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Office of Science

Enhanced Phonon Collection Efficiency in Aluminum MKIDs with Phonon Reflective Coating

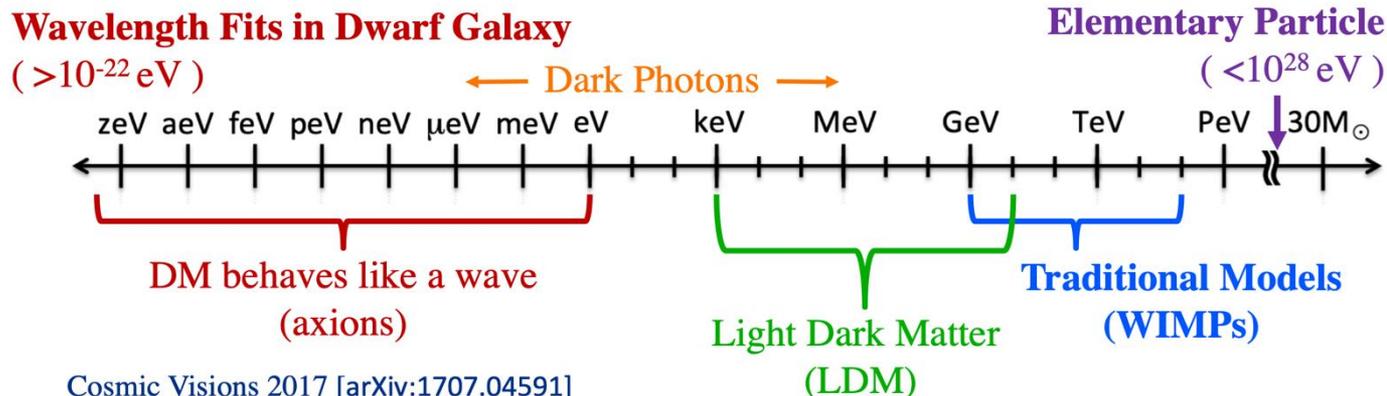
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CPAD Oct 2025

Dark Matter Detection

- **Dark matter** is predicted by evidences in the Cosmic microwave background (CMB), $\sim 24\%$ of the Universe's energy density is dark matter
- **Challenge:** Detect keV-100MeV DM requires Sub-eV energy threshold sensors
- **Phonon sensors:**
 1. Accesses the sub-eV regime
 2. Universally created regardless of the type of interactions



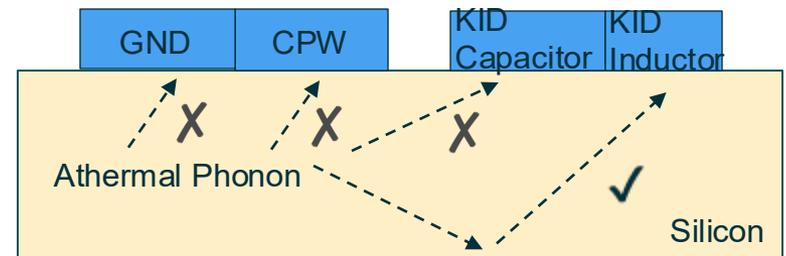
Phonon Sensitive Dark Matter Detector: MKID

How does MKID work:

- DM deposits energy in substrate \rightarrow Athermal phonons \rightarrow quasiparticle generation in superconductor \rightarrow change in resonator response (S_{21}).

Advantages of MKID:

- Multiplexing $O \sim (1000)$ channels
- No thermal fluctuation noise

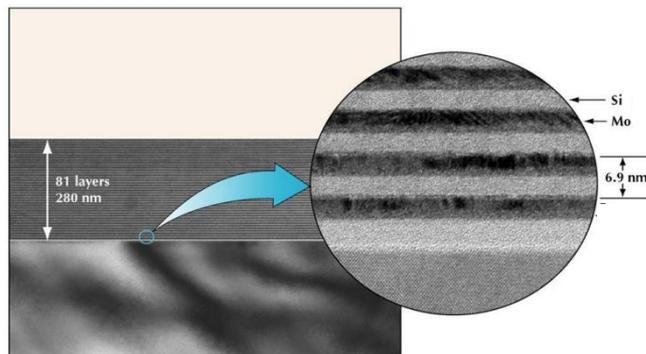


How to improve phonon collection efficiency:

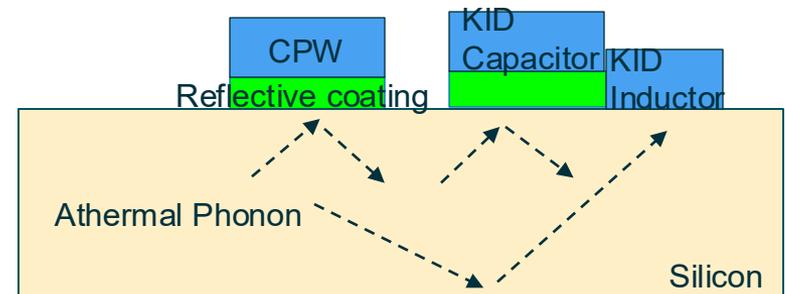
- Reduce passive material area: (Regular MKID device: $A_L / A_{Total} < 3\%$)
- Phonon reflective coating: PhononNext project (DOE accelerate fund: <https://phononics.lbl.gov/>)

Phonon Engineering- Reflective Coating

- **Originally developed for EUV lithography:** Reflective optics with multilayer coatings are used to bend and focus light.
- **Phonon Reflector:** Si/Mo multilayers can act as 100–200 GHz phonon reflectors by tailoring the thickness and periodicity.
- **Application:** Ideally placed beneath passive metal to prevent unwanted phonon absorption.



E. Gullikson, LBL Center for X-ray Optics (CXRO)



Device Preparation - Simulation

The proposed multilayer structure:

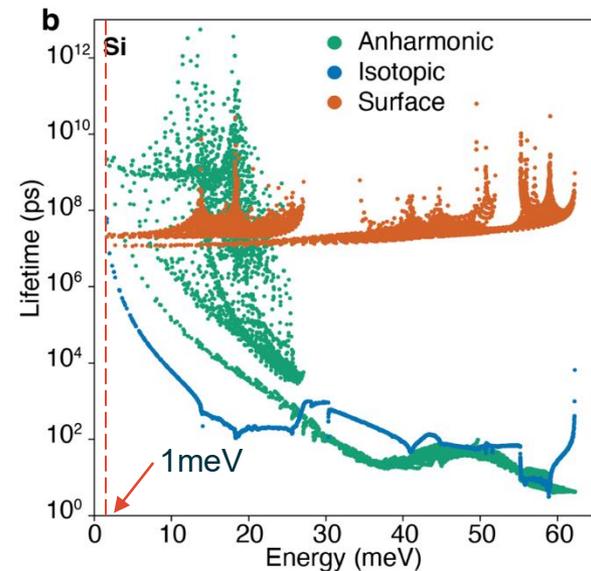
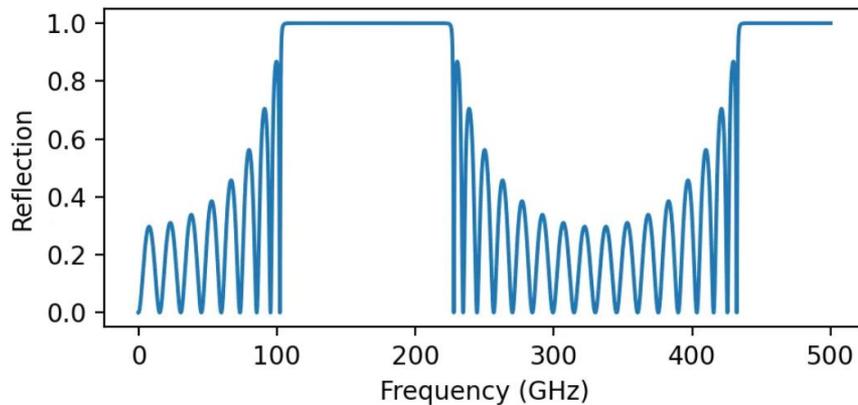
Material: Mo/Si bi-layer * 15

