Superconducting Nanowire Single Photon Detectors Based on MgB_2

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[5]*National Institute of Advanced Industrial Science and Technology, JPN*
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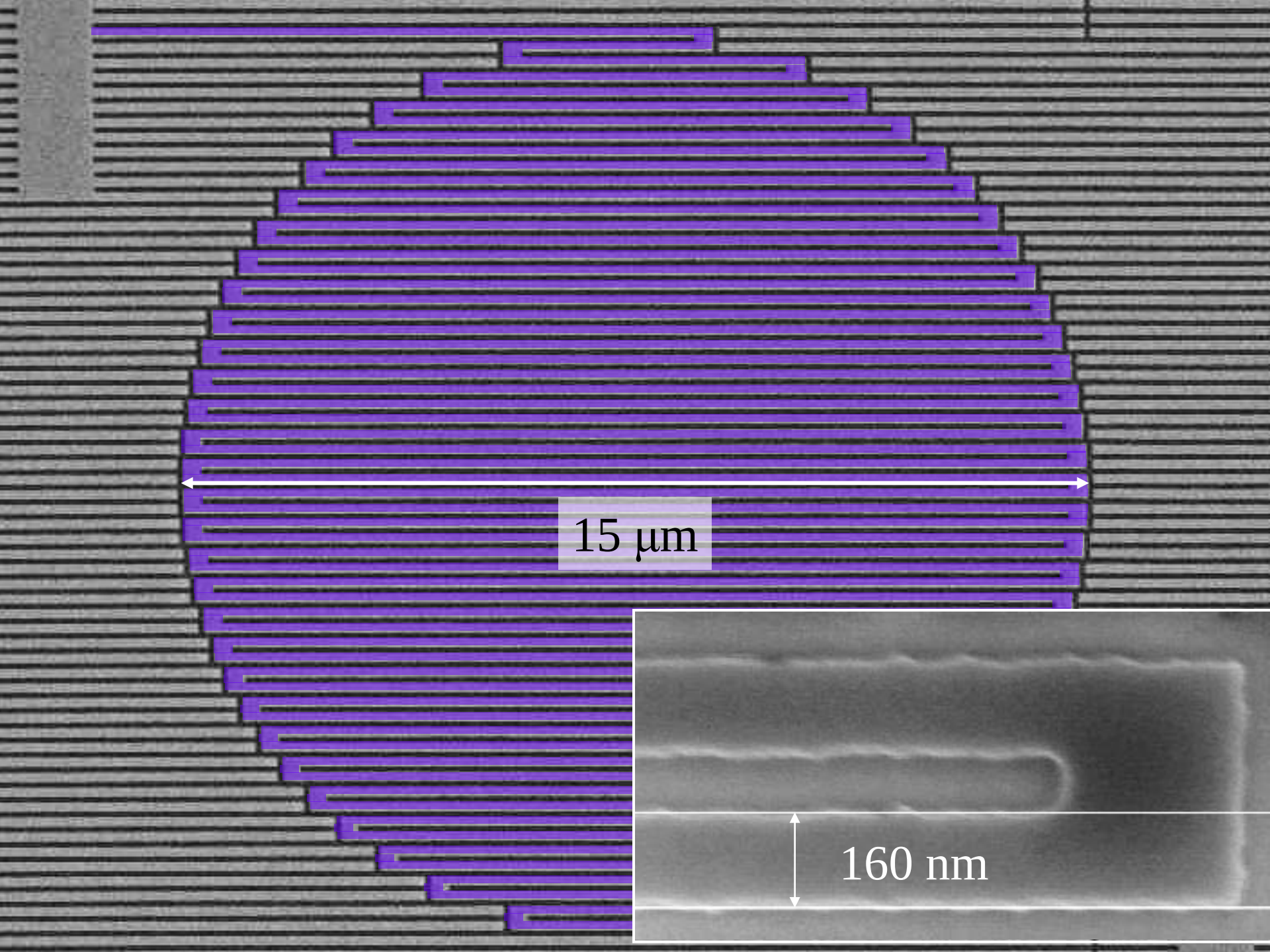
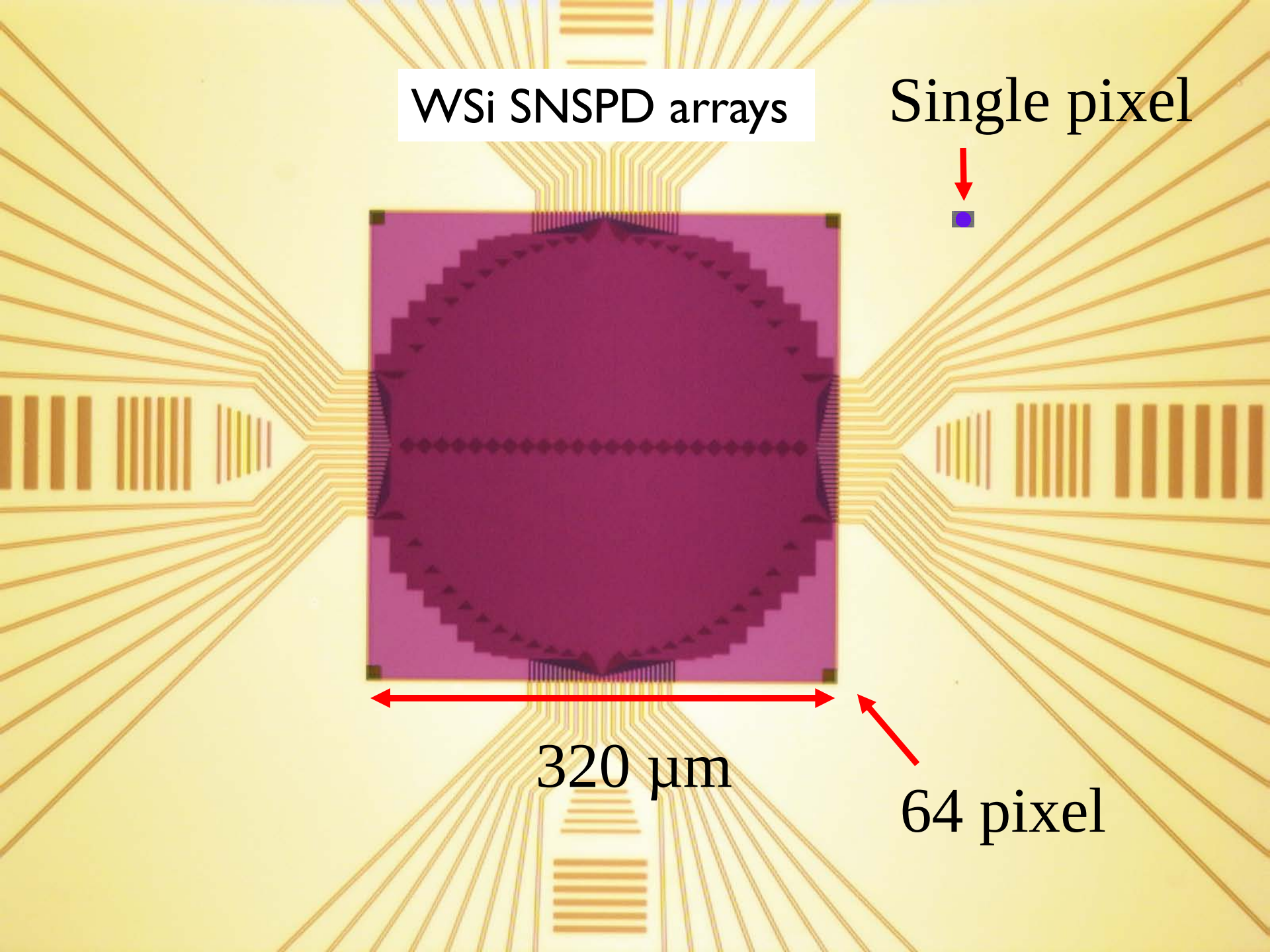
Tungsten Silicide (WSi) SNSPDs

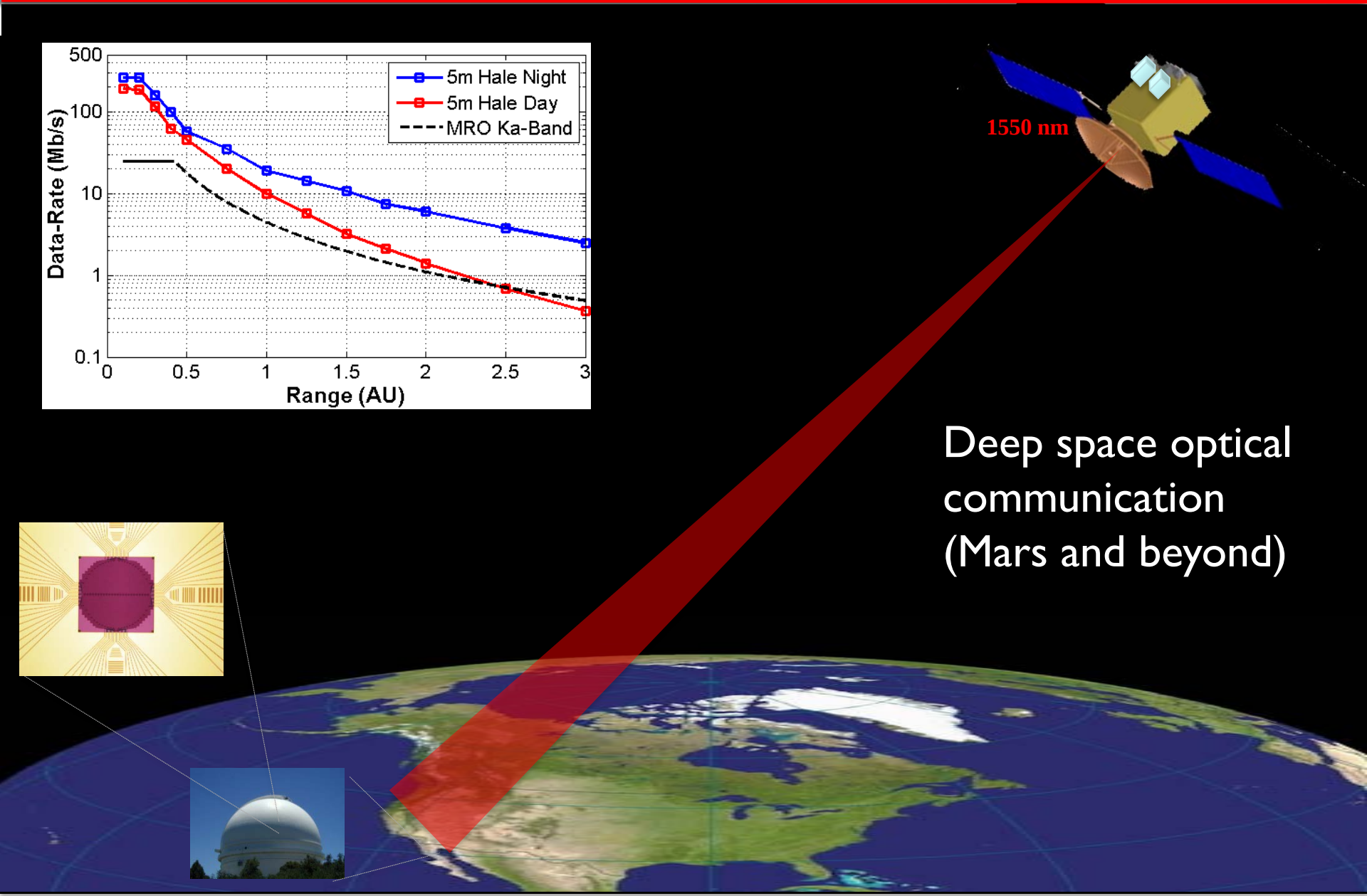
- High system detection efficiency (~ 90% at λ = 1550 nm)
- Low jitter (50 - 150 ps FWHM)
- Low intrinsic dark count rate (~ 1 cps)
- Low reset time (~ 25 ns)
- High maximum count rate (~20 Mcps)
- UV to mid-IR sensitivity

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


15 μm
160 nm


WSi SNSPD arrays
Single pixel
320 µm
64 pixel

Optical communication demonstration



Deep space optical communication (Mars and beyond)

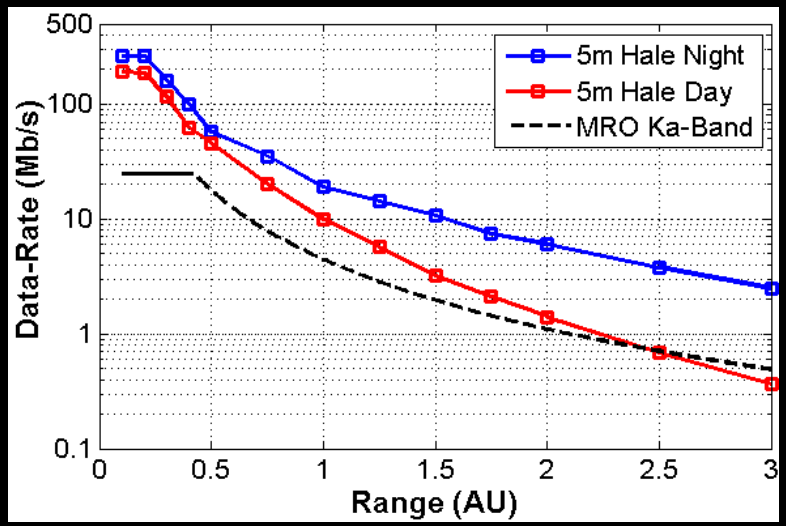
Tungsten Silicide (WSi) SNSPDs

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

↓

Complex cryogenics

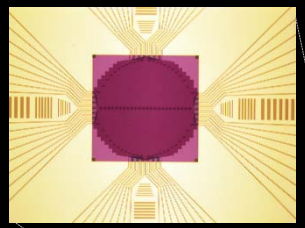
High T_C SNSPDs: Flight Applications



High T_C SNSPDs

1550 nm

Symmetric deep space optical communication (Mars and beyond)



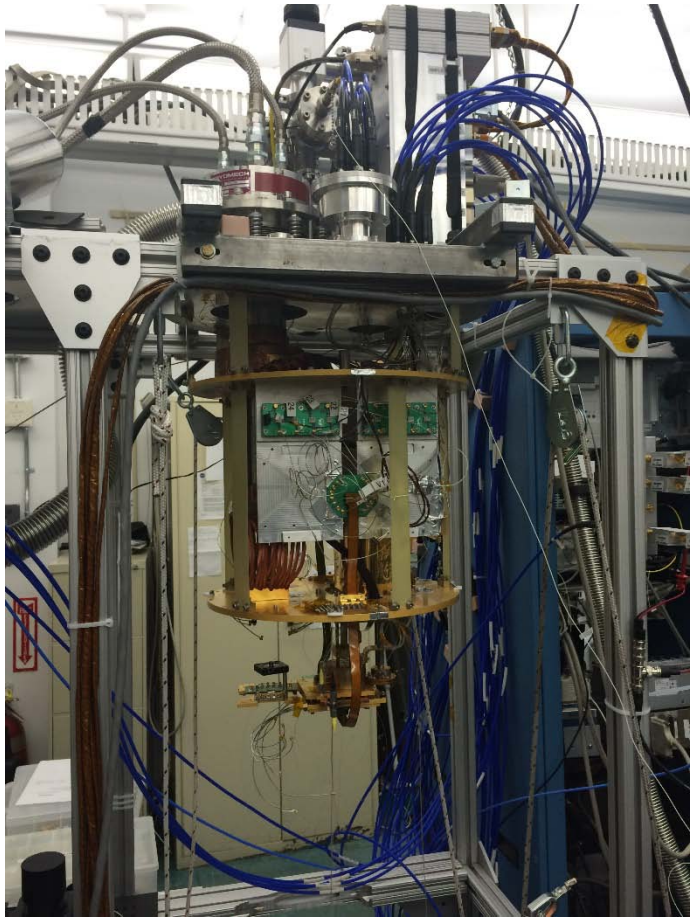
High T_C SNSPDs: Ground

- 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

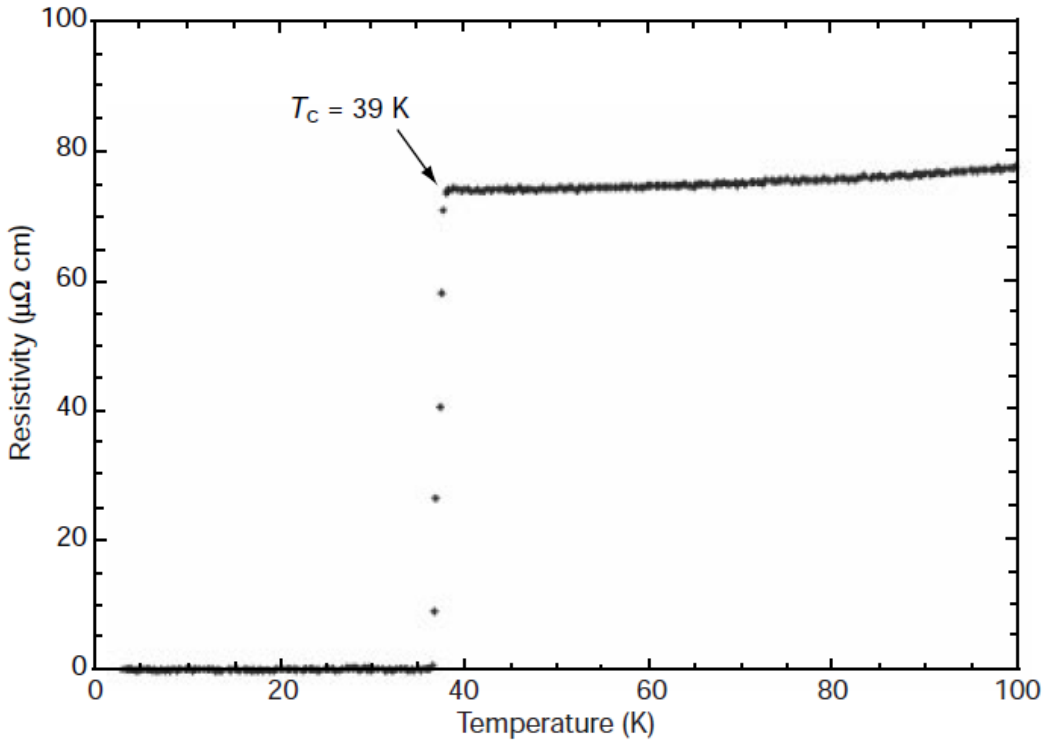
Stirling/Pulse Tube (Raytheon LT-RSP2)

~ 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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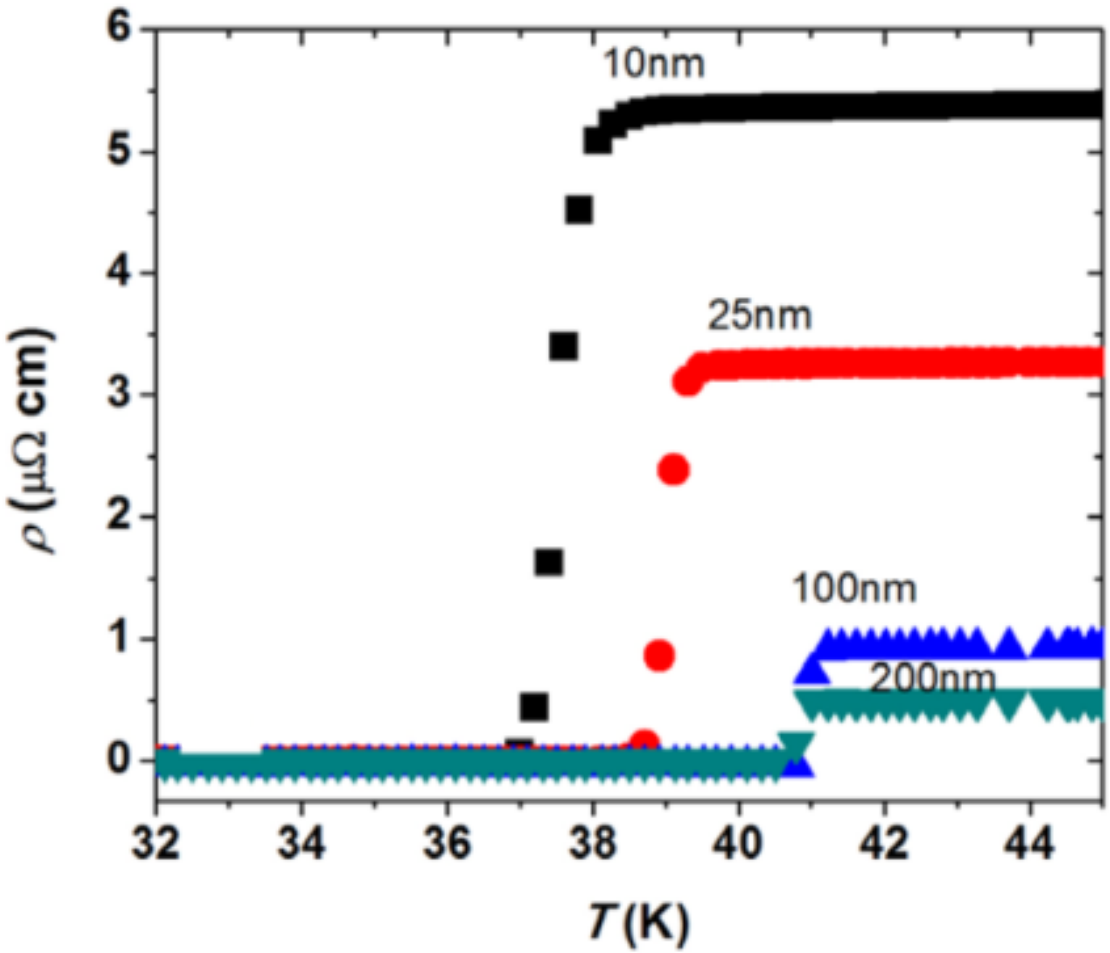
High Quality MgB_2 Thin Films

Hybrid Physical-Chemical Deposition (HPCVD)

