Direct-writing of advanced 3D nano-superconductors

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Innovative schemes have taken advantage of the third dimension (3D) for the development of advanced electronic components. Thus, 3D nano-superconductors could be implemented in the next generation of energy efficient electronic devices. Nevertheless, their fabrication and characterization are still challenging and only a few works addressing the growth of real 3D nanosuperconductors have been reported so far.

Here, we introduce a direct-write nanolithography method based on focused ion beam technologies to fabricate at-will advanced 3D nano-superconductors. Particularly, we have prepared 3D superconducting W-C hollow nanowires by decomposing tungsten hexacarbonyl molecules with a highly-focused He^+ ion beam, with outer diameters down to 32 nm and inner ones down to 6 nm [1]. In addition, by modifying the ion beam current, hollow nanowires with controllable inner and outer diameters have been achieved [2] (Fig. 1). The growth of the vertical W-C nanowire occurs around the ion beam spot, mainly due to the interaction of secondary electrons with the adsorbed precursor molecules, whereas a cavity at the center of the nanowire is created due to the He^+ beam milling effect on the growing material. In addition, we have grown nanohelices with at-will geometries, with dimensions down to 100 nm in diameter, and aspect ratio up to 65 (Fig. 2). These nanotubes and nanohelices become superconducting at 7 K and show large critical magnetic field and critical current density. Moreover, given the helical 3D geometry in nanohelices, fingerprints of vortex and phase-slip patterns are experimentally identified and supported by numerical simulations based on the time-dependent Ginzburg-Landau equation [3]. The fabrication of such advanced 3D nanomaterials with outstanding properties makes this technique at the cutting edge of nanofabrication methods based on focused beams of charged particles.

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[1] Córdoba,. *Nano Lett.* **2018**, *18* (2), 1379–1386; [2] Córdoba, R.;. *Beilstein J. Nanotechnol.* **2020**, *11* (1), 1198–1206; [3] Córdoba, R., *Nano Lett.* **2019**, *19* (12), 8597–8604.

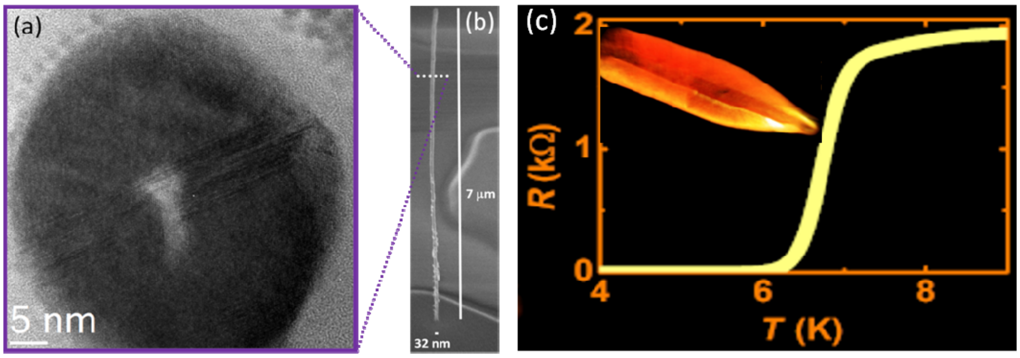

Figure 1: 3D superconducting hollow NWs with tailored diameters.

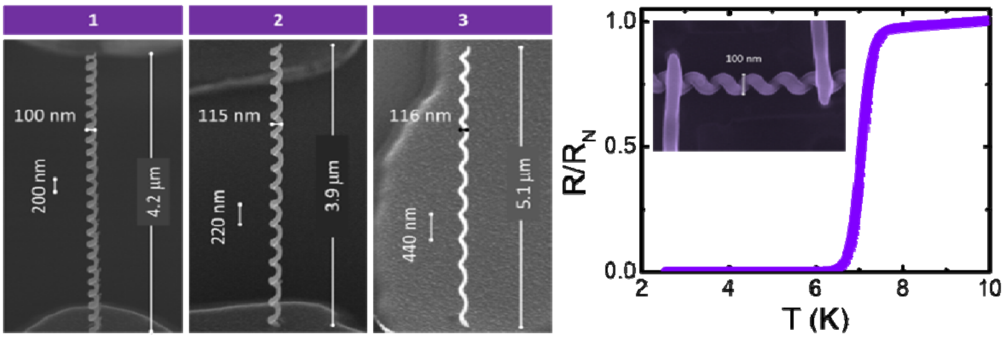

Figure 2: 3D superconducting nanohelices with tailored geometry.