Thickness (nm): Mo: 9.9 nm; Si:12.8 nm; Total thickness: 341 nm

Phonon frequency: 100~200GHz phonons

Superlattice for 100 - 225 GHz

- Mo 9.9 nm
- Si 12.8 nm



[2109.10988] Theoretical investigation of decoherence channels in athermal phonon sensors (arxiv.org)

Device Preparation - Design

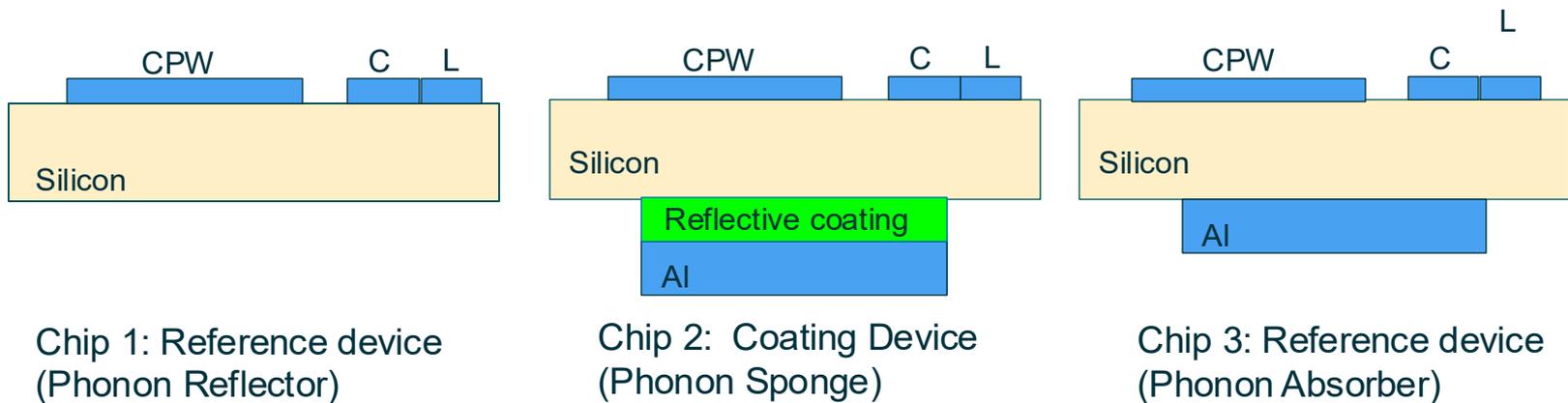
We propose 3 chips:

- Test to see if the phonon reflective coating works. (The Coating is under the substrate)
- If it works, what's the reflectivity of the coating layer. (Reflectivity: 0 - 1)

Chip 1: No coating

Chip 2: With backside coating (341 nm) + Al (500 nm)

Chip 3: With pure Al coating (500 nm)



Device Preparation - Design

Front Side MKID design:

- Al MKID devices ~ 2.28GHz
- Al thickness: 100 nm
- Reduce the CPW area:

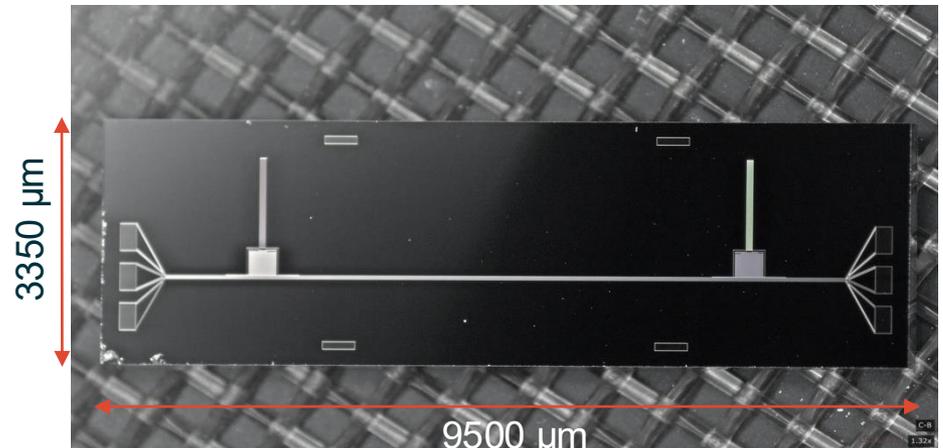
$$A_L = 1.2 * 10^6 \mu m^2$$

$$A_L / A_{Total} = 8\%$$

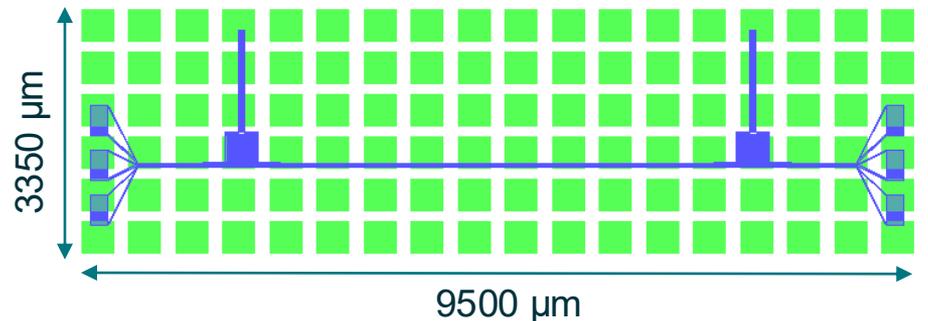
- Remove Ground Plane

Back Side MKID design:

- $A_{Coating} = 1.5 * 10^7 \mu m^2$
- Coating thickness: 341 nm
- Al thickness: 500 nm



