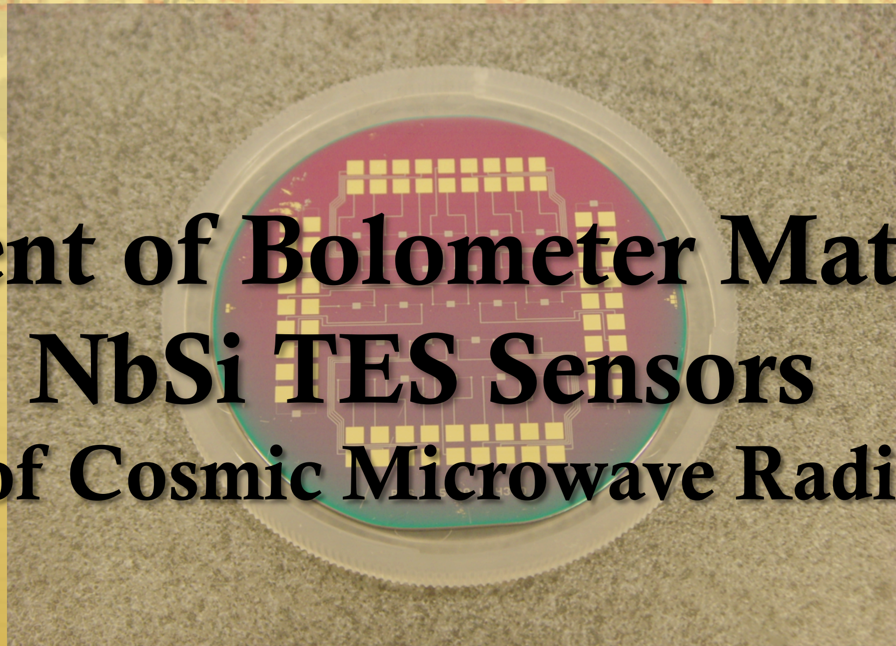
11th ICATPP Conference on

Astroparticle, Particle, Space Physics, Detectors and Medical Physics Applications



Development of Bolometer Matrices with NbSi TES Sensors

for the Study of Cosmic Microwave Radiation (CMB)

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October 6th, 2009

Outline

- Introduction to CMB— Cosmic Microwave Background
- Introduction to Bolometer Matrices and Transition Edge Sensors (TES)
- Fabrication Process of NbSi TES
- Electron-Phonon Coupling of NbSi thin film
- Noise Spectra and Sensitivity of NbSi TES Bolometers
- Conclusion

Cosmic Microwave Background

from the Big Bang 14 Billion Years Ago

CMB radiation is polarized because it was scattered off of free electrons during decoupling.

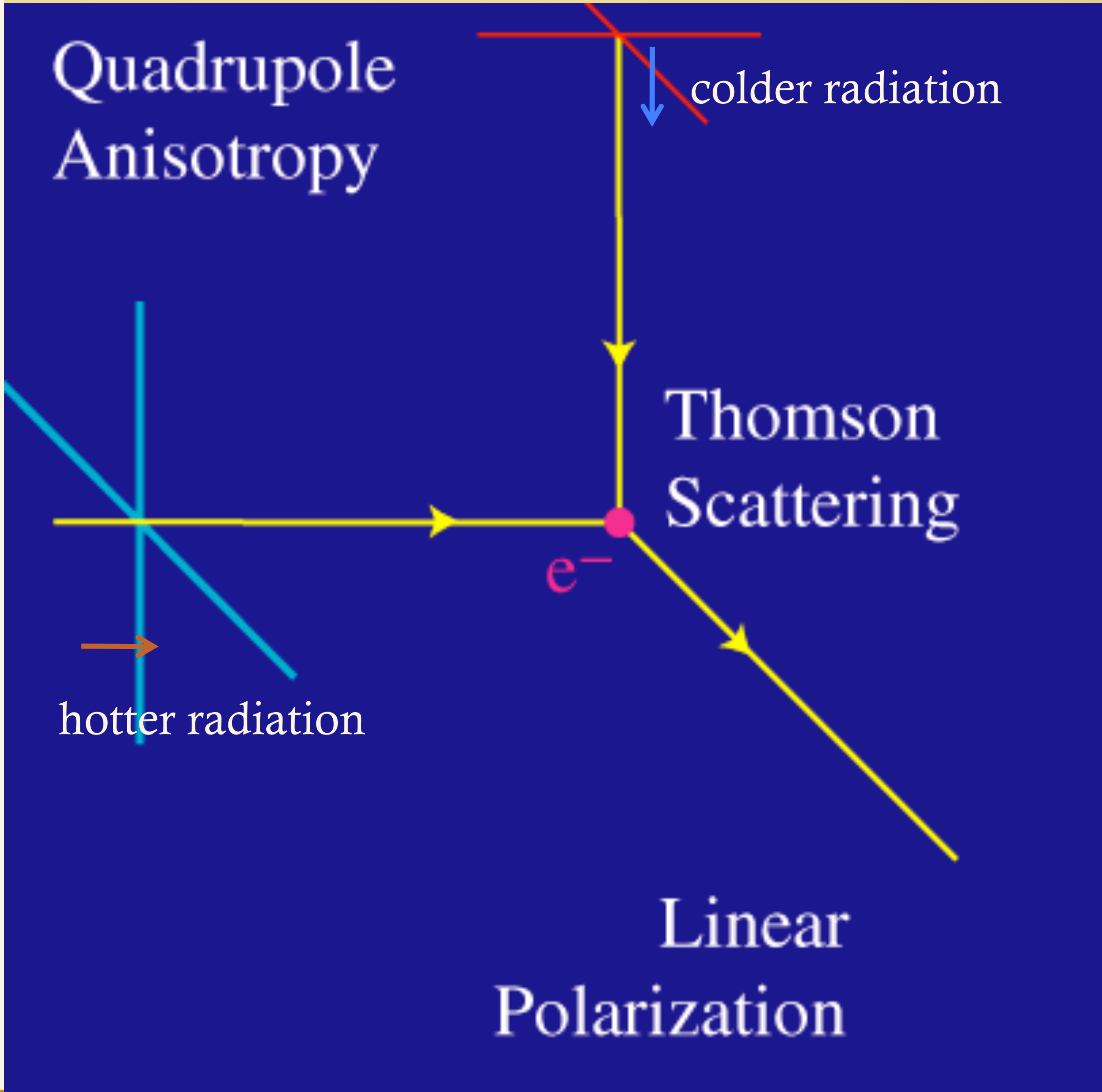
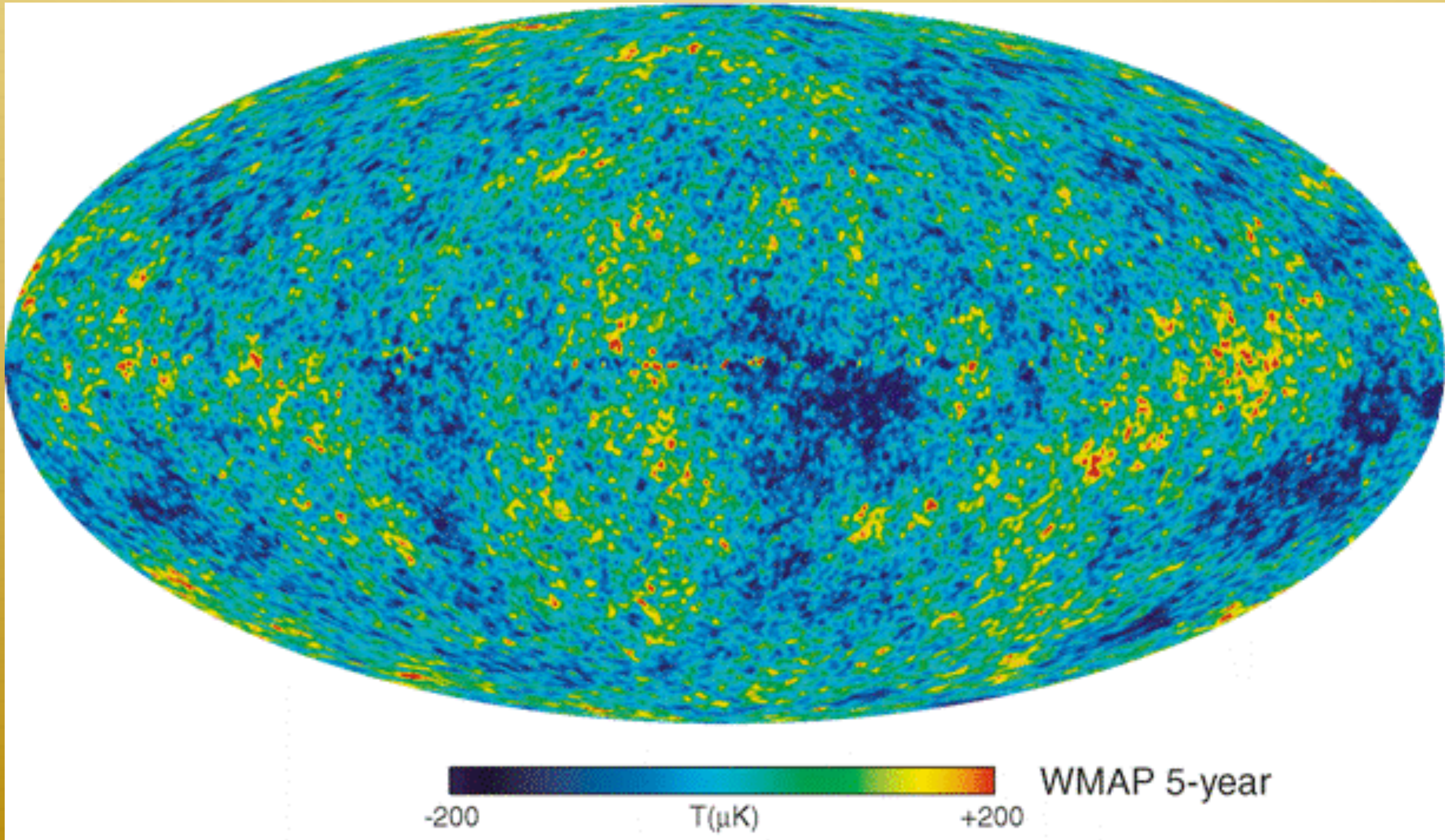


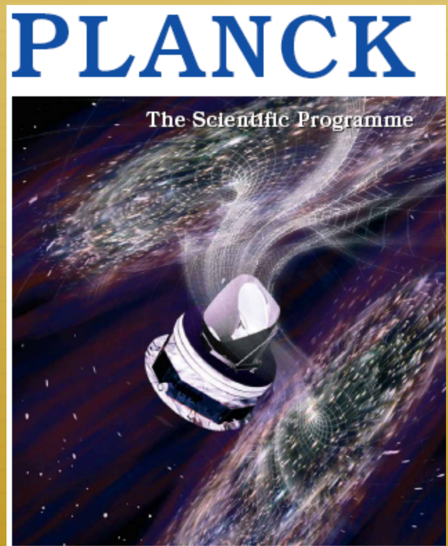
Image of CMB Radiation by WMAP



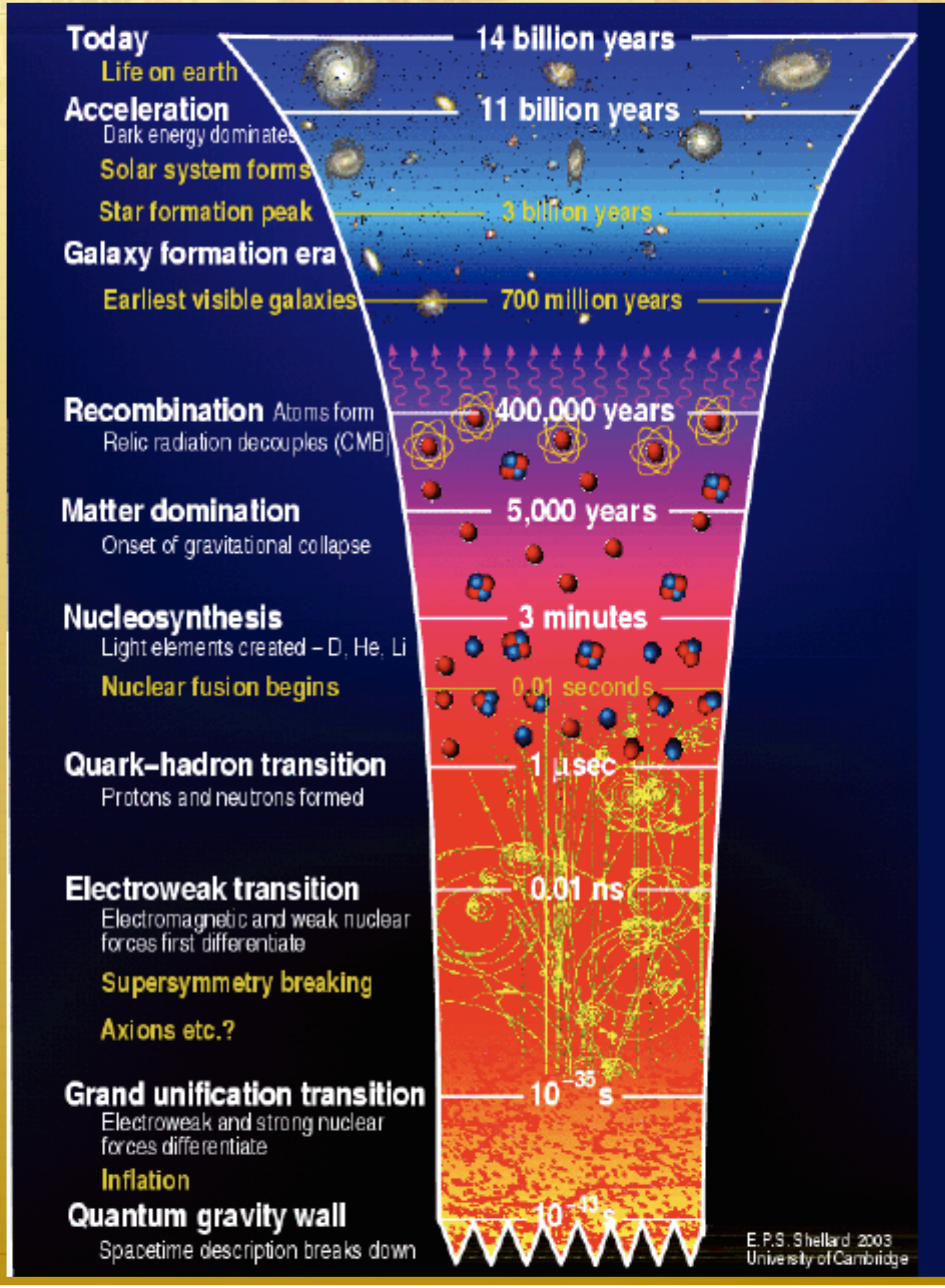
Cosmic Microwave Background

Schematic diagram of the history of the Universe from the Planck time to the present:

