High-Operating-Temperature Superconducting Nanowire Single Photon Detectors

A. E. Velasco[1], D. Cunnane[1], R. Briggs[1], A. Beyer[1] M. Shaw[1], B. S. Karasik[1], M. Wolak[2], N. Acharya[2], X. Xi[2], H. Shibata[3,4], M. Ohkubo[5], N. Zen[5], M. Ukibe[5], F. Marsili[1]

[1]*Jet Propulsion Laboratory, California Institute of Technology*
[2]*Temple University*
[3]*Kitami Institute of Technology*
[4]*NTT Basic Research Laboratories*
[5]*National Institute of Advanced Industrial Science and Technology*

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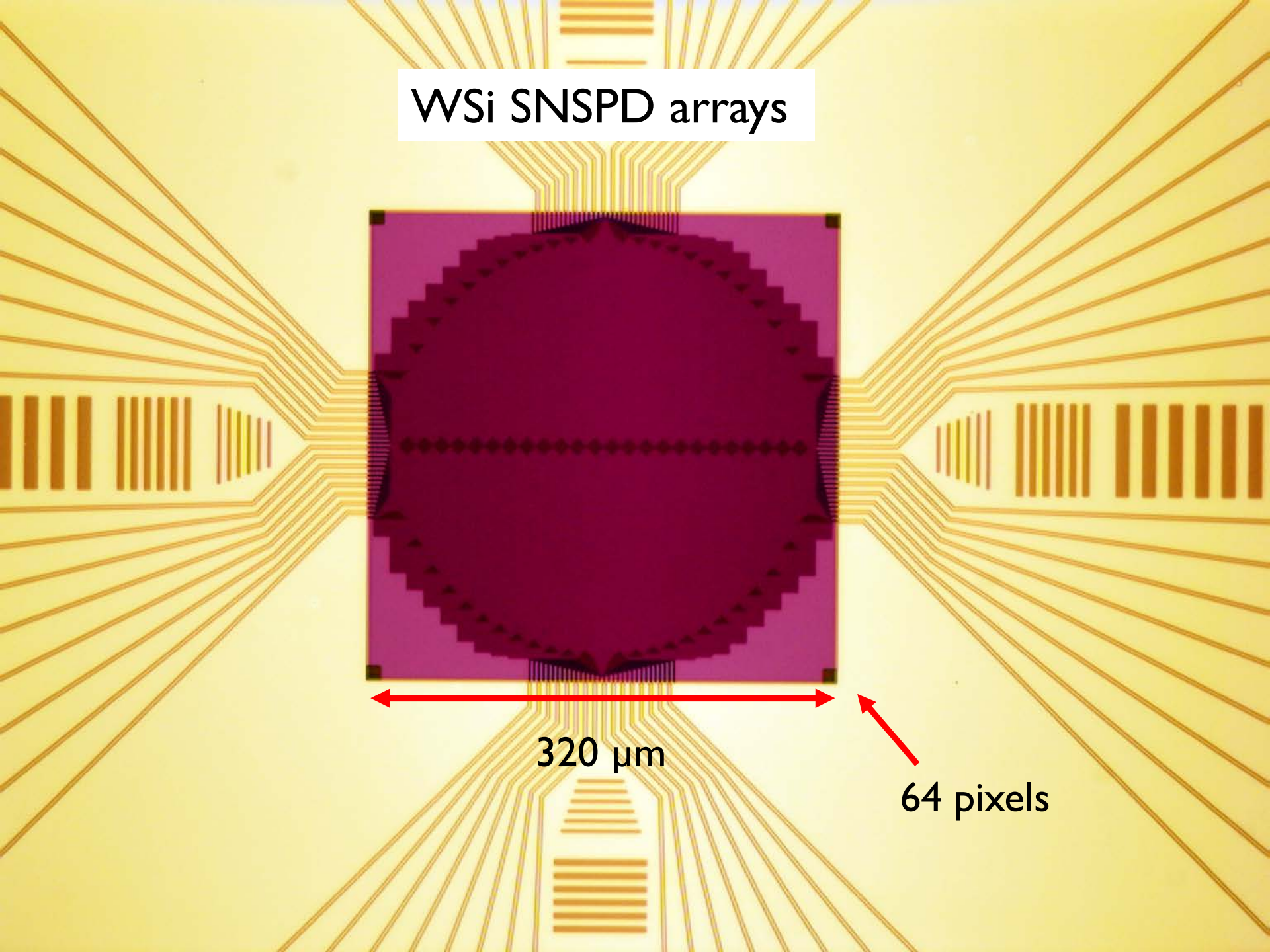
WSi Superconducting Nanowire Single Photon Detectors (SNSPD)

- High system detection efficiency: ~ 90% at 1550 nm wavelength
- 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)

WSi SNSPD arrays



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

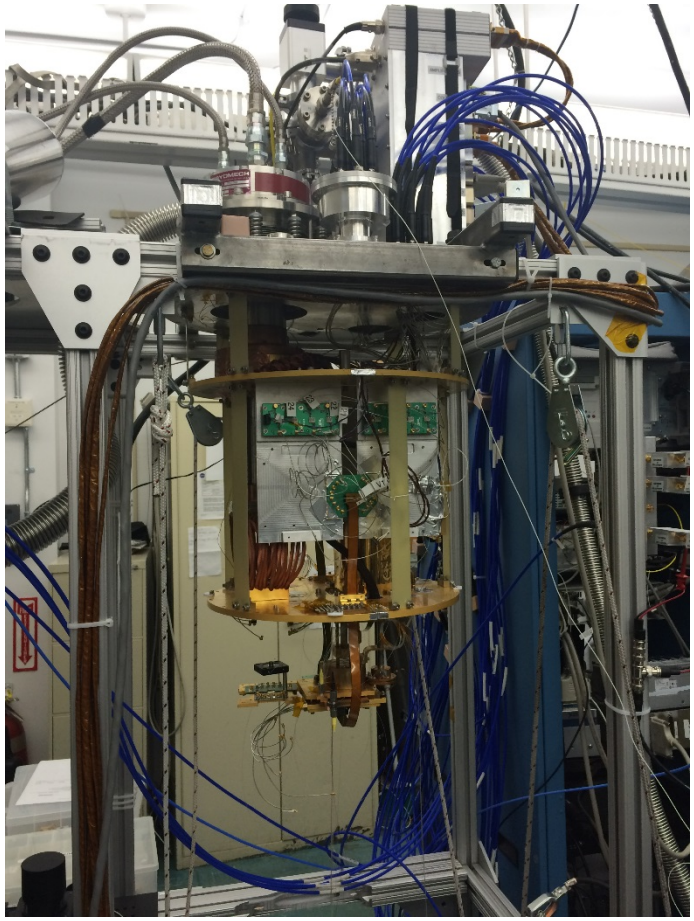
↓

Complex cryogenics

Refrigerator Comparison

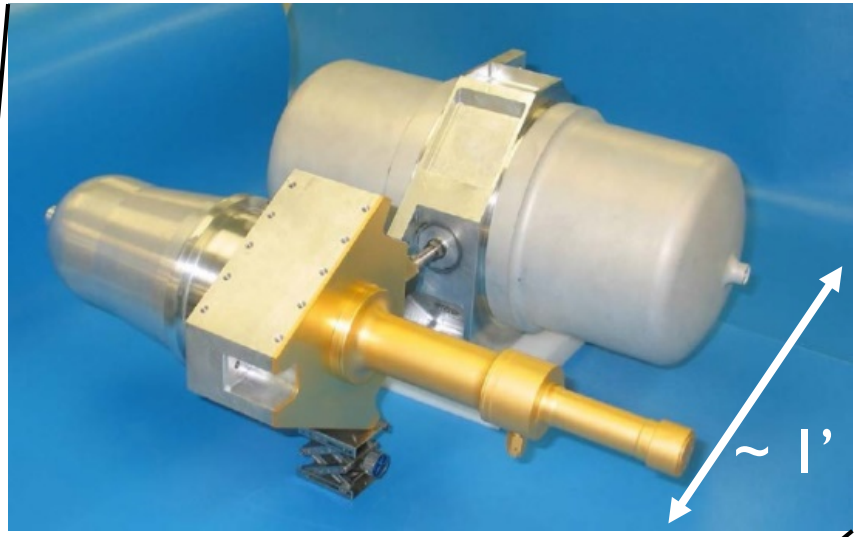
He^3/He^4 Sorption/Pulse Tube

~ 4.5’



T ~ 500 mK

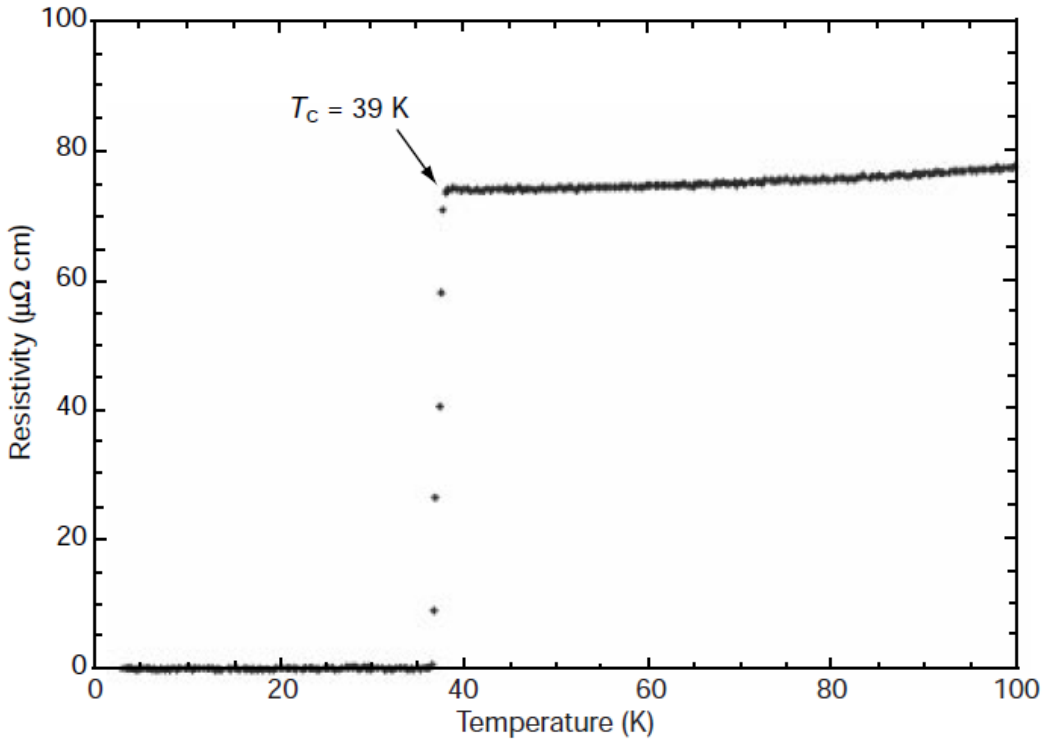
Stirling/Pulse Tube (Raytheon LT-RSP2)



T ~ 10 K

Our Approach: MgB_2 SNSPDs

- 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 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

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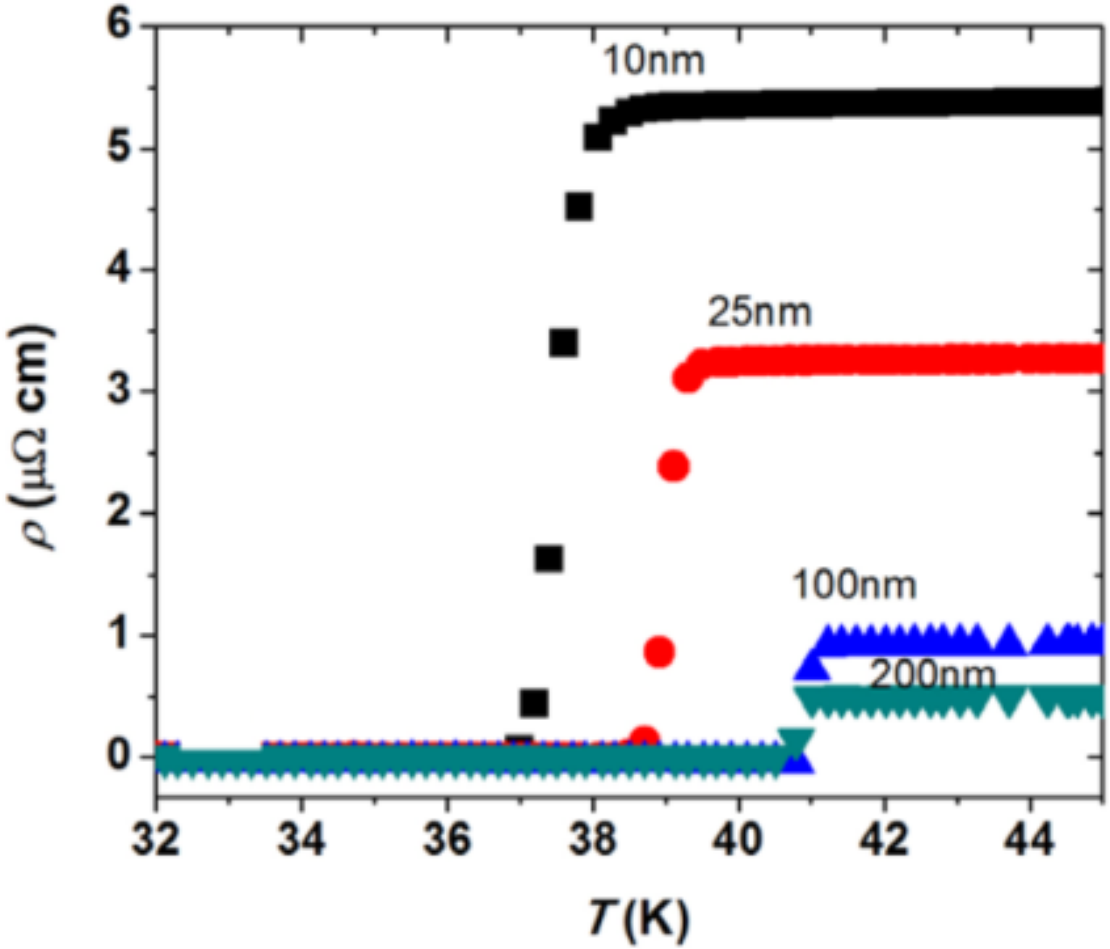
High Quality MgB_2 Thin Films

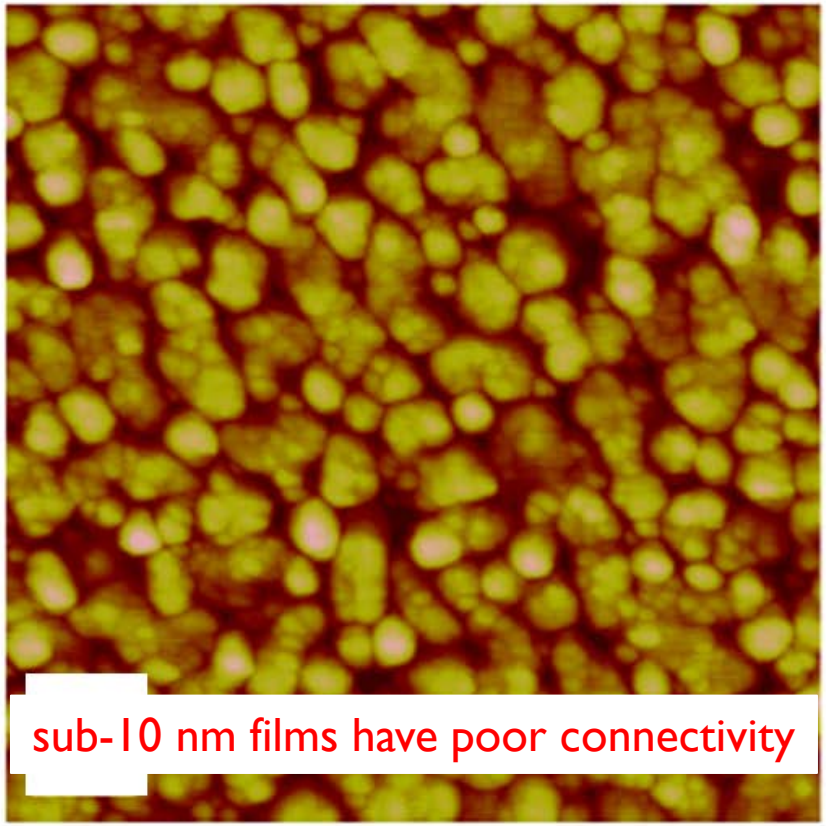
Hybrid Physical-Chemical Deposition (HPCVD)



