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 $T_c \approx 5$ K. [2]

FIB-CVD tungsten-composite (*FIB-W*) films have been found to be superconducting down to 25 nm. [3-4]

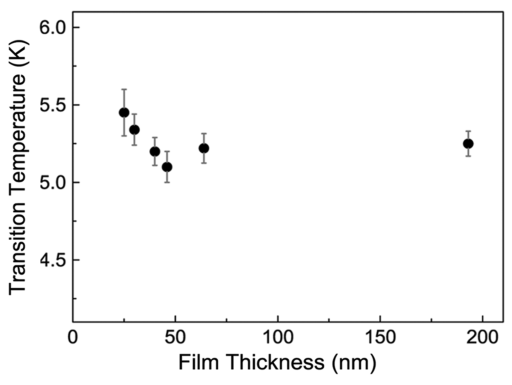
Ultra-thin superconducting films undergo a superconductor-insulator transition depending on thickness. [5]

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.

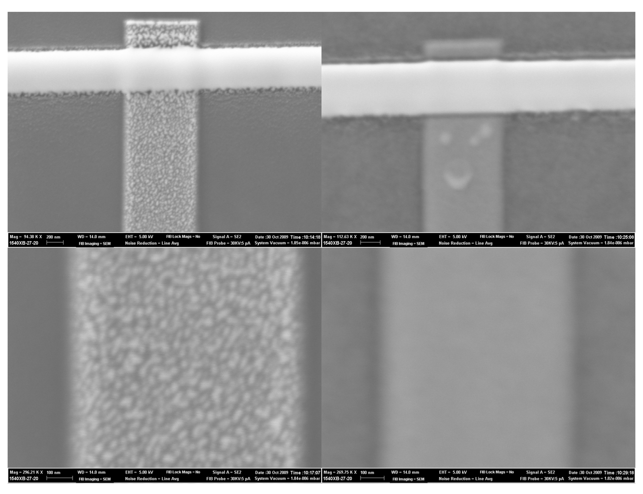
IMPROVING ON PREVIOUS WORK

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



Problem: films below 25 nm are not continuous. [4]

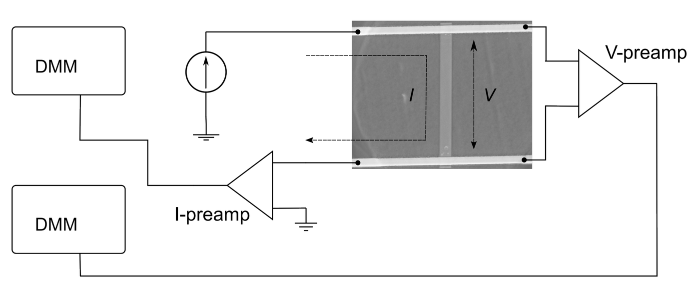
Solution: deposit on amorphous silicon, instead of silicon oxide:



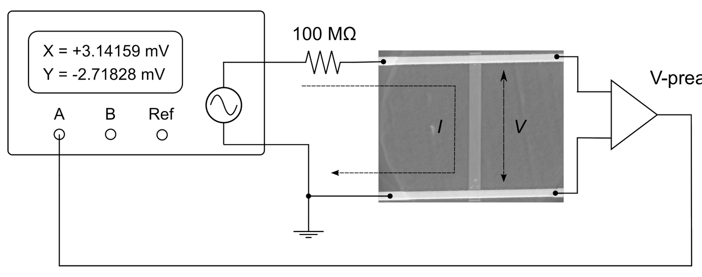
SEM micrographs of two ultra-thin films deposited with the same conditions, but on different substrates.

Measurement setups

System: *Oxford Instruments* ^{3}He with 9 T magnet



Setup for DC measurements. Current source: *Keithley 2400 Source-Meter*; preamplifiers: *Stanford Research Systems SR560* and *SR570*; digital multimeters: *Keithley 2000 DMM* and *4182 Nano-Voltmeter.*



Setup for AC measurements. Current source: *Wavetek* function generator and 100 MΩ resistor; preamplifiers: *SR560* and *SR570*; lock-in amplifier: *Princeton Applied Research 5207*.