Planck physics (on orbit since May 2009)



[The Scientific Programme of Planck, 2006, astro-ph/0604069]



Space Based CMB Experiments

Experiment	Description	Year	Location	Target
Relikt	Relikt-1 on Prognoz 9 mapped the sky at 37 GHz with an angular resolution of 5.5 degrees and a temperature resolution of 0.2 mK.	1983-1984	Earth orbit	Large scale temperature anisotropies
COBE	COBE (Cosmic Background Explorer) was developed by NASA's Goddard Space Flight Center to measure the diffuse infrared and microwave radiation from the early universe.	1989-1993	Earth orbit	CMB spectrum
WMAP	WMAP (Wilkinson Microwave Anisotropy Probe) is designed to determine the geometry, content, and evolution of the universe via a 13 arcminute FWHM resolution full sky map of the temperature anisotropy of the cosmic microwave background radiation.	2001-present		Temperature anisotropies; Polarization
Planck	Planck is the third Medium-Sized Mission (M3) of ESA's Horizon 2000 Scientific Program. The basic scientific goal of the Planck mission is to measure CMB anisotropies at all angular scales larger than 5 to 10 arcminutes over the entire sky with a precision of ~2 parts per million. (HEMT/Bolometer 30-857GHz)	2009-present	Lagrange 2	Polarization; Temperature anisotropies; Foregrounds
B-Pol	Primordial gravitational waves generated during inflation	Future-		B-Polarization

[http://en.wikipedia.org/wiki/List_of_cosmic_microwave_background_experiments; http://lambda.gsfc.nasa.gov/links/experimental_sites.cfm]

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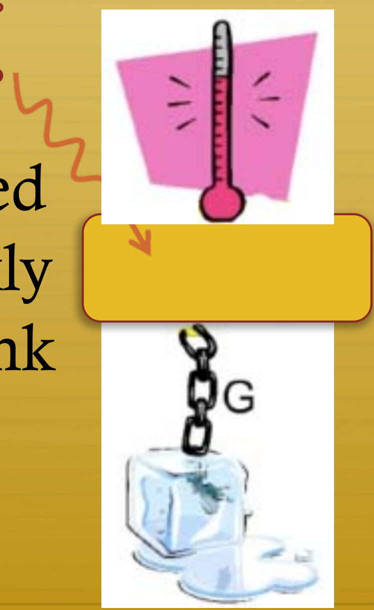
Basic Structure of One Pixel of Bolometer Matrices

1. Radiation absorber

- Feed horns
- Antennas
- Direct absorption by thin films (Bi or Cu)

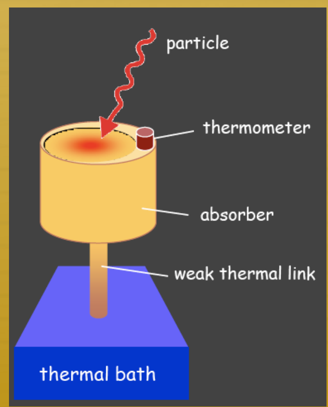
2. Thermometer

- Superconducting transition edge sensors (NbSi, Mo/Au, Ti, etc.)
- High impedance Anderson insulator (NbSi, NTD Ge, Si:P, etc.)



3. Thermally isolated sample holder weakly coupled to a heat sink

- SiN membrane-- Electron-phonon decoupling
- $\Delta T = P/G$

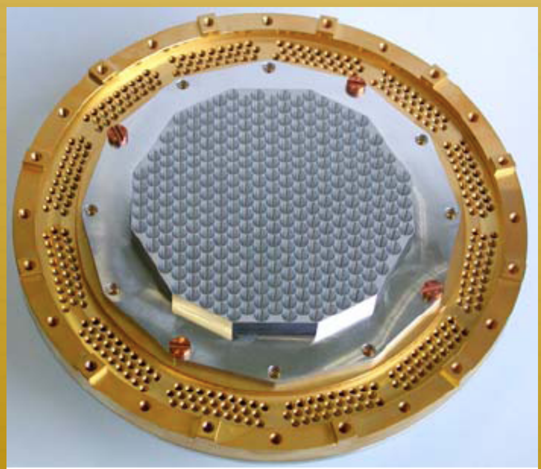


[Picture from Piet de Korte in SRON]

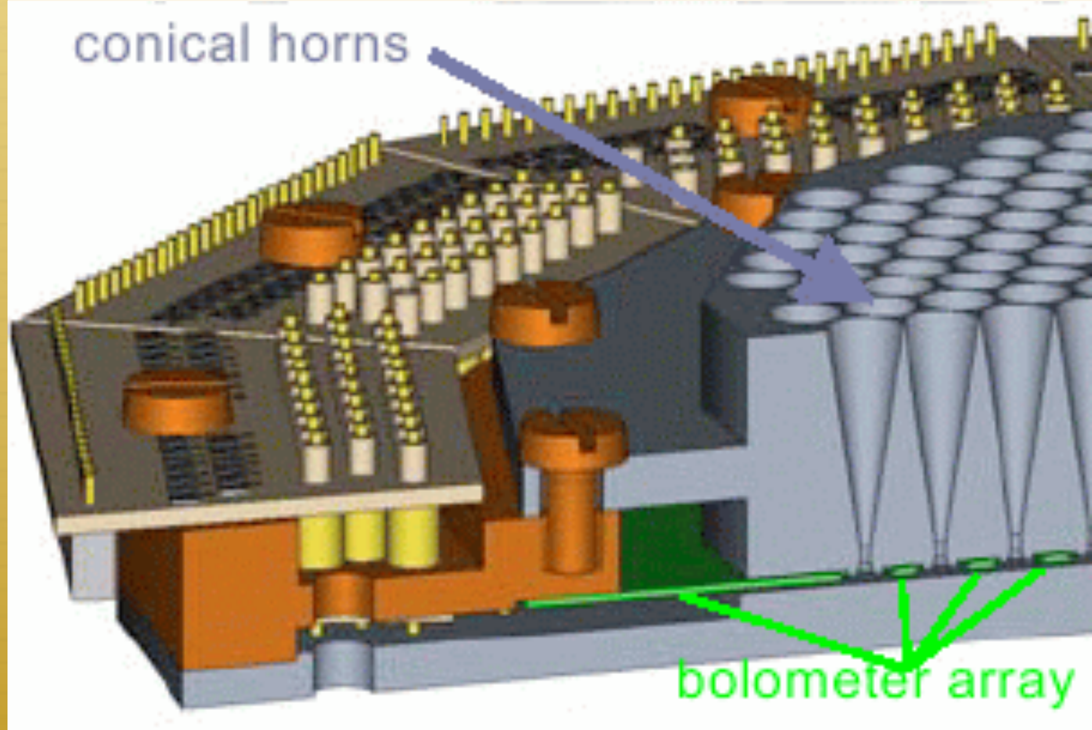
Absorbers of Bolometer Matrices

1. Radiation absorber

- Feed horns
- Antennas
- Direct absorption by thin films (Bi or Cu)



Atacama Pathfinder EXperiment (APEX)
Large Apex BOlometer Camera (LABOCA)



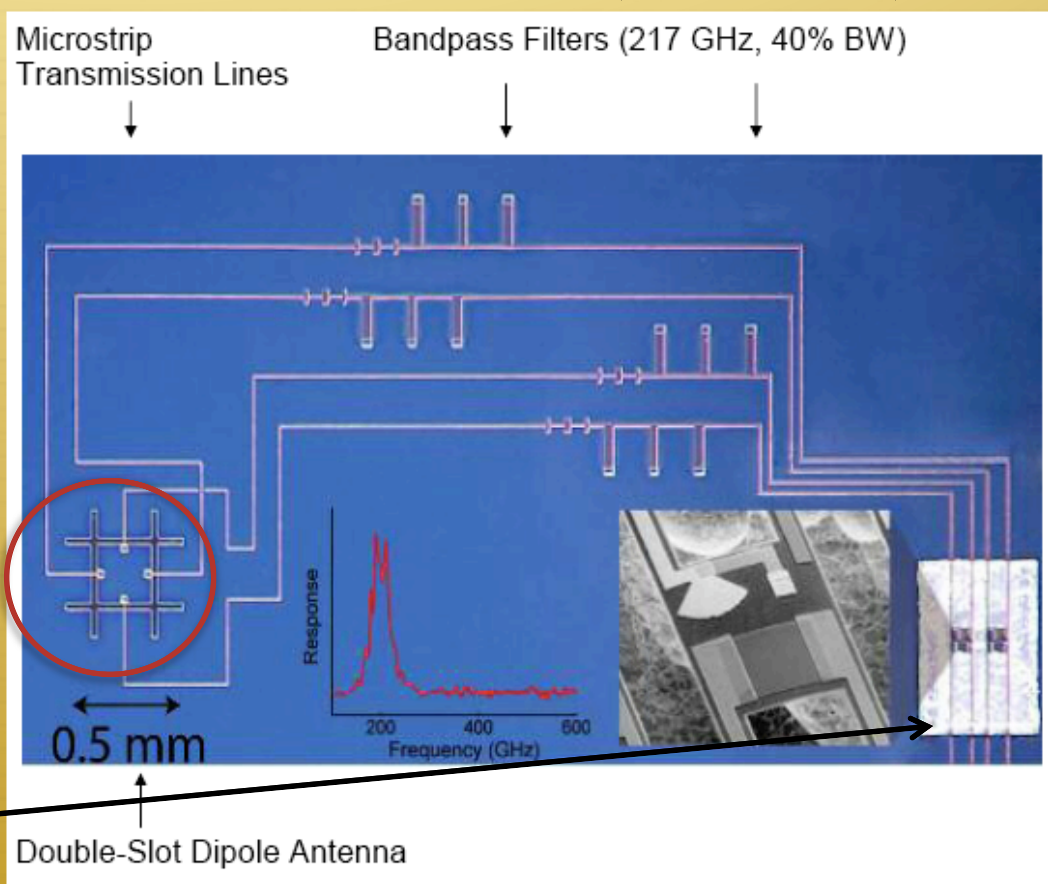
[http://www.apex-telescope.org/bolometer/laboca/technical]

Absorbers of Bolometer Matrices

(UCB/LBNL)

1. Radiation absorber

- Feed horns
- Antennas
- Direct absorption by thin films (Bi or Cu)



Microstrip terminated on a Si-nitride suspension.

Power measured with TES

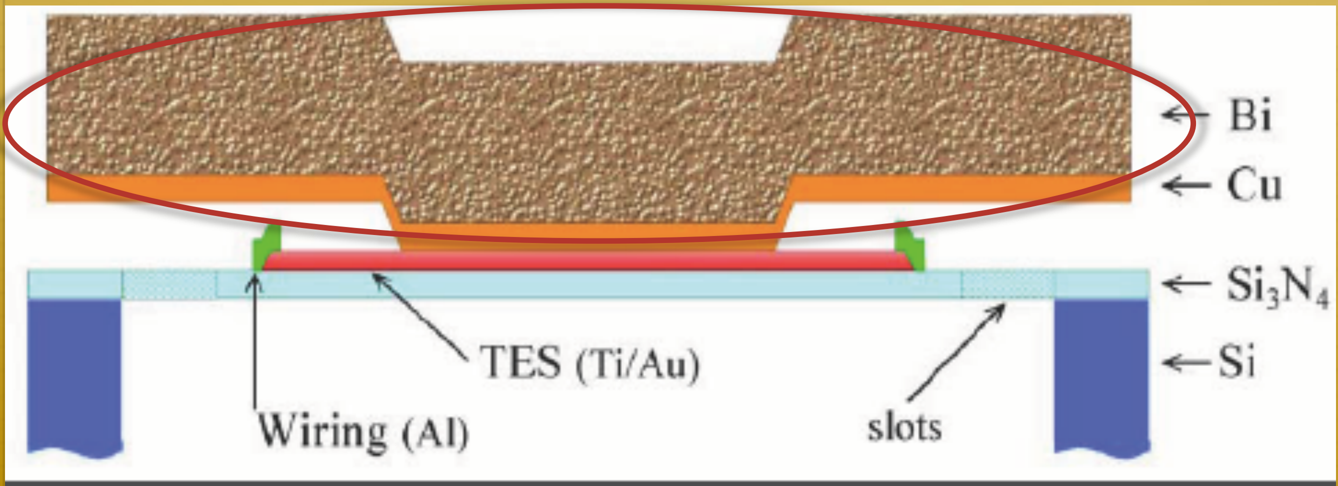
Antenna-Coupled Prototype Pixel (Mike Myers)

Absorbers of Bolometer Matrices

1. Radiation absorber

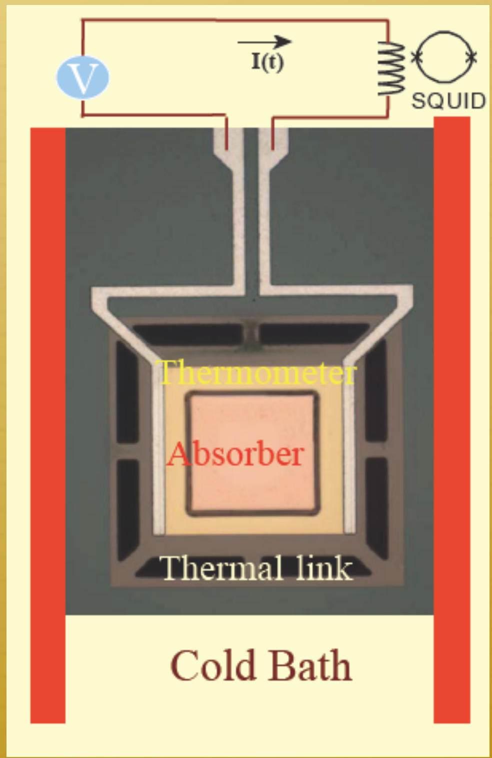
- Feed horns
- Antennas
- Direct absorption by thin films (Bi or Cu)