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

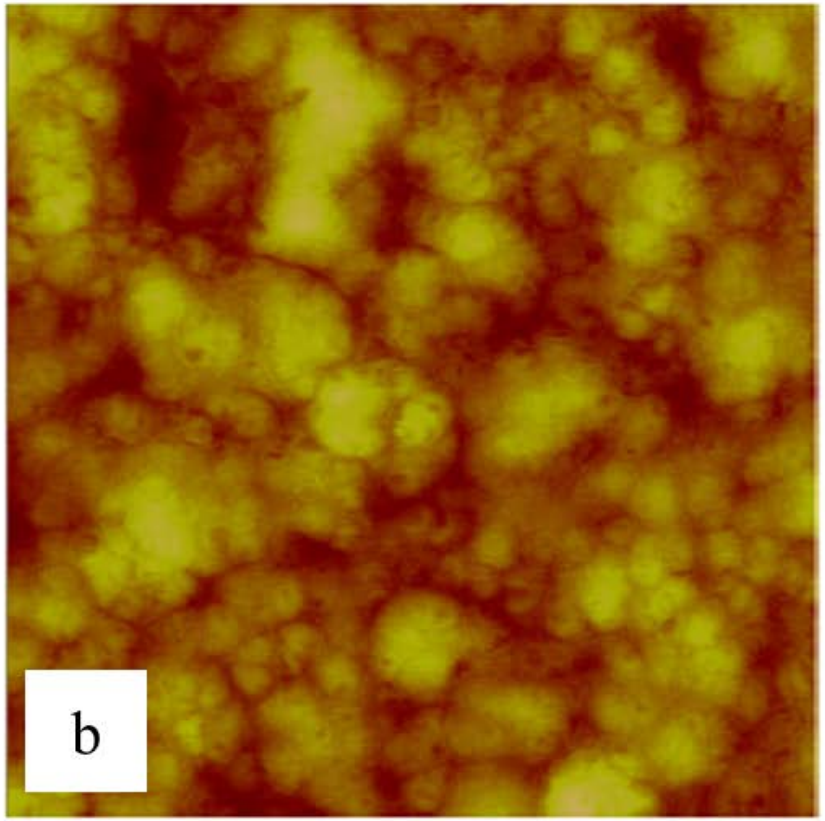
Problem with sub-10 nm films

d = 7.5 nm



1 μm

d = 25 nm

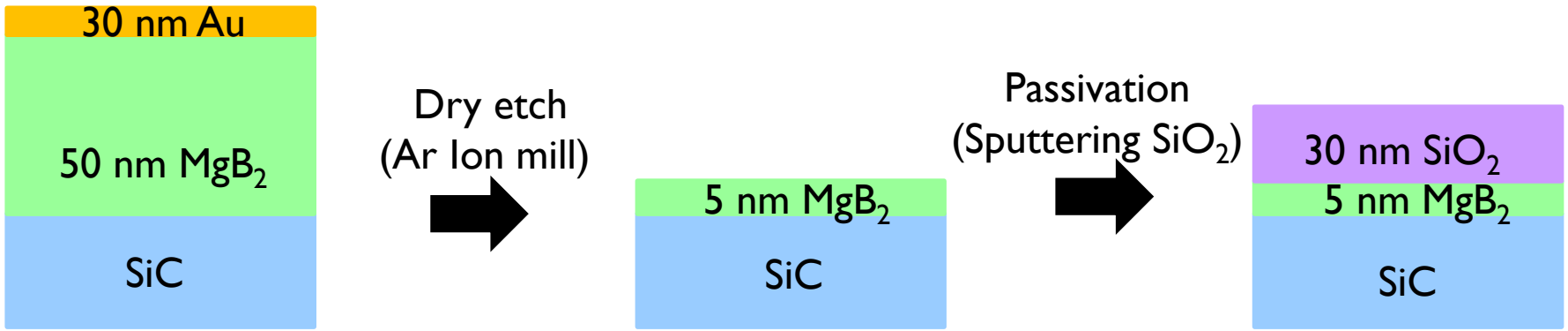


1 μm

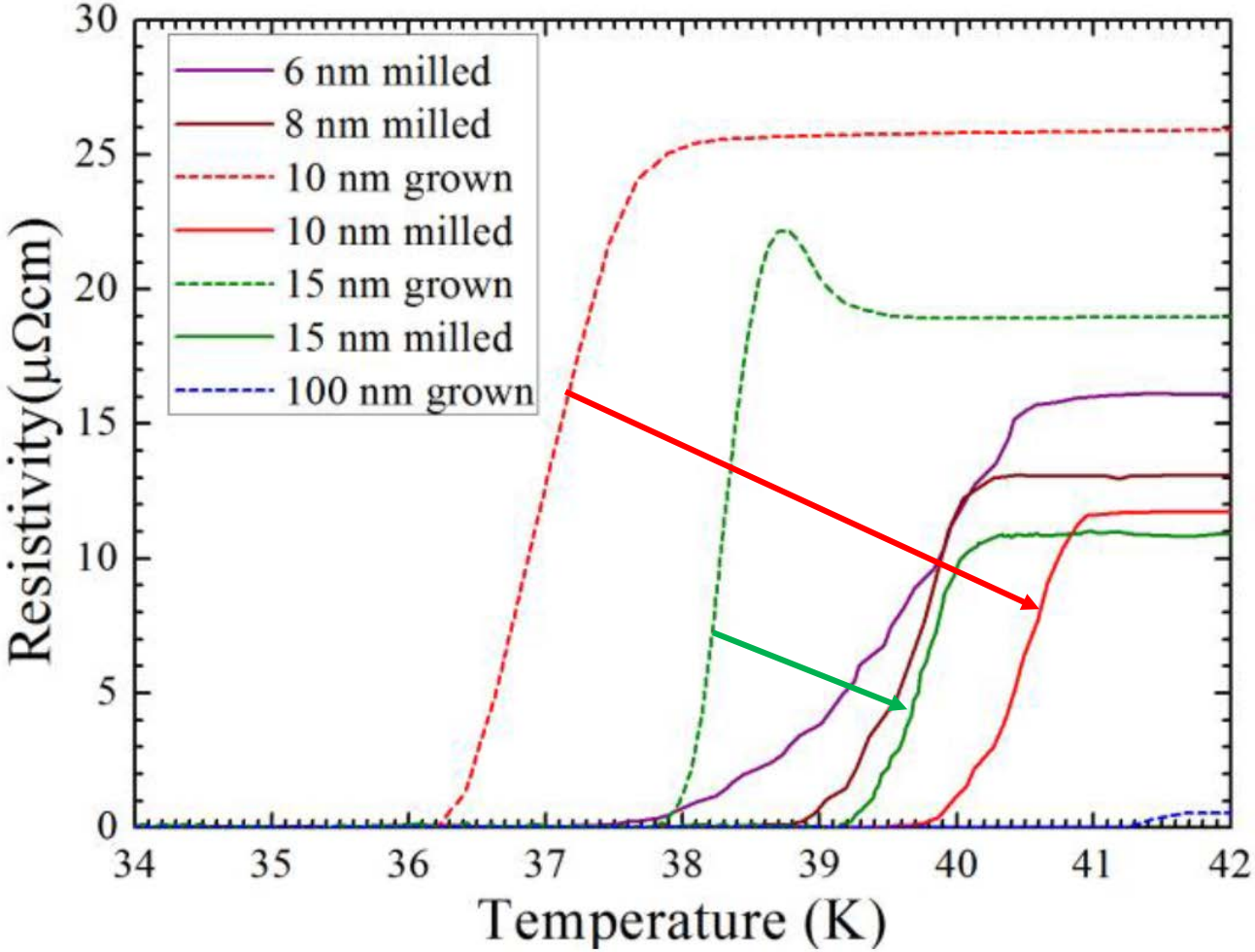
C. Zhuang *et al.*, Supercond. Sci. Technol. **23** (5), 055004 (2010)

Thin Film Fabrication Process

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



Preliminary Results



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

Challenges of MgB_2 SNSPDs

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  i. MgB_2 highly reactive with oxygen
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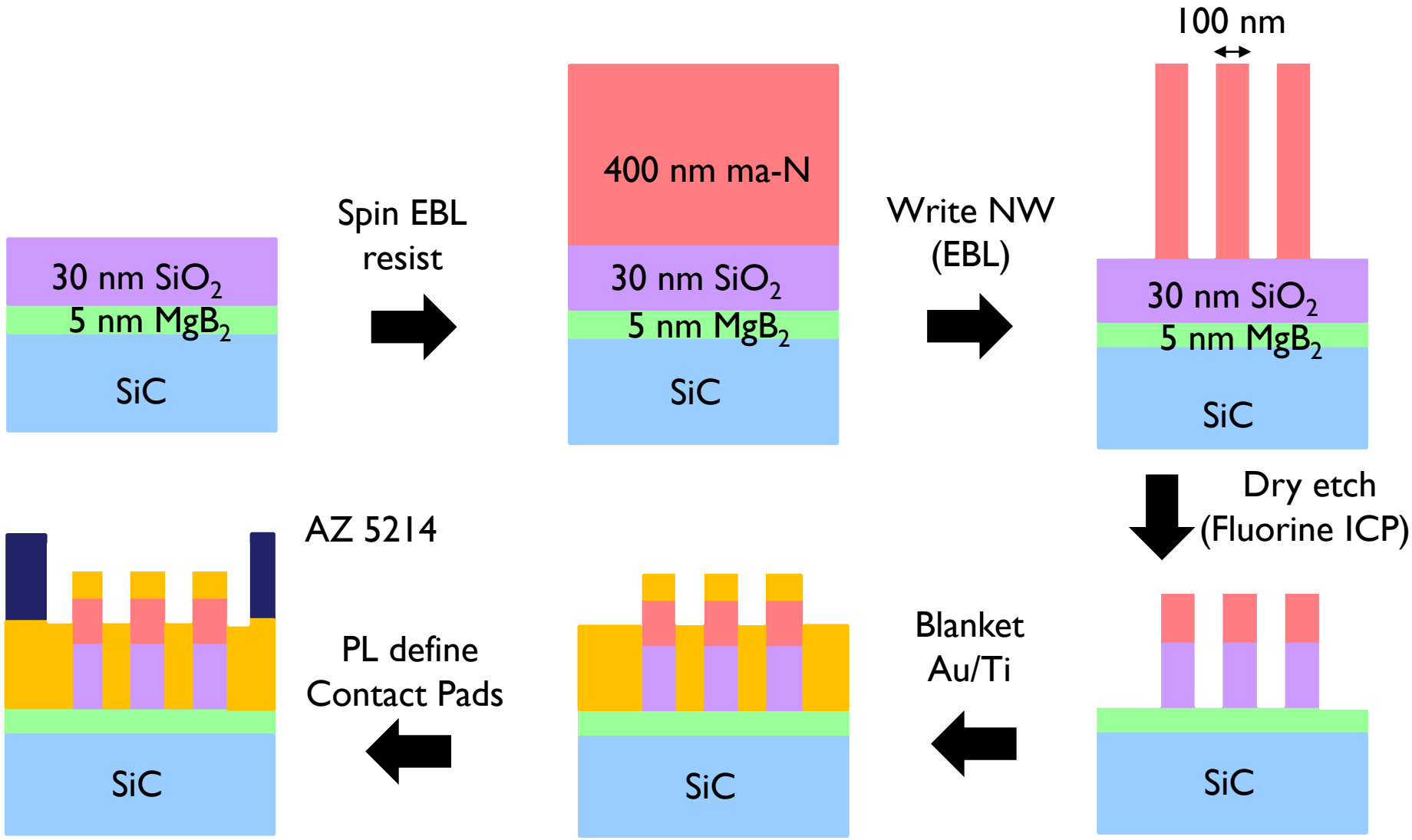
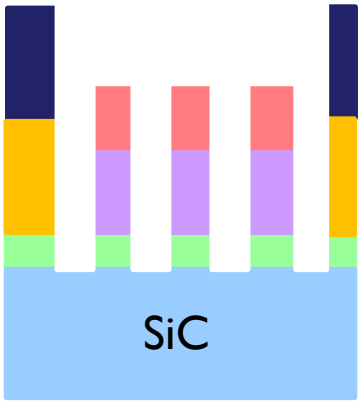
- Single photon detection at 20 K never demonstrated

Current fabrication process

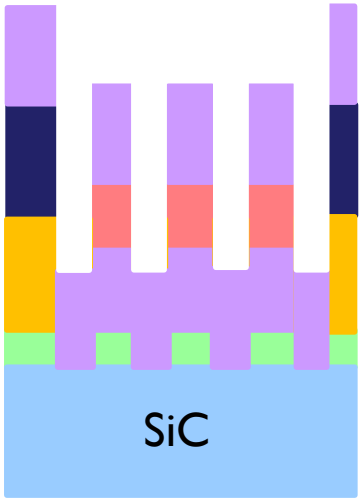


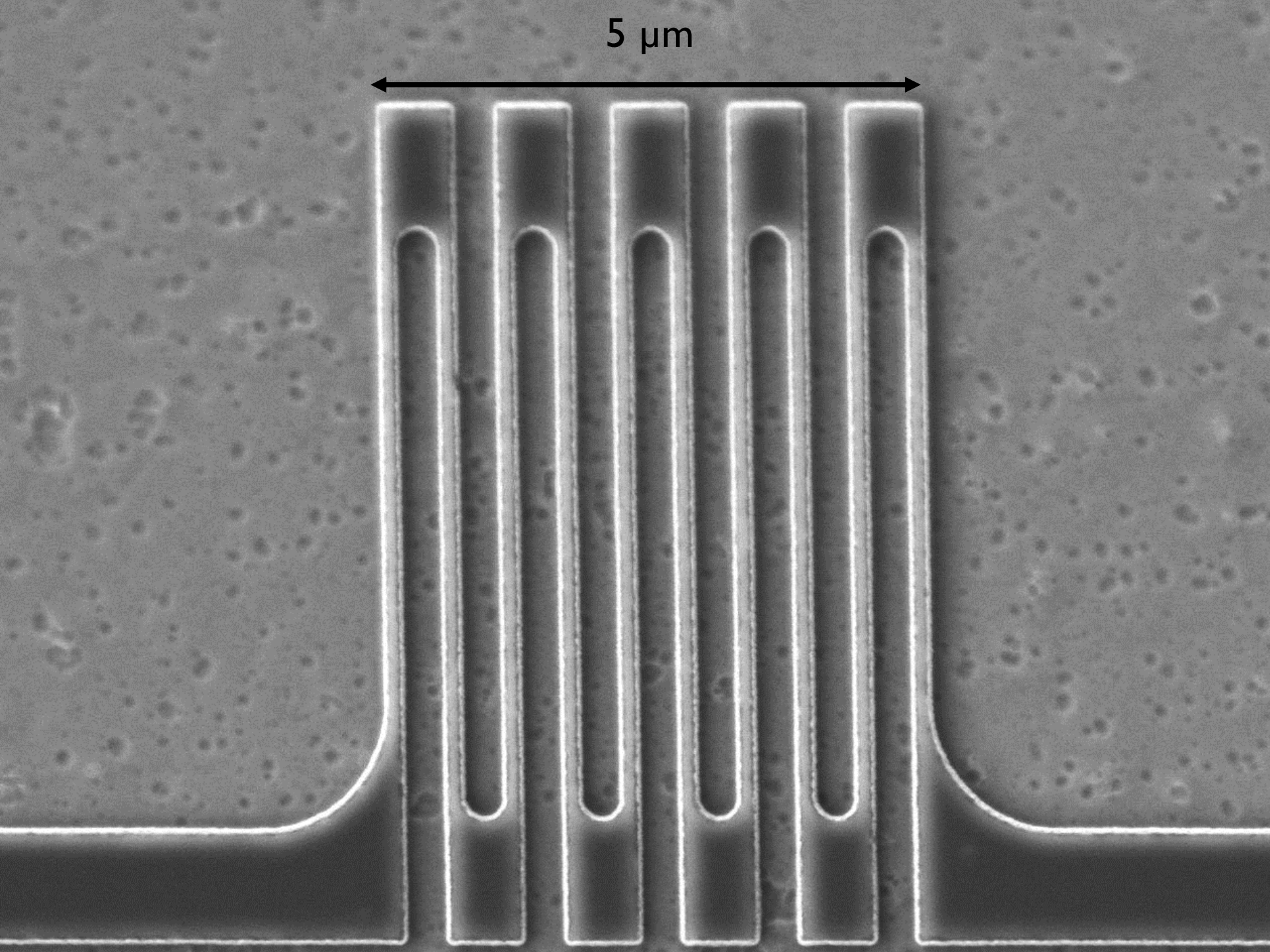
Current fabrication process

Dry etch
(Ar Ion mill)



