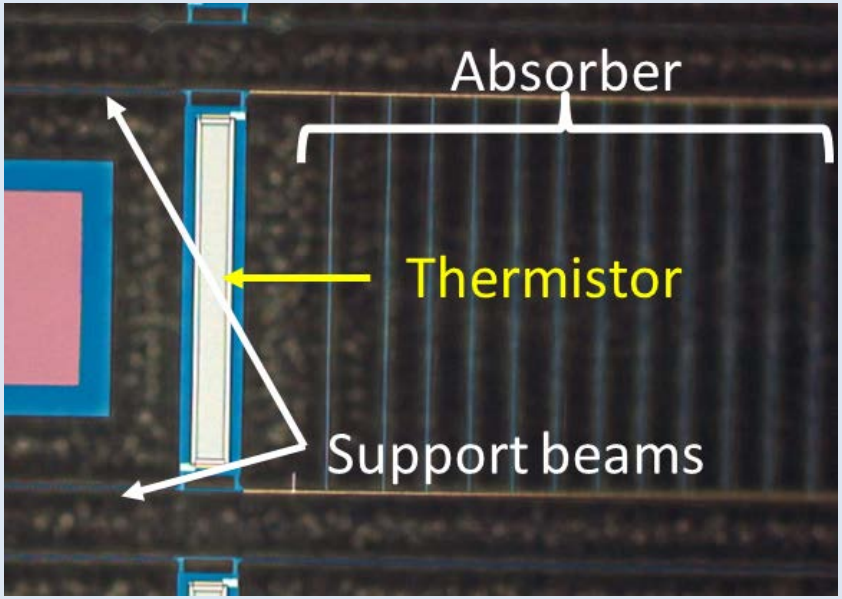
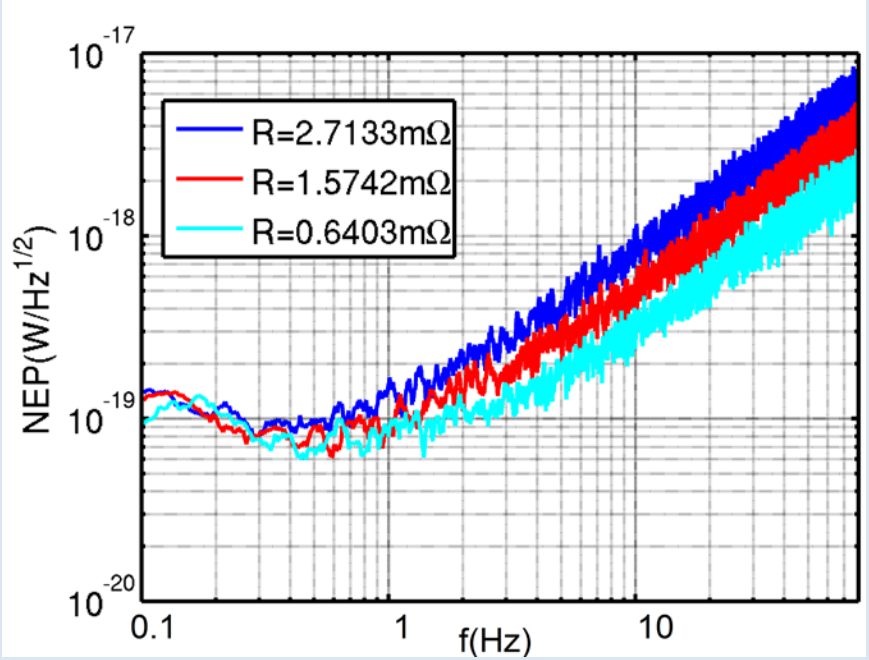
Demonstration and design criteria of transition-edge sensors (TESs) with noise equivalent power below 10^{-19} W/Hz$^{1/2}$ for space-borne grating spectrometers





A.D. Beyer, *M. E. Kenyon, B. Bumble, M. C. Runyan, P.E. Echternach, W.A. Holmes, J.J. Bock, and C. M. Bradford*

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA

Outline

1. Introduction to the Background Limited Infrared Sub-mm Spectrograph (BLISS):

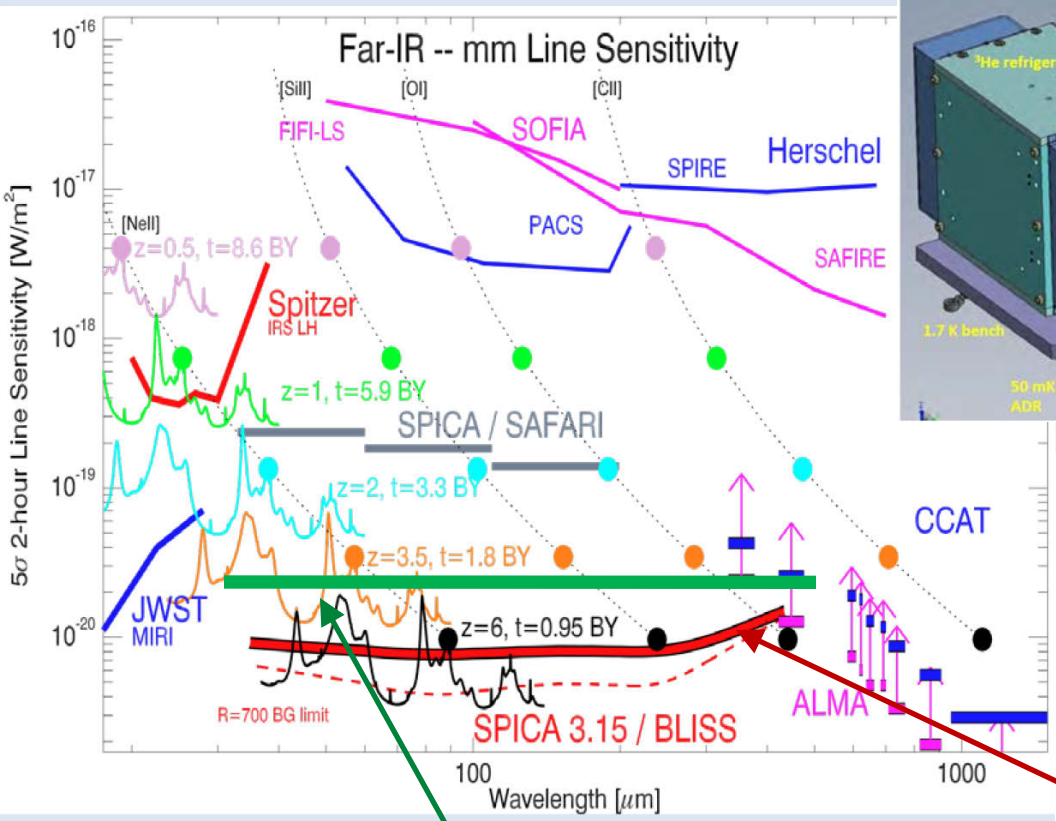
   Membrane-isolated transition-edge sensor (TES) goals/requirements.

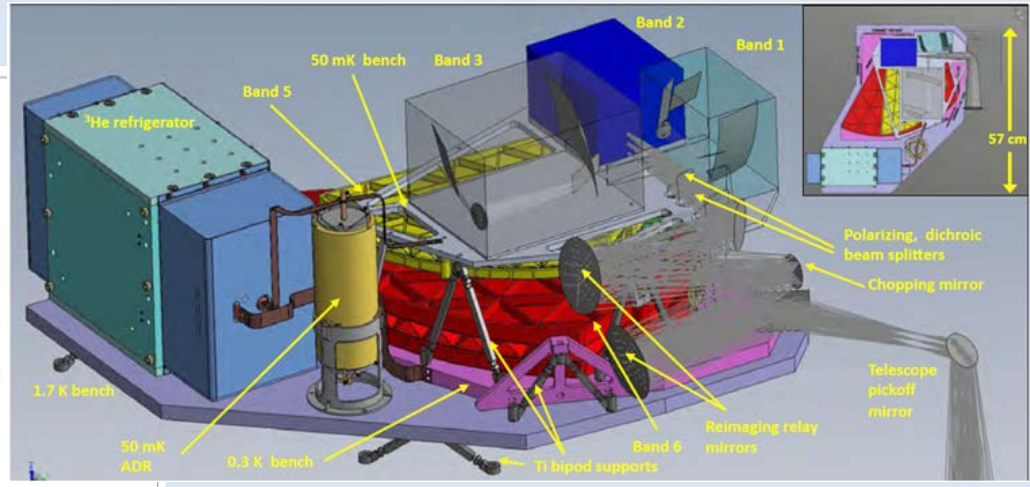
2. Detector-limited noise: readout 1/f and R_N.

3. Undesired proximity effects for α and T_C → response time τ.

4. Best performance TES:
   noise equivalent power (NEP)< 10^{-19} W/Hz$^{1/2}$ & τ ~360ms.

BLISS for SPICA



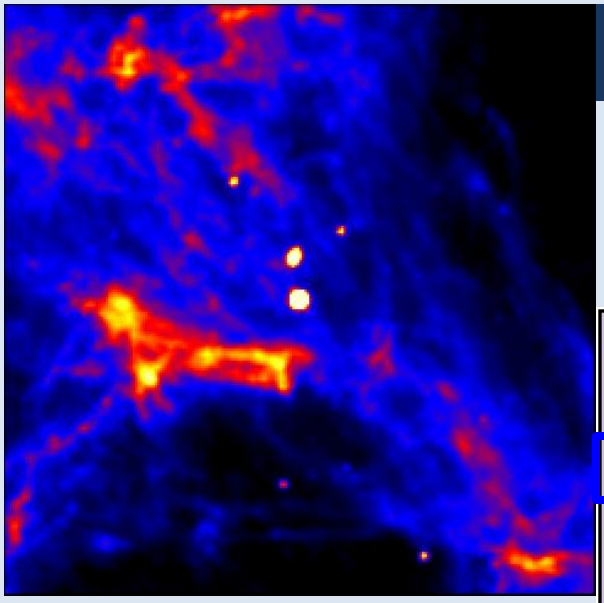


- Sensitive wideband grating spectrometer.
- 6 bands to cover 35-433 μm at R~500.
- Baseline 4224 TES bolometers at 50 mK with time-domain SQUID MUX.

- Desired sensitivity: **2e-20 W m^{-2} (5s, 2h) for Requirement** and **1e-20 W m^{-2} for Goal** under conservative assumptions (photons contributing equally at goal sensitivity).

- **Detector noise equivalent power (NEP)**: **Requirement: 1e-19 W Hz$^{-1/2}$, Goal: 5e-20 W Hz$^{-1/2}$**

BLISS design goal parameters



Galactic cirrus: Image Credits: Infrared Processing and Analysis Center, Caltech/JPL. IPAC is NASA's Infrared Astrophysics Data Center.

Loads on bolometer:

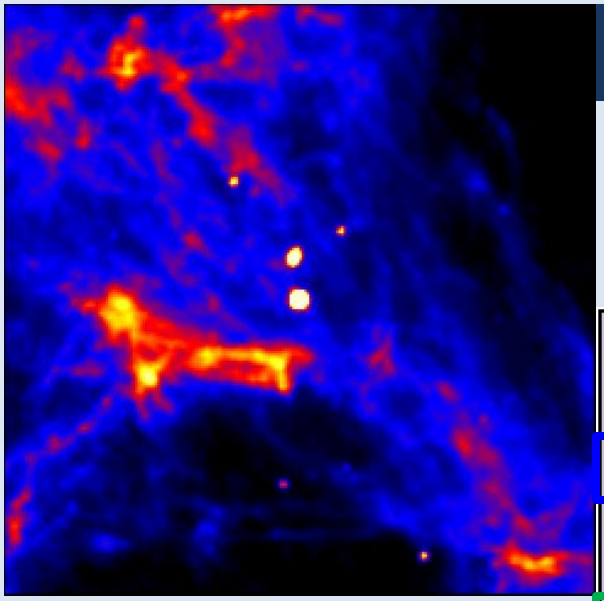
-Zodiacal light, galactic cirrus, CMB, telescope, baffles.

Estimated power load at bolometer

Band (μm)	(μm)	357	230	148	92	53
Safety factor		75	150	200	400	400
$P_{bolometer}$	(aW)	2.29	0.34	0.25	0.13	0.12
$P_{sat.}$	(aW)	172	51	49	52	50
C	(fJ/K)	13	13	13	13	13
G	(fW/K)	15	15	15	15	15
C/G	(s)	1.07	3.63	3.71	3.49	3.69
τ	(s)	0.05	0.16	0.16	0.15	0.16

- Base temperature = 50mK, T_C = 65mK.
- Thermal conductance G is chosen so that $NEP_{detector}$ matches NEP_{photon}.
- Heat capacity C expected from Si-N → suitable speeds for chosen G values.
- G, C shown for NEP goal. For BLISS NEP requirement G→G×10, C→C×10.

BLISS design goal parameters



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G needed at 65mK.

- Base temperature = 50mK, T_C = 65mK.
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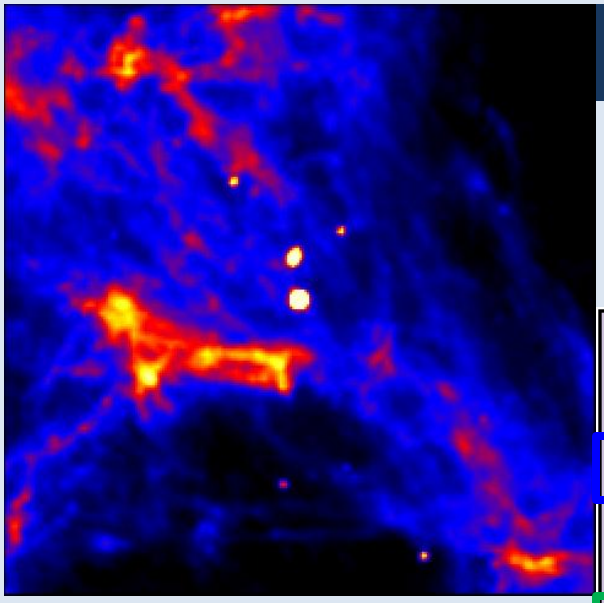
BLISS design goal parameters



Galactic cirrus: Image Credits: Infrared Processing and Analysis Center, Caltech/JPL. IPAC is NASA's Infrared Astrophysics Data Center.