(Piet de Korte in SRON)



Pixel design

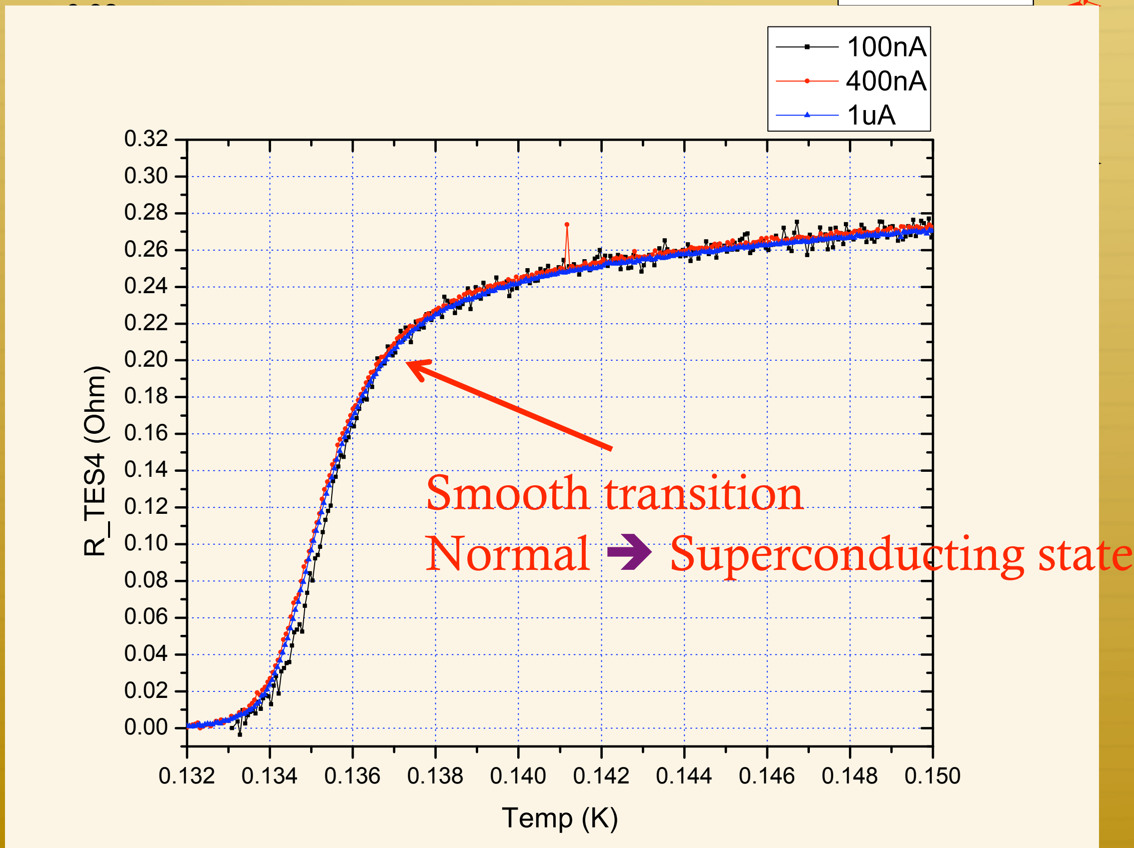
TES-based Micro-Calorimeter



Sensors of Bolometer Matrices

- Resistance versus Temperature curve:

$Nb_{0.14}Si_{0.86}$ thickness 50nm



2. Thermometer

- Superconducting transition edge sensors (NbSi, Mo/Au, Ti, etc.)
- High impedance Anderson insulator (NbSi, NTD, Si:P , etc.)

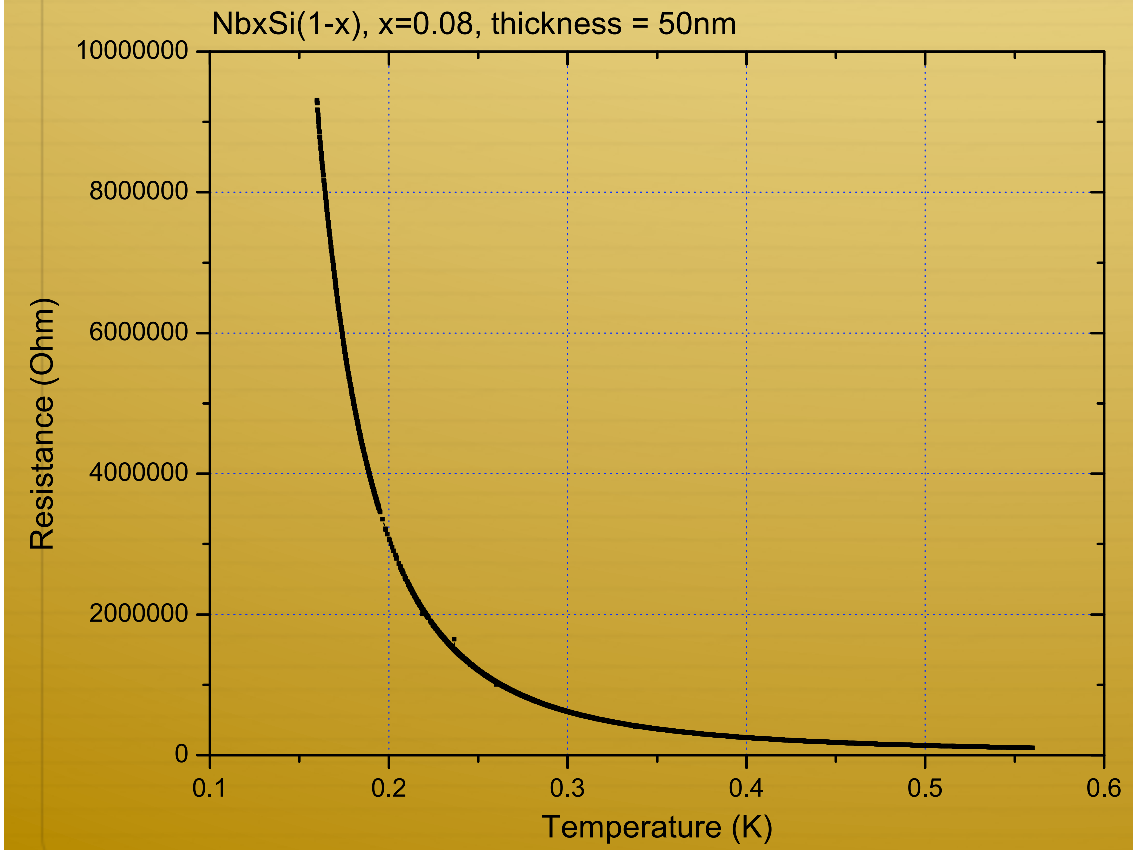
  - Materials:
    - Nb_xSi_{1-x} (x>0.12)
    - Ti/Au
    - Ir
    - Mo/Au
    - Mo/Cu
    - W

[CSNSM]

Sensors of Bolometer Matrices

- Resistance versus Temperature curve:

$Nb_{0.08}Si_{0.92}$ thickness 50nm

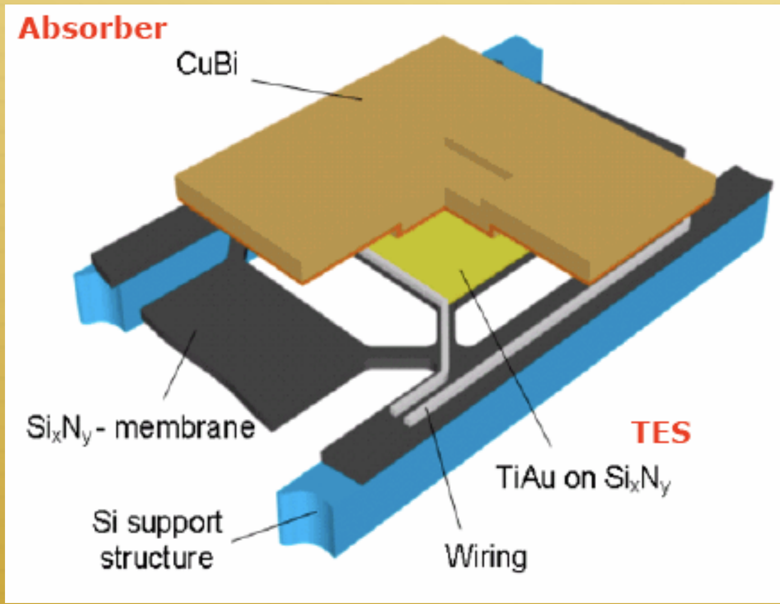


2. Thermometer

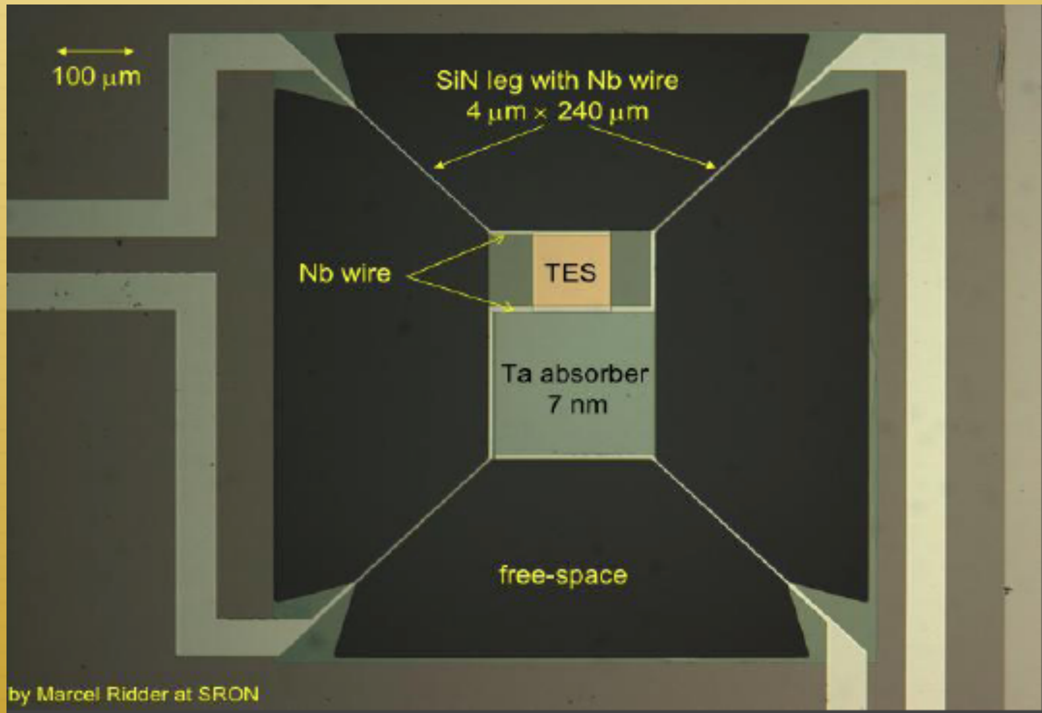
- Superconducting transition edge sensors (NbSi, Mo/Au, Ti, etc.)
- High impedance Anderson insulator (NbSi, NTD, Si:P , etc.)

[CSNSM]

Bolometer Matrices with Membranes



[Piet de Korte in SRON]



3. Thermally isolated sample holder weakly coupled to a heat sink

- SiN membrane

Single pixel with optical absorber (a real picture)

I will present here:
bolometer matrices without SiN membranes

NbSi is used to:

1. Absorption of radiation (with or without antennas): it needs impedance matching to vacuum impedance 377 Ω or to antenna termination.
2. Creation of thermal decoupling: electron-phonon decoupling of NbSi without membrane.
3. Temperature Sensor (TES NbSi or Anderson Insulator NbSi).

We will develop here e-ph coupling and TES performance of NbSi.

