Low-temperature transport in ultra-thin tungsten films grown by focused-ion-beam deposition

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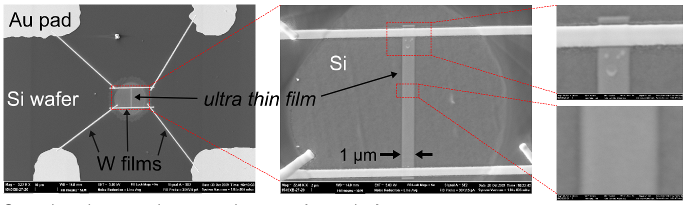
Motivation

- Amorphous tungsten alloys have higher superconducting critical temperatures than crystalline tungsten. [1]
- Tungsten composites deposited by focused-ion-beam (FIB) induced chemical vapour deposition (CVD) are amorphous and superconducting at low temperatures ($T_c \approx 5$ K). [2]
- FIB-CVD tungsten (FIB-W) thin films have been found to be superconducting for thickness down to 25 nm. [3-4]
- Ultra-thin superconducting films undergo a superconductor-insulator transition depending on thickness. [5]
- FIB-W can be used to fabricate superconducting three-dimensional structures by direct-writing. [6]
- Potential applications of ultra-thin FIB-W films include single-photon detectors and qubits based on quantum-phase-slip centres.

Samples

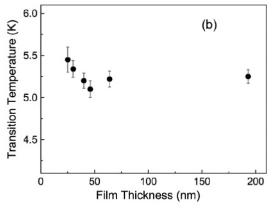


Scanning electron microscope images of sample A.

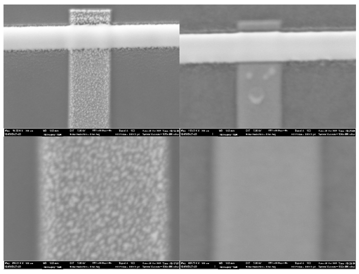
- Take a silicon wafer with a layer of silicon oxide and gold pads deposited by optical lithography and physical vapour deposition.
- Mill with the FIB through the oxide layer to a depth of about 300 nm, just below the Si/SiO_2 interface, leaving a substrate of amorphous Si.
- Use FIB-CVD with tungsten hexacarbonyl ($W(CO)_6$) as a precursor gas to deposit the FIB-W ultra-thin film and electrical connections to the gold pads.

Previous work

- Superconductivity has been found in FIB-W films down to 25 nm thickness (from [4]):



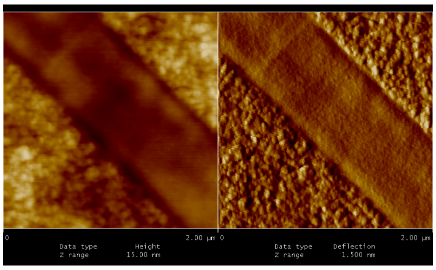
- **Problem:** films below 25 nm are not continuous. [4]
- **Solution**: deposit on amorphous silicon, instead of silicon oxide:



SEM micrographs of two ultra-thin films deposited with the same conditions, but on slightly different substrates.

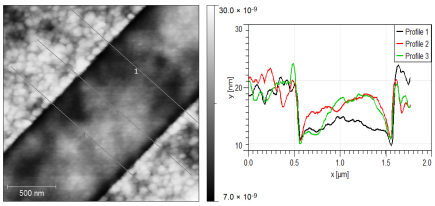
Sample	A	B
Dose (pC/µm²)	30	20
Length (µm)	8.4	8.9
Width (µm)	0.8	1.0
Thickness (nm)	9	6
Cross-sectional area (µm²)	0.007	0.006

Geometry and topography



AFM images of sample A: height (left) and deflection (right).

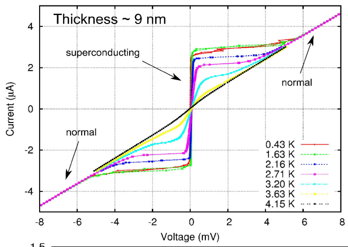
- Scanning electron microscope (SEM) to determine the planar geometry and the quality of the film.
- Atomic force microscope (AFM) in contact mode to determine the thickness and the topography of the film.

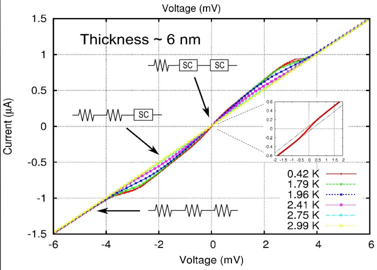


AFM topography image (left) and extracted height profiles (right) for sample A.