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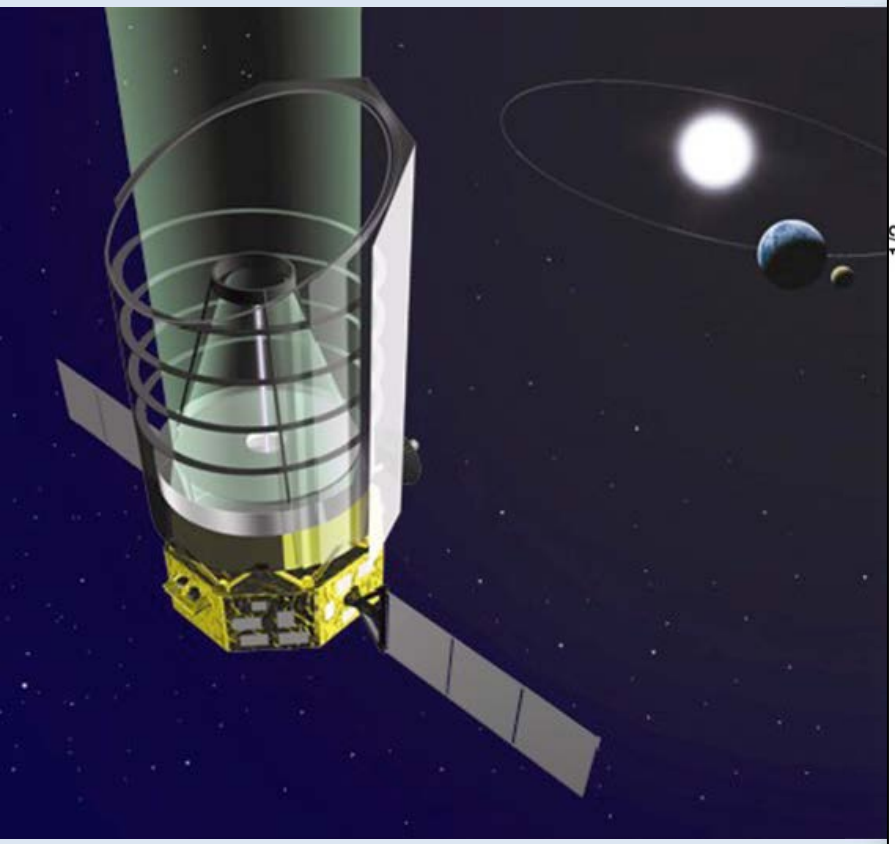
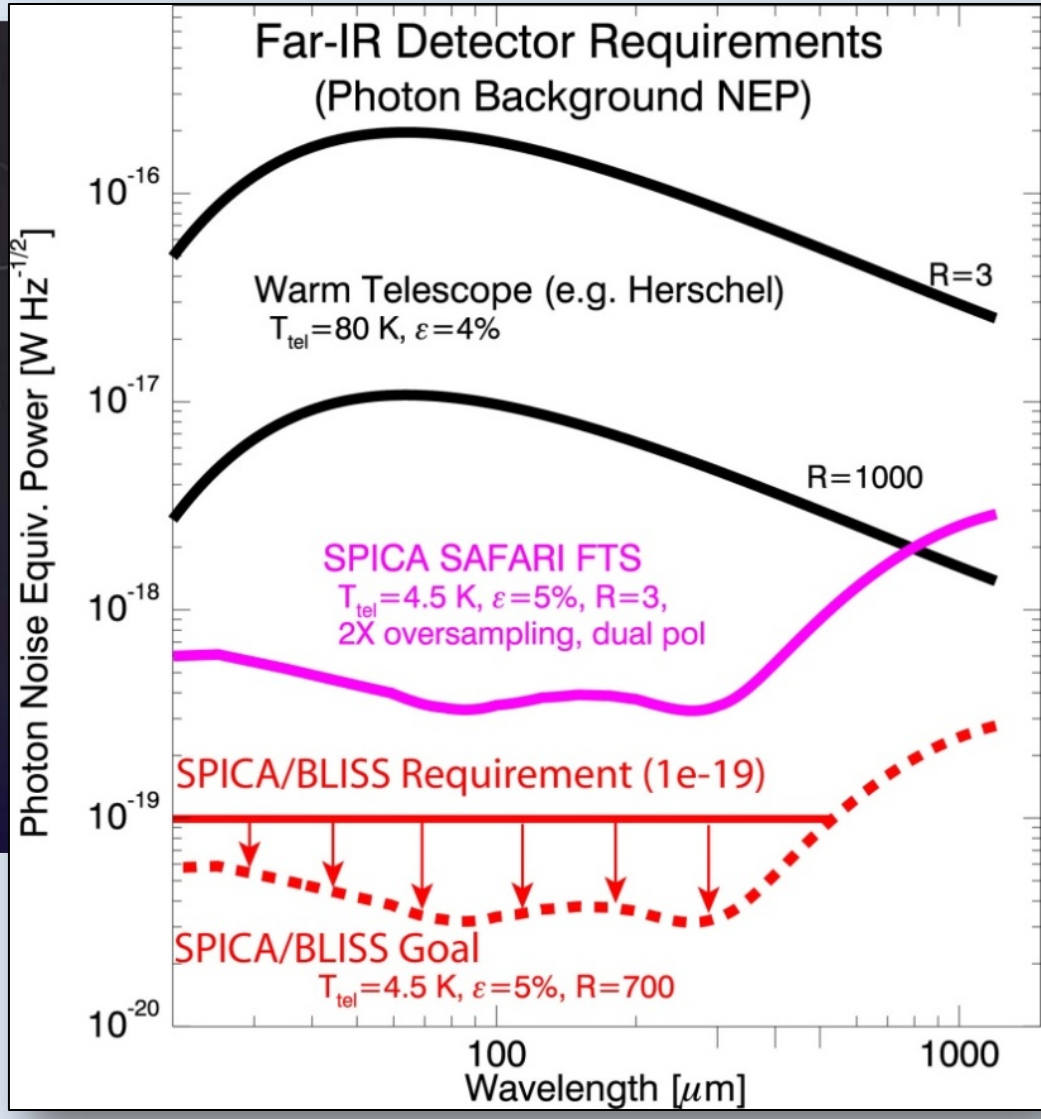
- Requirement: $NEP=10^{-19}$ W/Hz$^{1/2}$, $f_{roll\text{-}off}$ =1 to 5 Hz.
- Goal: $NEP=5\times10^{-20}$ W/Hz$^{1/2}$, $f_{roll\text{-}off}$ =1 to 5 Hz.

SPICA—the first large cryogenic observatory

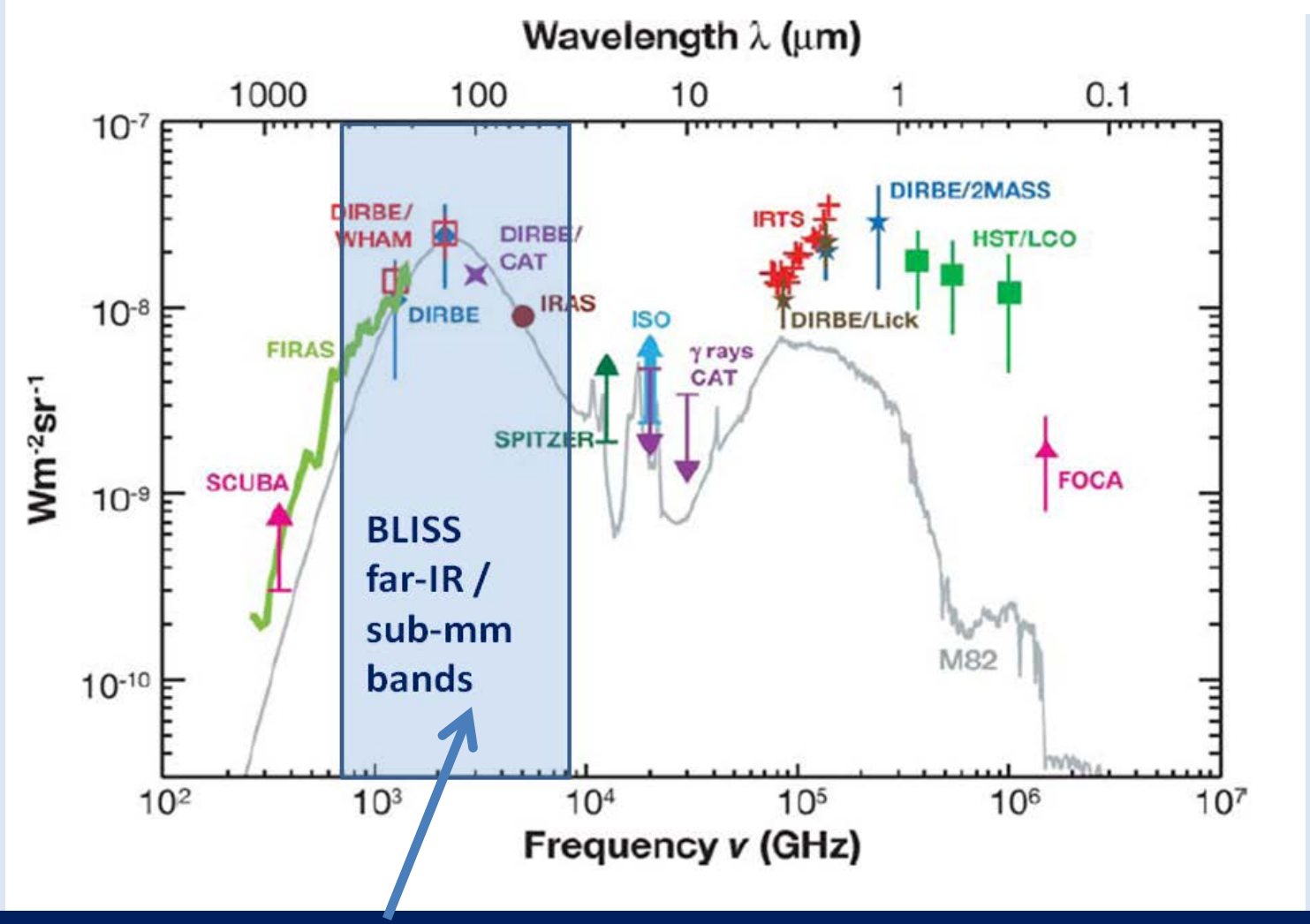




- Size: 3.5m .
- **T=4.5K.**
- Optimized for 10 to 600µm observations.

Space Infrared telescope for Cosmology and Astrophysics—ISAS/JAXA.

BLISS: Far-IR/sub-mm in space



Extragalactic background light:

- ½ is in the far-IR.
- Hidden evolution: dust-obscured star formation, black-hole growth.

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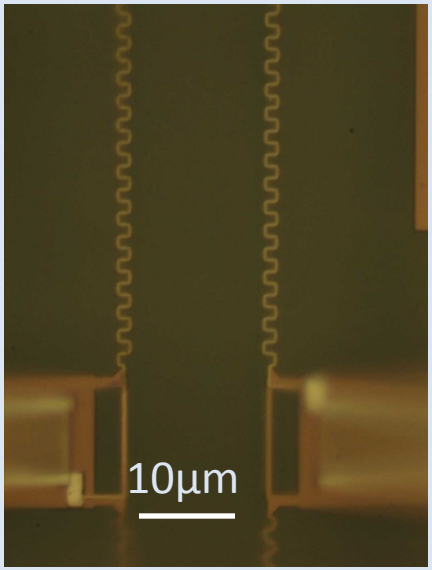
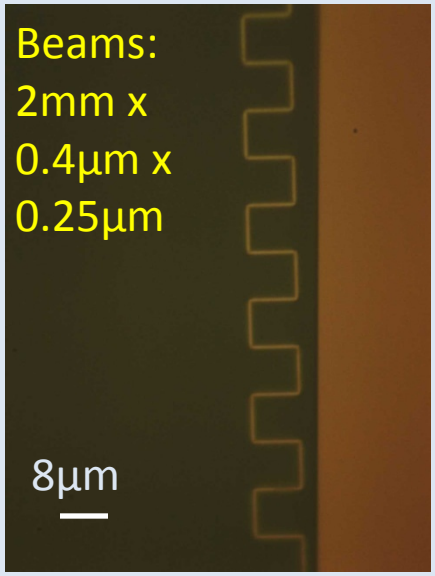
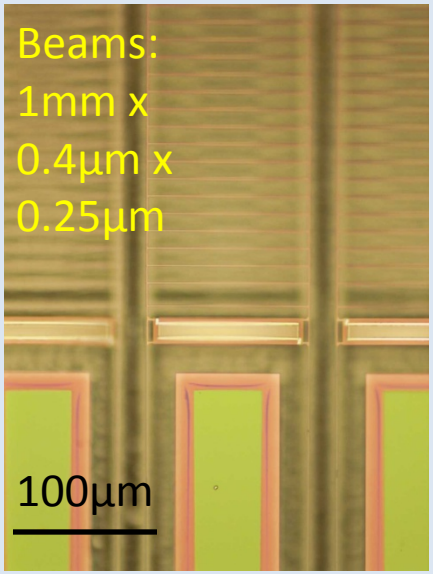
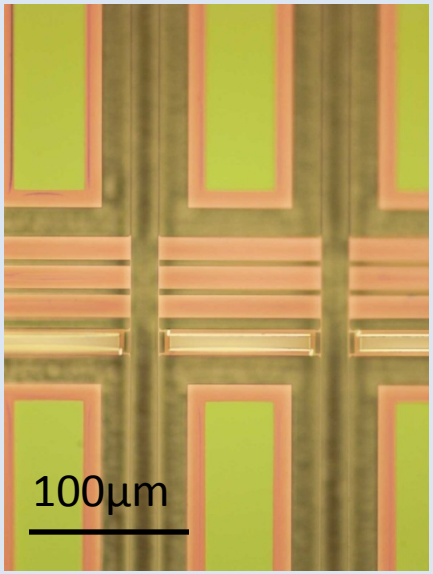
Ir BLISS arrays (T_C=135mK)