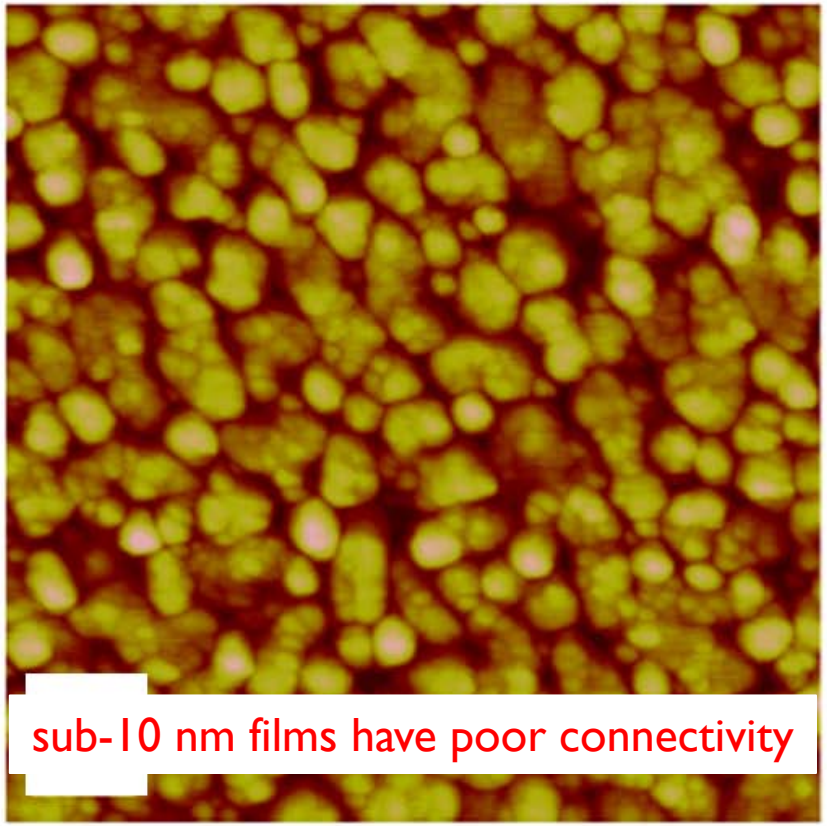


C. Zhuang *et al.*, Supercond. Sci. Technol. **23** (5), 055004 (2010)

Temple University

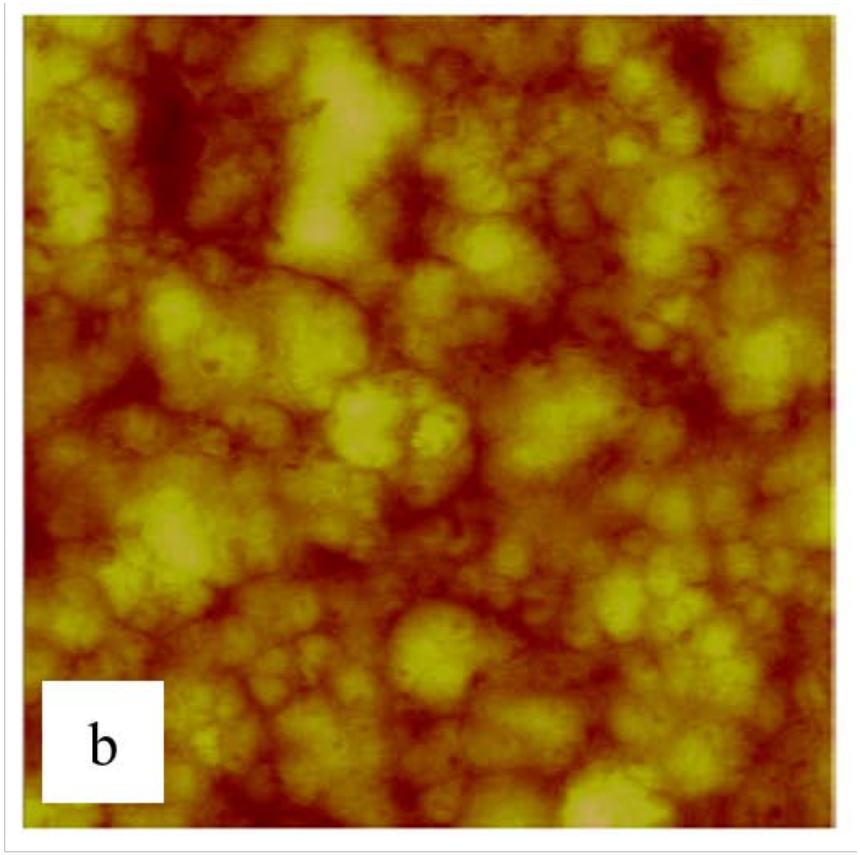
Problem with sub-10 nm films

d = 7.5 nm



1 μm

d = 25 nm

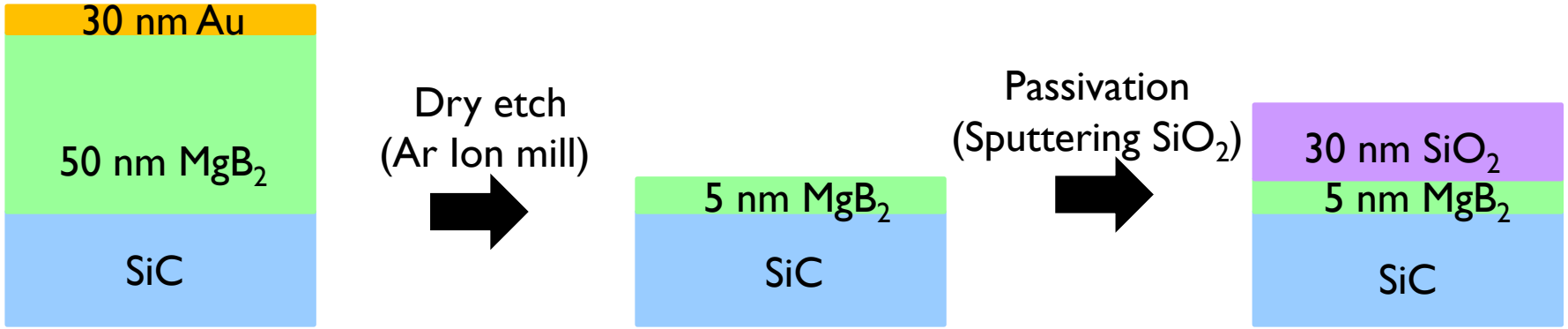


1 μm

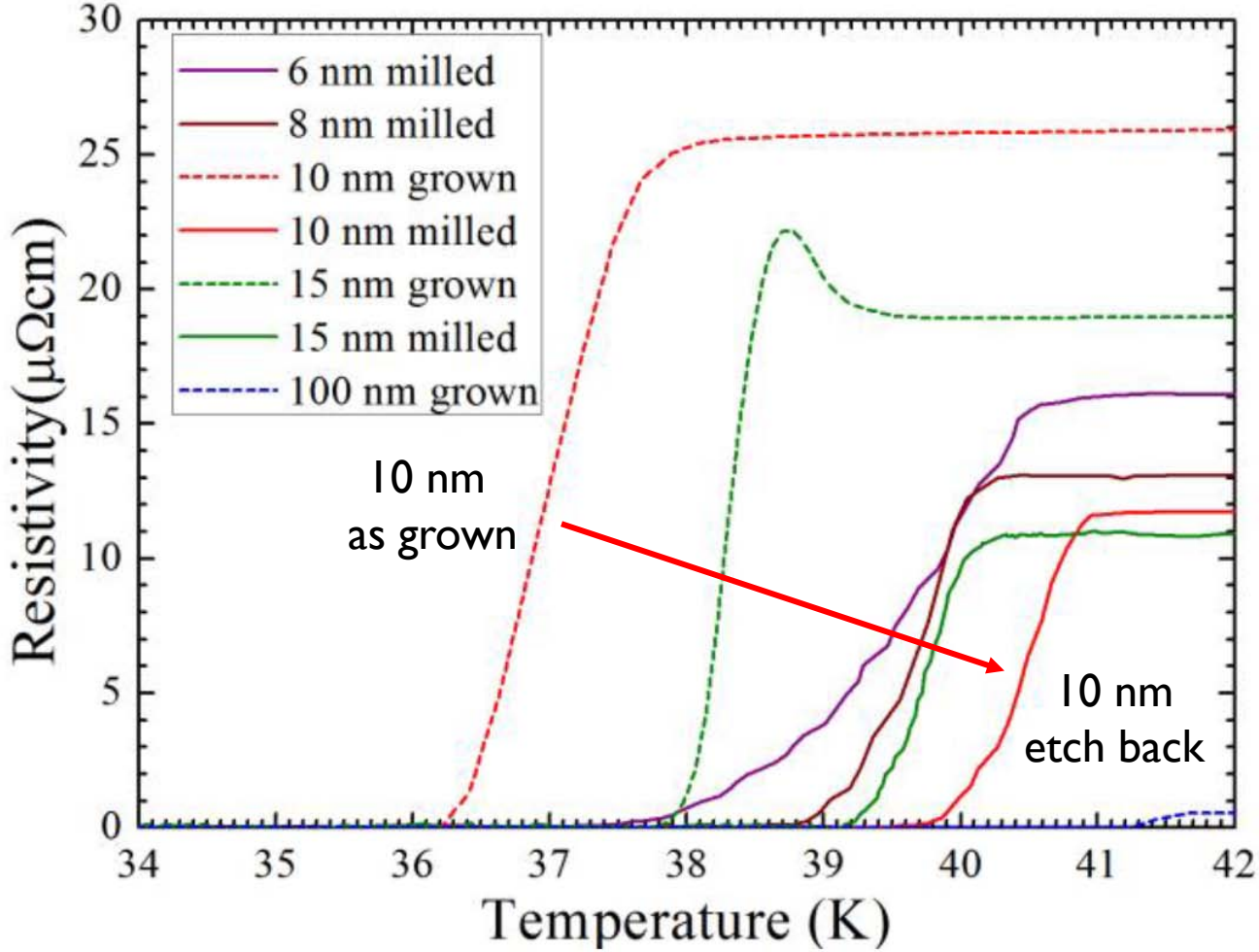
C. Zhuang *et al.*, Supercond. Sci. Technol. **23** (5), 055004 (2010)

Thin Film Fabrication Process

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

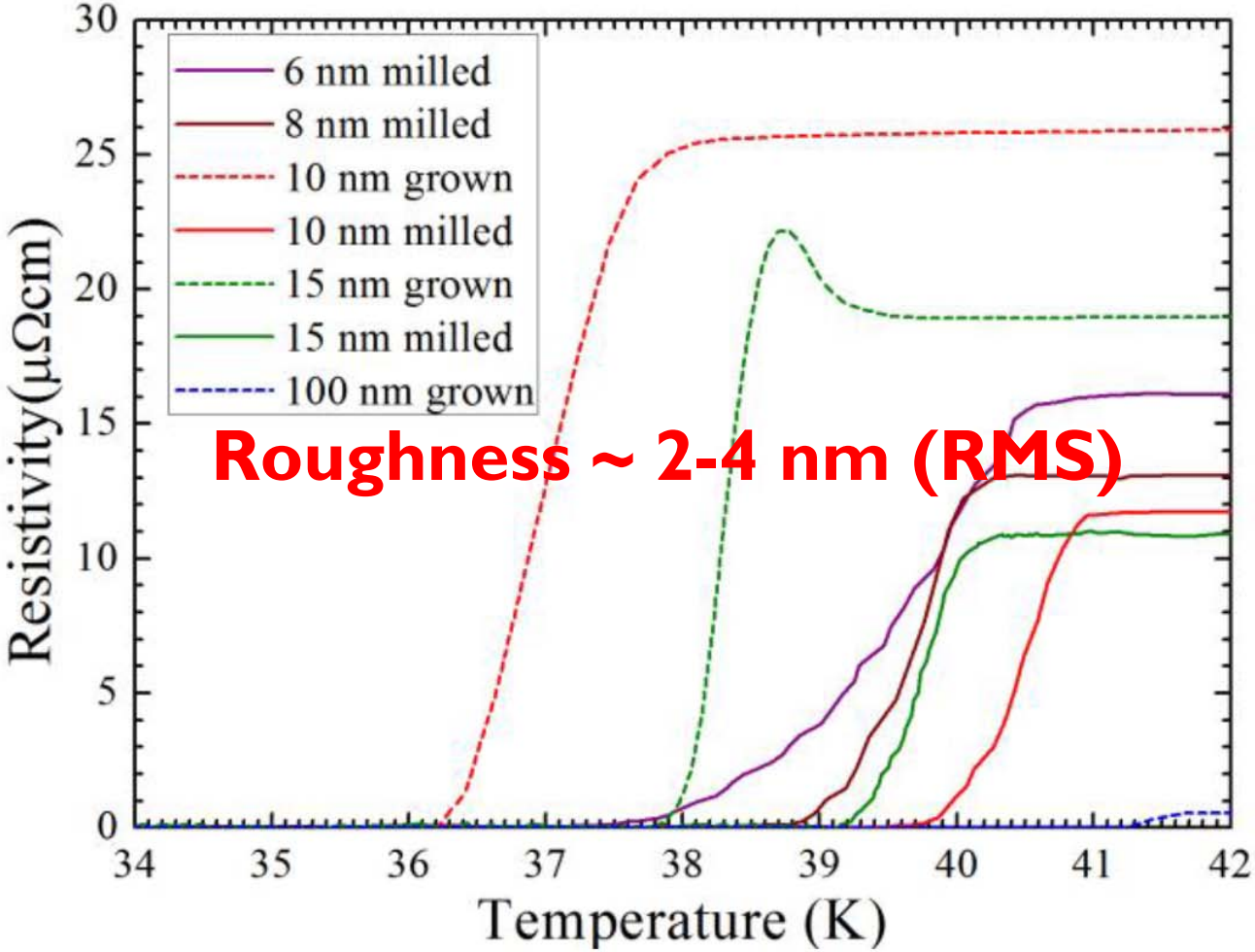


Etch back results



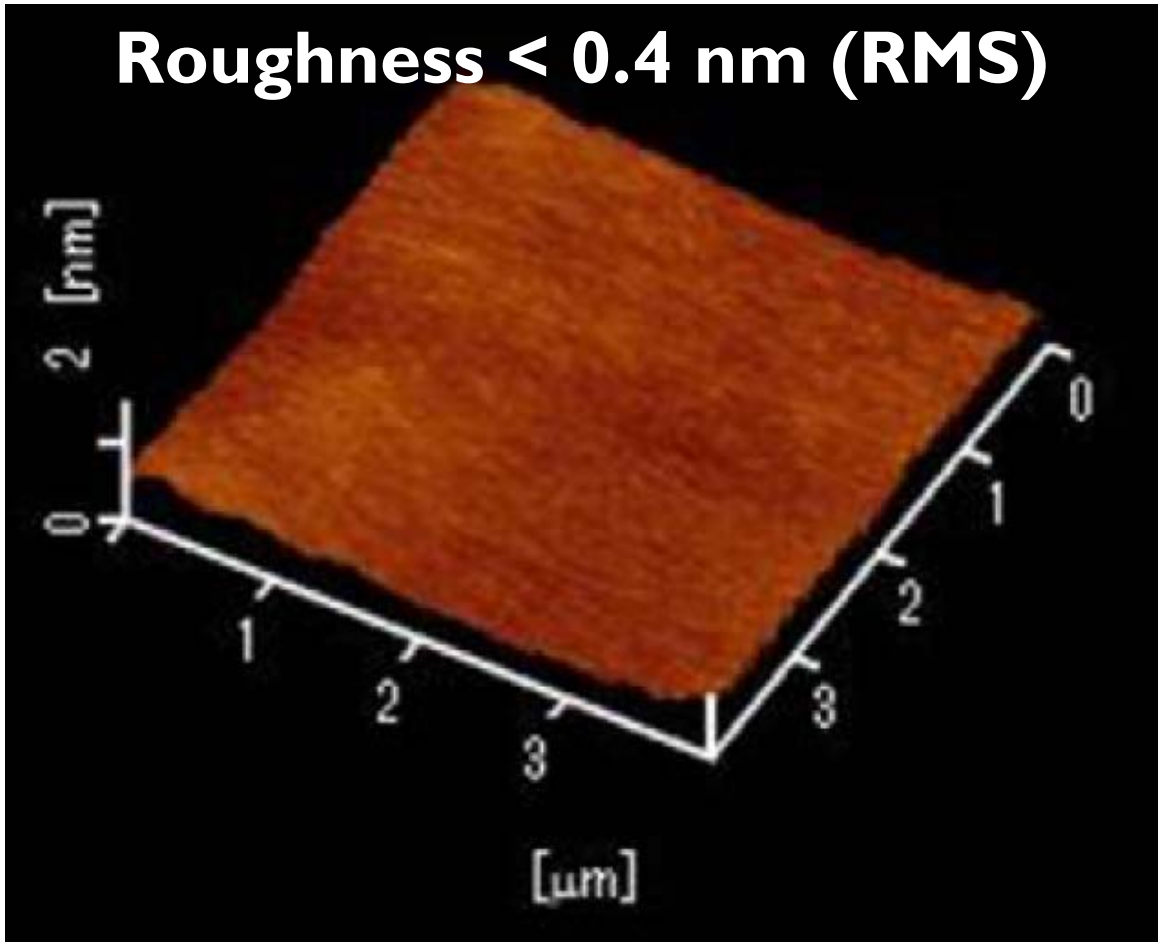
M.A. Wolak et al., IEEE Trans. Appl. Supercond. **25,** 3 7500905 (2015)

Etch back results



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

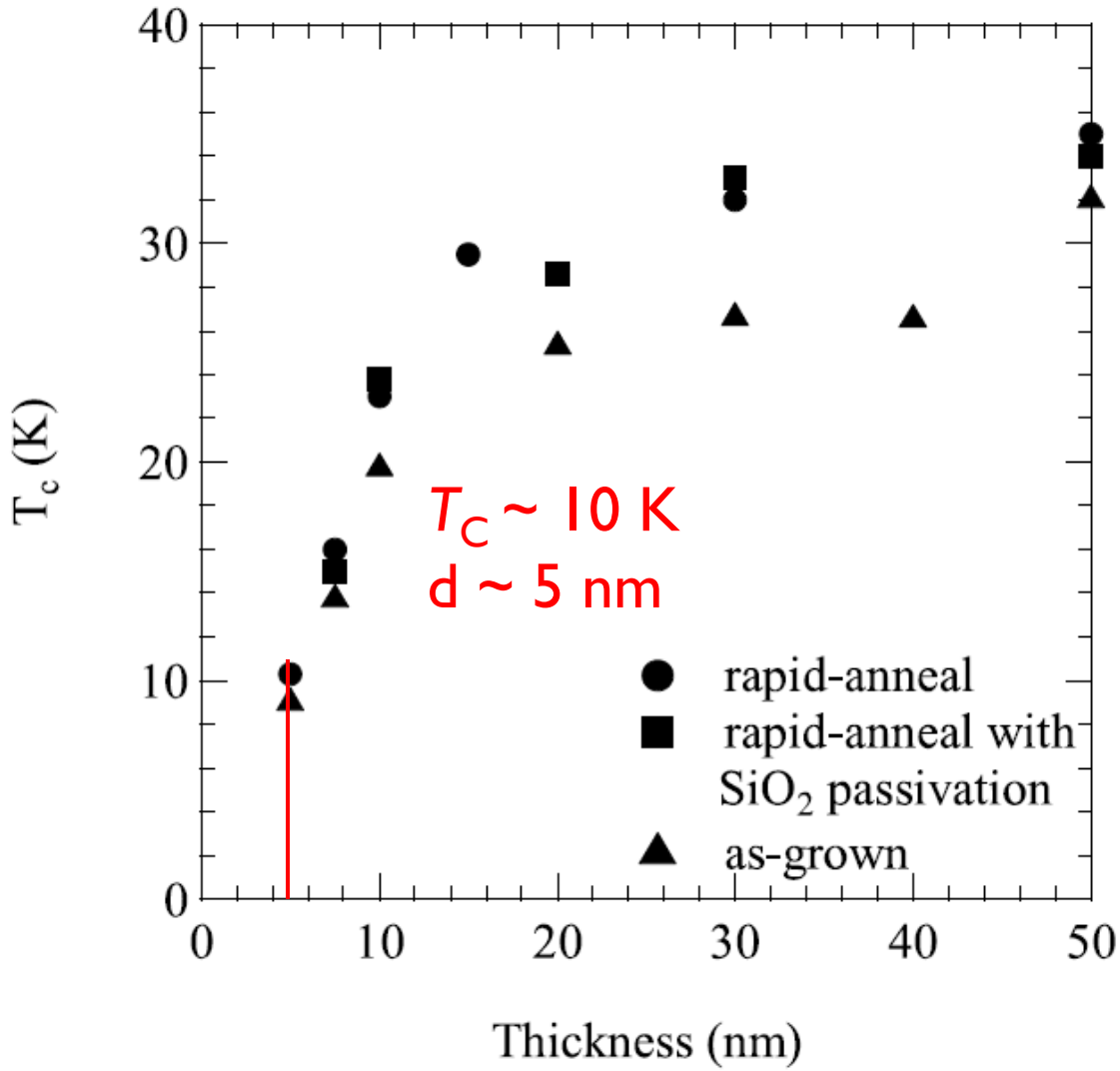
Molecular Beam Epitaxy films



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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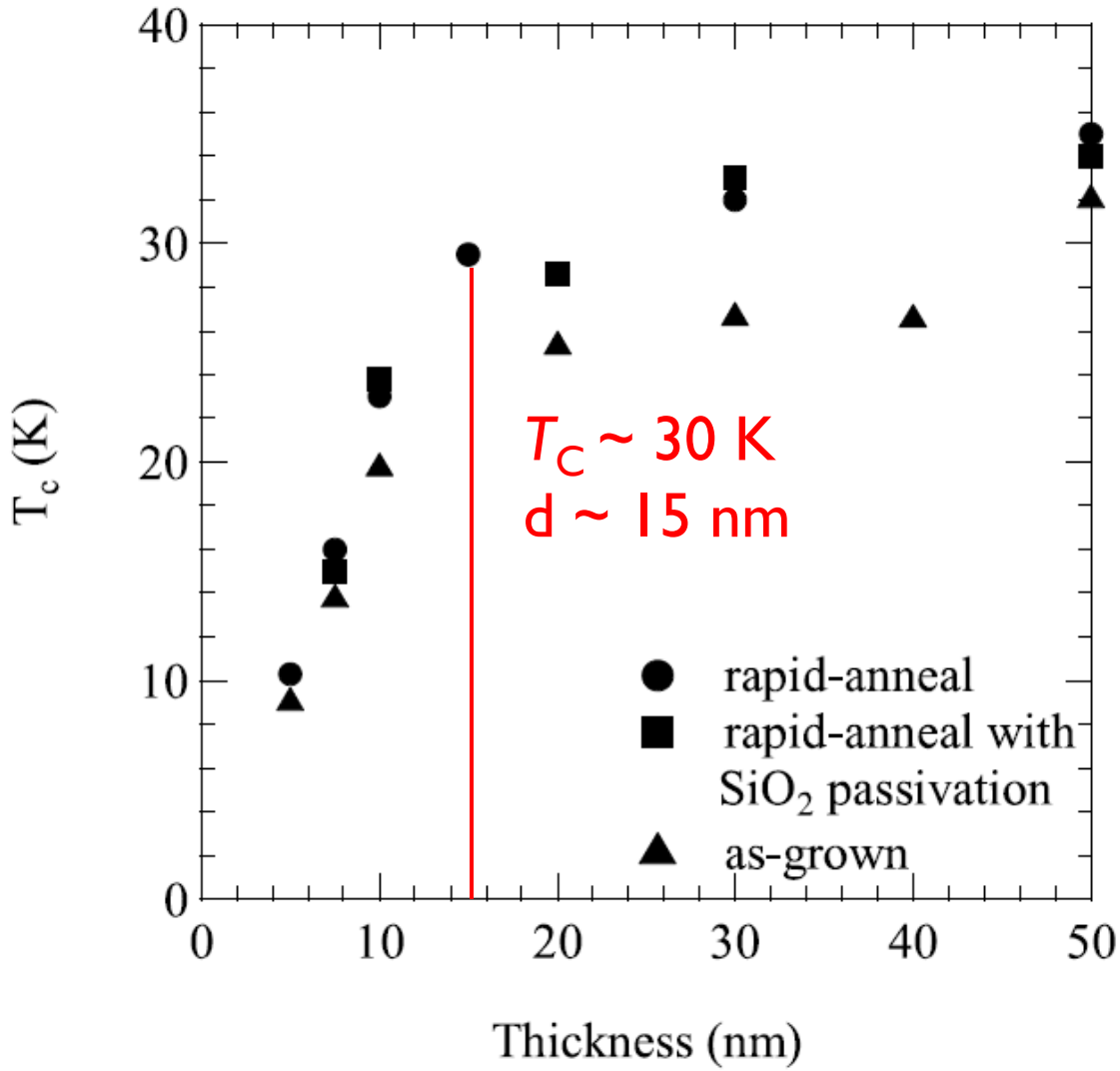
Molecular Beam Epitaxy (MBE) films



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

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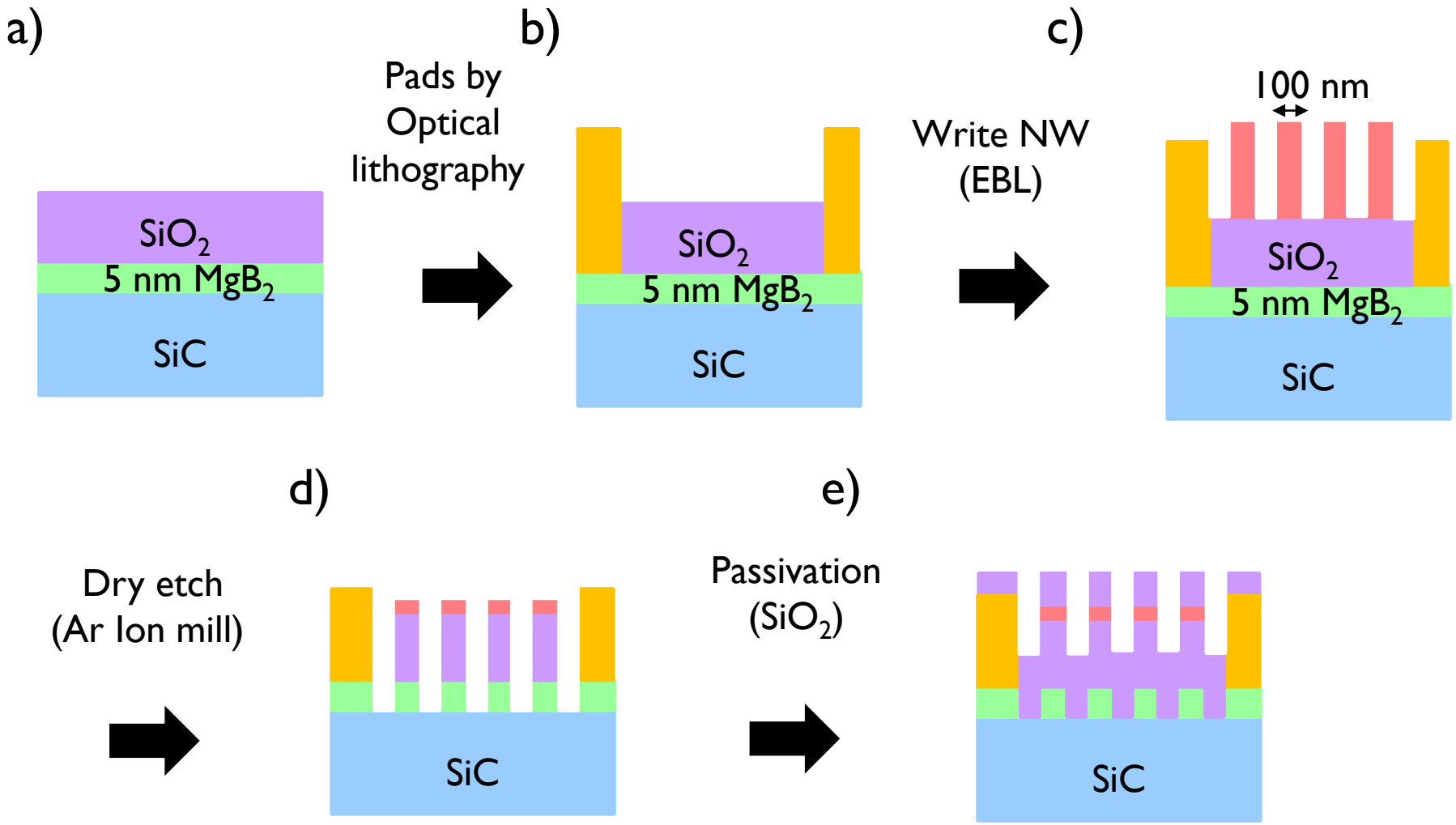
Film comparison

