Suppression of superconductivity due to spin imbalance in Co/Al/Co single electron transistor

Jan Johansson, Mattias Urech, David Haviland, and V. Korenivski

Citation: Journal of Applied Physics **93**, 8650 (2003); doi: 10.1063/1.1556284
View online: http://dx.doi.org/10.1063/1.1556284
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/93/10?ver=pdfcov
Published by the AIP Publishing

Suppression of superconductivity due to spin imbalance in Co/Al/Co single electron transistor

Jan Johansson, Mattias Urech, David Haviland, and V. Korenivski
Nanostructure Physics, KTH, AlbaNova University Center, 10691 Stockholm, Sweden

(Presented on 15 November 2002)

Transport properties of ferromagnetic/nonmagnetic/ferromagnetic single electron transistors are investigated as a function of external magnetic-field, temperature, bias, and gate voltage. By designing the magnetic electrodes to have different switching fields, a two-mode device is realized having two stable magnetization states, with the electrodes aligned in parallel and antiparallel. Magnetoresistance of approximately 100% is measured in $Co/AlO_X/Al/AlO_X/Co$ double tunnel junction spin valves at low bias, with the Al spacer in the superconducting state. The effect is substantially reduced at high bias and temperatures above the T_C of the Al. The experimental results are interpreted as due to spin imbalance of charge carriers resulting in suppression of the superconducting gap of the Al island.
[DOI: 10.1063/1.1556284]

I. INTRODUCTION

Electron tunneling from a ferromagnet into a normal metal or a superconductor results in a nonequilibrium spin population persisting over a characteristic distance known as the spin diffusion length, typically 10–100 nm at low temperatures.[1,2] With the recent advances in nanofabrication techniques it has become possible to study structures with dimensions on the same length scale, where spin coherence and relaxation effects play an important role. One of the implementations of a spin transport device is a double junction with ferromagnetic outer electrodes that can be magnetically switched to align in parallel (P) or antiparallel (AP). The spin imbalance and accumulation on the superconducting island in the AP configuration is expected to produce large conductance variations by suppressing the gap.[3] Recently reported experiments on Co/Al/Co double tunnel junctions[4,5] have indeed been interpreted in terms of suppressed superconductivity of Al in the magnetic AP state of the device. Interestingly, the magnitude of the magnetoresistance (gap suppression) was found to strongly depend on the sweep rate of the external magnetic field,[4] suggesting that the AP state of the device was unstable (''thermal activated'') on the experimental time scale of seconds to minutes. We show in this article that this reported *sweep-rate-dependent* magnetoresistance (MR) in Co/Al/Co double tunnel junctions is not connected with the relative magnetic alignment of the two ferromagnetic electrodes. By carefully designing the magnetic electrodes of the structure we are able to achieve a well controlled and stable AP to P switching, which results in a pronounced and *field-sweep-rate-independent* MR. Similar to[4,5] we observe a sweep-rate-dependent contribution to the MR of the devices, which we find to be unrelated to the magnetization reversal in the Co electrodes.

II. EXPERIMENTAL DETAILS

The structures, consisting of an aluminum island separating two cobalt electrodes as shown in Fig. 1, were fabricated using e-beam lithography and the two-angle shadow evaporation technique.[6] A 15 nm thick Al layer was deposited on oxidized Si and subsequently *in situ* oxidized in 100 mTorr of O_2 prior to deposition of 40 nm thick, 60 and 70 nm wide Co electrodes spaced by ~400 nm. The difference in width resulted in different magnetostatic shape anisotropy, which in turn determined the switching field of the electrodes. The orientation and length of the Co fingers (extending past the Al island) was chosen so as to minimize the stray fields in the Al due to the open ends, promote the AP magnetostatic coupling between the fingers as well as minimize magnetization curling in the junction area.[7] These considerations were important in achieving a stable AP magnetic state of the device. The external quasistatic field was applied along the Co electrodes, perpendicular to the longer side of

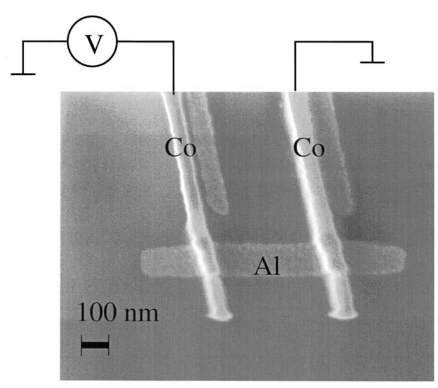

FIG. 1. SEM image of a Co/Al/Co double-tunnel junction.