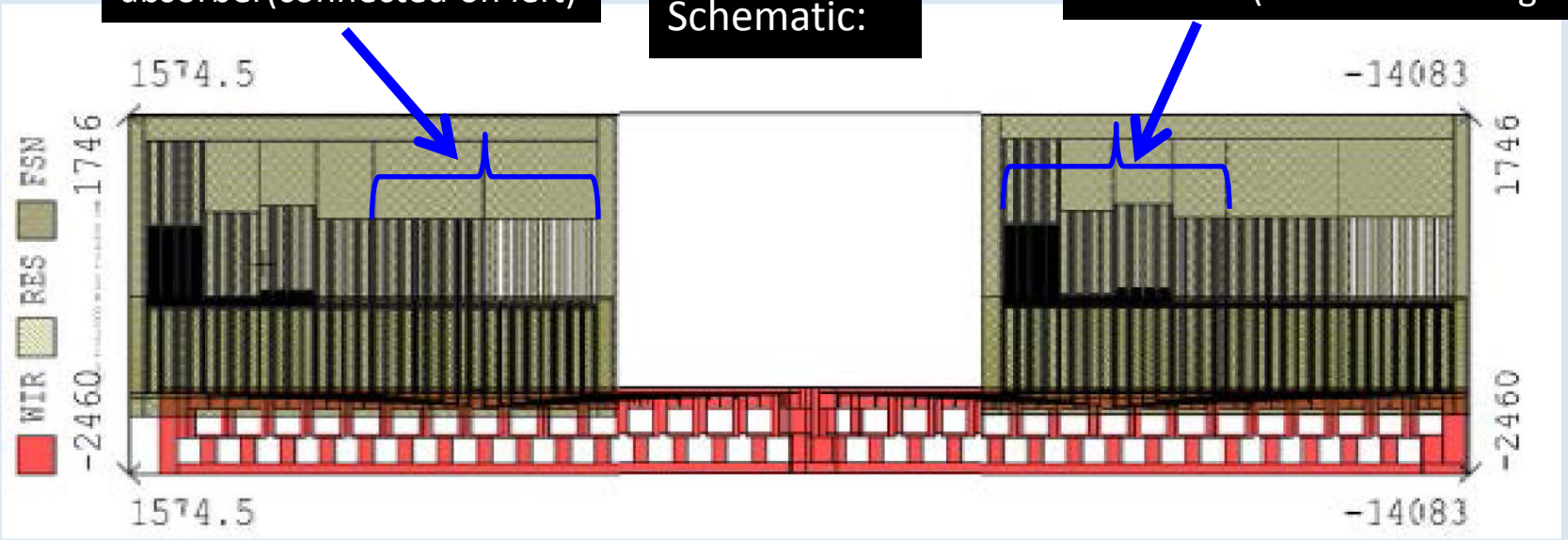




Meandered beams , no absorber(connected on left)

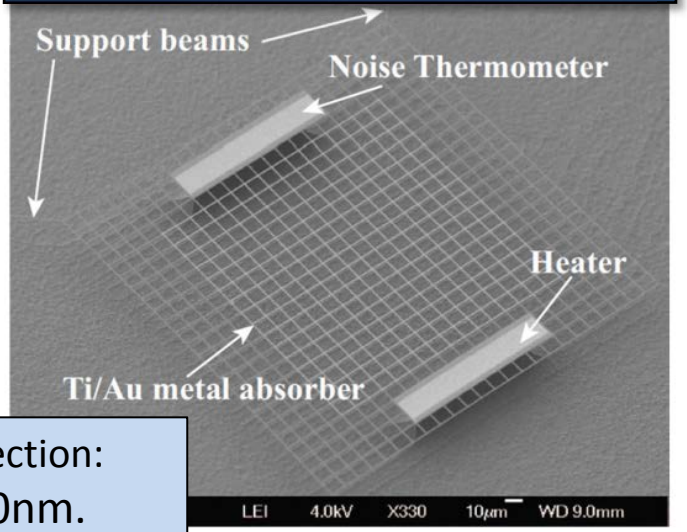
Straight beams, different absorbers (connected on right)

Schematic:



NEP, G expectations from noise thermometry

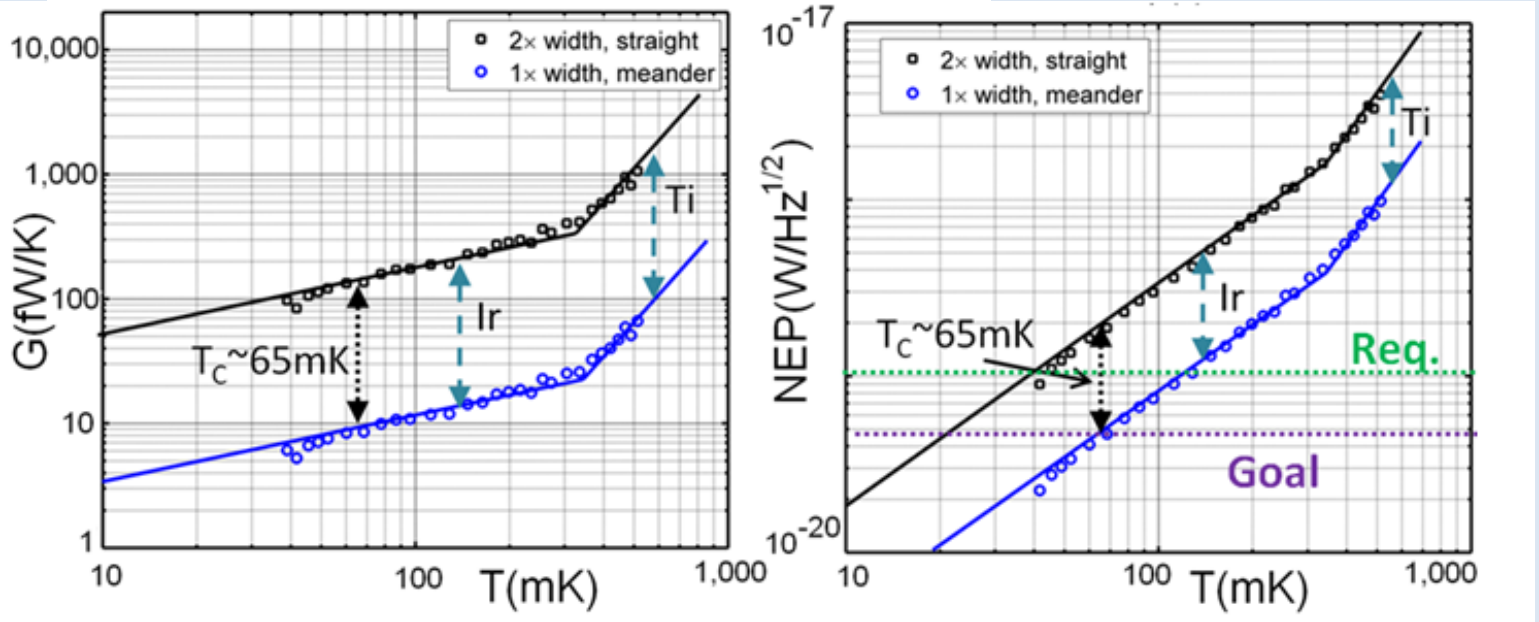
Micrograph of noise thermo. device:



Beam cross-section:
400nm x 250nm.

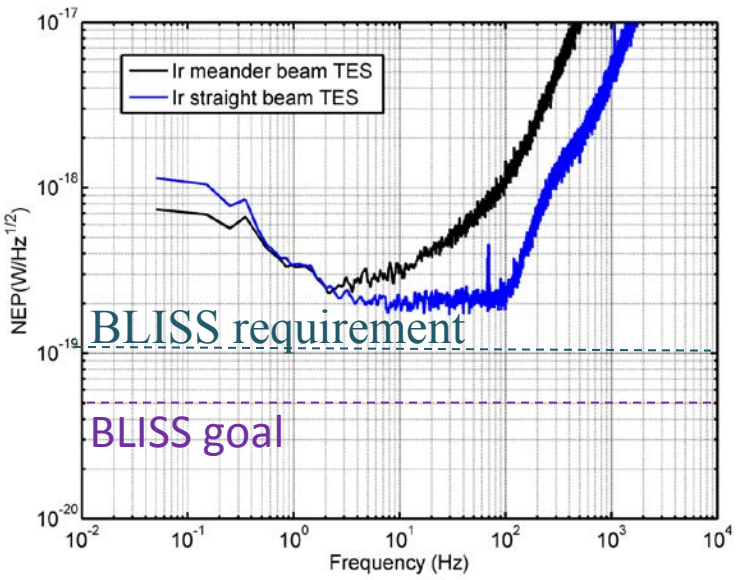
- Apply power: $P=I^2R_H$
- Measure temp: $4k_bT/R_N$
- Thermal conduct.: $G=dP/dT$

$$NEP_{TFN} = \sqrt{4k_B T_C^2 G}$$

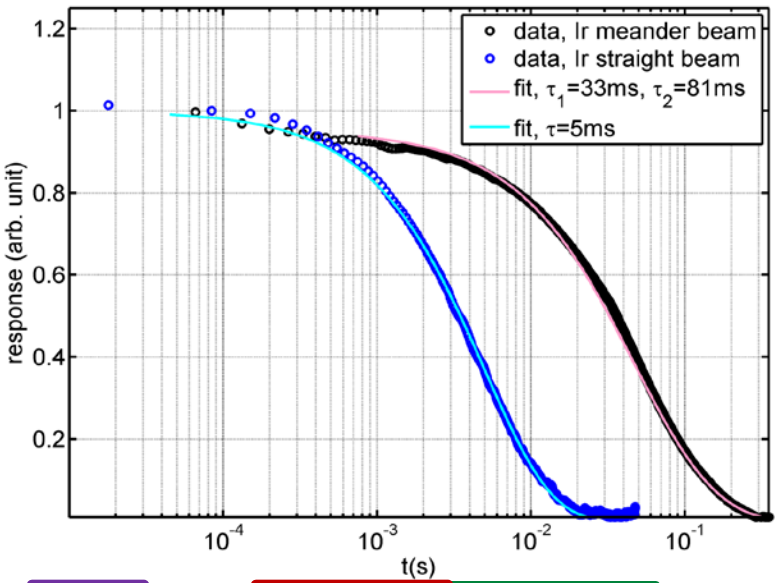


Previous results on BLISS arrays: Ir (T_C=135mK)

NEP



Response time



Material (T_C)	Type	G (fW/K)	n ($G \sim T^n$)	P_{dark} (fW)	γ (50mK)	NEP_{exp} (10^{-19}W/Hz$^{1/2}$)	NEP_{meas} (10^{-19}W/Hz$^{1/2}$)	τ (ms)	τ_{Band6} (ms)
Ir (130mK)	3M	35	0.5	0.9	0.71	1.5	2.5	7.9	131
Ir (130mK)	2M	30	0.5	0.9	0.71	1.4	2.5	16.5	274
Ir (130mK)	2M	30	0.5	0.9	0.71	1.4	2.5	30.2	502
Ir (130mK)	1M	35	1.5	0.9	0.59	1.4	2.5	32.3	537
Ir (130mK)	NP	110	0.5	2.5	0.71	2.7	2.5	4.8	79
Ir (130mK)	3P	115	1.5	2.0	0.59	2.5	2.5	5.2	86
Ir (130mK)	6P	120	1.5	1.5	0.59	2.6	2.6	5.0	83
Ir (130mK)	6P	120	1.5	1.5	0.59	2.6	2.6	4.7	77
Ir (130mK)	6P	110	1.5	1.0	0.59	2.5	2.5	4.5	76
Ir (130mK)	6P	110	1.5	1.0	0.59	2.5	2.5	4.7	78
Ir (130mK)	6P	120	0.5	4.8	0.71	2.8	2.8	1.3	22
Ir (130mK)	6P	110	0.5	4.8	0.71	2.7	2.9	3.7	61
Ir (130mK)	NP	140	0.5	4.0	0.71	3.0	3	1.5	24
Ir (130mK)	NP	100	0.5	4.6	0.71	2.6	2.6	3.3	55

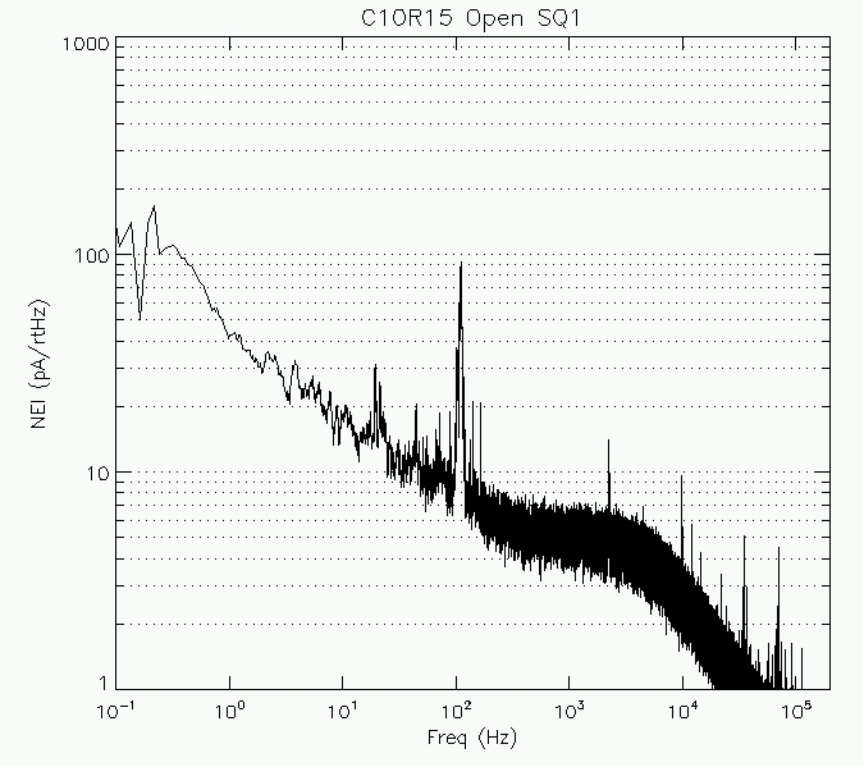
Meander beams & L/R filter (BW: 150kHz).

