Thermal Laser Epitaxy – A path to better materials for quantum computers?

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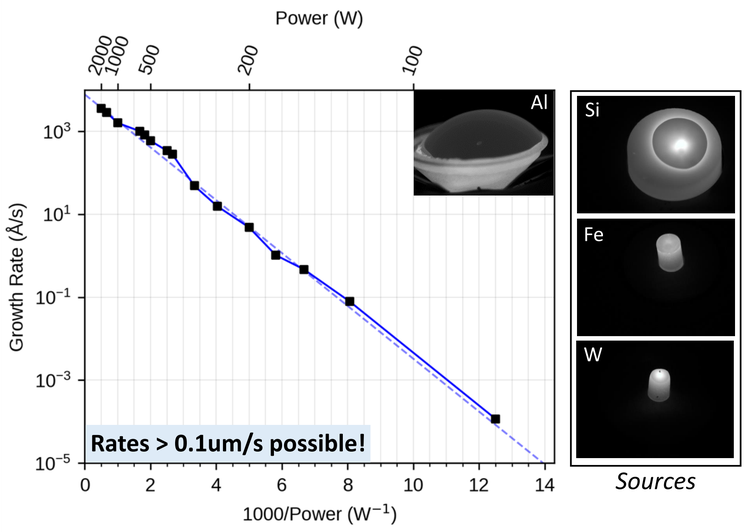
PGI-9 website

TLE wiki page

Project: TLE4HSQ

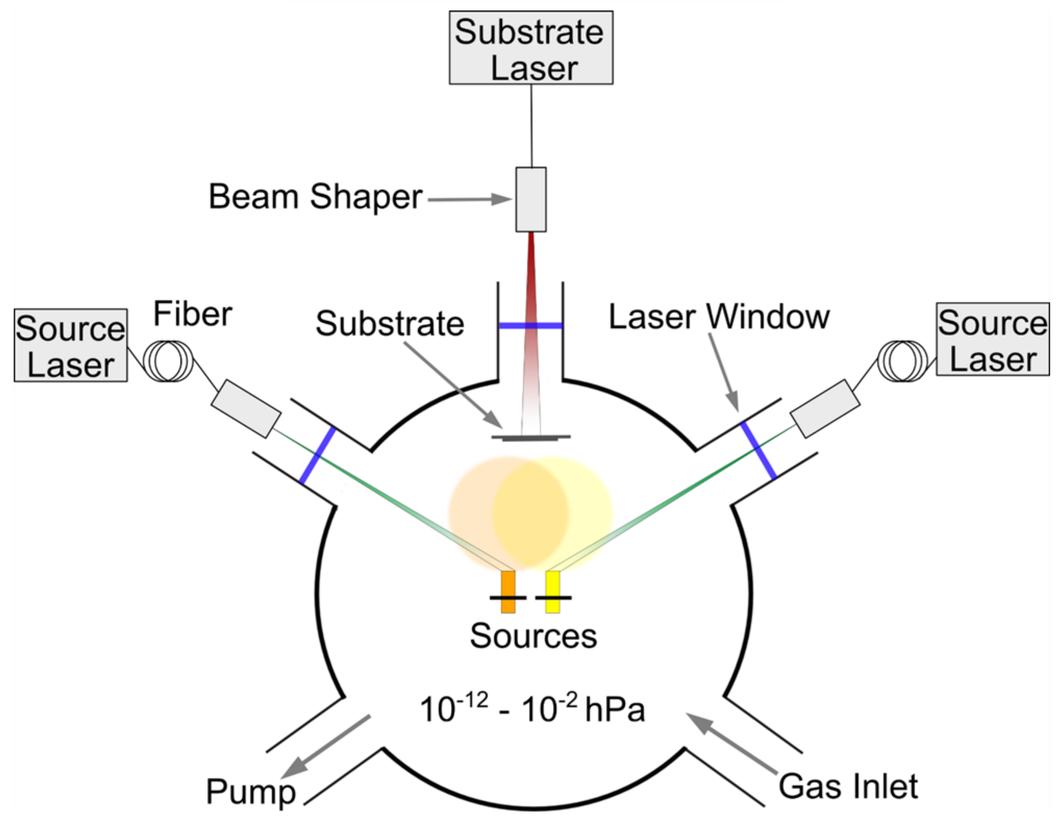
Working Principle of TLE [1]

- Focused CW laser on free-standing elemental sources.
- Co-evaporation allows for compound growth.
- Lack of external crucibles
- Short working distances
- Higher background pressures than typical deposition techniques.