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. 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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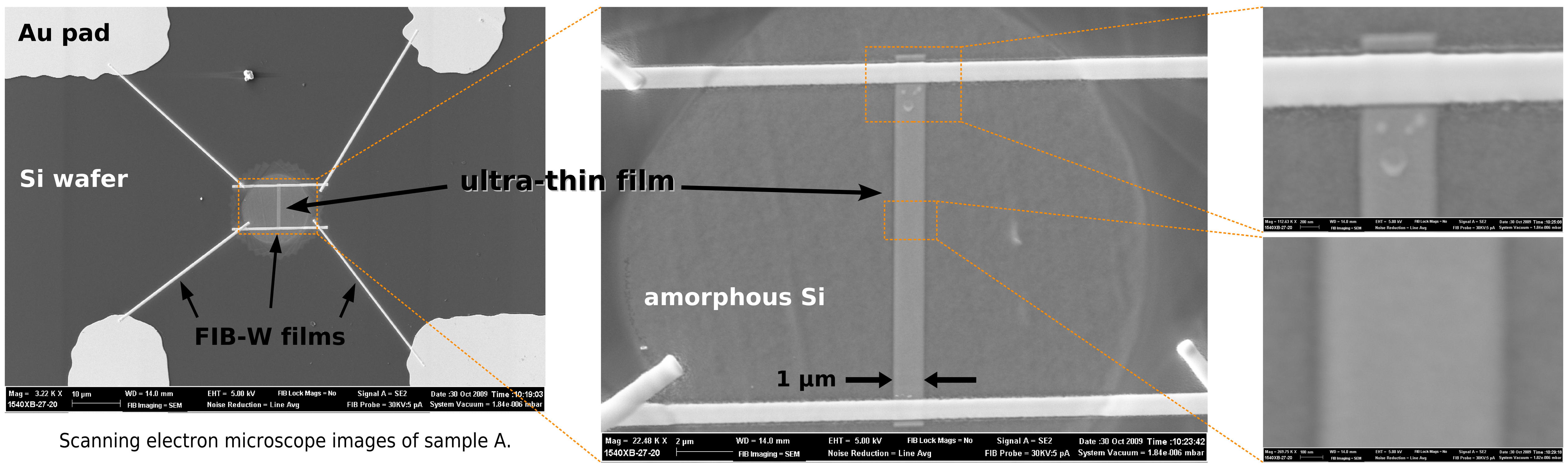
SAMPLE FABRICATION



Scanning electron microscope images of sample A.

Recipe

1. Take a silicon wafer with a layer of silicon oxide and gold pads deposited by optical lithography and physical vapour deposition.
2. 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.
3. 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.