Front side MKID chip

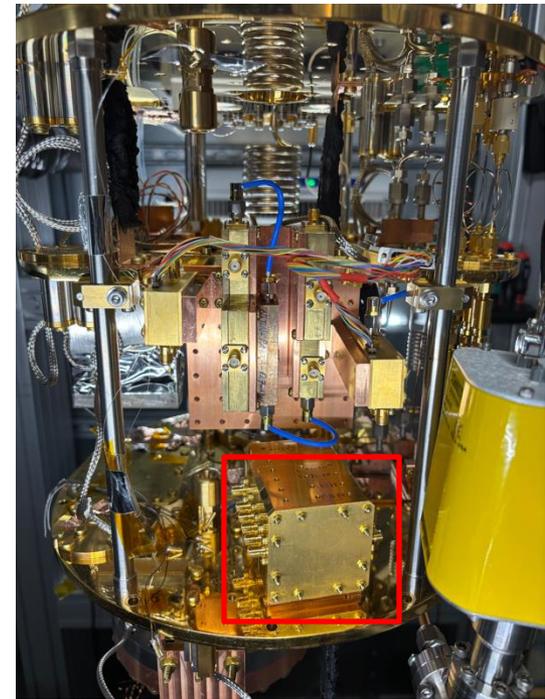


- Front side MKID structure
- Back side coating structure

Back side of Chip 2

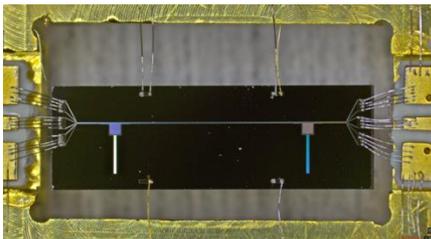
Device Measurement Setup

- Chips mounted with **wire hanging**
- Measure **Chip1** and **Chip 2**
(Chip 3 is for future test)
- Radioactive Source: Americium - 241,
Gamma Ray energy: ~ **59.54 keV**



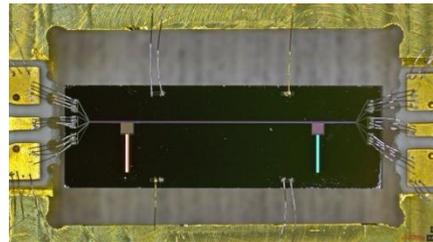
Measurement setup

Chip 1: No coating



Front side

Chip 2: with backside coating



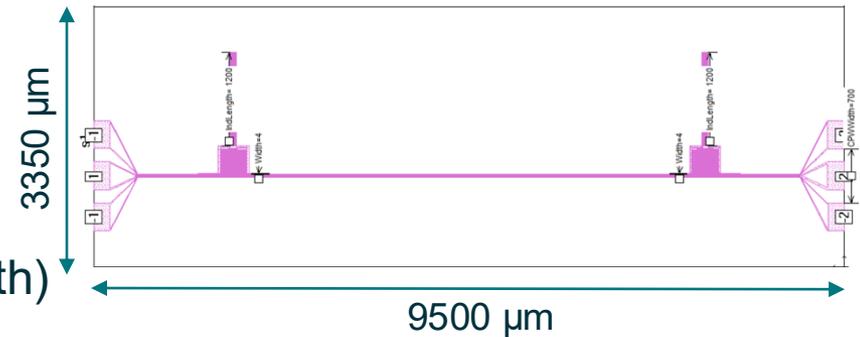
Front side



Backside

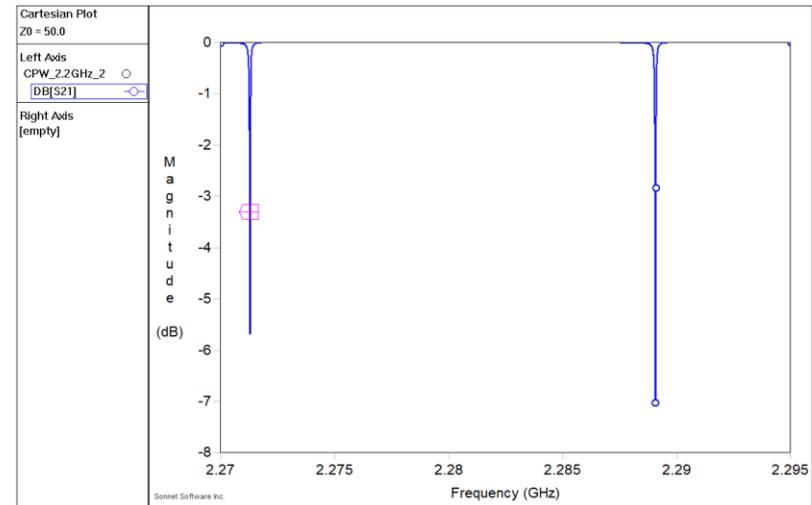
Device Preparation - Characterization

- Chip 1 and Chip 2 have identical front side MKID designs
- Each chip has 2 almost identical MKID devices (differ only by capacitor finger length)



Device Name	Coating type	f (GHz)	f (GHz) - simulation
Chip 1	Without Coating	2.2732	2.271
		2.2928	2.289
Chip 2	With Coating	2.2900	2.271
		2.3064	2.289

- The measured frequencies are very close to the simulations



Simulation results of the 2 MKID devices

Device Measurement

QP energy maximum at 225mK:

Chip 1 (without coating) : 1250 ± 21 eV

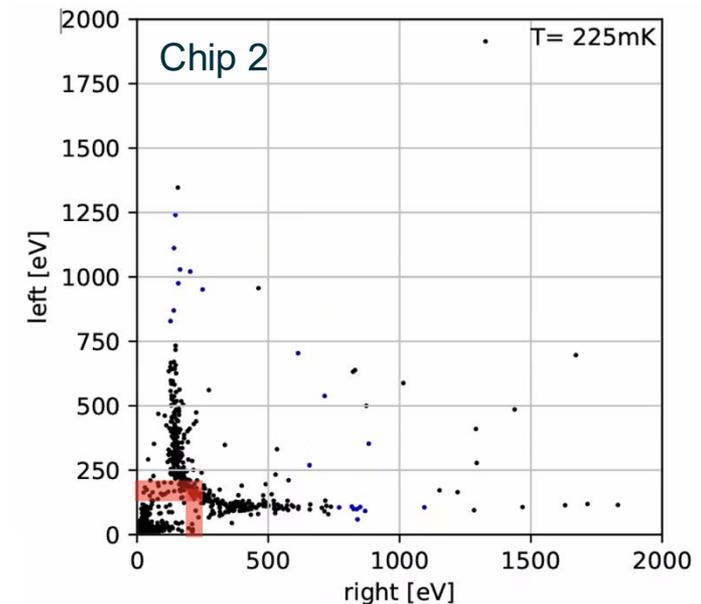
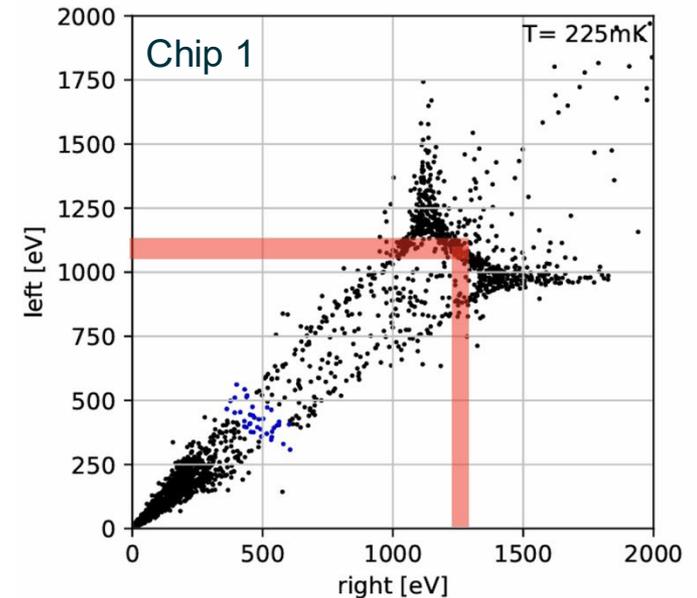
Chip 2 (with coating): $200 \text{ eV} \pm 21 \text{ eV}$