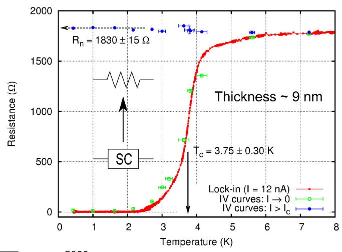
Low-temperature transport measurements

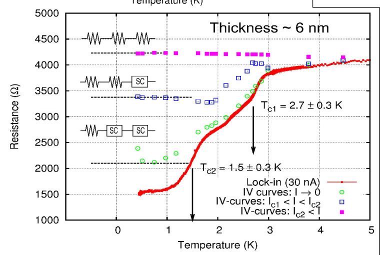
Current-voltage characteristics





Resistance vs. Temperature





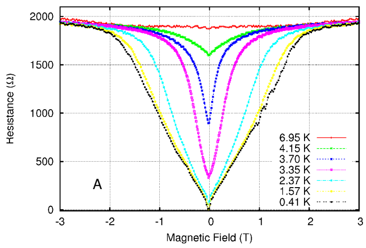
Sample A (9 nm)

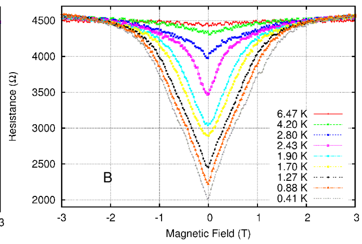
- Single type II superconductor
- $T_c(H = 0) = 3.75$ K
- $j_c(T = 0, H = 0) = 3 \times 10^4$ A/cm²
- $H_{c2}(T = 0) = 1.0$ T $\rightarrow \xi_0 = 18$ nm
- Coherence length > thickness

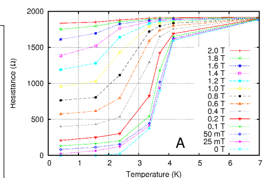
Sample B (6 nm)

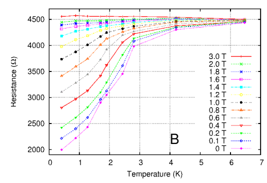
- Two type II superconducting regions in series with a normal-resistive region
- $T_c(H = 0) = 1.5$ K and 2.7 K
- $j_c(T = 0, H = 0) = 1.3 \times 10^3$ and 1×10^4 A/cm²
- $H_{c2}(T = 0) = 1.25$ T $\rightarrow \xi_0 = 16$ nm

Magnetoresistance in perpendicular field

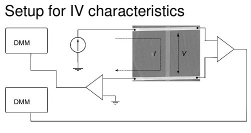




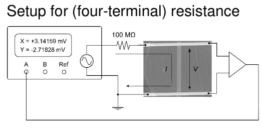




Setup for IV characteristics



Setup for (four-terminal) resistance



Fabrication details

- System: Carl Zeiss Crossbeam XB1540

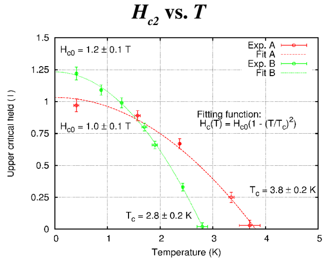
Milling through silicon oxide:

- $I(Ga^+) =$ 1 nA at 30 kV
- *time* = 100 sec
- *Number of layers* = 10

Deposition of ultra-thin film:

- $I(Ga^+) =$ 5 pA at 30 kV
- *area* = 1 µm x 10 µm
- *scan frequencies* = 200 Hz x 20 kHz
- *time* = 40 – 100 sec
- *precursor pressure* = 2 – 3 x 10^{-5} mbar

H_{c2} vs. T



Upper critical field H_{c2} as a function of temperature for sample A (red) and B (green).

References

[1] Collver and Hammond, *Phys. Rev. Lett.* 30, 92 (1973)
[2] Sadki *et al.*, *Appl. Phys. Lett.* 85, 6206 (2004)
[3] Li *et al.*, *J. Appl. Phys.* 104, 093913 (2008)
[4] Li *et al.*, *IEEE Trans. on Appl. Superc.* 19, 2819 (2009)
[5] Jaeger *et al.*, *Phys. Rev. B* 40, 182 (1989)
[6] Li and Warburton, *Nanotechnology* 18, 485305 (2007)

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Transport measurements setup details

- Current source (dc): *Keithley* 2400 Source-Meter.
- Current source (ac): *Wavetek* function generator and 100 MΩ resistor.
- Voltage preampl.: *Stanford Research Systems* SR560.
- Current preampl.: *Stanford Research Systems* SR570.
- Digital Multi-Meter: *Keithley* 2000 DMM and 2182 Nano-Voltmeter.
- Lock-in amplifier: *Princeton Applied Research* 5207.
- Cryostat: *Oxford Instruments* ³He with 9 T magnet.

Outlook

- Fabrication of ultra-thin films of varying thickness and width.
- Investigation of superconductor-insulator transition.