Preparation and light collection simulation of W-TES in 0νββ experiments

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Research Background: **Current Status at Home and Abroad**

➢ Neutrinoless Double Beta Decay (NLDBD) is an important scientific frontier in the field of particle physics and nuclear physics research, and it is one of the research directions that may break through the Standard Model of particle physics.

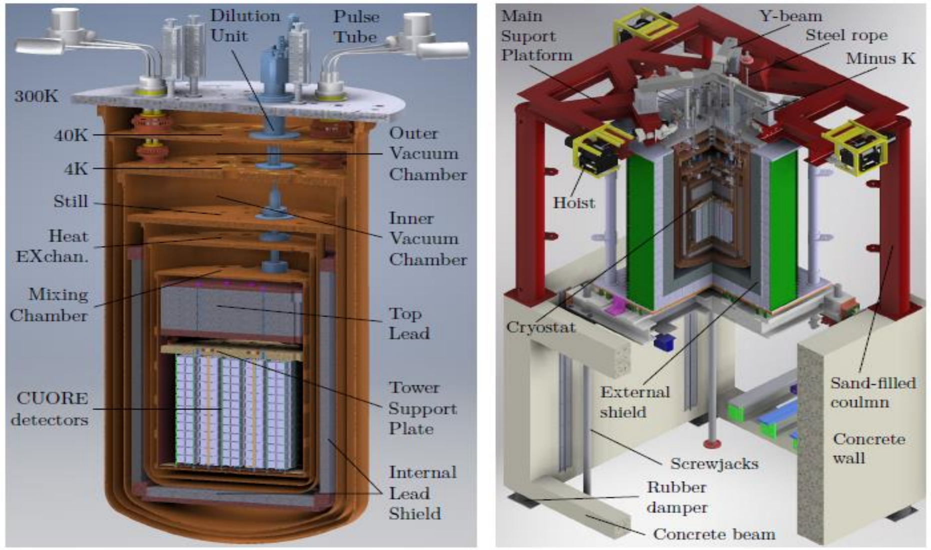
	CUORE	LEGEND-200	KamLAND-Zen	PandaX-III
Detector	**cryogenic crystal calorimeter**	**HPGe**	**Liquid Scintillator Antineutrino Detector**	**Micromegas**
Element	**~200 kg^{130}Te**	**35.6 kg^{76}Ge**	**680 kg ^{136}Xe**	**150 kg ^{136}Xe**
background index **counts/(keV·kg·yr)**	**10^{-2}**	**10^{-4}**	**10^{-3}**	**10^{-4}**
limit of half-life **(90% C.L.)**	**3.8×10^{25}**	**1.9×10^{26}**	**3.8×10^{26}**	**9×10^{25}**

◆ Detecting the Majorana nature of neutrinos.
◆ Indirect measurement of the effective neutrino mass.
◆ Testing lepton number conservation.
◆ Explaining the matter-antimatter asymmetry in the process of cosmic evolution.

Research Background: **Research on Key Issues**

Isotopes	Q-value (keV)	N.A. (%)	$T_{1/2}^{2\nu}$ (year) measurement PDG2015, no error included	$T_{1/2}^{0\nu}(50\,\mathrm{meV})$ calculation PRC 79, 055501 (2009), (R)QRPA (CCM SRC)	Pros & Cons
^{48}Ca	4273.6 ± 4	0.19	4.4 × 10^{19}	-	Q-value highest, N.A. small, enrichment difficult
^{76}Ge	2039.006 ± 0.050	7.6	1.84 × 10^{21}	(2.99-7.95)×10^{26}	2v long, enrichment ~90%
^{82}Se	2995.50 ± 1.87	8.7	9.6 × 10^{19}	(0.85-2.38)×10^{26}	enrichment >90%
^{96}Zr	3347.7 ± 2.2	2.8	2.35 × 10^{19}	(3.16-6.94)×10^{26}	
^{100}Mo	3034.40 ± 0.17	9.4	7.11 × 10^{18}	(0.59-2.15)×10^{26}	2vshort, enrichment >90%
^{110}Pd	2017.85 ± 0.64	7.5	-	-	
^{116}Cd	2813.50 ± 0.13	7.5	2.8 × 10^{19}	(0.98-3.17)×10^{26}	enrichment 80~90%
^{124}Sn	2287.80 ± 1.52	5.8	-	-	
^{130}Te	2527.01 ± 0.32	34.1	7.0 × 10^{20}	(7.42-2.21)×10^{26}	N.A. high
^{136}Xe	2457.83 ± 0.37	8.9	2.165 × 10^{21}	(1.68-7.17)×10^{26}	2v long, enrichment ~90%
^{150}Nd	3317.38 ± 0.20	5.7	9.11 × 10^{18}	-	2v short, enrichment difficult

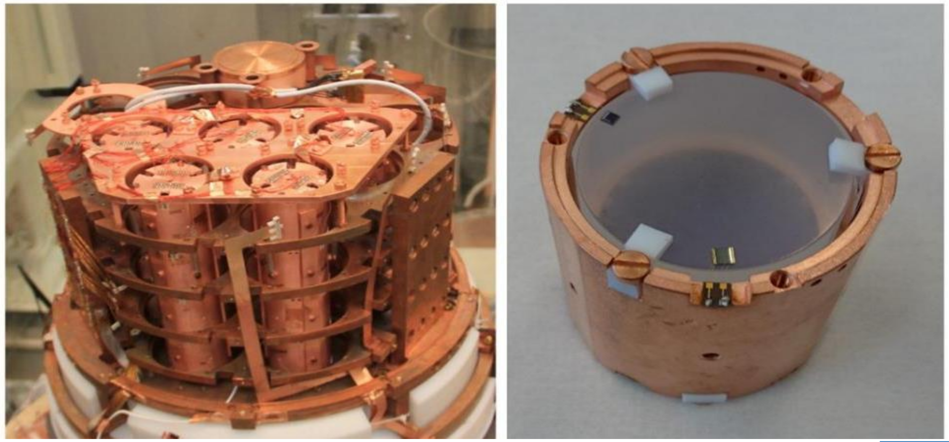
CUORE-^{130}Te



Source of background:

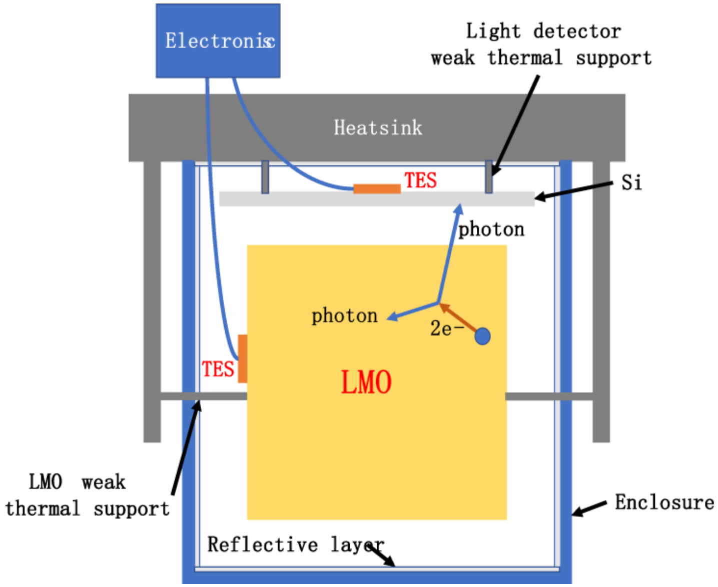
- **CUORE:** Alpha particles from natural decay, after losing part of their energy, are absorbed by the crystal and become background.
- **CUPID:** The stacked signals generated by the 2νββ decay become the main background source of the 0νββ signal.