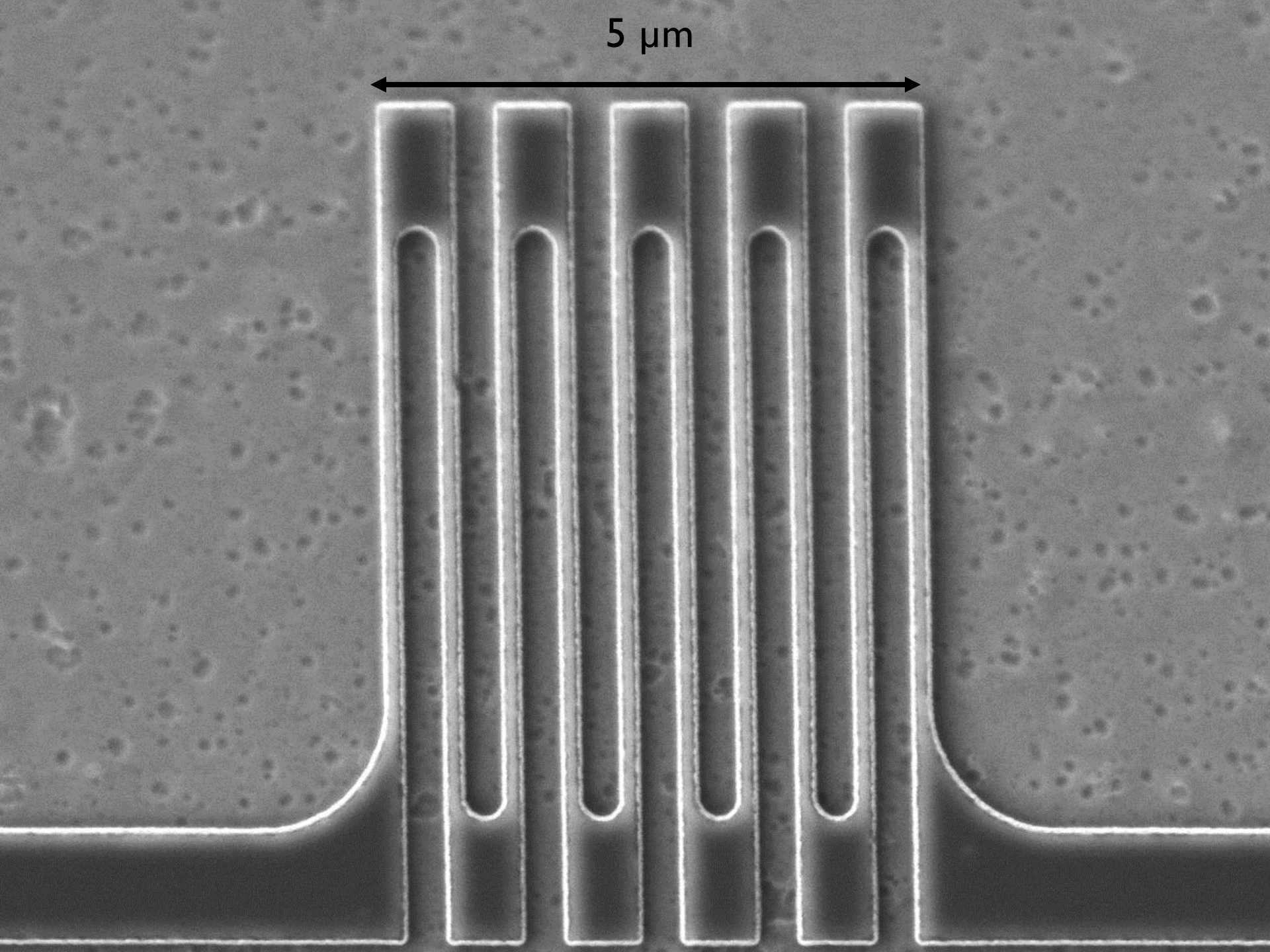
	Roughness (RMS)	T_C	Thickness
Ideal	< 1nm	40 K	5 nm
MBE	<0.35 nm	10 K	5 nm
HPCVD	2-4 nm	39 K	6 nm

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




5 μm

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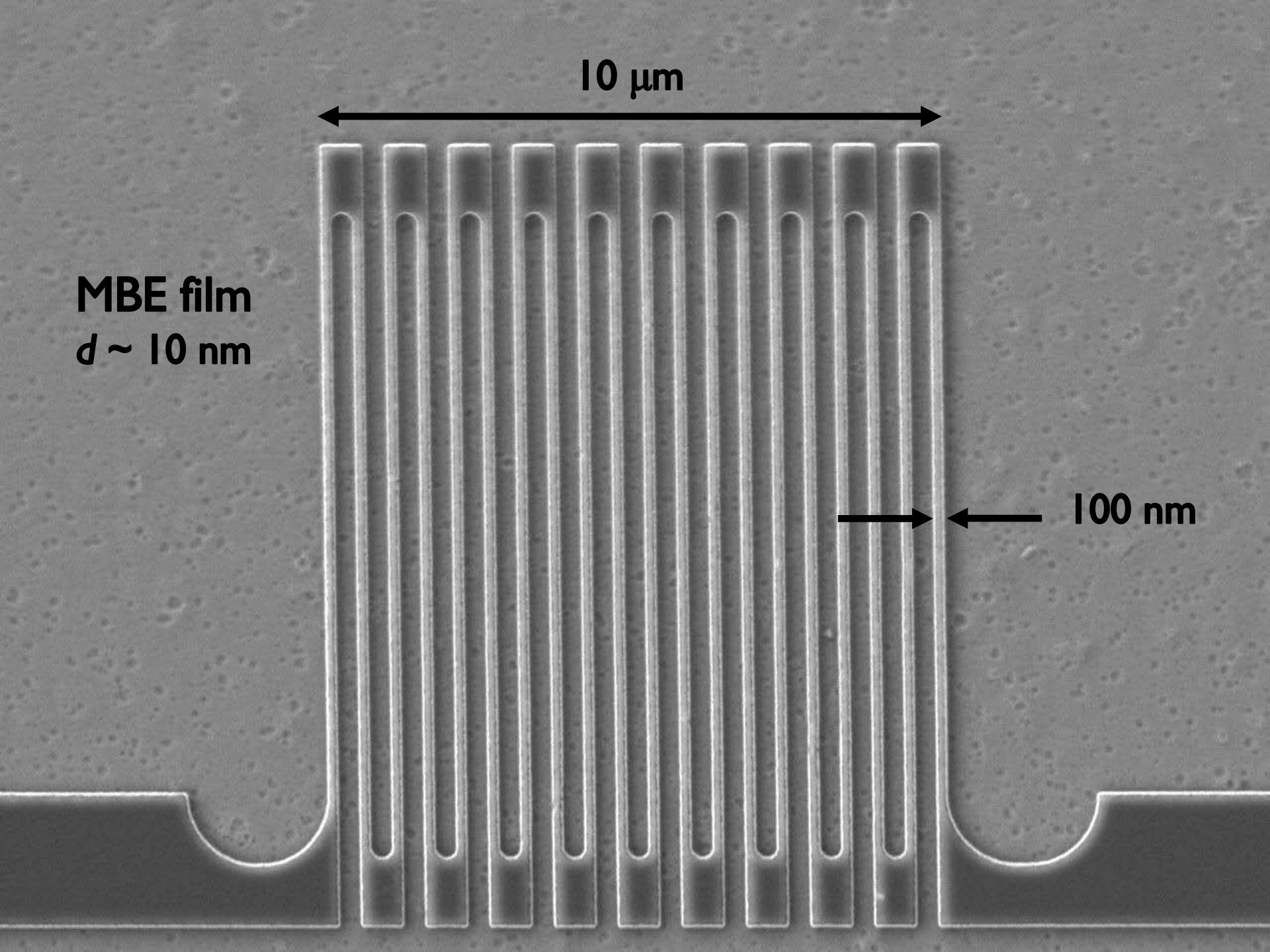
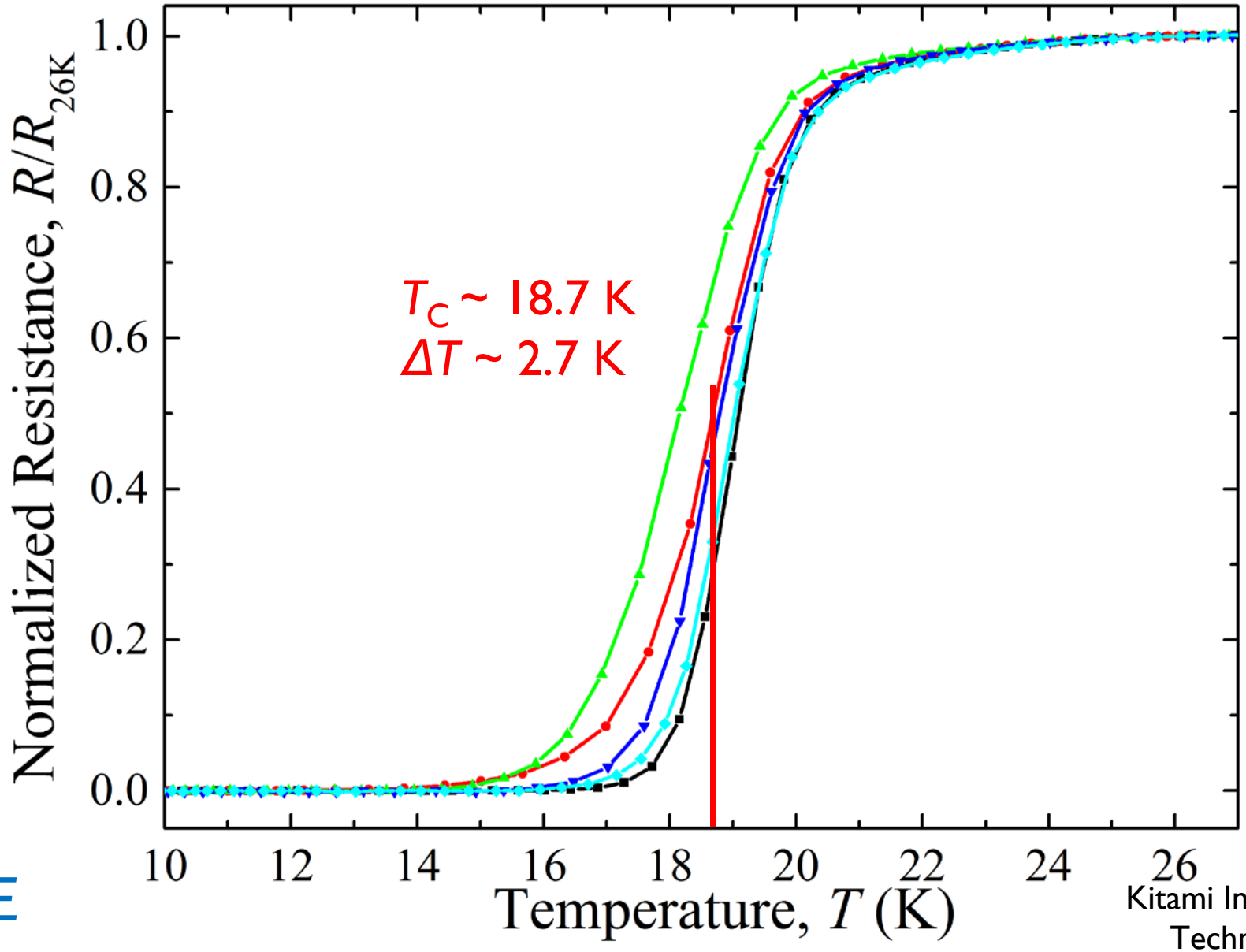

10 μm
MBE film
d ~ 10 nm
100 nm

Transition temperature, T_C



MBE

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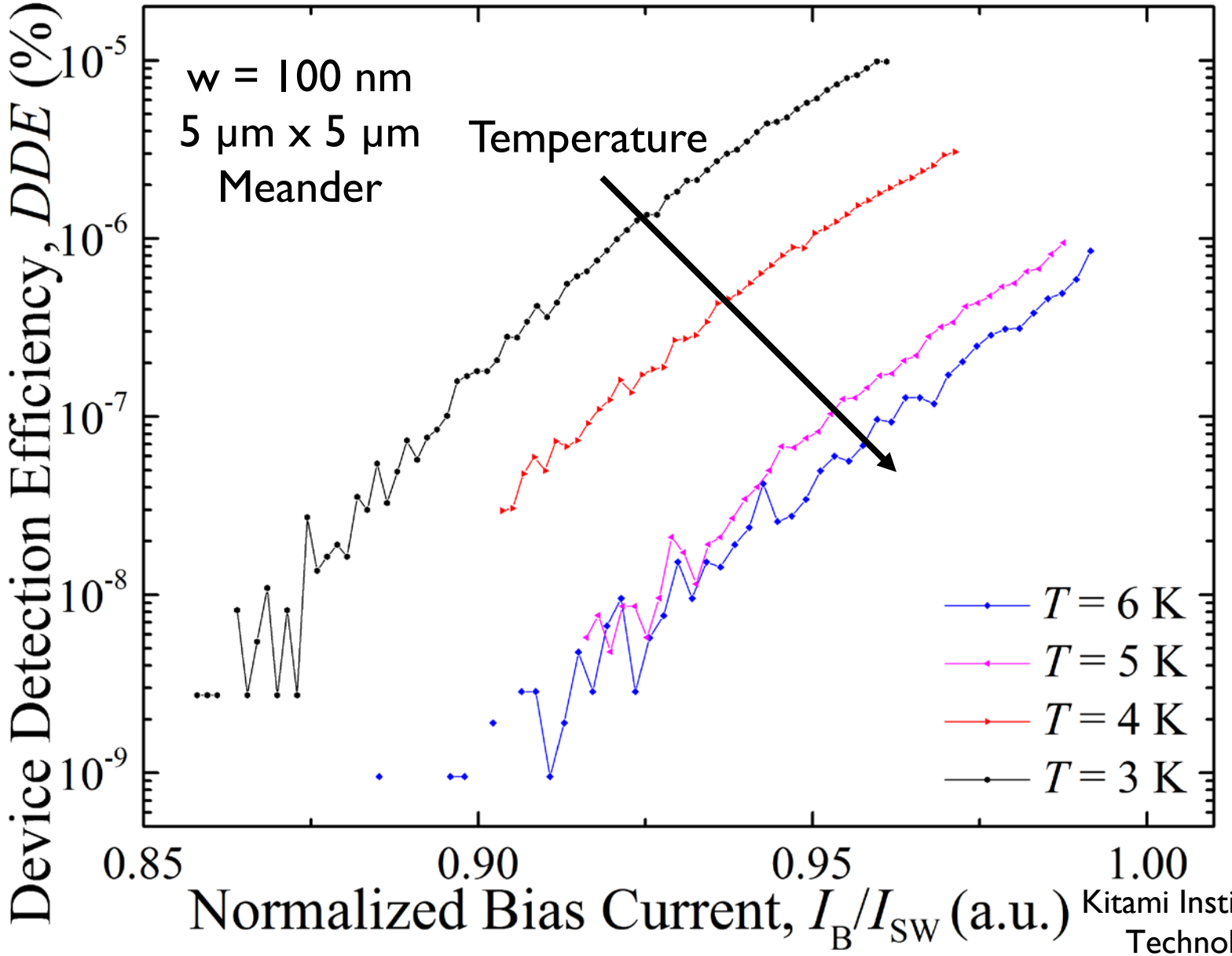
Device detection efficiency at 1550 nm



MBE

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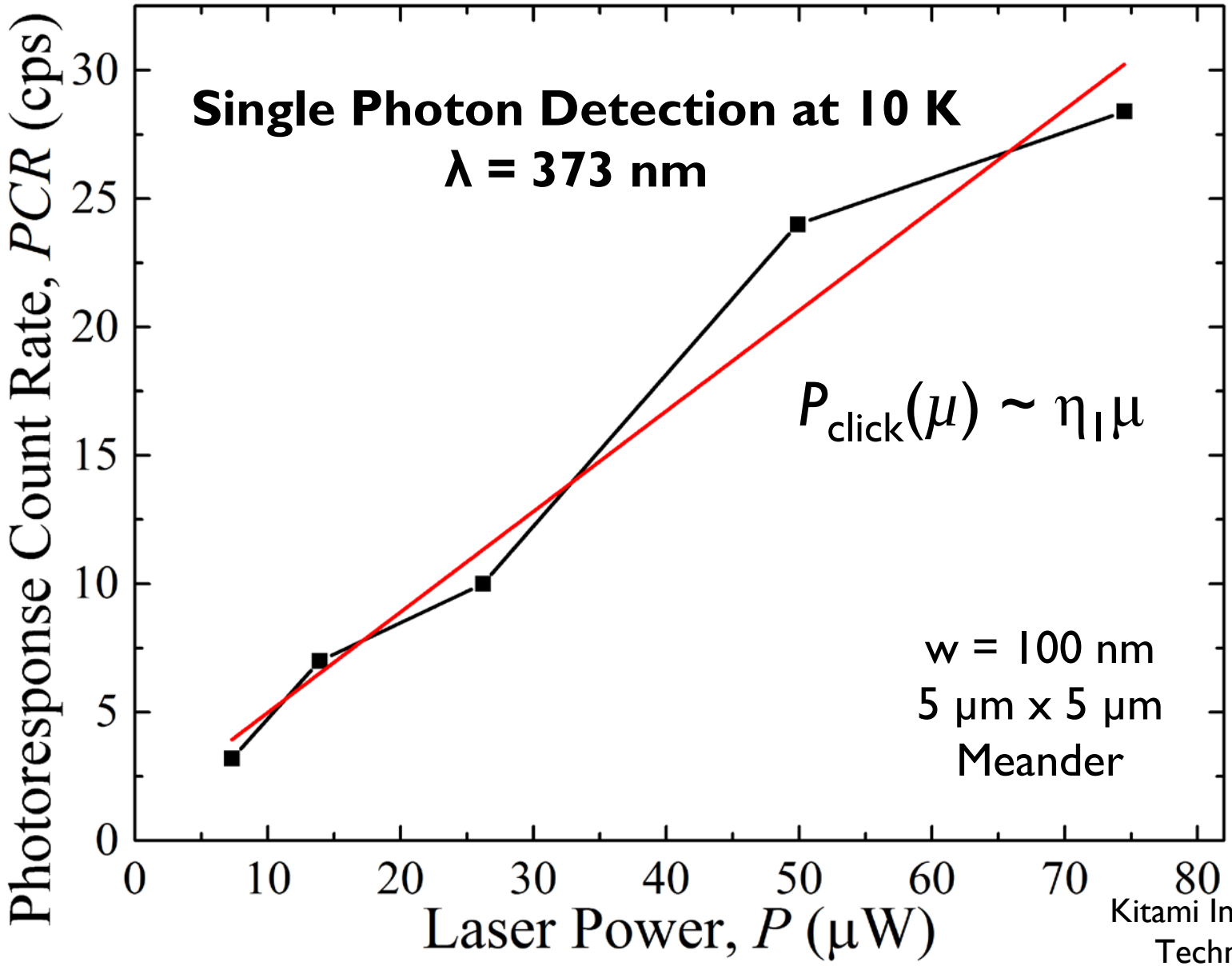
Single photon sensitive at T = 10 K



MBE

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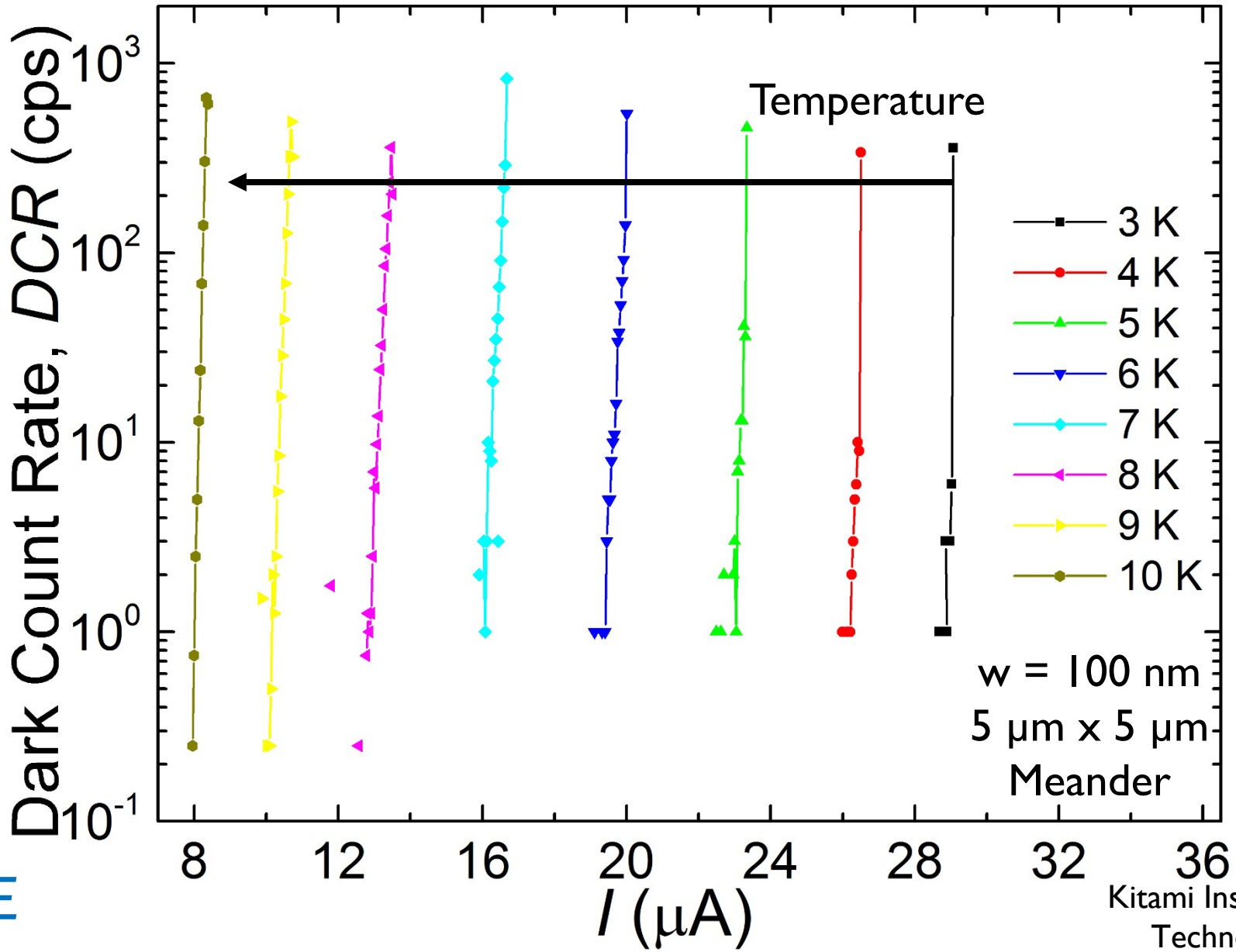
Dark count rate, *DCR*



MBE

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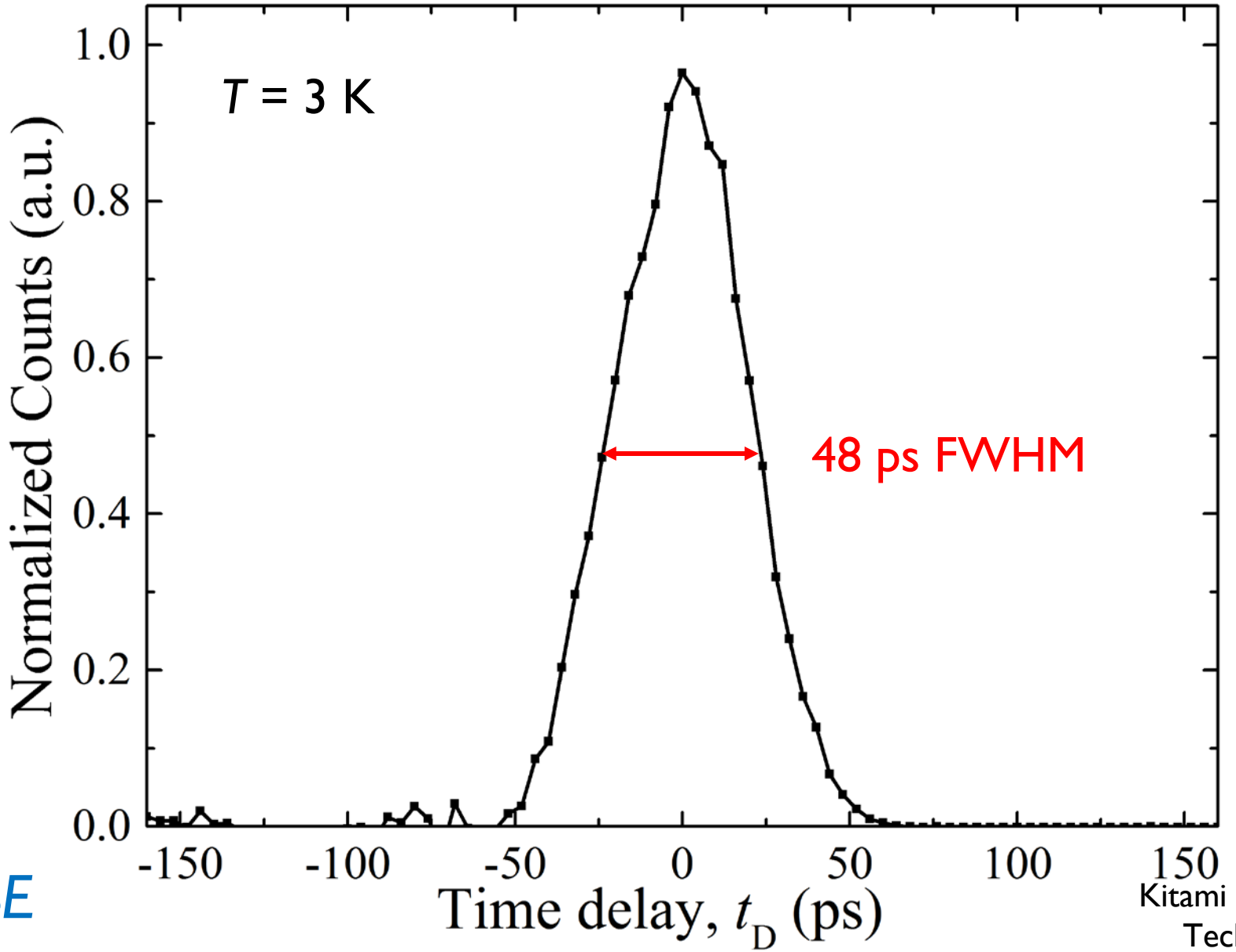
Instrument response function