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

Fabrication details

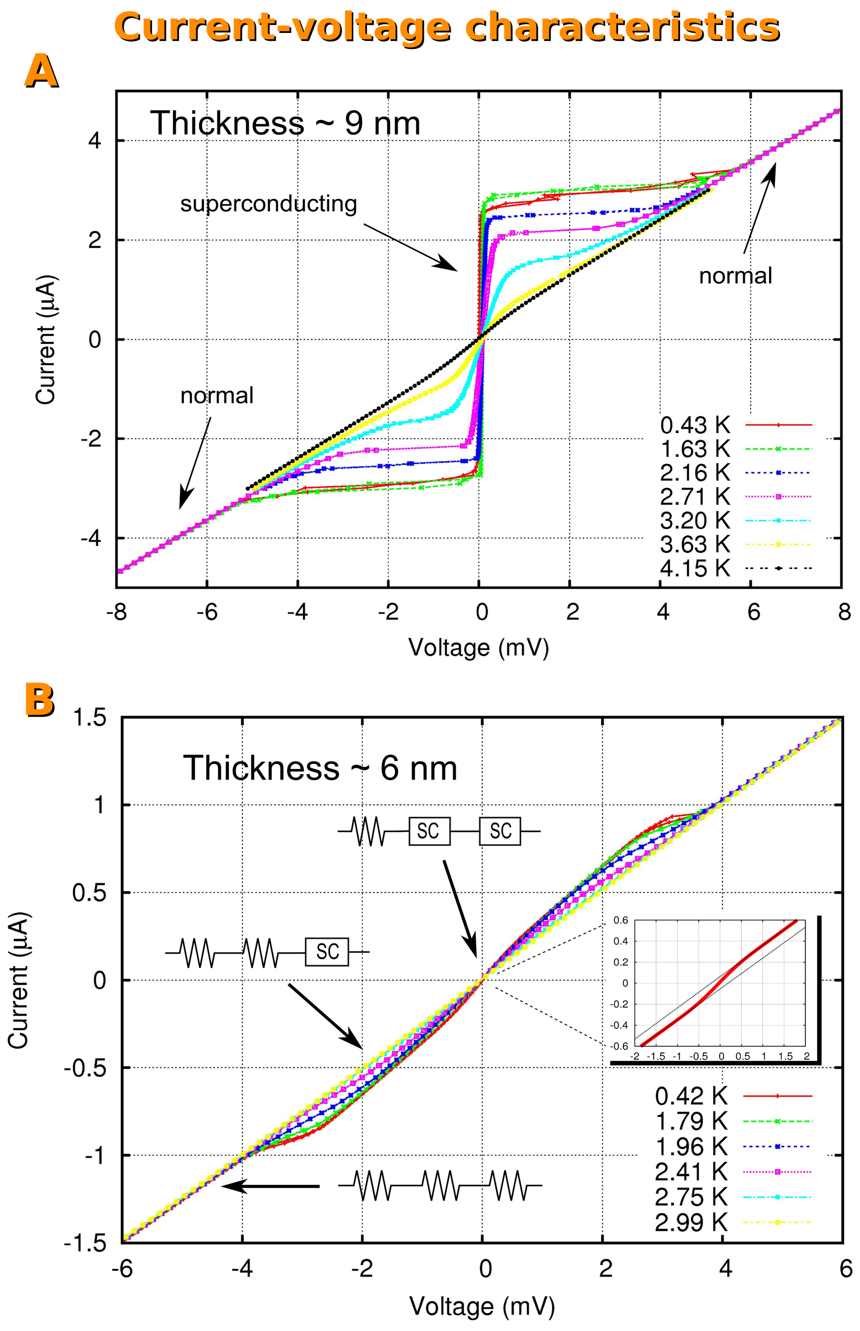
System: Carl Zeiss Crossbeam XB1540

Milling through silicon oxide:
I(Ga⁺) = 1 nA at 30 kV
time = 100 sec
Number of layers = 10

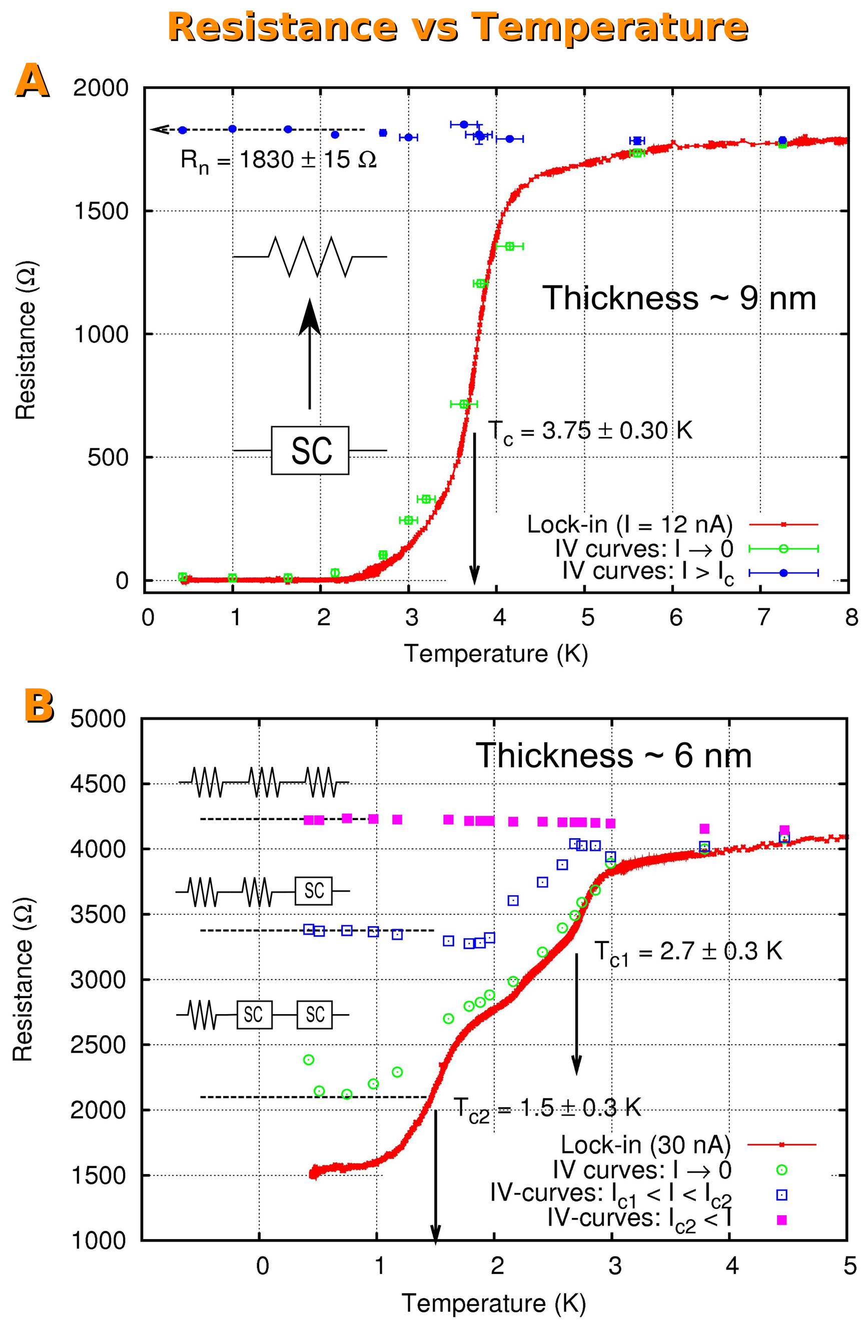
Deposition of ultra-thin film:
I(Ga⁺) = 5 pA at 30 kV
area = 1 µm x 10 µm
scan frequencies = 200 Hz x 20 kHz
time = 40 – 100 sec
precursor pressure = 1–3 x 10^{-5} mbar

