鋁/氧化鋁/銃穿隧接點於低溫下微分電導之研究

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摘　　要

我們製作了數個鋁/氧化鋁/銃穿隧接點，並於低溫下量測其微分電導$G \equiv dI/dV$以研究穿隧電子與絕緣層中局域的磁性雜質之間的偶合。當溫度T在鋁的超導溫度T_c以下，我們量測到一個很深的超導能隙，以此證明穿過此絕緣層的漏電流可以忽略，所以經由此位能障的導電機制為電子穿隧。

當$T_c < T \leq 32$ K，我們觀測到在零偏壓附近出現微分電導峰，此峰疊加在一個背景上。為了得到$s-d$ exchange interaction 對電導的貢獻，我們將此由位能障所貢獻的背景予以扣除。扣除此背景後，我們發現餘下的電導包含一個主要的對稱項，$G_{even,data}(V,T)$，以及一個次要的反對稱項，$G_{odd,data}(V,T)$。

因為所有這些樣品的$G(V,T)$有相類似的行為，我們選取其中一個樣品，”20061002”，以 Appelbaum 的$s-d$ exchange 理論來進行擬合。當$T \leq 32$ K，此對稱項於零偏壓的值$G_{even,data}(0,T)$隨溫度降低而變大。在 14 K$\leq T \leq 32$ K 這個溫度區間，$G_{even,data}(0,T)$對溫度有$a-b\log T$的函數關係，當溫度低於 14 K 時，$G_{even,data}(0,T)$開始偏離此$\log T$的關係，隨著溫度愈低，偏離愈大，當$T \leq 3.6$ K 時，$G_{even,data}(0,T)$對溫度有$c-dT^2$的關係。在這個$a-b\log T$關係的溫度區間，$G_{even,data}(V,T)$可以被 Appelbaum 的弱偶合的$s-d$ exchange 理論所擬合，而在$c-dT^2$關係的溫度區間，$G_{even,data}(V,T)$則可以被 Appelbaum 的強偶合的$s-d$ exchange 理論所描述。在後者的情形，根據擬合的參數，我們可以得到 Kondo 溫度$T_K^{Appelbaum}$約為 34.8 K。另一方面，零偏壓的電導$G_{even,data}(0,T)$可以被數值重整群 (NRG) 的計算很好地擬合，由此擬合，可以得到 Kondo 溫度T_K^{NRG}約等於 38 K，這與前述的$T_K^{Appelbaum}$的值相當吻合。我們也以

數值重整群的計算來擬合另兩個樣品(“20060321”與“20061030”)的 $G_{even,data}(0,T)$，得到其 Kondo 溫度分別為 20 K 與 27 K。這三個樣品的 $G_{even,data}(0,T)$ 遵守某個由數值重整群計算所預測的標度行為。我們將反對稱的電導 $G_{odd,data}(V,T)$ 歸因於透過 $s-d$ exchange 穿隧與透過雜質穿隧兩者間的干涉效應。但是理論只能定性地描述我們的數據，更進一步理論方面的研究需要被進行。

此外，我們也研究了加磁場的效應。對”20061002”這樣品，我們於 $T=2.5$ K 下，加了 4 T 的磁場，發現零偏壓處的電導值下降了約 3.4 % 左右，但是，並沒有發現 Zeeman splitting。沒有觀測到 Zeeman splitting 這件事與此樣品較高的 Kondo 溫度有關。根據理論計算，若以 Kondo 溫度 $T_K^{NRG} \approx 38$ K 來估計，需要一個約為 14 T 的臨界磁場，大於此臨界磁場，Zeeman splitting 才會發生。

總結而言，我們經由 dI/dV 的量測來研究穿隧電子與位能障中局域磁矩的交互作用。我們觀察到從弱偶合過度到強偶合的行為，並且，對應的 dI/dV 可以由 Appelbaum 的 $s-d$ exchange 分別在這兩種偶合下的理論來擬合。經由這樣的擬合，Kondo 溫度 $T_K^{Appelbaum}$ 可以被決定為約 34.8 K。另一方面，零偏壓電導可以被數值重整群的計算所預測的標度函數所描述，經由擬合，可以得到 T_K^{NRG} 約為 38 K，這與 $T_K^{Appelbaum}$ 的值相當一致。我們觀測到一個小的反對稱項，並將之歸因於透過 $s-d$ exchange 穿隧與透過雜質穿隧兩者間的干涉效應，但理論的計算只能定性地描述實驗數據。在溫度為 2.5 K 時，我們外加一 4 T 的磁場，但是並沒有觀察到 Zeeman splitting，這是因為 Kondo 溫度比較高的關係。若以 $T_K^{NRG} \approx 38$ K 來估計，需要一個 14 T 的臨界磁場，以造成 Zeeman splitting。

