# OUT-OF-PLANE CHARGE TRANSPORT IN THE NORMAL STATE OF PURE AND Ti-DOPED $Sr_2RuO_4$*

K. Pucher[a,†], A. Loidl[a], N. Kikugawa[b] and Y. Maeno[b,c]

[a]Experimentalphysik V, Elektronische Korrelationen und Magnetismus Institut für Physik, Universität Augsburg, 86135 Augsburg, Germany

[b]Department of Physics, Kyoto University, Kyoto 606-8502, Japan

[c]Kyoto University International Innovation Center, Kyoto 606-8501, Japan

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We have performed studies of the out-of-plane reflectivity in the normal conducting state of pure and Ti-doped $Sr_2RuO_4$ single crystals. The scattering rate in $Sr_2RuO_4$ can be explained by a gap-like behavior with an exponential increase of the scattering rate which convincingly describes the temperature dependence of the out-of-plane dc resistance. On doping with non-magnetic Ti the gap becomes reduced and is fully closed for $x = 0.05$.

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Beside the discovery of superconductivity by Maeno and coworkers [1] the layered perovskite $Sr_2RuO_4$, have been triggered considerably research activities by the fact that the normal-state properties can be well described as a highly correlated two-dimensional Fermi-liquid (FL) up to $T \approx 25$ K [2]. In contrast to the in-plane resistivity $\rho_{ab}$, the out-of-plane resistivity $\rho_c$ only partly agrees with the Fermi-liquid theory at low temperatures. Although $\rho_c$ shows a $T^2$ behavior, the Kadowaki–Woods ratio strongly deviates from the universal FL ratio [2]. Up to high temperatures $\rho_{ab}$ reveals metallic behavior, in contrast to $\rho_c$, which passes through a broad maximum close to a characteristic temperature $T^* \approx 100$ K and is only weakly $T$-dependent for higher temperatures [3]. This behavior has been explained assuming a superposition of coherent ($AT^2$) and incoherent ($1/T$) charge transport [4]. On Ti-doping the transport properties at low temperatures change to a non-metallic behavior [5,6]. NMR experiments gave hints for strongly anisotropic

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† Corresponding author e-mail: klaus.pucher@physik.uni-augsburg.de

anti-ferromagnetic (AFM) spin fluctuations at low temperatures [7,8], but also $q$-independent fluctuations exist [8]. Inelastic neutron scattering experiments [9] again reveal the existence of incommensurate spin fluctuations and in comparison with forenamed NMR results it was concluded that ferromagnetic (FM) fluctuations, if they exist at all, obviously are shifted to higher energies.

In this letter we focus on the normal-state dynamic conductivity along $c$-axis in pure and Ti-doped $Sr_2RuO_4$. To shed some further light on charge transport properties we performed a series of infrared (IR) reflectivity measurements on $Sr_2Ru_{1-x}Ti_xO_4$ samples with Ti concentrations $0 < x < 0.09$. The crystals were grown by the floating zone melting technique in an infrared image furnace as described elsewhere [5, 10]. While the pure sample reveals superconductivity below $T_c = 1.43$ K, it is suppressed beyond $x \approx 0.0015$ [11]. The reflectivity measurements were carried out in two Fourier transformation infrared spectrometers (BRUKER IFS 113v and IFS 66v/S) as described previously [6]. For the orientation of the samples we used an IR microscope (BRUKER IRscope II).

The frequency-dependence of the $c$-axis reflectivity $R$ for pure $Sr_2RuO_4$ is shown in Fig. 1. Two phonons are evident and below 100 $cm^{-1}$ the reflectivity increases metallic-like. In contrast to the slight increase at room temperature, a plasma edge close to 80 $cm^{-1}$ becomes visible at low temperatures. It was not possible to describe the electronic contribution using the standard Drude model solely. Therefore, we used a two-component model

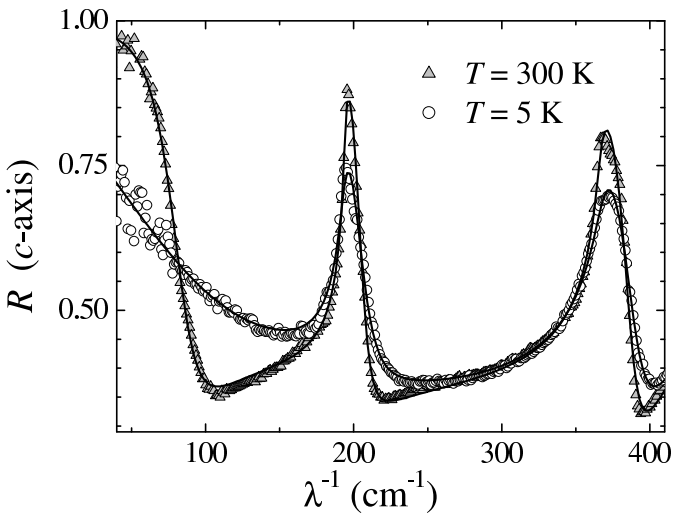


Fig. 1. $c$-axis reflectivity *vs* wave number of pure $Sr_2RuO_4$ ($T_c = 1.43$ K) for $T = 5$ K and 300 K. The solid lines result from fits as described in the text.