Absorbed energy significantly reduced.

With $A_{Total} = 1.2 * 10^6 \mu m^2$, $A_{Coating} = 1.5 * 10^7 \mu m^2$:

$R = 0.58 \pm 0.05$

The reflectivity of the coating is $\sim 60\%$



Conclusions:

- **Phonon engineering** with multilayer coating is a promising way to improve phonon collection efficiency and MKID detector performance:
 - Successfully fabricated and characterized double- sized coated devices.
 - Measured coating reflectivity $\approx 60\%$ \Rightarrow works as a phonon reflector.
- **Future work:**
 - Test MKID devices with reduced coating area to optimize energy response.
(chips ready)
 - Test different multilayer structures to better understand phonon reflection mechanisms. (chips ready)
 - Fabricate MKIDs with coating layers placed directly under the AI MKID device (excluding the inductor region) and test the devices.

Thank You

Backup Slides

Device Preparation

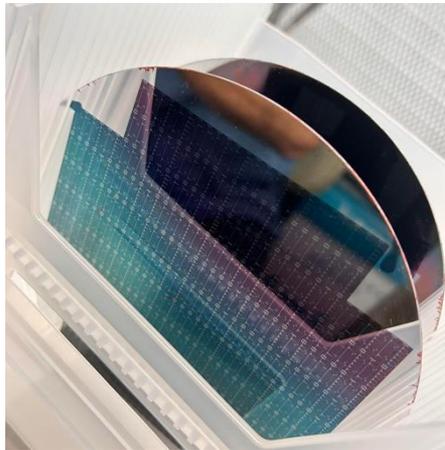
Step 1: Wafer Lithography (both front and back side)

Step 2: Fabricate front side MKID device (100 nm)

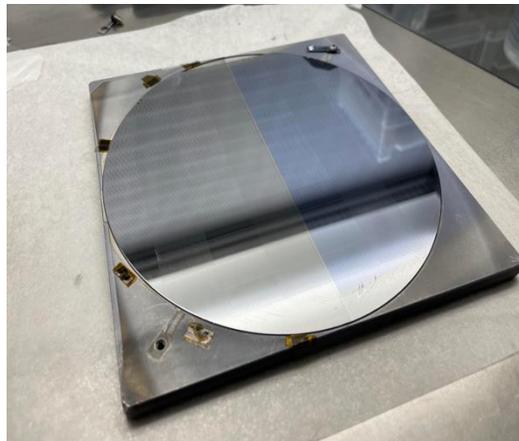
Step 3: Fabricate back side coating:

Mo/Si bi-layer : Thickness: 341 nm, Area: $1.5 * 10^7 \mu m^2$
+ Al: 500 nm, Area: $1.5 * 10^7 \mu m^2$

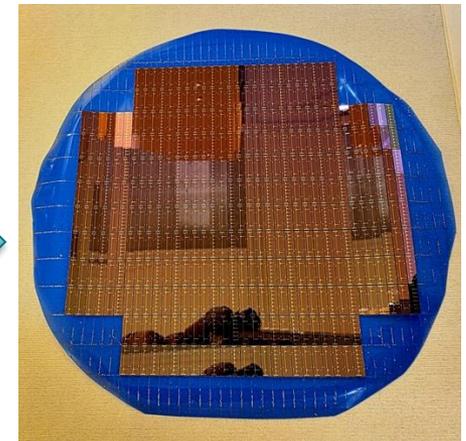
Step 4: Wafer Lift-off



Front side MKID fab



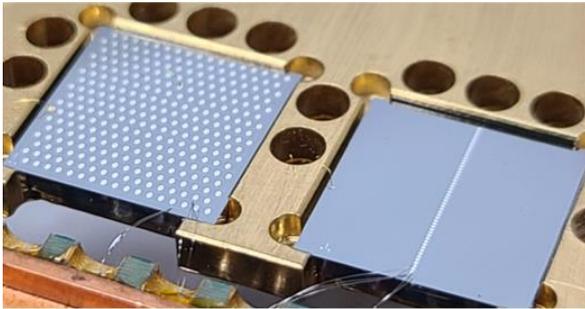
Back side coating fab



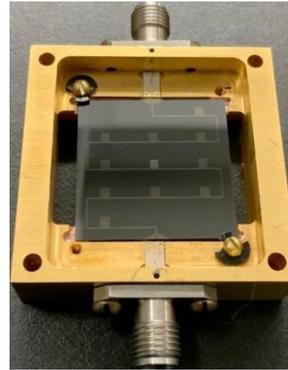
Lift-off and dicing

Phonon sensitive dark matter detectors

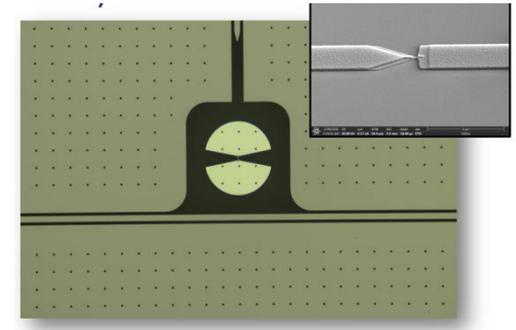
- Principles: Athermal phonon breaks Cooper pairs in superconductors:



TESSERACT Phonon Sensor



NEXUS KID Sensor



SQUATs

Transition edge sensors | **Kinetic inductance device** | **Qubits**

- Advantages of KIDs:

- Multiplexing $O\sim(1000)$ channels
- Scale from g to kg of DM target mass
- No thermal fluctuation noise

Phonon sensitive dark matter detectors

Detection Principle:

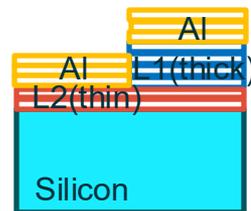
- Dark matter scatters and deposits energy in the substrate.
- Energy propagates as athermal phonons, which being captured directly by the KID inductor
- Athermal phonons create quasiparticles in Al
- Quasiparticles in Al modify the kinetic inductance, which leads to a change in resonator transmission (S_{21})

