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Comment on "Half-metallicity in europium oxide conductively matched with silicon"

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In this Comment we clarify the misconceptions expressed by Panguluri *et al.* [R. P. Panguluri, T. S. Santos, E. Negusse, J. Dvorak, Y. Idzerda, J. S. Moodera, and B. Nadgorny, Phys. Rev. B **78**, 125307 (2008)] regarding the experimental procedures and data interpretation used in our work [A. Schmehl, V. Vaithyanathan, A. Herrnberger, S. Thiel, C. Richter, M. Liberati, T. Heeg, M. Rockerath, L. F. Kourkoutis, S. Muhlbauer, P. Boni, D. A. Muller, Y. Barash, J. Schubert, Y. Idzerda, J. Mannhart, and D. G. Schlom, Nature Mater. **6**, 882 (2007)]. We show that our experimental procedures and resulting data are direct consequences of the materials and sample geometries we used and demonstrate that our carefully chosen approach has advantages over the techniques used in the criticizing publication.

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In their publication[1] the authors comment on our prior Andreev-reflection measurements of the spin polarization in lanthanum-doped europium oxide from our paper.[2] These comments express several misconceptions concerning our experimental approach, the data acquisition, and the data interpretation. Specifically they refer to the introduction of a series resistance into the Blonder-Tinkham-Klapwjik (BTK) model[3] to interpret our Andreev-reflection data, about the suppressed superconducting gap of 0.88 eV with respect to the expected BCS value of 1.33 eV for the measured superconducting transition temperature (T_c) of niobium of 8.5 K and the use of lanthanum to dope EuO instead of using undoped films like the authors do in their work. Here we clarify these misconceptions.

As in their work, we used the BTK model[3] to extract the polarization values from fits to the measured voltage-dependent conductance characteristics of the europium oxide-superconductor contacts we fabricated. The BTK model can be used to calculate the interface contribution to the total differential conductance of a device containing a ferromagnet-superconductor contact. The total conductance of such a device is therefore composed of the interface contribution and of the contributions originating from the normal conducting materials in the device. Only in those cases in which the latter can be neglected and in which the total device conductance is dominated by the interface, can the BTK model be directly used to assess the measured data. If the resistance contributions of the materials composing the ferromagnet-superconductor contact are of the same order of magnitude as those of the interface, they have to be accounted for in the modeling of the device. Therefore, careful evaluations of the specific resistances of the normal conducting materials and the device geometry have to precede the data interpretation.

In the design of our Andreev-reflection experiment, we analyzed and tested several contact geometries, including the one used by the authors of Ref. 1. We found that latter configuration has several drawbacks that cannot easily be overcome and therefore refrained from using it. In current-perpendicular-to-plane (cpp) heterostructures consisting of several materials and interfaces, the independent measurement of the diverse contributions to the total conductance of the device is challenging. To avoid these problems, we chose to realize the Andreev contact in an in-plane geometry with only a single interface between europium oxide and superconducting niobium. To avoid shunting of this structure by a conducting substrate, the films were prepared on highly insulating $YAlO_3$, which does not contribute to the overall device resistance. The chosen geometry allows for the independent four-point measurement of the transport properties of the Andreev contact, of the superconducting niobium, and of the EuO on the very same bridge that contains the interface. This configuration therefore provides better control of the individual contributions to the overall device conductance than the geometry used in Ref. 1.

The device geometry we selected for our measurements utilizes a long and narrow bridge that is patterned out of a thin EuO film. This geometry, combined with the high specific resistance of the EuO at low temperatures, creates a non-negligible contribution to the overall device conductance. To account for this linear resistance contribution, we have expanded the BTK model to include the series resistance R. This resistance is a natural consequence of the materials used and the geometry of the device. It can be determined in two independent ways. First, it can be derived as a fitting parameter from the expanded BKT model. Second, R can be calculated independently from the device geometry and the measured specific resistance of the EuO. In our experiments both values of R, the ones extracted from the fits to measured data and the ones measured independently are in good agreement. This approach therefore provides the possibility to double check of the validity of the derived polarization values. This means of independently assessing the data is a great advantage over cpp geometries, where one has to assume that R is small compared to the interface resistance and therefore can be neglected.

A further consequence of the lateral geometry of the Andreev contact we have chosen to use is a strong suppression of the superconducting energy gap Δ at the EuO-Nb interface. With a europium density that exceeds that of europium metal and with $7\mu_B/\mathrm{Eu}$ magnetic moment, EuO is the third strongest ferromagnet after dysprosium and gadolinium. In thin films, the magnetic easy axis lies in plane. Furthermore, because of shape anisotropy considerations, the net magnetization direction of a long narrow bridge is parallel to its long edge. Therefore the magnetic field is coupled into the superconducting niobium with maximum amplitude perpendicularly to the EuO-Nb interface. The strong magnetic field in the lateral geometry leads to a suppression of the superconducting order parameter on the length scale of the London penetration depth. The electrons that undergo Andreev reflection are therefore subject to a superconducting energy gap that is smaller than the bulk gap. This suppression is by far more pronounced in the lateral geometry than in cpp structures, where the magnetization of the EuO film is parallel to the EuO-superconductor interface and hence the field strength in the superconductor negligible. The critical temperature T_c that is determined by temperature-dependent resistance measurements of the superconducting niobium reflects the bulk energy gap and not the gap at the EuO-Nb interface. The smaller value of Δ compared to the BCS value therefore is expected and again reflects the physics of the materials used and the device geometry.

Because undoped EuO is a semiconductor, a contact to a superconducting metal inevitably creates a Schottky diode. The device is therefore characterized by a highly nonlinear current-voltage characteristic, even without the presence of Andreev reflection. As the BTK model does not include this Schottky diode behavior, such contacts cannot be modeled without additional knowledge of the interface parameters and heavy data processing. Indeed, our experiments with undoped EuO-La heterostructures in cpp configuration, comparable to those of Ref. 1, showed conductance curves that were composed of Andreev-reflection-like behavior superimposed on a nonlinear and Schottky-type background conductance. The authors of Ref. 1 seem to have elegantly circumvented this problem but unfortunately do not comment on this key issue in their paper. As we found it impossible to extract meaningful data from an $I(V)$ characteristic distorted by a Schottky behavior, we chose to dope EuO with lanthanum and were thus able to raise the charge-carrier density to level, at which the $\mathrm{Eu}_{0.995}\mathrm{La}_{0.05}\mathrm{O}$-Nb contacts became Ohmic. We therefore were able to use the BKT model to evaluate the measured data. Furthermore the La doping reduces the overall device resistance, making the interface contribution due to Andreev reflection more prominent in the transport measurements, which reduces the error margin of the subsequent data analysis.

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[1] R. P. Panguluri, T. S. Santos, E. Negusse, J. Dvorak, Y. Idzerda, J. S. Moodera, and B. Nadgorny, Phys. Rev. B **78**, 125307 (2008).

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