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Impact of Annealing on Superconducting Properties of Tantalum Thin Films

APS Global Physics Summit 2026: MAR-P05

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Motivation

Chemical Analysis of Tantalum Thin Films compared to Niobium Thin Films using SIMS and XPS

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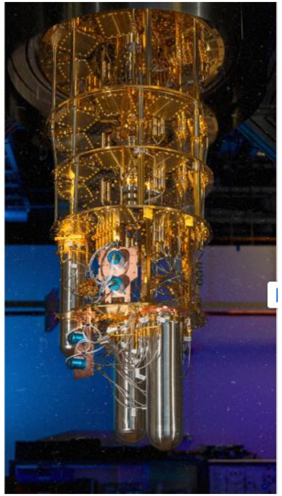
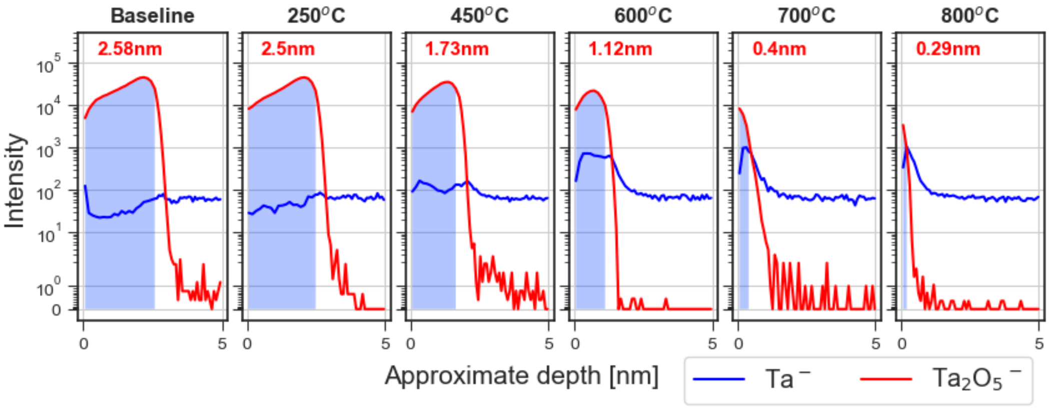


Vacuum heat treatments of Niobium cavities at 340˚C dissolve the native oxide and decrease TLS-induced losses. (Romanenko et al., 2020)

Will annealing Ta and reducing the surface oxide also lower TLS losses and consequently, increase qubit lifetime?

	Nb	Ta
Ambient Oxide Thickness	5 nm	2.5 nm
Sub-oxides	Nb^{5+}, **Nb^{4+}**, Nb^{2+}	Ta^{5+}, Ta^{2+}
UHV Oxide Dissolution	400˚C	> 800˚C