Passivation
(SiO2)




5 µm

Challenges of MgB_2 SNSPDs

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  ii. MgB_2 etch limited to argon ion milling
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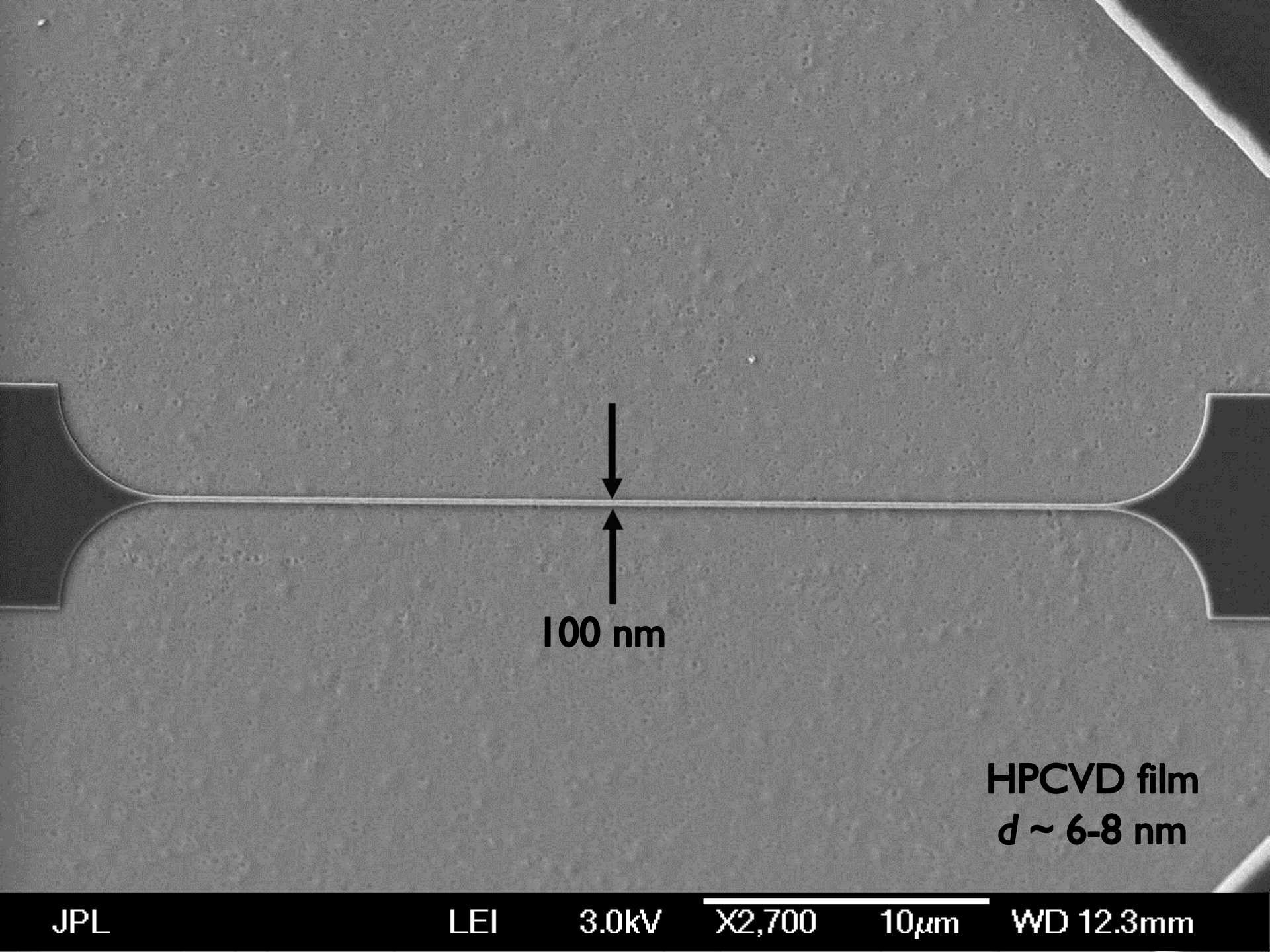
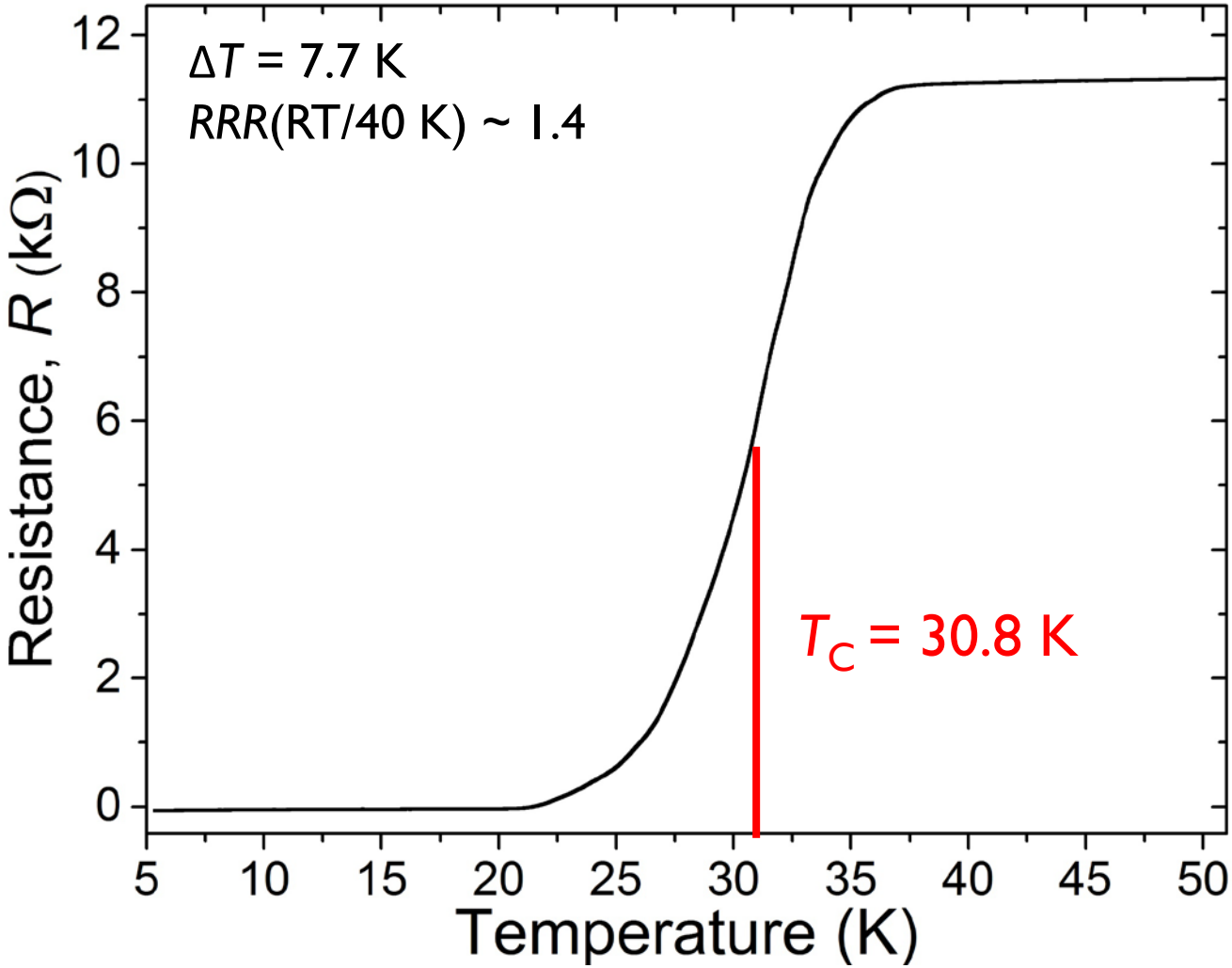

100 nm
HPCVD film
d ~ 6-8 nm
JPL
LEI
3.0kV
X2,700
10μm
WD 12.3mm

Transition Temperature, T_C



Single Photon Sensitivity

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

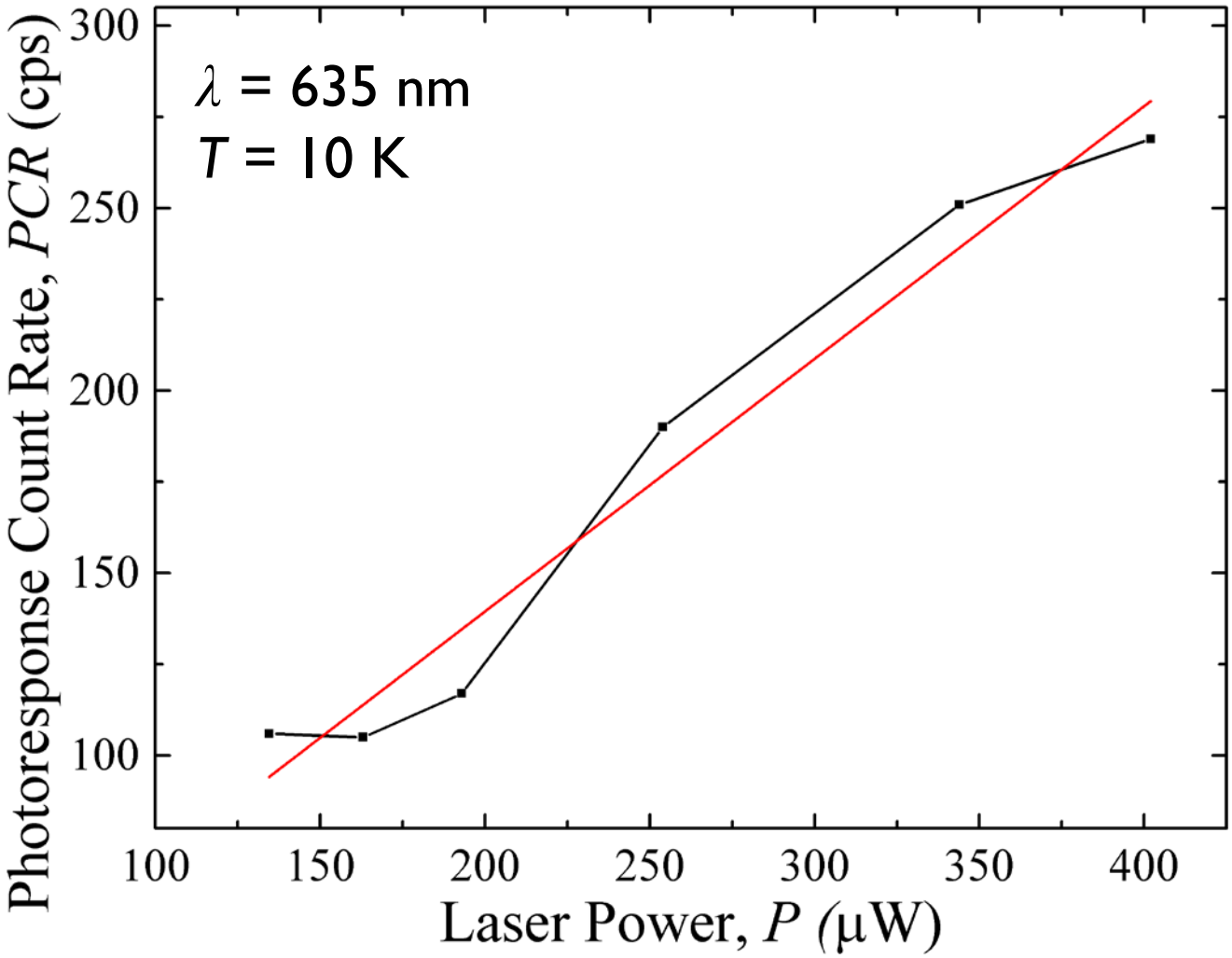
$$\eta_2 = 0,\ \mu\eta_1 << 1$$

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

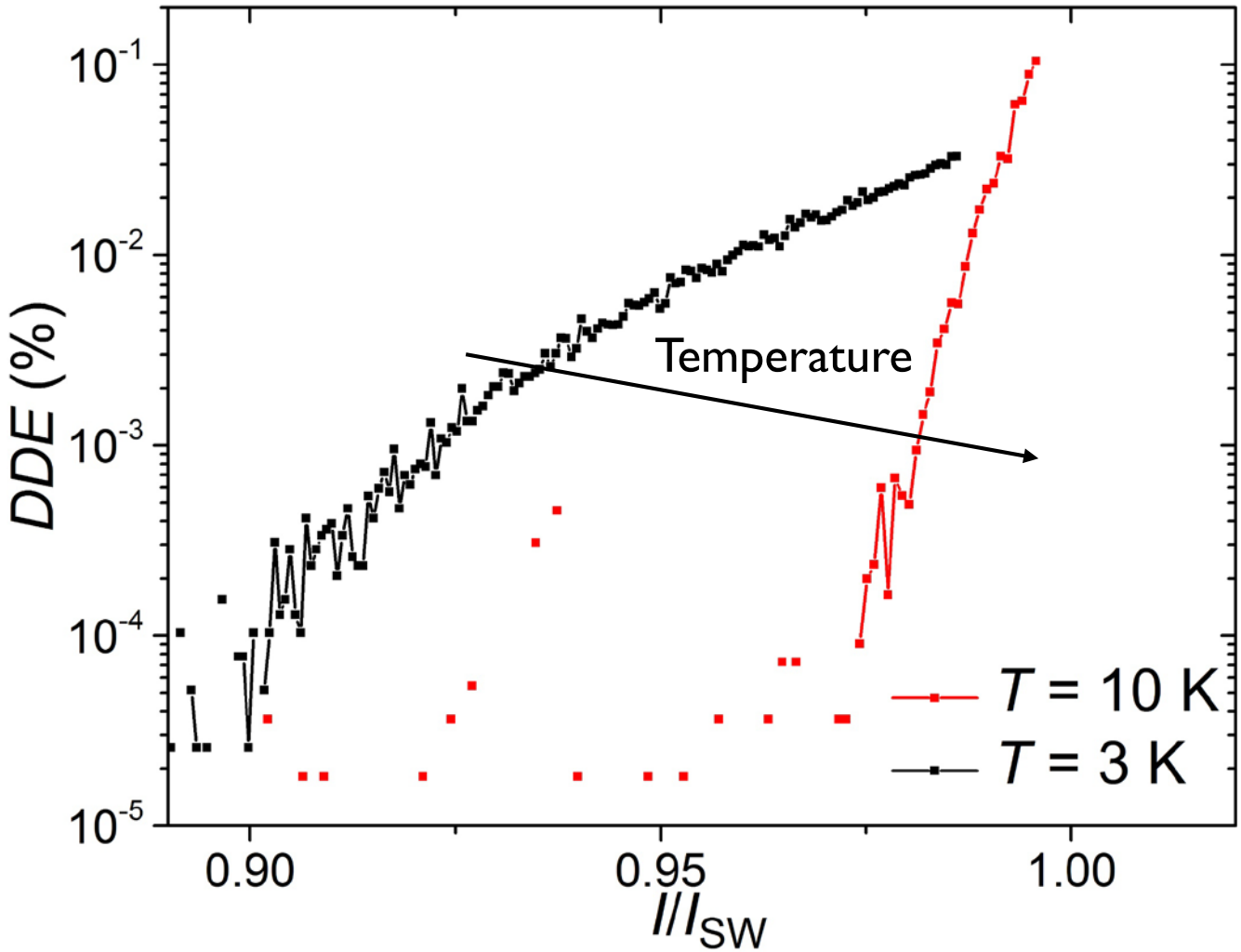
μ = mean photon flux
η_1 = single photon detection efficiency
η_2 = two photon detection efficiency

Single Photon Detection at 10 K!