with an additional incoherent contribution described by a $T$-independent broad Lorentzian function. Former studies on the pure compound solved this problem applying a extended Drude model [12,13]. Our two component model provides excellent fits of $R$, which are shown as solid lines in Fig. 1 for $T = 5\,\mathrm{K}$ and $300\,\mathrm{K}$.

As mentioned above, we use the standard Drude model $\sigma_1(\omega) = \sigma_{\mathrm{dc}}/(1+\omega^2\tau^2)$ with a $T$-dependent dc conductivity $\sigma_{\mathrm{dc}} = e^2N/m^*$ and a temperature dependent, but frequency independent, scattering rate $\gamma = 1/\tau$. The temperature dependence of the fit parameter $\sigma_{\mathrm{dc}}$ and $\gamma$ are shown in Fig. 2. The dc conductivity (lower frame) strongly increases below 100 K and roughly follows the dc conductivity (dashed line) measured via 4-probe techniques [5]. The scattering rate exponentially decreases towards low temperatures (upper frame) and can nicely be fitted by $\gamma(T) = \gamma_0 + \gamma_1 e^{-\Delta/T}$. This thermally activated behavior with a gap energy $\Delta = 6.3\,\mathrm{meV}$, $\gamma_0 = 4.7\,\mathrm{cm}^{-1}$ and $\gamma_1 = 121\,\mathrm{cm}^{-1}$ reproduces almost perfectly the complete temperature range.

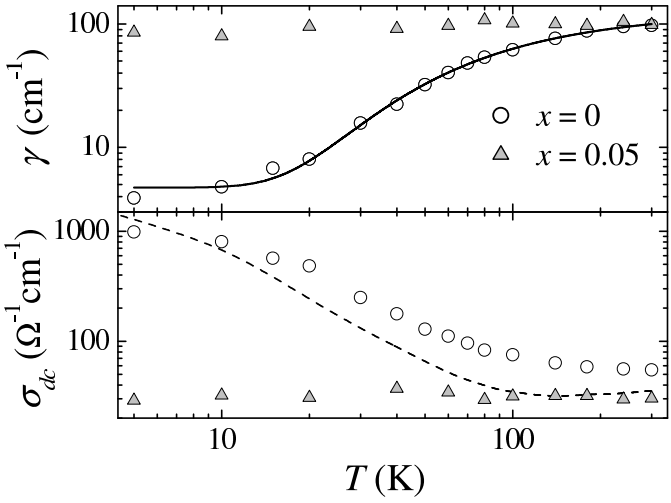


Fig. 2. Temperature dependence of the fit parameter $\gamma$ and $\sigma_{\mathrm{dc}}$ as obtained from the standard Drude model for $Sr_2Ru_{1-x}Ti_xO_4$. The solid line in the middle panel is given by fitting $R$ for $x = 0$. The dc conductivity for measured by four-probe technique is indicated as dashed line in the lower panel.

Finally, we measured and analyzed the $T$-dependence of the reflectivity for $Sr_2Ru_{0.95}Ti_{0.5}O_4$. The resulting parameters are also shown in Fig. 2. Both, $\sigma_{\mathrm{dc}}$ and $\gamma$ are almost temperature independent. The dc conductivity becomes reduced in agreement with the dc measurements [5], while the scattering rate is enlarged and $T$-independent indicating that the gap has been fully suppressed.

In conclusion we have shown that the $c$-axis dynamic conductivity of pure and slightly doped $Sr_2Ru_{1-x}Ti_xO_4$ can be well described in terms of a two component model with a narrow standard Drude contribution and a broad mid-infrared feature. For $T < 300$ K the $c$-axis dc transport is dominated by coherent contributions and the scattering rate depends exponentially on $T$ with a gap energy of 6 meV. On doping the gap becomes closed. Furthermore, we speculate that the gap is of magnetic origin, despite the fact that the magnetic susceptibility for $x = 0$ is rather isotropic and almost temperature independent. From NMR and neutron scattering experiments no gapped features were observed in the spin fluctuation spectra, but a shift of FM fluctuations to higher energies was suggested and on Ti-doping a strongly anisotropic FM component evolves. Therefore, we suspect that FM fluctuations with finite energies are present in the pure compound, too, and result in the observed gap-like temperature dependence of the scattering rate.

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