Wafer Design

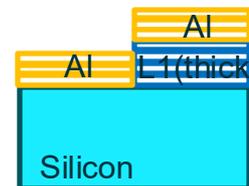
Base on the simulations, the proposed multilayer structure:

Multilayer Structure	Thickness (nm)	Repeat(N)	Phonon Frequency (GHz)	Total Thickness (nm)
L1	Mo: 16.3 Si: 21.1	15	62-138	561
L2	Mo: 9.9 Si: 12.8	15	100-225	341
L2 + L1	Mo: 9.9/16.3 Si: 12.8/21.1	15+15	100-225&62-138	902

Note that a layer of 500 nm Al is also deposited after the multilayer:



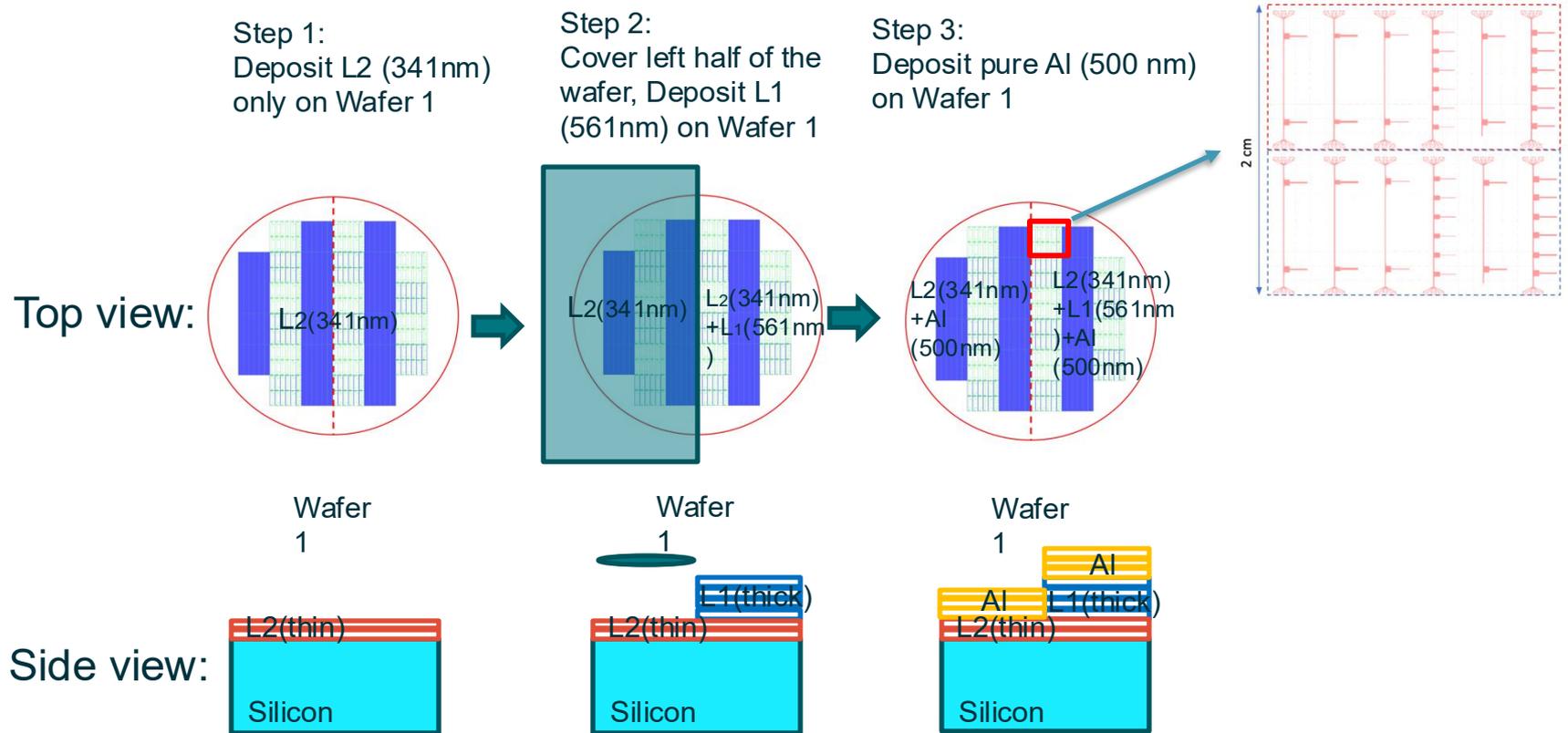
Wafer No.1
(Sideview)



Wafer No.2
(Sideview)

Wafer Design

Fabrication of wafer 1



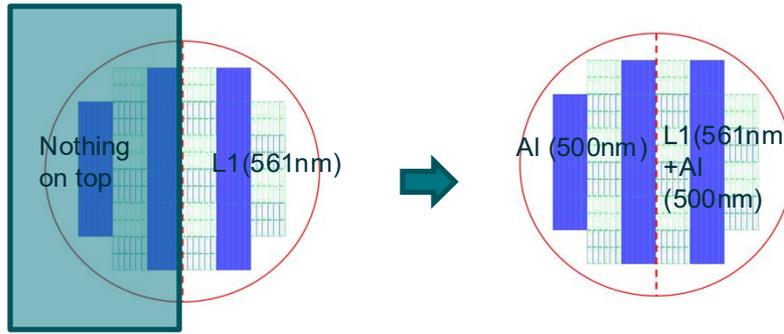
Wafer Design

Fabrication of wafer 2

Step 1:
Cover the left half of the wafer,
Deposit L1(561nm) on wafer 2

Step 2:
Deposit pure Al
(500nm) on Wafer 2

Top view:



Wafer
2

Wafer
2

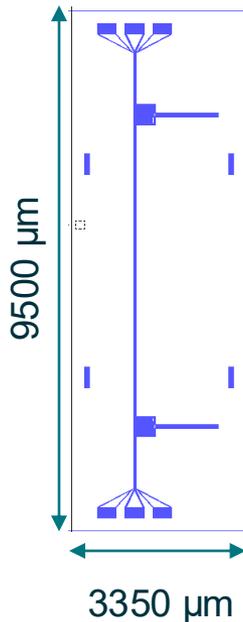
Side view:



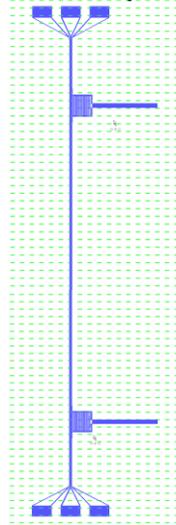
Backside coating design

- For each coating structure, we designed 4 different backside coating areas, one structure is without any backside coating, while others having three different etching areas (blue patterns are front MKIDs, green patterns are backside coating).
- The backside coating areas are decided from the uncertainty analysis

