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Taking the heat off tantalum

Tae Gyu Ahn & Alp Sipahigil

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Krypton-assisted growth of low-loss α -phase tantalum on silicon stays within back-end-of-line semiconductor thermal budgets while delivering state-of-the-art qubit coherence.

Superconducting quantum processors are made using the fabrication techniques of the semiconductor industry. However, the materials advances that helped carry qubit lifetimes from nanoseconds to milliseconds over the past quarter-century¹ have leaned on laboratory recipes that strain the thermal budgets of production lines. State-of-the-art qubits use thin films of α -phase tantalum on high-purity substrates². Tantalum withstands the acid treatments used to clean the rest of the device and regrows only a thin, self-terminating, low-loss surface oxide³. But growing the α -phase directly on silicon has demanded a 450–650 °C process with a narrow window. Industrial lines cap metal-on-wafer

processing near 400 °C – the back-end-of-line (BEOL) limit that guards against metal–semiconductor interdiffusion. A route to device-grade α -tantalum within industrial thermal budgets has been missing.

Now, writing in *Nature Materials*, Maciej Olszewski, Simon Reinhardt, Valla Fatemi and colleagues⁴ report that replacing the argon in a sputtering chamber with krypton lowers the temperature at which α -tantalum forms on silicon from 350 °C or more down to 200 °C, opening a process window that is 200 °C wide beneath the BEOL ceiling. The films support microwave resonators and qubits whose coherence matches the best tantalum devices reported so far.

The α -phase of tantalum is the only stable phase of the bulk material, but kinetics controls what actually grows in thin-film form. Atoms landing on a cold substrate freeze before finding the correct lattice and condense into the metastable β -phase, which superconducts only below roughly 0.5 K, an order of magnitude short of the α -phase. Substrate heating supplies the missing mobility, but it also invites tantalum and silicon to interdiffuse – the same degradation the BEOL processes avoid. Energy transfer between colliding atoms peaks when

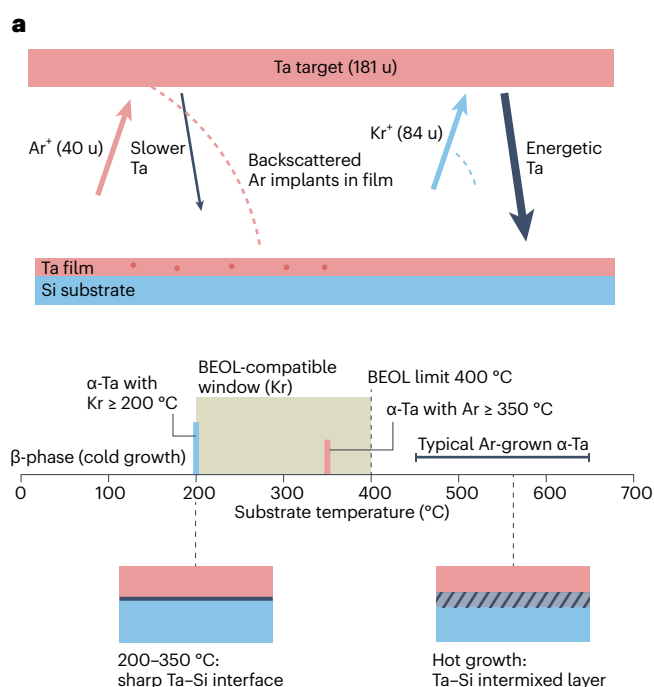
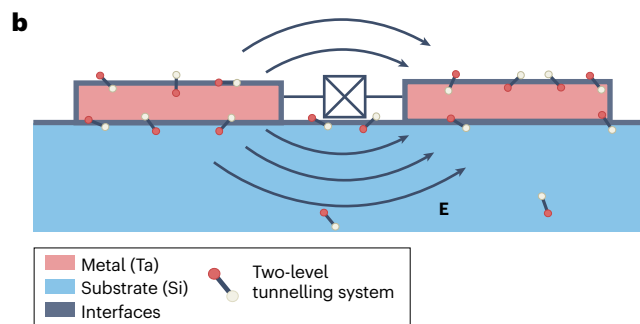


Fig. 1 | Krypton sputtering brings the low-loss α -phase of tantalum within the thermal budget of BEOL semiconductor processing. **a**, Top, in magnetron sputtering, ions of a noble process gas strike a target and eject metal atoms towards the wafer. Because collisional energy transfer peaks for matched masses, krypton (84 u) ejects tantalum atoms (181 u) with more kinetic energy than argon (40 u) does, and the arriving atoms carry the mobility needed to crystallize the α -phase at substrate temperatures as low as 200 °C – inside the approximately 400 °C BEOL window of semiconductor manufacturing. Bottom, typical argon-based growth requires temperatures above the BEOL limit. Lower growth



temperature also suppresses the amorphous Ta–Si interlayer that forms by interdiffusion. Krypton, unlike argon, leaves no detectable trace in the film. **b**, Cross-section of a transmon qubit made from tantalum-on-silicon. The electric field between the capacitor electrodes (arrows, **E**) is stored almost entirely in the substrate and the vacuum, yet dissipation is dominated by two-level tunnelling systems hosted in nanometre-thin amorphous layers (grey) at the metal–air, metal–substrate and substrate–air interfaces. Defects in the bulk substrate and near the Josephson junction (crossed square) provide additional loss channels. Figure adapted from ref. 9 under a Creative Commons license CC BY 4.0.

their masses are equal; krypton (84 u) is closer to tantalum (181 u) than argon (40 u) is, so the sputtered atoms can arrive carrying the required mobility themselves (Fig. 1a). Argon also backscatters off the heavy target with much of its energy intact and buries itself in the growing film, whereas krypton barely rebounds, leaving cleaner metal. Krypton – Greek for ‘the hidden one’, and namesake of a famous weakness – has been hiding these strengths in the sputtering literature since the 1990s⁵.