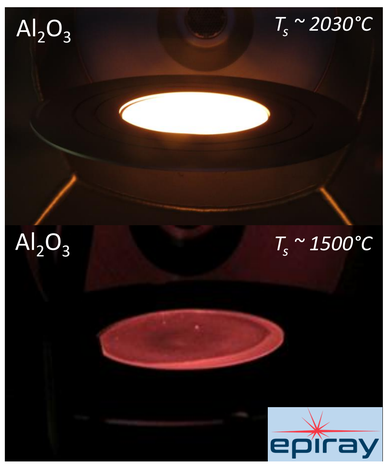


Al growth rate as function of laser power (λ = 1030nm)

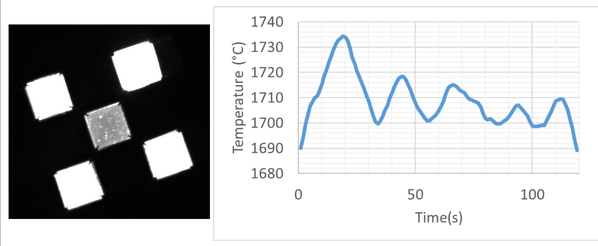
Cross-section of TLE chamber [2]



Substrate laser system



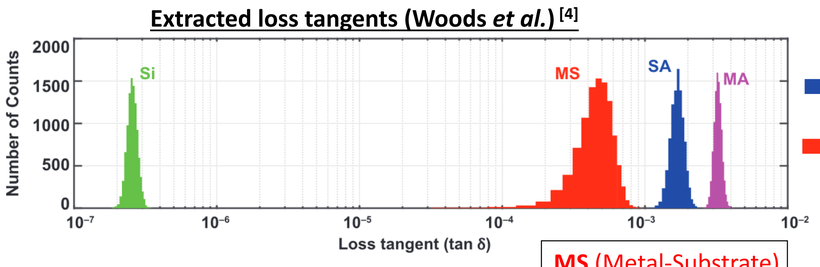
Al_2O_3 substrate during melting and upon cooling



10x10mm Al_2O_3 substrates annealing at T_s ~ 1700°C

What could TLE improve?

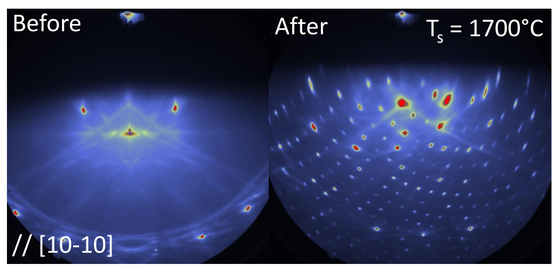
Extracted loss tangents (Woods *et al.*) [4]



MS and **SA** addressed by TLE
MA improvement by fabrication

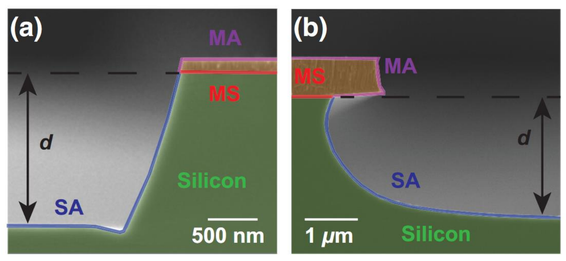
MS (Metal-Substrate)
SA (Substrate-Air)
MA (Metal-Air)

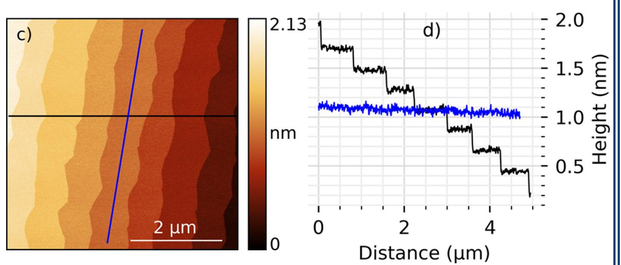
RHEED of TLE-annealed sapphire



- **Highly crystalline surface** of c-plane sapphire after annealing.
- **Ideal substrate** for superconducting circuits.

Etched TiN resonators on Si [4]





Al_2O_3 substrate after annealing at T_s ~ 1400°C [3]

TLE Periodic Table [2]

73% of all solid, non-radioactive elements successfully deposited as of April 2023.