No any coating

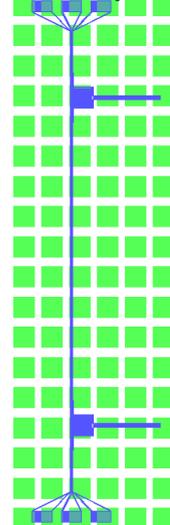


$$S_1 = 2.0 * 10^6 \mu\text{m}^2$$



Run 2 structure

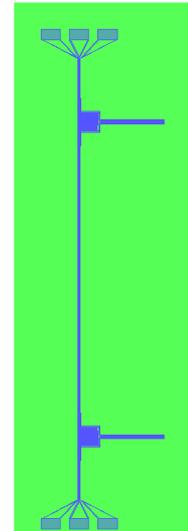
$$S_2 = 1.5 * 10^7 \mu\text{m}^2$$



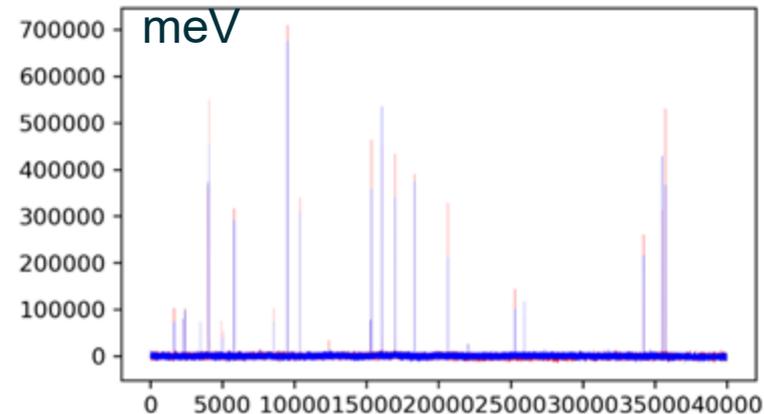
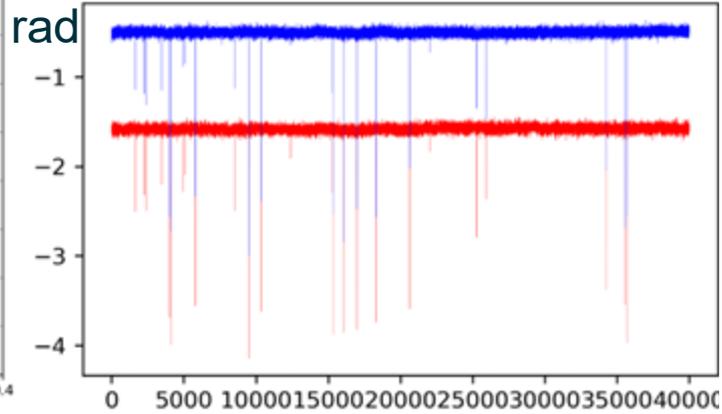
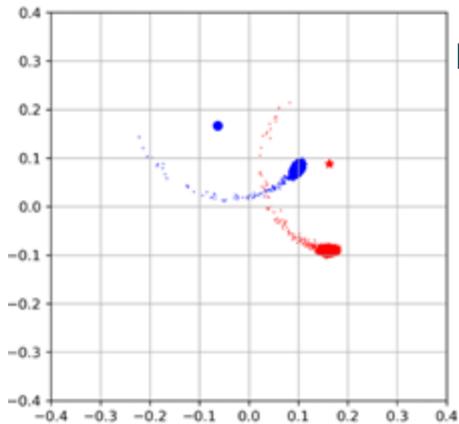
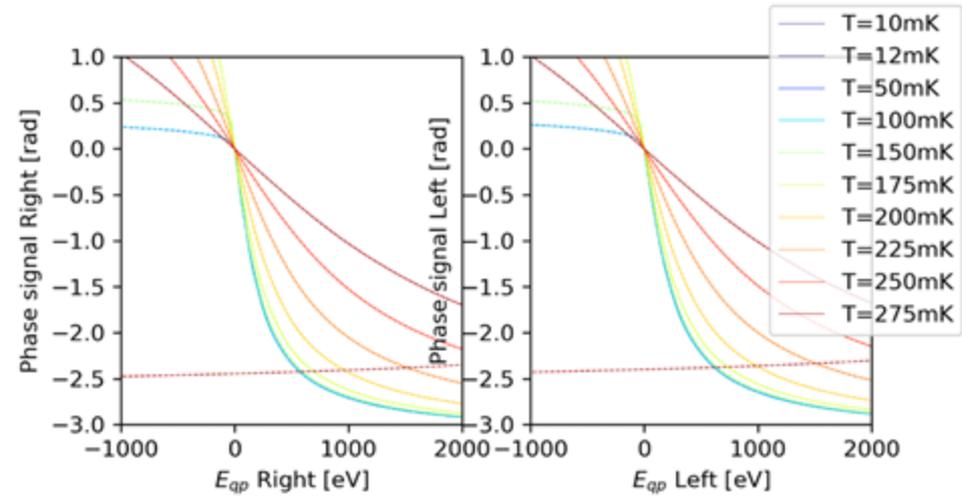
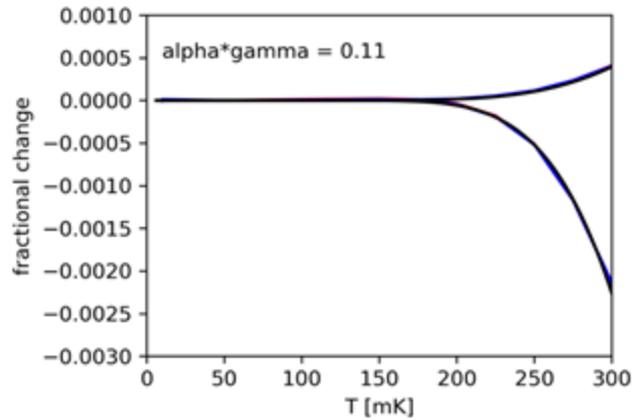
Run 1 structure