Krypton-grown films display superior transport properties compared with argon-grown films. They show a larger residual resistivity ratio, a longer mean free path approaching the clean limit of superconductivity and a longer coherence length, without any signature of krypton content in the film. Yet these bulk properties do not translate into superconducting resonator and qubit performance. Krypton- and argon-grown resonators, prepared with comparable margins above their thresholds, show similar microwave losses. The reason is that direct-current transport and microwave device performance are limited by different physics. A superconducting qubit is at heart a non-linear electrical oscillator, and its coherence is bounded by the quality factor, the number of oscillations completed before the stored energy dissipates. In a planar circuit, the electric-field energy resides almost entirely in the substrate and the vacuum, and the fields vanish inside the superconductor (Fig. 1b). The loss arises from nanometre-thin amorphous layers at the metal–air, metal–substrate and substrate–air interfaces. These layers store barely a few thousandths of the field energy, yet their two-level defects cause essentially all of the dissipation. Low-temperature deposition improves the metal–substrate interface: films deposited at 200–350 °C display an abrupt boundary with the silicon, whereas hotter growth builds a Ta–Si interdiffused layer linked to microwave loss that is not fully understood. Krypton-assisted deposition delivers these sharp interfaces across a broad range of growth temperatures.

The researchers show that krypton-grown resonators and qubits reach state-of-the-art performance. Any quality-factor measurement depends sensitively on device geometry: the narrower the gaps between electrodes, the more the electric field samples the lossy interfaces, and the team’s designs intentionally use this sensitivity. Resonators with small 3- μm gaps reach single-photon quality factors near 4 million, and transmons with a 20- μm capacitor gap reach median quality factors of 14 million, and 16.9 million for the best device. The transmons match the best reported tantalum-on-silicon qubits², whose electrodes sit 3.5 times farther apart. Reaching these values despite the higher surface participation solidly establishes a manufacturable process that achieves state-of-the-art performance.

With these results, tantalum now has two routes into industrial fabrication. An alternative to direct growth⁶ is to grow the films at room temperature on a thin niobium seed that templates the α -phase, and reaches losses comparable to high-temperature tantalum. The same approach has crossed onto 300-mm complementary metal–oxide–semiconductor (CMOS) pilot lines, where resonators with wide, field-diluting gaps reach median quality factors of 48 million (ref. 7). Olszewski, Reinhardt, Fatemi and co-workers compare the two

routes directly: niobium-seeded films show slightly higher losses than direct krypton-grown tantalum and might degrade faster as they age. A plausible culprit is niobium’s lossier, regrowing oxide, which sits exposed at the film edges⁴. Future work is needed to clarify the ageing behaviour of the two approaches. Direct krypton growth sidesteps the seed-layer ageing question, and is currently the only route that pairs an all-tantalum surface with temperatures a production line can accept.

These advances open a new frontier of questions across the stack, from resonators to qubits and processors. The efficient momentum transfer by krypton, although physically sensible, rests on correlations, and could be tested by a systematic neon-to-xenon series study. With base-layer losses for resonators this low, the Josephson junction and its low-loss integration become the next frontier. First, a passivation strategy against losses and ageing at the metal–air and substrate–air interfaces is still lacking. The acid cleans that rejuvenate resonators would destroy a qubit’s aluminium junctions. Second, unlike large-area resonators, whose loss averages over many weakly coupled defects, the nanoscale junction couples strongly to individual two-level defects that cannot be captured by a simple loss tangent model. Mapping them will require translating these material advances into frequency-tunable qubits, and delivering quantitative statistics on the defects behind coherent errors in processors. Finally, this demonstration concerns a single film on bare silicon. The multilayer wiring envisioned for error-correcting codes with long-range connectivity⁸ will multiply both the interfaces to protect and the thermal budgets to respect, and low-temperature growth routes such as this one will be part of the answer.

The ingredients of a foundry-ready tantalum qubit are assembling – and one of them turns out to be as simple as changing the gas in a sputtering chamber.

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References

- de Leon, N. P. et al. *Science* **372**, eabb2823 (2021).
- Bland, M. P. et al. *Nature* **647**, 343–348 (2025).
- Crowley, K. D. et al. *Phys. Rev. X* **13**, 041005 (2023).
- Olszewski, M. W. et al. *Nat. Mater.* <https://doi.org/10.1038/s41563-026-02718-z> (2026).
- Petrov, I., Ivanov, I., Orlinov, V. & Sundgren, J.-E. *J. Vac. Sci. Technol. A* **11**, 2733–2741 (1993).
- Marcaud, G. et al. *Commun. Mater.* **6**, 182 (2025).
- Acharya, R. et al. Preprint at <https://doi.org/10.48550/arXiv.2606.10719> (2026).
- Bravyi, S. et al. *Nature* **627**, 778–782 (2024).
- Zhang, Z.-H. et al. *Phys. Rev. X* **14**, 041022 (2024).

Competing interests

The authors declare no competing interests.