CUPID-^{100}Mo



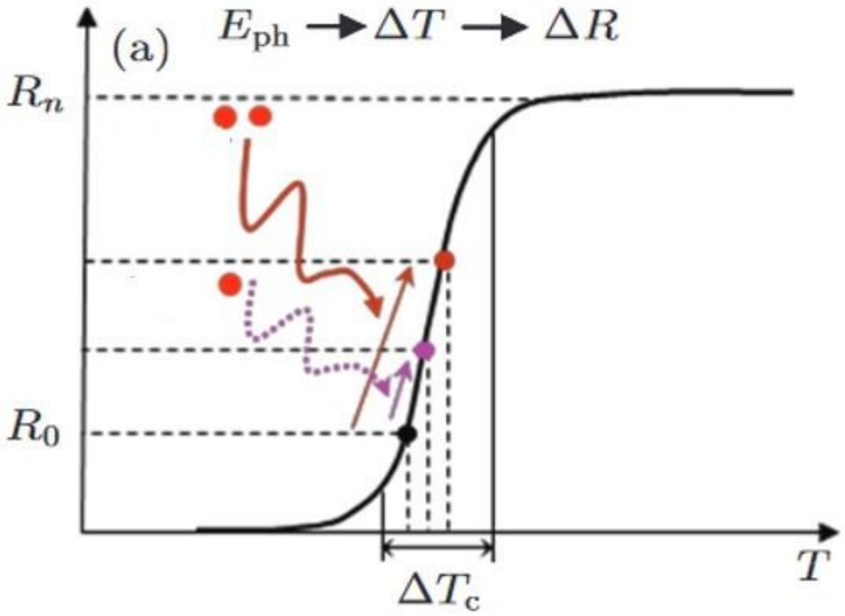
Research Background:
Advantages of Transition Edge Sensors (TES)

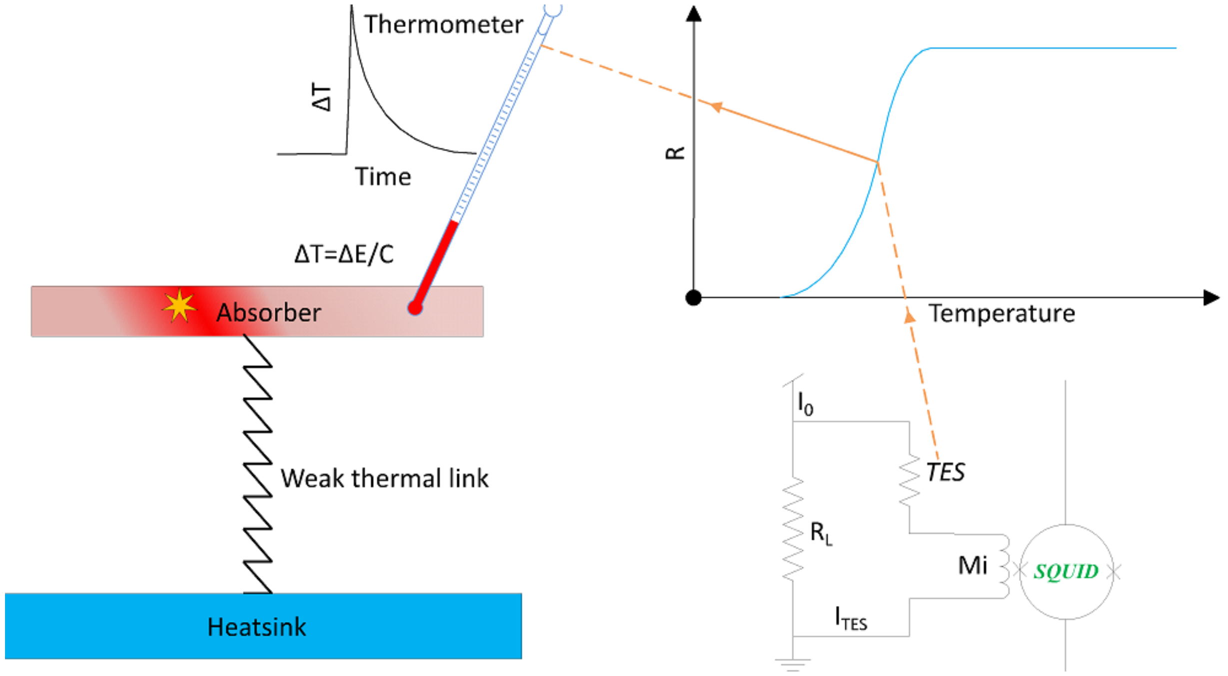
parameter	TES	NTD
Detection medium	Superconducting film	Ge-NTD
Temperature sensitivity coefficient	several tens to several thousands	≤10
Energy resolution	**1.6eV@5.9keV (FWHM)**	~3eV@5.9keV (FWHM)
Response time	**~μs**	~ms
Readout electronics	**SQUID**	JFET、simple
Multiplexing method	Multiplexing	no



For small-scale applications, TES is relatively complex due to its use of SQUIDs for readout electronics. NTD-germanium photodetectors can also meet the requirements of CUPID's baseline design, but in future ton-scale experiments, TES will be indispensable.

- **Lower background requirements demand higher time resolution.**
- **The readout method simplifies wiring complexity and reduces the thermal load on refrigerators.**

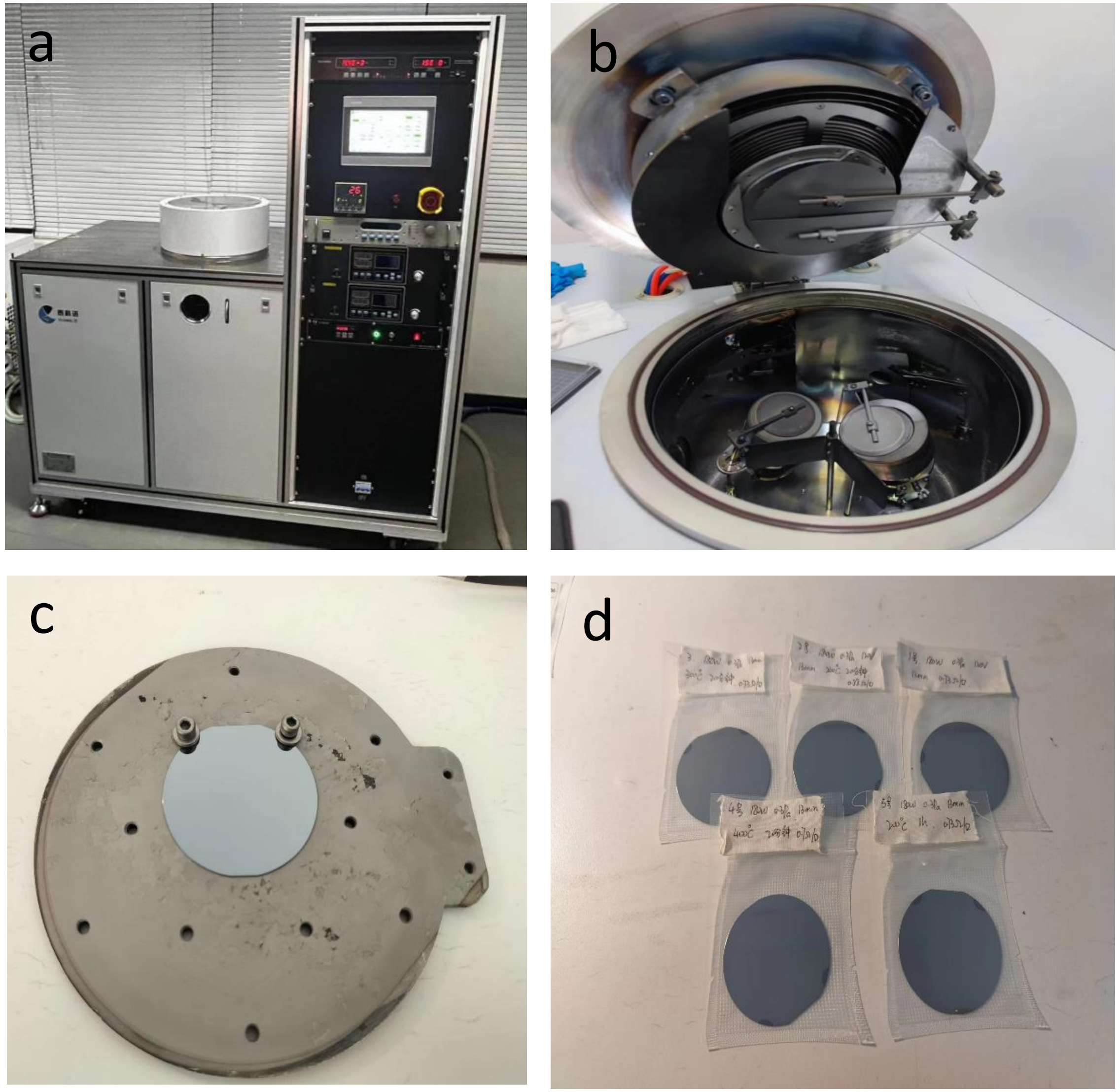




- **The superconducting transition-edge sensor (TES)** consists primarily of **a superconducting thin film biased within the transition region from the superconducting to the normal state.** Leveraging its steep resistance-temperature (R-T) relationship to measure heat deposition, it is a highly sensitive detector.
- **The thermo-electric negative feedback** enables the TES to accelerate cooling and return to the operating point, giving the TES the advantage of a rapid response.

- Research Background
- **Preparation of W-TES**
- Light collection simulation for W-TES
- Summary and Outlook

Tungsten thin film preparation platform



- **Experimental Objective**: Tungsten thin films with low resistivity and a transition temperature of 15–20 mK.