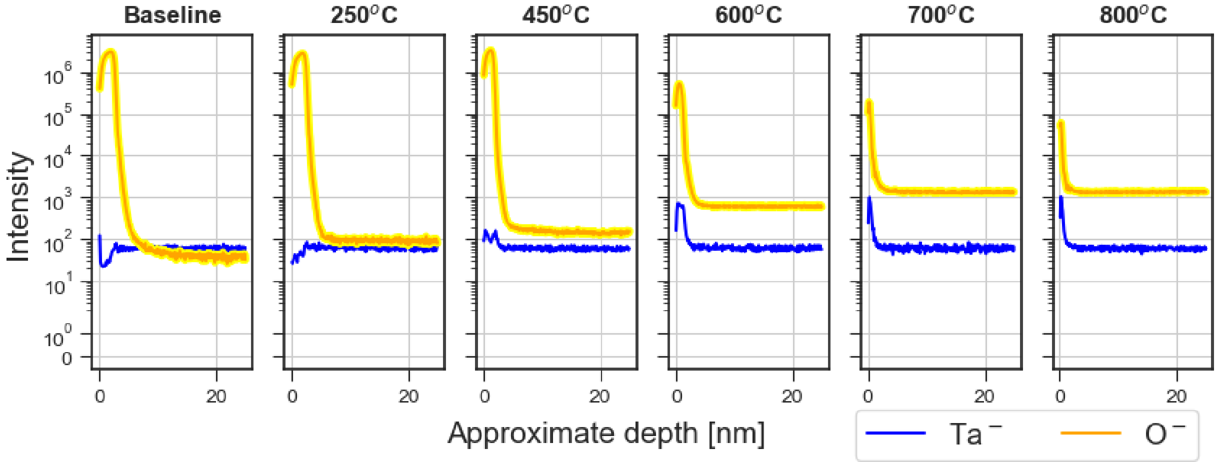
Motivation

But annealing leads to

1. Decomposition of the native oxide,

   $Ta_2O_5 \rightarrow TaO + Ta + 4O$

2. Dissolution of the oxygen into the metal.



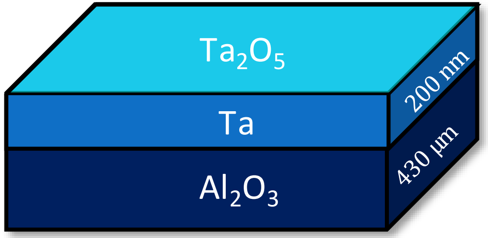
How do annealing and interstitial oxygen affect the superconducting properties of Ta? →

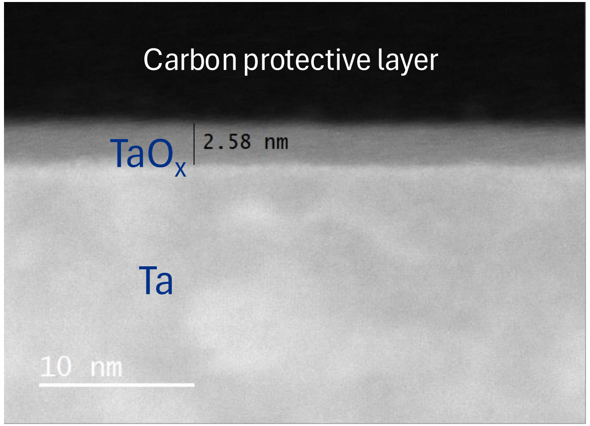
a. critical temperature,
b. residual resistivity ratio,
c. upper critical field, and
d. coherence length

Sample

- ☐ 200 nm of Tantalum on 430μm of MSE Sapphire.
- ☐ **Deposited** using DC magnetron sputtering **at 800˚C**.
- ☐ EBSD confirms an **epitaxial** metal layer with a [110] orientation.
- ☐ Oxide thickness from TEM is approximately **2.6 nm**.
- ☐ **Film is unprocessed**, with no photoresist or e-beam lithography.