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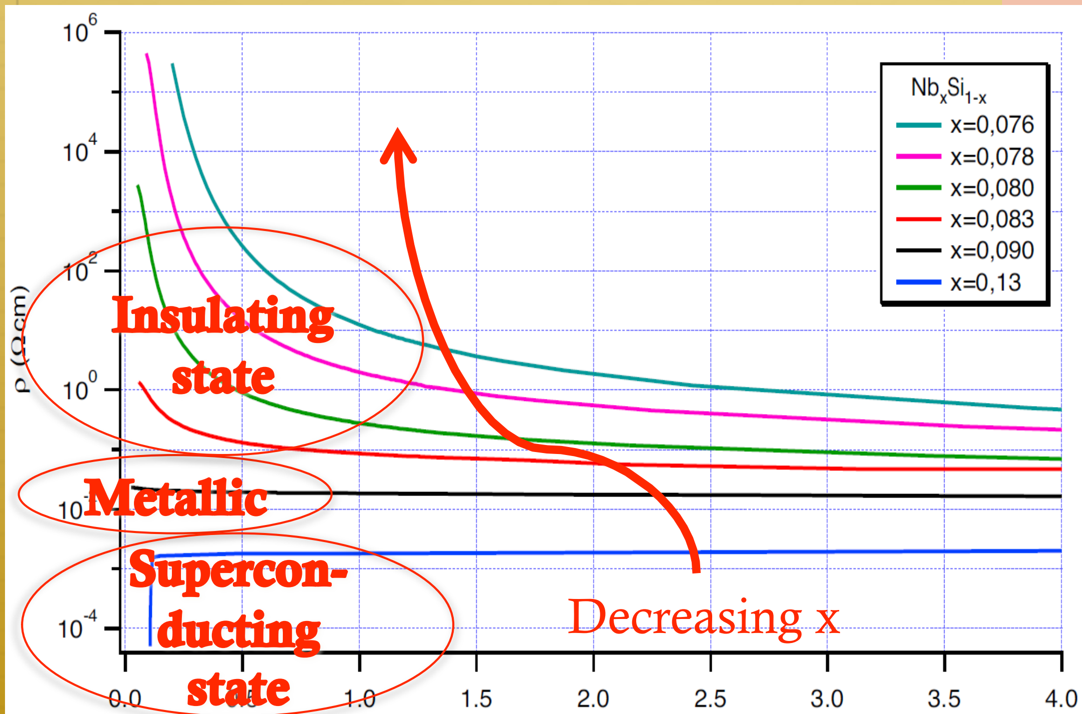
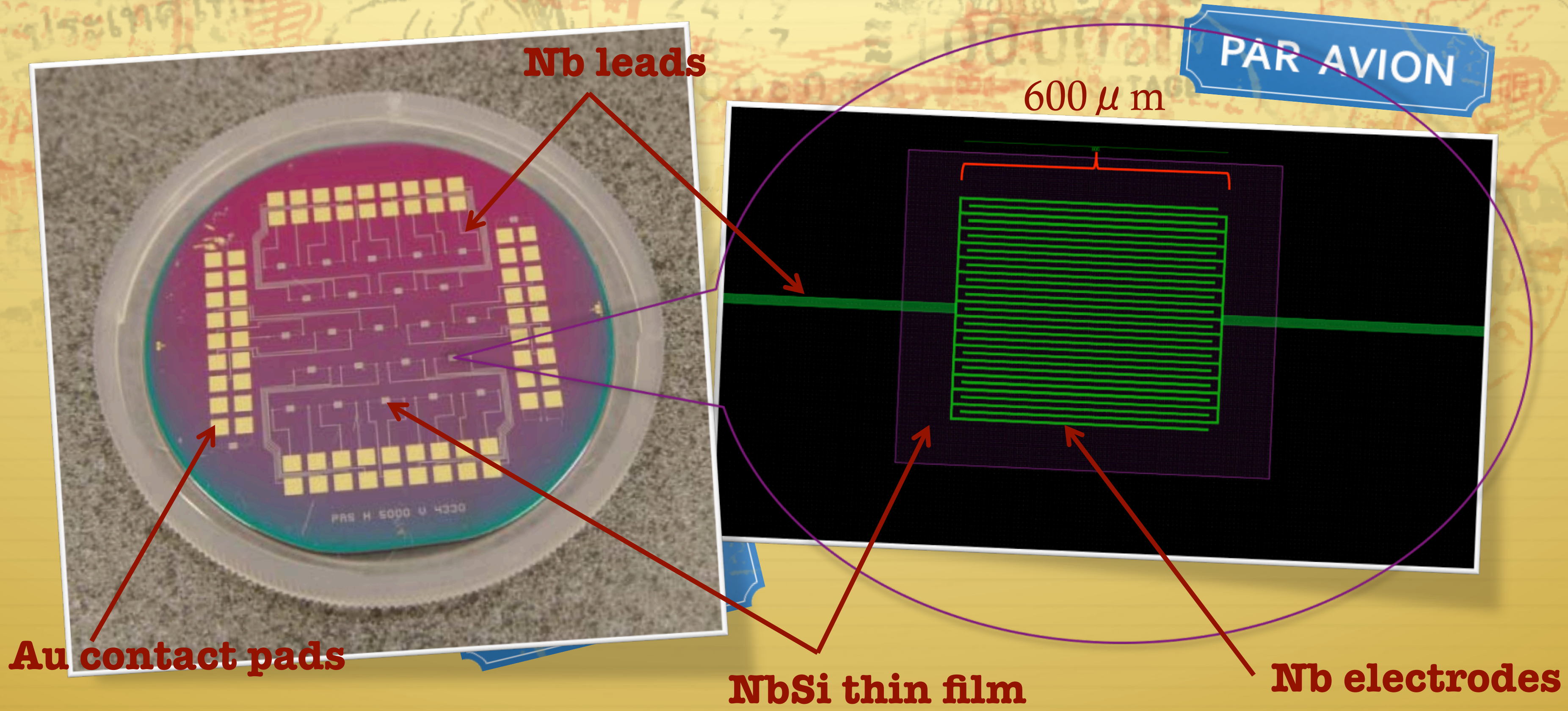
Phase Transitions of NbSi

- For 3-dimensional Nb_xSi_{1-x} thin film (e.g. 100nm):
  - x < 9%: Anderson Insulator state
  - 9% < x < 12%: metallic state
  - x > 12%: superconducting state



Temperature (K)

[CSNSM]



NbSi Thin Film Bolometer Matrices

Prototype of 23-pixel matrices of superconducting NbSi alloy transition sensors:

1. NbSi thin film
2. Niobium leads
3. Niobium electrodes interlacing on NbSi thin film ➔ to reduce normal resistance
4. Gold contact pads

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Thermal Conduction and Power Law

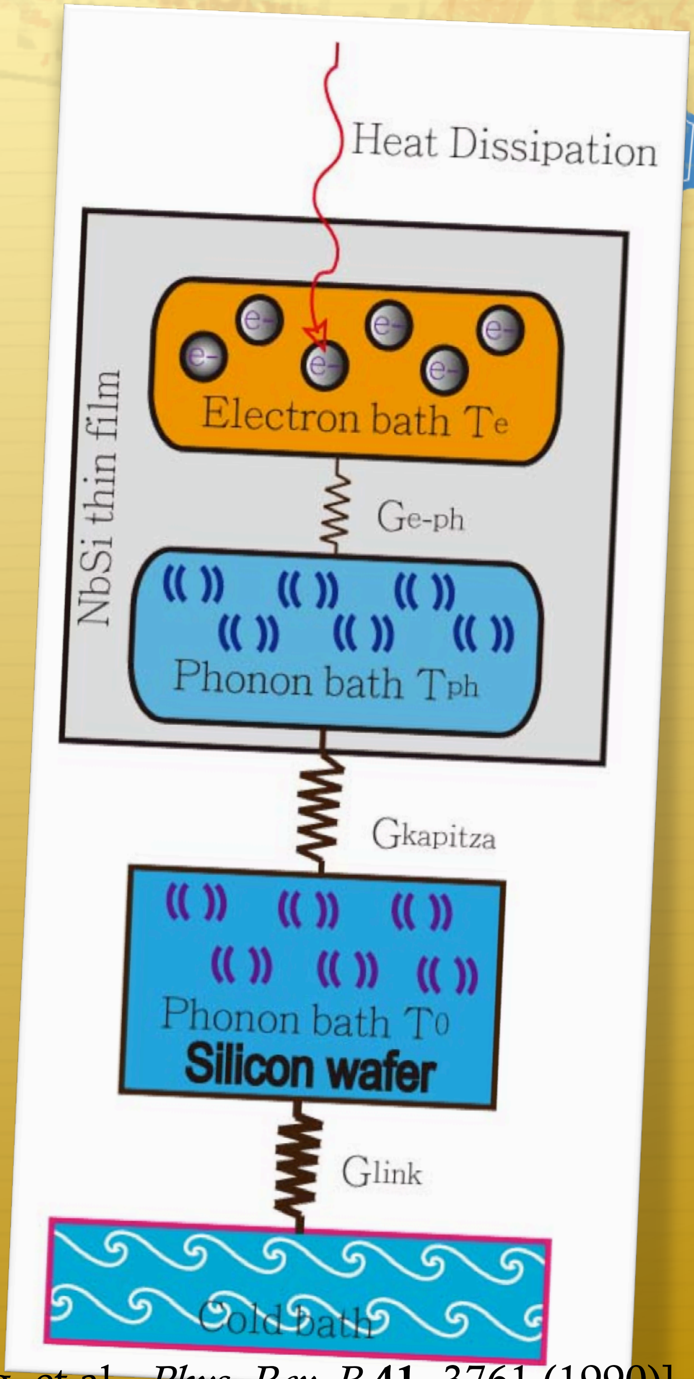
For electrical power dissipated to the electron bath of the bolometer thin film:

$$\frac{P}{\Omega} = g_{e-ph}\left(T_e^{\beta} - T_{ph}^{\beta}\right),\ \beta = 5$$

g_{e-ph} : electron - phonon coupling coefficient

Thermal conductance between the electrons and the phonons:

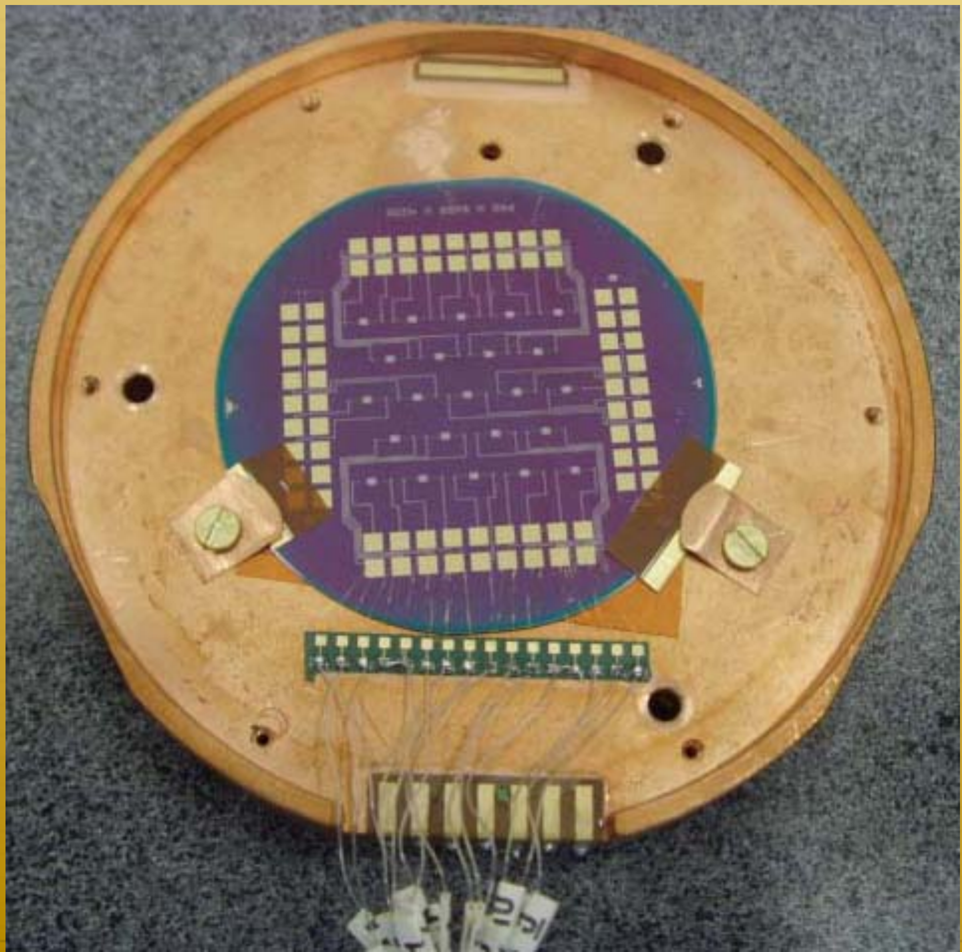
$$G_{e-ph} = \left(\frac{\partial P}{\partial T_e}\right)_{T_{ph}} = g_{e-ph}\beta T_e^{(\beta-1)}$$



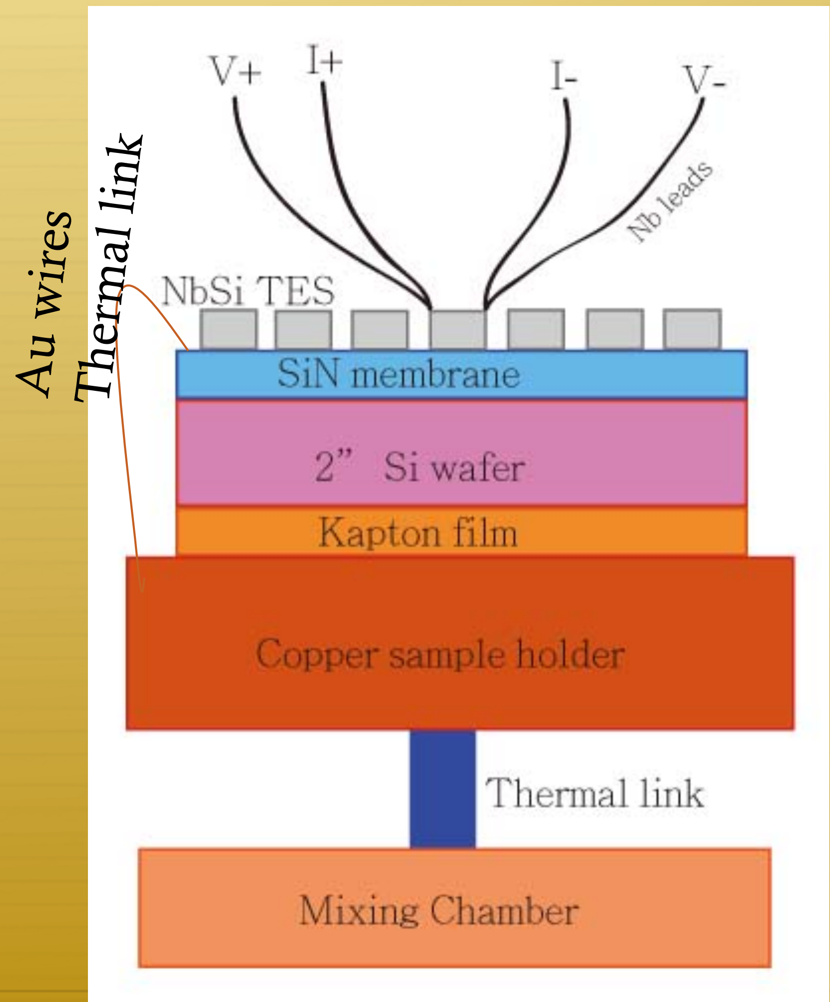
[S. Marnieros, et al., *Phys. Rev. Lett.* **84**, 2469 (2000); N. Wang, et al., *Phys. Rev. B* **41**, 3761 (1990)]