Straight beams & L/R filter (BW: 150kHz).

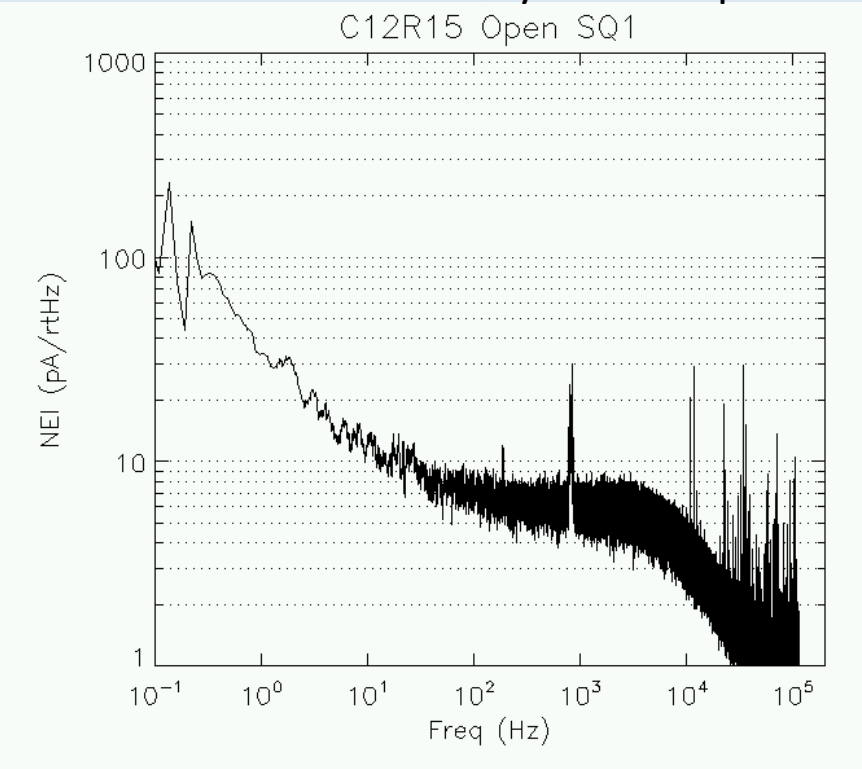
Straight beams & π filter (BW: ~15MHz).

Issue in array test system: Large 1/f noise

MUX05 + array test setup



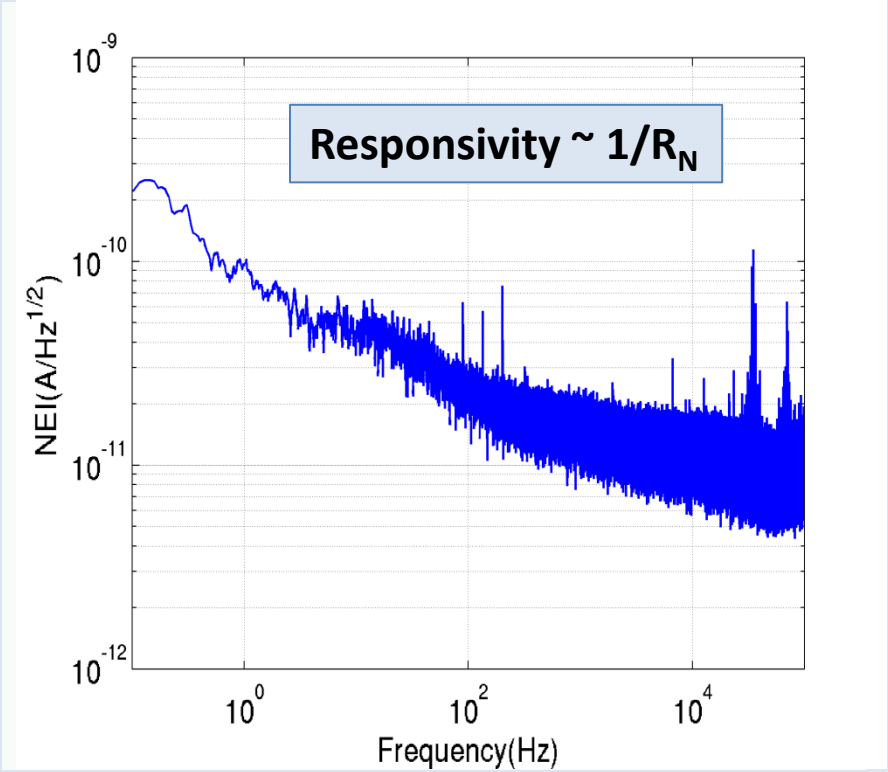
MUX09 + array test setup



1/f comes in at a bit higher frequency in MUX05, but noise level below 1 Hz doesn't appear to be much worse (ignoring huge spikes).

Issue in array test system: Large 1/f noise

Ir meander device



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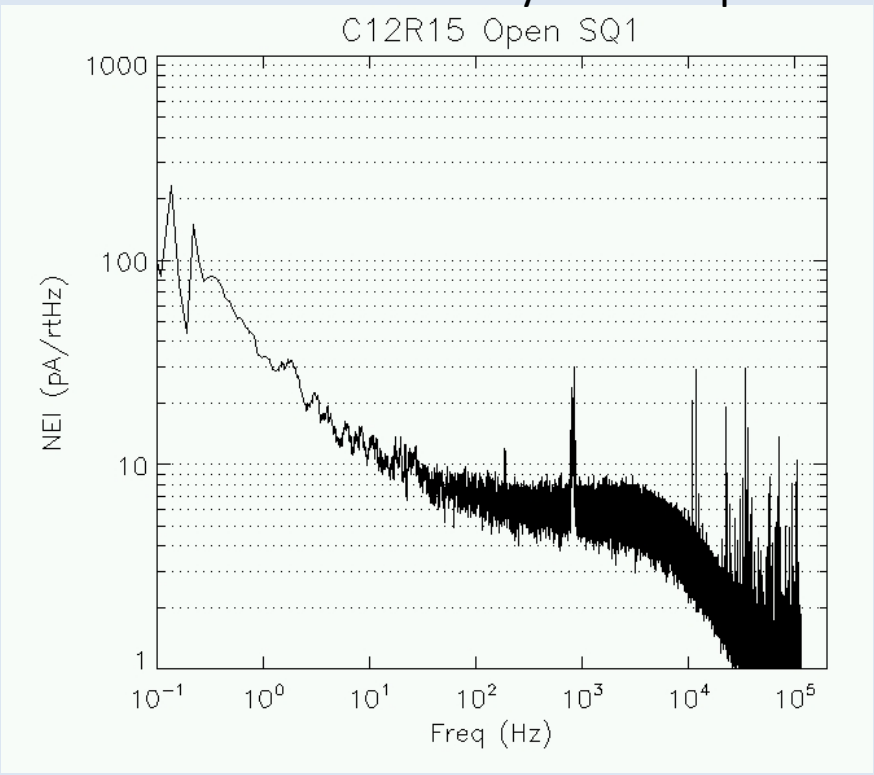

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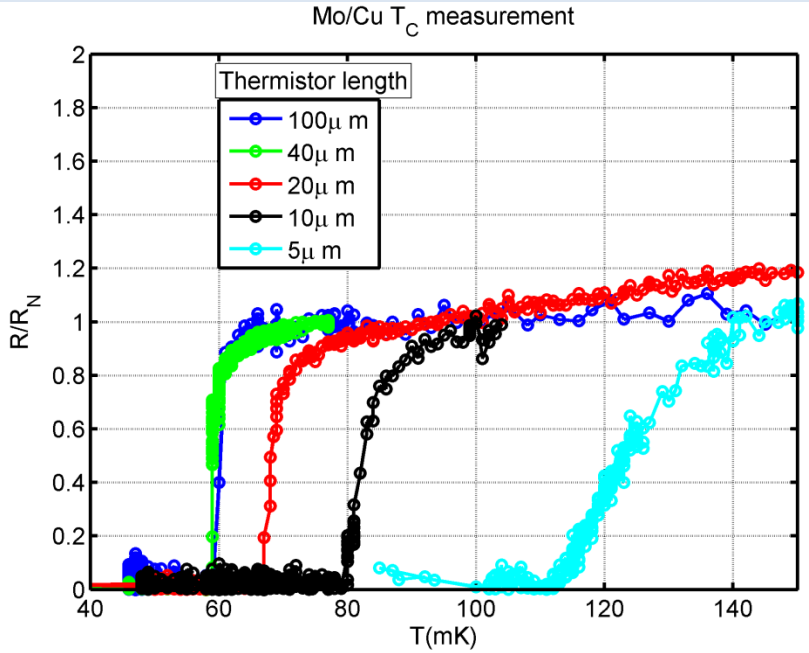
R/□=30mΩ.

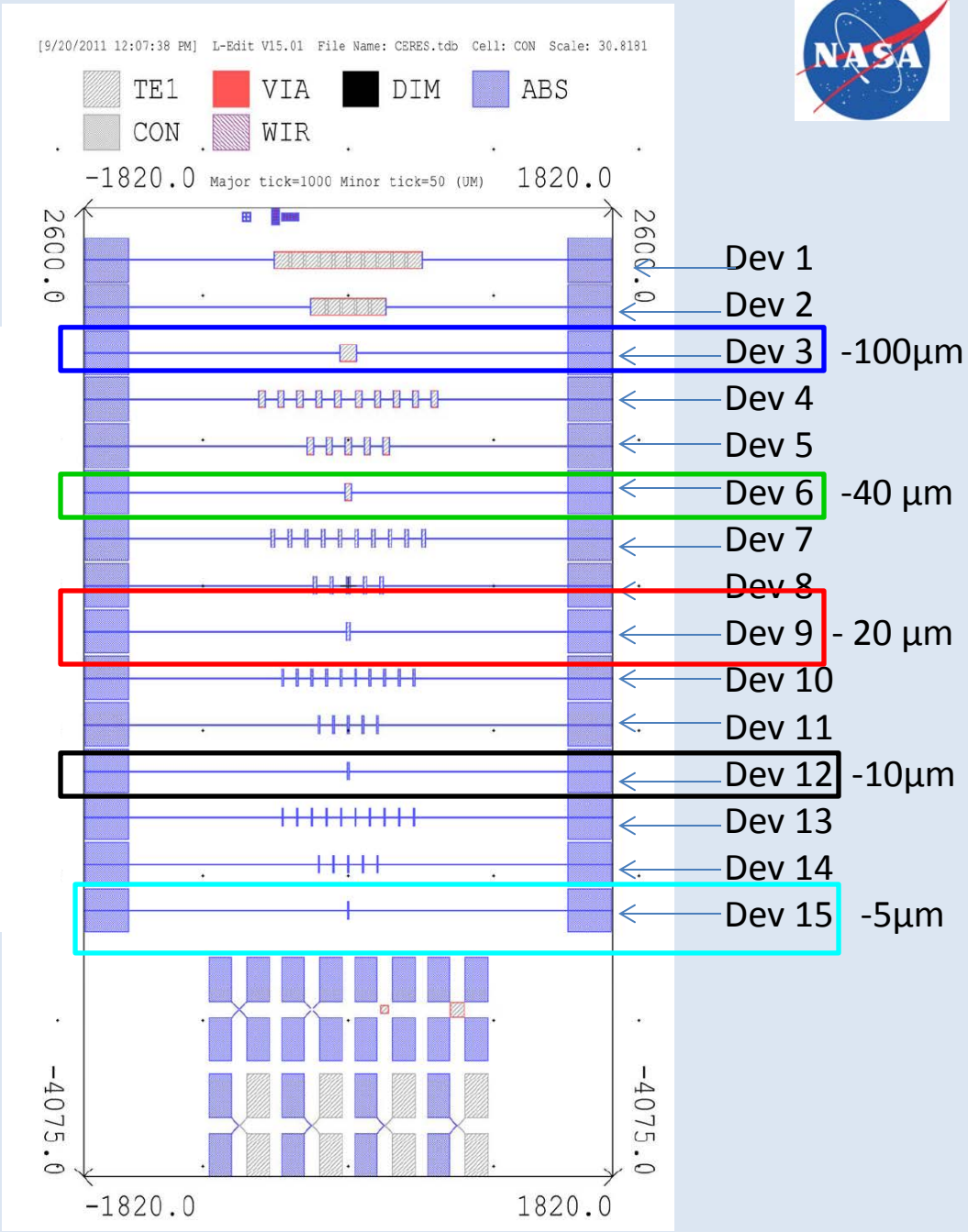
→R_N =3m Ω at 10μm.