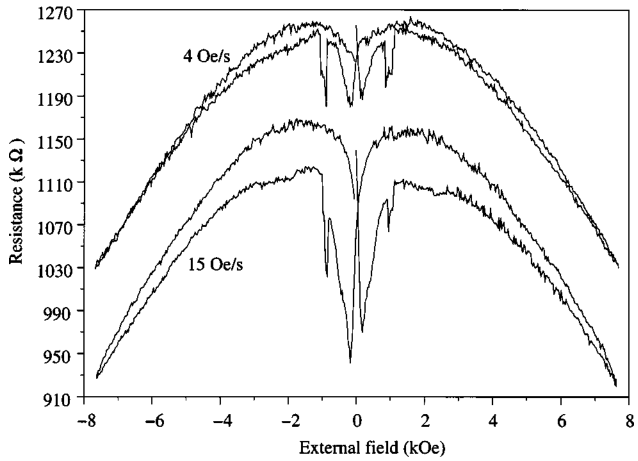

FIG. 2. Magnetoresistance of a Co/Al/Co double-tunnel junction measured with the field swept at 4 and 15 Oe/s. The 4 Oe/s curve is offset by +100 kΩ.

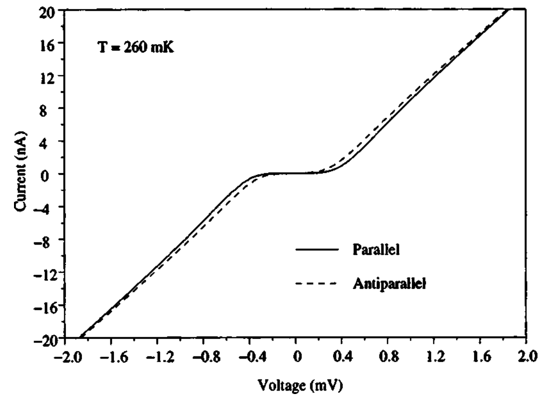

FIG. 3. I-V characteristics of a Co/Al/Co double-tunnel junction, in the stable parallel (P) and antiparallel (AP) state of the Co electrodes.

the Al island. MR and I-V characteristics were measured at temperatures ranging from 250 mK to above the T_C of Al (~1.2 K).

III. RESULTS AND DISCUSSION

Figure 2 shows the resistance of a typical double junction as a function of external field swept at two different rates, 4 and 15 Oe/s. The decrease in the resistance at high fields is caused by the direct influence of the external field, which suppresses the superconducting gap of the Al and thereby enhances the quasiparticle tunneling. As the field is lowered (see the 15 Oe/s curve in Fig. 2) the resistance increases and would be expected to follow a bell-like shape before decreasing again at high-negative fields. However, a pronounced minimum is observed at a relatively low field (~−150 Oe), which appears similar to giant magnetoresistance in spin-valves or magnetic tunnel junctions,[8] and has previously been interpreted as arising from magnetic P to AP switching.[4,5] This minimum is significantly reduced in magnitude (three-fold) as the sweep rate of the magnetic field is reduced to 4 Oe/s (upper curve in Fig. 2) and eventually vanishes in quasistatic field measurements (sweep rate <1 Oe/s). Additionally, we observe a second, somewhat less pronounced minimum at ~1 kOe. The second minimum, however, is essentially unchanged as the sweep rate is reduced. Clearly, two effects must be at work here. We believe that the interpretation of the sweep-rate dependent MR minimum (see Refs. 4, 5) as arising from the P to AP switching of the Co electrodes is faced with two large difficulties. Indeed, after the sample has undergone a complete saturation the resistance versus H levels off and starts to decrease sharply before the external field reverses direction, where the field continues to favor a parallel alignment of the magnetic electrodes (even more so in the geometry of Ref. 5, where the interelectrode magnetostatic coupling favours the P state). Only when the sign of the external field is reversed one (or both) of the electrodes can switch in order to minimize the Zeeman energy. The switching field is then negative and determined by the shape anisotropy of the electrode. Second, the measured time dependence on the scale of seconds to minutes was argued to come from a slow magnetic switching/relaxation of the Co electrodes.[4] This argument, however, is off by at least ten orders of magnitude since nanomagnets are known to switch on the subnanosecond scale.[9] The characteristic precessional time scale is set by the inverse of the ferromagnetic resonance frequency, $f_r = \gamma\sqrt{4\pi M_s H_a} \sim 10$ GHz, where $4\pi M_s(\mathrm{Co}) = 16$ kG and the anisotropy field is $H_a \sim 1$ kG for our geometry. We obtain magnetic reversal times of the order of 10^{-10} s using micromagnetic simulations for our electrode geometry. We therefore conclude, in contrast to,[4,5] that the *sweep-rate-dependent* part of the observed MR is unrelated to magnetic switching of the Co electrodes and must have a different origin. We can only point out that the field scale at which the sweep-rate-dependent minimum of MR is observed is approximately seven times lower in our case than of Ref. 5. The location of the minimum scales inversely with the cross section of the Al island perpendicular to the applied field. This implies that in these two experiments the minimum in resistance is observed at roughly the same flux through the Al spacer.