MBE

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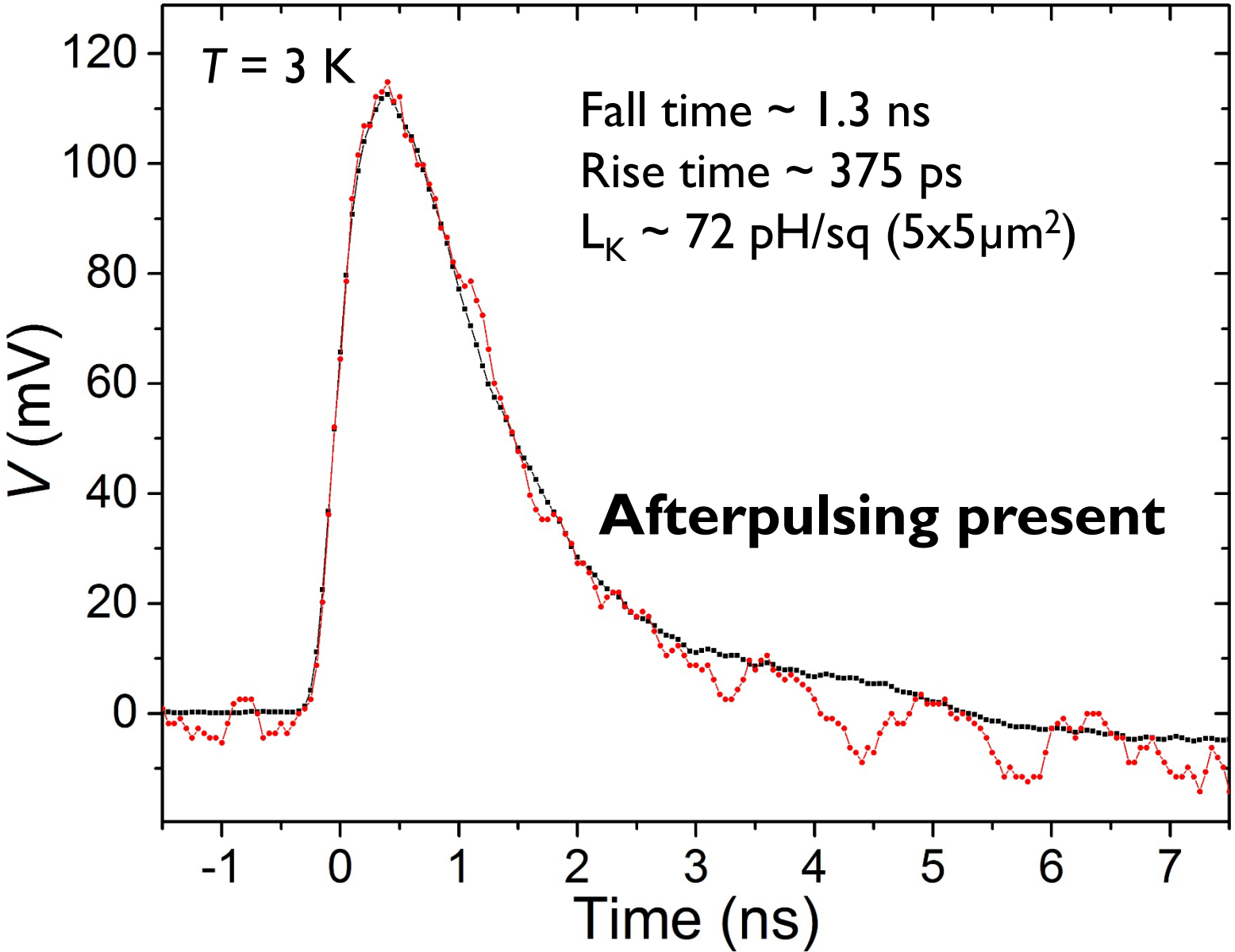
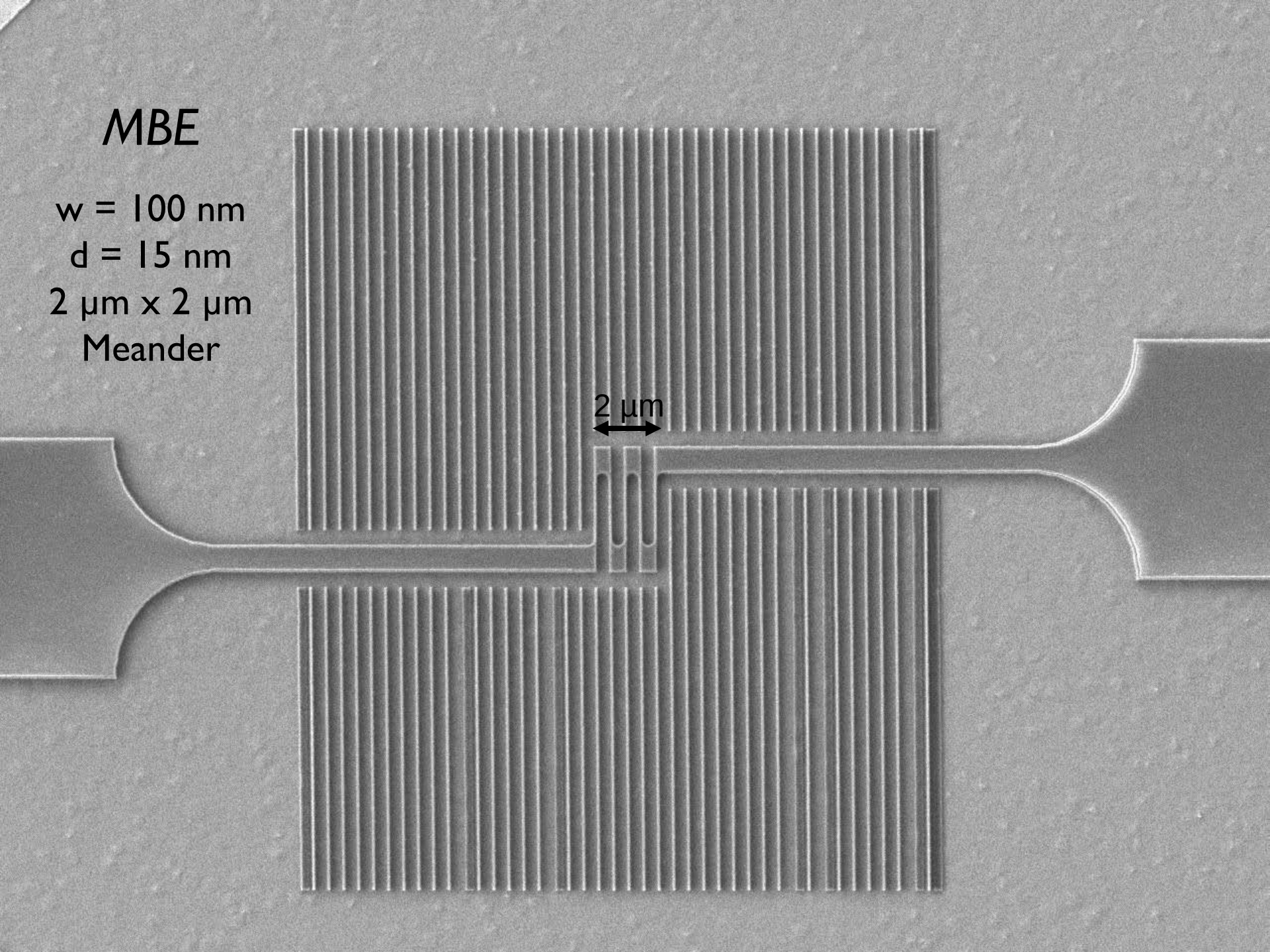
Optical response at 1550 nm

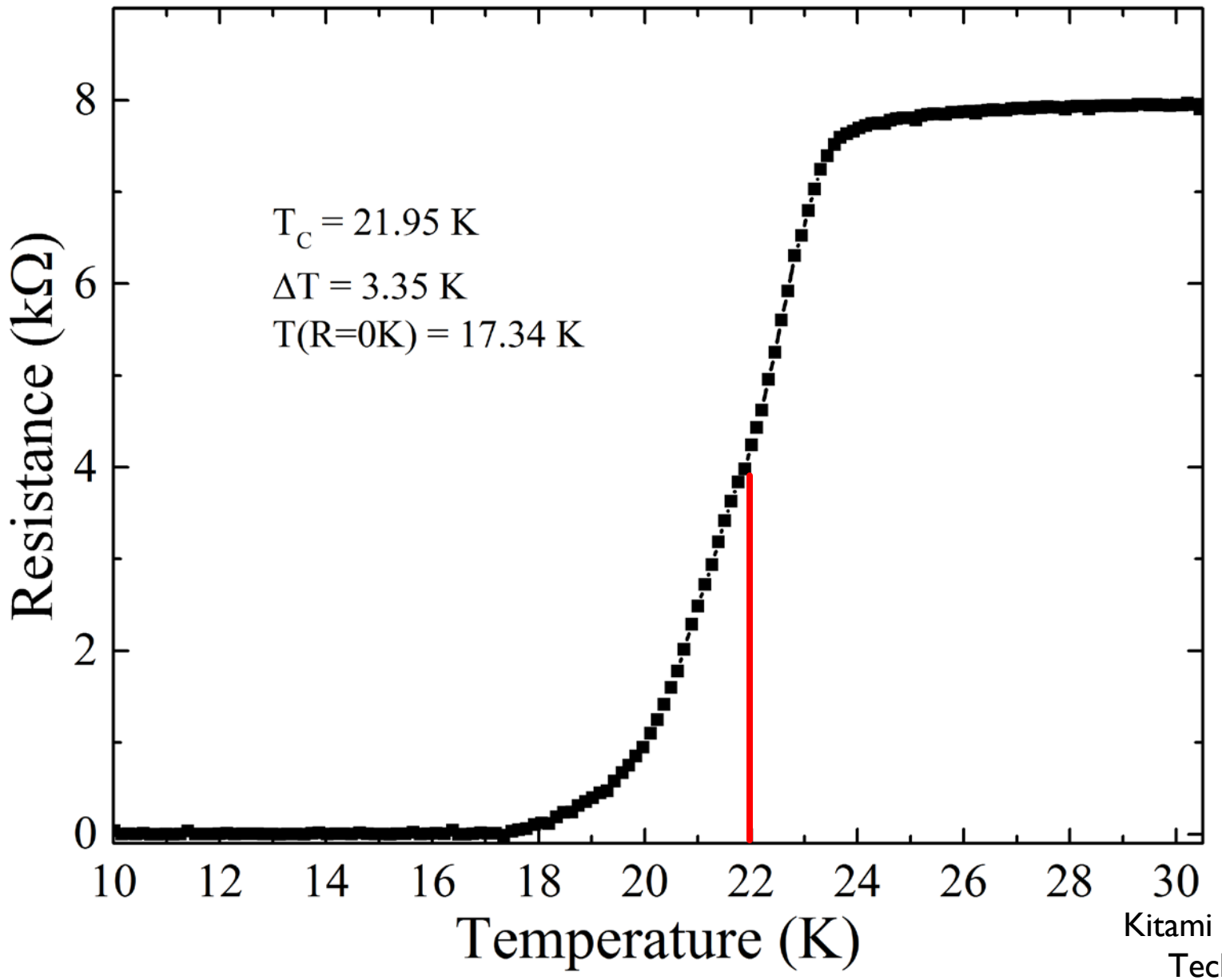


MBE

w = 100 nm
d = 15 nm
2 μm x 2 μm
Meander



Resistance vs Temperature



MBE

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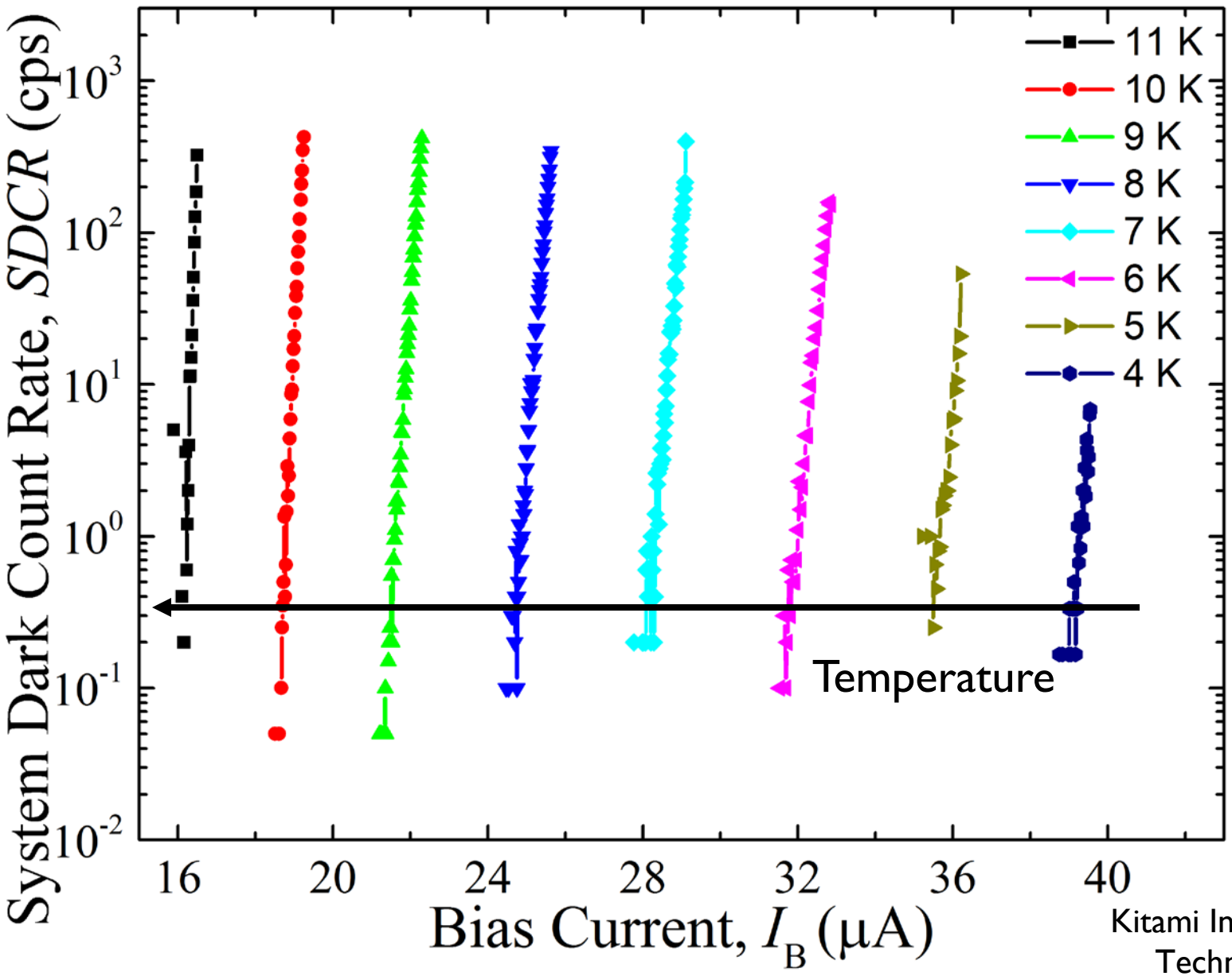
System dark count rate (*SDCR*) vs Temperature



MBE

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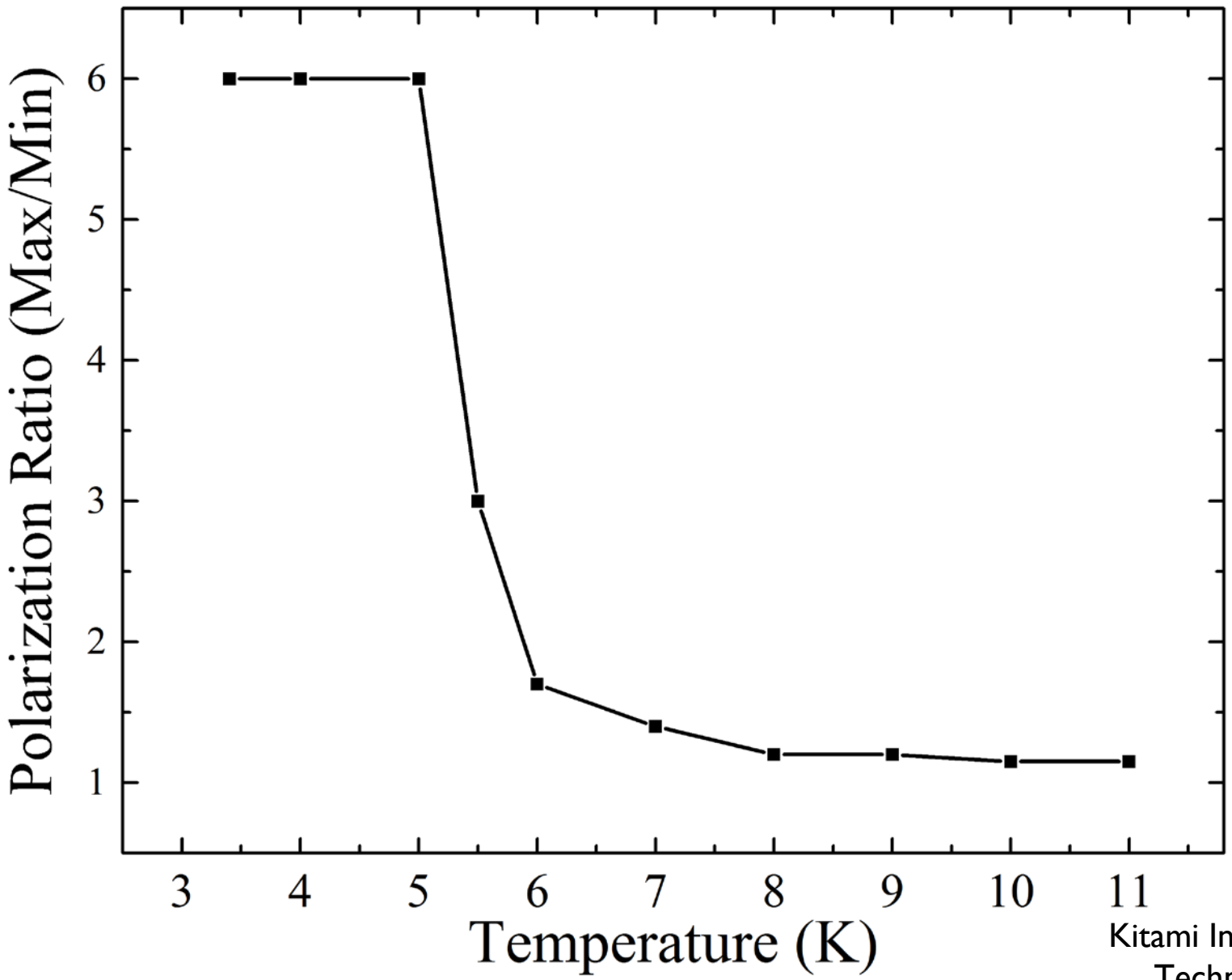
Polarization Ratio vs Temperature



MBE

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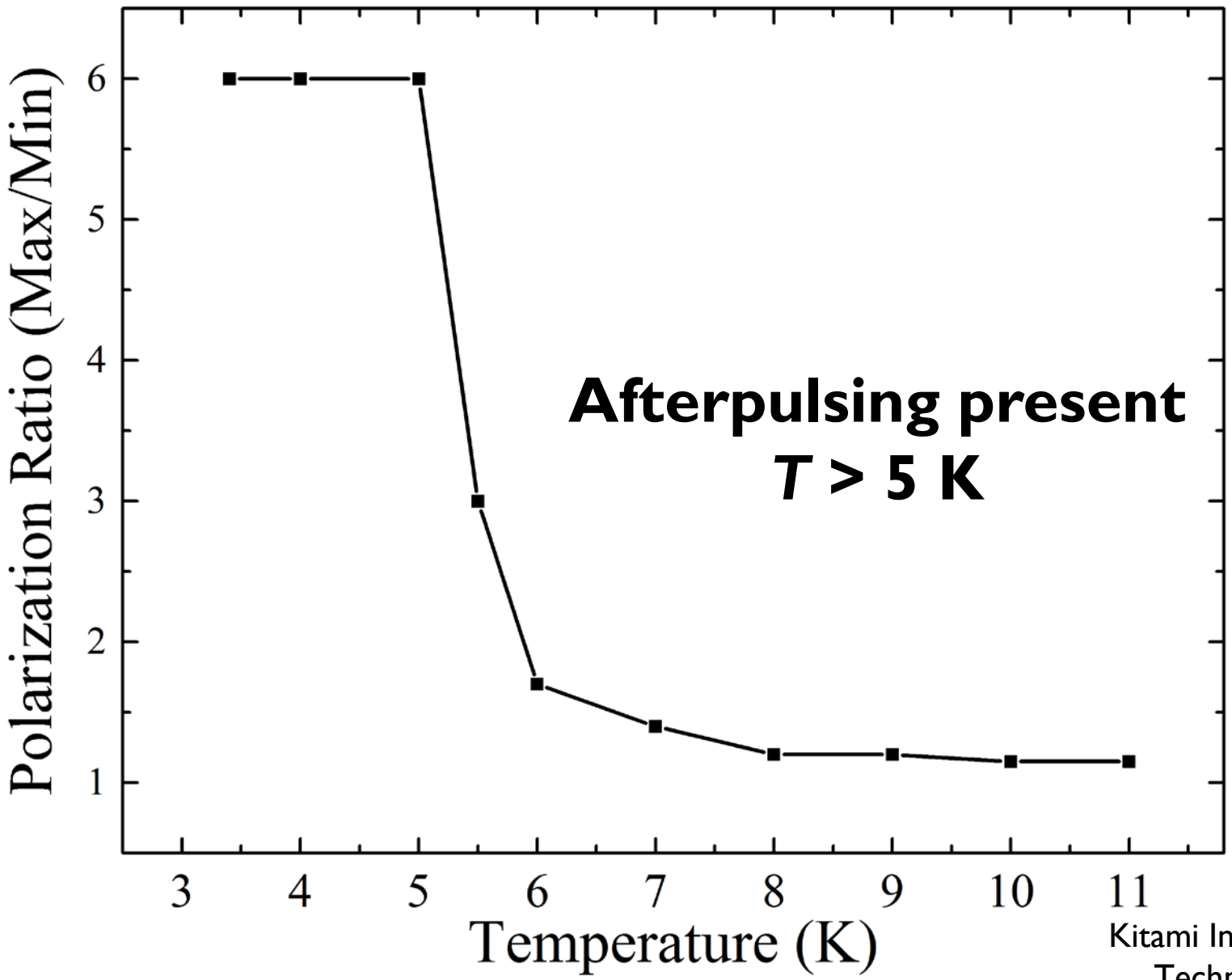
Polarization Ratio vs Temperature



