Cryogenically grown α-Ta on InAs for 2DEG-based Josephson Junctions

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Josephson Junctions (JJs) are critical components in superconducting quantum circuits, including qubits, because of their nonlinear inductance [1]. Most commonly, JJ's in qubits consist of two aluminum superconductors separated by a thin aluminum oxide barrier. However, external control over the critical current and thus frequency of the qubit can only be achieved by applying magnetic flux through a superconducting quantum interference device. An alternative approach uses a semiconductor-superconductor heterostructure, allowing electric gate control of the JJ's critical current. In these systems, disorder, often introduced by superconductor/semiconductor interfacial reactions and during nanofabrication processes such as etching, can lead to heightened surface scattering [2], potentially leading to loss or decoherence.

Here, we are exploring the growth of Ta on InAs 2DEGs using a shadow mask technique in a low-temperature molecular beam epitaxy (MBE) system. This approach aims to eliminate nanofabrication-induced disorder near the junction. The 2DEGs are grown in an III-V MBE system, achieving mobilities exceeding 10^4 cm²/V·s. After growth, the InAs samples were capped with As. Before shadow mask deposition, the As cap was removed *in situ* by atomic hydrogen anneal. Reflective high energy electron diffraction (RHEED), scanning tunneling microscopy (STM), and X-ray photo spectroscopy (XPS) are used to investigate the semiconductor starting surface, the superconductor growth mode and the extent of interfacial reactions. The Ta is grown at cryogenic temperatures (~7 K) to minimize interfacial reactions and to ensure the formation of the superconducting α-phase [3], allowing for the formation of highly transparent superconducting contacts. After optimization of the growth and resulting interface, JJ devices are fabricated using a shadow mask (Fig. 1(a)). Low-temperature electrical measurements (around 60 mK) are performed to determine the junction properties, including the critical current (Ic), the I_cR_n product, and the $I_{ex}R_n$ product (Fig. 1(b)). These values will allow us to evaluate the transparency of the superconducting contacts and determine if the junctions exhibit ballistic transport behavior. Comparisons will be made for Ta films grown at different substrate temperatures and we will report on correlations between interfacial reactions and Ta crystal structure with junction properties.

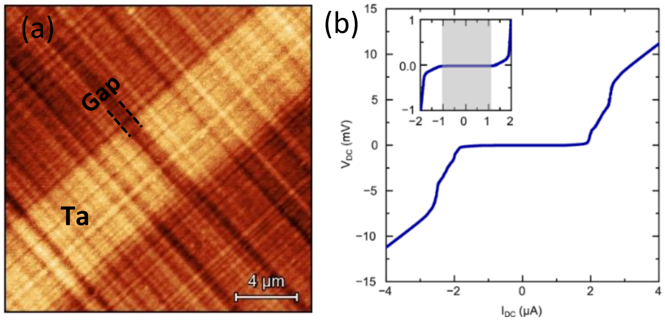

Figure 1: (a) Atomic Force Microscopy image of Ta deposited on InAs 2DEG using a shadow mask. (b) Current-voltage measured over the gap between two Ta leads showing superconductivity through the junction.

[1] P. Krantz, et al., Appl. Phys. Rev. 6, 021318 (2019)
[2] S. J. Pauka, et al., J. Appl. Phys. 128, 114301 (2020)
[3] T.A.J. van Schijndel, et al., arXiv preprint arXiv:2405.12417 (2024)

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Supplementary information:

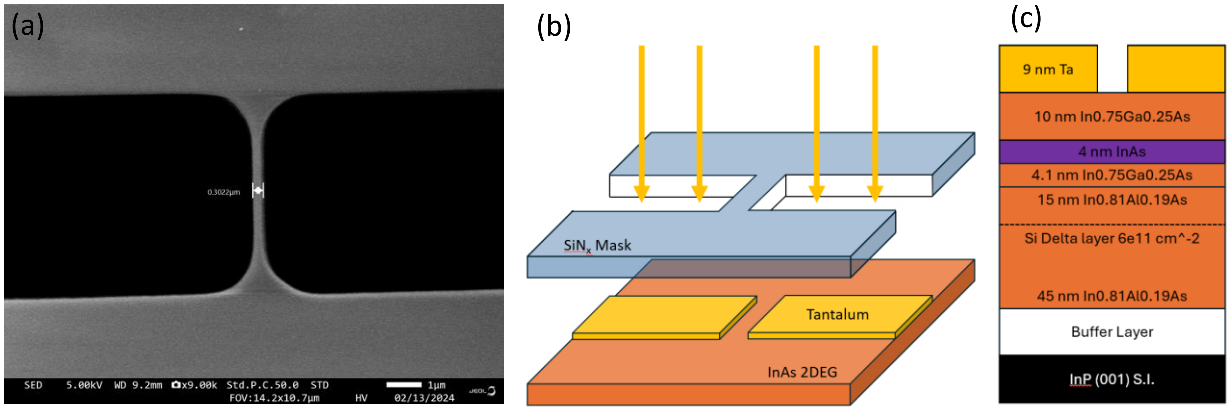

Figure 2: (a) Scanning Electron Microscope image of a patterned shadow mask with 300 nm wide break. (b) Schematic of the shadow mask deposition, to form two superconducting tantalum leads with a small break. (c) Vertical layer stack of the InAs 2DEG grown on InP(001).