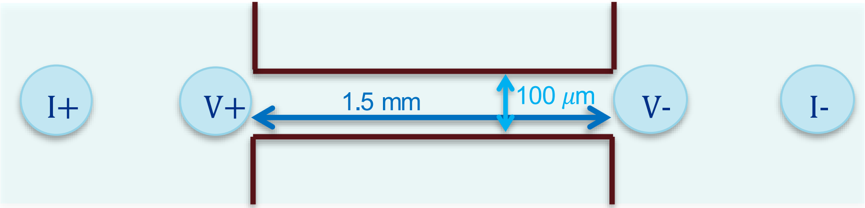
Ta Thin Film

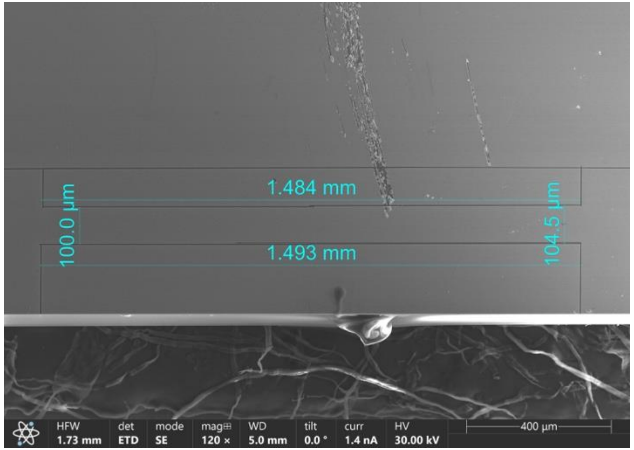




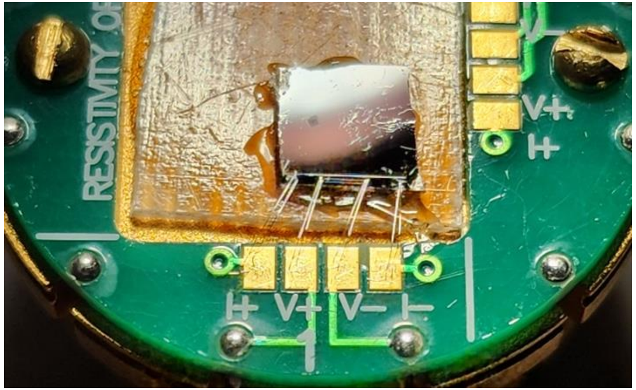
PPMS Sample Preparation

- A 1.5 mm x 100 μm channel was patterned on each sample using the FIB.





- A **four-point probe method** was used for the electromagnetic transport measurement.

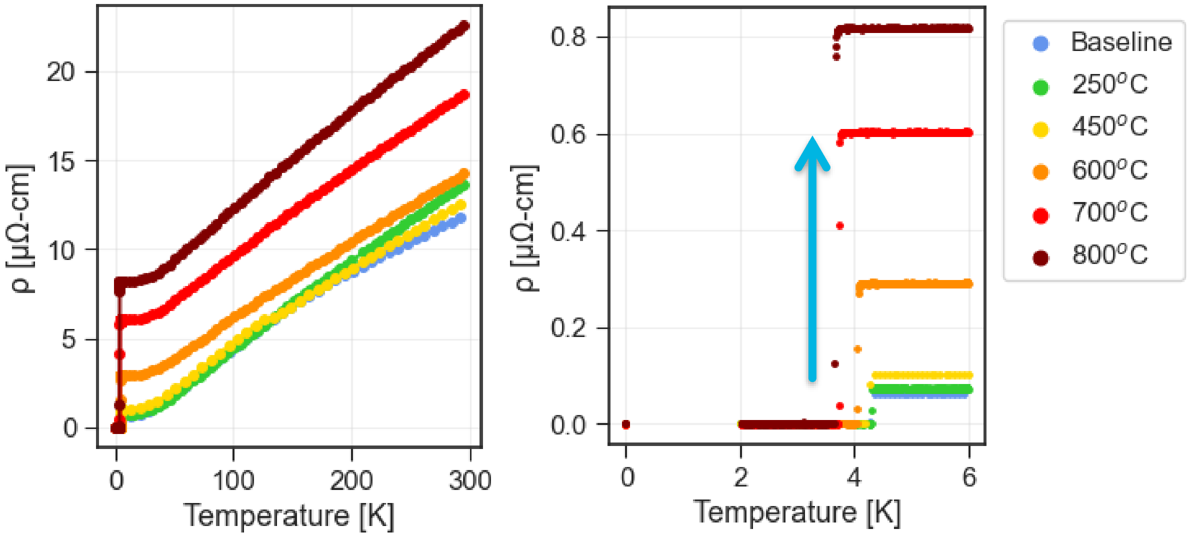


Resistivity

Electrical Resistivity was measured from 300K to 2K in 0 T.