MBE

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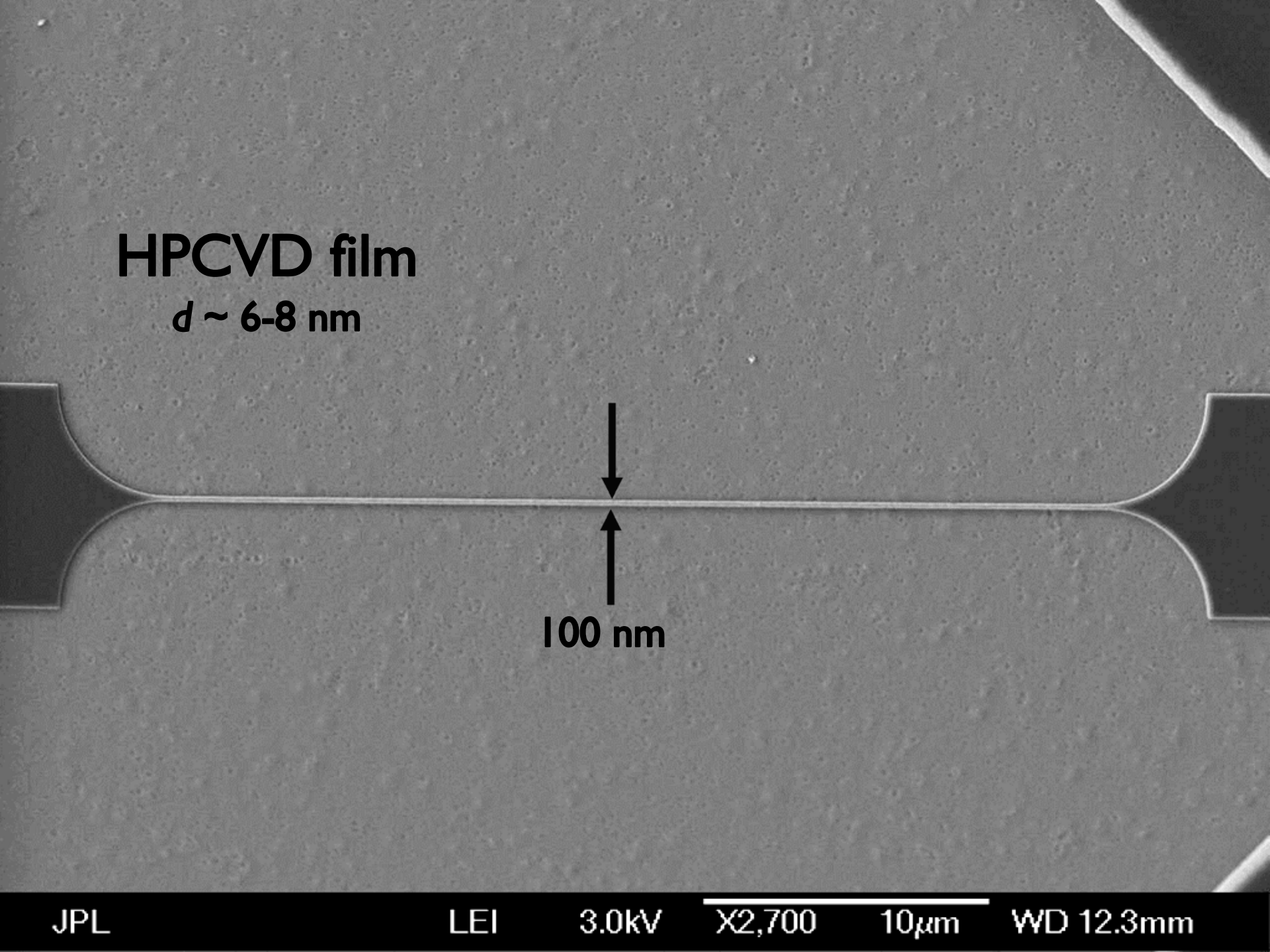
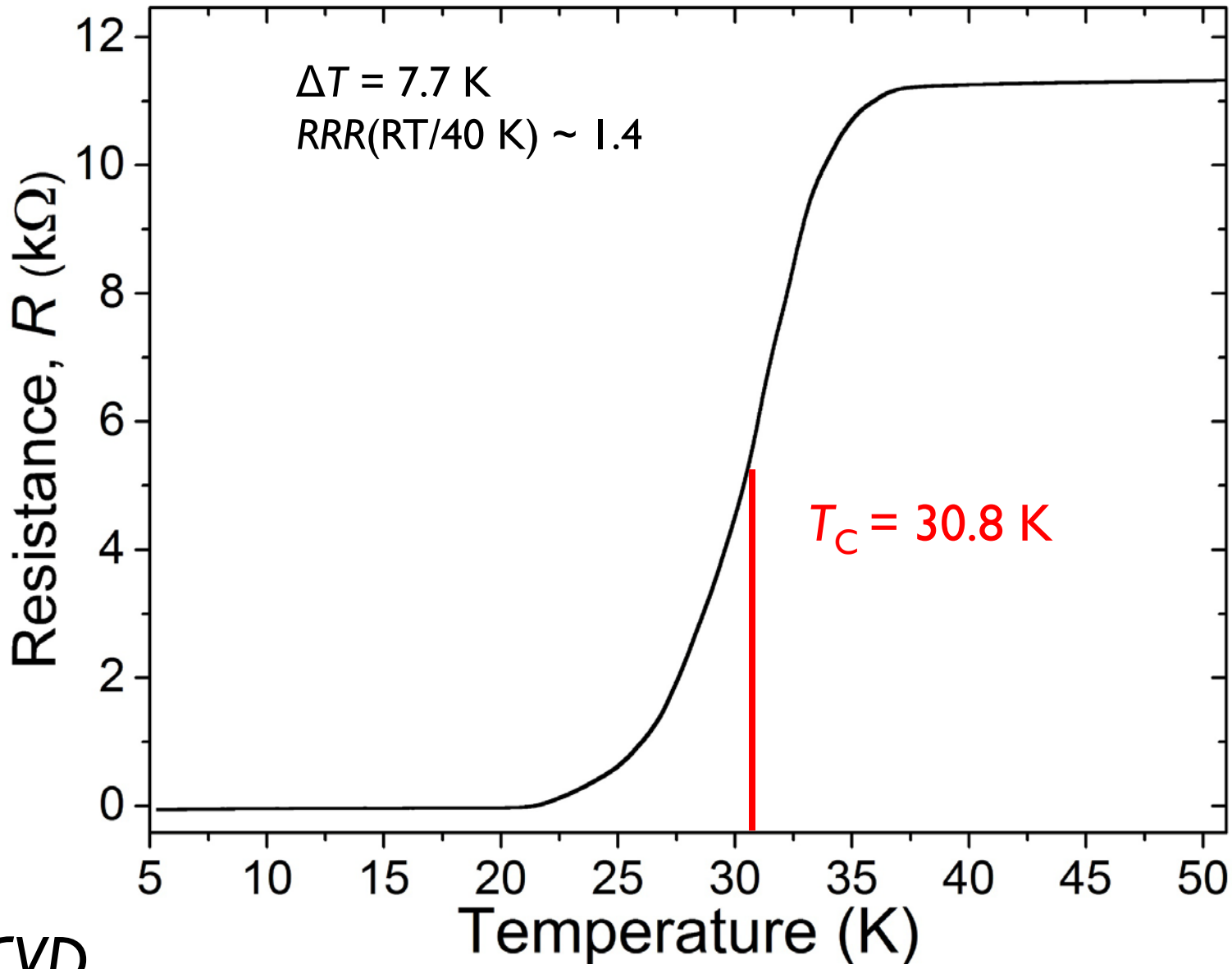
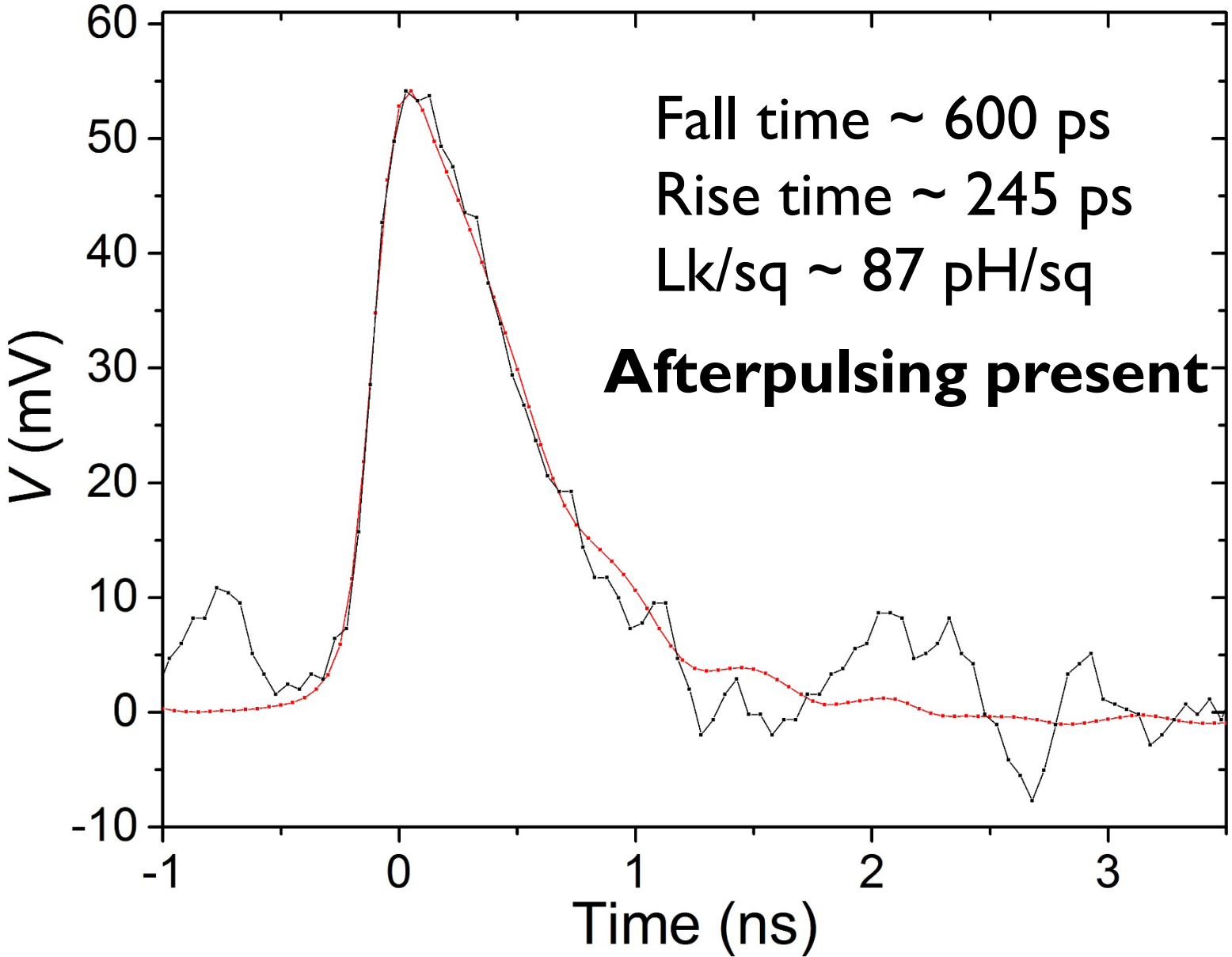

HPCVD film
d ~ 6-8 nm
100 nm
JPL
LEI
3.0kV
X2,700
10μm
WD 12.3mm

Transition Temperature, T_C

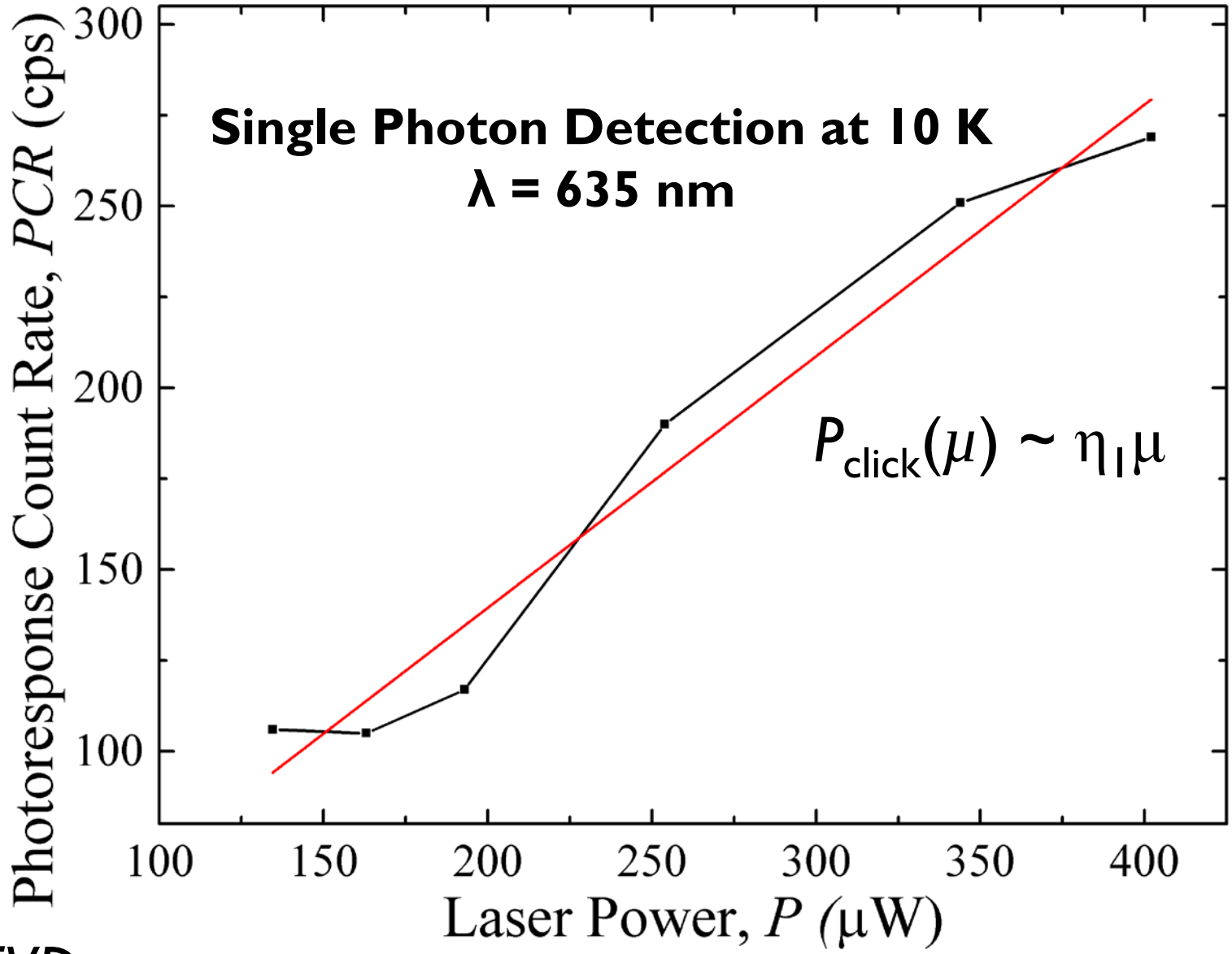


HPCVD

Optical pulse at 635 nm

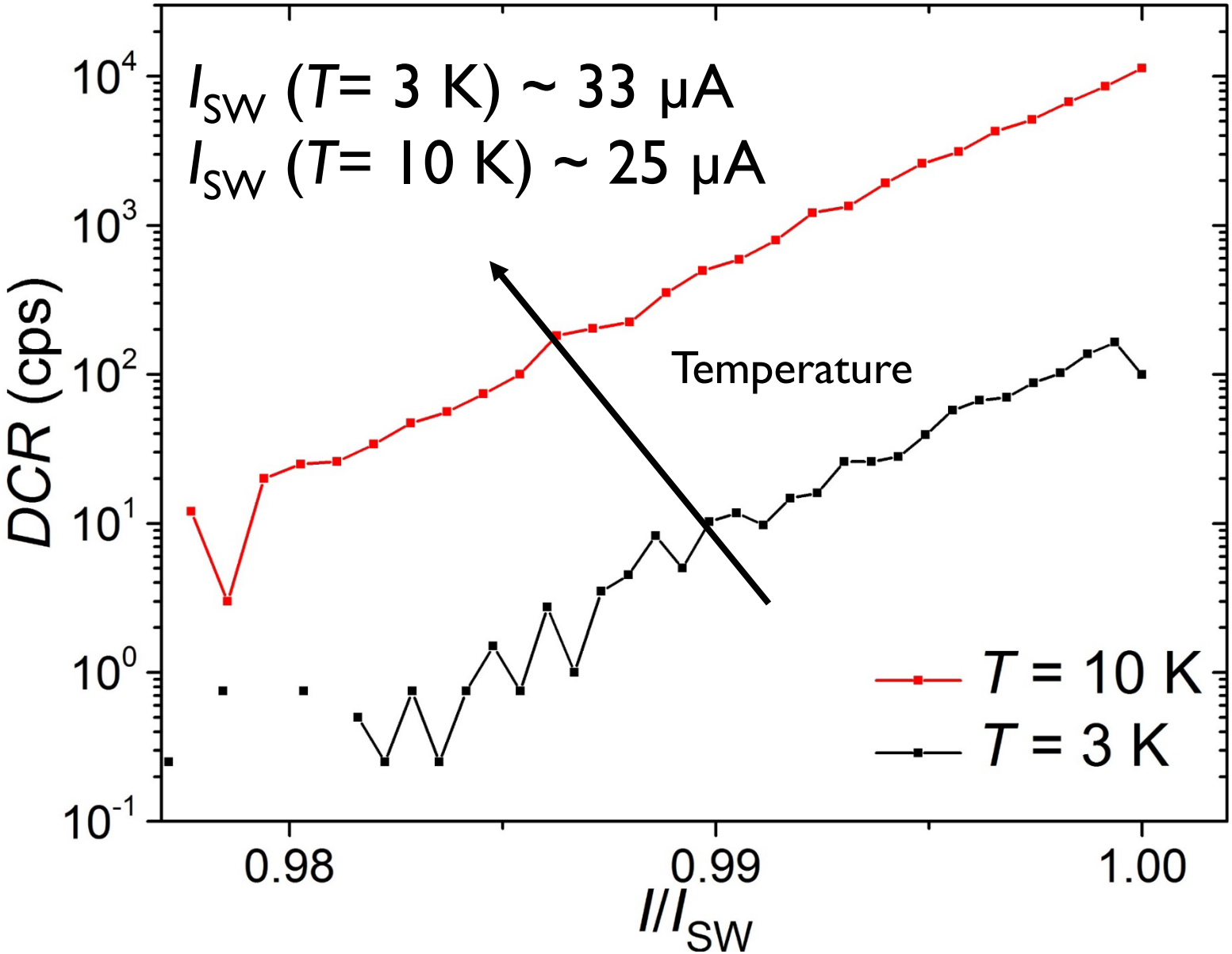


Single Photon Detection at 10 K



HPCVD

Dark count rate, *DCR*



Summary

- Single-photon response with MBE film
  a) λ = 373 nm
  b) Up to 10 K
  c) Timing jitter 48 ps (T = 3 K)
  d) Large active area (10 μm × 10 μm)
  e) Afterpulsing present for ~1 ns pulses

- Single-photon response with HPCVD film
  a) λ = 635 nm
  b) Up to 10 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

Acknowledgements

Kitami Institute of Technology, JPN

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National Institute of Advanced Industrial Science and Technology, JPN

Temple University, USA

National Institute of Standards and Technology, USA

NASA Jet Propulsion Laboratory, California Institute of Technology, USA

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Questions ?

Single photon sensitivity

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

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

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

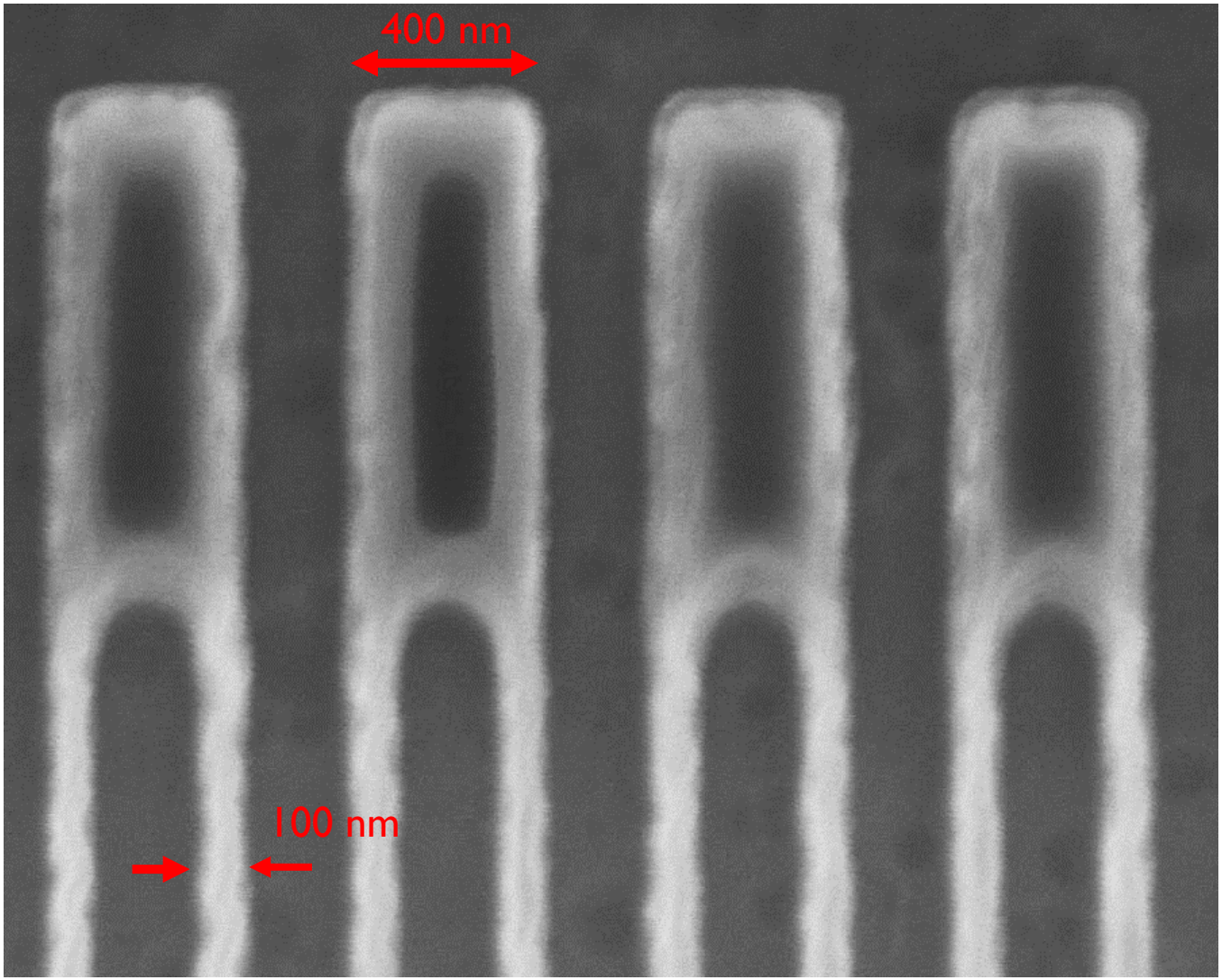
μ = mean photon flux
η_1 = single photon detection efficiency
η_2 = two photon detection efficiency

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

Challenges of MgB_2 SNSPDs

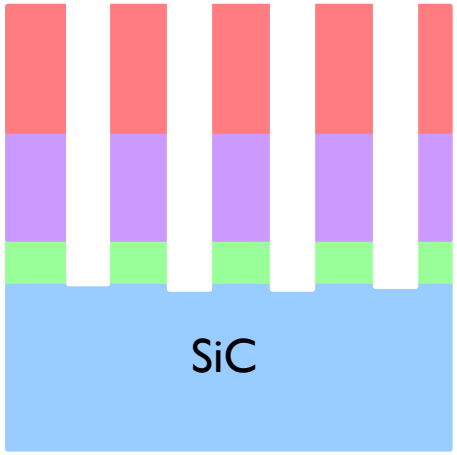
- Fabrication issues:
  i. MgB_2 highly reactive with oxygen
  ii. MgB_2 etch limited to argon ion milling

SEM after ion mill:100 nm meander

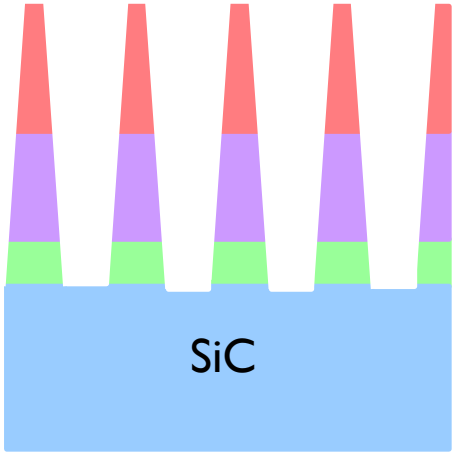


Low yield: Dry etch (Ar ion mill)

