CryoMBE

Unlocking new material phases at ultra-low growth temperatures

Cryogenic MBE (CryoMBE) at substrate temperatures < 15 K offers an off-the-shelf solution to synthesize a new class of alloys to push the frontiers of material science.
With state-of-the-art thermal heat management and flexible sample-source geometries the CryoMBE system stands apart in a new class of surface science synthesis tools: A new route to advanced superconductor/ semiconductor device synthesis.

Superconductor-semiconductor nanowires enable the route to quantum information devices, like topological qubits [1]. Such hybrid nanowires can be grown in a bottom-up approach by Molecular Beam Epitaxy (MBE). Low-temperature evaporation of the superconductor was d emonstrated to promote a continuous and flat film morphology growth and thereby assist the fabrication of disorder-free hard gaps superconductor/semiconductor epitaxial hybrids [2]. As pristine surfaces and interfaces are key, eliminating post-growth etch processes by the employment of "shadow epitaxy" is seen as a promising approach [3].

Cryogenic temperature deposition

The heart of the new MBE system is an ultra-low temperature manipulator with exceptional thermal management properties to maintain sample temperatures of ~15 K during deposition from both e-beam and standard effusion sources. The e-beam source is located in a separate sub-chamber with gate valve isolation for ease of service.

Sample-source geometries

The cryogenic manipulator is combined with optimized chamber geometry for shallow angle epitaxy which enables exploration of so far uncharted growth parameters. The closed-cycle liquid-He manipulator with a base temperature of < 15 K can be precisely positioned in the azimuthal and polar rotation axis allowing defined growth of half-shell or full-shell structure. At normal incidence line of sight access is available for in situ characterization with standard epitaxy tools, for example RHEED.

[1] M. Kjaergaard, F. Nichele, H. J. Suominen, M.P. Nowak, M. Wimmer, A.R. Akhmerov, J.A. Folk, K. Flensberg, J. Shabani, C.J. Palmstrom, C.M. Marcus, Nature Communications 2016, 7, 12841.

[2] P. Krogstrup, N. L. B. Ziino, W. Chang, S. M. Albrecht, M. H. Madsen, E. Johnson, J. Nygard, C. M. Marcus, T. S. Jespersen, Nature Materials 2015, 14, 400.

[3] D. J. Carrad, M. Bjergfelt, T. Kanne, M. Aagesen, F. Krizek, E. M. Fioraliso, E. Johnson, J. Nygard, T. S. Jespersen, Adv. Mater. 2020, 32, 1908411

[4] T. A. J. van Schijndel, A. P. McFadden A N. Engel, J. T. Dong, W. J. Yánez-Parreño, M. Parthasarathy, R. W. Simmonds, C. J. Palmstrøm, arXiv:2405.12417 [cond-mat.supr-con

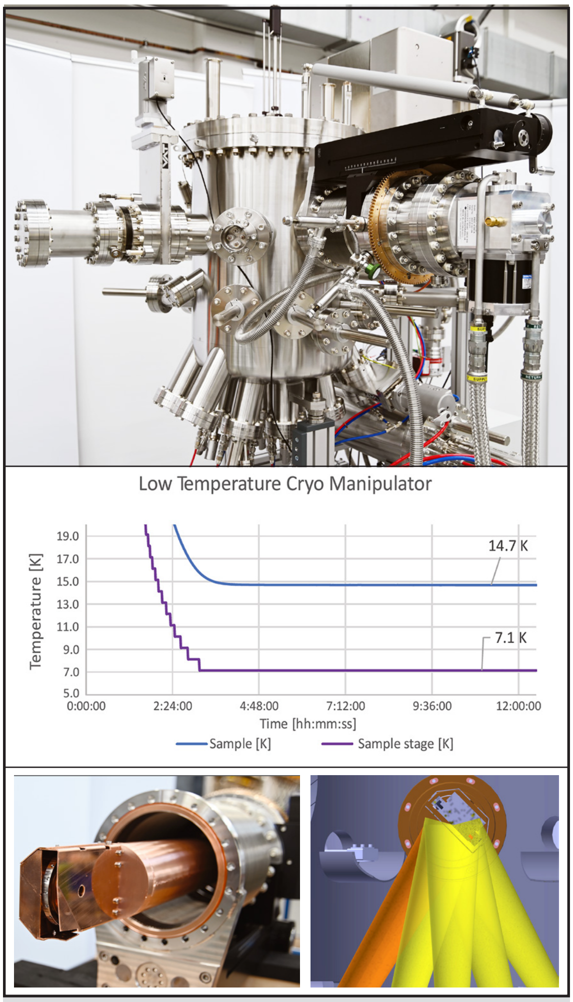

Figure 1, top image: CryoMBE system with ten source ports and horizontal closed-cycle LHe manipulator pumped by an IGP and a cryogenic pump.
Middle image: Stage and sample temperatures of ~7 K and ~14 K respectively.
Bottom-left: Cryogenic manipulator with adaptable "shadow-mask" shield.
Bottom-right: Beam flux and sample geometries.

Key Features

- Cryogenic temperature deposition
- Excellent cooling performance (< 10 K)
- Up to 2" samples
- 2.5-axis manipulation for Precision growth control
- Normal and grazing incidence deposition
- Advanced source design to minimise heat load
- In-situ characterisation

Unlocking new crystal phases

Every material has an optimum growth window. In surface science we are often presented with the challenges of pushing the boundaries of what is possible in terms of miscibility, stability and possibility.