LOW-TEMPERATURE TRANSPORT MEASUREMENTS

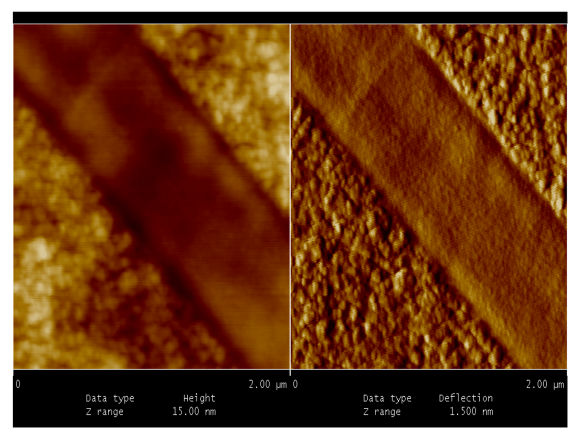
Current-voltage characteristics



Resistance vs Temperature



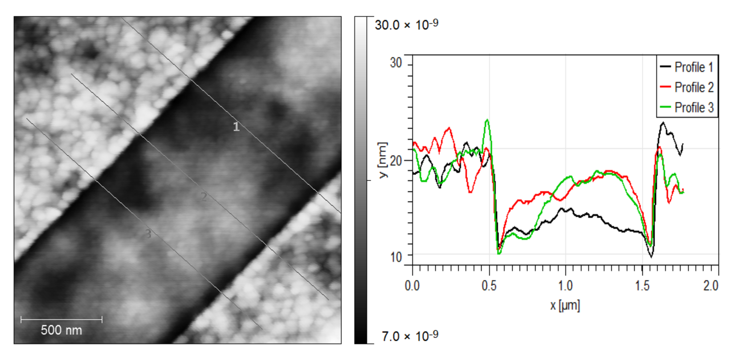
Geometry and topography



Atomic force microscope images of sample A.

Scanning electron microscope (SEM) to determine the planar geometry and the quality of the film.