→R_N =10m Ω at 33μm.

$$\tau = C/G \times 1/[1+P_J\alpha/(GT_C)]$$



BLISS T_C test design
Mo/Cu/Ti recipe.



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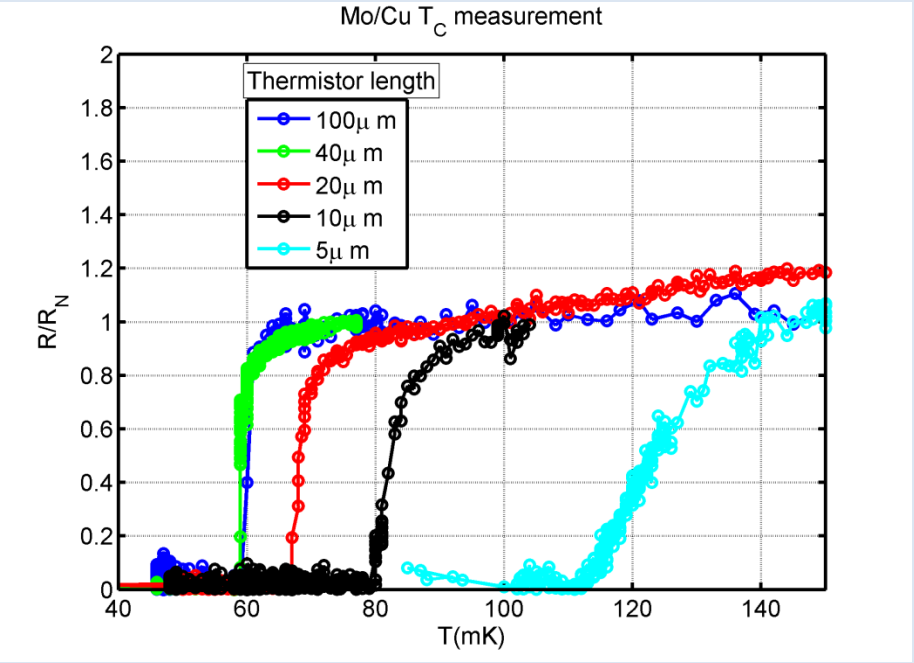
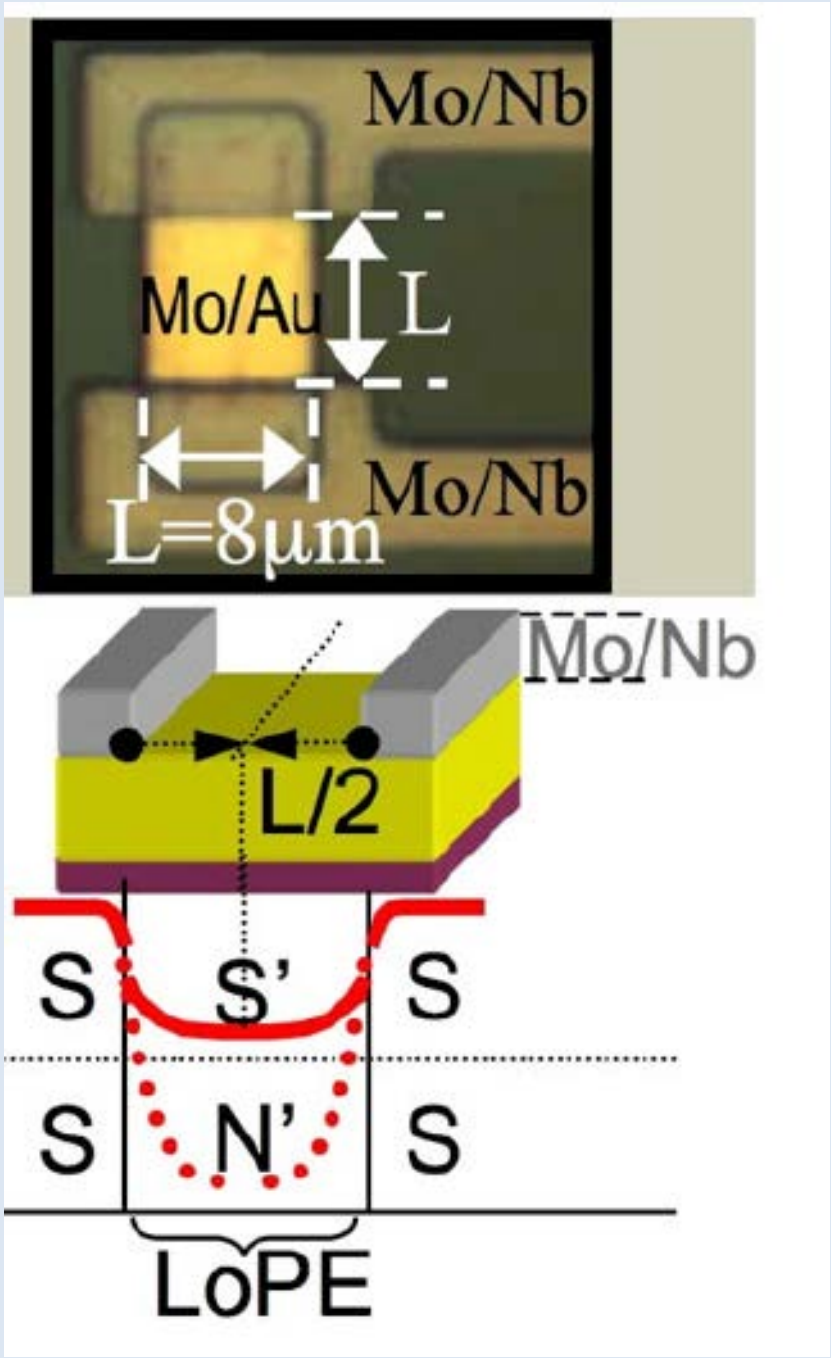


BLISS T_C test design

Mo/Cu/Ti recipe

TiN wire



- Figure from Sadleir et. al. PRL 104, 047003 (2010).

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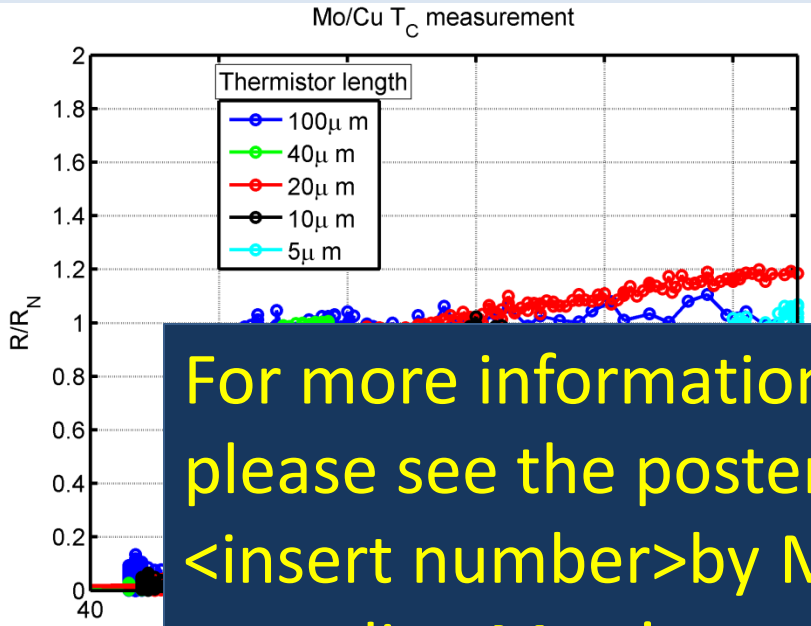
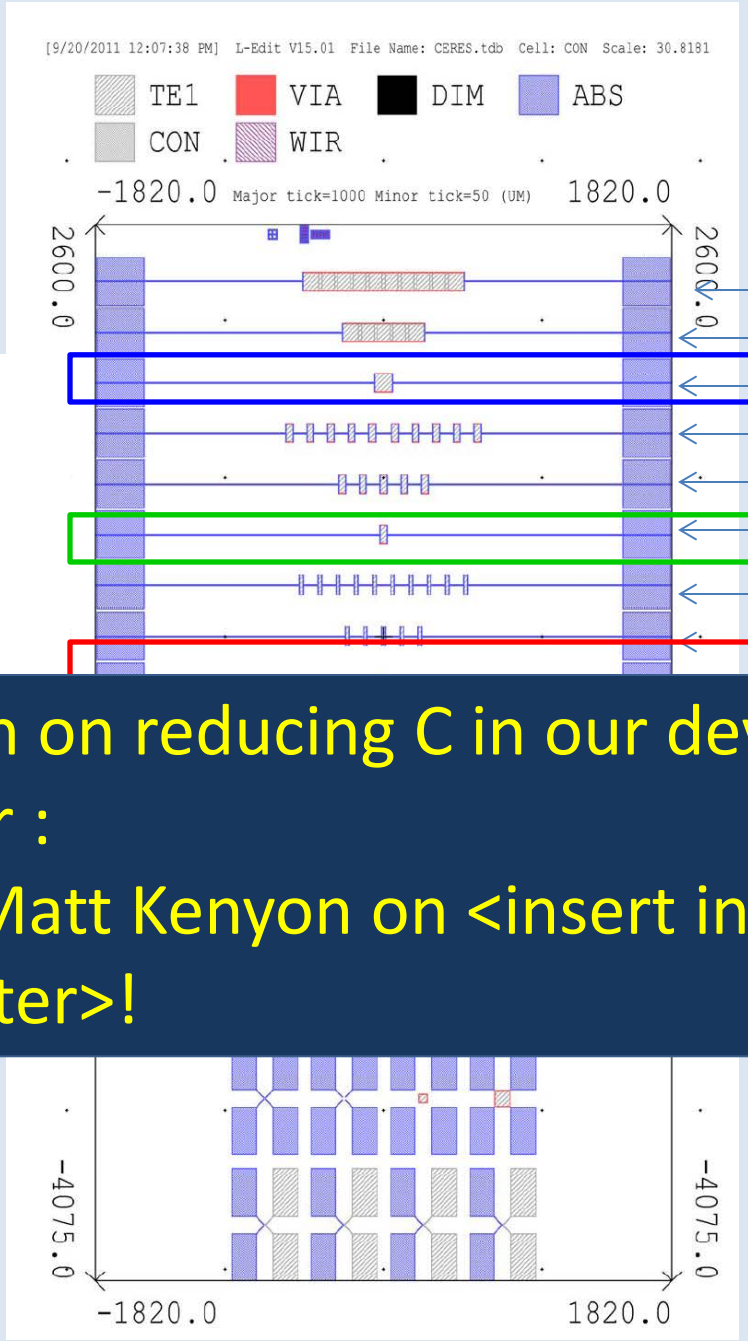
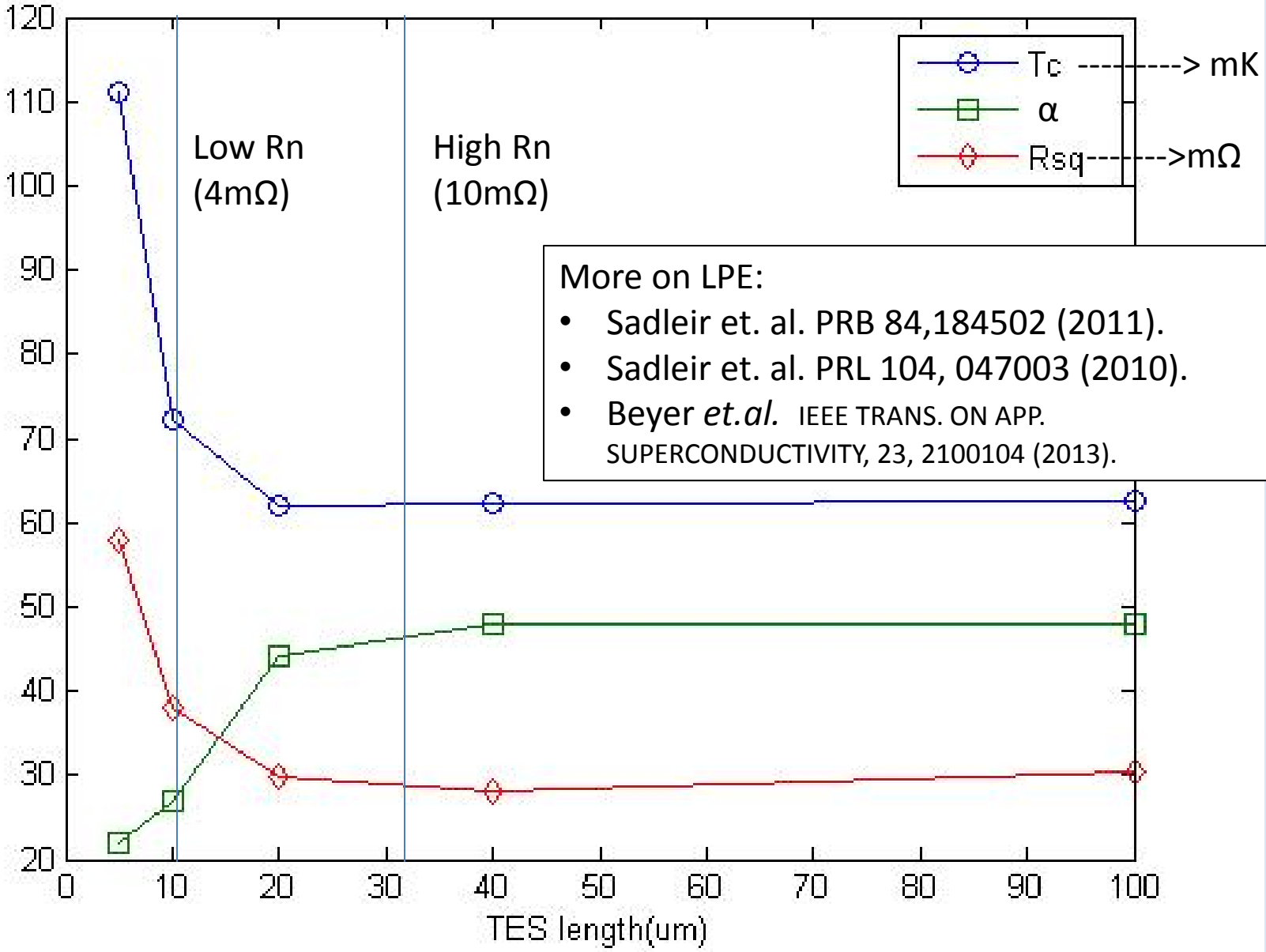




For more information on reducing C in our devices, please see the poster :
<insert number>by Matt Kenyon on <insert info regarding Matt's poster>!