Ideal

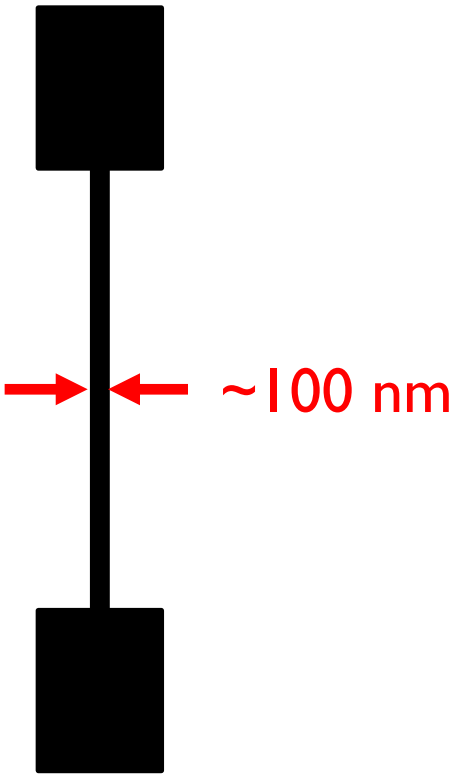


Reality

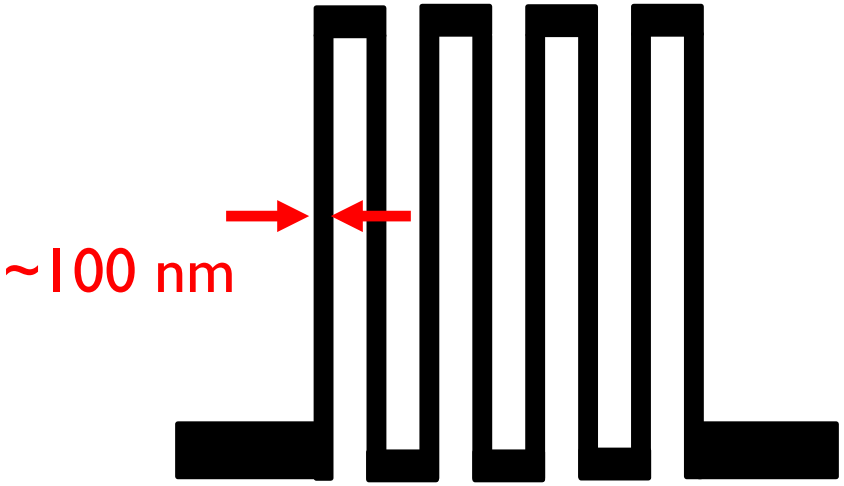


Etching: Bridges and Meanders

Bridges

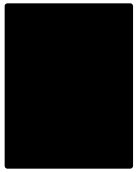


Meander

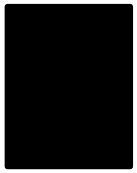


Etching: Bridges and Meanders

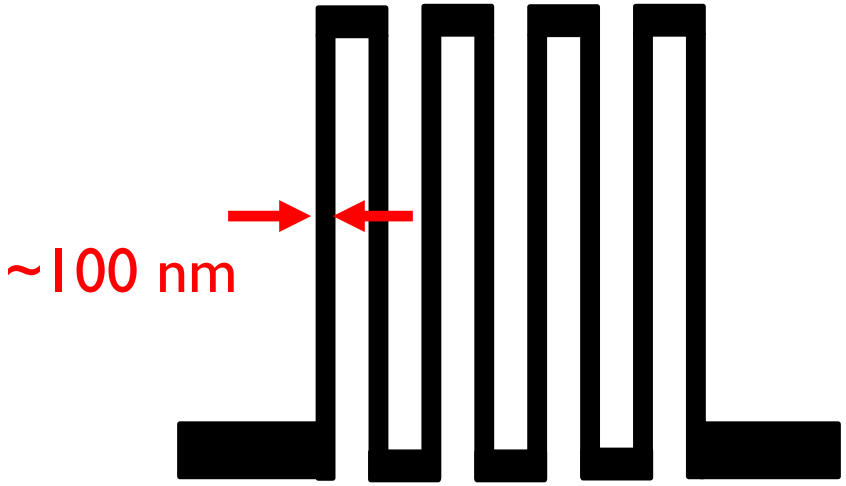
Bridges



Etched first



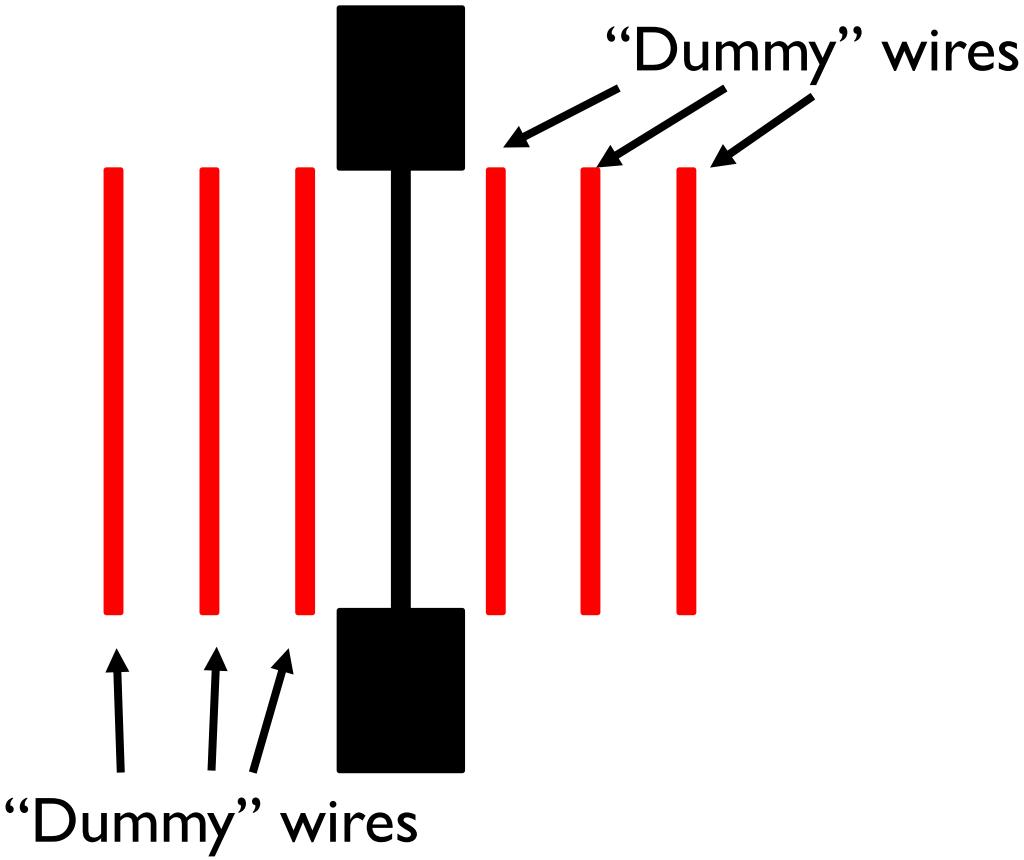
Meander



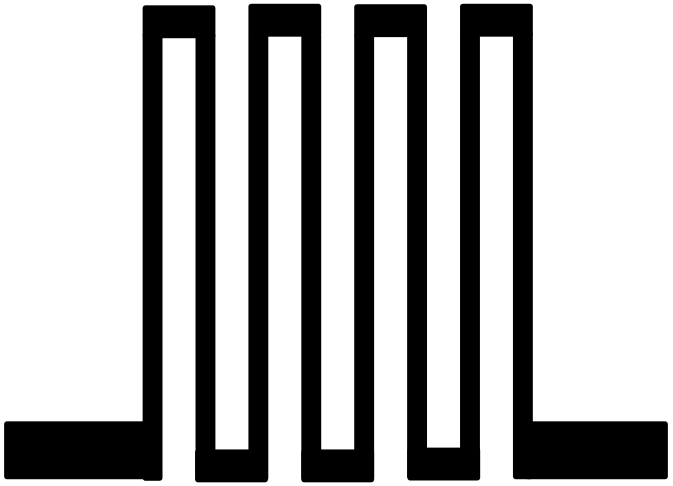
Survives etch

Etching: Bridges and Meanders

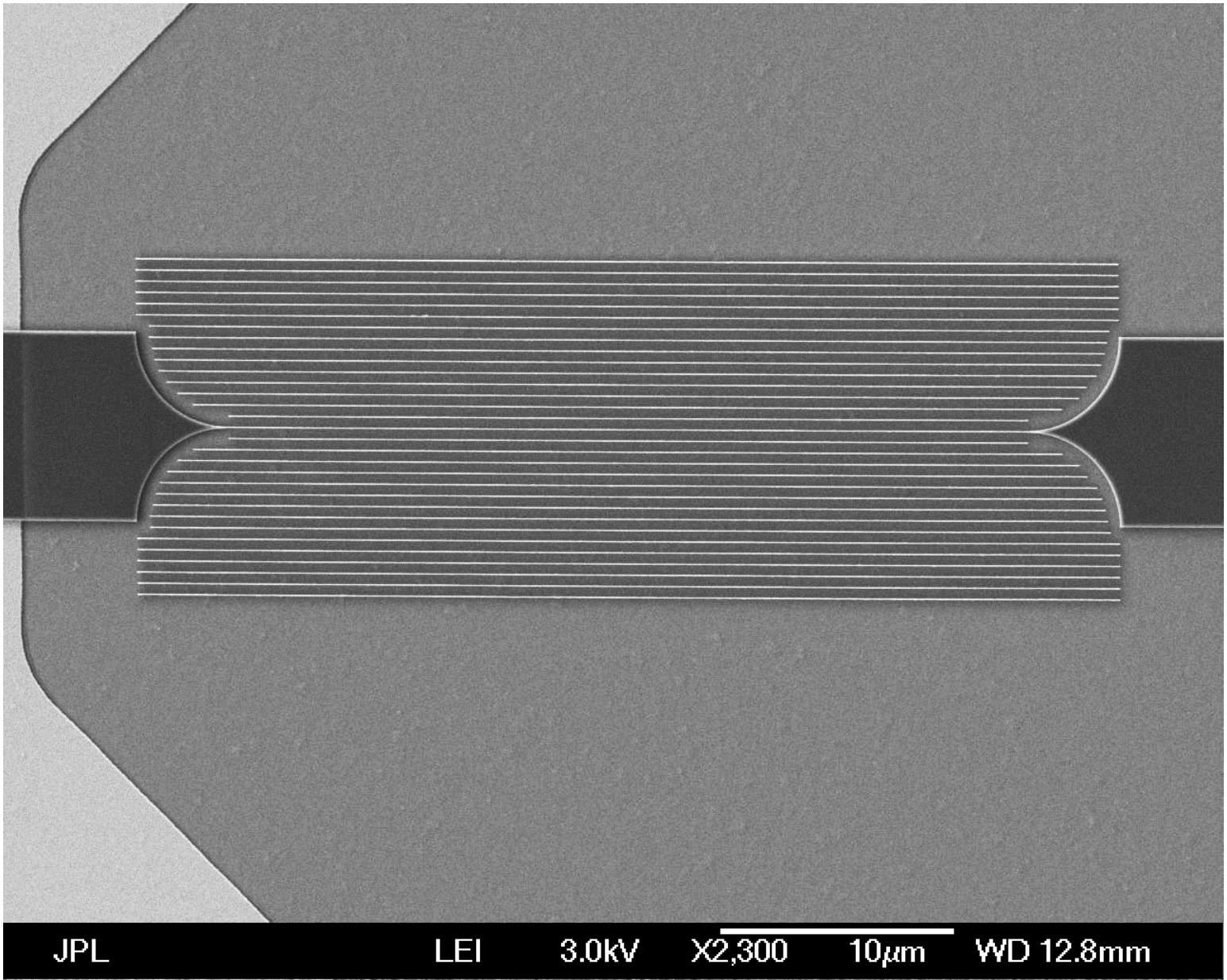
Bridges



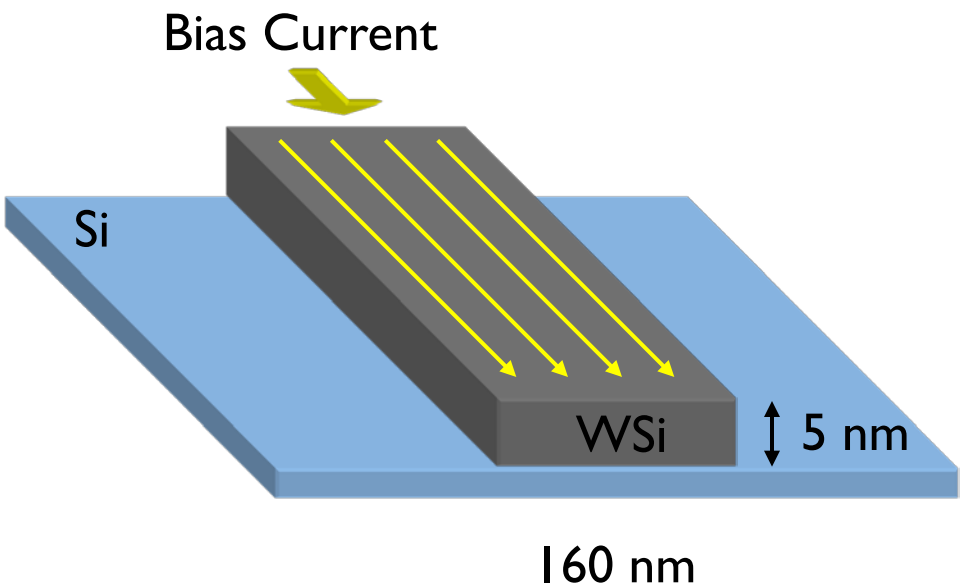
Meander

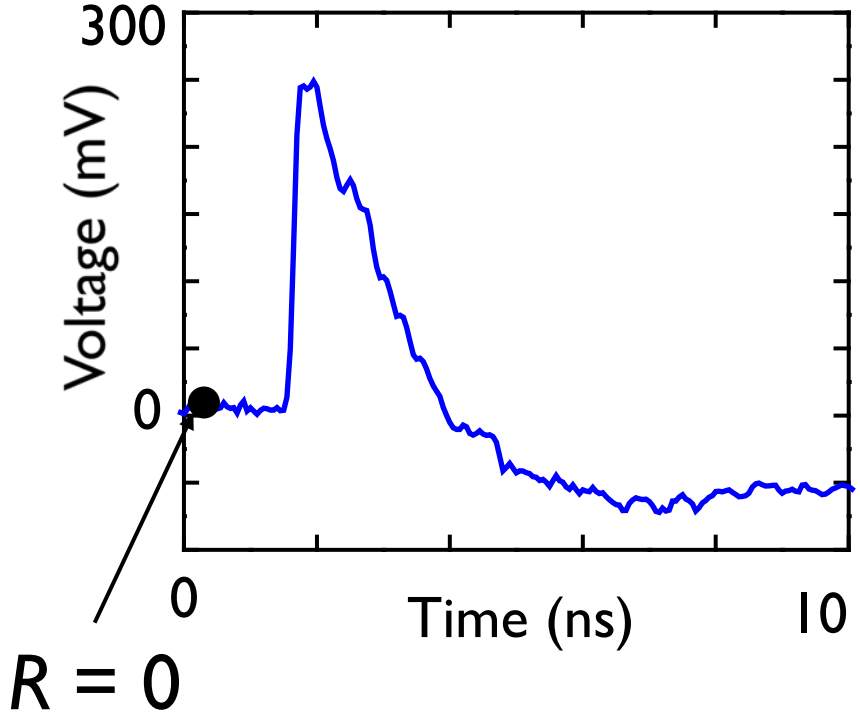


Bridges with "dummy" wires



Superconducting Nanowire Single-Photon Detector (SNSPD)

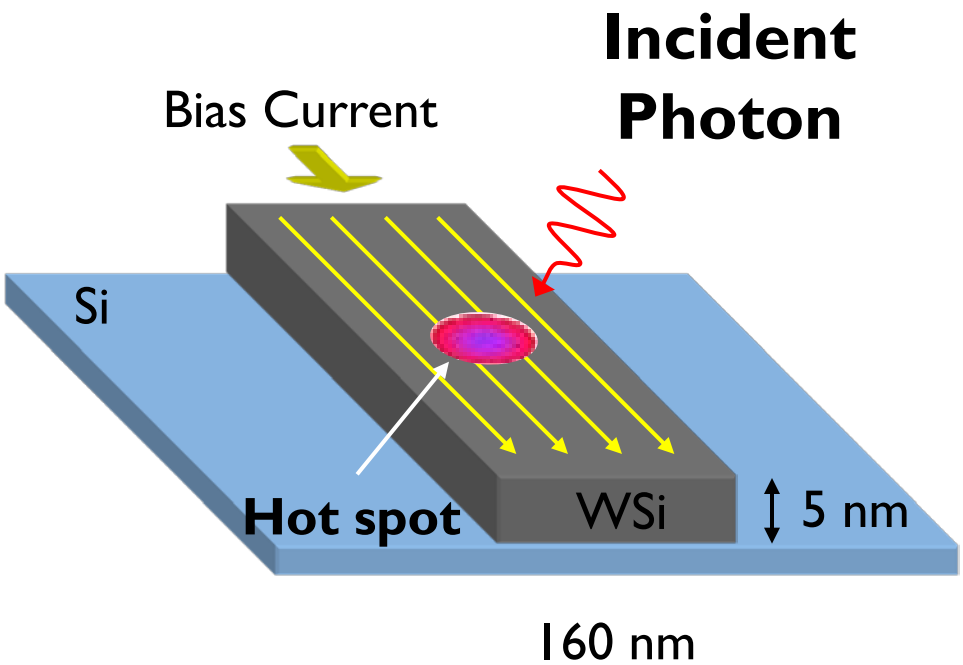


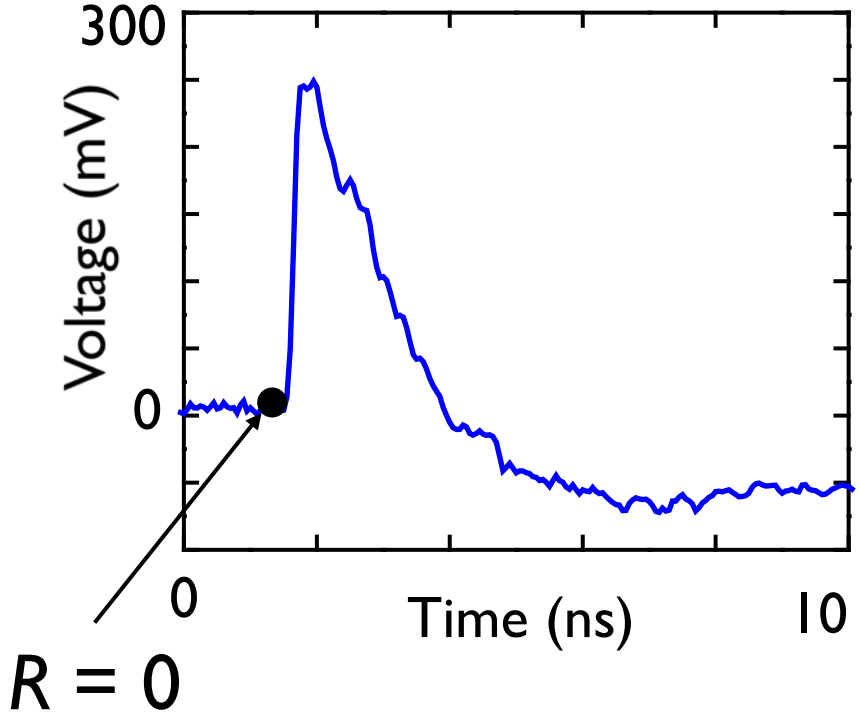


- Temperature < T_C
- Current density < J_C

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

Superconducting Nanowire Single-Photon Detector (SNSPD)

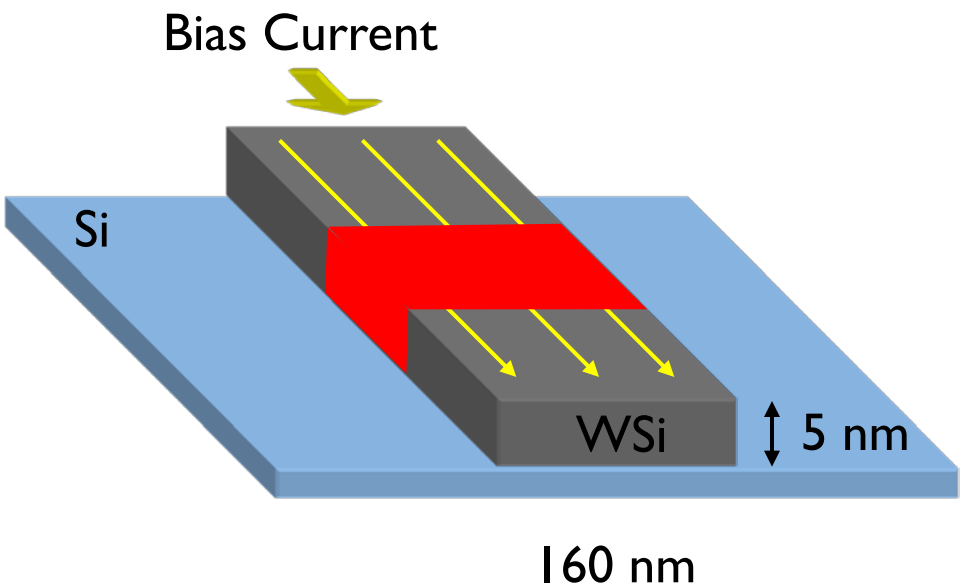


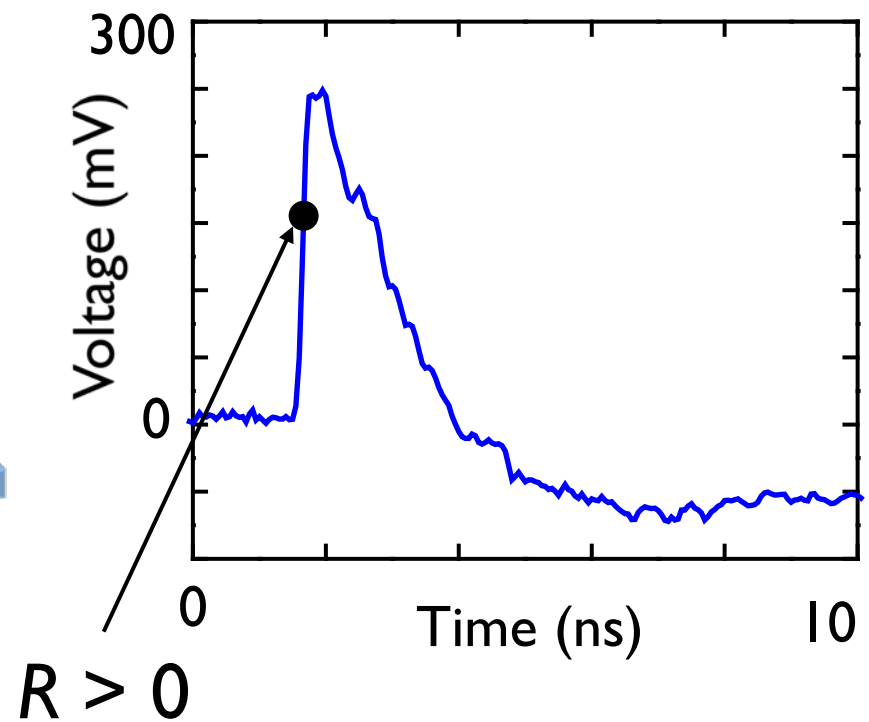


- Temperature < T_C
- Current density < J_C

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

Superconducting Nanowire Single-Photon Detector (SNSPD)

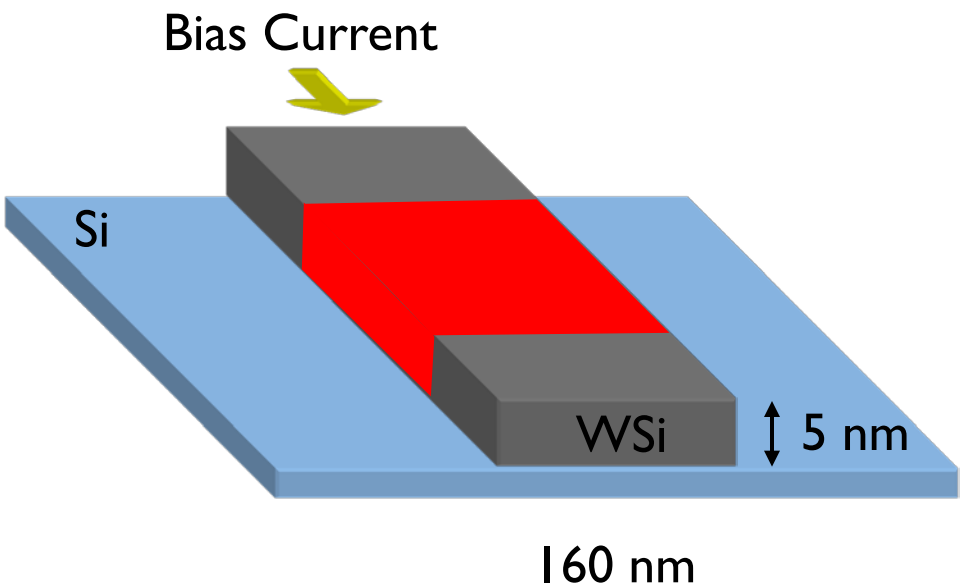


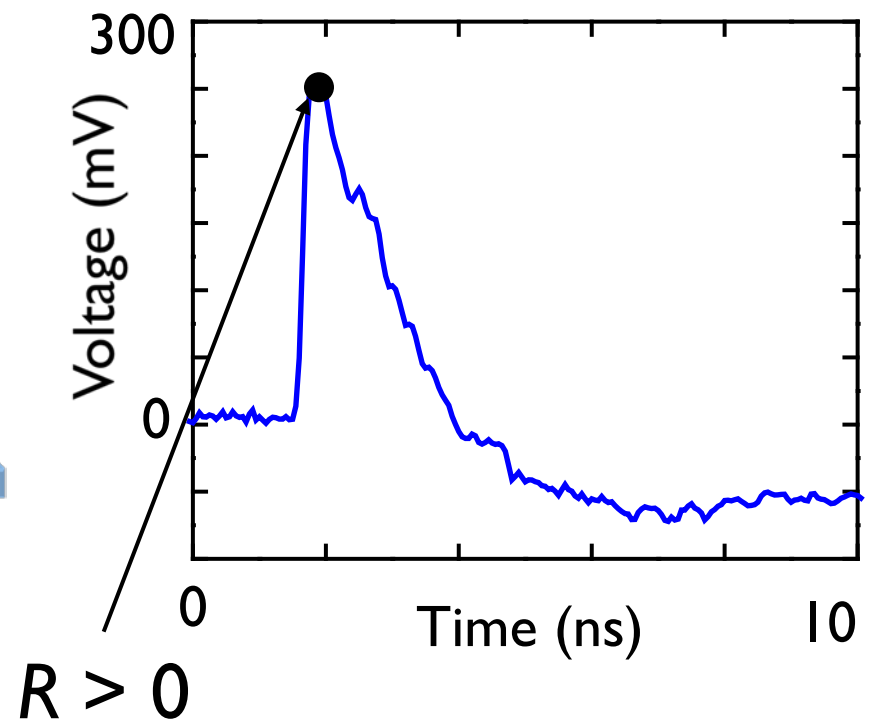


- Temperature < T_C
- Current density < J_C

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

Superconducting Nanowire Single-Photon Detector (SNSPD)

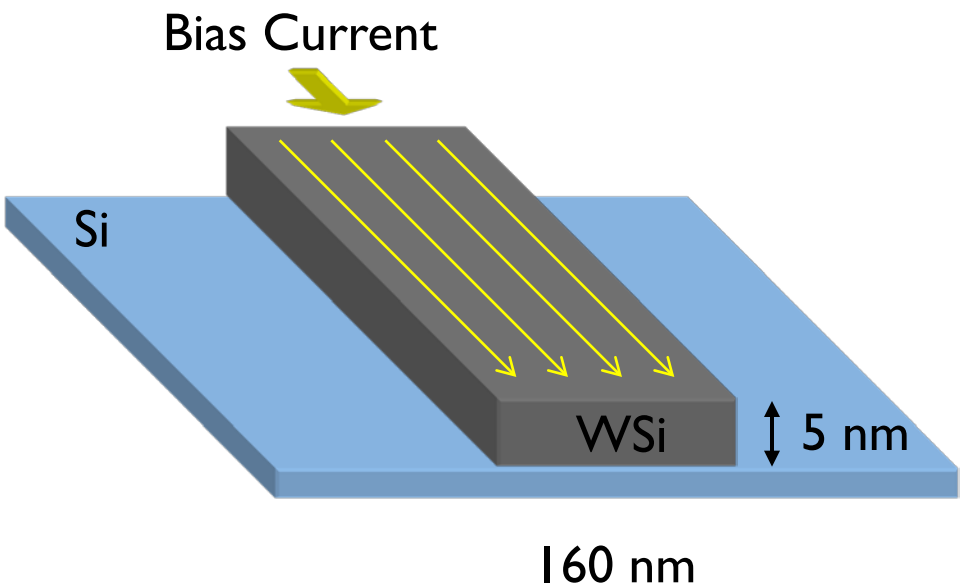


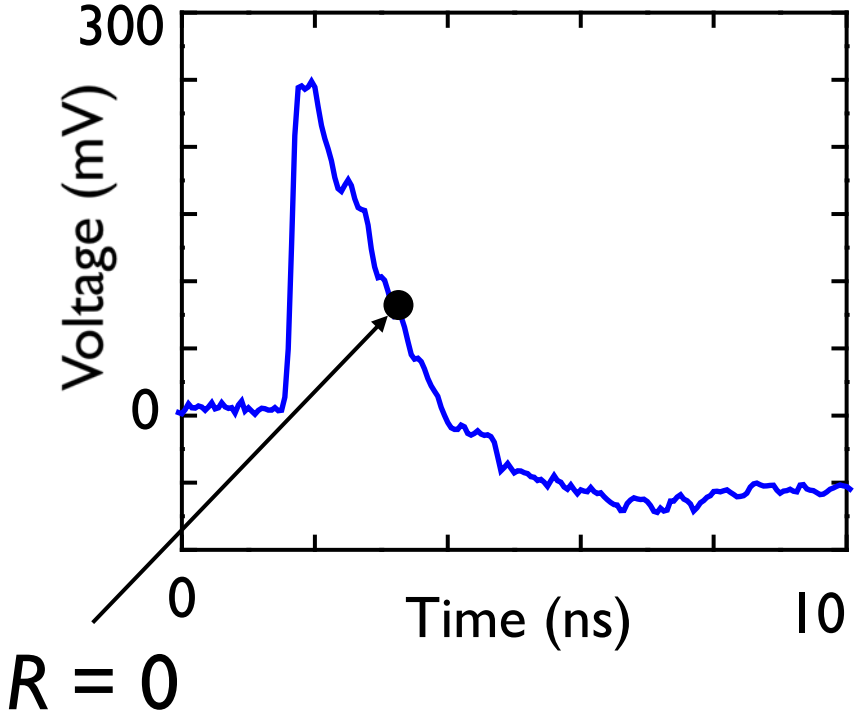


- Temperature < T_C
- Current density < J_C

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

Superconducting Nanowire Single-Photon Detector (SNSPD)

