STM Studies of Individual Ti Impurity Atoms in Sr_2RuO_4

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Abstract

The unconventional superconductor, Sr_2RuO_4, was studied with an ultra-low temperature scanning tunneling microscope. Atomic resolution images of the SrO plane were obtained with perturbations caused by Ti impurities substituted for 0.125% of the Ru atoms clearly visible. A complicated gap-like structure in local density of states was measured at all locations on the surface, with some modifications caused by the Ti atoms. The superconducting gap was not clearly visible, possibly due to surface termination effects, but other gap-like structures were found at ~5meV and ~50meV.

Key words: scanning tunneling microscope; STM; Sr_2RuO_4; impurity

1. Introduction

The discovery of superconductivity in the perovskite ruthenate, Sr_2RuO_4, [1] aroused interest due to the similarities in crystal structure with the Lanthanum Cuprates and the presence of superconductivity in a perovskite without Copper. Early measurements [2,3] indicated non-s-wave superconductivity. In particular, measurements of the Knight shift [3] showed strong evidence for spin- triplet pairing. This work, combined with theoretical considerations [4], led to the belief that Sr_2RuO_4 was a p-wave superconductor, similar to the A phase of superfluid ^{3}He.

More recent work has shown that the case of Sr_2RuO_4 is not as straightforward as first believed. Measurements of specific heat, [5] penetration depth, [6] and nuclear quadrupole resonance [7] all indicated the presence of line nodes in the superconducting gap, while thermal conductivity [8] and ultrasound attenuation [9] specified *horizontal* line nodes. Based on advances in STM techniques for studies of correlated electronic materials [10], we decided to attempt similar measurements on Sr_2RuO_4. In the cuprate superconductors, Zn and Ni were substituted for the Cu atoms in the CuO_2 planes. [11,12] In Sr_2RuO_4, we chose to use Ti atoms to substitute for the Ru atoms. Other work [13,14] on Ti-doped Sr_2RuO_4 indicates magnetic ordering near the Ti atoms as well as rapid destruction of the superconducting state by substitutional impurities. In the following sections, we will discuss the topographic images obtained with an ultra-low temperature scanning tunneling microscope (ULT-STM) [15] before presenting spectroscopic measurements which probe the density of quasiparticle states. All measurements were obtained on a dilution-refrigerator-based STM with sample temperatures of 20 mK as measured by calibrated thermometers attached directly to the sample. The samples were cleaved in cryogenic ultra-high vacuum at temperatures above 100 K.

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2. Results

The primitive crystal structure of Sr_2RuO_4 is composed of a layer of RuO_2 and two SrO layers. The weakest bonds lie between the SrO layers, [16] so the crystal naturally cleaves there, leaving a SrO layer at the surface with RuO_2 one layer below. Figure 1a shows the topographic image of Ti-doped Sr_2RuO_4 with the square lattice of Sr atoms clearly visible. The four dark spots correspond to the Ti atoms replacing the Ru atoms one layer below the surface. This identification is made based on the frequency observed in samples with different Ti density and the location of these objects (Fig. 1b shows the spot is located at an anti-site on the surface, as expected for Ti atoms). Some evidence is also seen for Freidel-like oscillations near the Ti atoms.

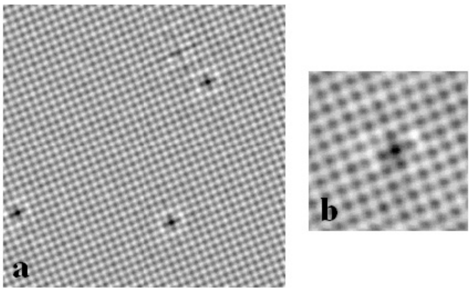

Fig. 1. Topographic image of $Sr_2Ti_xRu_{1-x}O_4$ where x=0.00125. The white lattice is the SrO plane, and the black cross-like objects are the Ti atoms located one layer below the surface. (a) 120 Å ×120 Å image, (b) enlarged (35 Å square) view of single impurity. [Images taken at 0.1 nA and -100 mV.]

The conductance of Sr_2RuO_4 at a position away from any impurities is shown in Fig. 2. All the structure seen in Fig. 2 is present over the entire surface of pure samples and all locations away from impurities for doped samples. The source of the gap-like structures at 50meV and 5meV are unknown. The inset to Fig. 2 shows the modification of the 5 meV gap by the Ti impurities. The Ti atoms do not appear to modify the 50 meV feature appreciably. No clear superconducting gap was seen on multiple samples with multiple types of tips, possibly due to suppression of the superconducting gap near surfaces. This raises the hope that different sample preparation techniques may present a different crystal layer to the STM, allowing direct measurements of the superconducting properties of Sr_2RuO_4.

One possible source for the gap-like structures seen in this material is a surface reconstruction. Indeed, there is very weak evidence in our topographic images for a secondary modulation of the surface in addition to the atomic corrugation. Another possibility is that the 5 meV gap may be related to the magnetic ordering seen in Refs. [13] and [14]. It is believed the magnetic order is located on Ru neighbors of the Ti atoms, [13]

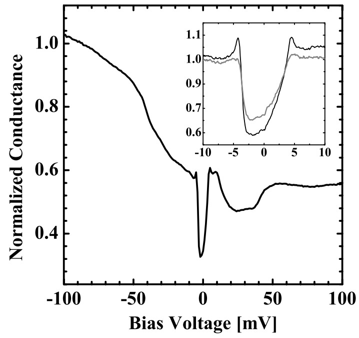

Fig. 2. Local Differential Conductance of $Sr_2Ti_xRu_{1-x}O_4$ where x=0.00125 away from Ti sites. This spectrum is typical of the entire surface. The inset shows the low energy spectra on (gray) and far away (black) from an impurity.

precisely where Fig. 1 shows the largest modifications to the electronic structure. Present and future work to probe the superconducting gap will, of course, be invaluable in understanding these results, as would theoretical determination of the electronic structure of the surface of Sr_2RuO_4.

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