	Resistivity	Grain size	Transition temperature
α-W	5.3 uΩ·cm	>130nm	~15mK
β-W	200 uΩ·cm	~5nm	1-4K

- **Method:** DC magnetron sputtering (Teconno-JCP350)
- **Substrate:** 400 μm thick, (100) single crystal, 2-inch silicon wafer
- **Initial vacuum：** 2×10^{-4} Pa

Effects of Annealing and Substrate Temperatures on Thin Films - **XRD**

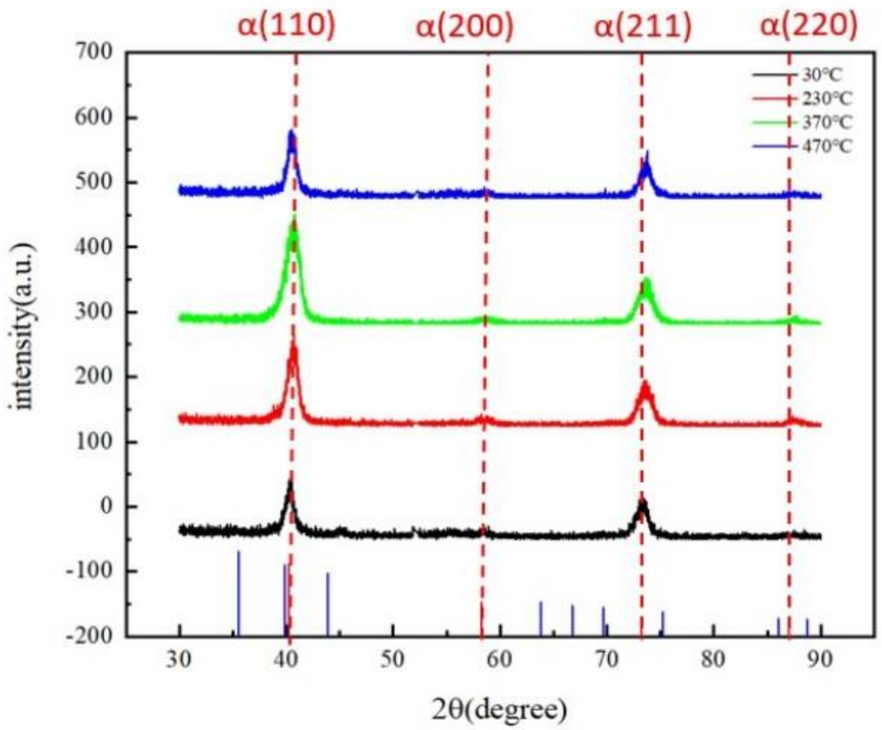


Figure1. XRD patterns of tungsten thin films after annealing at different temperatures.

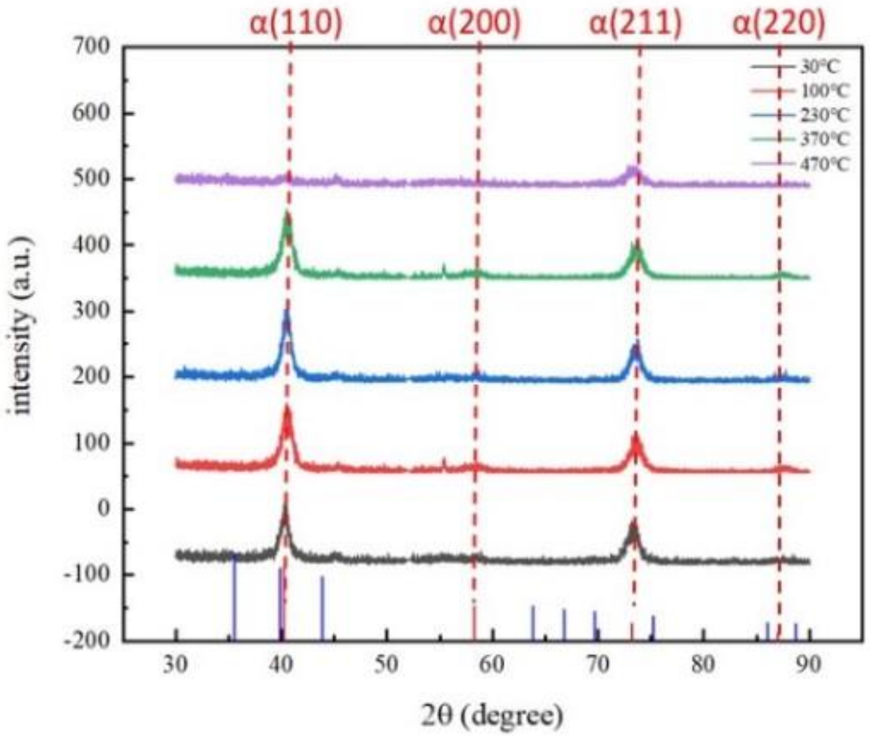


Figure 2. XRD patterns of tungsten thin films prepared at different substrate temperatures.

- With the increase of annealing temperature, the intensity of the α-phase in the thin film first increases and then decreases.
- An appropriate substrate temperature is conducive to the formation of α-W thin films.

high annealing temperature / appropriate substrate temperature ⟹ α-phase tungsten thin film.

Effects of Annealing and Substrate Temperatures on Thin Films - **SEM**

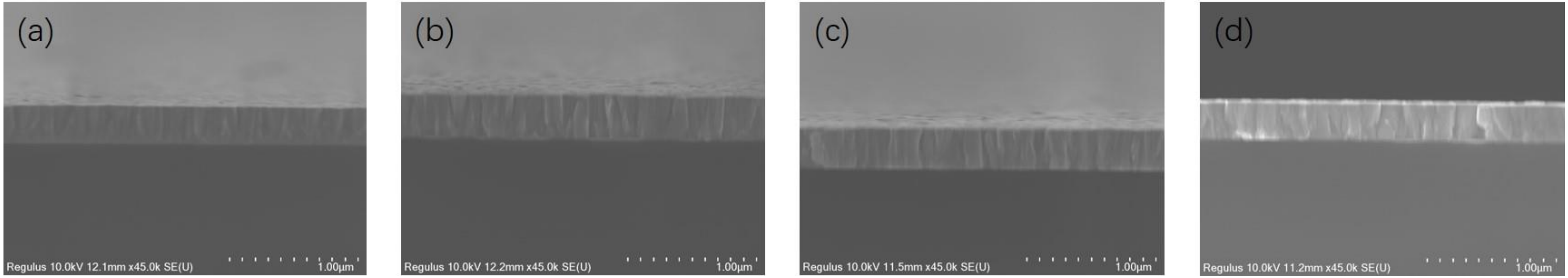


Figure 1. SEM images of tungsten thin films after annealing at different temperatures: (a) unannealed; (2) 230°C; (3) 370°C; (4) 470°C

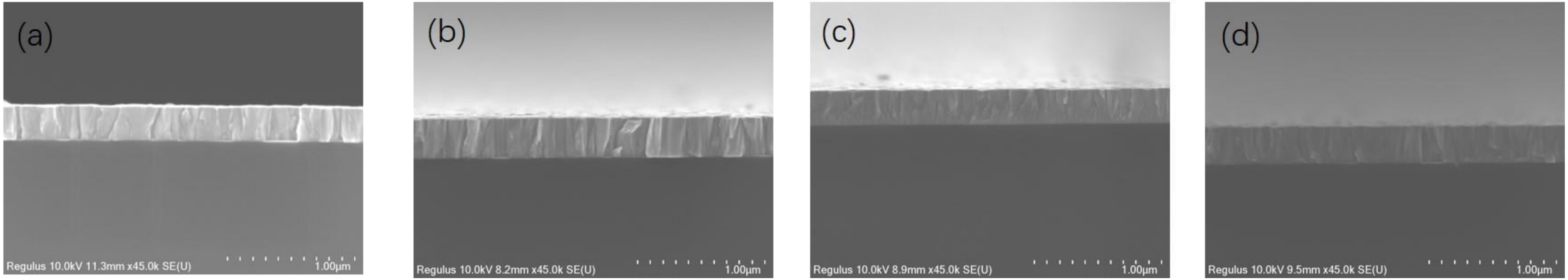


Figure 2. SEM images of tungsten thin films at different substrate temperatures: (a) 100°C; (b) 230°C; (c) 370°C; (d) 470°C

- Annealing increases the grain size;
- The thin films deposited at substrate temperatures ranging from 100°C to 230°C have the largest grain size.