Figure 2a shows how low temperature deposition can unlock access to new and highly desirable crystalline phases like α-Ta on Al_2O_3. New phases with the exceptional surface morphologies shown in Figure 3b readily offer high quality, low defect device ready material.

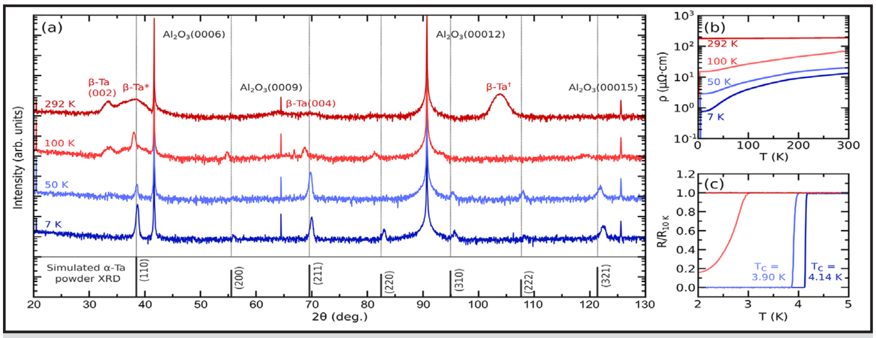

Figure 2: Structural and electrical characterization of tantalum as a function of growth temperature. (a) X-ray diffraction pattern for Ta films grown at different temperatures and compared to simulated α-Ta powder diffraction. (b) Resistivity as a function of temperature for different growth temperatures. (c) Normalized resistance near the superconducting transition temperature of tantalum [from reference 4].

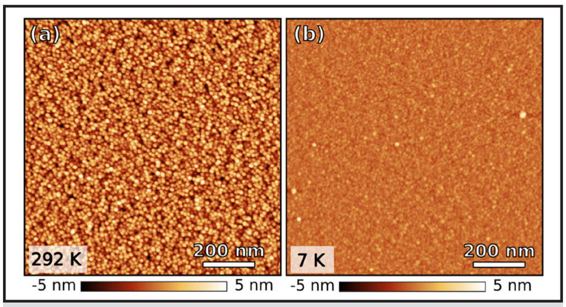

Figure 3: Surface morphology of Ta on Al2O3 at (a) 292 K and (b) 7 K by AFM [ref 4].

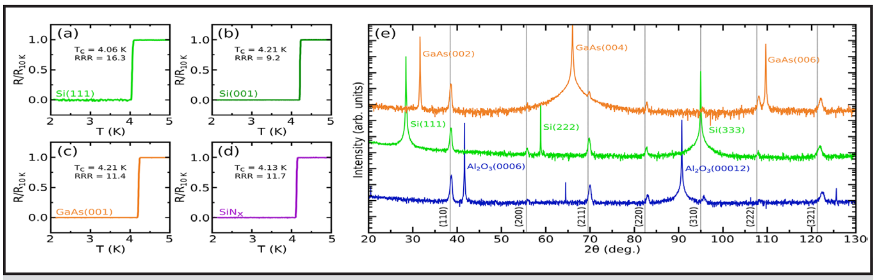

Figure 4: Electrical and structural characterization of Tantalum grown at different substrates. (a) Normalized resistance of Ta grown on Si(111), (b) Si(001), (c) GaAs(001), (d) and SiNx. (e) XRD patterns of Ta on Al2O3(0001), Si(111), and GaAs(001) [ref 4]

Ground-breaking material properties

It is no surprise that superior films exhibit superior electrical properties. With room temperature resistivities of 13.4 μΩ.cm and superconducting transition temperatures of 4.14 K, as shown in Figure 4, thin film layers with comparable bulk values are paving the way for superconducting qubit applications.

Patterning CPW resonators offer a direct means to study and compare losses in these innovative material systems. Figure 5 shows how the standard figure of merit, $Qi_{,LP}$, for ultra-low power excitation reveal an average loss of $\delta_{LP} = 5 \times 10^{-7}$ and how these materials truly define the state-of-the-art in the exciting realm of superconducting devices.

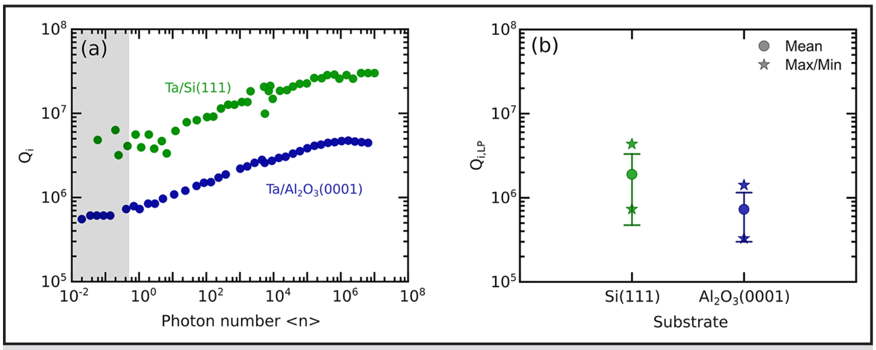

Figure 5: Microwave characterization of Ta on $Al_2O_3(0001)$ and Si(111). (a) Qi as a function of the applied microwave power (b) The average, maximum, and minimum values for the $Qi_{,LP}$ plotted for the different substrates [from reference 4].

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