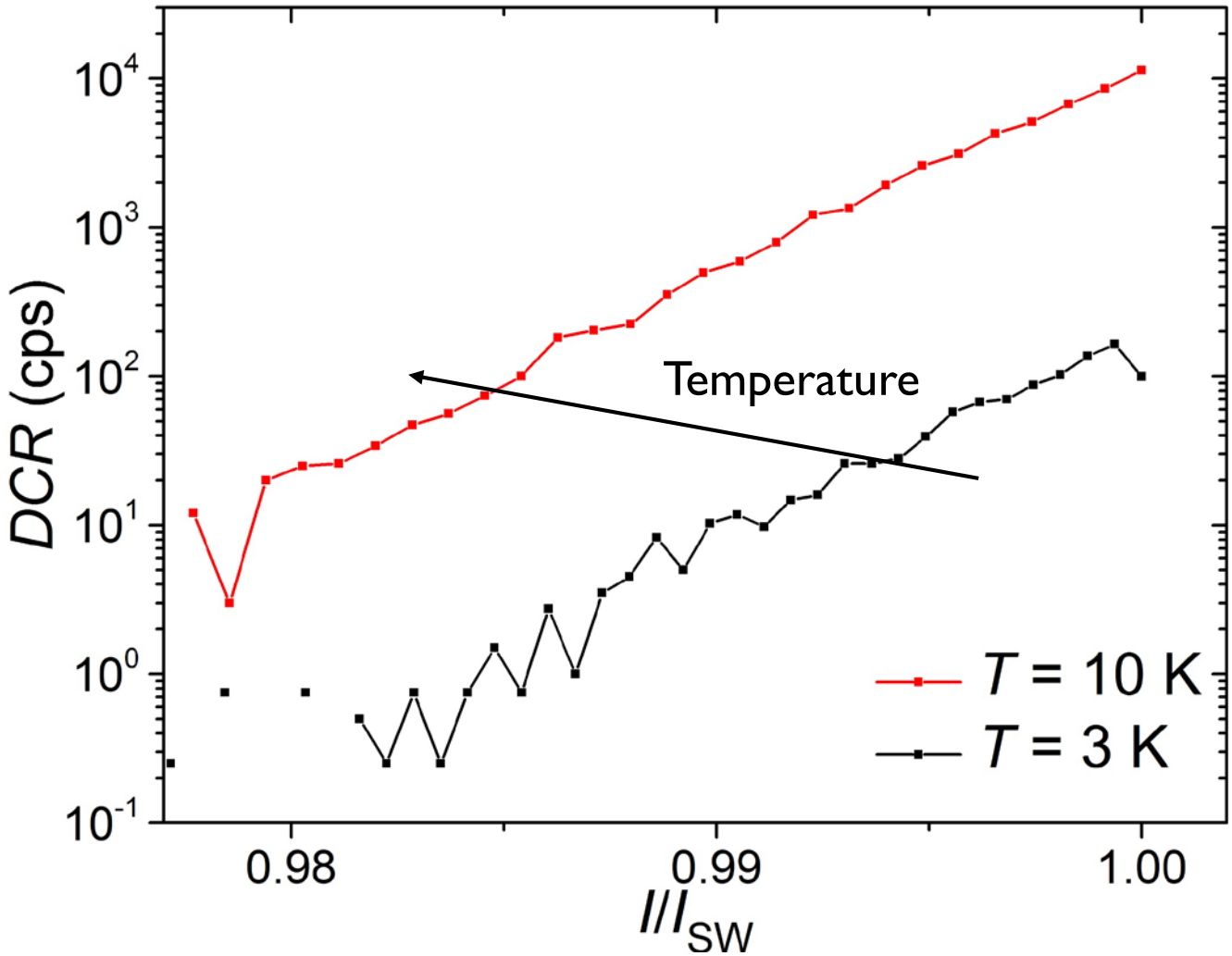
PCR is linear with laser power: $P_{click}(\mu) \sim \mu\eta_1$