Annealing

- ❑ **Increases Resistivity**
- ❑ **Suppresses T_c**

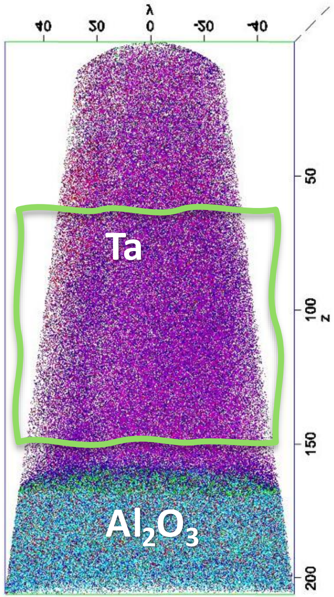


Sample	T_c	RRR
Baseline	4.33 K	19.14
Annealed at **250˚C**	4.30 K	18.68
Annealed at **450˚C**	4.27K	12.26
Annealed at **600˚C**	4.03K	4.91
Annealed at **700˚C**	3.72 K	3.11
Annealed at **800˚C**	3.65 K	2.76

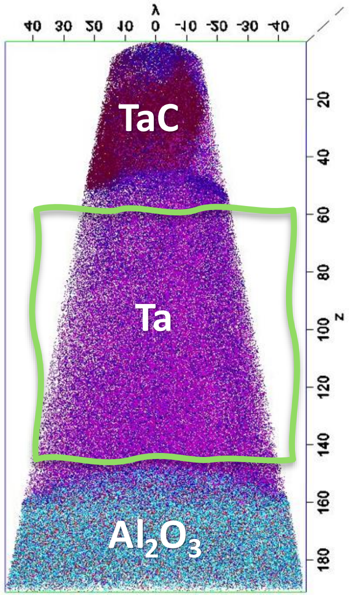
$$RRR = \frac{\rho_{300K}}{\rho_{10K}}$$