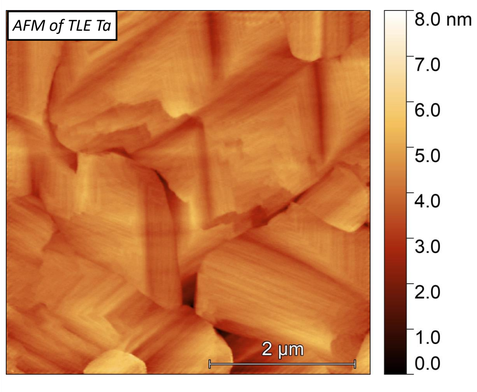
Possible

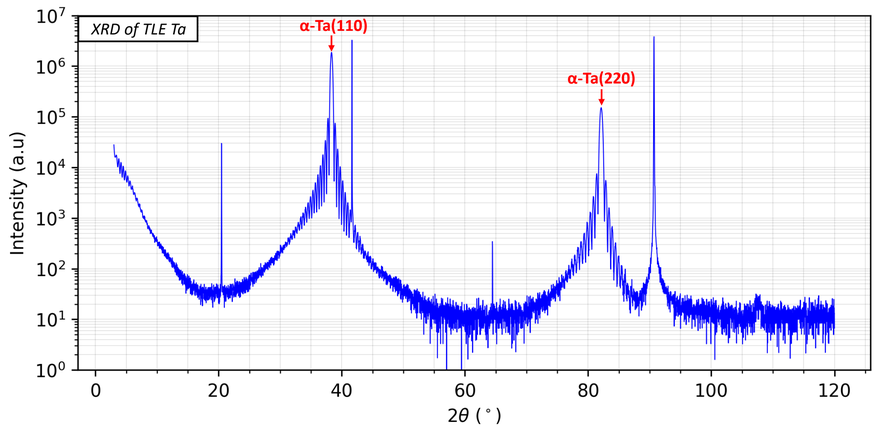
Of current interest for qubits

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	**	Rf	Ha	Sg	Ns	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

*	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
**	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

A Pathway towards Superconducting devices from TLE:

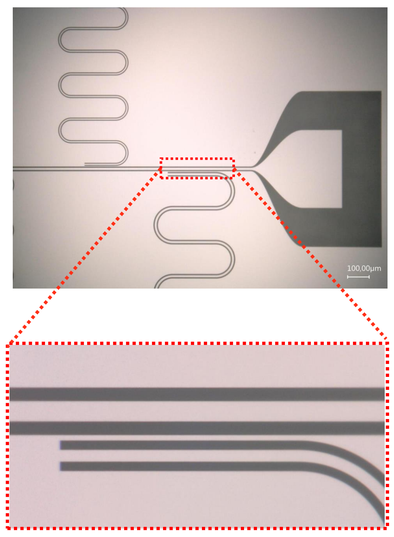




- Initially, we wish to use TLE to fabricate high quality α-Ta films to construct Ta-based qubits and superconducting resonators.
- Initial tests indicate annealing c-plane sapphire at 1700°C and depositing at T_s = 1150°C produces highly crystalline films of Ta.
- Superconducting resonators produced from TLE-grown Ta films display a quality factor Q_i close to the stare of the art. Further refinement will likely increase Q_i further.

α-Ta has a higher T_c (4.4K) than β-Ta (0.6-0.9K).
Beneficial for Qubits

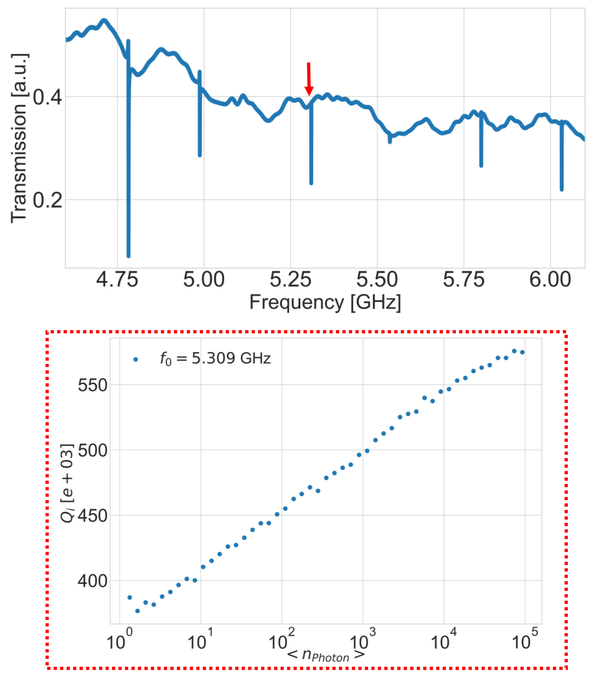
Etched Ta superconducting resonator



Dry etching of Ta via SF_6.

Q_i state-of-the-art: 2×10^6 ($< n_{photon} > \sim 1$) [5]
TLE Ta Q_i: 3.5×10^5

Preliminary results of Ta resonator grown by TLE.



Summary

- Thermal Laser Epitaxy (TLE) presents many advantages for superconducting devices, including extremely high substrate temperatures and applicability to all non-radioactive solid elements.
- High temperature thermal annealing of sapphire substrates will potentially reduce sources of loss and improve coherence times.
- TLE-grown Ta superconducting resonators produce quality factors close to the state of the art without further refinement.

What is next?

- Continue to refine growth via changes in substrate cut, deposition temperature and speed of deposition to remove grain boundaries and improve quality factor of resonators.
- Construction of Ta-based qubits after refinement of growth and fabrication
- Expand growth to other superconducting materials like metal nitrides.

Acknowledgments

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References:

[1] W. Braun & J. Mannhart, *AIP Advances* **9**, 085310 (2019)
[2] T. J Smart *et al.* , *Journal of Laser Applications* **33** (2021)
[3] W. Braun *et al.* ,*APL Materials,* **8**, 071112 (2020)
[4] W. Woods *et al.* , *Physical Review Applied* **12**, 014012 (2019)
[5] A. Megrant *et al.* , *Appl. Phys. Lett.* **100**, 113510 (2012)