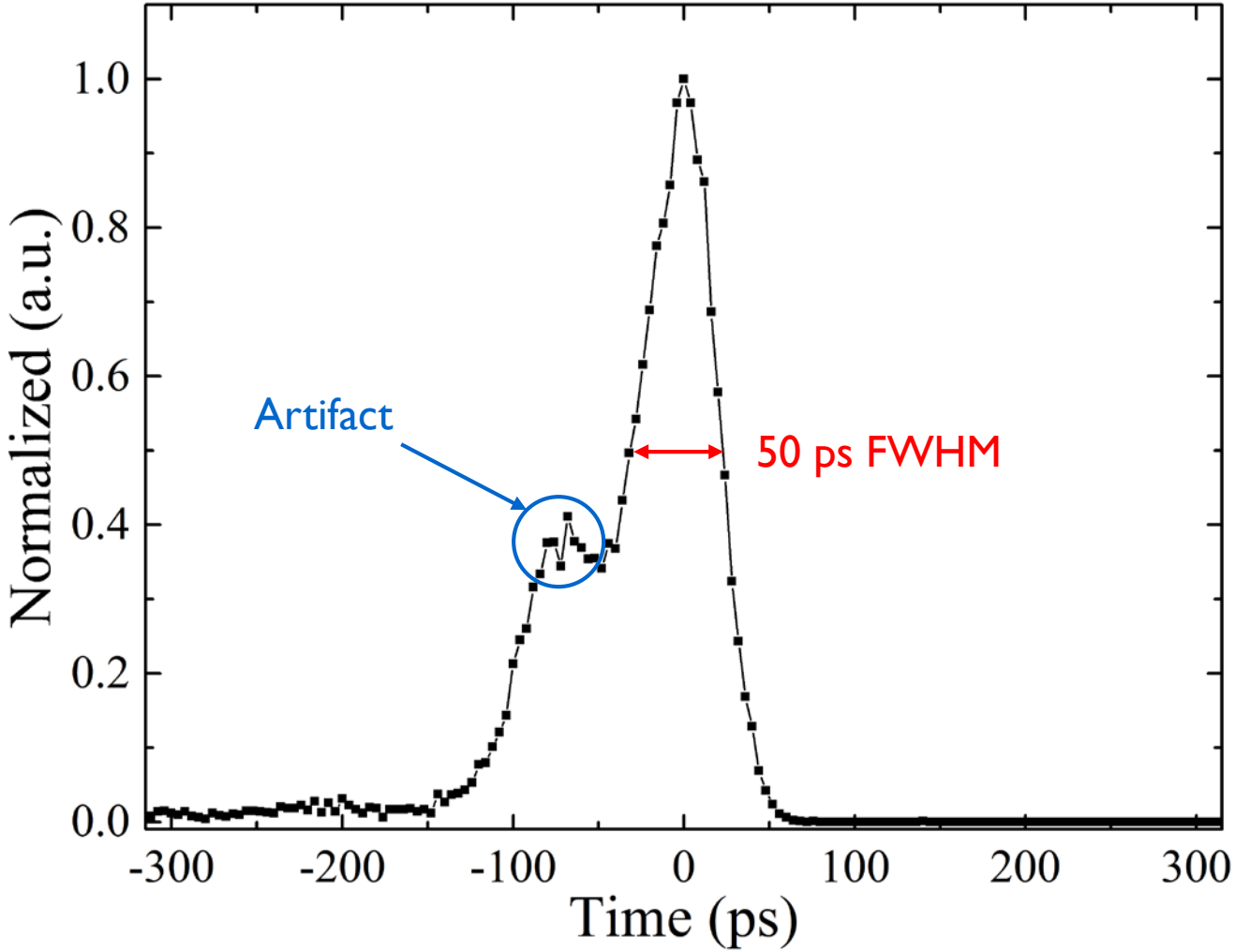
Device Detection Efficiency, *DDE*



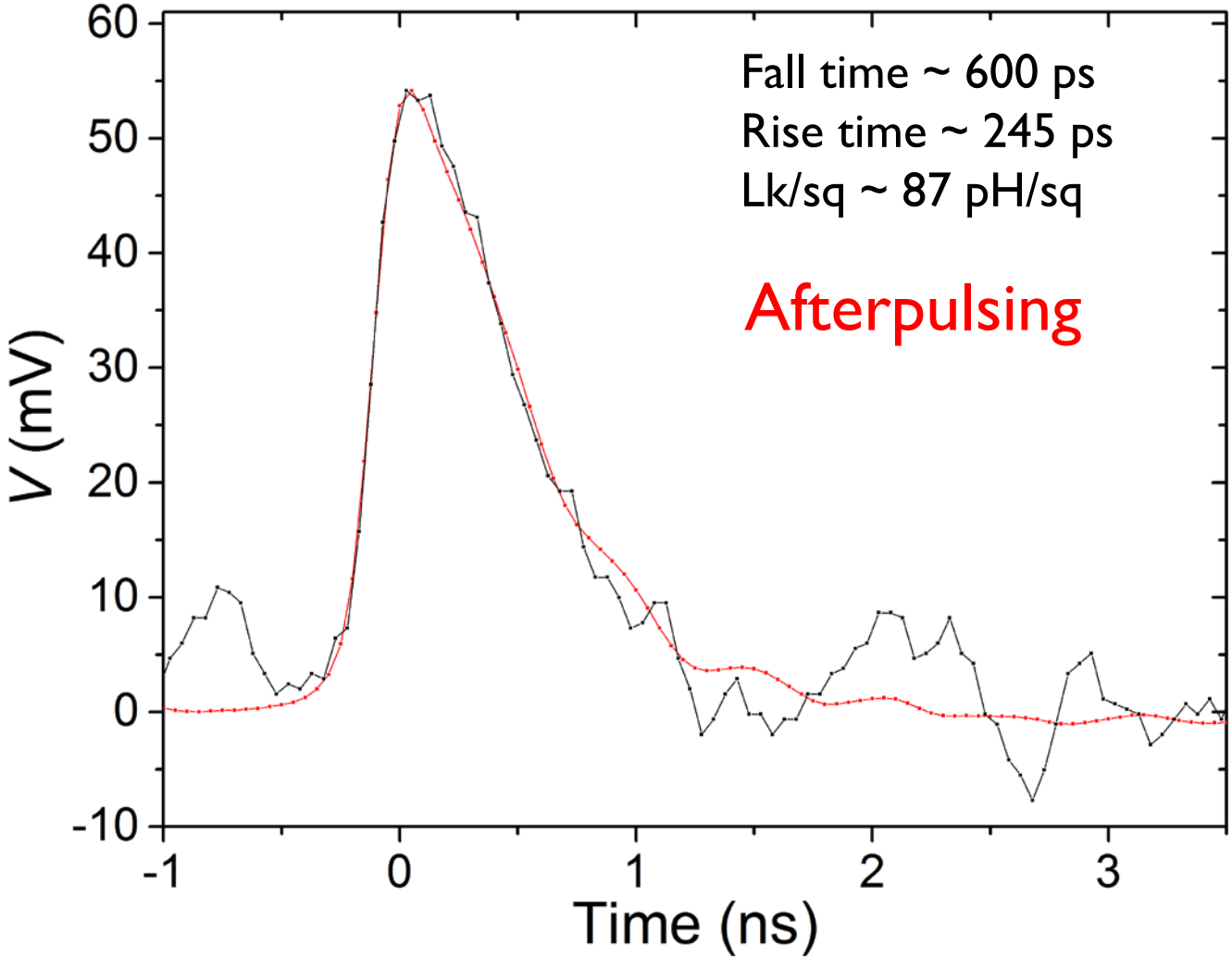
Dark Count Rate, *DCR*

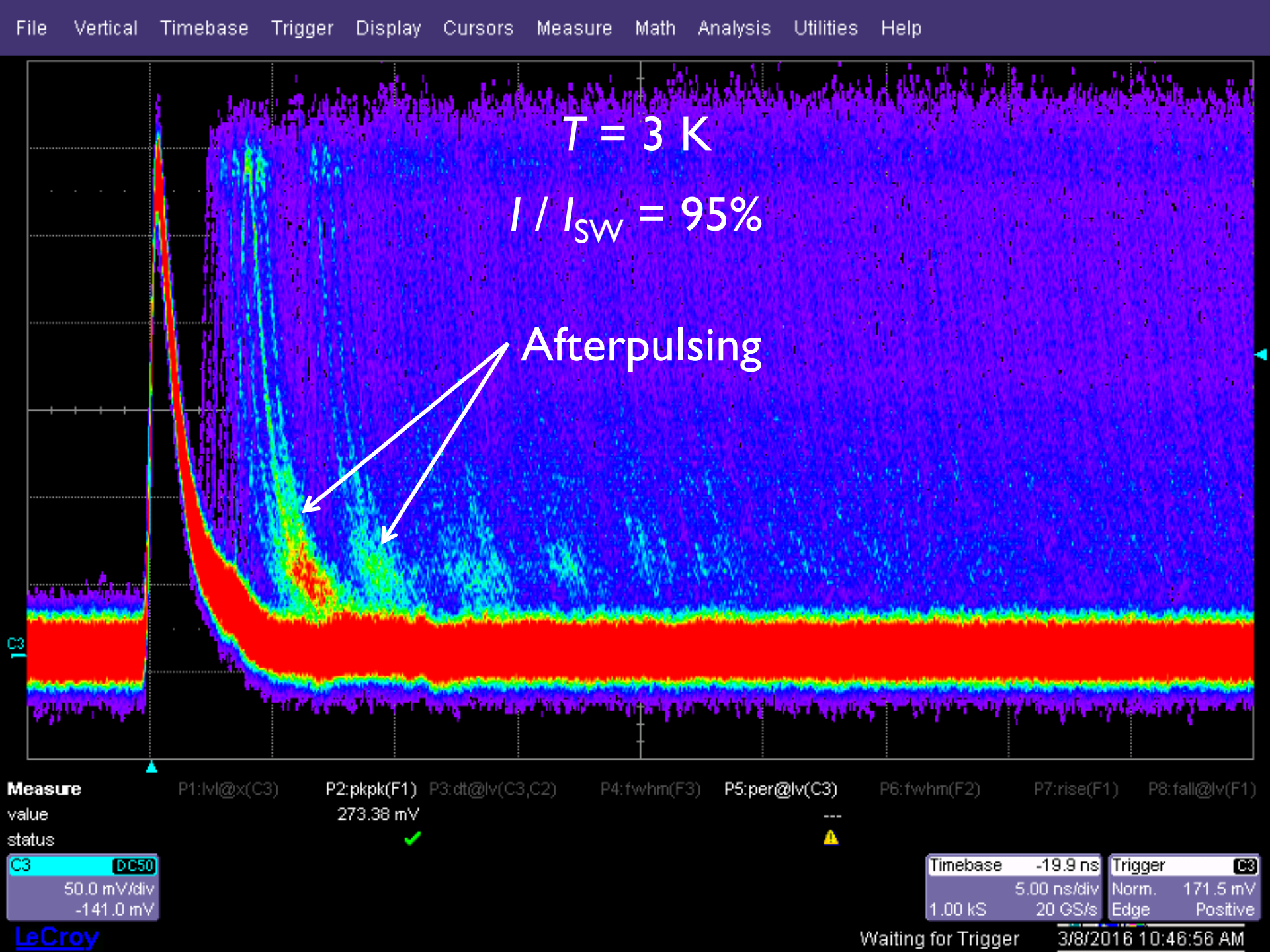


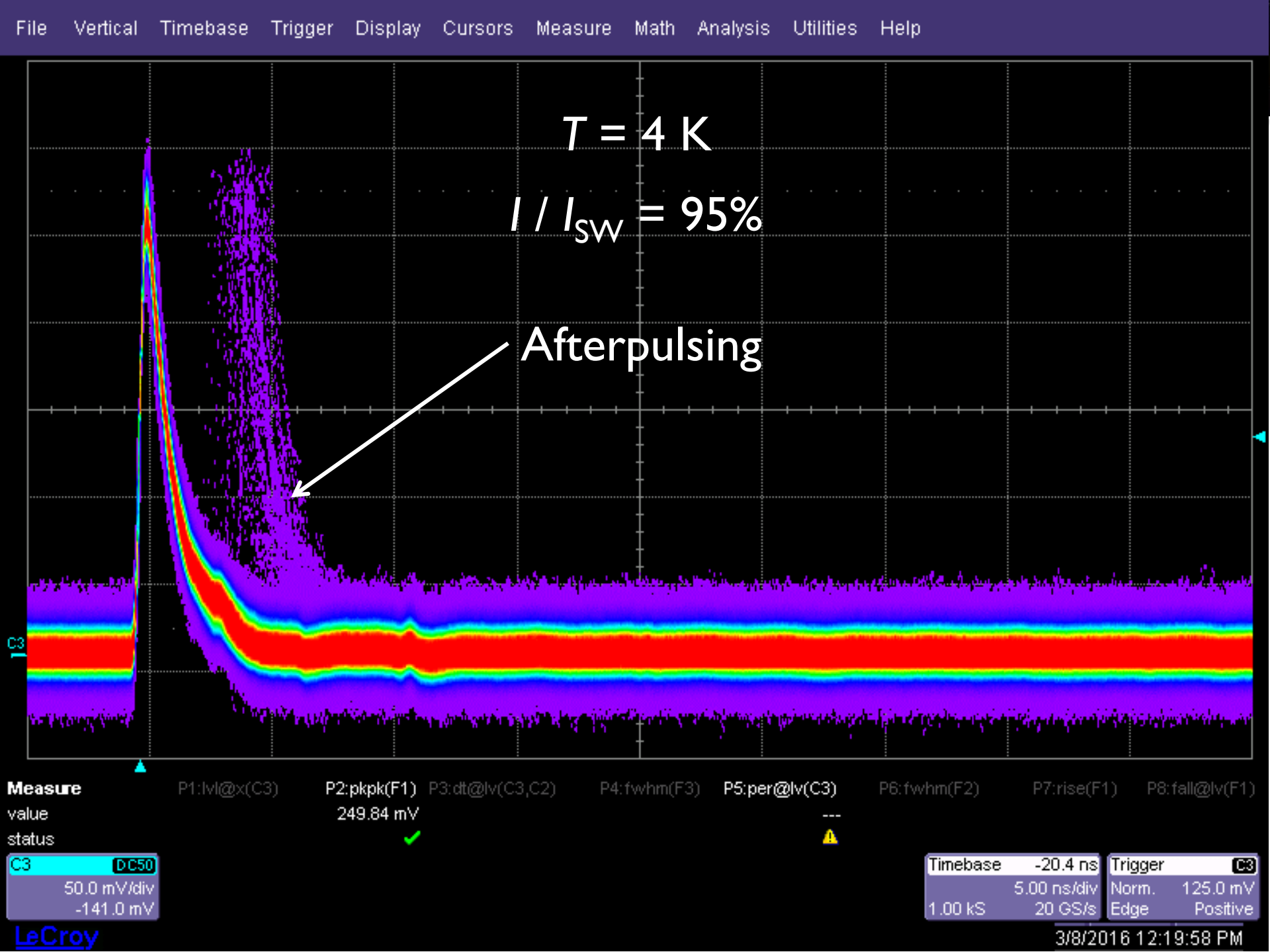
Jitter

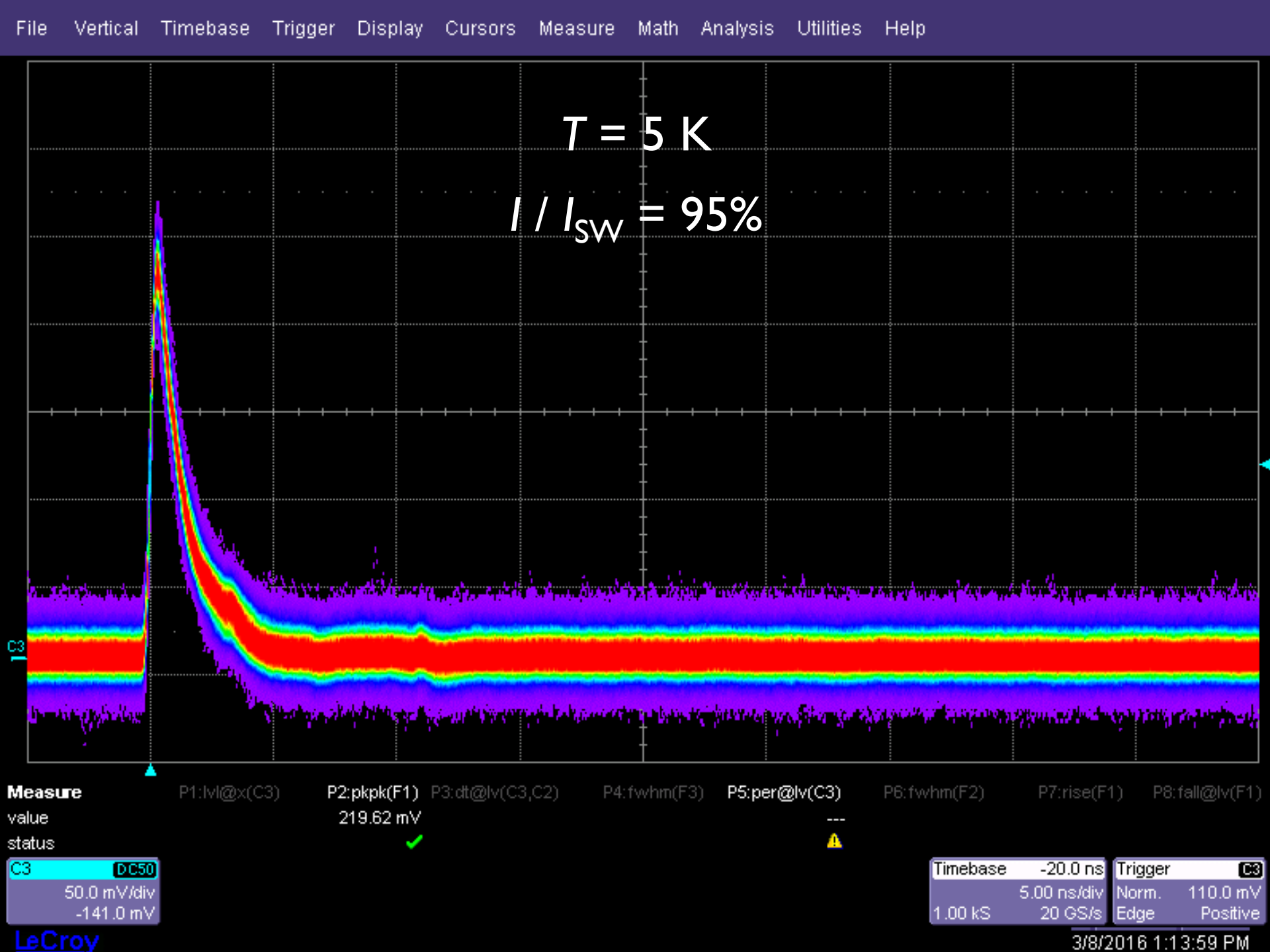

Normalized (a.u.)
1.0
0.8
0.6
0.4
0.2
0.0
-300
-200
-100
0
100
200
300
Time (ps)
Artifact
50 ps FWHM

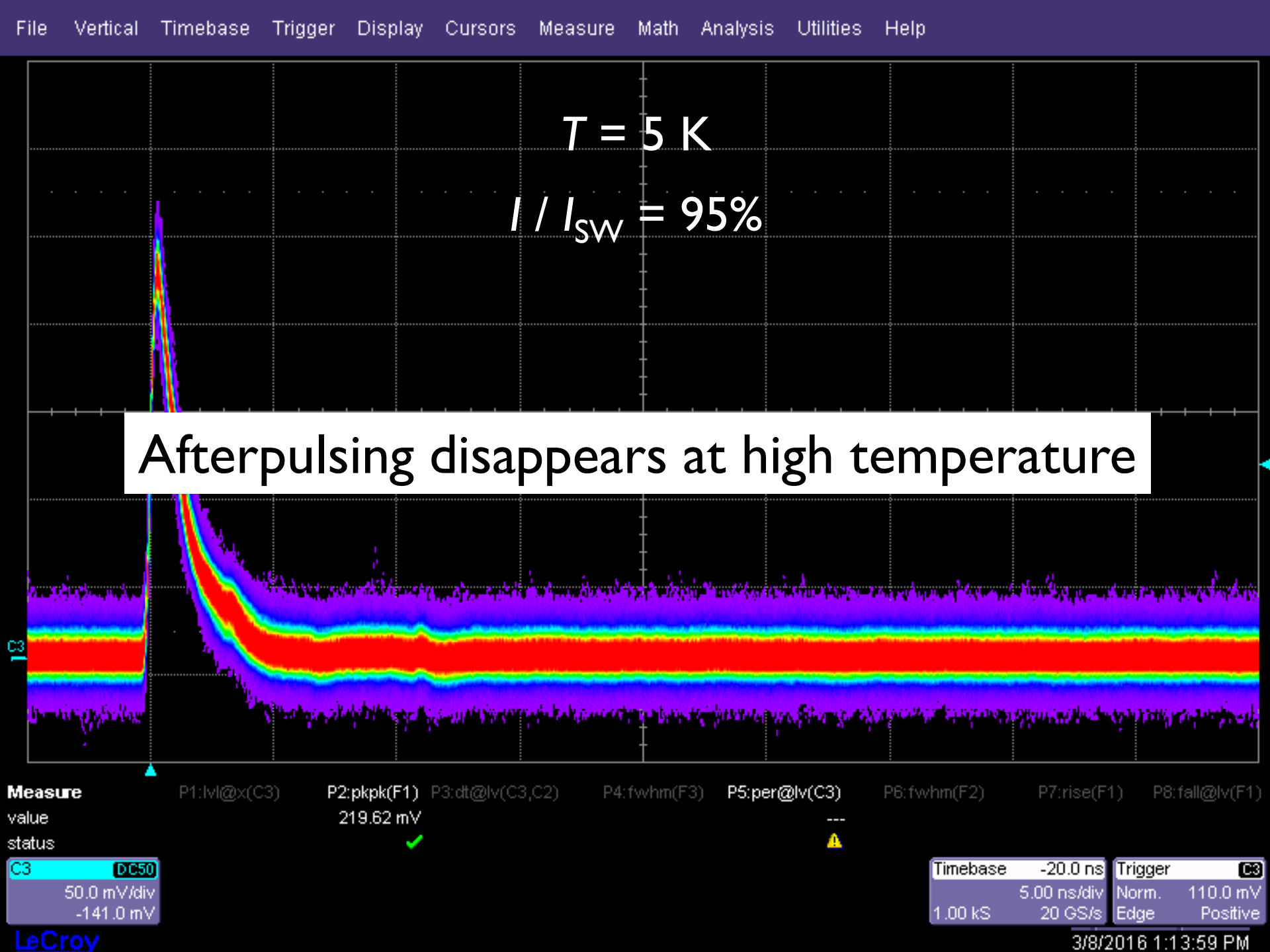
Photoresponse Pulse




File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help
T = 3 K
I / I_SW = 95%
Afterpulsing
C3
Measure
P1:lvl@x(C3)
P2:pkpk(F1)
P3:dt@lv(C3,C2)
P4:fwhm(F3)
P5:per@lv(C3)
P6:fwhm(F2)
P7:rise(F1)
P8:fall@lv(F1)
value
273.38 mV
---
status
C3 DC50
50.0 mV/div
-141.0 mV
Timebase -19.9 ns
5.00 ns/div
1.00 kS 20 GS/s
Trigger C3
Norm. 171.5 mV
Edge Positive
LeCroy
Waiting for Trigger
3/8/2016 10:46:56 AM


File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help
T = 4 K
I / Isw = 95%
Afterpulsing
C3
Measure
P1:lvl@x(C3)
P2:pkpk(F1)
P3:dt@lv(C3,C2)
P4:fwhm(F3)
P5:per@lv(C3)
P6:fwhm(F2)
P7:rise(F1)
P8:fall@lv(F1)
value
249.84 mV
---
status
C3 DC50
50.0 mV/div
-141.0 mV
Timebase -20.4 ns
5.00 ns/div
1.00 kS 20 GS/s
Trigger C3
Norm. 125.0 mV
Edge Positive
LeCroy
3/8/2016 12:19:58 PM


File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help
T = 5 K
I / I_SW = 95%
C3
Measure
P1:lvl@x(C3)
P2:pkpk(F1)
P3:dt@lv(C3,C2)
P4:fwhm(F3)
P5:per@lv(C3)
P6:fwhm(F2)
P7:rise(F1)
P8:fall@lv(F1)
value
219.62 mV
---
status
C3 DC50
50.0 mV/div
-141.0 mV
Timebase -20.0 ns
5.00 ns/div
1.00 kS 20 GS/s
Trigger C3
Norm. 110.0 mV
Edge Positive
LeCroy
3/8/2016 1:13:59 PM