Experimental Setup

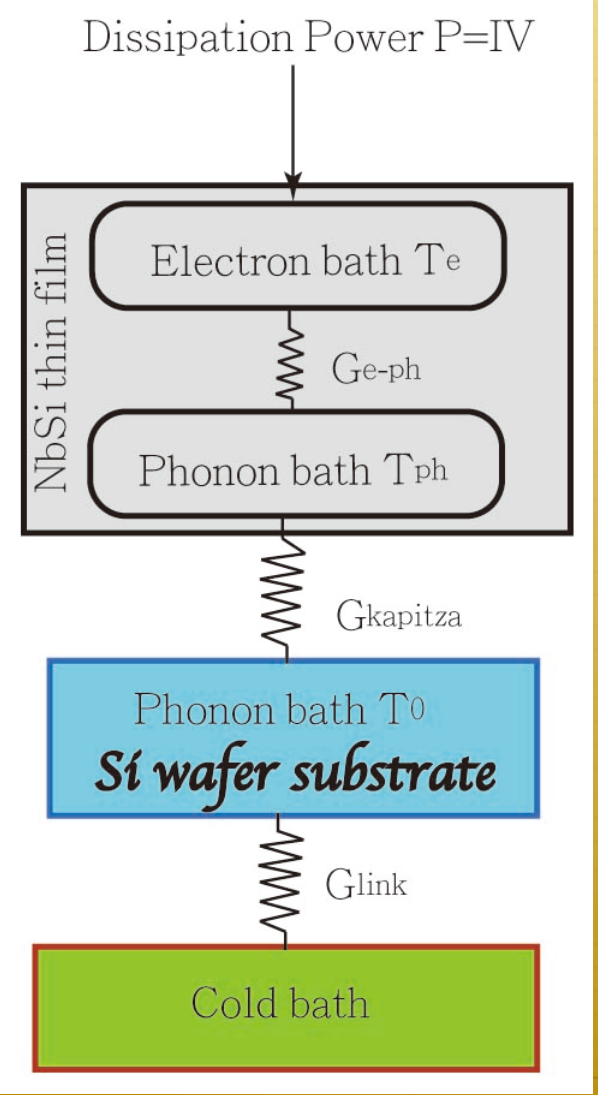
Mounting and wiring of Si wafer with 23 pixels of NbSi TES's on the copper sample holder



Schematic of the sample setup

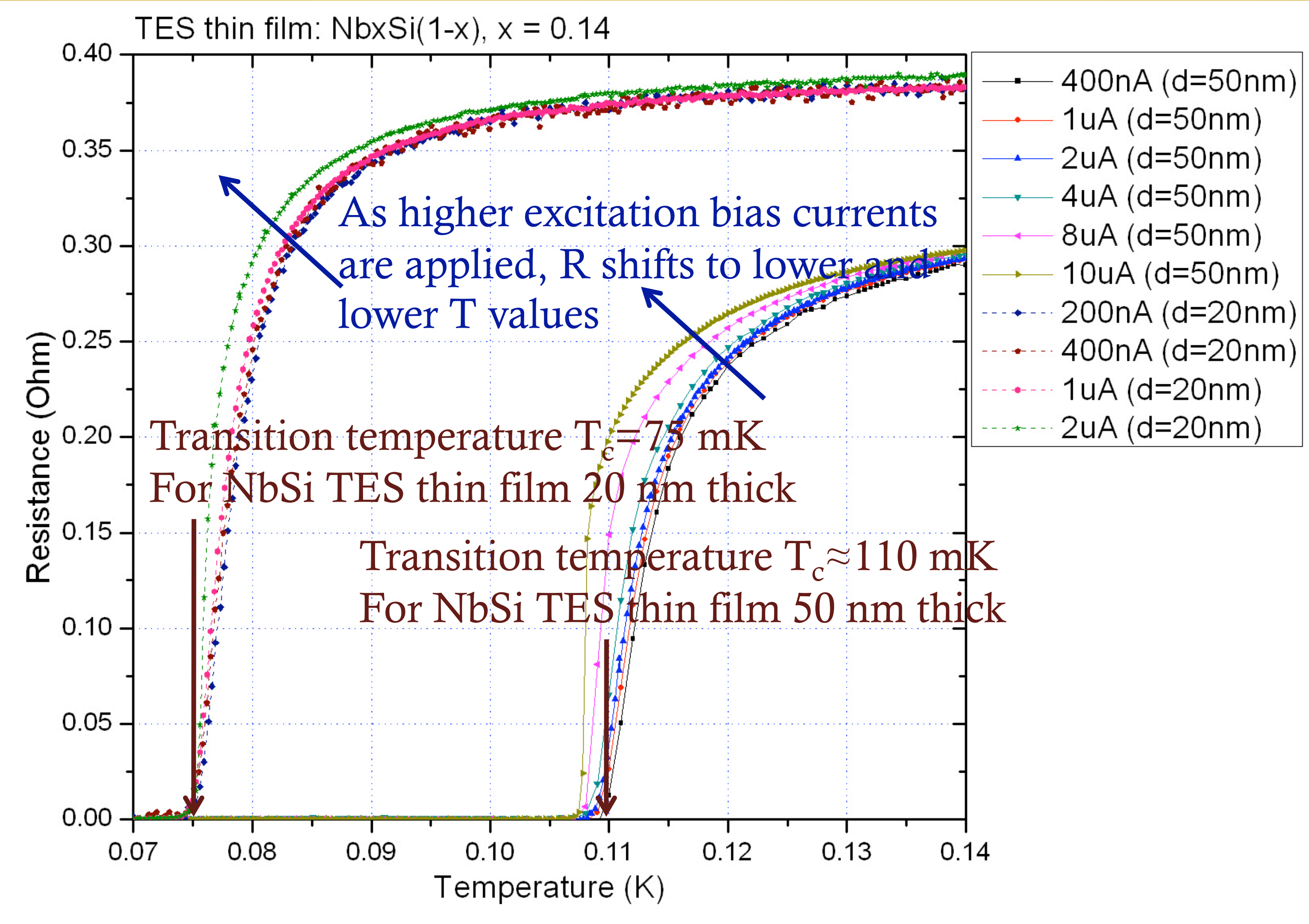


Model for Electron-Phonon Coupling

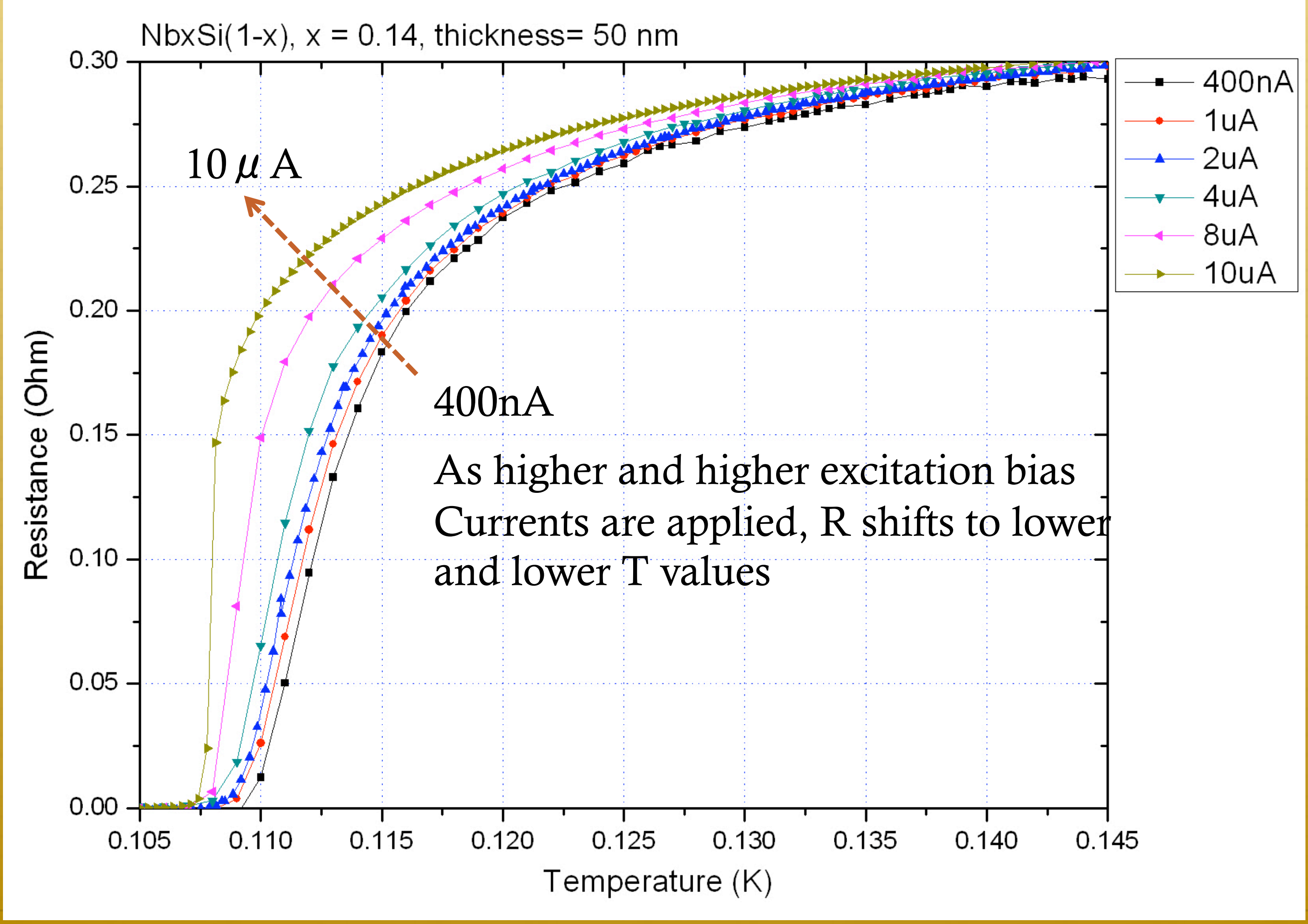


- The lowest bias current is applied to the NbSi TES (e.g. 200 nA, P < 16 f W), sensor resistance (R) versus temperature (T) is acquired $\Rightarrow$ $T_e \approx T_{ph} \approx T_0$
- Higher dc bias currents are applied to the NbSi TES, increasing the temperature of the NbSi electron bath by Joule heating effect, $P=I^2R$. Then the energy is transferred to the NbSi phonon bath via the electron-phonon interaction ($G_{e\text{-}ph}$) and to the Si substrate by Kapitza interface thermal conductance ($G_{kapitza}$).
- The Si wafer is thermally connected to the cryostat cold bath by the gold wires (thermal conductance, G_{link}).
- Assume $G_{link} >> G_{Kapitza} >> G_{e\text{-}ph}$ and $T_e > T_{ph} \approx T_0$.

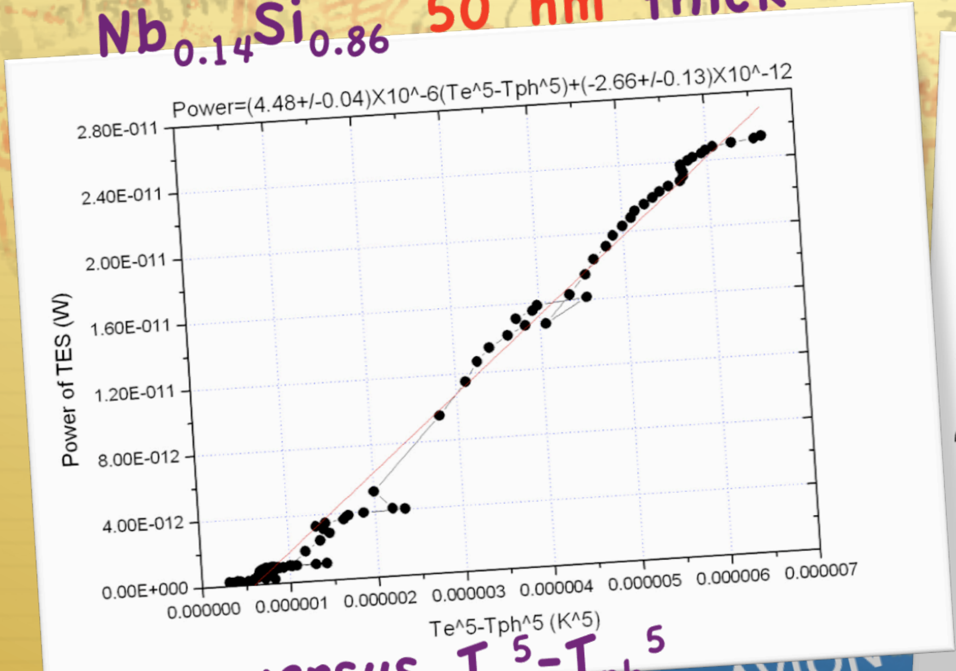
Resistance versus Temperature Curves of $Nb_{0.14}Si_{0.86}$ TES thin film



Resistance versus Temperature Curves of $Nb_{0.14}Si_{0.86}$ TES thin film

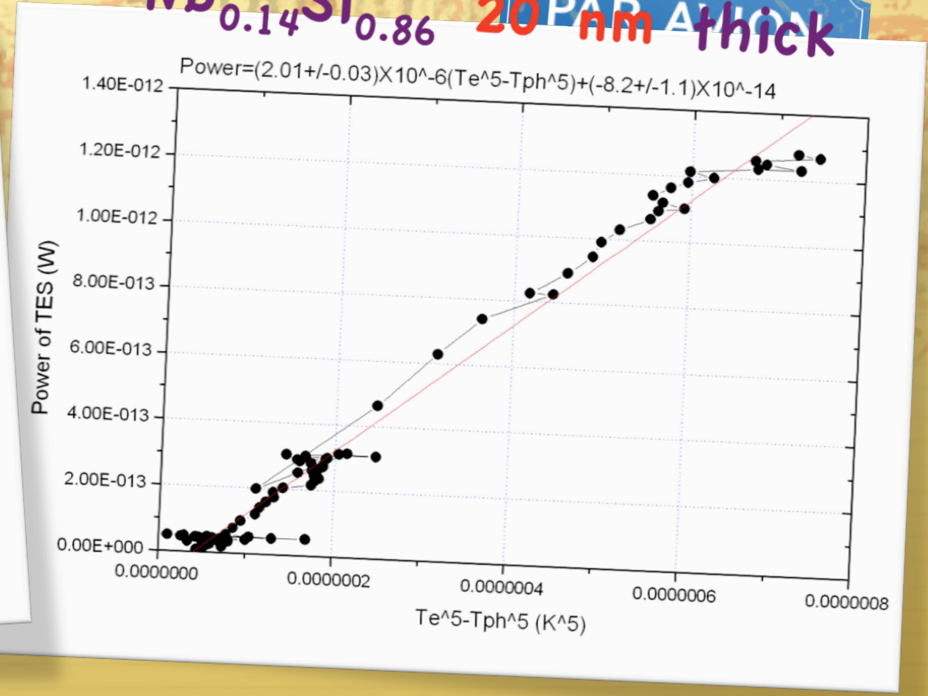


$Nb_{0.14}Si_{0.86}$ 50 nm thick



Power versus $T_e^5 - T_{ph}^5$

$Nb_{0.14}Si_{0.86}$ 20 nm thick



Electron-Phonon Coupling Coefficient

$P = I^2 R$,
$R = 0.1R_n \sim 0.8R_n$

Slope $= 4.48\times10^{-6}$ W/K^5 (50nm) ; Slope $= 2.01\times10^{-6}$ W/K^5 (20nm)

Electron-phonon coupling coefficient:

$g_{e\text{-}ph} \approx 498$ W/K^{5}cm^3 (50nm); $g_{e\text{-}ph} \approx 558$ W/K^{5}cm^3 (20nm)

Thermal conductance between electrons and phonons:

$G_{e\text{-}ph} \approx 3.28\times10^{-9}$ W/K (50nm); $G_{e\text{-}ph} \approx 3.18\times10^{-10}$ W/K (20nm)

Thickness: 20 nm ➔ 50 nm …… (×2.5)

$g_{e\text{-}ph}$: 558 ➔ 498 W/K^{5}cm^3 …… (×0.89)

$G_{e\text{-}ph}$: 3.18×10^{-10} ➔ 3.28×10^{-9} W/K …… (×10.3)

Electron-phonon coupling coefficient is constant, in agreement with the theory!