Effects of Annealing and Substrate Temperature on Thin Films—**EBSD**

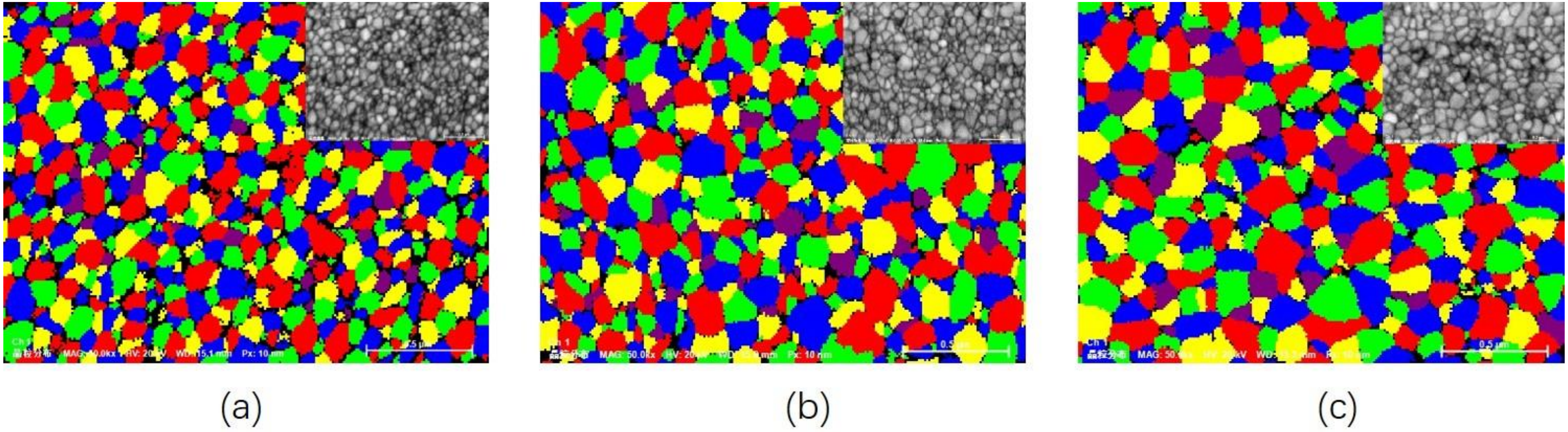


Figure. 1. EBSD images of tungsten films at different substrate temperatures: (a) coated at room temperature without annealing; (b) coated at room temperature and annealed at 470°C; (c) coated at 100°C without annealing.

- The room-temperature sputtered, unannealed film has an average grain size of 119 nm.
- The room-temperature sputtered film annealed at 470°C has an average grain size of 149 nm.
- The unannealed film deposited at 100°C has an average grain size of 154 nm.

high annealing temperature / appropriate substrate temperature can increase the grain size and reduce grain boundary .

Effects of Annealing and Substrate Temperatures on Thin Films—**Resistivity and Stress**

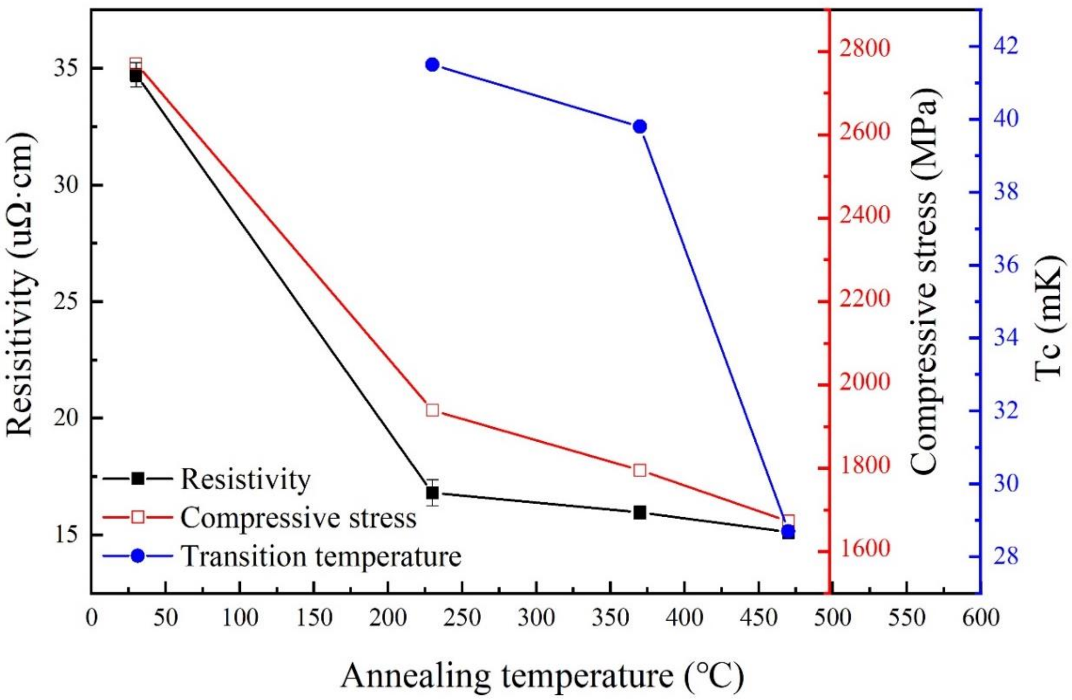


Figure. 1. Relationship between thin film annealing temperature and thin film resistivity and compressive stress.

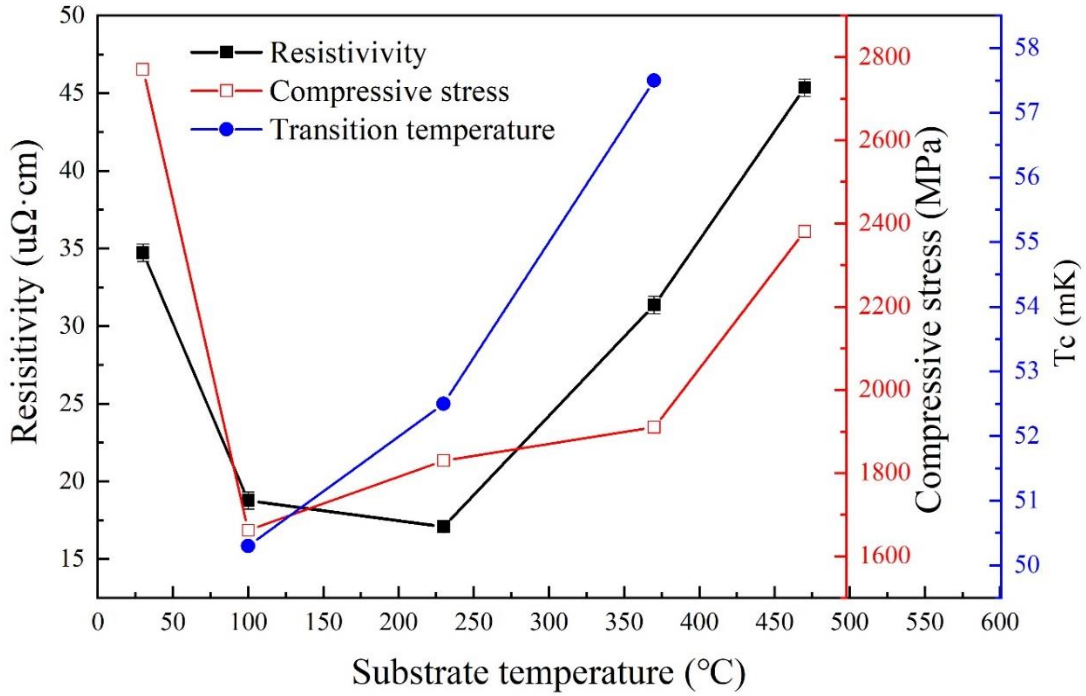


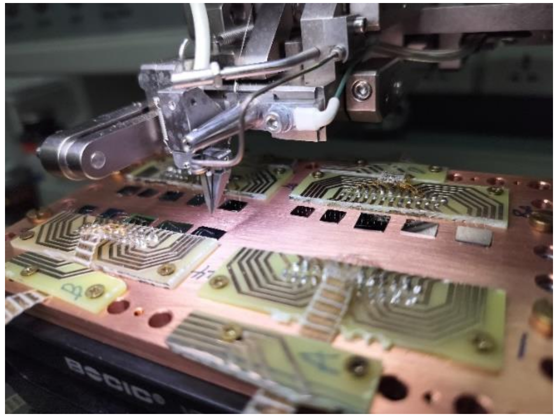
Figure. 2. Relationship between thin film substrate temperature and thin film resistivity and compressive stress.

◆ As the annealing temperature of the film increases, the resistivity of the film decreases, and the compressive stress of the film is released; annealing is beneficial to reducing internal defects in the film.

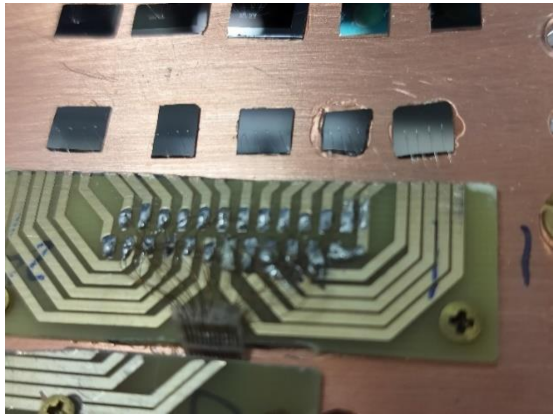
◆ As the substrate temperature increases, both the resistivity and compressive stress of the film first decrease and then increase. An appropriate substrate temperature facilitates the formation of α-tungsten films.