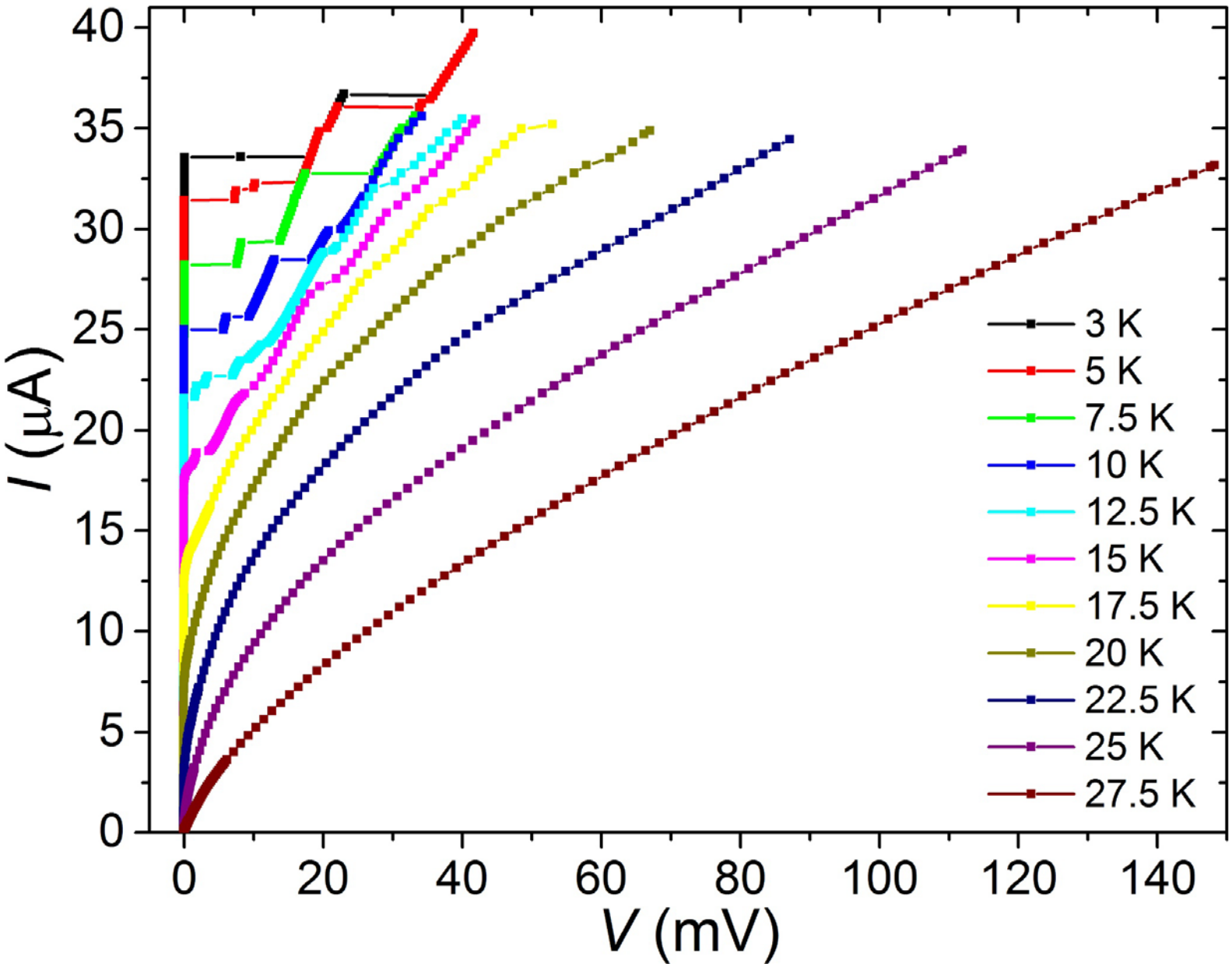

File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help
T = 5 K
I / I_SW = 95%
Afterpulsing disappears at high temperature
C3
Measure
P1:lvl@x(C3)
P2:pkpk(F1)
P3:dt@lv(C3,C2)
P4:fwhm(F3)
P5:per@lv(C3)
P6:fwhm(F2)
P7:rise(F1)
P8:fall@lv(F1)
value
219.62 mV
---
status
C3 DC50
50.0 mV/div
-141.0 mV
Timebase -20.0 ns
5.00 ns/div
1.00 kS 20 GS/s
Trigger C3
Norm. 110.0 mV
Edge Positive
LeCroy
3/8/2016 1:13:59 PM

Conclusion

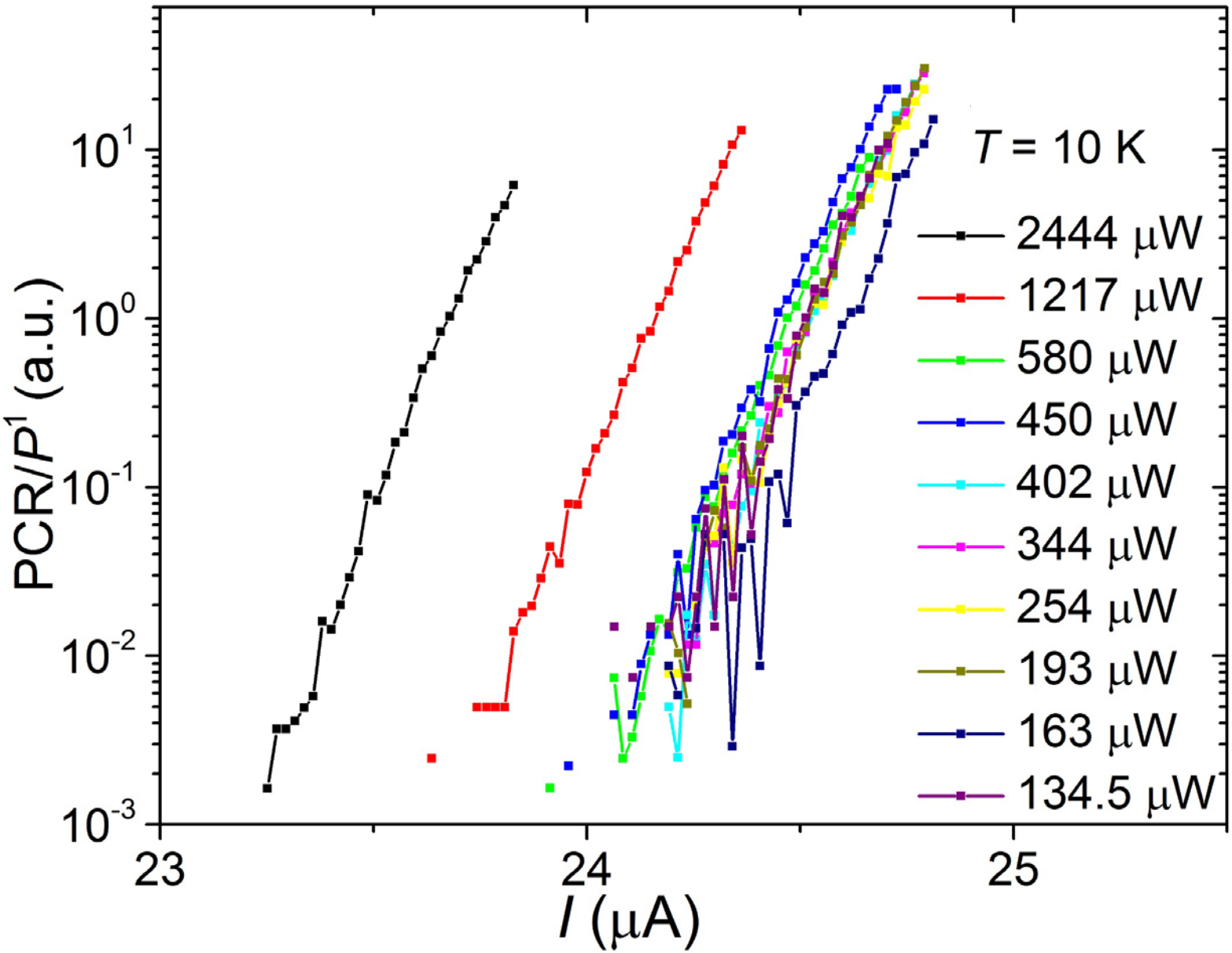
- Fabrication of thin (< 10 nm) MgB_2 films with high critical temperature (T_C > 30 K)
- Fabrication of MgB_2 superconducting nanowires with high critical temperature (T_C > 30 K)
- Single-photon response up to 10 K temperature
- 50 ps FWHM jitter
- High speed operation may be possible at high temperature

