Resistivity scaling in Weyl semimetal NbAs nanowires and thin slabs

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Abstract:

Topological semimetals possess topologically protected surface states that can enhance electrical conduction at reduced dimensions. Theory predicts certain topological semimetals, such as niobium arsenide (NbAs), can exhibit unusual resistivity scaling, i.e., decreasing resistivity with decreasing size, highlighting their potential as next-generation interconnects. However, experimental studies over a wide size range remain limited, particularly for 1D-confined nanostructures relevant to practical applications. In this work, we synthesize NbAs nanowires and thin slabs using thermomechanical nanomolding and focused ion beam (FIB) milling, respectively. Electrical measurements on nanomolded NbAs nanowires show that 40 nm-diameter wires exhibit a room-temperature resistivity of 10.5 ± 2.4 μΩ·cm, which is ~3 times lower than bulk. This is attributed to the suppressed surface electron scattering, corroborated by theoretical simulations showing a substantially longer carrier lifetime for surface states than for bulk states. In contrast, FIB-prepared NbAs thin slabs with larger cross-section areas and ion-beam induced damage show higher resistivity, suggesting the impact of surface damage on electrical transport.

Summary of Research:

Previous approaches for synthesizing NbAs nanostructures have employed bottom-up methods such as chemical vapor deposition or molecular beam epitaxy, as well as top-down methods like FIB milling. However, these approaches have been limited in either crystal quality or accessible sample sizes. Here, we use thermomechanical nanomolding to synthesize single-crystal NbAs nanowires with diameters down to 40 nm.

To test the electrical properties of NbAs nanowires, we fabricate four-terminal devices via standard e-beam lithography, using shared facilities in CNF. Notably, our NbAs nanowires exhibit decreasing resistivity with decreasing size, which is opposite to the trend observed in conventional metals such as Cu. Specifically, 40 nm diameter NbAs nanowires show a room-temperature resistivity of 10.5 ± 2.4 μΩ·cm, which is ~3 times lower than single-crystal bulk. Based on theoretical calculations, we attribute this resistivity reduction to a significantly longer carrier lifetime in surface states compared to bulk states.

Since the nanomolding process relies on interfacial diffusion, it becomes increasingly challenging to produce samples with large cross-section areas. To complement the nanowire study, we fabricate NbAs thin slabs using FIB milling and study their transport properties across different geometries and surface facets. Despite performing the final milling at a low accelerating voltage of 2 kV, Ga^+-induced damage leads to the formation of an Nb-rich surface shell, which causes a superconducting transition at ~2 K. In contrast to the nanomolded nanowires, these FIB-prepared slabs show higher resistivity than bulk, suggesting the absence of the surface-dominant transport observed in nanowires, possibly due to surface damage.

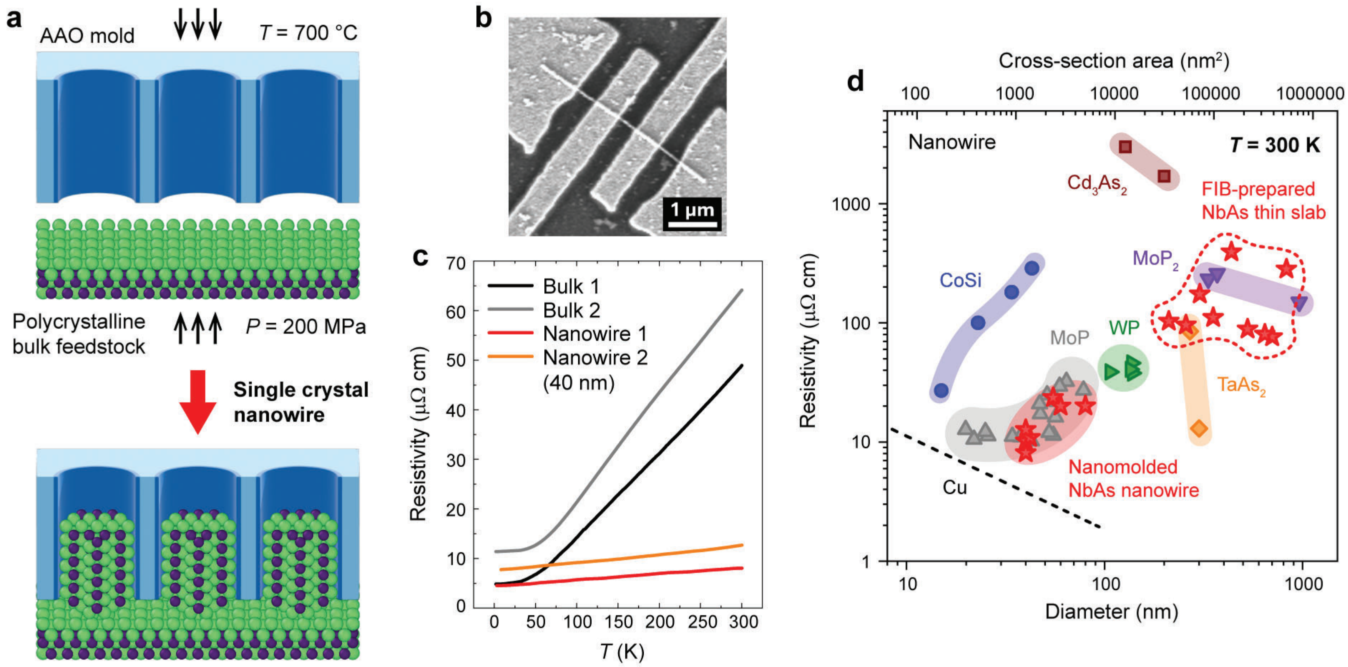

Figure 1. (a) Schematic of the thermomechanical nanomolding process. (b) Representative SEM image of a four-terminal NbAs nanowire device. (c) Temperature-dependent electrical resistivity of bulk single crystals and nanowires. (d) Room-temperature resistivity as a function of diameter (cross-section area) for NbAs nanowires, NbAs thin slabs, and various other topological semimetal nanowires.

Conclusions and Future Steps:

Our results demonstrate surface-dominant transport in NbAs nanowires, highlighting the significant role of topologically protected surface states at reduced dimensions. We will continue measuring nanowire and thin slab devices of varied sizes, with particular focus on further reducing nanowire diameters to enhance surface-state contributions. In addition, we plan to systematically investigate how the surface orientations of NbAs thin slabs influence transport behavior.

References:

[1] Cheon, Y. et al. Surface-dominant transport in Weyl semimetal NbAs nanowires for next-generation interconnects. arXiv:2503.04621 (2025).

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