Abstract

We study phenomena related to spin-dependent electron transport in quantum dots, which are in contact with metallic, ferromagnetic or superconducting leads. Experimental results for linear conductance dI/dV of quantum dots in low temperatures and high magnetic fields obtained in two laboratories - RIKEN (Japan) under prof. K. Ishibashi supervision and IBM Almaden (USA) under prof. S. S. P. Parkin supervision - are explained by our theoretical analyses.

We explain the complex conductance dependence on gate voltage and magnetic field in Coulomb's blockade regime for a carbon nanotube coupled to normal metal leads. We analyse the two highest non-empty orbitals of the nanotube quantum dot, which are filled with two electrons (*half-shell* filling). A singlet-triplet system of energy and spin levels is effectively created in the dot. We model elastic and inelastic electron cotunneling through singlet-triplet levels and possible transitions between them in second order perturbation theory formalism. We show, that the magnetic state of the system can be modified by changing solely the gate voltage. We take into account an asymmetry in coupling of carbon nanotube orbitals to the electrodes, which leads to effective spin asymmetry, because the orbitals possess different spin indexes. This produces an effective spin polarization of couplings between the leads and the nanotube in analogy to a dot coupled to ferromagnetic leads, where the spin asymmetry appears in natural way due to spin-dependent densities of states. The value of the effective spin polarization can be modified and controlled by means of electric field produced by the gate voltage. From the theoretical results, which are in very good agreement with the experiment, we conclude, that a strong relaxation to a state with lower spin and orbital energy is present in the system.

In the second system, for low transport voltages, we find a zero-bias anomaly (ZBA) in conductance in form of a single or a split peak in planar magnetic tunnel junctions (MTJ) with a thin layer of magnetic CoFe nanodots inserted between the tunnel barriers made of crystalline MgO. By examination of the temperature-dependences of the ZBA peak height, we show that the peak is due to the Kondo assisted tunnelling. It is a split conductance peak or a single peak for configurations of ferromagnetic leads' magnetizations, parallel and antiparallel, respectively. We observe also a similar dependence of the peak splitting on the external magnetic field. With use of the Anderson model for quantum dot attached to ferromagnetic electrodes, we show, that the spin splitting is due to an exchange interaction with ferromagnetic leads, which renormalizes spin levels' positions. We conducted the calculations by means of the standard equations of motion (EOM) technique for quantum dot Green functions. The level positions' renormalization was treated self-consistently.

We have also examined the coexistence of the superconducting phase, magnetism and Kondo effect in planar tunnel junctions with CoFe nanodots between crystalline MgO tunnel barriers coupled to superconducting leads. The effects induced by superconducting leads made of Al, generate a clear conductance signal of superconducting origin: two peaks - each centered around voltages of both signs equal to twice the superconducting gap of Al (for $|eV| = 2\Delta_{\mathrm{Al}}$). They are, however, superimposed on a broad Kondo peak. This behaviour can be related to the fact that in Al, the superconducting gap is smaller than the Kondo temperature $\Delta_{\mathrm{Al}} \ll k_{\mathrm{B}}T_{\mathrm{K,\ Al}}$ and the Kondo

electron cloud can be treated in the Fermi liquid picture as a broad conducting channel. Such an effect was not observed in the experiment in which the leads were made of superconducting NbN. The superconducting gap in NbN is much larger than the Kondo temperature of the system, $\Delta_{\mathrm{NbN}} \gg k_{\mathrm{B}} T_{\mathrm{K,NbN}}$, what leads to the suppression of the Kondo effect and the ZBA disappearance below the critical temperature, $T_{\mathrm{c,NbN}}$, for NbN, when the leads are in the superconducting state. A different non-trivial effect appears, however, in this system in the conductance signal: for each transport voltage sign, a double peak structure is visible. It is most well-defined in zero magnetic field and it decays slowly without changing the peak positions with increasing of magnetic field. We explain these phenomena by a two-impurity Anderson model for two interacting quantum dots with a singlet-triplet levels system and transitions between the levels by means of inelastic electron cotunneling. The peak for lower transport voltages is related to the elastic cotunneling and the peak for higher voltages is related to the inelastic cotunneling processes and excitations in the system. Using a complex superconducting densities of states' dependence on the external magnetic field in thin NbN layers, we are able to obtain a very good fitting of our theoretical results to the experimental data.

In summary, this work contributes to understanding of electron spin-dependent processes present when electric currents flow through three types of systems with quantum dots coupled to normal metallic, ferromagnetic and superconducting leads. The effects include ferromagnetic interaction, transitions between different electron quantum dot states, Kondo effect, superconductivity of the leads and external magnetic field influence. We consider our results important for the developing area of spintronics.