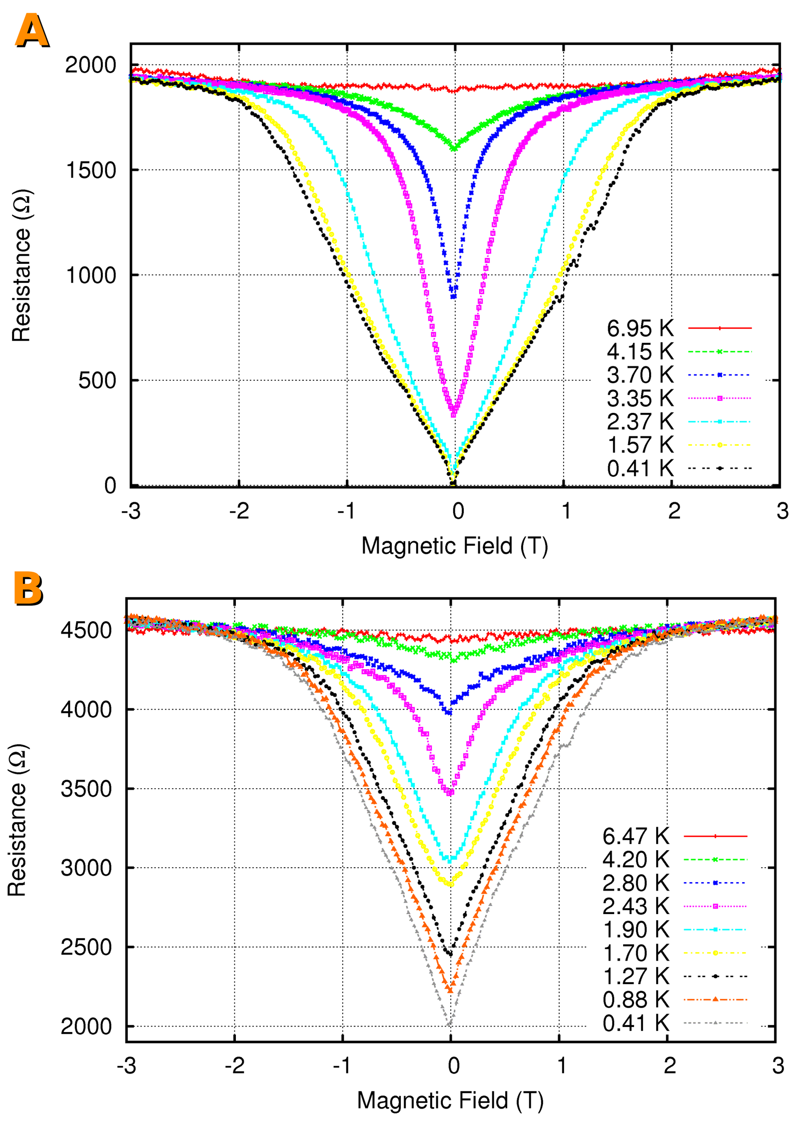
Atomic force microscope (AFM) in contact mode to determine the thickness and the topography of the film.



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

MAGNETORESISTANCE

in field perpendicular to film



RESULTS

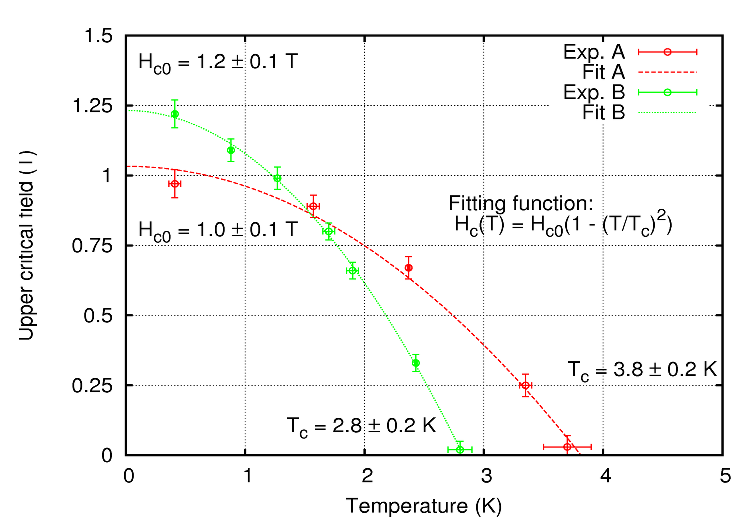
Sample A (9 nm)

- Single type II superconductor
- $T_c(H = 0) = 3.75$ K
- $j_c(T = 0, H = 0) = 3\text{x}10^4$ A/cm²
- $H_{c2}(T = 0) = 1.0$ T → $\xi_0 = 18$ 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
- $j_c(T = 0, H = 0) = 1.3\text{x}10^3$ and $1\text{x}10^4$ A/cm²
- $H_{c2}(T = 0) = 1.25$ T → $\xi_0 = 16$ nm

H-T phase diagram



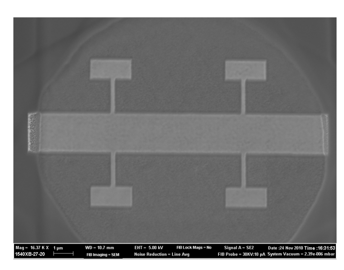
Magnetic-field-Temperature phase diagram of samples A and B.
The $H_c(T)$ curves have been fitted with a function using two free parameters.

OUTLOOK

Fabrication of ultra-thin films of varying thickness and width.

Investigation of superconductor-insulator transition.

Collaboration with Heriot-Watt University for single-photon detectors.



FIB-W ultra-thin film deposited as a Hall-bar.

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