BLISS T_C test design
Mo/Cu/Ti recipe.

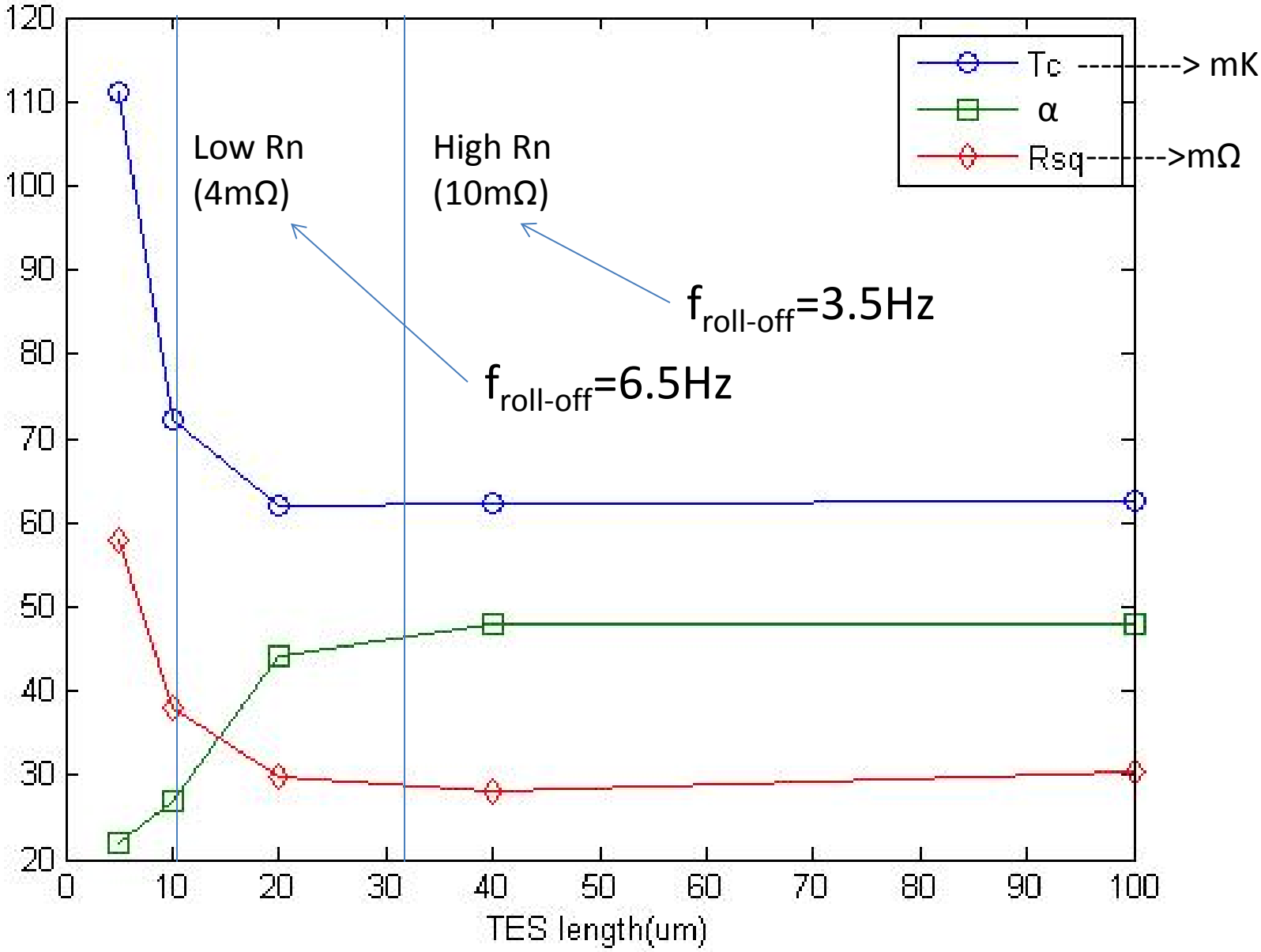
Mo/Cu bilayers (T_C=65mK): longitudinal proximity effects (LPE)



More on LPE:

- Sadleir et. al. PRB 84,184502 (2011).
- Sadleir et. al. PRL 104, 047003 (2010).
- Beyer *et.al.* IEEE TRANS. ON APP. SUPERCONDUCTIVITY, 23, 2100104 (2013).

Longitudinal proximity effects



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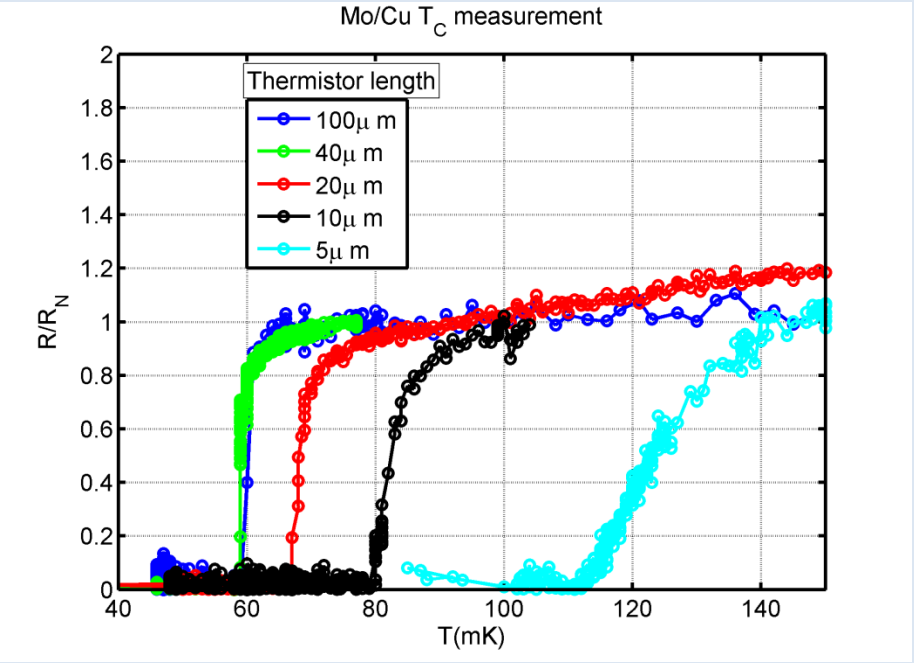
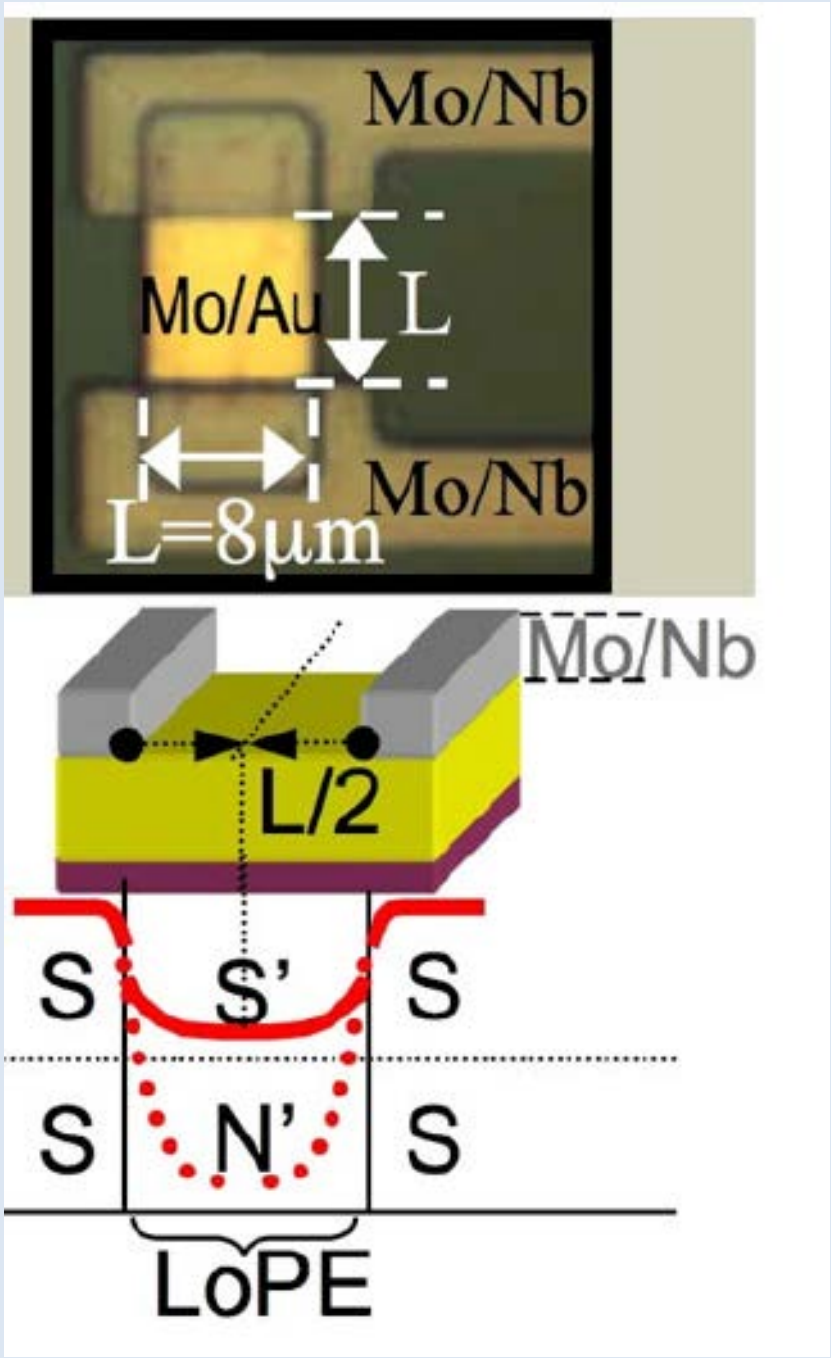