End of Presentation

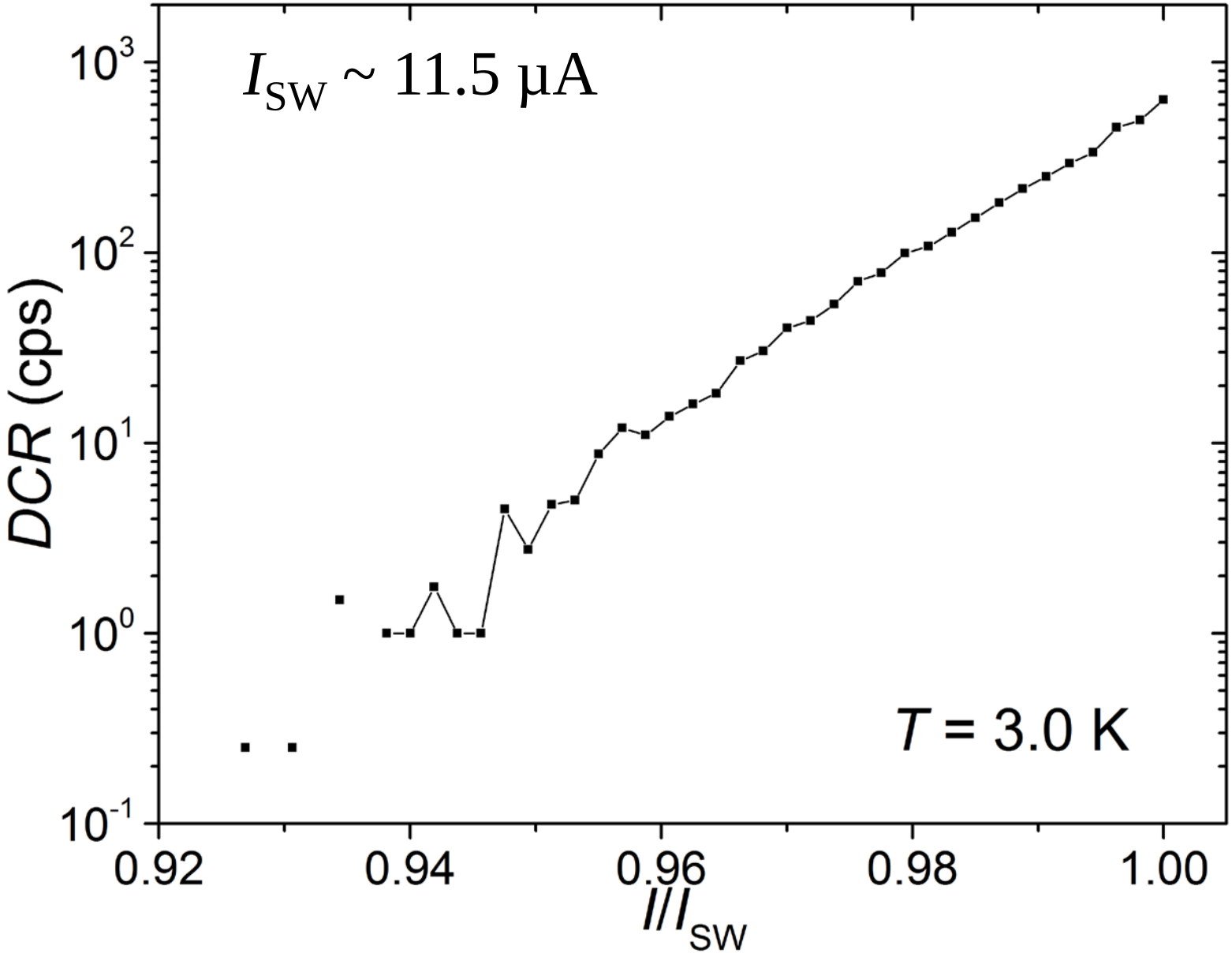
S-N Transition



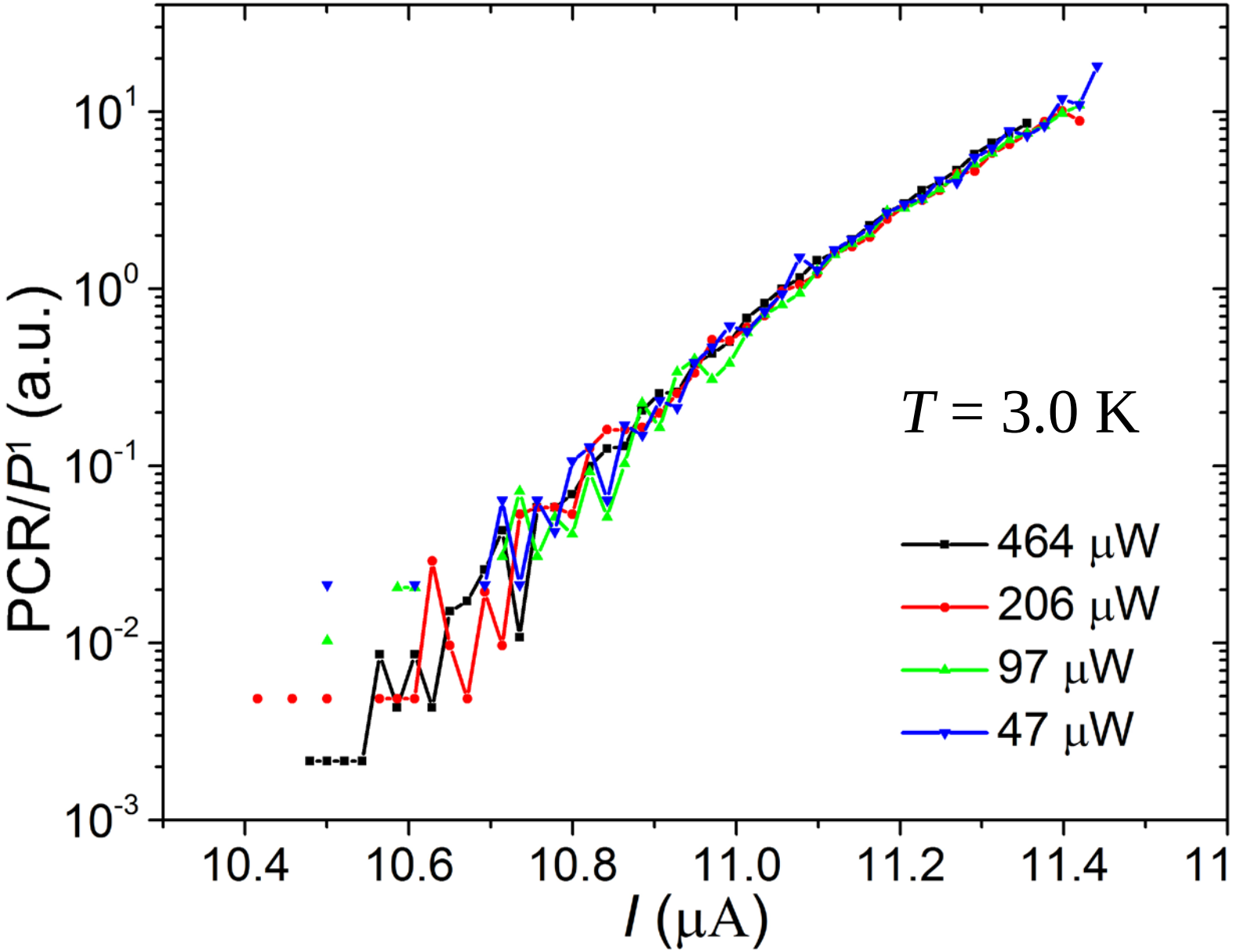
Single Photon Sensitivity at 635 nm



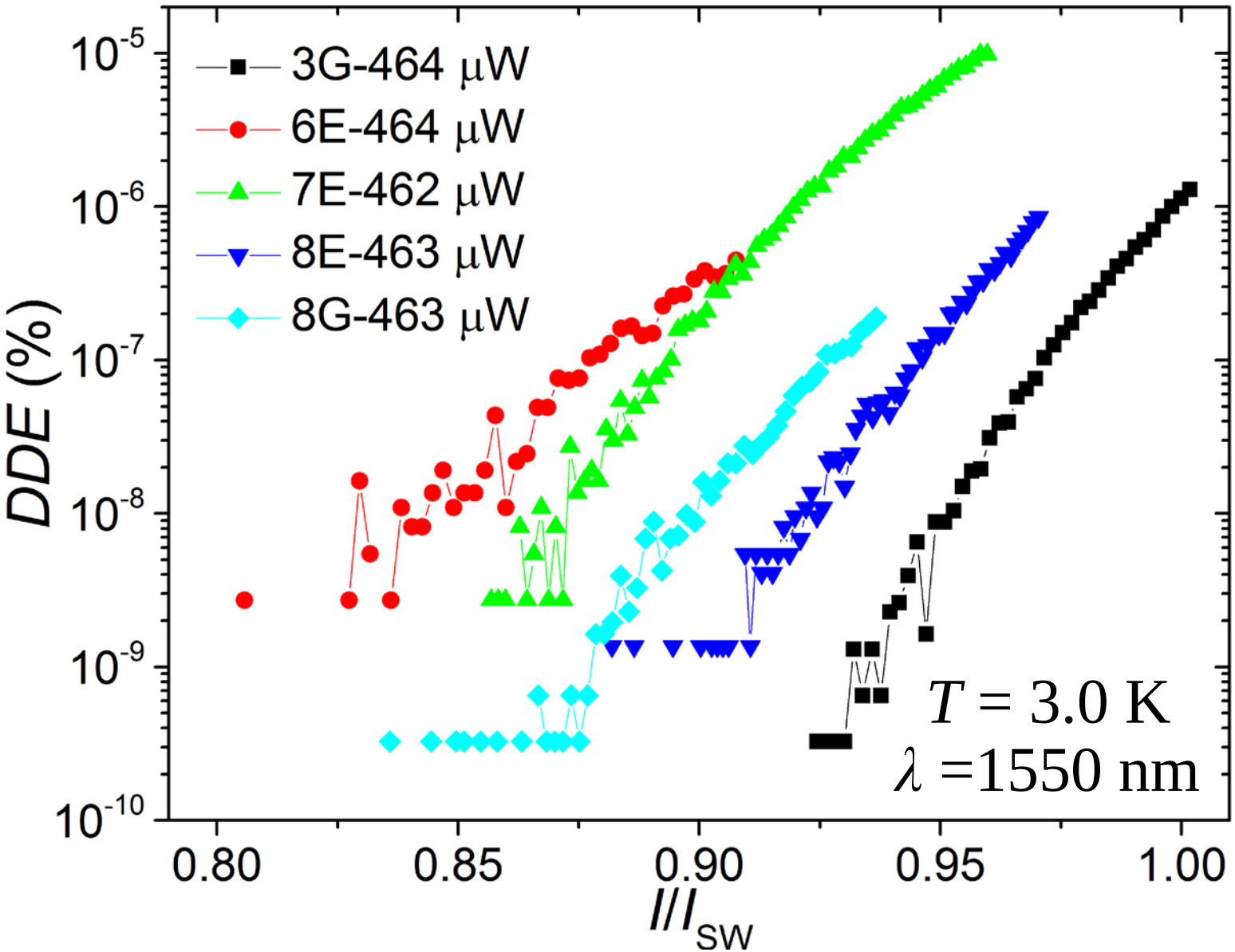
Dark count rate, *DCR*



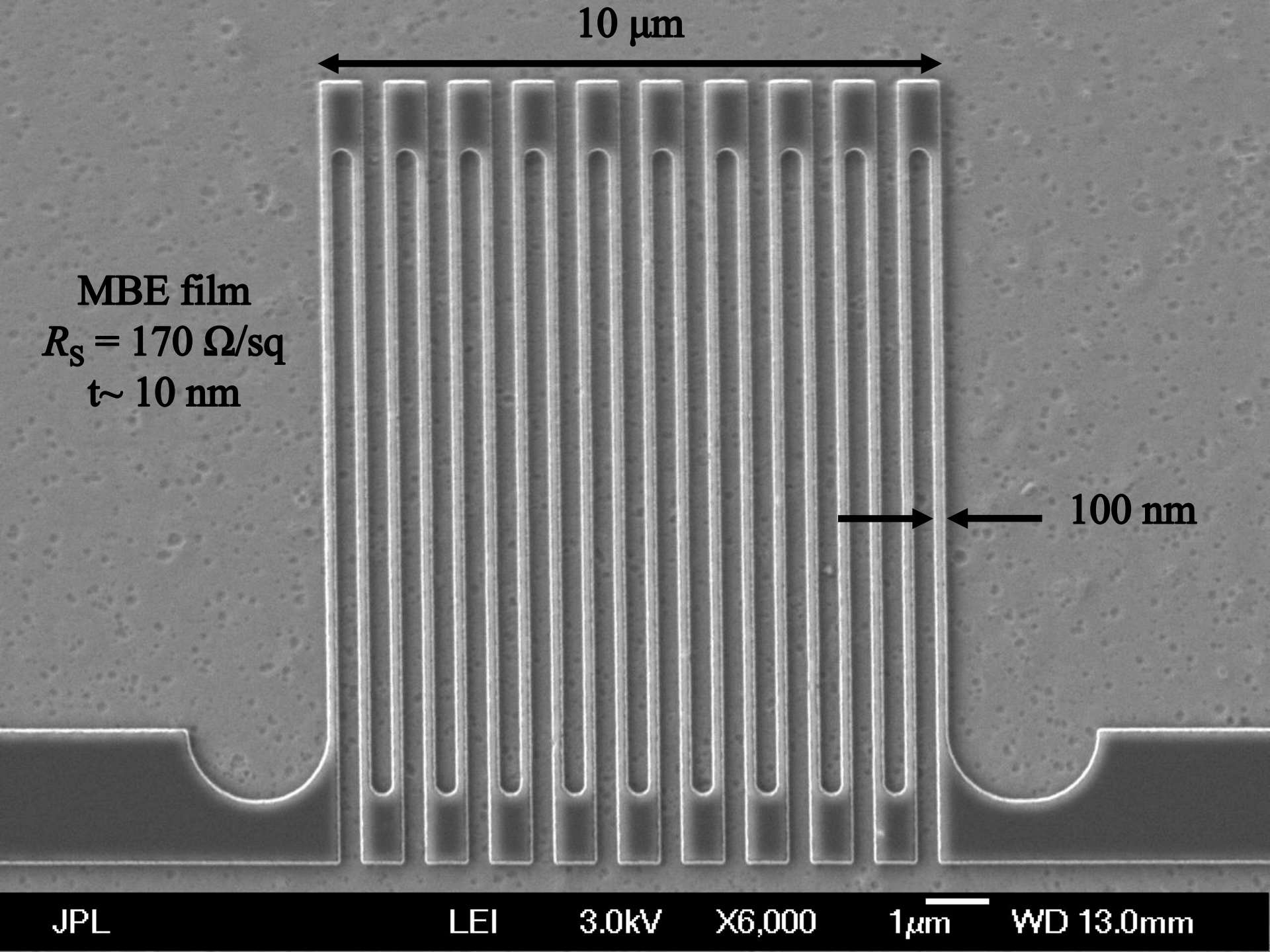
Single Photon Sensitivity @ 1550 nm



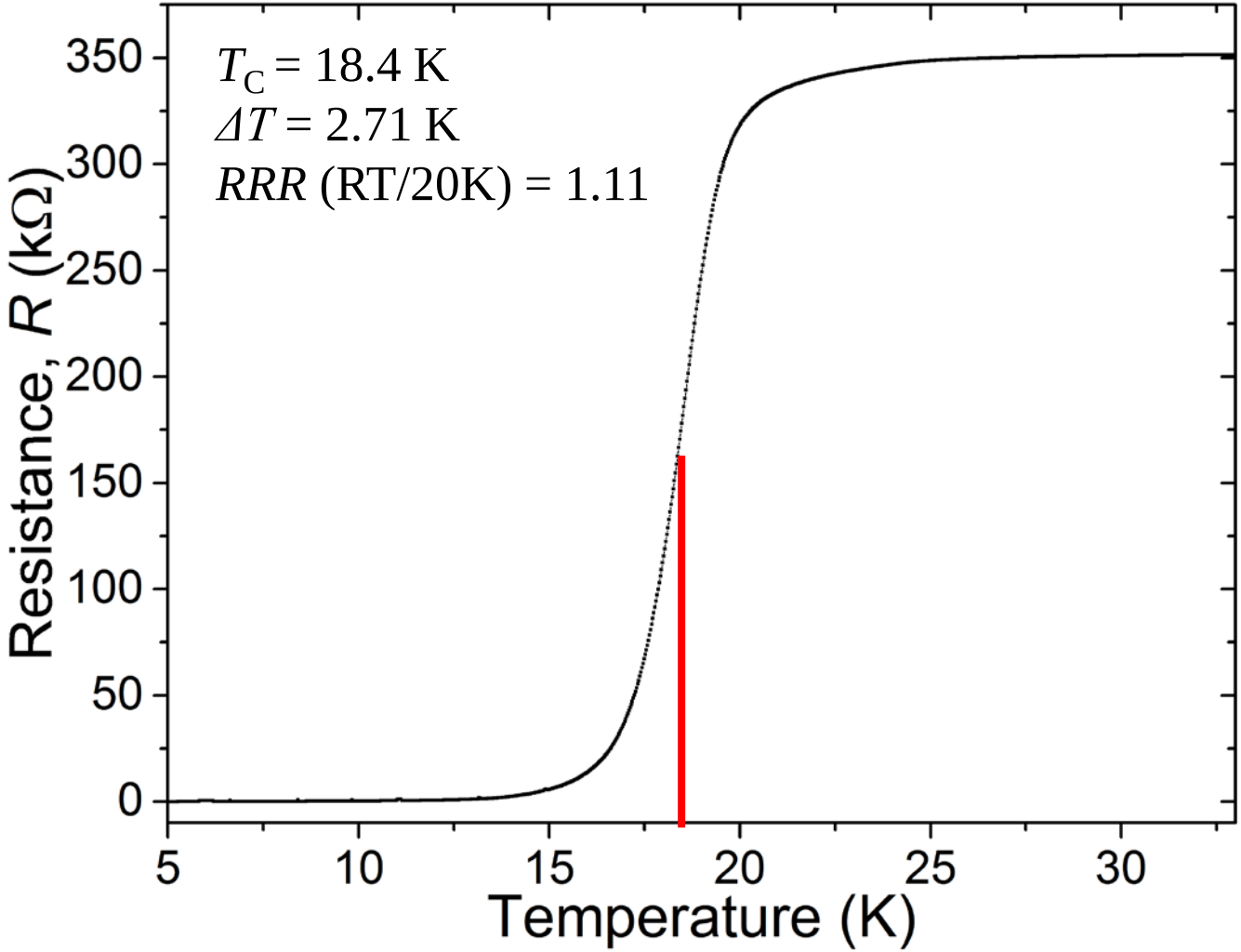
Device detection efficiency, *DDE*



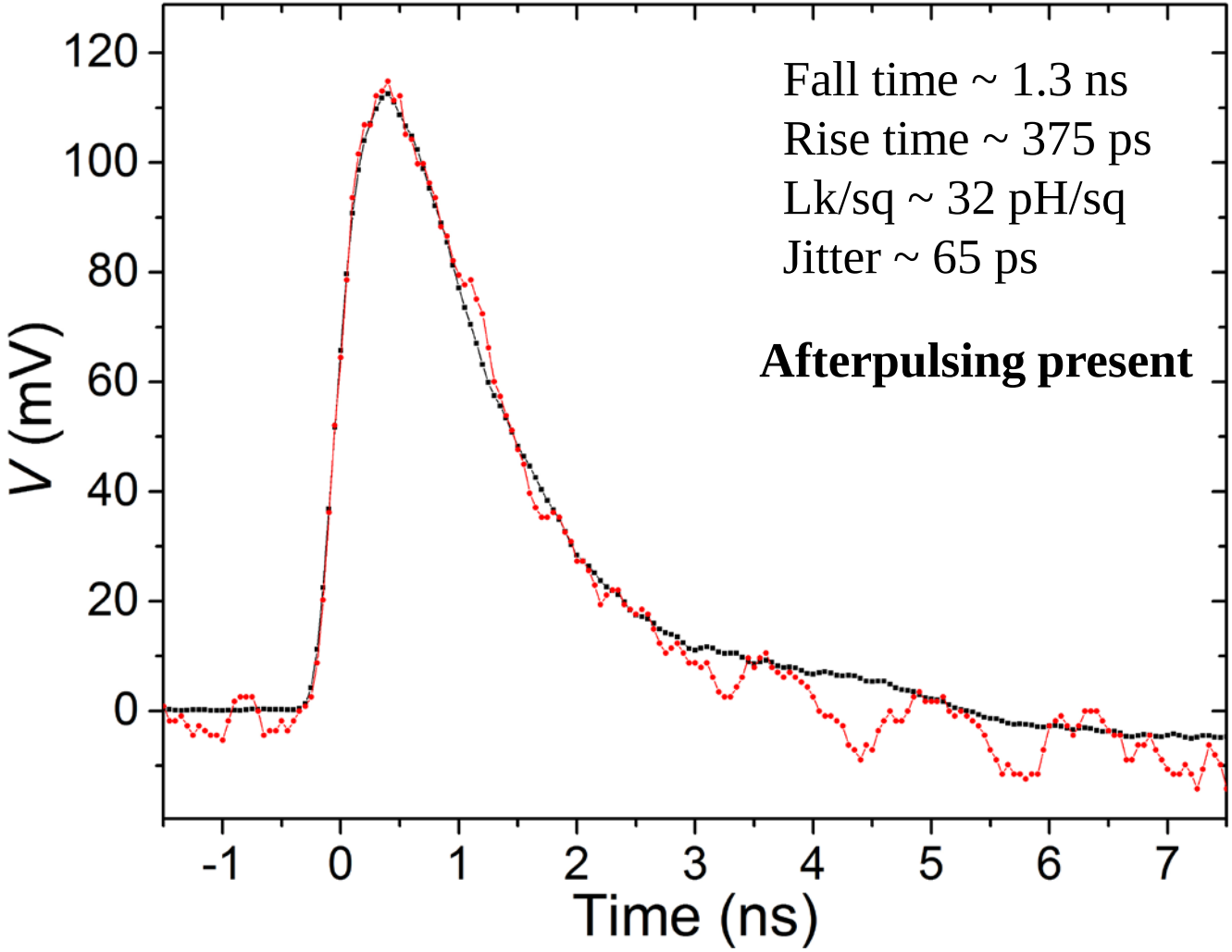
NTT


10 μm
MBE film
R_S = 170 Ω/sq
t~ 10 nm