Effects of Annealing and Substrate Temperature on Thin Films—**Transition temperature**

Test



Sample Fixation



Wire Bonding (four-point method)

Installation

Evacuation

Result

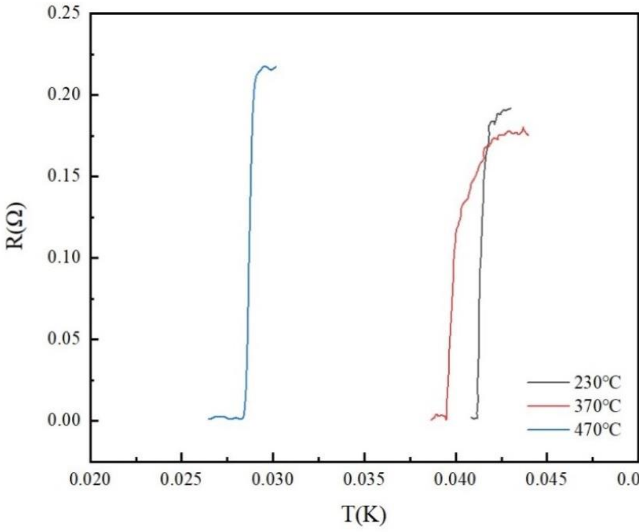


Figure. 1. R-T curves of tungsten films at different annealing temperatures.

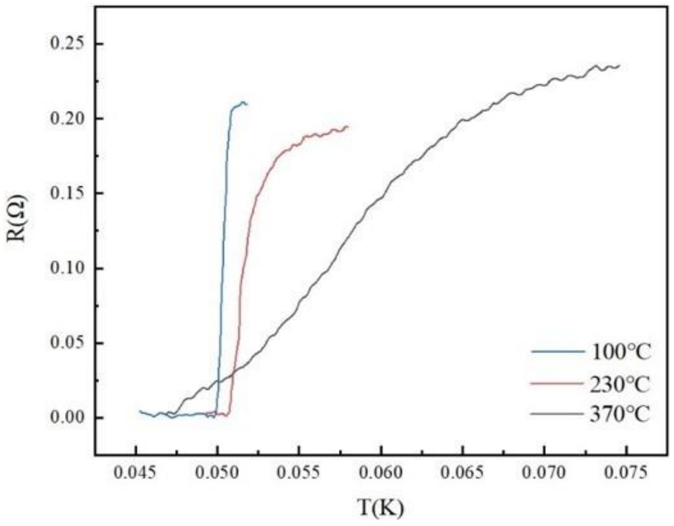
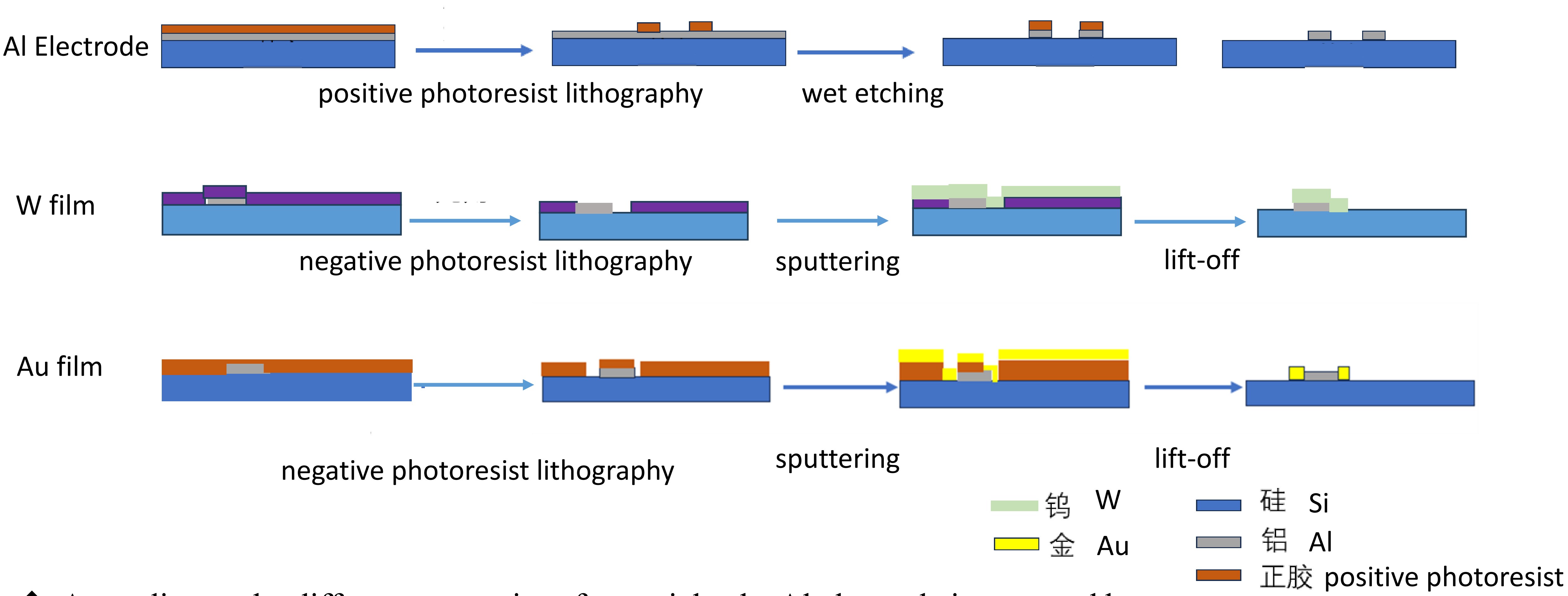


Figure. 2. R-T curves of tungsten films at different substrate temperatures

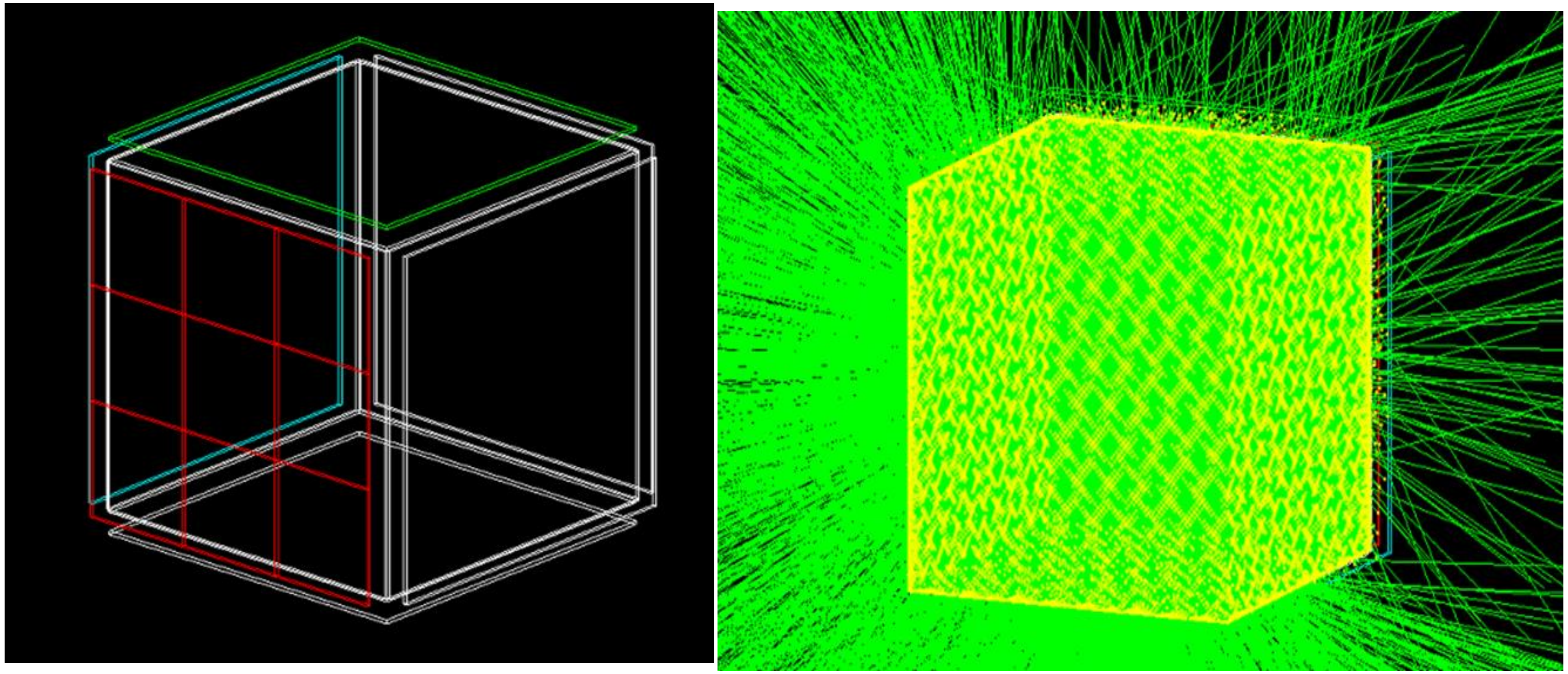
- As the annealing temperature rises, the film's transition temperature decreases.
- The transition temperature range narrows.
- An appropriate substrate temperature helps reduce the film's transition temperature.