Oxygen concentration using APT

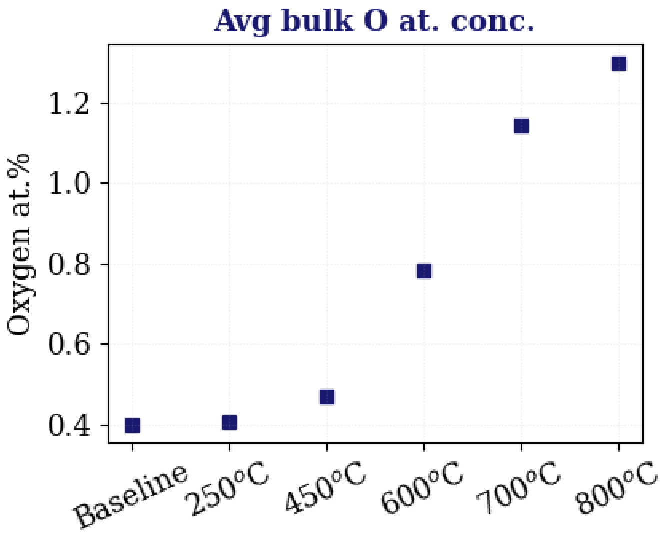
As-deposited

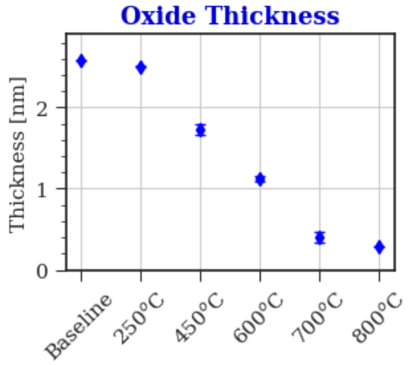


800˚C annealed

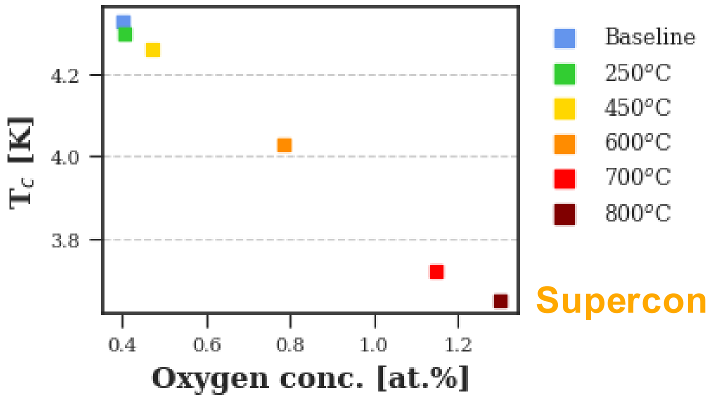


Courtesy of Jae Yel Lee

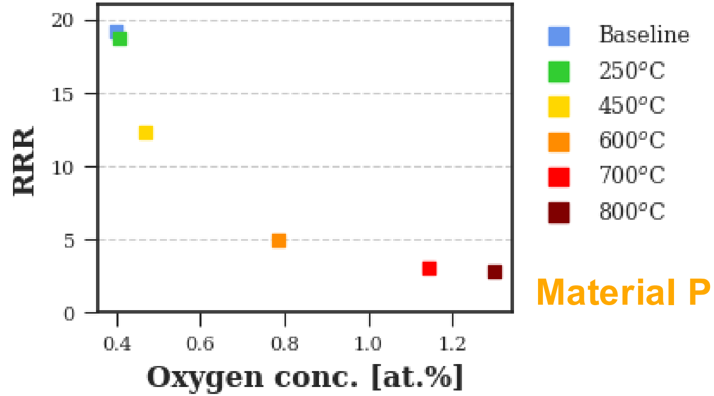




Tc, RRR vs O at. Conc.



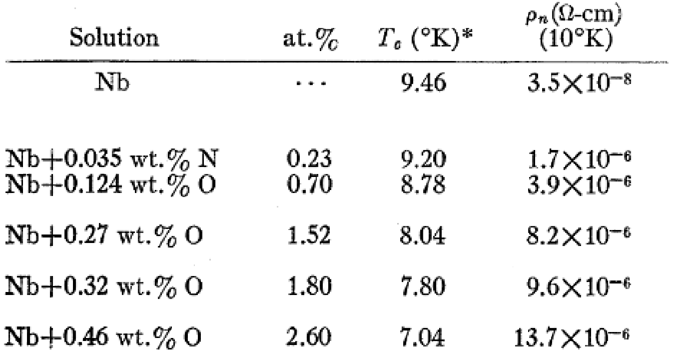
Superconducting property



Material Property

For every 1 at. % increase in oxygen concentration, the T_c decreases by ~ 0.7 K.

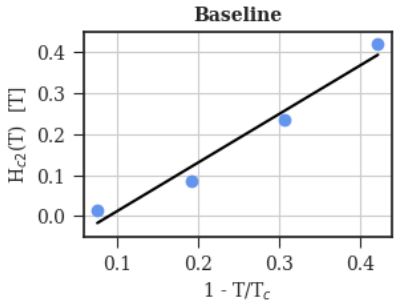
DeSorbo, W. (1963). Effect of Dissolved Gases on Some Superconducting Properties of Niobium. *Physical Review*, *132*(1), 107–121.

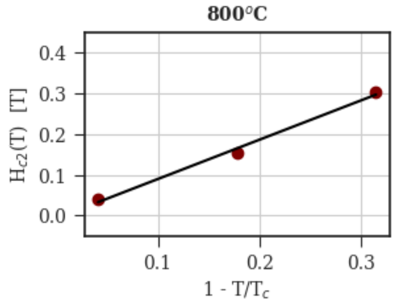


Solution	at.%	T_c (°K)*	ρ_n(Ω-cm) (10°K)
Nb	· · ·	9.46	3.5×10^{-8}
Nb+0.035 wt.% N	0.23	9.20	1.7×10^{-6}
Nb+0.124 wt.% O	0.70	8.78	3.9×10^{-6}
Nb+0.27 wt.% O	1.52	8.04	8.2×10^{-6}
Nb+0.32 wt.% O	1.80	7.80	9.6×10^{-6}
Nb+0.46 wt.% O	2.60	7.04	13.7×10^{-6}

Upper critical field

Temperature-dependent **upper critical field $H_{c2}(T)$** is extracted from electrical resistivity measurements at varying magnetic fields.