Comparison

Category	Material	Size	$g_{e\text{-}ph}$ ($W/K^{\beta}cm^3$)	$G_{e\text{-}ph}$ (W/K)	β	Group
TES	$Nb_{0.14}Si_{0.86}$	300 μm×600 μm×50nm	498	3.28×10^{-9}	5	S. Marnieros, et al.
		300 μm×600 μm×20nm	558	3.18×10^{-10}	5	
Anderson insulator	$Nb_{0.083}Si_{0.917}$	100 μm×100 μm×100nm	100	5×10^{-11} @ 100mk	5	
Anderson insulator	NTD Ge	1mm×1mm×0.2mm	40		6	N. Wang, et al.
			6.5		5.5	
TES	Ti/Au	1mm×1mm×20nm	3000		4	R. Horn, et al.
TES	Ir	75×75 μm^2		1.2×10^{-11}		D. Bagliani, et al.
TES	Mo/Au	700 μm×0.35 μm 700 μm×0.5 μm		19×10^{-15} 72×10^{-15}		M. Kenyon, et al.
TES	Ti/Au	150 μm×150 μm×75nm	2000	2×10^{-9}	5	P. Korte (SRON)

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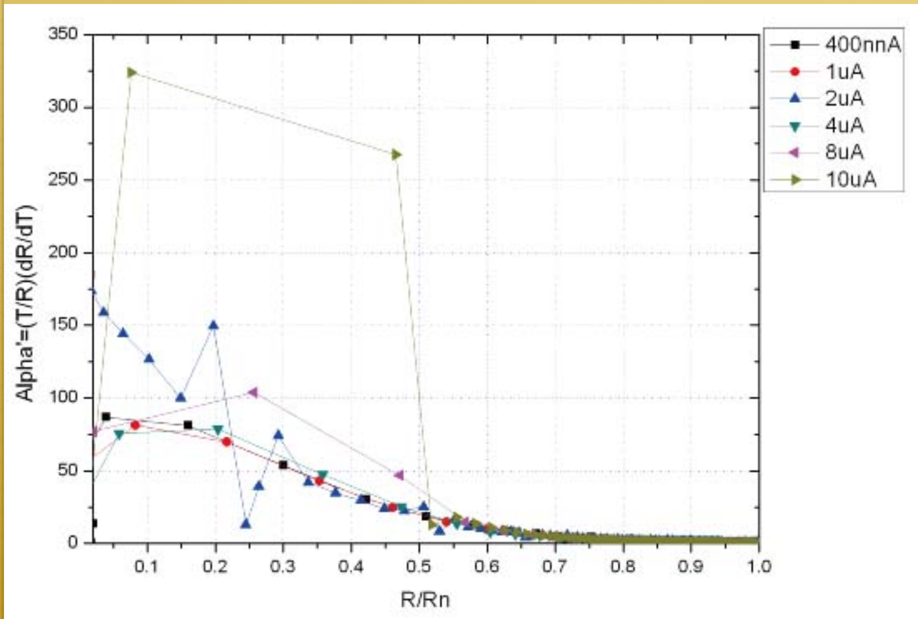
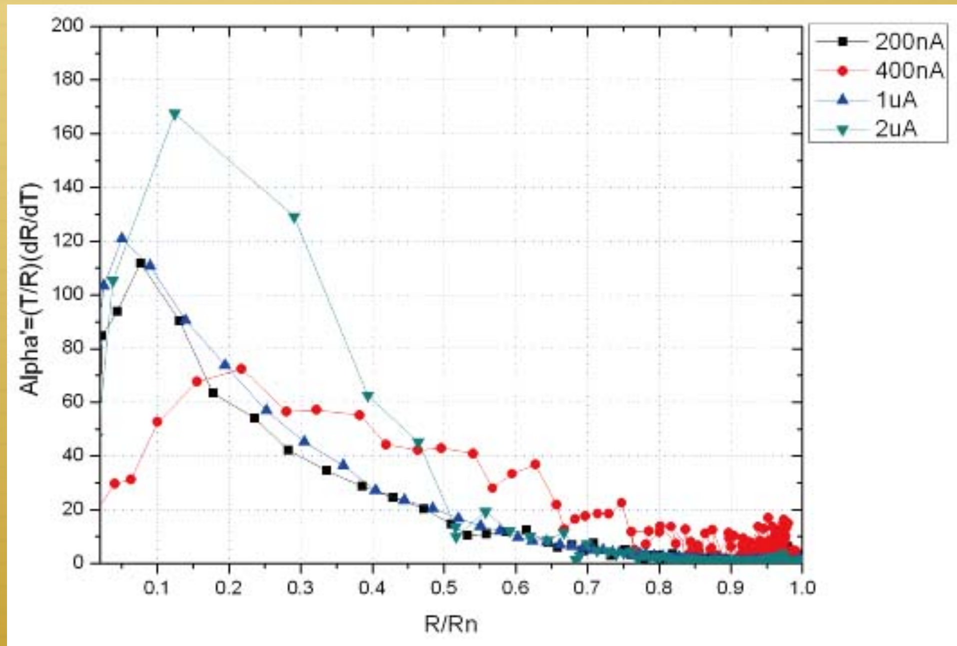
Dimensionless Sensitivity of NbSi TES Bolometer

$$\alpha' = \frac{d\log R}{d\log T} = \left(\frac{T}{R}\right)\left(\frac{dR}{dT}\right)$$





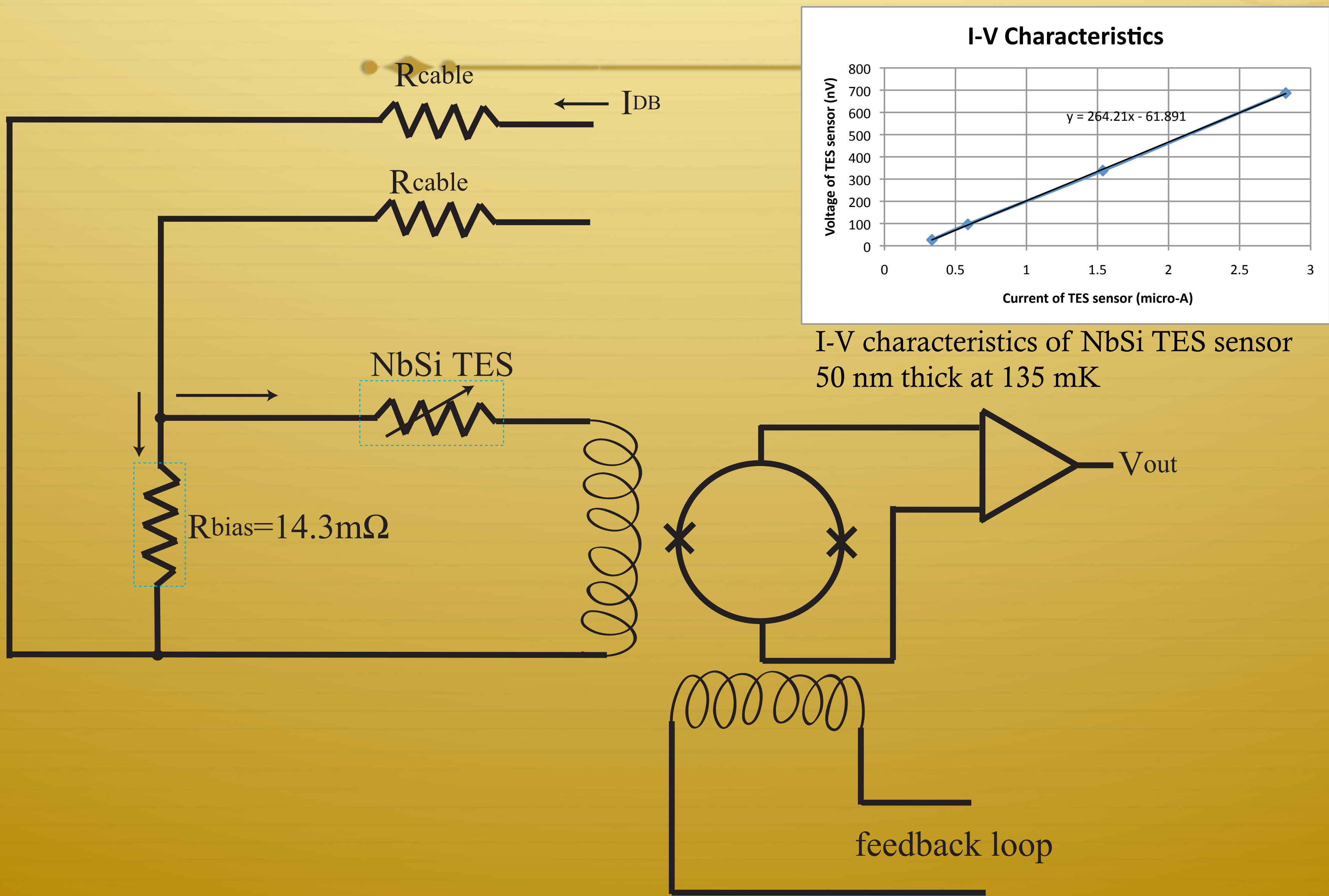
$Nb_{0.14}Si_{0.86}$ TES thickness 50 nm

Maximum sensitivity ~ 75-325
for I=400nA-10 μ A

$Nb_{0.14}Si_{0.86}$ TES thickness 20 nm

Maximum sensitivity ~ 70-170
for I=200nA-2 μ A

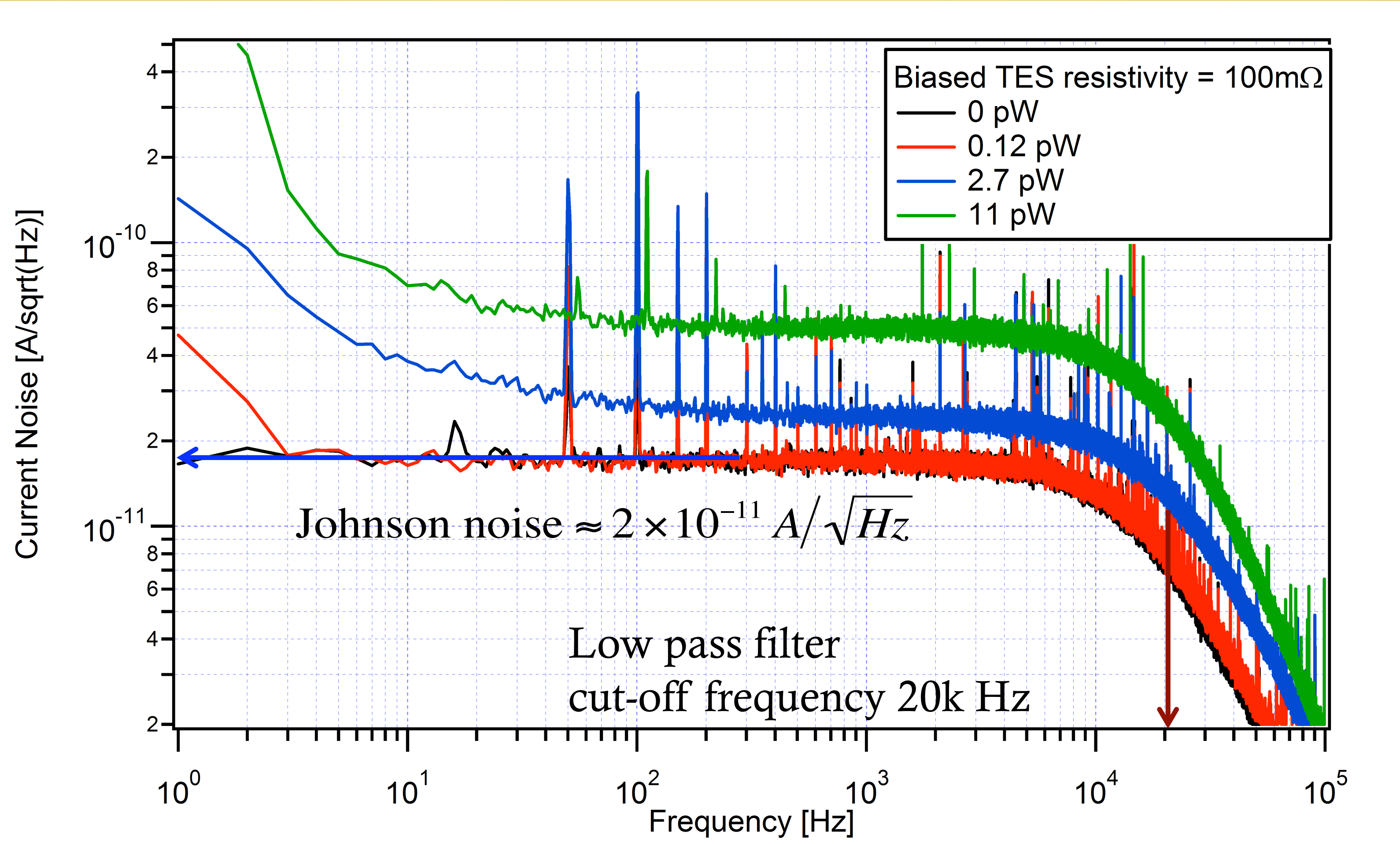
Schematic Circuitry of dc-SQUID



I-V characteristics of NbSi TES sensor
50 nm thick at 135 mK

Noise Spectra of NbSi TES

Using dc-SQUID



Intrinsic Noise Source of a Bolometer

- Noise equivalent power (NEP) of Johnson noise:

$$NEP_J^2 = \frac{4kTR}{\Re^2} \quad \left[\mathrm{W}^2/Hz\right] \propto \mathrm{T}$$

R: the electrical resistance at the temperature T; k: Boltzman constant; $\Re$: responsivity (V/W)

- Noise equivalent power (NEP) of phonon noise:

$$NEP_{ph}^2 = 4kT^2G_d \left[\mathrm{W}^2/Hz\right] \propto \mathrm{T}^2$$

G_d: the conduction at uniform temperature T

- Total intrinsic noise of the bolometer:

$$NEP_{bol}^2 = NEP_J^2 + NEP_{ph}^2$$

- So a TES should be operated at very low temperatures below 100 mK

- Other noise sources: excess noise

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Conclusion

- We have developed sensitive and low noise bolometer matrices with NbSi TES sensors to measure the temperature fluctuations of the CMB (Cosmic Microwave Background radiation).