W-TES Design and Fabrication Process

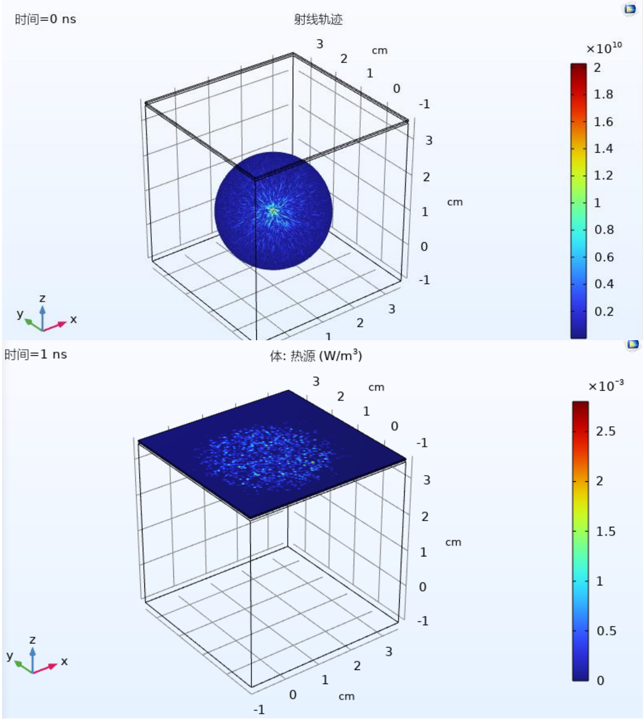


- According to the different properties of materials, the Al electrode is prepared by wet etching, while the W film and Au film are prepared by lift-off.

Geant4+COMSOL Simulation



Geant4 simulation model

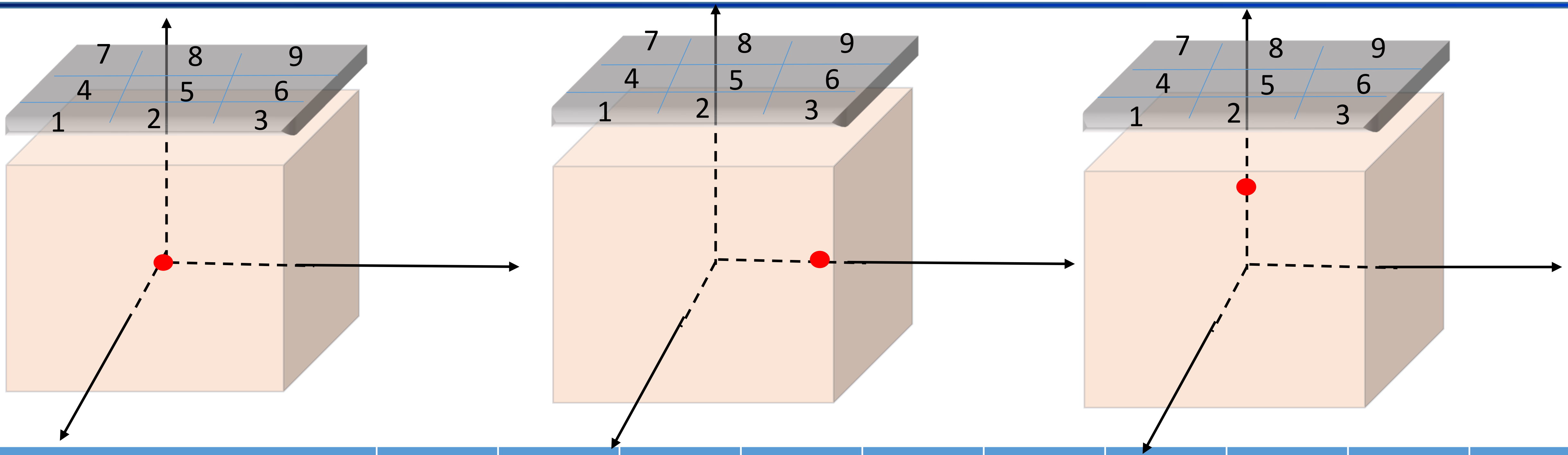


COMSOL simulation model

The objective of this study is to investigate the influence of variation in decay sites within lithium molybdate crystals on temperature changes in photodetectors positioned above the crystal.

- **Geant 4 simulation:** The generation of scintillation light.
- **COMSOL simulation:** The conversion of optical energy into thermal energy.

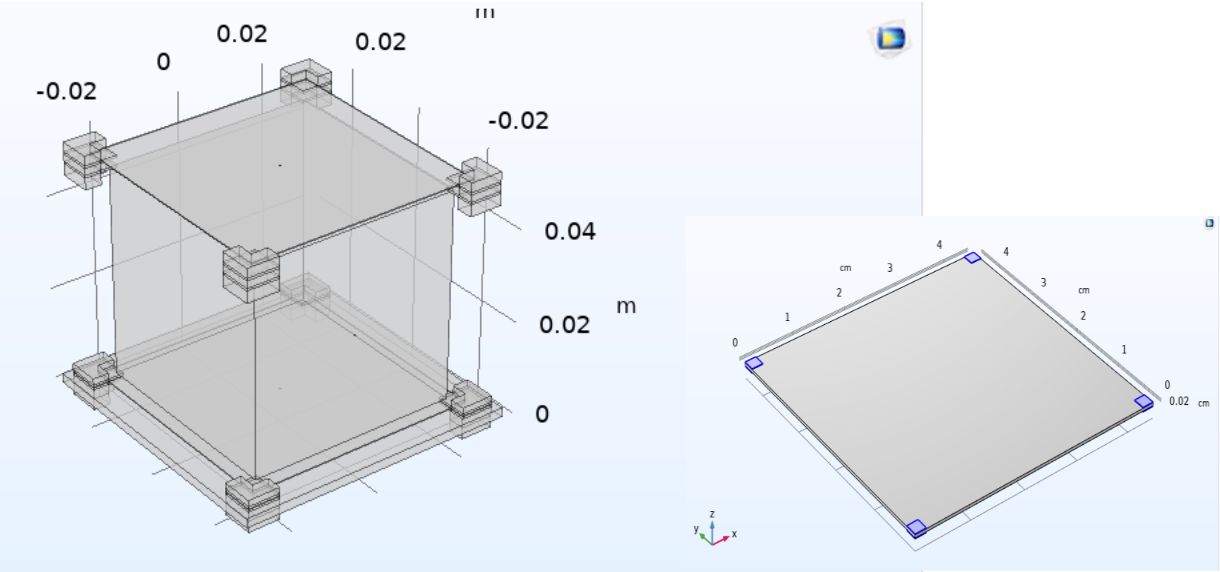
Geant4 Simulation

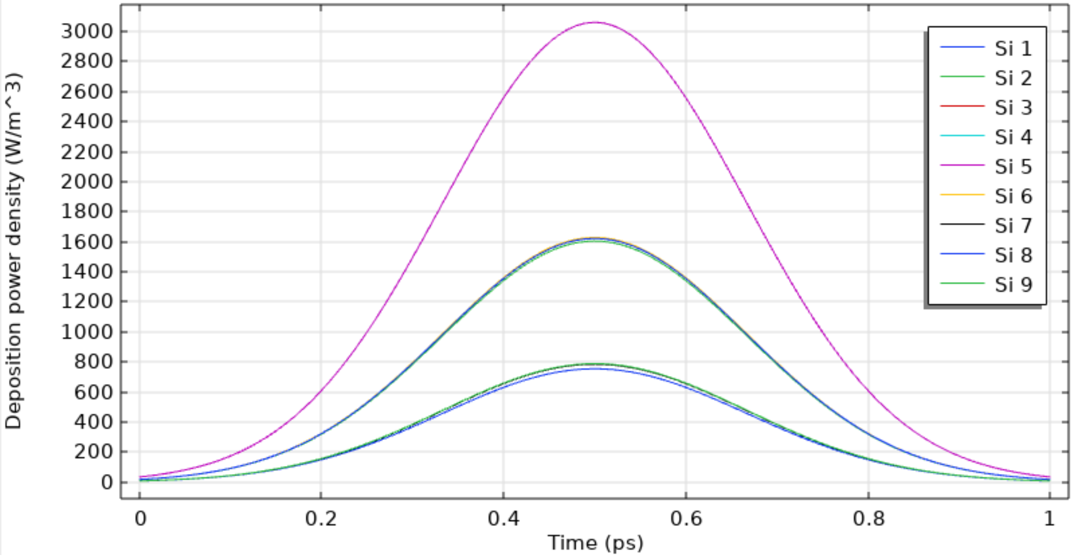


Decay position\Deposited energy (eV)	mppc1	mppc2	mppc3	mppc4	mppc5	mppc6	mppc7	mppc8	mppc9	总
(0,0,0)	222	472	232	477	900	479	231	477	232	3725
(2,0,0)	42	169	689	51	372	1404	38	173	702	3640
(0,0,2)	57	154	57	159	2992	158	57	159	59	3852

It can be observed that when electrons with a total energy of 3.034 MeV are generated at different positions, the energy deposited in the silicon wafer varies across locations.