Low Temperature Differential Conductances in $Al/AlO_x/Sc$ Tunnel Junctions

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Abstract

We have fabricated several $Al/AlO_x/Sc$ tunnel junctions and measured the differential conductance $G \equiv dI/dV$ at low temperatures to study the coupling between the tunneling electrons and the magnetic impurities which localized in the insulating barrier. Below the superconducting transition temperature T_C of the Al film, a deep superconducting gap was observed which demonstrates that any leakage through the insulating barrier can be neglected and the conduction mechanism through the barrier is dominated by electron tunneling.

For temperature in the range $T_C < T \lesssim 32$ K, a zero-bias conductance peak was observed. To extract the contribution of the $s-d$ exchange interaction to the conductance, a background due to the barrier was subtracted. After subtracting the background, the remainder conductance was found to contains a dominating even term, $G_{even,data}(V,T)$, and a minor odd term, $G_{odd,data}(V,T)$.

Since the $G(V,T)$ spectra in all these junctions had the similar behavior, we fitted the spectra of one of them, namely "20061002", in terms of Appelbaum's $s-d$ exchange theory [1, 2, 3]. At zero bias, the even conductance $G_{even,data}(0,T)$ increased as T decreased for $T \lesssim 32$ K. $G_{even,data}(0,T)$ obeys an $a - b$ log$T$ dependence for 14 K $\lesssim T \lesssim$ 32 K and crossed over to a $c - d\ T^2$ dependence for $T \lesssim 3.6$ K. In the "$a - b$ log$T$" dependence regime, the $G_{even,data}(V,T)$ spectra could be well fitted by the Appelbaum's theory in the weak coupling limit [1, 2], while in the "$c - d\ T^2$" dependence regime, the data could be well described by Appelbaum's theory in the strong coupling limit [3]. In the latter case, the Kondo temperature $T_K^{Appelbaum}$ was determined to be ≈ 34.8 K from the fitting parameters. On the other hand, the $G_{even,data}(0,T)$ could be quite well fitted by the numerical renormalization group (NRG) calculations for the whole temperature regime, and a $T_K^{NRG} \approx 38$ K could be deduced which was in good agreement with the value of $T_K^{Appelbaum}$. We have also fitted the $G_{even,data}(0,T)$ data of other two junctions (20060321 and 20061030) in terms of the NRG calculations and obtained the T_K^{NRG} to be ≈ 20 K and 27 K respectively. All the $G_{even,data}(0,T)$ data in these three junctions (20061002, 20060321, and 20061030) obey a scaling behavior which was predicted by the NRG calculations. The odd conductance $G_{odd,data}(V,T)$ was attributed to the interference between the $s-d$ exchange tunneling and the impurity-assisted tunneling. But the theoretical calculation could only qualitatively describe the data. Further theoretical studies are required.

In addition, we have studied the effect of an externally applied magnetic field. For the sample "20061002" at 2.5 K, under the magnetic field 4 T, the zero-bias conductance decreased by $\approx 3.4\%$, but no Zeeman splitting was observed. The absence of a Zeeman splitting was due to the high T_K in this sample. A critical field of $H_c \approx 14$ T, which was predicted using $T_K^{NRG} \approx 38$ K, would be required to cause a Zeeman splitting.

In a summary, we have studied the interaction between the tunneling electrons and the magnetic moments which localized in the barrier through the dI/dV spectra measurement. We observed a crossover from a weak coupling regime to a strong coupling regime, and the corresponding dI/dV spectra could be fitted in terms of Appelbaum's $s-d$ exchange interaction theory in both these regimes. The Kondo temperature $T_K^{Appelbaum}$ determined from the fitting was ≈ 34.8 K. On the other hand, the zero-bias conductance could be well described by a scaling form predicted by the NRG calculations and a T_K^{NRG} was deduced to be ≈ 38 K, which was in good agreement with the value of $T_K^{Appelbaum}$. A small asymmetric conductance was observed and was attributed to the interference between the $s-d$ exchange interaction tunneling and the impurity-assisted tunneling, but the theoretical calculations could only describe the data. At 2.5 K, a 4 T external magnetic field was applied but no Zeeman splitting was observed, which was due to the high T_K in this sample. A critical field 14 T, which was predicted using $T_K^{NRG} \approx 38$ K, would be required to cause a Zeeman splitting.