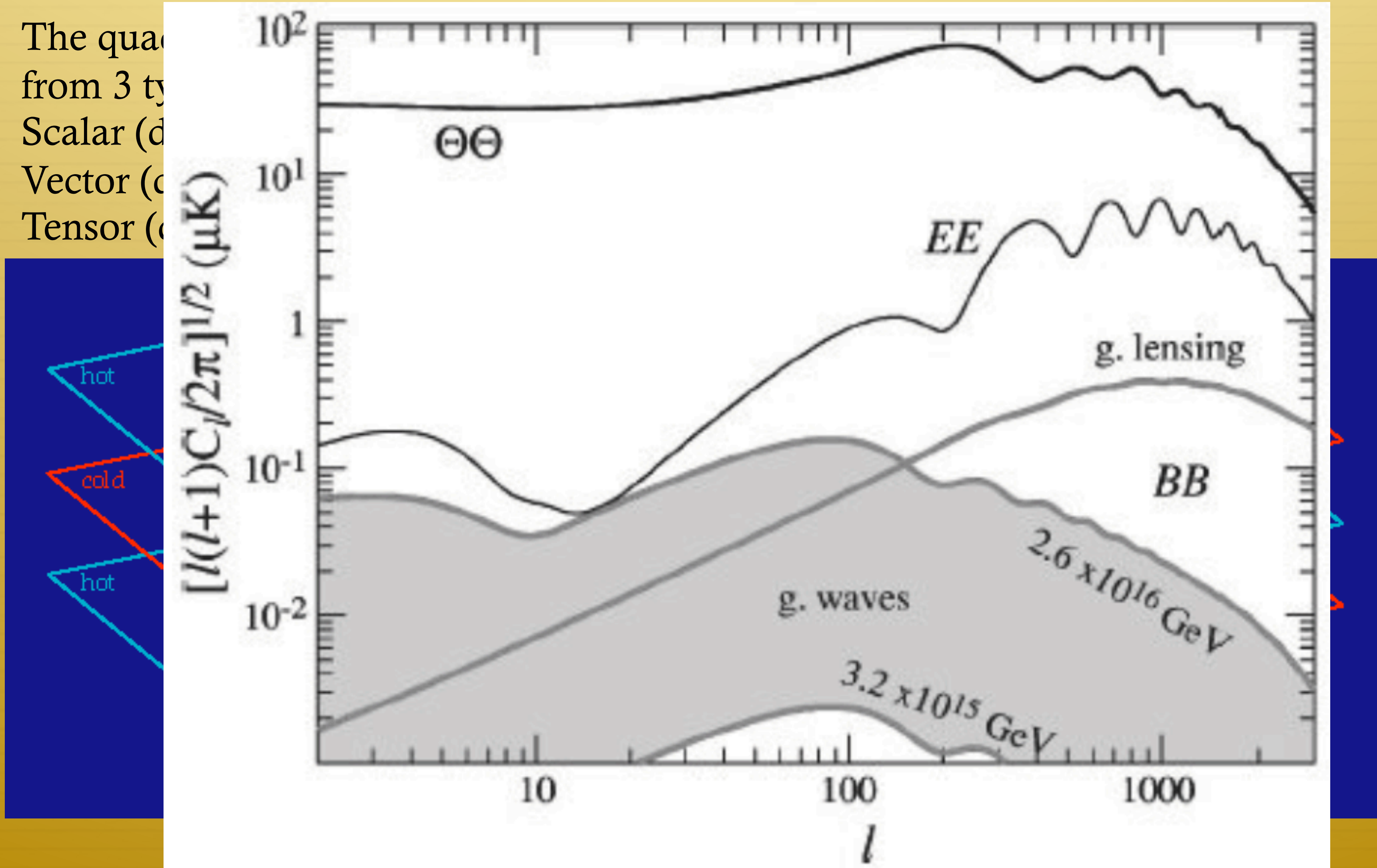
- The structure of bolometer matrices, transition edge sensors and fabrication process of our NbSi TES have been discussed. Our NbSi TES works not only as a temperature sensor but also as an absorber of radiation and due to its intrinsic thermal decoupling it does not need SiN membranes.

- We build an electron-phonon coupling model for NbSi thin films. The electron-phonon coupling coefficients are calculated for different thickness, and are quite comparable to those found in metallic samples by other groups.

- We also discuss about the performance of our NbSi TES bolometers. Their high sensitivity and low noise are very encouraging for Astroparticle detection experiments.

B Mode Polarization of CMB

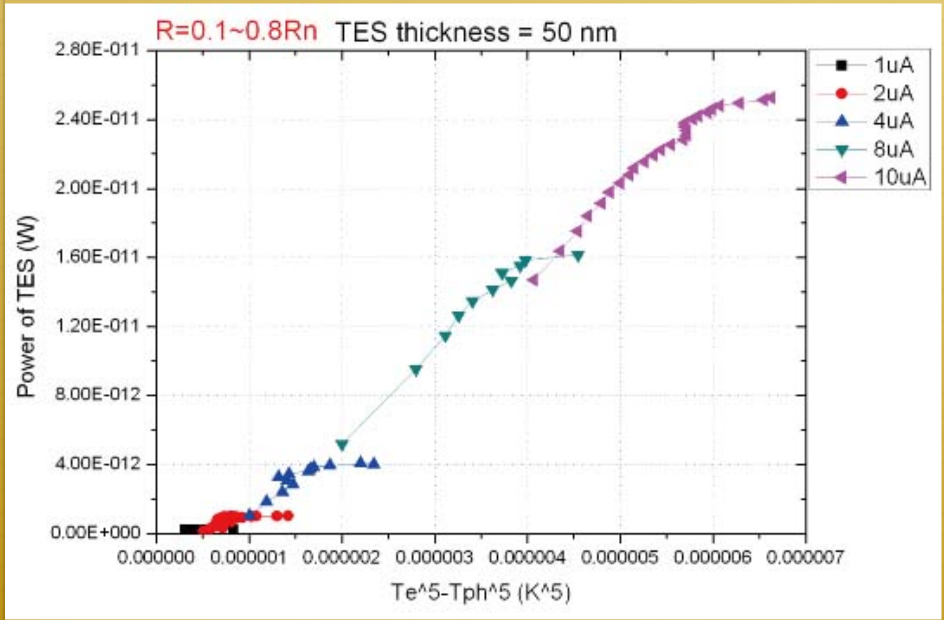
The qua
from 3 ty
Scalar (d
Vector (c
Tensor (c



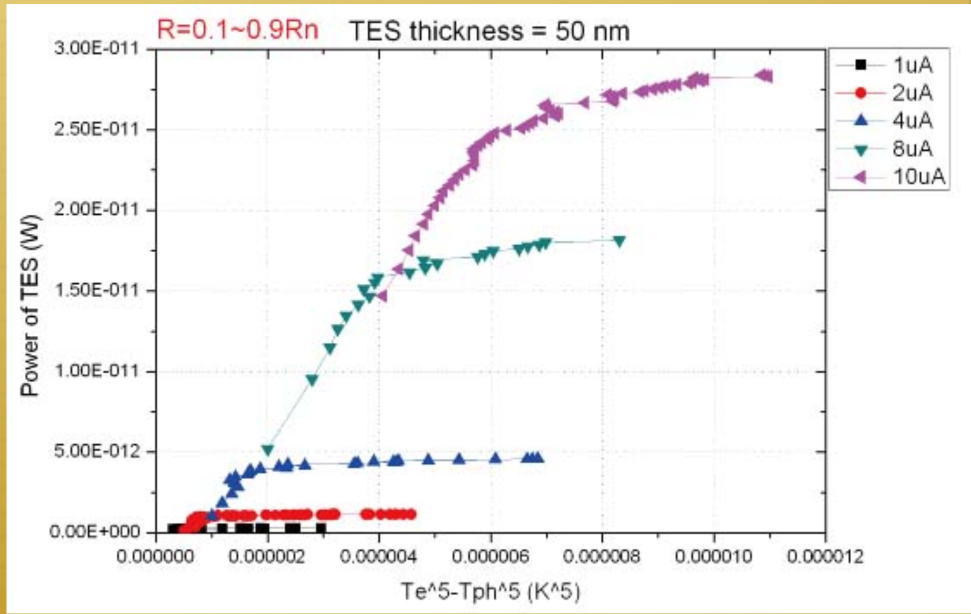
[http://cosmology.berkeley.edu/~yuki/CMBpol/CMBpol.htm]

Deviation from the Power Law of Heat conduction

Power versus T_e^5-T_{ph}^5 for
R=0.1~0.8R_n
$Nb_{0.14}Si_{0.85}$ thin film 50 nm thick

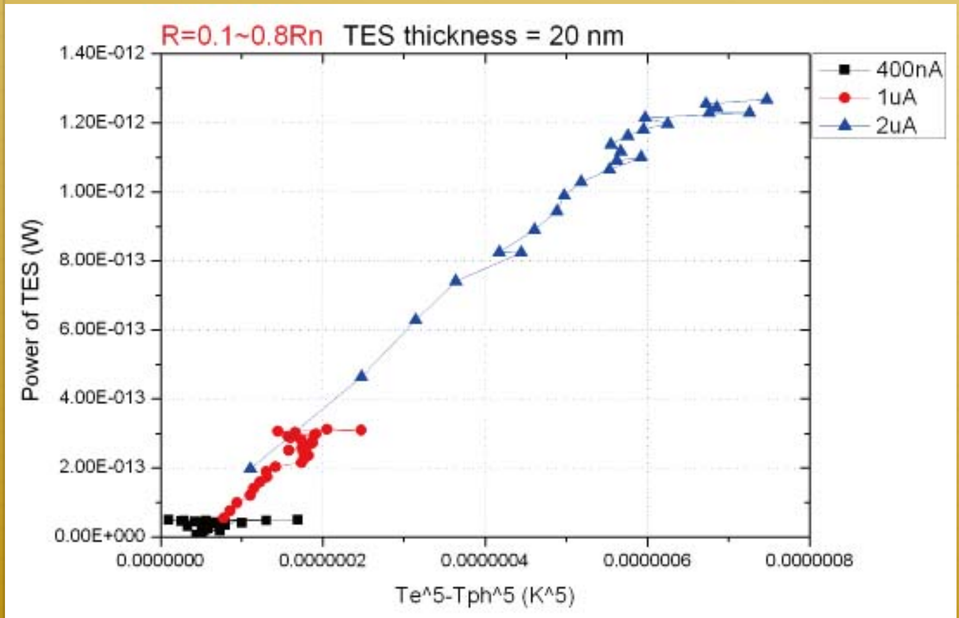


Power versus T_e^5-T_{ph}^5 for
R=0.1~0.9R_n
$Nb_{0.14}Si_{0.85}$ thin film 50 nm thick



Deviation from the Power Law of Heat conduction

Power versus T_e^5-T_{ph}^5 for
$R=0.1\sim0.8R_n$
$Nb_{0.14}Si_{0.85}$ thin film 20 nm thick