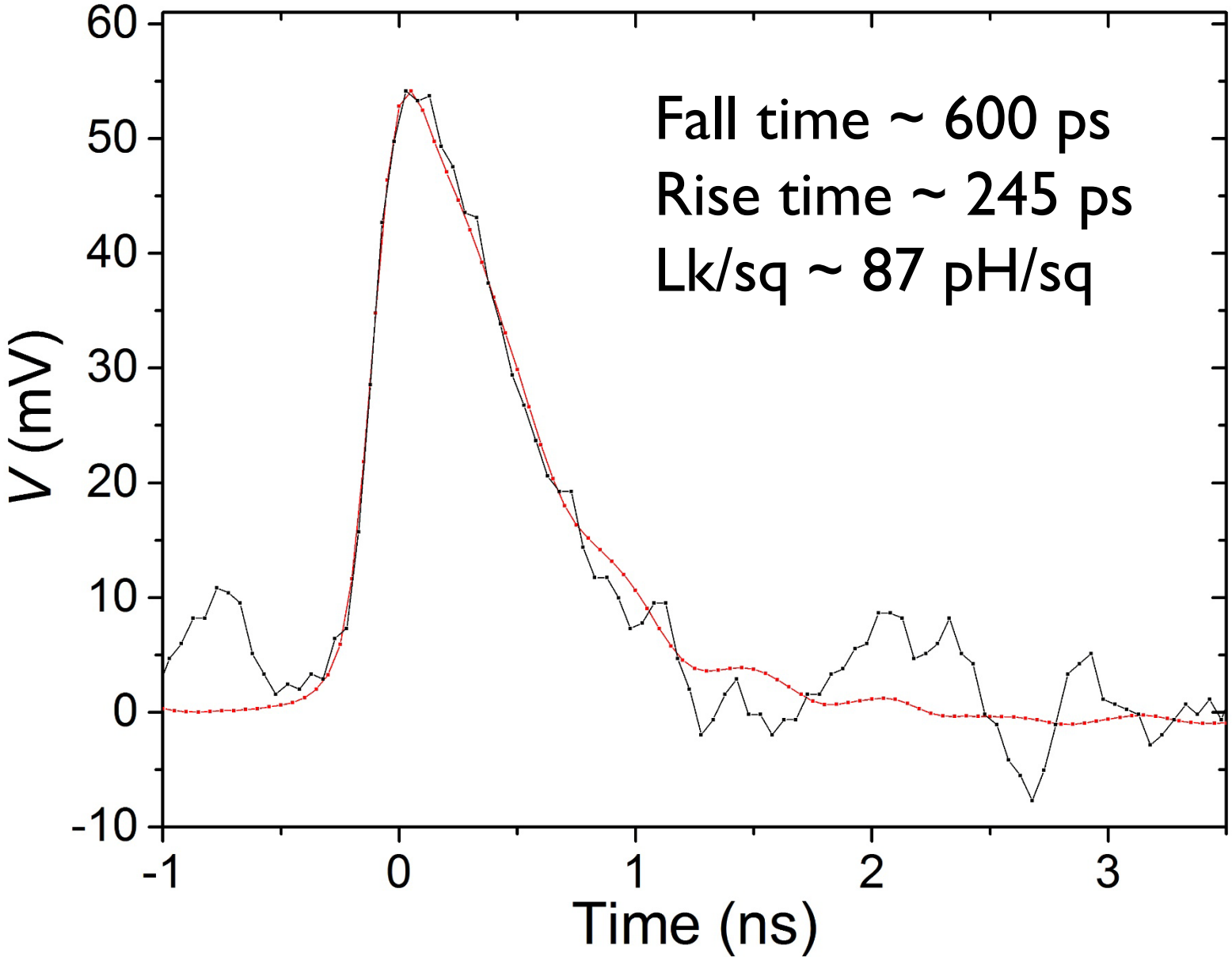




- Temperature < T_C
- Current density < J_C

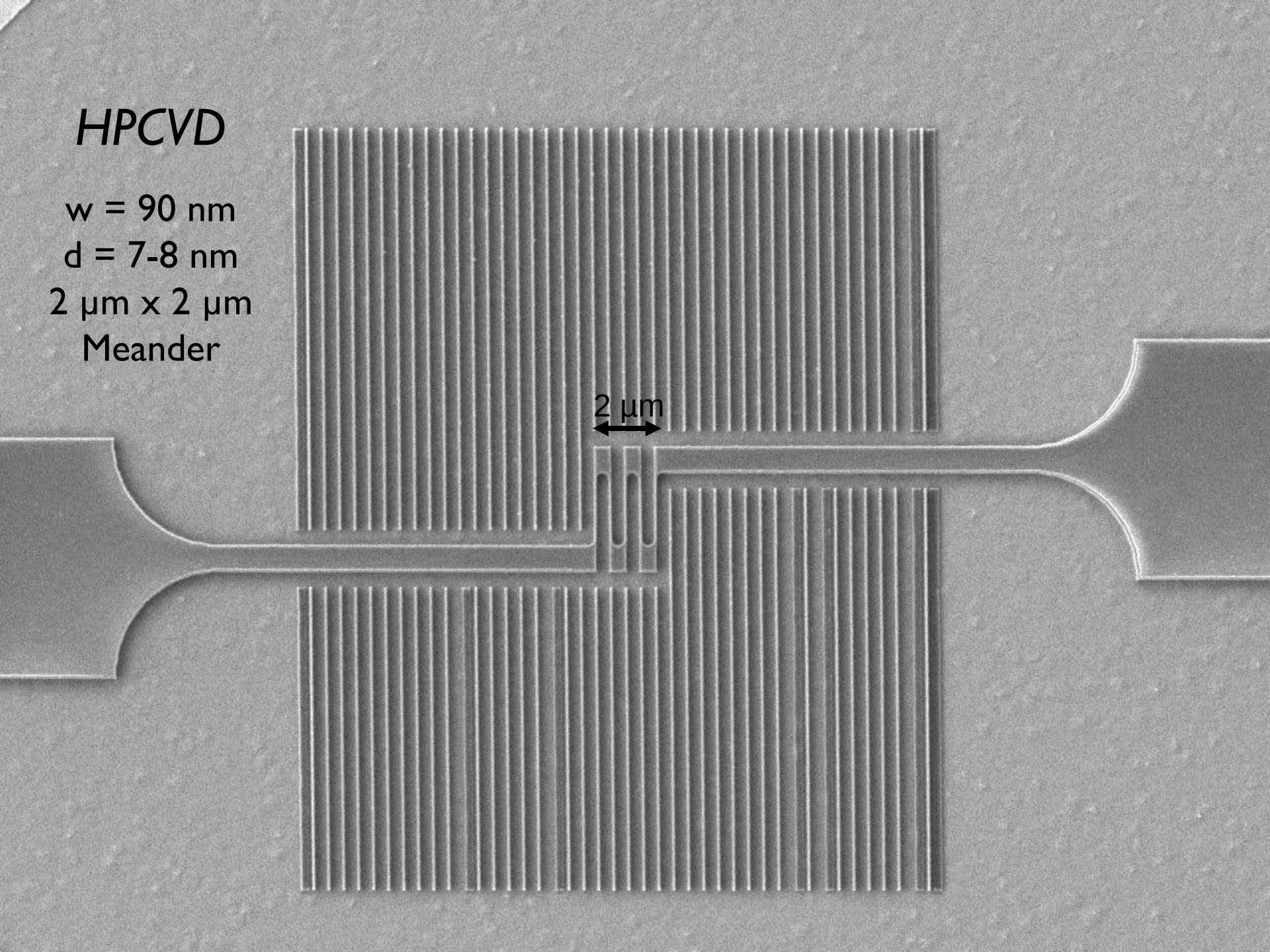
Gol'tsman *et al.*, APL 79, 705 (2001)