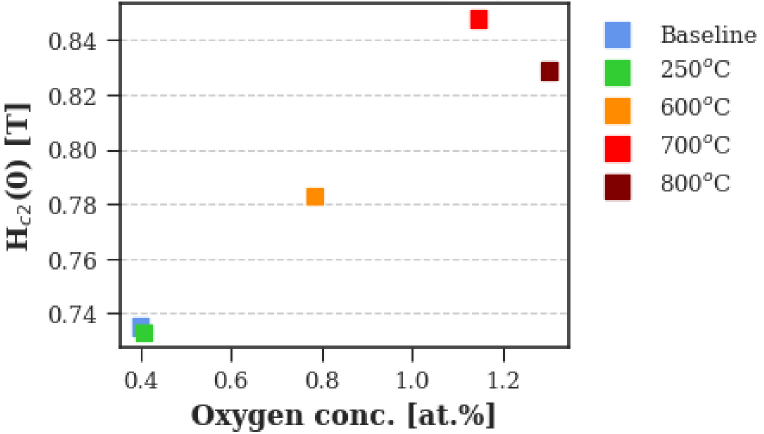




Ginzburg-Landau equation:

$$H_{C2}(T) = \boxed{H_{C2}(0)}\left[\frac{1-\left(T/T_c\right)^2}{1+\left(T/T_c\right)^2}\right]$$

Upper critical field at 0K



$H_{c2}(T) \propto \left(1-\frac{T}{T_c}\right)$, near T_c

Coherence length

Annealing

↑ Interstitial impurities

Leads to an

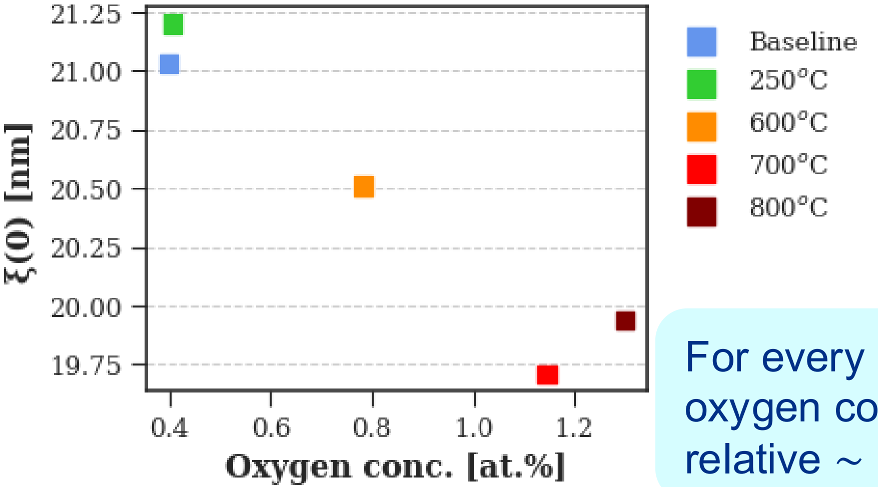
↑ $H_{c2}(0)$

Which implies that

↓ Mean free path

Ginzburg-Landau coherence length $\xi_{GL}(0)$

$$H_{c2}(0) = \frac{\Phi_o}{2\pi\xi_{GL}^2(0)} \longrightarrow \xi_{GL}(0) = \sqrt{\frac{\Phi_0}{2\pi \, . \, H_{c2}(0)}}$$



For every 1 at. % increase in oxygen concentration, a relative ~ 5% in the $\xi_{GL}(0)$

Summary

Annealing Ta thin Films for resonators/qubits

Benefits

- ☐ Dissolves oxide
- ☐ Ta_2O_5 , TaO oxide
  and
  no new suboxide

Concerns

- ☐ Suppresses T_c
- ☐ Film quality degrades
- ☐ $H_{C2}(0)$ increases
  and
  $\xi_{GL}(0)$ dereases

Next Steps

Correlate these studies to superconducting resonators and qubits.