Power versus T_e^5-T_{ph}^5 for
$R=0.1\sim0.9R_n$
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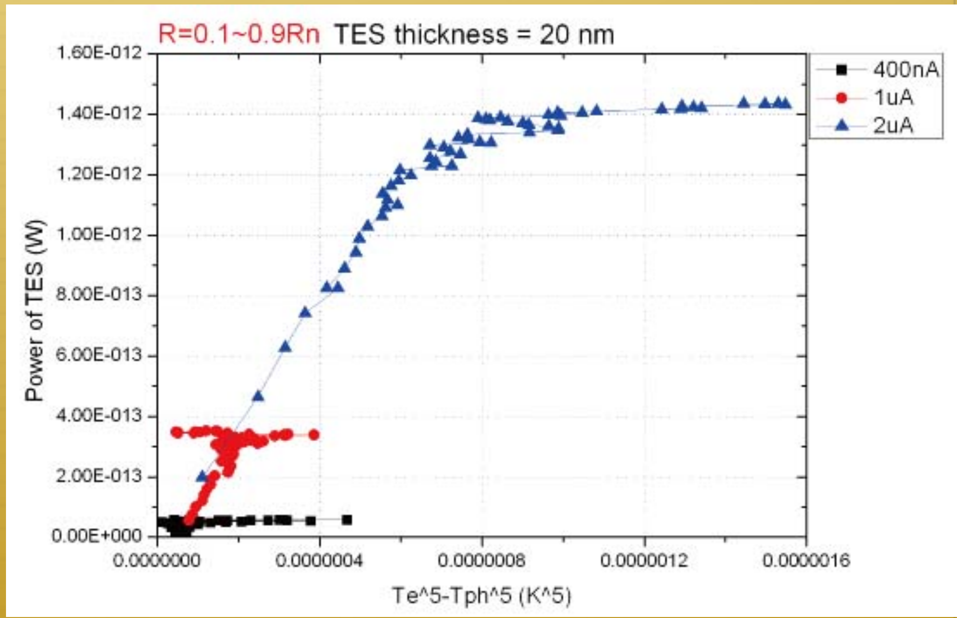
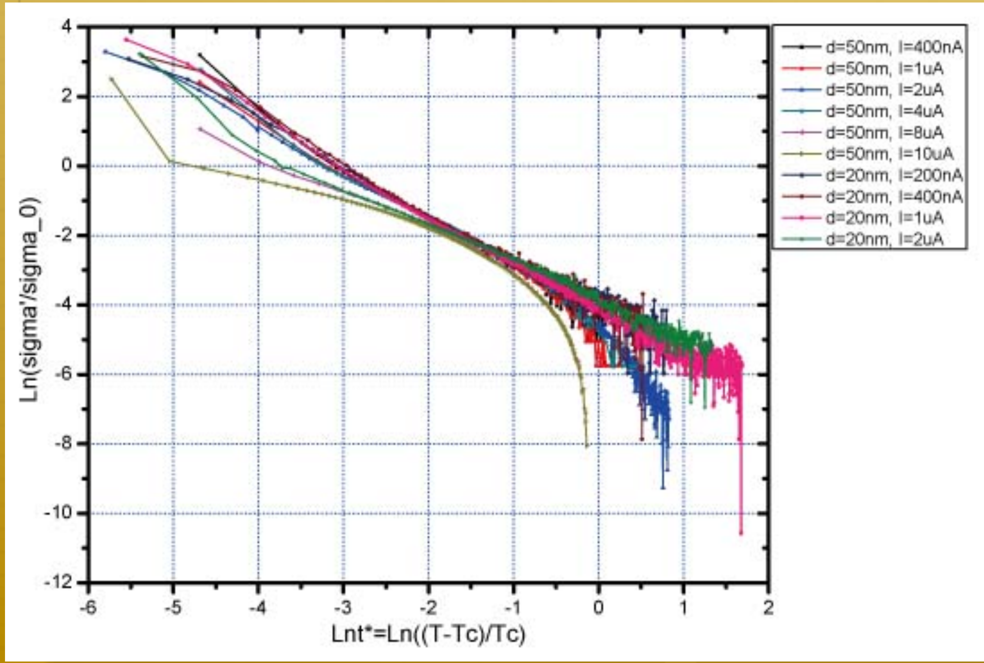


Paraconductivity Calculation

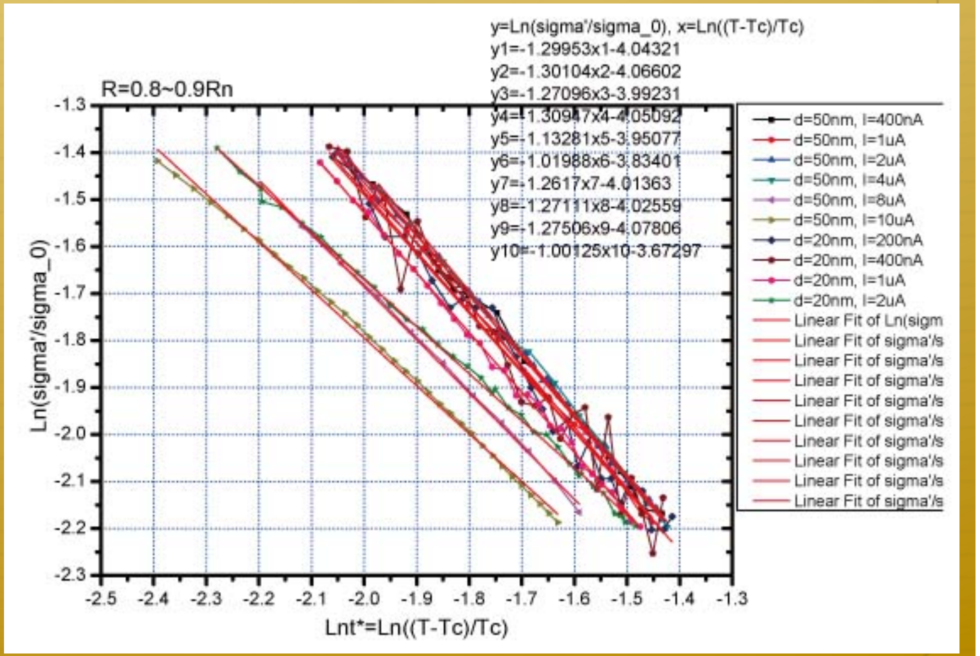
Paraconductivity=excess conductivity=
conductivity-normal state conductivity

$$\sigma' = \sigma - \sigma_0$$

Ln(σ'/σ_0) versus Ln[(T-T_c)/T_c]
for the whole range of R

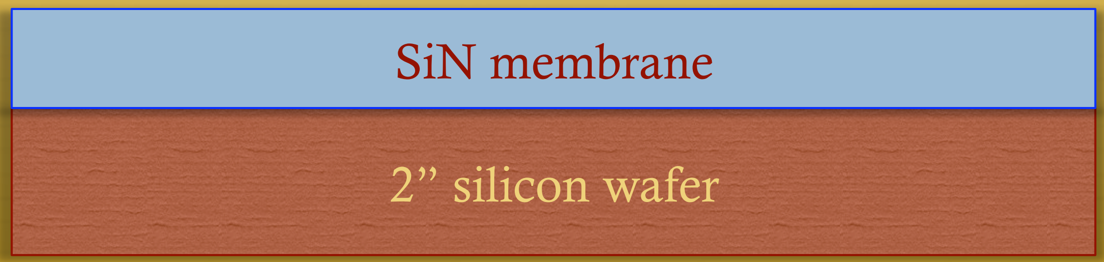


Ln(σ'/σ_0) versus Ln[(T-T_c)/T_c]
for R=0.8~0.9R_n



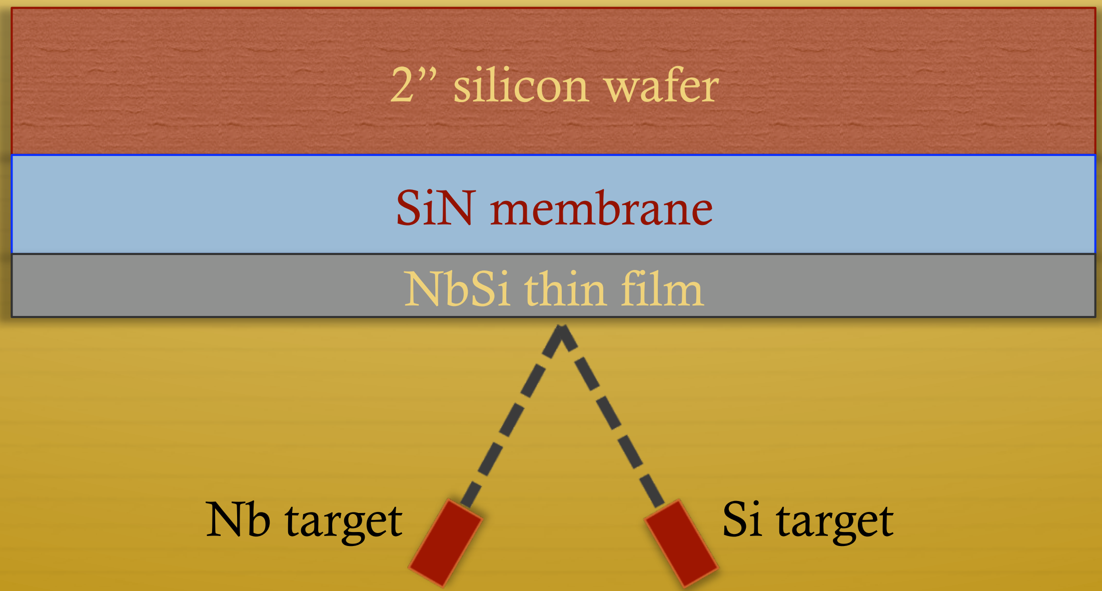
Fabrication Process of NbSi TES Thin Film Bolometer

1. Deposition of membranes materials by PECVD (Plasma Enhanced Chemical Vapor Deposition) device (SiO_2+Si_3N_4:SiO_2/SiN/SiO_2=290/230/100nm) on a silicon wafer of 2” diameter ➔ for electrical and thermal insulation



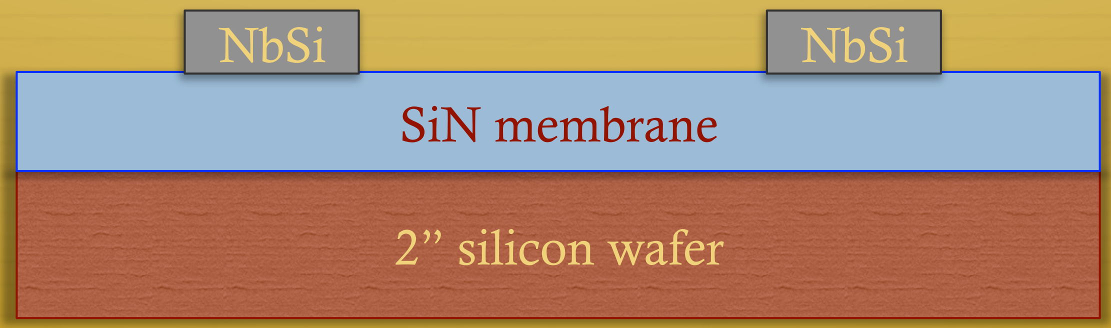
Fabrication Process of NbSi TES Thin Film Bolometer

2. Nb_xSi_{1-x} co-evaporation (x=0.14, 20-50 nm thick): NbSi thin film is manufactured by electron-beam co-evaporation by irradiating two targets of Nb and Si simultaneously.



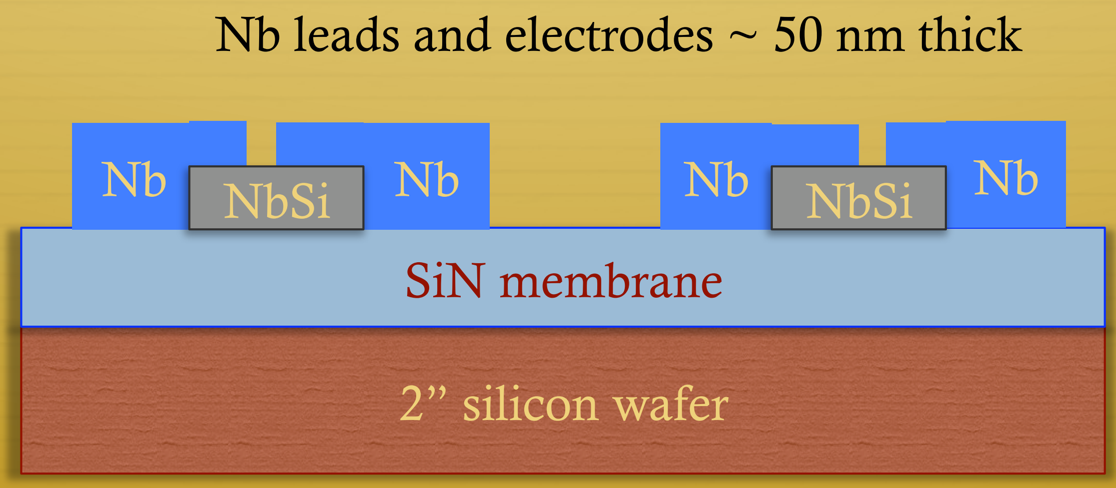
Fabrication Process of NbSi TES Thin Film Bolometer

3. Photolithography to form Nb_xSi_{1-x} bolometer matrices.



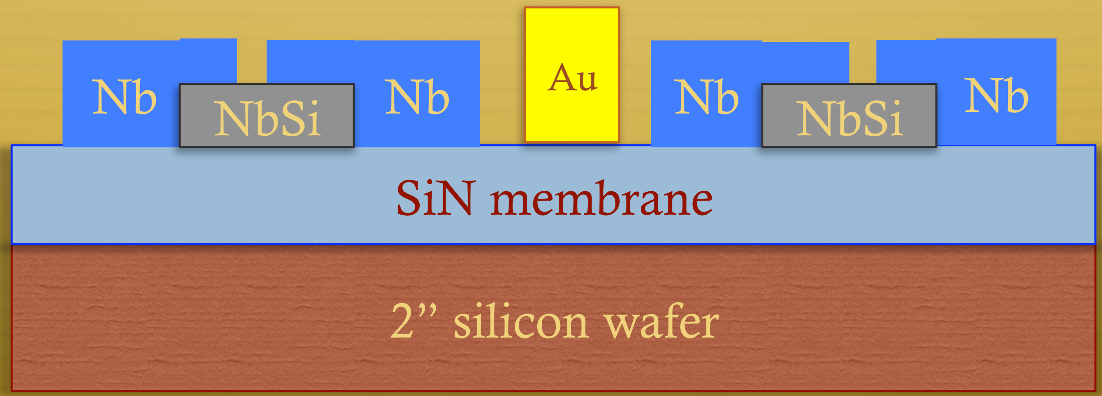
Fabrication Process of NbSi TES Thin Film Bolometer

4. Nb evaporation (50 nm) and photolithography to form Nb tracks and electrodes.



Fabrication Process of NbSi TES Thin Film Bolometer

5. Au evaporation and photolithography: a gold layer (100-150 nm) is deposited on the wafer to form the square contact pads connecting between the Nb leads extending to the NbSi thin film and the external readout electronics.



Fabrication Process of NbSi TES Thin Film Bolometer

6. Silicon deep etching.