Optical pulse at 635 nm

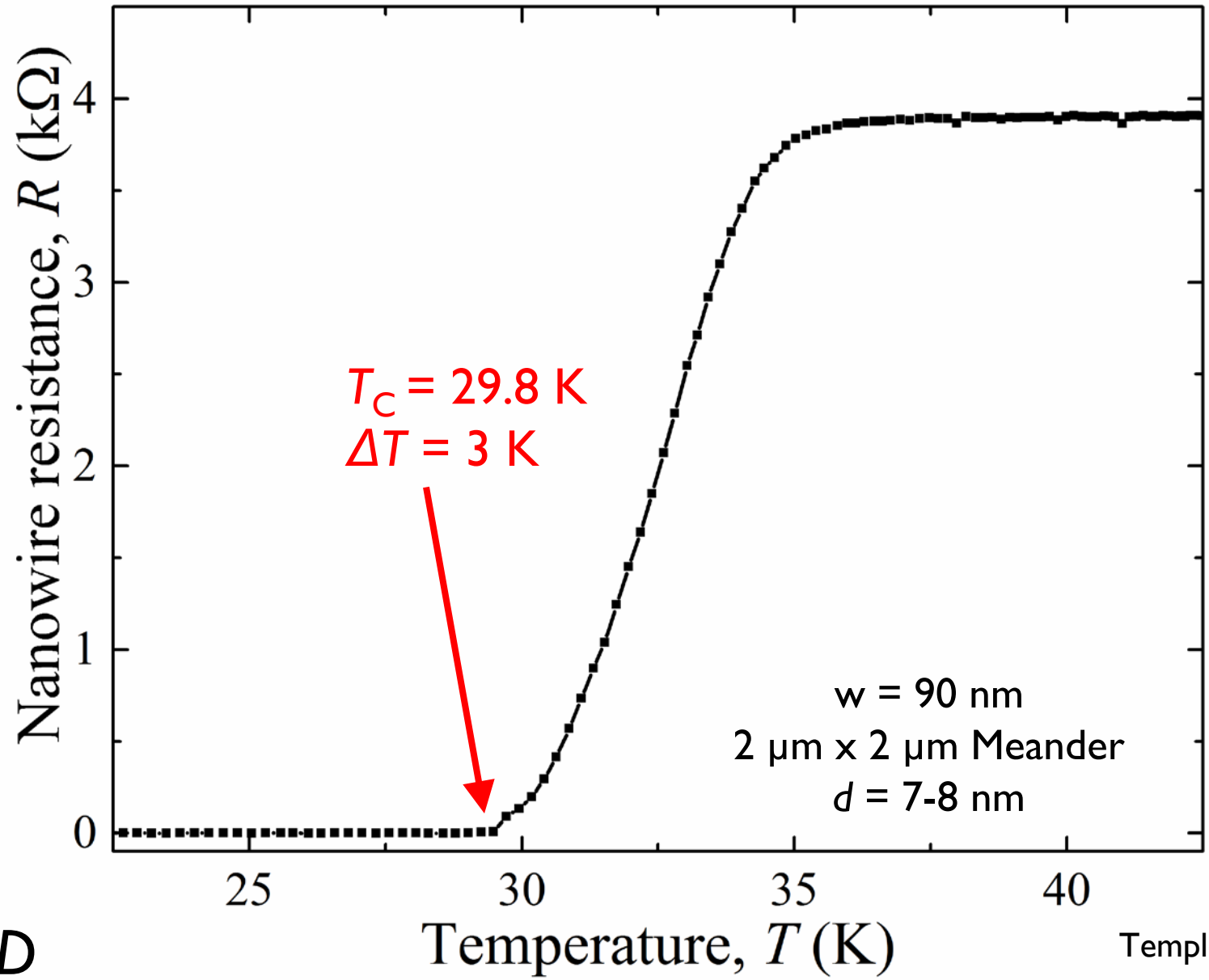


HPCVD

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



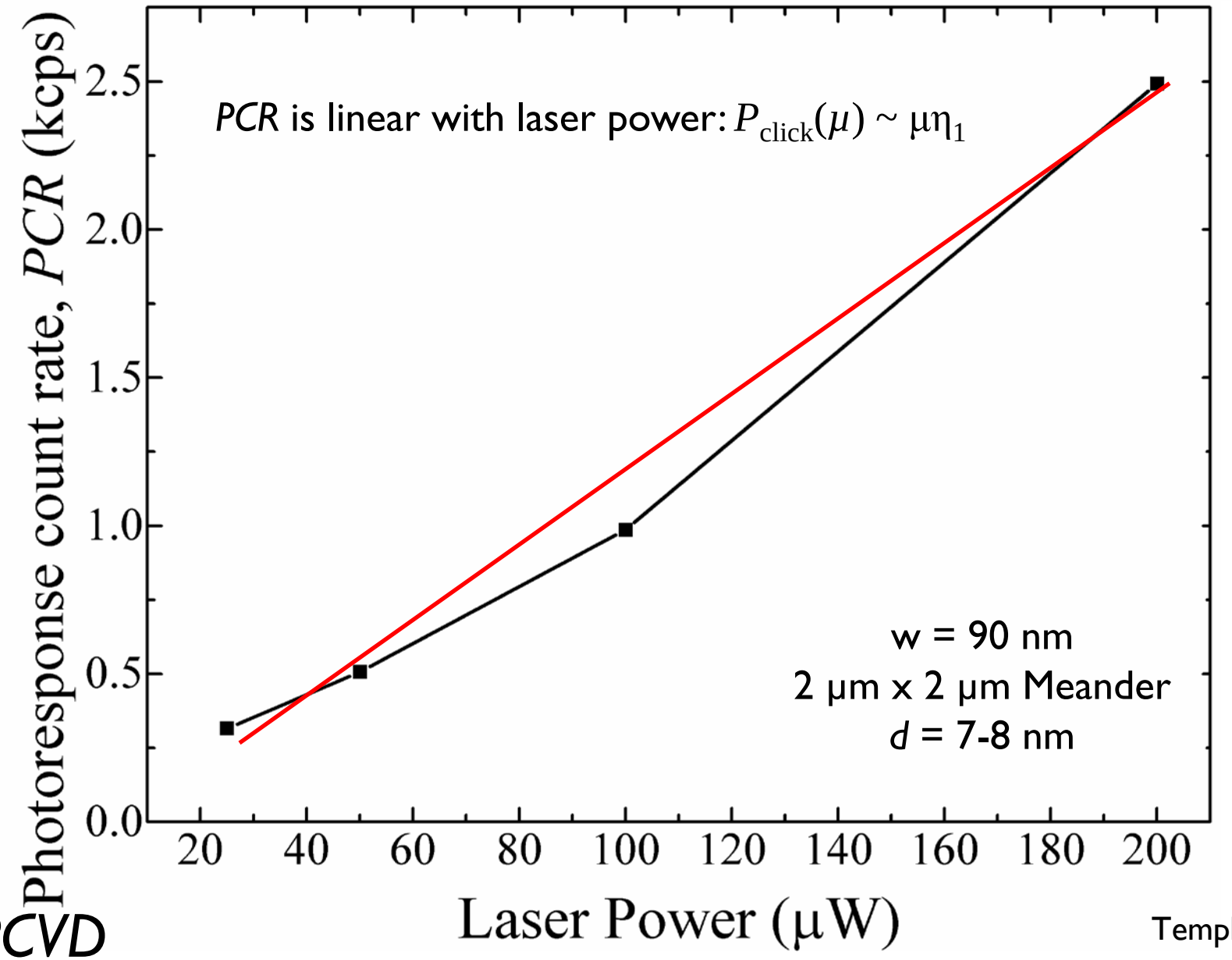
Transition temperature, T_C



HPCVD

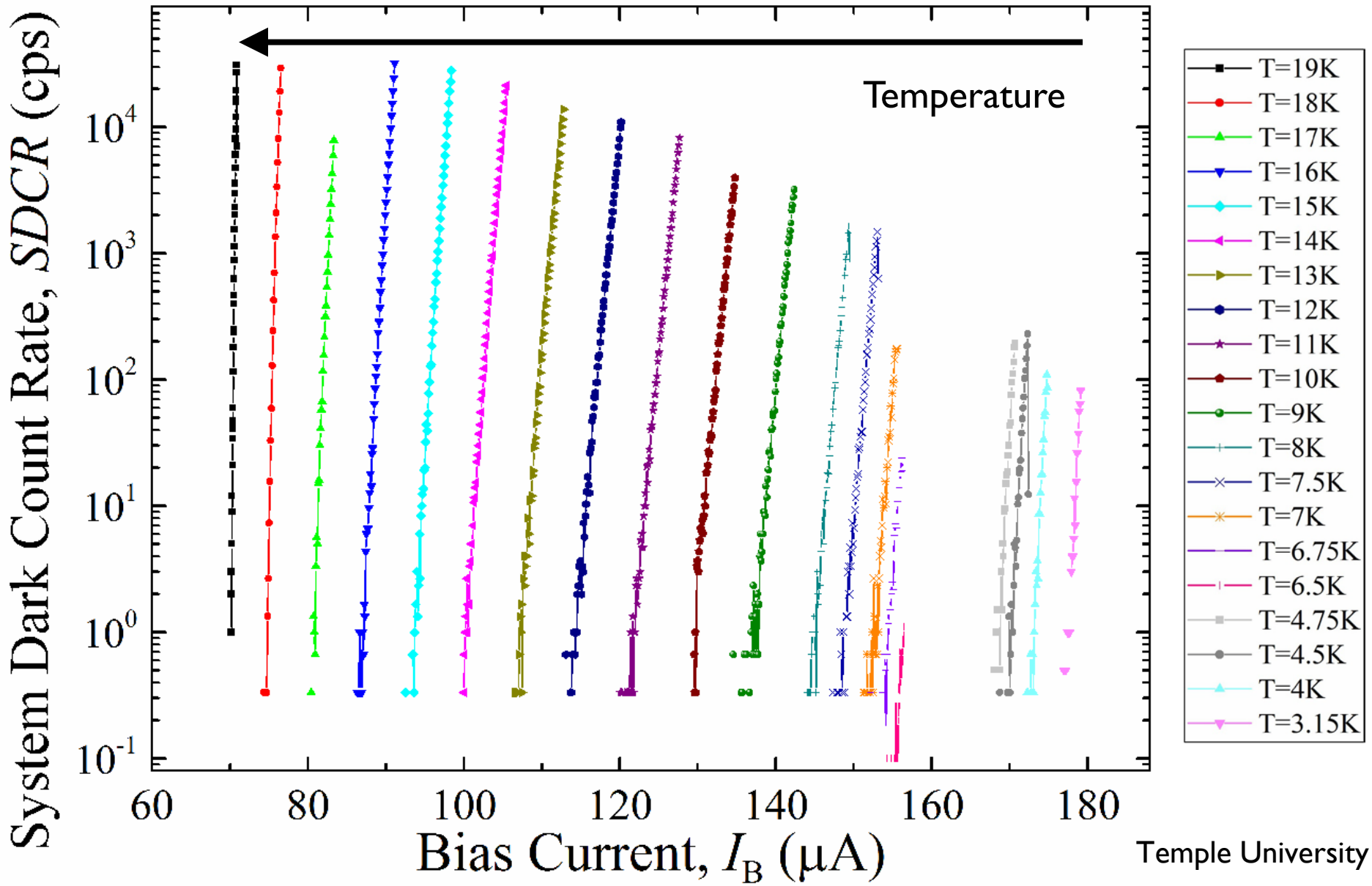
Temple University

Single Photon Detection at 18 K

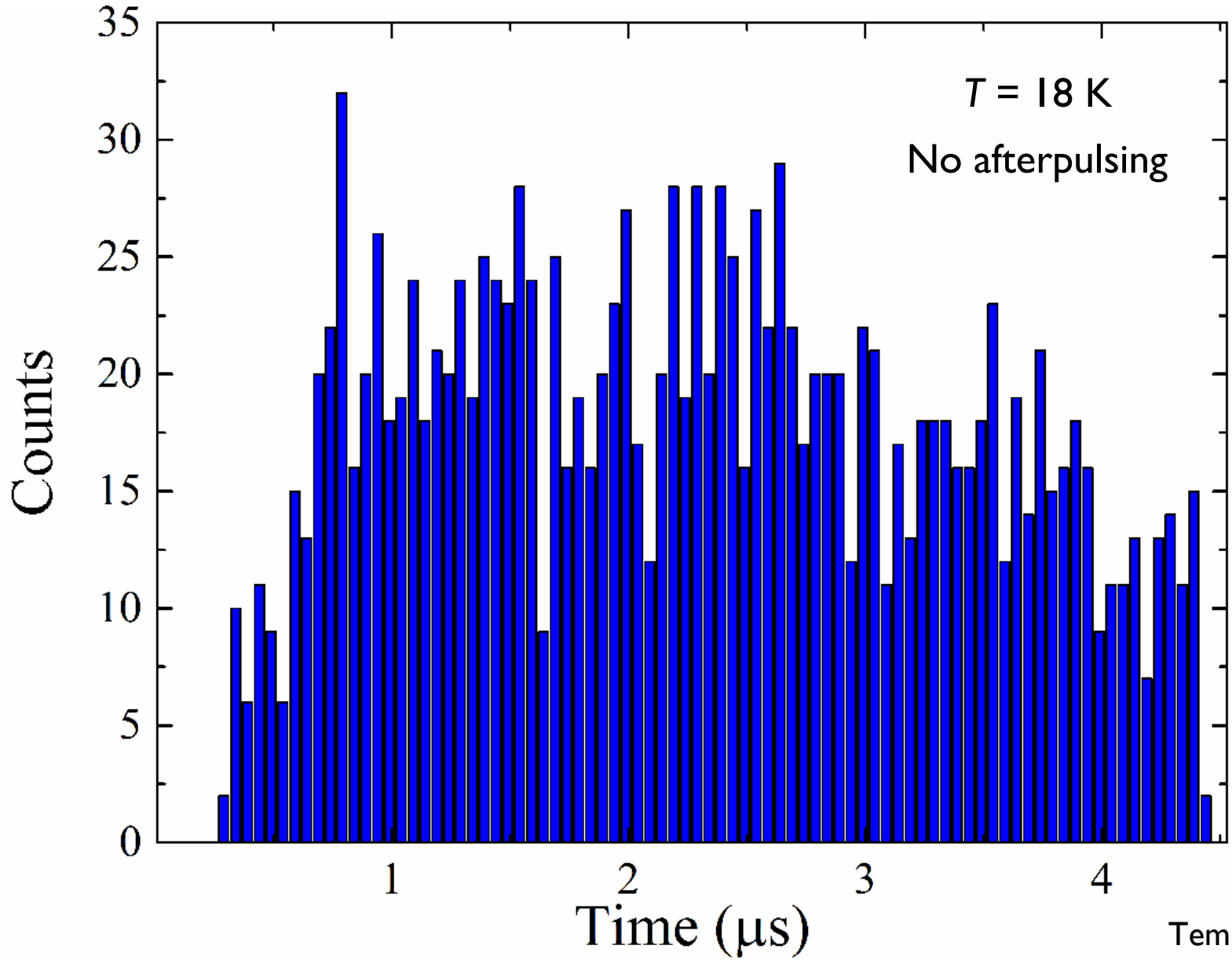


HPCVD

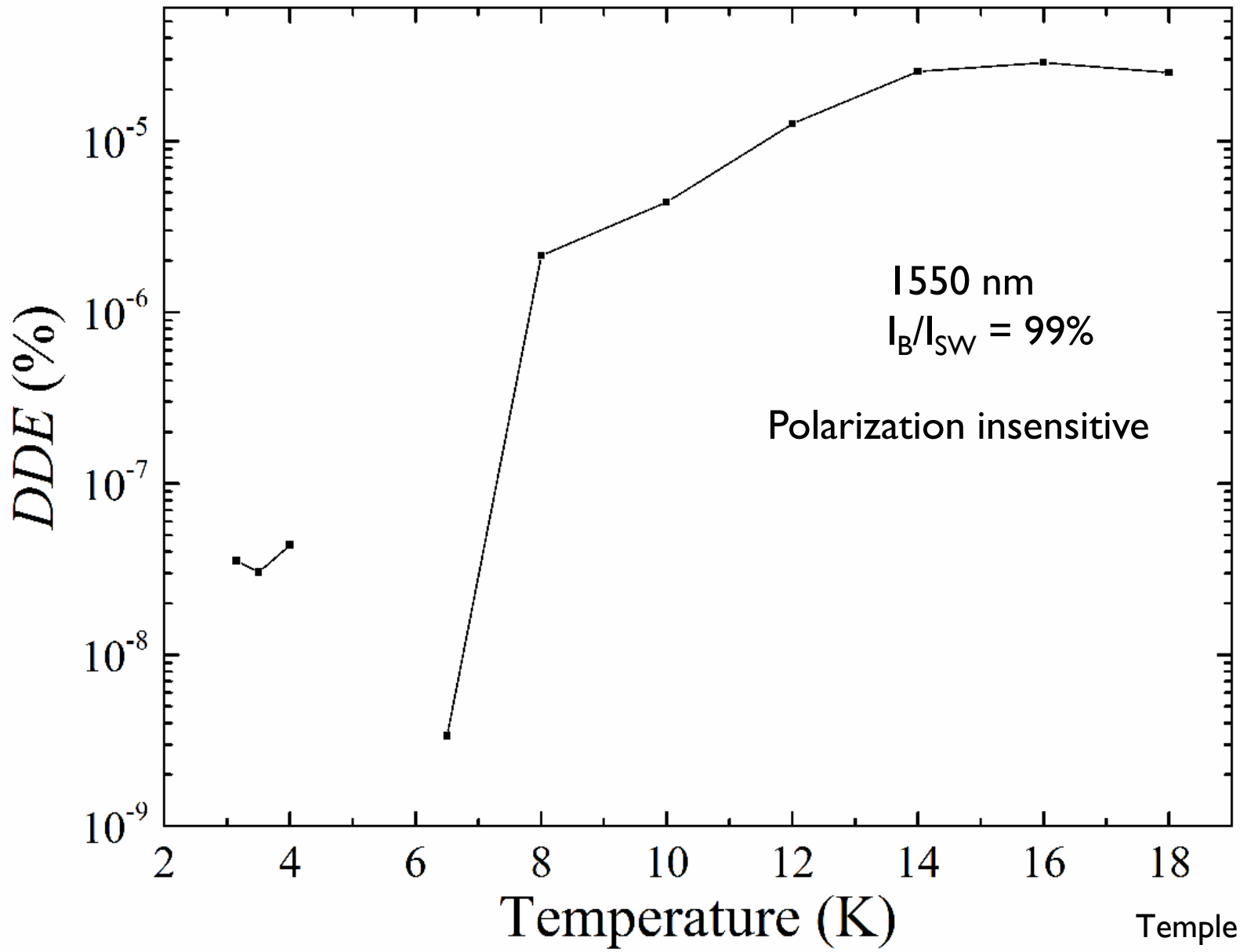
System Dark Count Rate vs Temperature



Inter-arrival time measurement



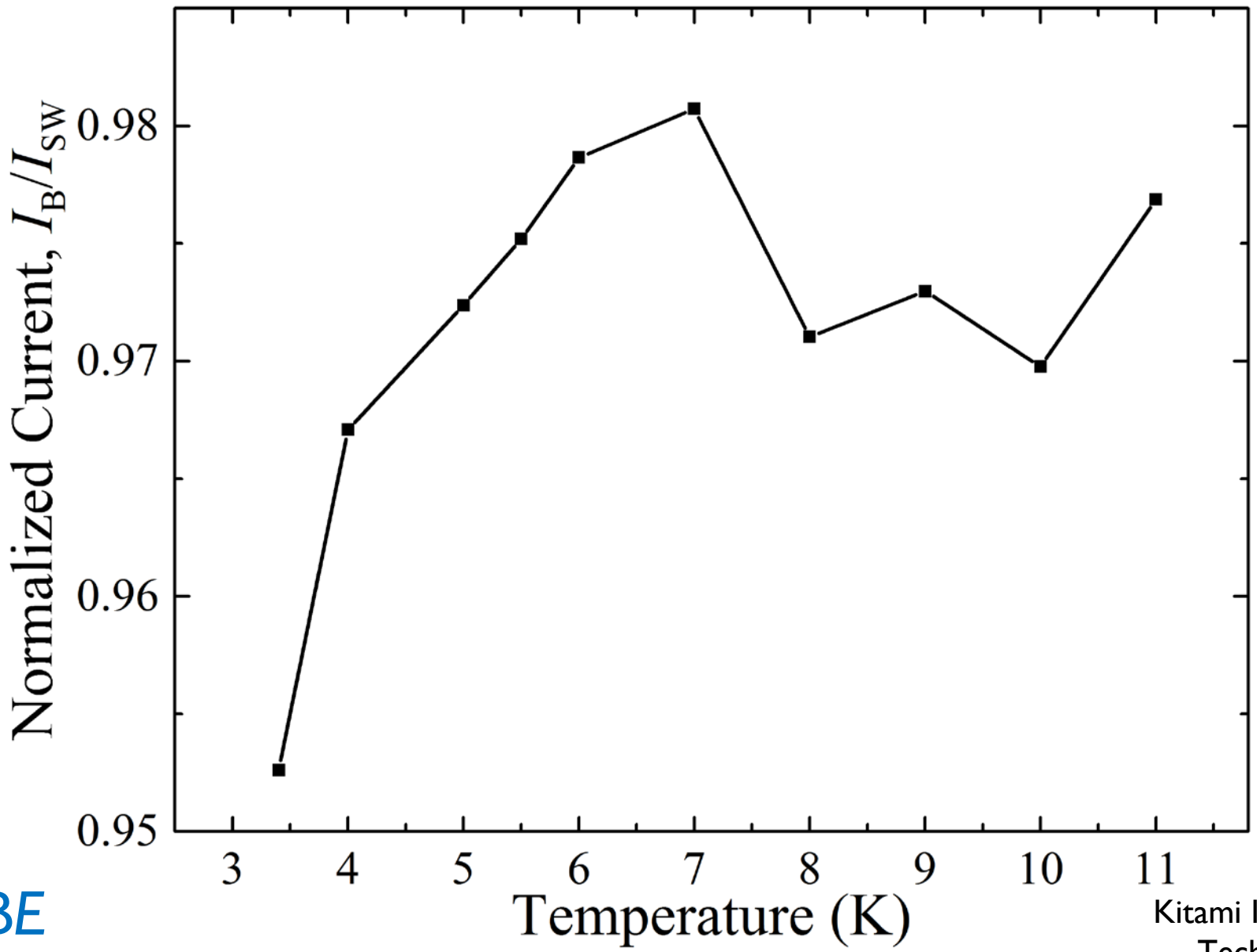
Device detection efficiency (*DDE*) vs Temperature



Temple University

B2 100 nm 1um x 1um
MBE
15 nm thick

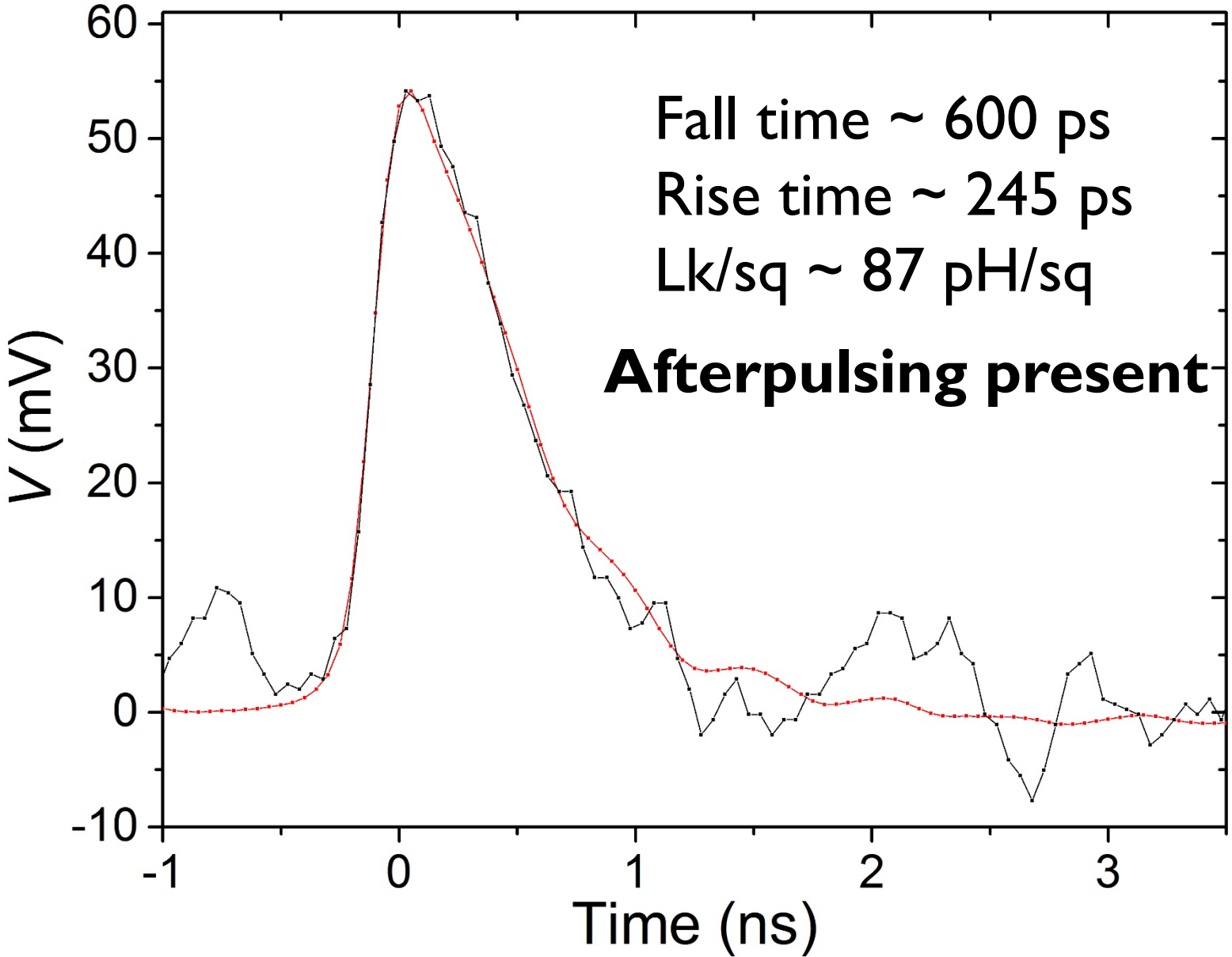
Normalized Current for Polarization vs Temperature



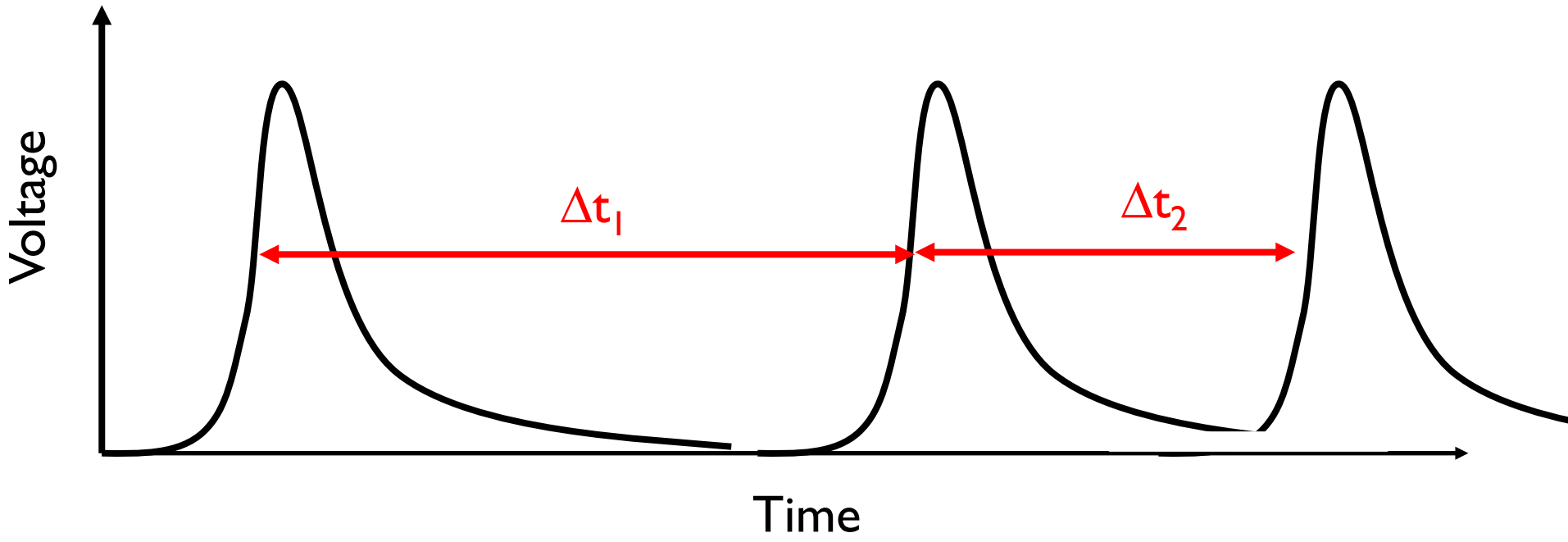
MBE

Kitami Institute of Technology

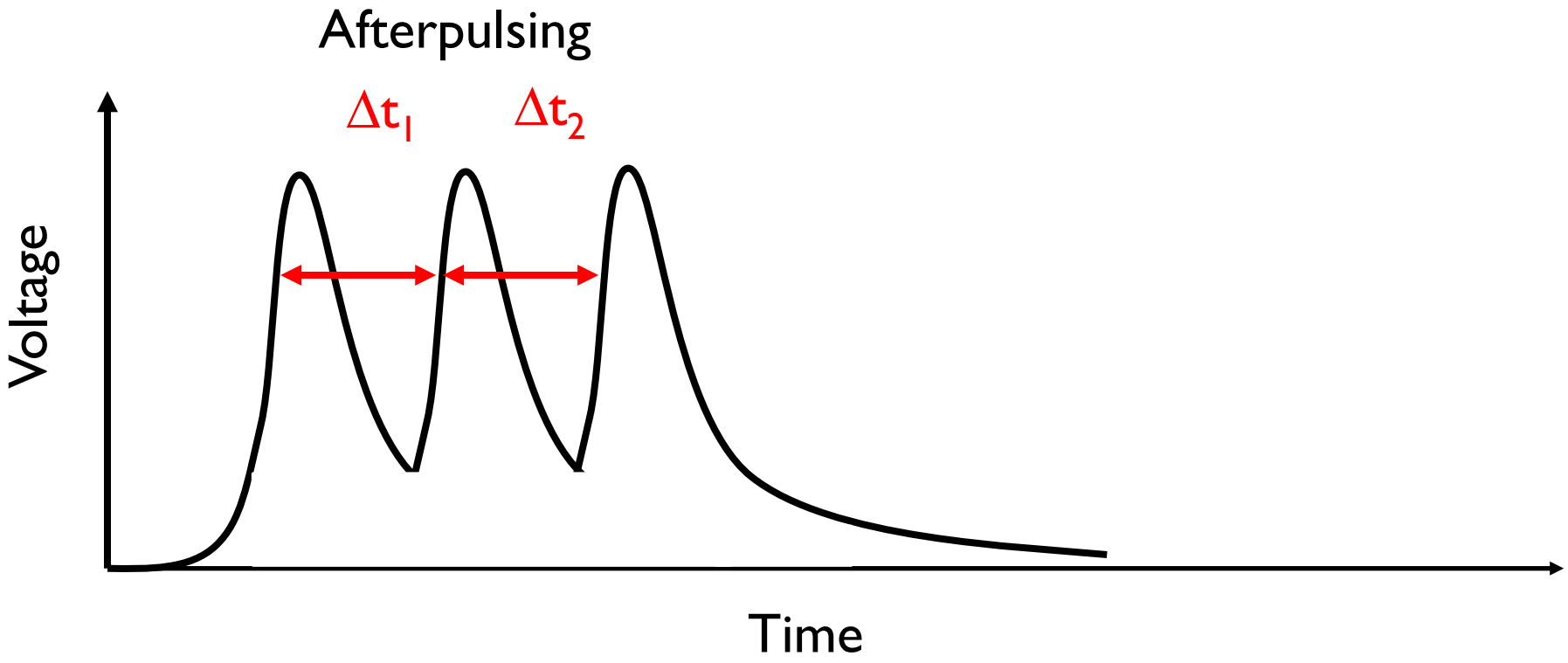
Optical pulse at 635 nm



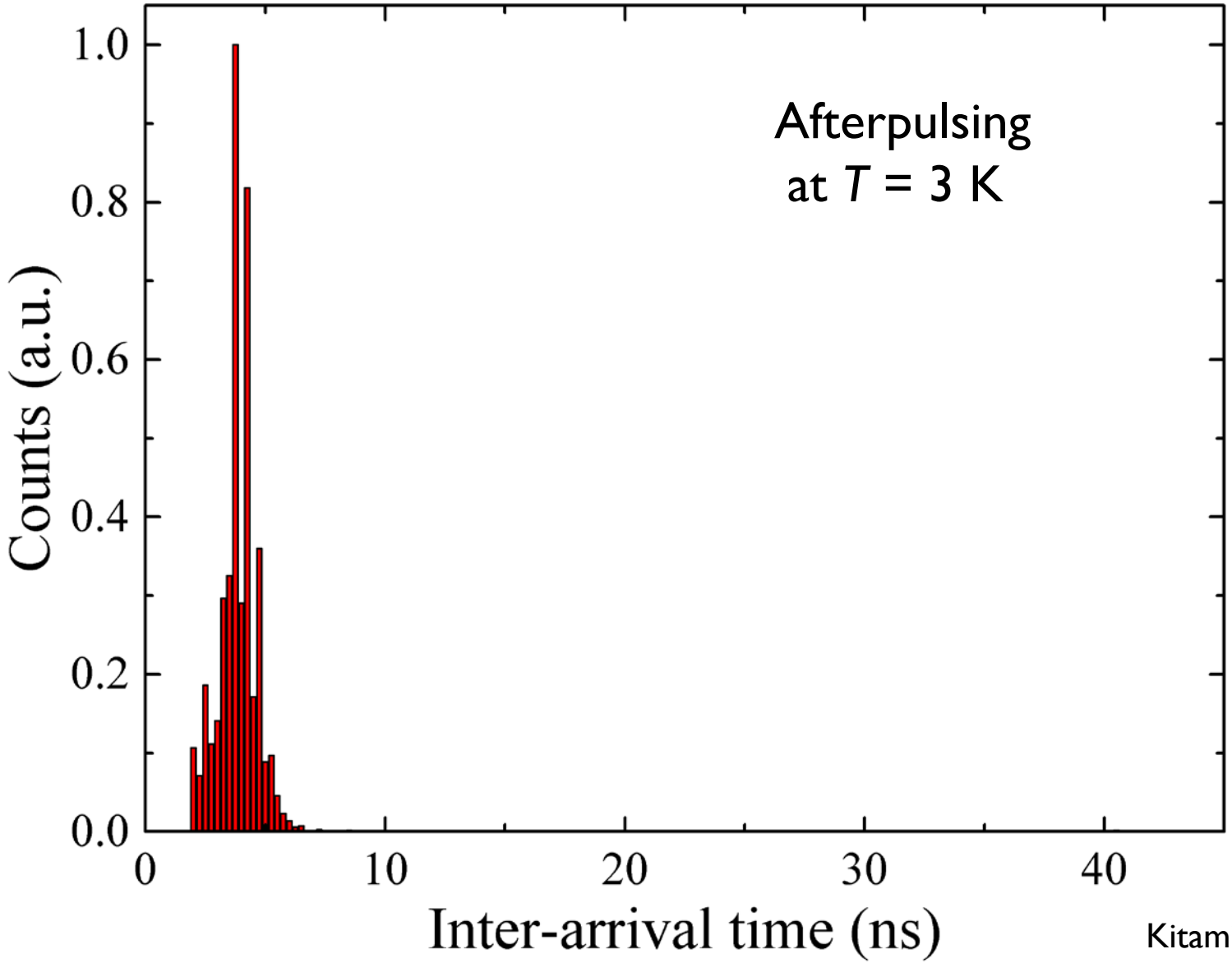
Inter-arrival time measurement



Inter-arrival time measurement



Increasing device speed with temperature



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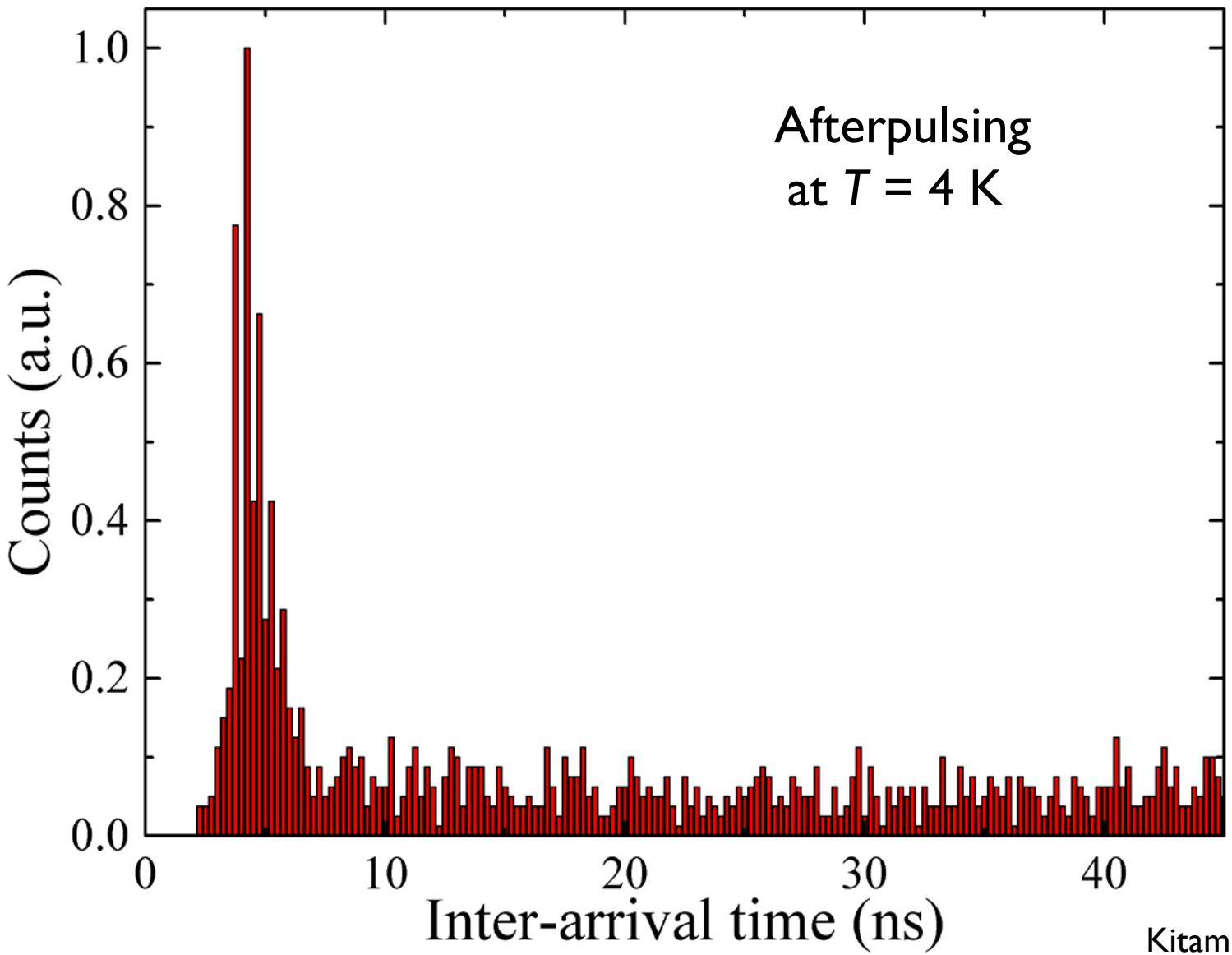
Increasing device speed with temperature



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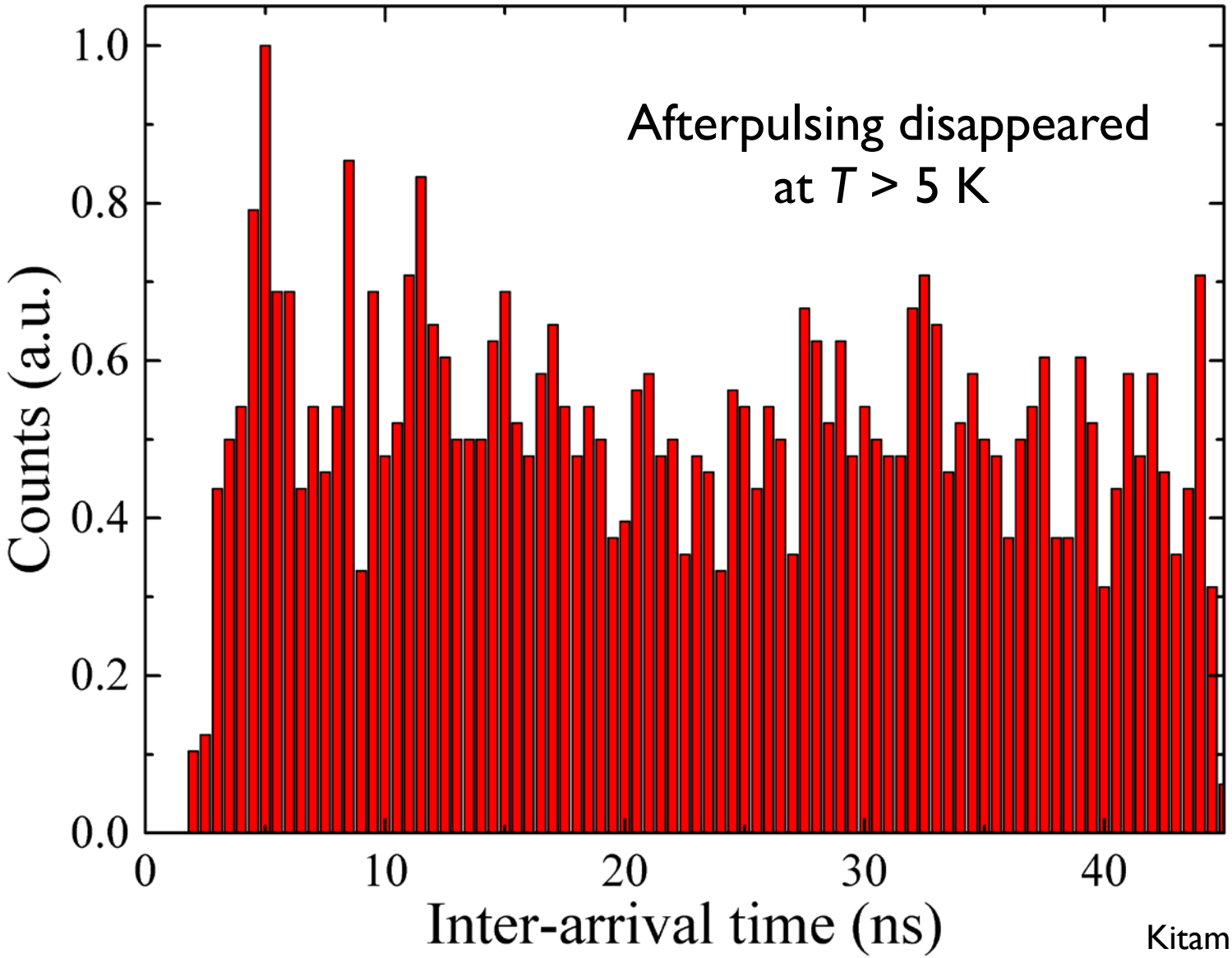
Increasing device speed with temperature



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