Electrical and Structural Characterization of Superconducting Ruthenate Ruddlesen-Popper Thin Films

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Abstract:

Strontium ruthenate (Sr_2RuO_4) is the only known example of a spin-triplet superconductor. This exotic spin-triplet pairing allows for the possibility of using Sr_2RuO_4 for ground-state quantum computing. However, for practical applications it is essential to fabricate epitaxial thin films of Sr_2RuO_4. Moreover, thin films could potentially provide a route for enhancing the T_c through strain engineering. Indeed, uniaxial strain studies on Sr_2RuO_4 single crystals indicate that T_c can be enhanced from 1.4 K up to 3.4 K. Thin films of Sr_2RuO_4 were grown using molecular beam epitaxy (MBE). Films were characterized structurally using x-ray diffraction (XRD) to ensure phase purity. Four-point probe resistivity measurements were carried out in order to optimize the MBE growth parameters. Films grown under these optimized conditions had low residual resistivities on the order of 4.0 μΩ·cm and were superconducting with a T_c ~ 0.8 K. To date these are the only superconducting Sr_2RuO_4 thin films grown using MBE.

Summary of Research:

Sr_2RuO_4 is a layered perovskite oxide with a spin-triplet superconducting state [1]. This superconducting ground state, in which the Cooper pairs of the material can occupy three quantum states, allows for Sr_2RuO_4 to be a potential material for the realization of quantum computing. To use Sr_2RuO_4 in quantum computers, however, requires the fabrication of epitaxial thin films and the enhancement of the T_c. In order to achieve superconductivity in this material, the disorder of the film must be minimized. Prior to our work, only two examples of a superconducting thin film had been reported. These films were both grown by pulsed laser deposition and showed superconductivity, with the better of the two films having a T_c of 0.9 K [2,3].

Enhancement of T_c in bulk crystals has been demonstrated through the application of uniaxial strain. Under a uniaxial compressive strain of -0.6%, the T_c of a Sr_2RuO_4 crystal was increased from 1.4 K up to 3.4 K [4].

In thin films, strain can be built into the crystal through the use of epitaxy. Using molecular beam epitaxy, we can grow both tensile and compressive strained thin films, as the crystal lattice of the film elastically deforms to match the crystal lattice of the substrate upon which it the film is grown.

This summer, our research focused on growing on $NdGaO_3$ (NGO), a substrate with a smaller crystal lattice than Sr_2RuO_4. This introduced a compressive strain of 0.1 % in one direction and 0.3 % in the other.

To determine the proper growth parameters to achieve superconductivity in the film, we used a cyclical optimization scheme. Films were grown using MBE, then temperature dependent resistivity measured using a four-point probe measurement and finally structural characterization was done using XRD. Based on the results of these measurements, alterations in growth parameters, such as strontium/ruthenium flux ratio, substrate temperature, and oxidizer pressure were modified as necessary and the scheme was repeated.

Results and Conclusions:

θ-2θ XRD scans were conducted to ensure phase purity of the Sr_2RuO_4 films. An example is shown in Figure 1. The presence of five film Bragg peaks, all indexed to Sr_2RuO_4, in the diffraction pattern is indicative of a phase pure film. Presence of Kiessig fringes indicate good crystallinity and smooth interface between film and substrate.

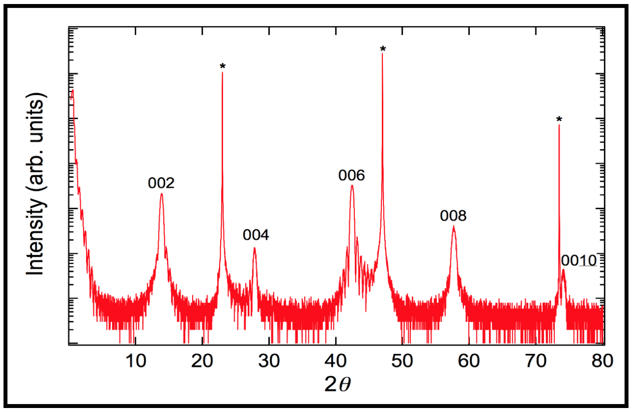

Figure 1: θ-2θ x-ray diffraction pattern of the Sr_2RuO_4 film with asterisks denoting the substrate peaks.

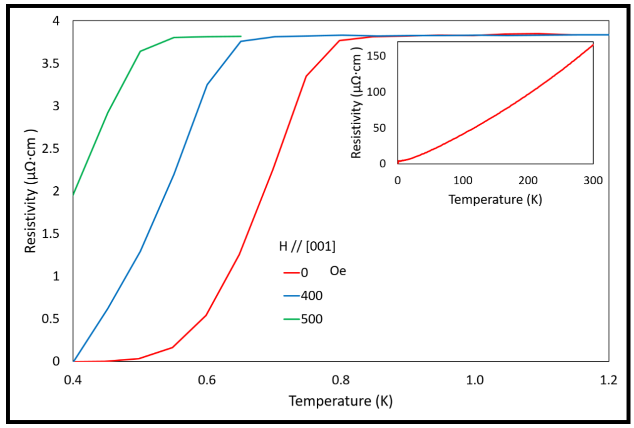

Figure 2: Resistivity as a function of temperature (<1.2 K) under various magnetic fields applied parallel to the c-axis of the film. Inset shows resistivity as a function of temperature up to room temperature.

To characterize the disorder of the film, resistivity versus temperature measurements were taken between 300 K and 4 K using a four-point probe with standard van der Pauw geometry [5]. Disorder is minimized when residual resistivity at low temperature (4 K) is small (< 4.0 µΩ.•cm) and residual resistivity ratio (RRR) is large (> 40). Films with low residual resistivity were measured down to 0.4 K using an in-line probe geometry on a Quantum Design Physical Property Measurement System. Superconductivity over the bulk of the sample was observed in multiple films with a $T_c \sim 0.8$ K. Application of a magnetic field, which suppresses the T_c of the sample, provides further support of superconductivity.

In conclusion, cyclical modification and characterization of films allowed for determination of the optimal parameters for the growth of superconducting Sr_2RuO_4 thin films on NGO using MBE and better knowledge of the growth space of Sr_2RuO_4.

Future Work:

In continuing this work, the Schlom group will be conducting further magnetic field dependence studies on the samples that have already demonstrated superconductivity. The enhanced knowledge of the growth space will be used to grow Sr_2RuO_4 films on different substrates, therefore altering the strain state. This will allow for studies on the dependence of T_c on epitaxial strain.

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