COMSOL light collection simulation





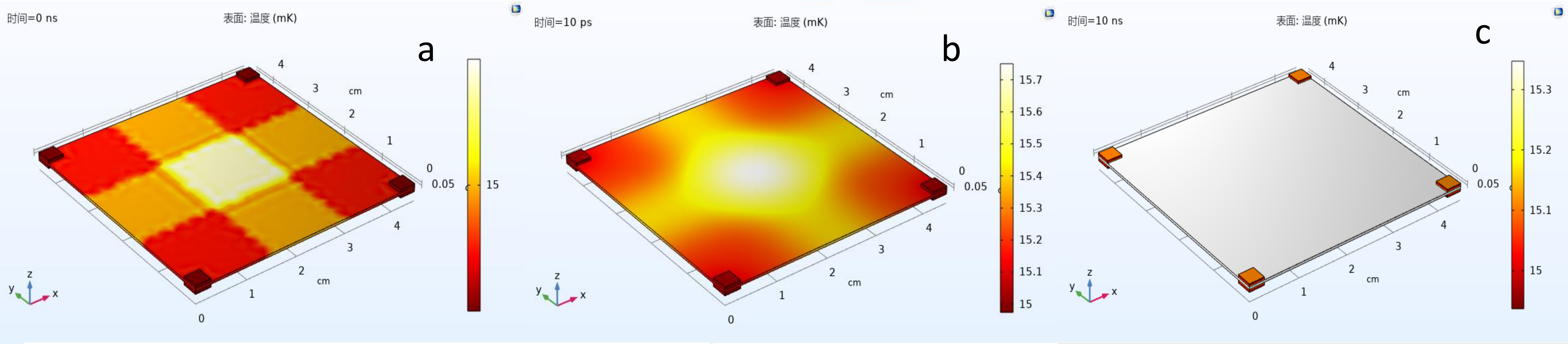
Model：

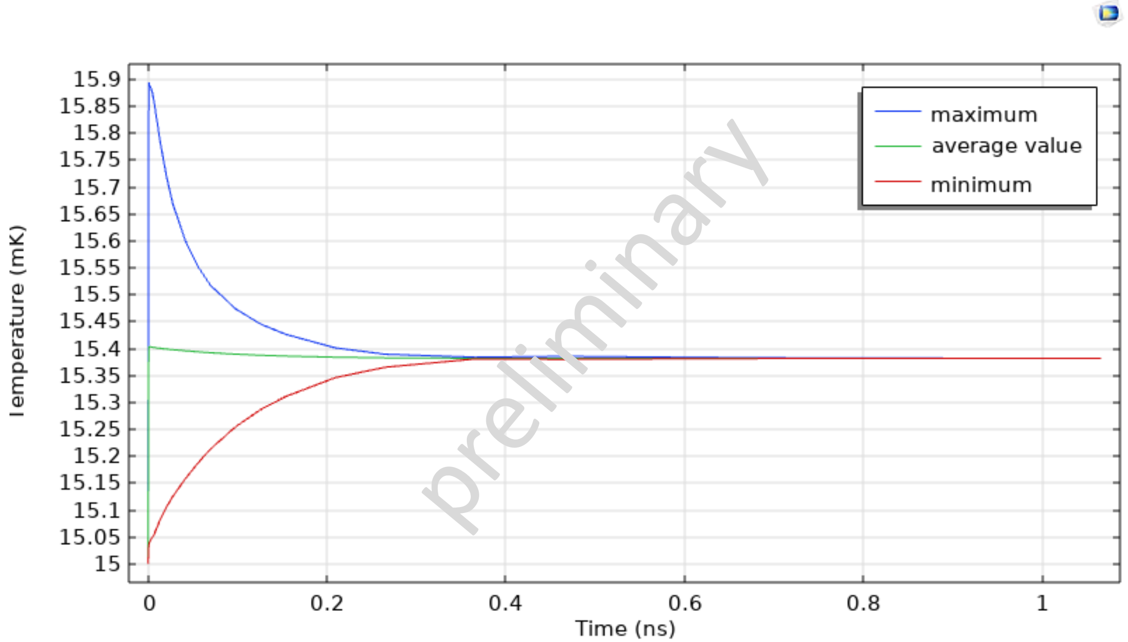
- **Si：** 4.5cm×4.5cm×400um
- **PTFE:** 0.2cm×0.2cm×0.01cm
- **Si heat capacity：** 6.75×10^{-10} J/(kg·K)
- **PTFE thermal conductivity：** 3.75×10^{-7} W/(m·K)

Settings:

- **Heat source setting:** Heat flux (power pulse)
- **Heat dissipation method:** thermal conduction
- **Heat source pulse duration:** 1 ps
- **Ambient temperature:** 15 mK

COMSOL light collection simulation





- When the decay event occurs at the position (0, 0, 0), the temperature across the silicon surface reaches uniformity after approximately 0.5 ns.
- Through heat dissipation solely by PTFE thermal conduction, the temperature of the silicon wafer recovers to 15 mK within about 7 μs.

Summary

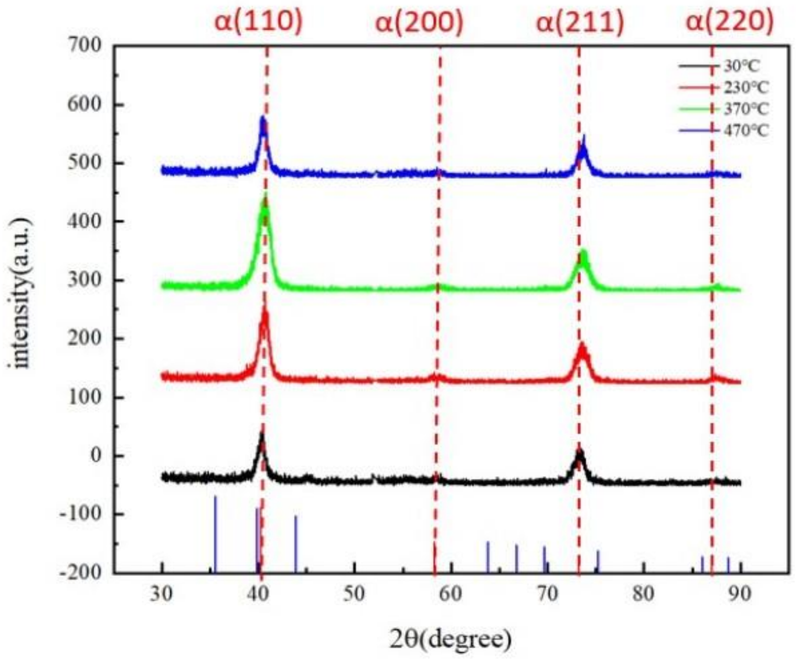
- Increasing the sputtering power and reducing the sputtering pressure are beneficial to the formation of α-W.
- An appropriate substrate temperature and a relatively high annealing temperature will be beneficial to reducing the transition temperature of the thin film.
- Preparation of W-TES is in the works.
- Preliminary optical simulation for W-TES has been done.

Outlook

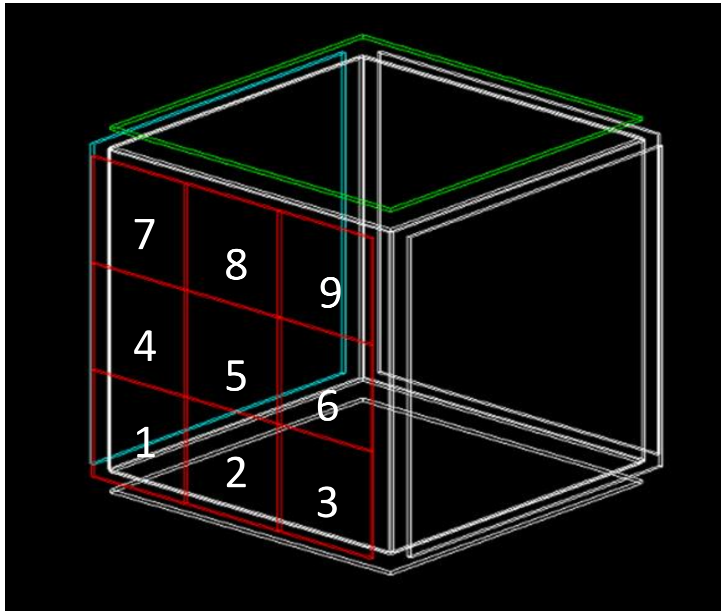
- Adjust the parameters to reduce the transition temperature of the thin film and improve the quality of the tungsten thin film.
- More detailed optical simulations for LMO + TES detectors setup in the detector simulation.

