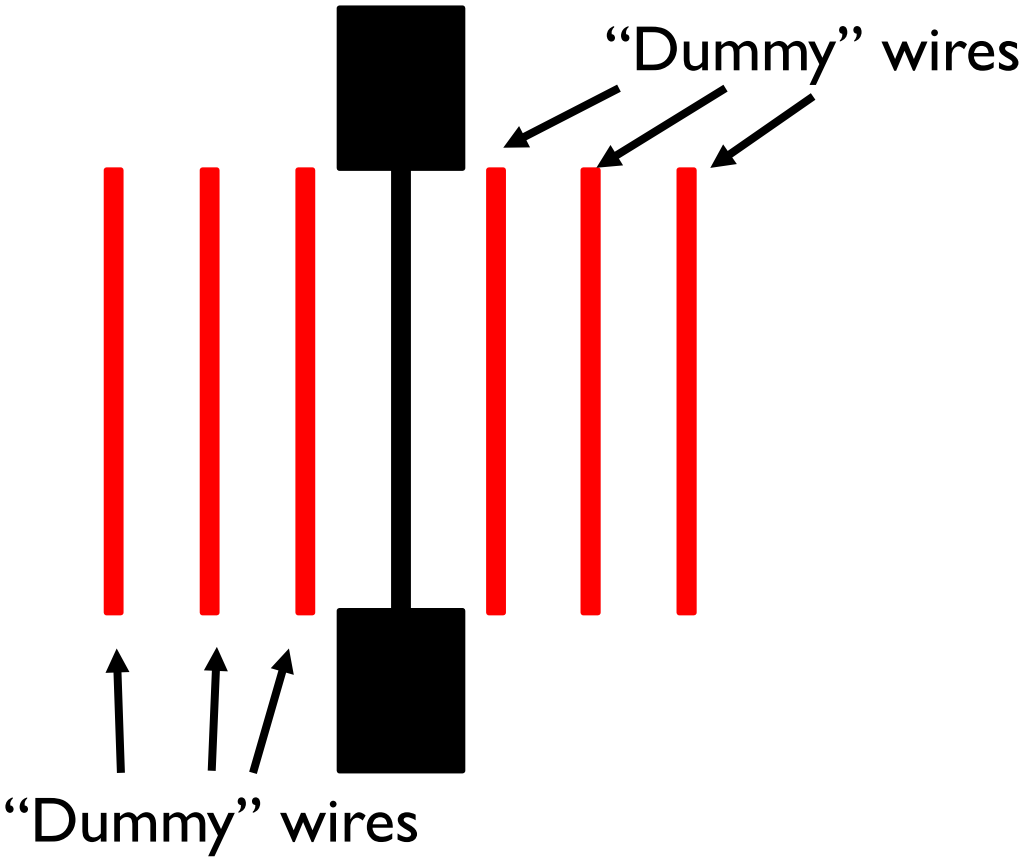
Meander



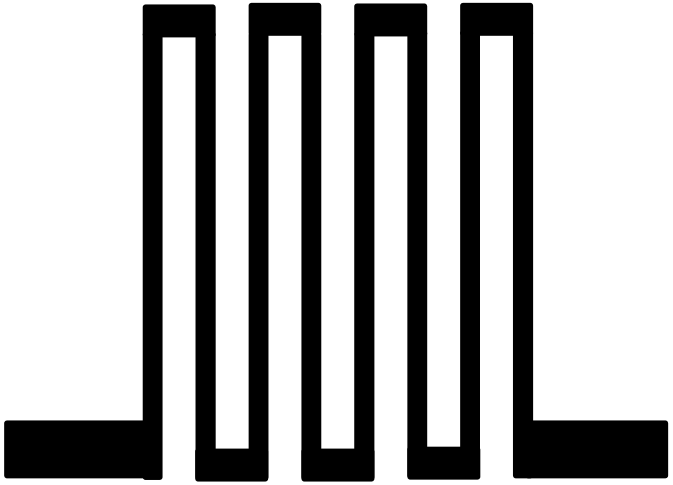
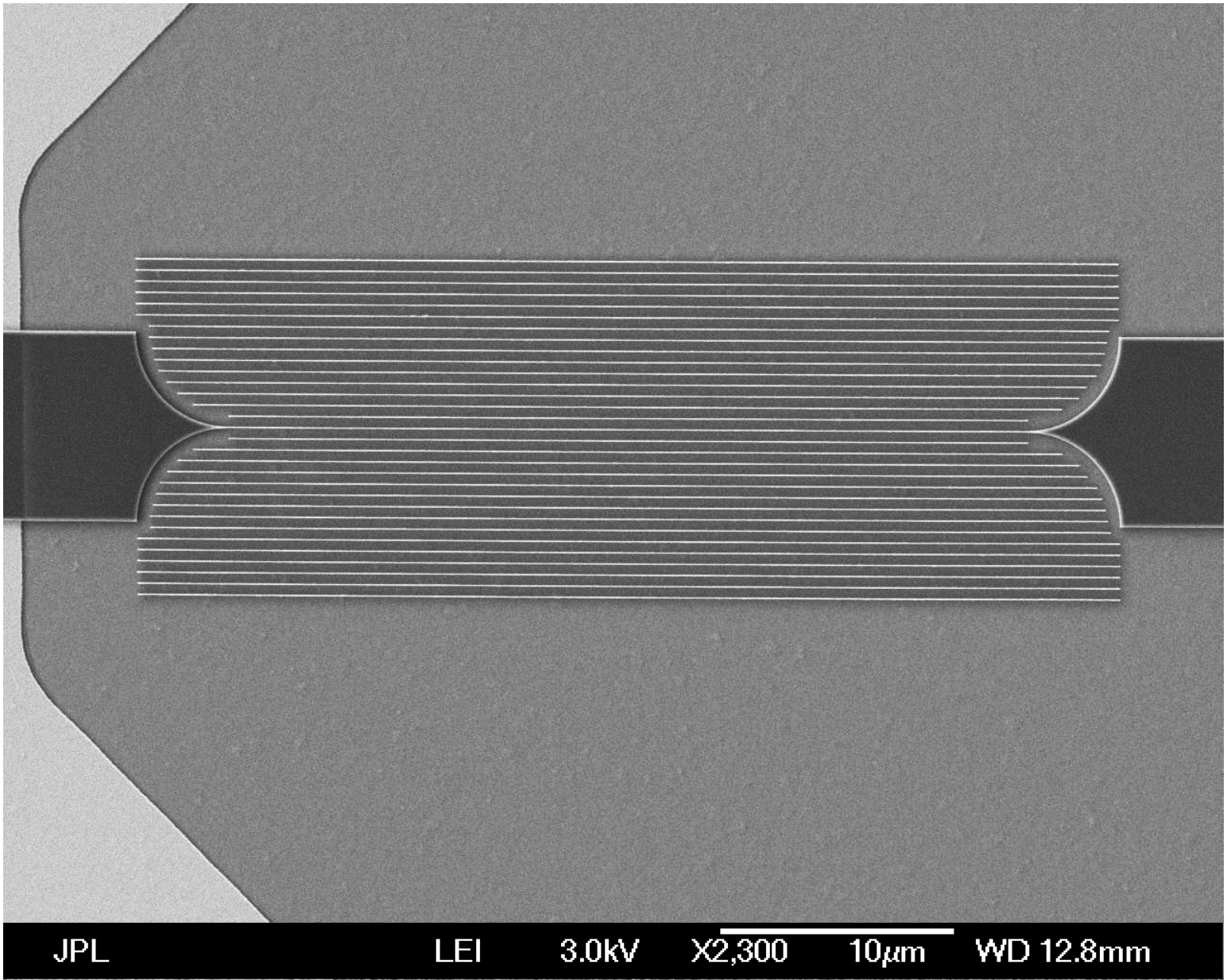
Survives etch

Etching: Bridges and Meanders

Bridges



Meander



Bridges with "dummy" wires