BLISS T_C test design

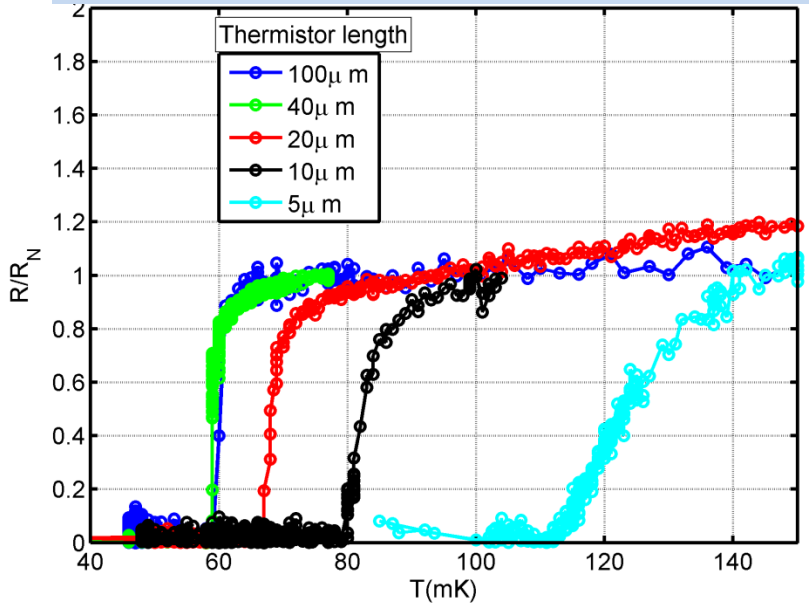
Mo/Cu/Ti recipe

TiN wire

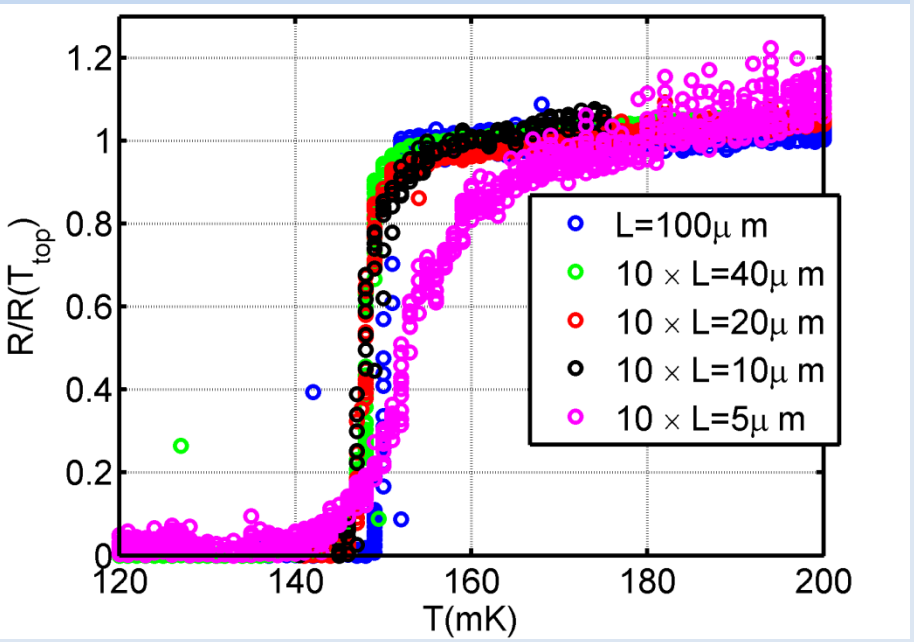


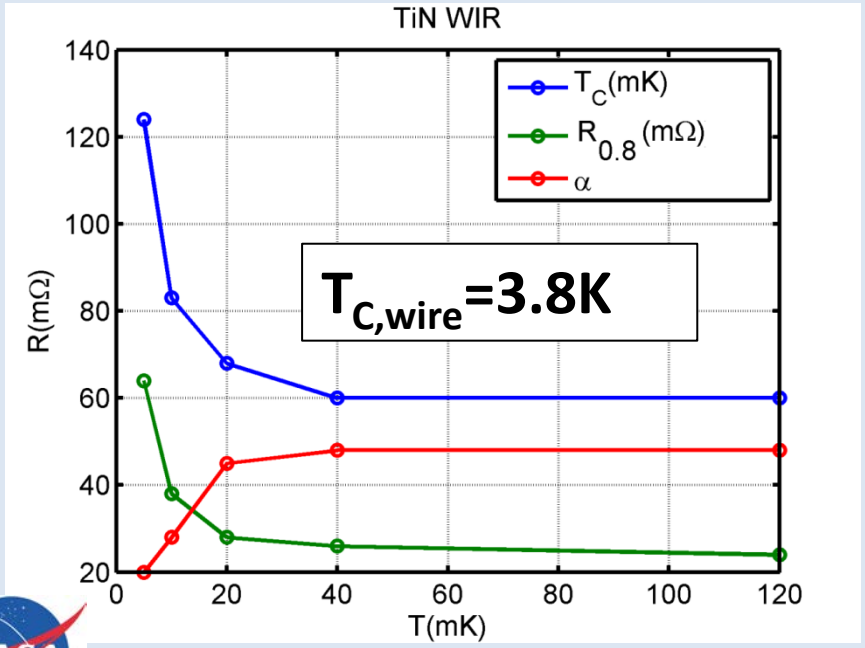
- Figure from Sadleir et. al. PRL 104, 047003 (2010).

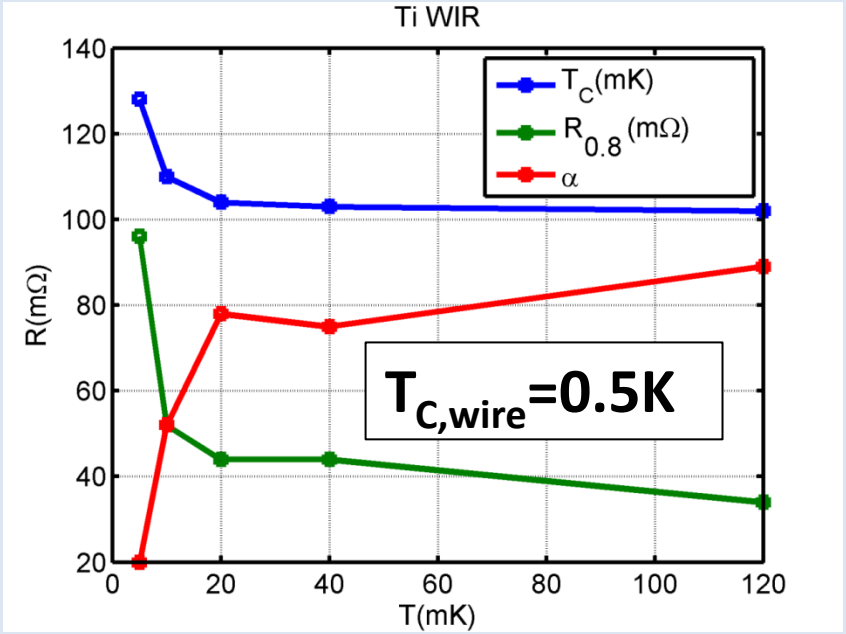
TiN wiring (~4K TiN)



Ti wiring







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   Membrane-isolated transition-edge sensor (TES) goals/requirements.

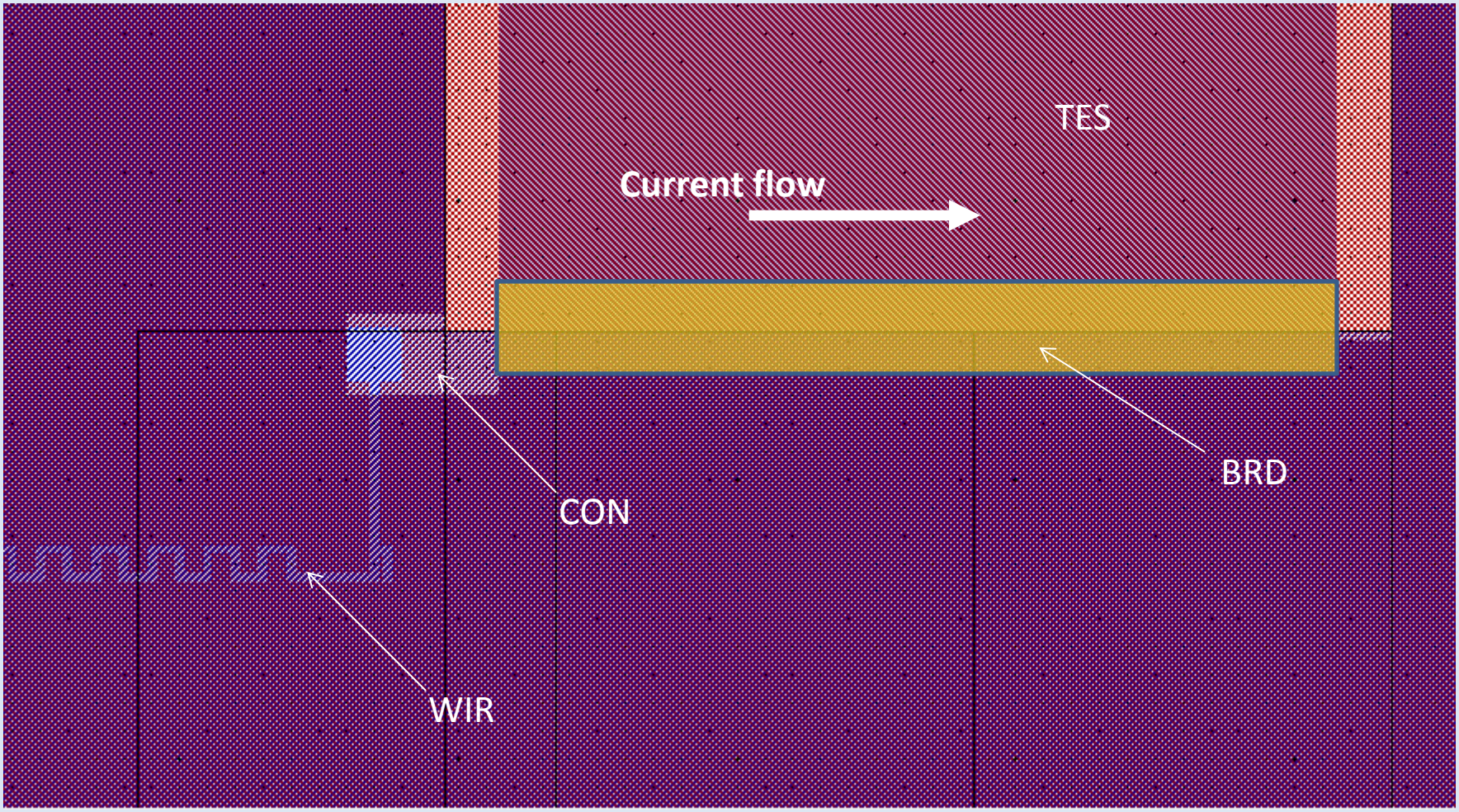
2. Detector-limited noise: readout 1/f and R_N.

3. Undesired proximity effects for α and T_C → response time τ.

4. Best performance TES:
   noise equivalent power (NEP)< 10^{-19} W/Hz$^{1/2}$ & τ ~360ms.

Reducing unwanted proximity effects

WIR: wiring layer→ TiN ($T_{C,\ TiN} >> T_{c,\ Mo/Cu}$)→ Prevents wire contribution to G.
CON: contact layer→Ti ($T_{C,TiN} > T_{C,Ti} > T_{C,Mo/Cu}$).
BRD: Prevents "footing" problems and adds normal excitations to reduce LPE.



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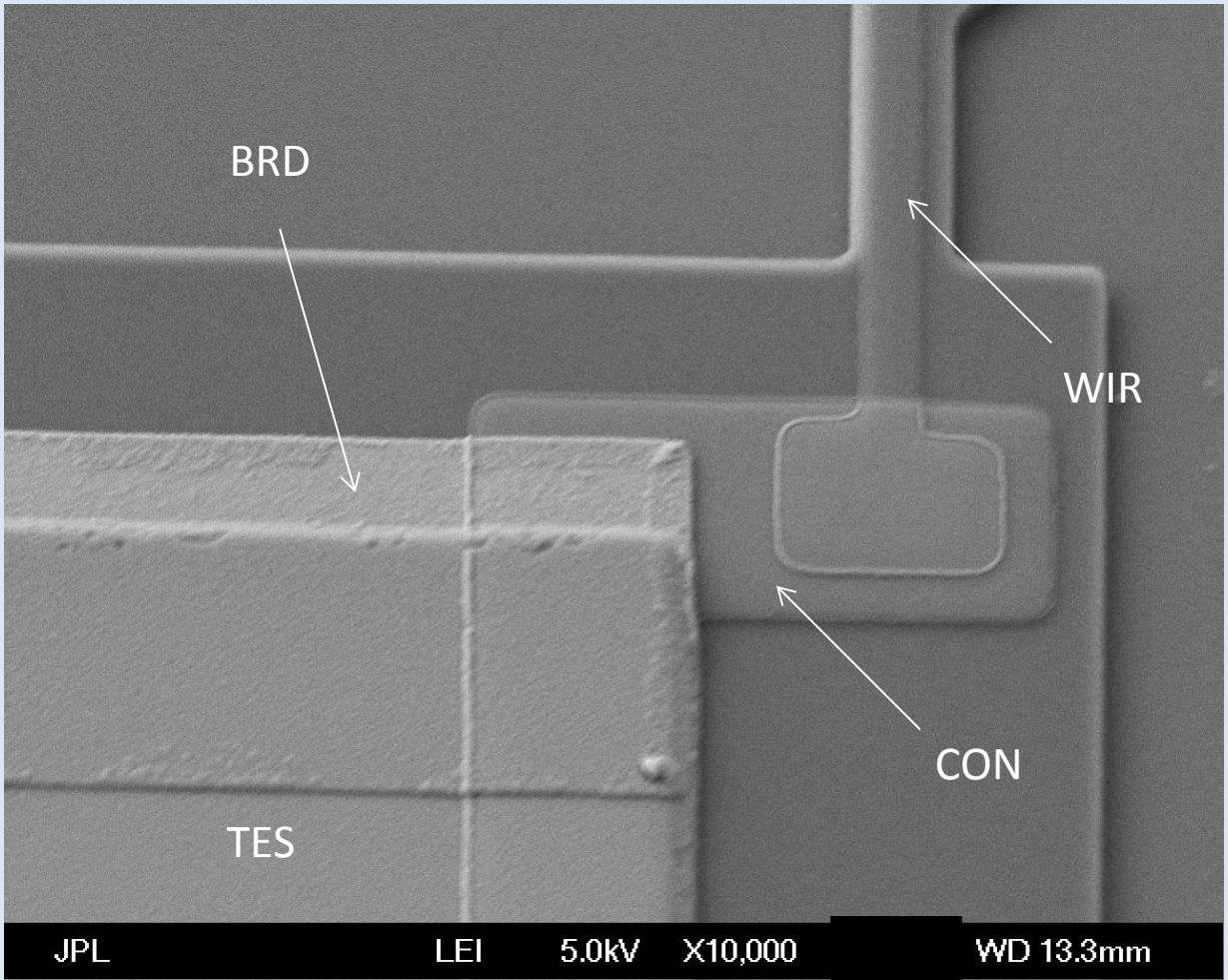
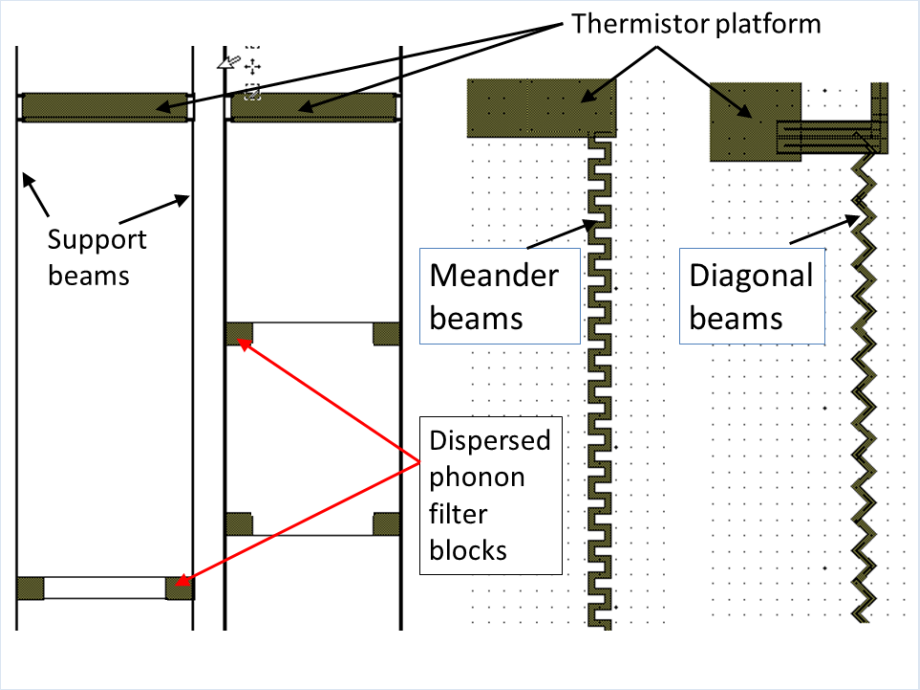
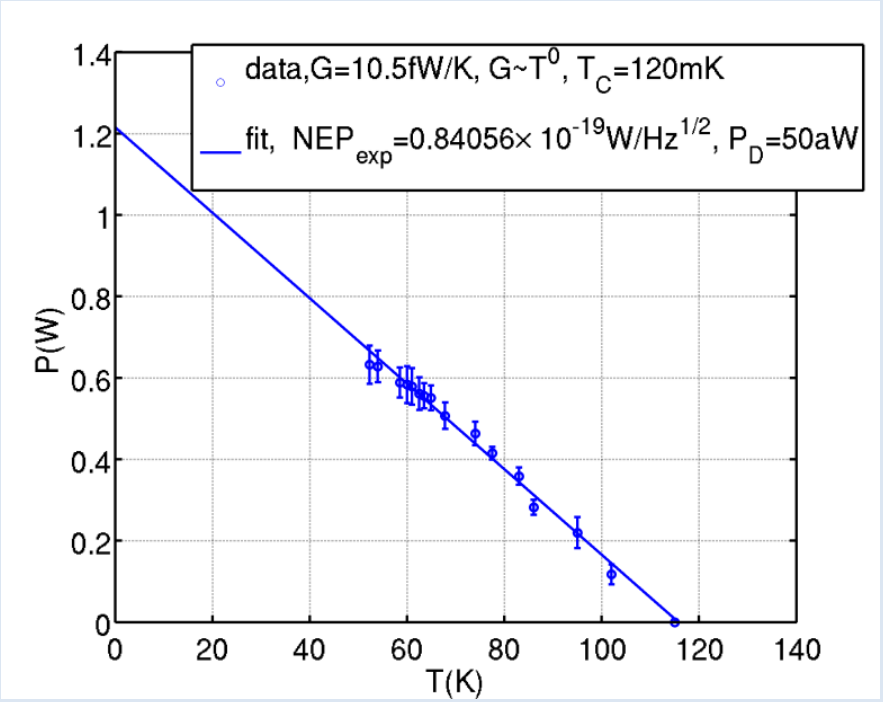