Any constructive criticism and/or feedback is very appreciated.

Supplementary Information



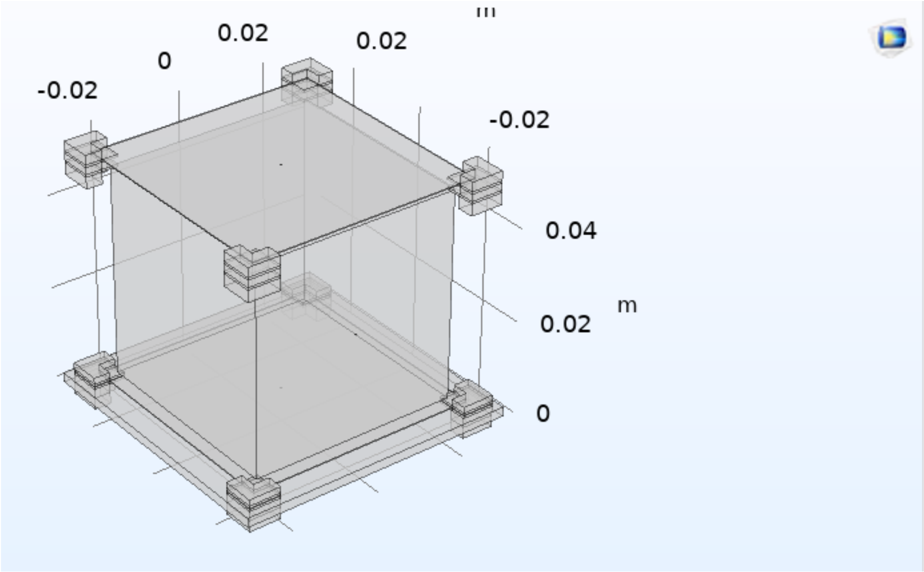
The XRD results indicate that a higher peak intensity corresponds to better crystallinity along that crystallographic orientation.



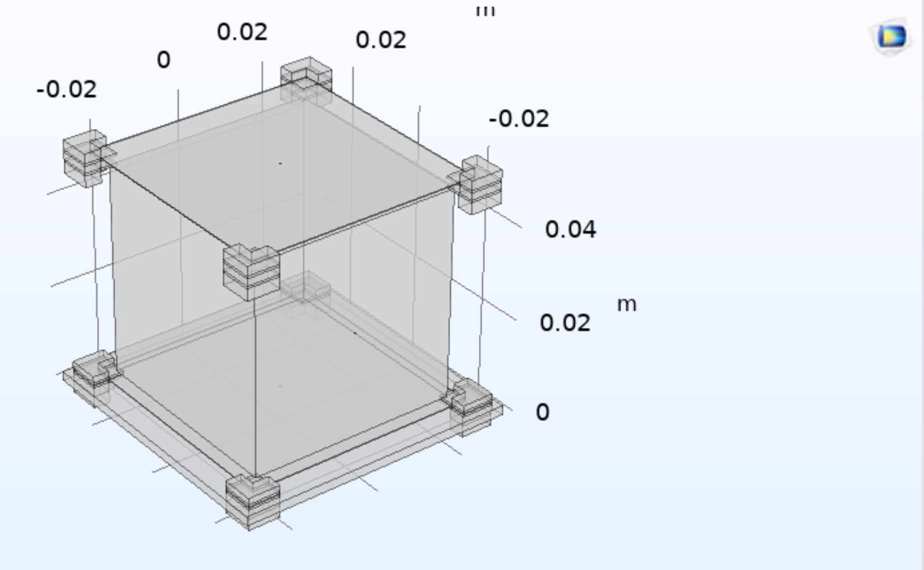
$$F(T_1,T_2,\cos\theta)=(T_1+1)^2(T_2+1)^2\times\delta(T_0-T_1-T_2)(1-\beta_1\beta_2\cos\theta) \quad (1)$$

$$F_1(T_1)=(T_1+1)^2(T_0+1-T_1)^2 \quad (2)$$

- The energy of two electrons and the angular distribution of the direction of their momentum are determined by Formula (1).
- The energy distribution of a single electron can be described by Formula (1).



COMSOL is based on the finite element analysis (FEA) method for computation, and there are some issues with the interface settings between the silicon wafer and PTFE.



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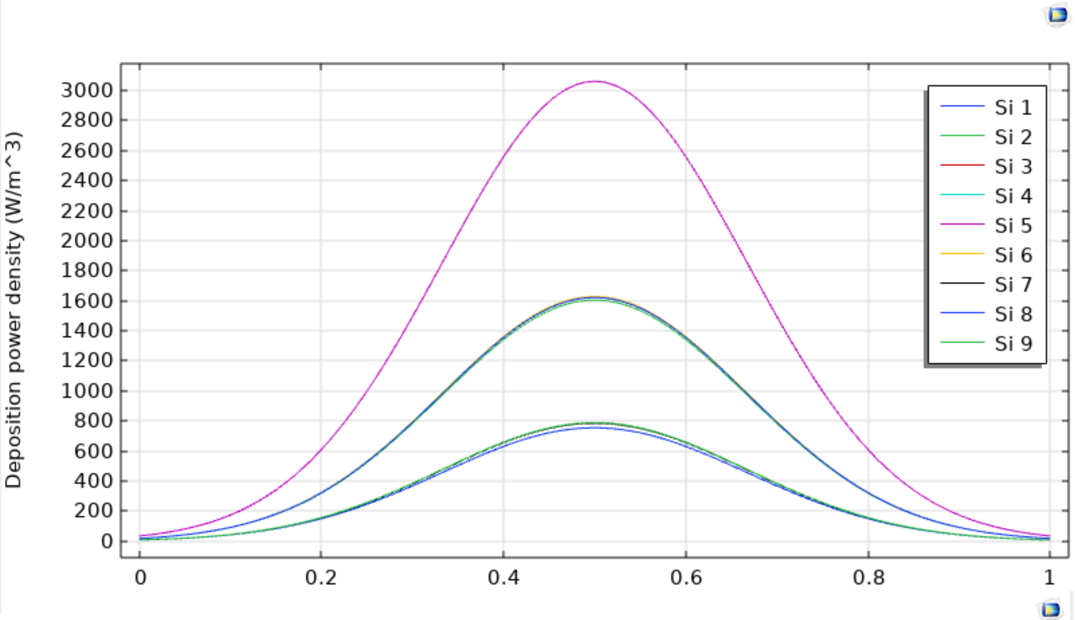
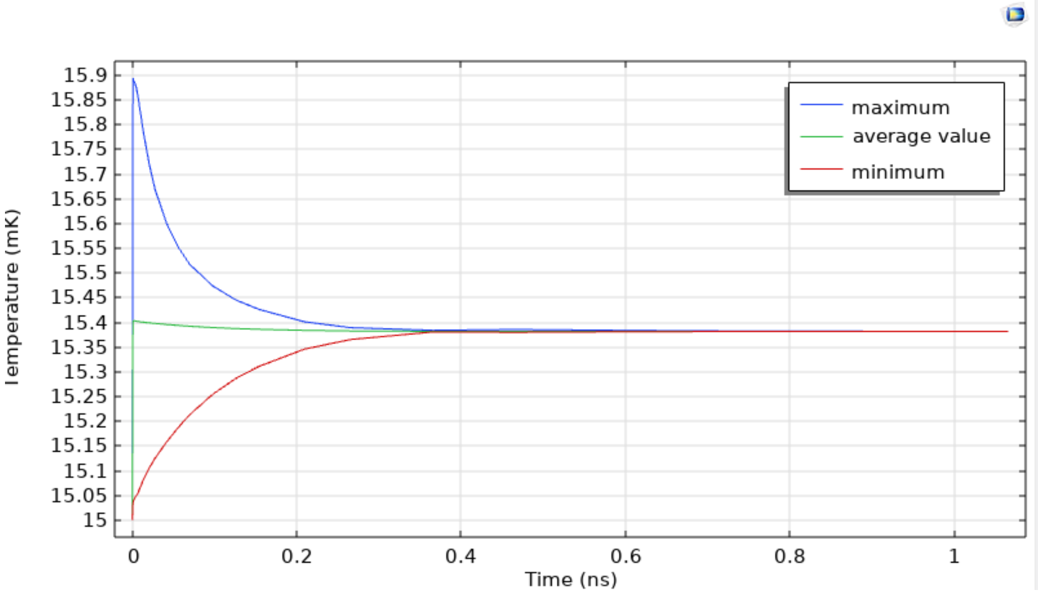


The energy deposited is obtained by integrating the deposited power density over time and multiplying by the volume. **A square wave can also be used.**



This part continues to decrease, exhibiting a very shallow slope.