100 nm
JPL
LEI
3.0kV
X6,000
1μm
WD 13.0mm

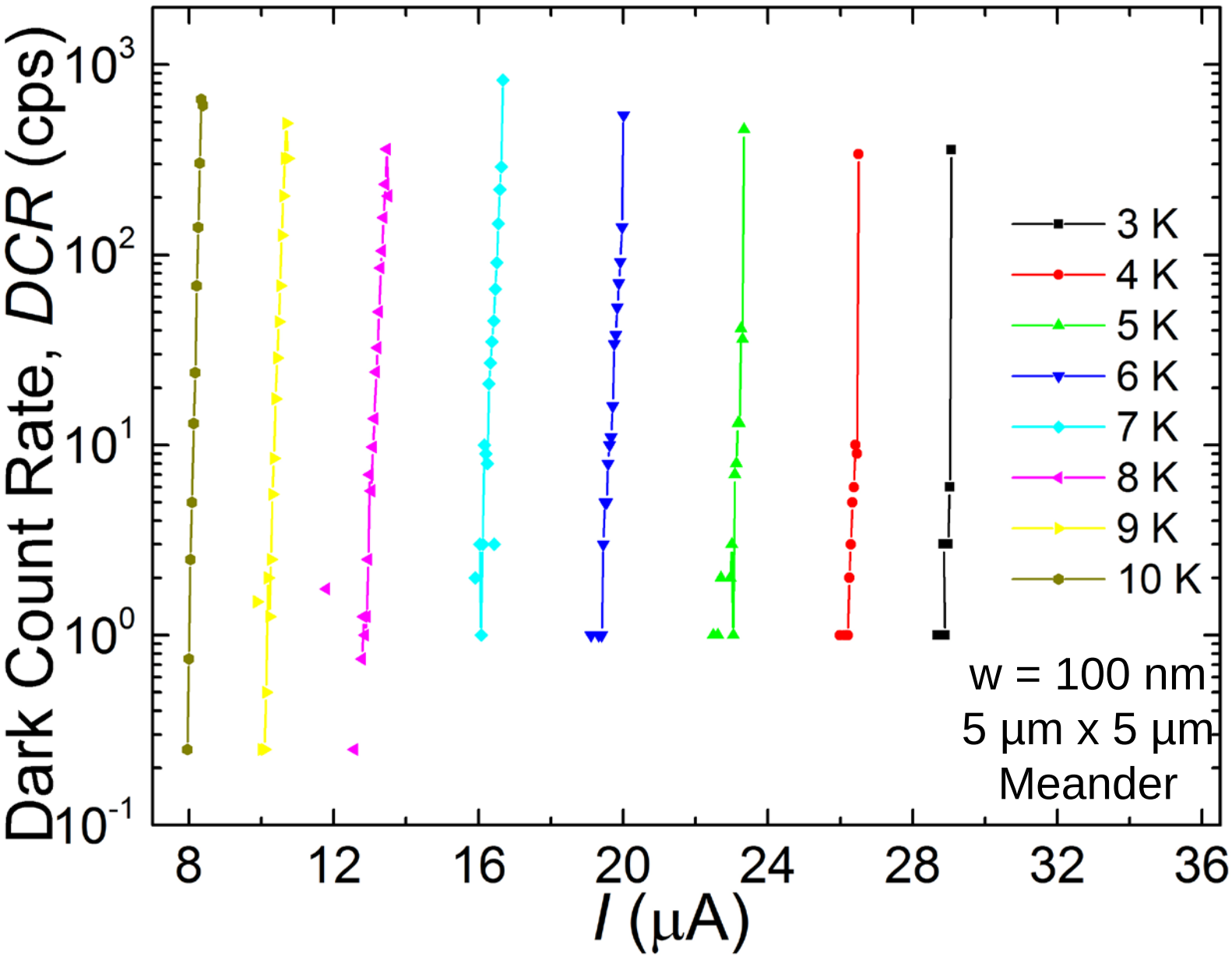
Transition temperature, T_C



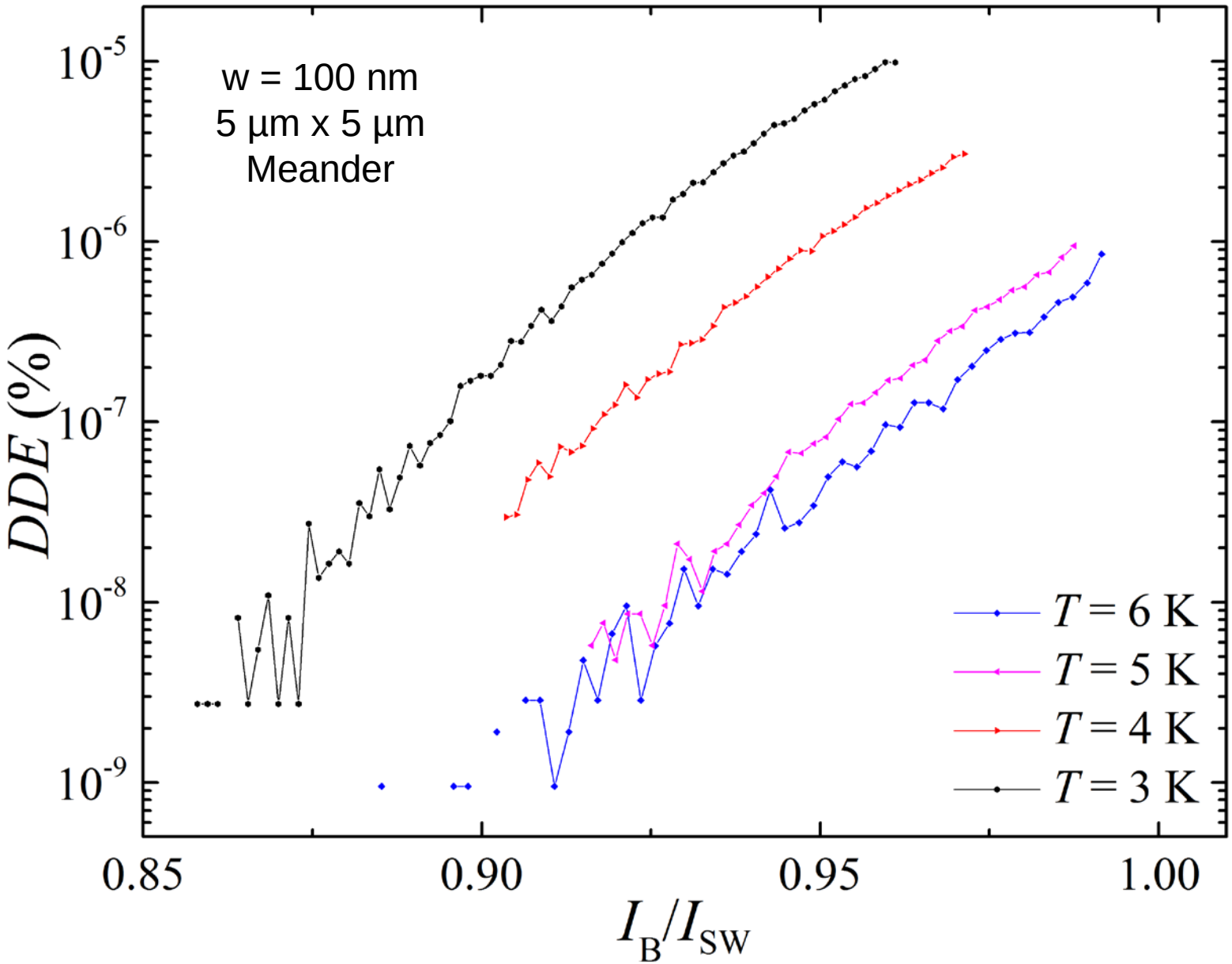
Optical response at 1550 nm



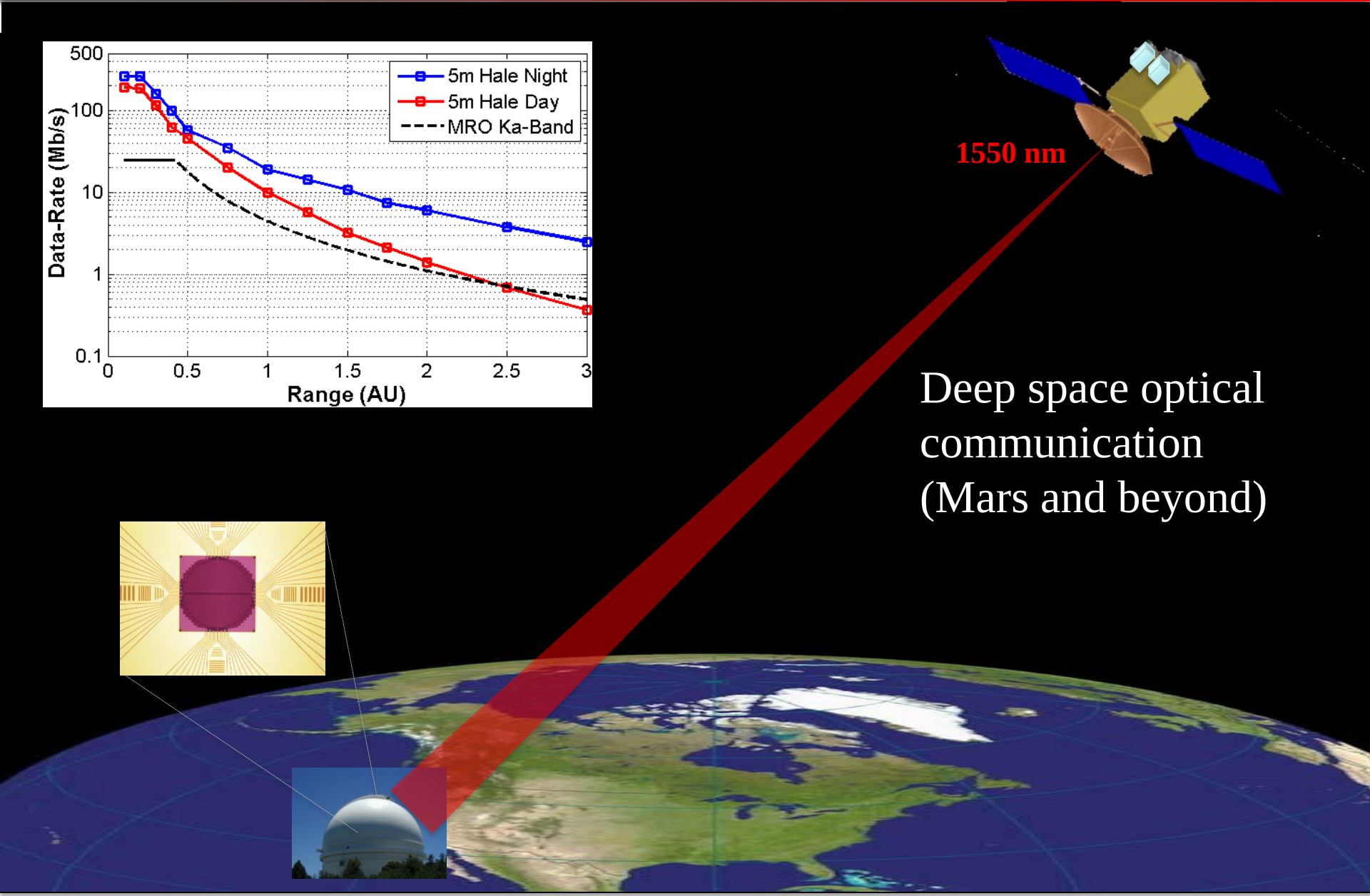
Dark count rate, *DCR*

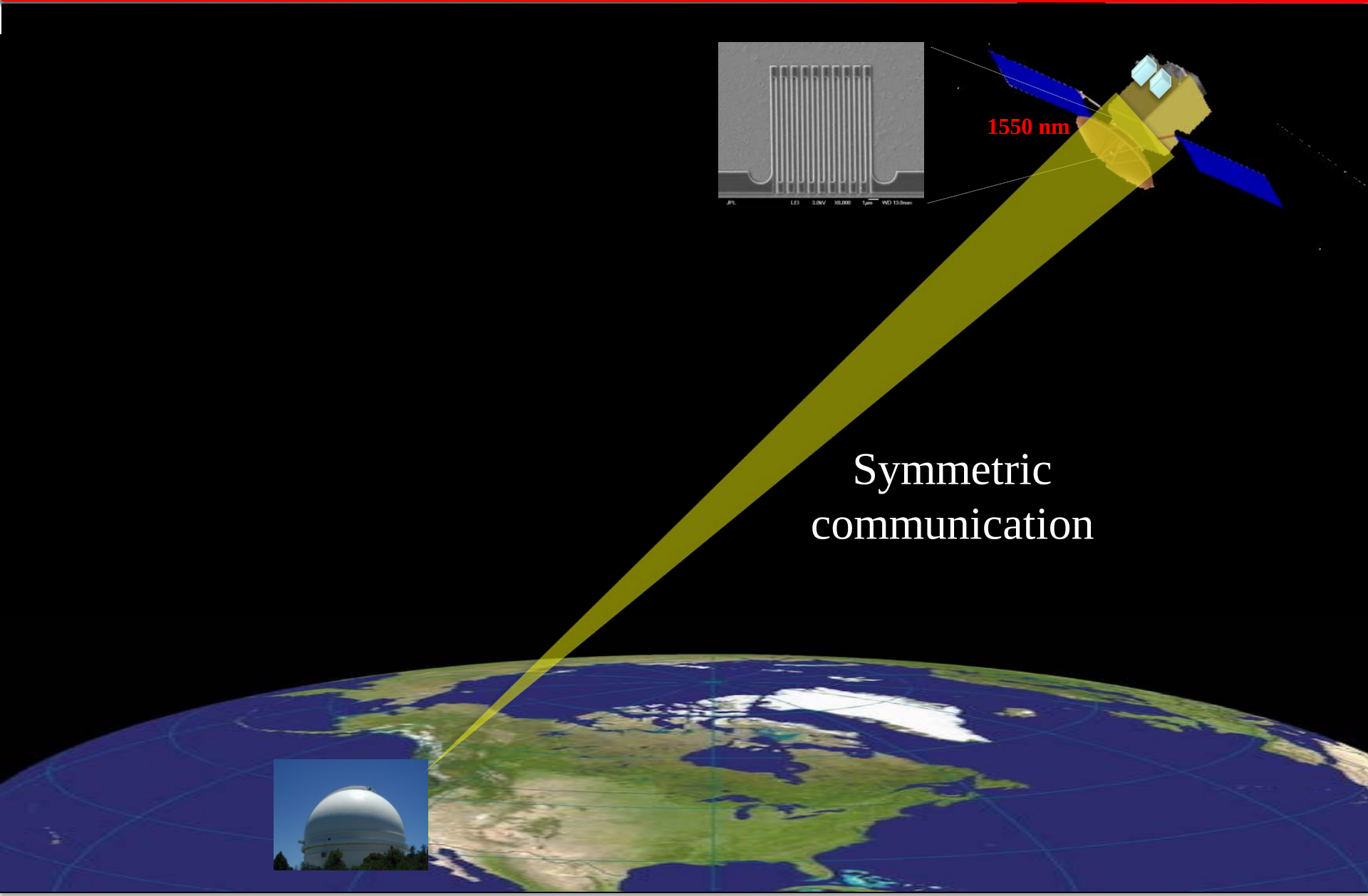


Device detection efficiency at 1550 nm



High T_C SNSPDs: Flight Applications



Deep space optical communication (Mars and beyond)

High T_C SNSPDs: Flight Applications