Kondo Effect and Local Disorder in Ion Irradiated AuFe

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Polycrystalline Au films with thicknesses between 30 nm and 80 nm were stepwise implanted with Fe\(^+\) ions at liquid helium temperature up to a concentration of 130 ppm and the resulting Kondo behavior was determined in situ down to 1.4 K applying an ac-technique with a resistance resolution of \(2 \times 10^{-5}\). Combining the implantation with various annealing steps as well as further Ar\(^+\) ion irradiations, the degree of disorder within the samples could be systematically varied. From the results, it is concluded that different types of defects must be distinguished when discussing the effect of disorder on the Kondo behavior: Defects which are closely trapped by the Fe atoms and strongly influence the Kondo effect, while hardly affecting the value of the residual resistivity, and defects which are sufficiently far away from the Fe atoms to exclude any direct influence. This second type strongly contributes to the residual resistivity without a correspondingly large effect on the Kondo behavior.

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1. INTRODUCTION

Ever since the early theoretical treatment of the experimentally observed resistance minimum at low temperatures in some dilute magnetic alloys by Jun Kondo in 1964,\(^1\) this phenomenon, from then on called Kondo effect, remained a subject of ongoing theoretical as well as experimental interest. Being intrinsically a many particle problem, it took more than 25 years until satisfying theoretical answers could be given.\(^2\) Despite its principal understanding, the Kondo effect experienced a recent revival\(^3\) due to the experimental progress in preparing various nanostructures. For instance, the electronic transport through semiconductor quantum dots can be described in terms of pseudo-spins leading to a theoretical description being
equivalent to the Kondo effect and, similarly, to corresponding experimental observations\(^5\) even without the presence of magnetic impurities. Furthermore, the advent of scanning tunnelling microscopy (STM) allowing to locally perform tunnelling spectroscopy on an atomic scale, lead to convincing experimental proofs of theoretical concepts like Kondo resonances.\(^6\) Progress also in the field of controlled preparation of thin films triggered the question of whether the size of a sample will affect the Kondo effect. Experimentally, a clear trend towards smaller Kondo slopes \(B_K\) was observed for AuFe films of decreasing thickness.\(^9\) Here, \(B_K\) is defined by the relation \(\rho_K = -\frac{e^2}{2h} B_K \ln T\) describing the temperature dependence of the electrical resistivity below the resistance minimum and above the Kondo-temperature \(T_K\), setting the energy scale of the problem. Similarly, lateral confinement of samples also resulted in size effects of the Kondo behavior.\(^10\) More recent theories dealing with these dimensional effects are based on a spin anisotropy induced by surfaces and predict a different behavior for half integer and integer spin impurities.\(^11\)\(^,\)\(^12\)

Experimental approaches to test those theories on the thickness dependence of the Kondo effect suffer from a very specific problem. Since the Kondo effect is also known to depend on the degree of disorder within a sample, one has to guarantee that films of different thicknesses are all of identical structural quality. However, in practice such a guarantee can never be given. Furthermore, the experimental reports on the influence of disorder on the Kondo effect are controversial. Measurements on CuFe and AuFe films, both vapor quenched onto substrates held at 77 K in order to introduce structural disorder, revealed an increase of the Kondo slope for increasing disorder.\(^13\) In contrast, a similar analysis on CuFe samples with different residual resistances, reflecting different degrees of disorder, exhibited a depression of the Kondo effect due to growing disorder.\(^10\)\(^,\)\(^14\) A possible explanation of this seemingly contradicting results was delivered by the theoretical contribution of Martin et al.\(^15\) predicting a change of the Kondo slope depending on both, the mean-free-path of the sample as well as its thickness. While for very diluted magnetic alloys a decrease of the Kondo slope is expected when increasing the disorder, for concentrated alloys the opposite behavior should be observed. It is noteworthy that for thin CuMn films (thickness = 275 Å) this theory is quantitatively consistent with experimental data of the disorder dependence of \(B_K\), while for thicker samples (400 Å and 700 Å) deviations from the theory were observed.\(^16\) This suggests additional mechanisms which are not considered in the model by Martin et al.\(^15\) The still unresolved situation of disorder dependence of the Kondo effect motivated us to perform additional tests based on improved experimental techniques.

A promising approach, in this context, is offered by ion implantation