The *sweep-rate-independent* MR shows the field dependence of a classical spin valve (see Fig. 2). After saturation in a large positive field (P state) one of the Co electrodes (the wider of the two, having weaker shape anisotropy) switches only when the field is reversed to −800 Oe. The second (narrower, higher-shape anisotropy) electrode switches at −1000 Oe. In this 200 Oe field window, an AP state of the device is achieved, which results in a pronounced and stable MR. Once the device is set in the AP state by ending the sweep between 800 and 1000 Oe, it remains in it after removal of the field, stabilized by the magnetic shape anisotropy of the Co strips. The I-V characteristics measured in a so-prepared AP state together with the I-V of P are shown in Fig. 3. From the I-V characteristics in the P state and the response to a gate voltage, a good estimate of the sample parameters can be obtained: Superconducting gap of $\Delta_0 = 200\ \mu$V, junction capacitance of 0.57 *fF*, junction resistance 42.5 kΩ and gate capacitance of 1 *aF*. The gap in the AP state is clearly reduced. The spin accumulation on the Al island, due to the spin-valve effect, results in Cooper pair

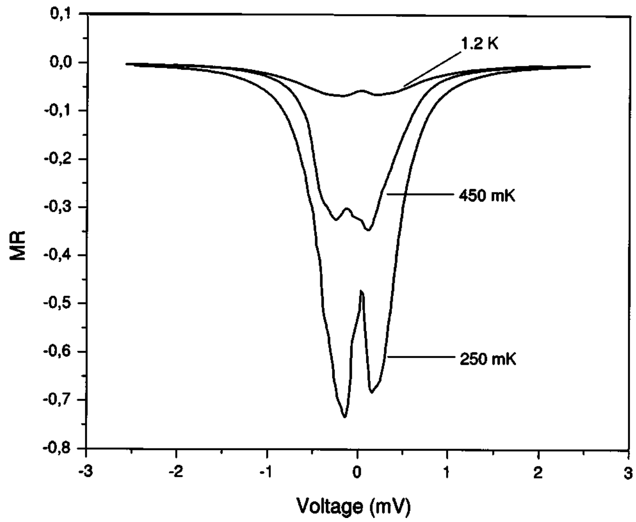

FIG. 4. Magnetoresistance of a Co/Al/Co double-tunnel junction, MR $=(R_{AP}-R_P)/R_P$, as a function of bias voltage.

braking which reduces the gap thereby increasing quasiparticle tunneling and thus in a lower resistance of the double tunnel junction.[3]

The MR, defined as the difference between the P and AP resistances normalized to the P resistance, is shown in Fig. 4 as a function of bias voltage. The three curves correspond to the temperatures 250, 450, and 1200 mK. The resistance, $R = V/I$ at fixed V, is obtained from the I-V data for the stable P and AP states, such as shown in Fig. 3. The spin-valve effect is most pronounced at a low bias of $\sim 200\ \mu$V, which approximately equals the superconducting gap. Above and below this voltage the effect is weaker, and asymptoticly goes to zero for large bias. As the temperature is increased the MR decreases. Above T_c we see no MR indicating that the spin coherence length in the normal state is shorter than the distance between the two Co electrodes. The noise in the data at very low bias is due to numerical uncertainties in this range ($V\rightarrow 0/I\rightarrow 0$) and fluctuating background charges in the vicinity of the Al island. The measured behavior is qualitatively consistent with the theoretical results of Ref. 3. We observe a negative, bias, dependent MR, which decreases with increasing temperature, see Figs. 2 and 3 of Ref. 3.

Thus, we have achieved a controlled P to AP switching in Co/Al/Co magnetic single electron transistors. In the AP state, we observe a clear reduction of the superconducting gap due to the spin accumulation effect, which results in a maximum MR of close to 100% at a voltage bias close to the superconducting gap. The MR vanishes at large bias and above the T_c of the Al island.

ACKNOWLEDGMENT

J.J. and M.U. gratefully acknowledge support from the Swedish SSF under the Graduate School for Quantum Devices.

[1] R. Meservey and P. M. Tedrow, Phys. Rep. **238**, 173 (1994).
[2] M. Johnson and R. H. Silsbee, Phys. Rev. B **37**, 5326 (1988).
[3] S. Takahashi, H. Imamura, and S. Maekawa, Phys. Rev. Lett. **82**, 3911 (1999).
[4] C. D. Chen, W. Kuo, D. S. Chung, J. H. Shyu, and C. S. Wu, arXiv: cond-mat/0103523.
[5] C. D. Chen, W. Kuo, D. S. Chung, J. H. Shyu, and C. S. Wu, Phys. Rev. Lett. **88**, 047 004 (2002).
[6] G. J. Dolan, Appl. Phys. Lett. **31**, 337 (1977).
[7] M. Urech, V. Korenivski, and D. B. Haviland, J. Appl. Phys. (submitted).
[8] J. S. Modera, L. R. Kinder, T. M. Wong, and R. Meservey, Phys. Rev. Lett. **74**, 3273 (1995).
[9] W. F. Brown, Phys. Rev. **130**, 1677 (1963).