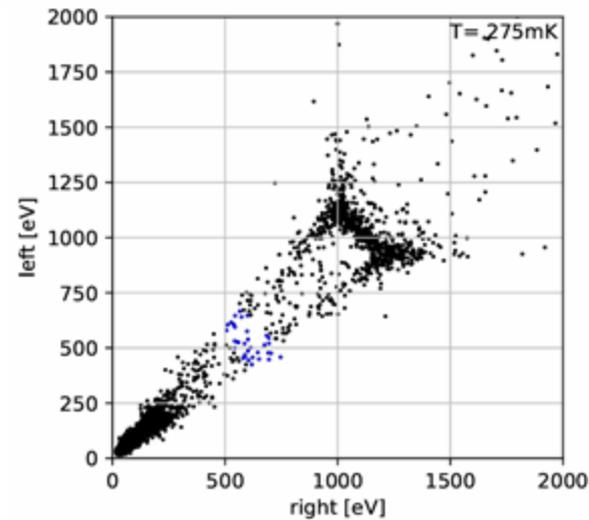
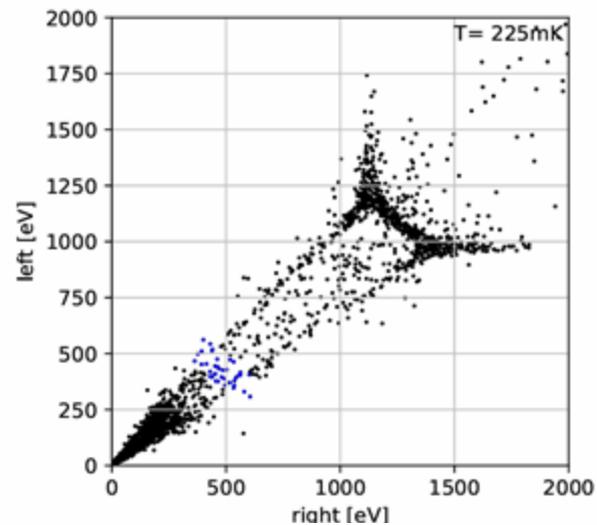
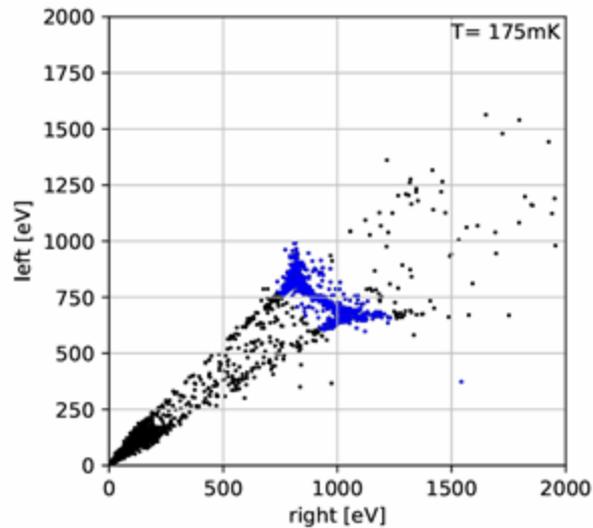
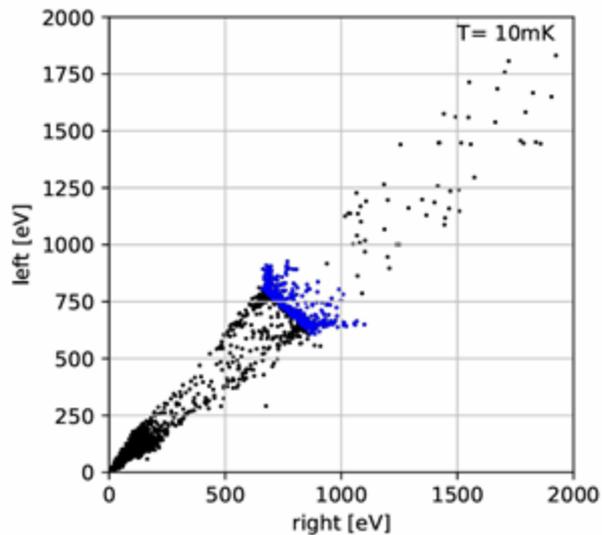
$$S_3 = 3.0 * 10^7 \mu\text{m}^2$$

(cover whole chip)



KID energy scale





Absorbed energy changes with temperature??

Estimation from inductor area:

$60\text{keV} * 38.5\text{e}3\mu\text{m}^2 / 1190.5\text{e}3\mu\text{m}^2 = 1940 \text{ eV}$ in each channel.

QP energy maximum at 225mK: 1250eV

Phonon to QP energy efficiency changes with temperature?

Uncertainty in Rc

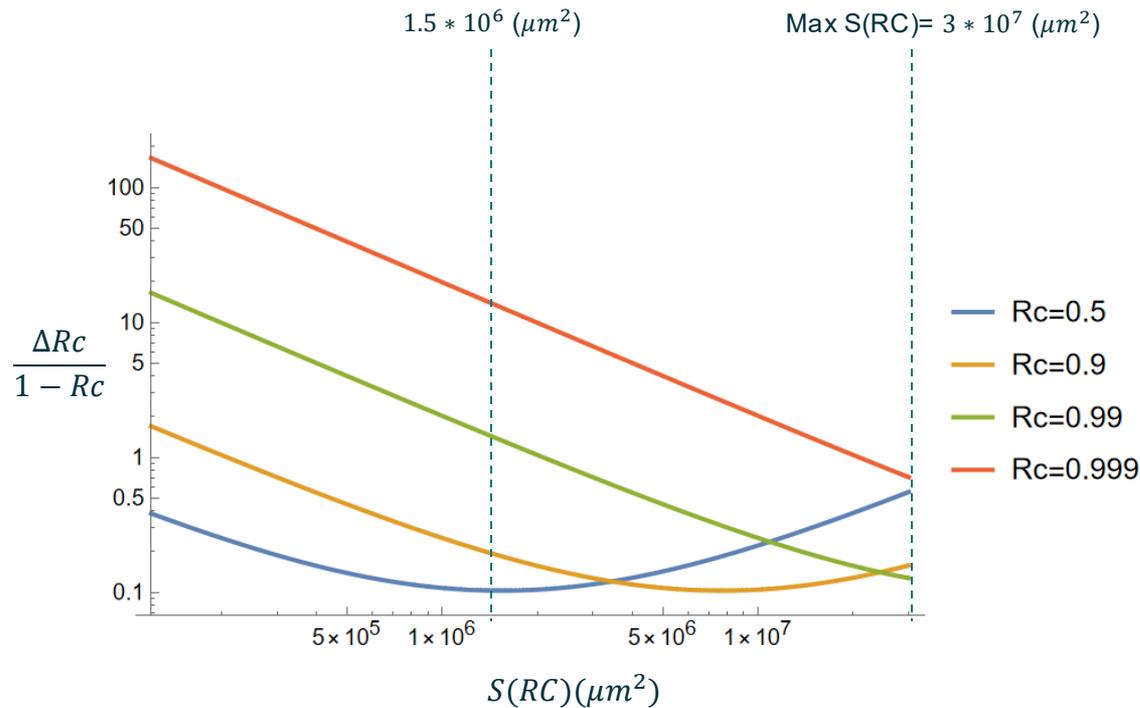
$$\begin{aligned}\Delta R_c &= \frac{dR_c}{d\eta} * \frac{d\eta}{dE'} * \Delta E' \\ &= \frac{((1-R_c)*S(RC)+S(KID)+S(CPW))^2}{S(I)*S(RC)} * \frac{1}{E} * \Delta E' \\ \Delta E' &= C*S(I) \propto S(I)\end{aligned}$$

Measure Rc with small uncertainties, we want: $\Delta R_c \ll 1 - R_c$, which is to have a small: $\frac{\Delta R_c}{1-R_c}$

$$\frac{\Delta R_c}{1-R_c} \approx \frac{C*((1-R_c)*S(RC)+S(CPW))^2}{S(RC)*(1-R_c)} * \frac{1}{E}$$

