Magnetoresistance & Variable Range Hopping Conduction in Strontium Ruthenates

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Conducting Magnetic $SrRuO_3$

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Replace Ru with Magnetic & *Non*magnetic Ion (M)

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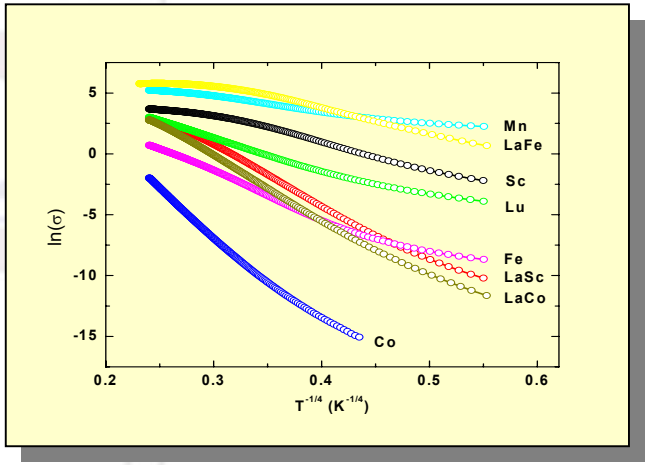
$(Sr,X)(Ru,M)O_3$

- Insulating spin glass *via* random site substitution
- Large MR due to altered spin-state populations of hopping electrons
- Variable range hopping model predicts MR

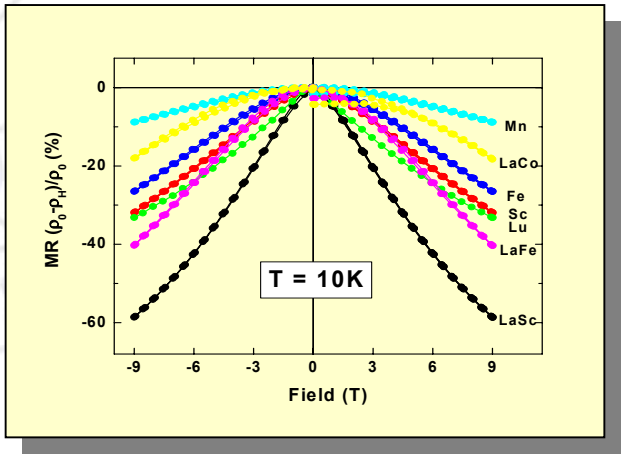
Intrinsic Feature of Insulating Spin Glass

Conductivity lnσ vs. $T^{-1/4}$



Data for 30% M substitution

Magnetoresistance vs. Field



Variable range hopping (VRH) is a conduction mechanism proposed by Mott in 1968. It has since been found in numerous insulating/semiconducting amorphous and crystalline, but disordered, solids. There is even a recent report that the conductivity along the chain of DNA follows this mechanism. In VRH, electrons sample nearby states of various energy and distance away to maximize the hopping probability. As a result, the activation energy is rapidly decreasing as the temperature lowers, resulting in much higher conductivity than classically predicted by the simple activation model. We now show, for the first time, that large negative magnetoresistance is an intrinsic feature of VRH when the insulator is also a spin glass.

In our previous work, we already showed for the first time that a large magnetoresistance can be observed in ruthenates that contain Fe and Co. The ruthenates included $SrRuO_3$ and $CaRuO_3$, and Fe and Co were introduced to substitute Ru on the B-sites. These doped materials lack long-range magnetic order and should be considered as a spin glass. However, it was also found that a large electron polarization is induced around the magnetic Fe and Co impurities, forming giant moments. This arises because of the very large density of state of $SrRuO_3$, which renders its electron easily polarizable. (This is also the origin of ferromagnetism in undoped $SrRuO_3$.) It is therefore unclear whether the magnetic character of the substitutional impurities is necessary for the large magnetoresistance or not. To resolve this issue, we have used Sc and Lu, in addition to Mn, Fe and Co, and repeated the above experiments. Sc and Lu are both trivalent cations that have either empty (Sc) or full (Lu) d-shells. Therefore, unlike Mn, Fe and Co, they have no magnetic moment and can not spin-polarize conducting electrons.

We found $SrRuO_3$ substituted by Sc or Lu, and optionally substituted by La (on A-site, to maintain the valence of Ru at 4+) always form a spin glass. Their conductivity follows Mott's $T^{1/4}$ law at low temperature, indicating VRH. Such behavior is similar to the one found with Mn, Fe and Co substitution. Moreover, they also exhibit a large negative magnetoresistance (MR), which has the essentially similar dependence on temperature (increasing MR with decreasing temperature) and magnetization (MR linearly scaled with M^2). As much as a three-fold increase in conductivity was observed at 10K and 9 T in one composition. These results firmly established the conclusion that the MR does not result from the magnetic character of the impurities, but from the magnetic character of the host material.

We have reconsidered Mott's VRH model to incorporate the consideration of spin-polarized localized electrons. The new model correctly predicted the observed temperature and magnetization dependence of magnetoresistance. This result suggests that magnetoresistance is an intrinsic feature of VRH provided the insulator is also a spin glass. The spin of the VRH electrons is tunable by an external field, and a higher conductivity and a spin-polarized current can be achieved in such materials.