Lowering G to meet NEP requirement





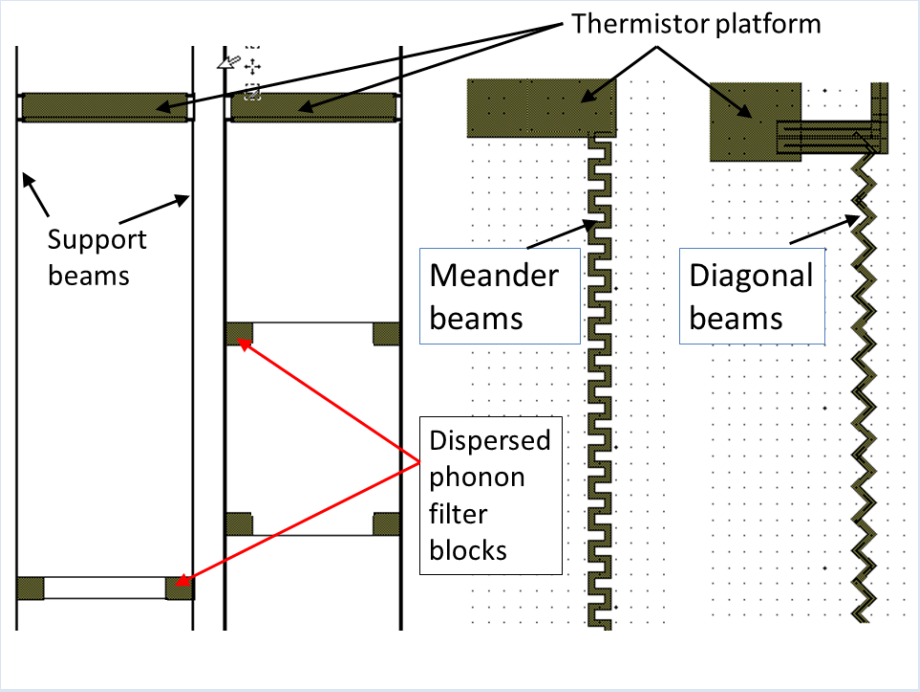
$G=(15\pm5)fW/K$, $T_C=(120.5\pm3.5)mK$, $10<\alpha<60$, and $\tau=(360\pm30)ms$.

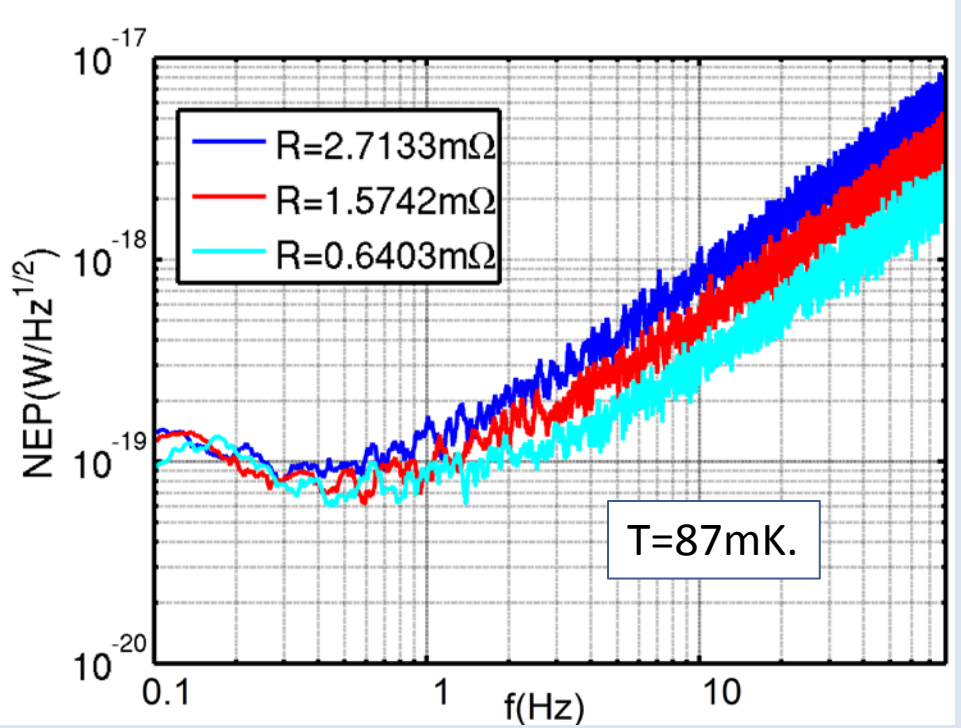
Stray power $P_D=(135\pm85)aW$.

Approximate transfer function: $1/(V_{bias}\sqrt{(1+(\omega\tau)^2)})$.

NEP=$(0.95\pm0.2)\times10^{-19}W/Hz^{1/2}$, while the expected NEP is $(8.5\pm1.5)\times10^{-20}W/Hz^{1/2}$

Lowering G to meet NEP requirement





G=(15±5)fW/K, T_C=(120.5±3.5)mK, 10<α<60, and **τ=(360±30)ms.**

Stray power P_D=(135±85)aW.

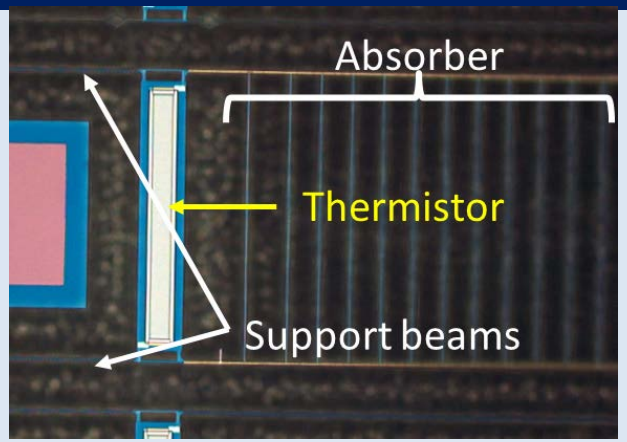
Approximate transfer function: $1/(V_{bias}\sqrt{(1+(\omega\tau)^2)})$.

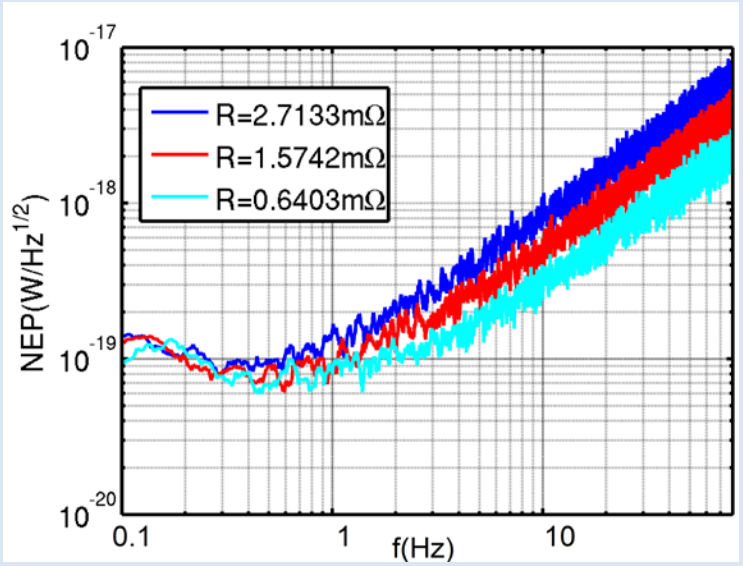
NEP=(0.95±0.2)×10^{-19}W/Hz$^{1/2}$, while the expected NEP is (8.5±1.5)×10^{-20}W/Hz$^{1/2}$

Conclusions

1. BLISS goals:

- NEP<10^{-19} W/Hz$^{1/2}$
- τ<160ms.

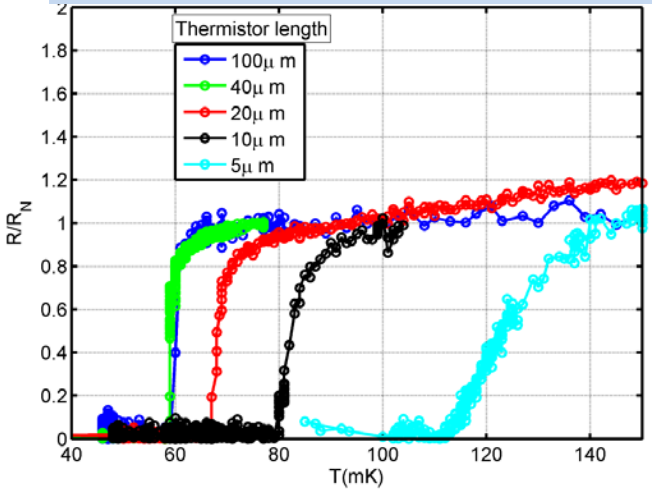




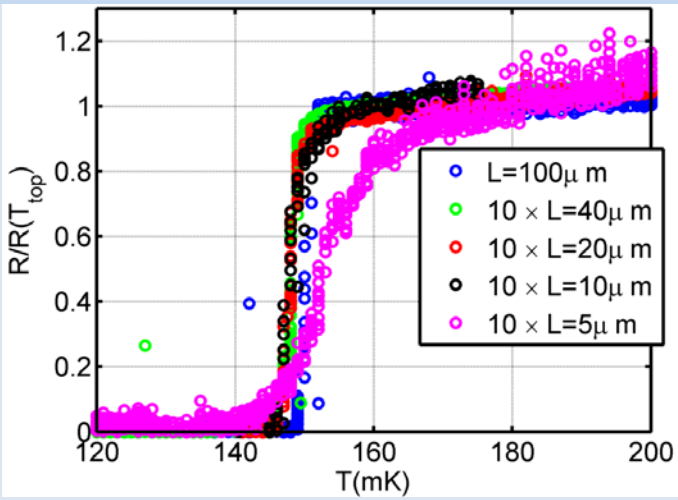
2. Demonstrated:

- **τ=(360±30)ms**
- **NEP=(0.95±0.2)×10^{-19}W/Hz$^{1/2}$**

TiN wiring (~4K TiN)



Ti wiring



3. Built Mo/Cu thermistors with:

- **New contact, wire scheme.**
- **Low R_N** → improved responsivity.
- **Improved α.**