The uncertainty in Rc is too large for current CPW design
Next step: reduce the CPW area

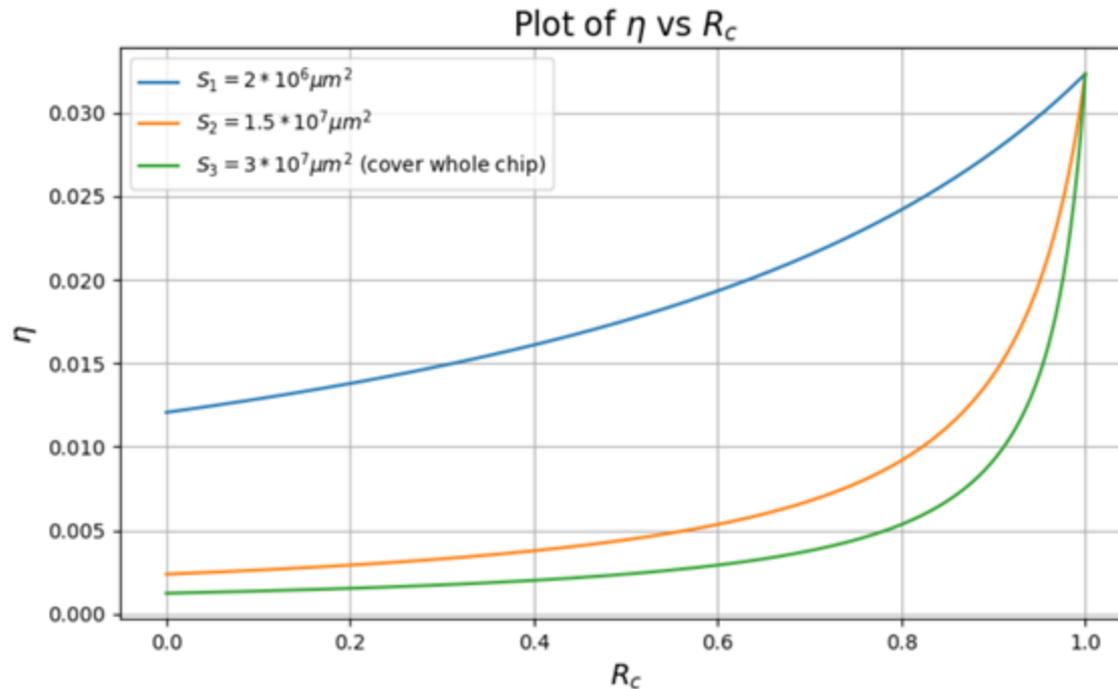
Reflective coating design



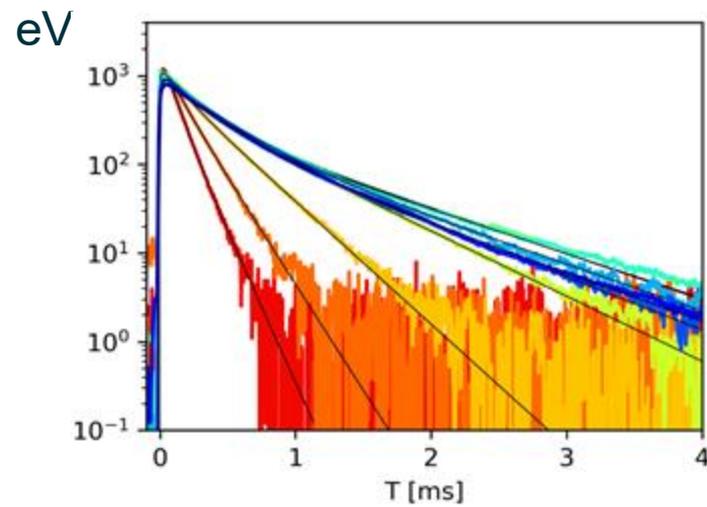
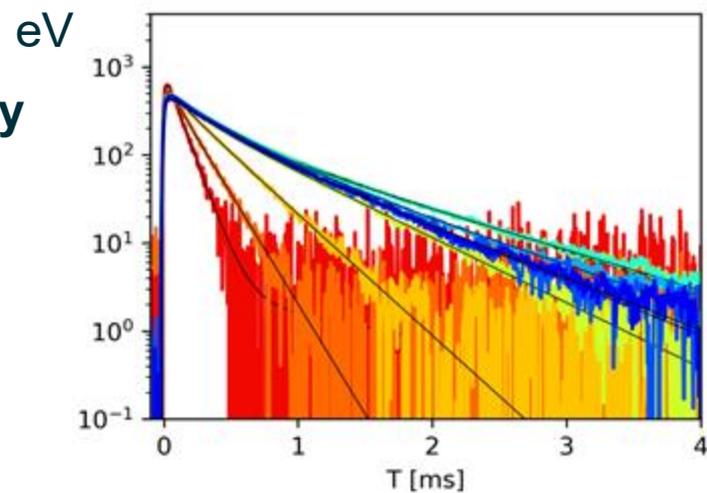
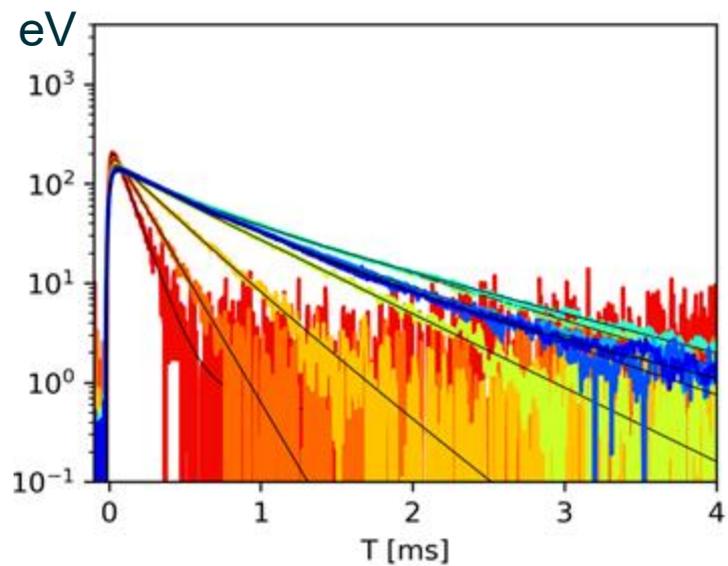
Design different Reflective Coating area: (in μm^2)
 1.5×10^6 , 5×10^6 , 1.0×10^7 , 3×10^7

Calculation of Reflectivity

- Phonon collection efficiency vs reflectivity of the multilayer coating:
- Reflectivity is between 0 -1
- From phonon collection efficiency, we can get the reflectivity of the multilayer



Pulse shape at 10, 30, 60keV total energy



Fit with 2-fall times (Solid: 10keV, Dash dot: 30keV, dot: 60keV)