THANK YOU

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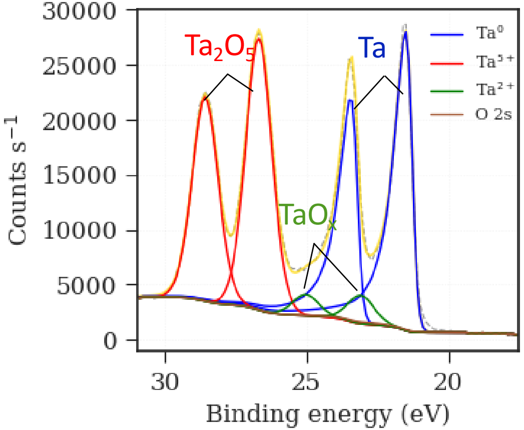
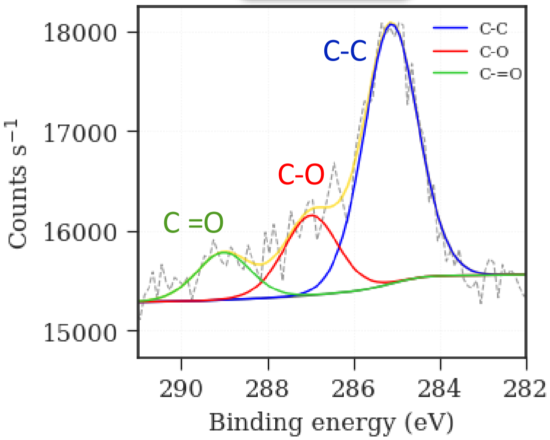
Tantalum Carbide

Ta 4f

C 1s

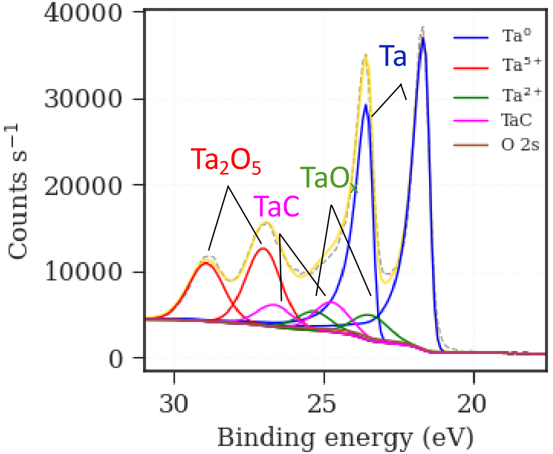
As Deposited

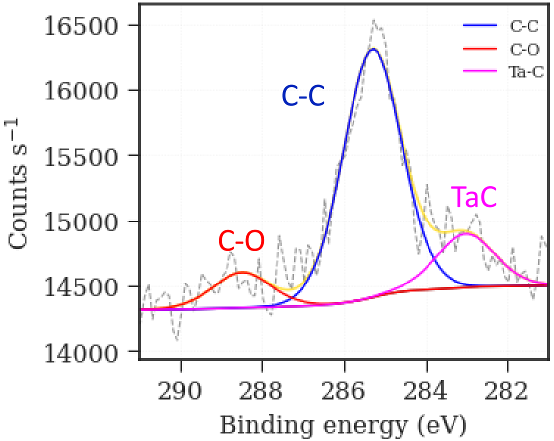




At temperatures above 450 °C, we observe the formation of TaC.

450˚C





Sample	ρ_{300K} [$\mu\Omega$.cm]	ρ_{10K} [$\mu\Omega$.cm]	RRR	Tc [K]	Hc2(0) [T]	ξ(0) [nm]
Baseline	11.78	0.062	19.16	4.33	0.75	21.03
250˚C	13.66	0.073	18.68	4.3	0.73	21.20
450˚C	12.53	0.102	10.42	4.27	0.70	21.70
600˚C	14.26	0.290	4.91	4.03	0.78	20.51
700˚C	18.73	0.603	3.11	3.72	0.85	19.71
800˚C	22.60	0.818	2.76	3.65	0.83	19.94

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