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

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In a recent paper [R. P. Panguluri *et al.*, Phys. Rev. B **78**, 125307 (2008)] we measured the spin polarization of europium oxide in direct contact with highly conductive silicon. In this Reply we address the issues raised in the preceding Comment [A. Schmehl *et al.* Phys. Rev. B **80**, 237301 (2009)] by discussing the rationale behind the choice of experimental geometries. We argue that the choice of geometries is primarily determined by the objectives of the measurements. While the main goal of our work was to determine the spin polarization of polycrystalline EuO_{1-x} fabricated on a conductive Si substrate, the aim of A. Schmehl *et al.*, Nature Mater. **6**, 882 (2007) was to perform the spin-polarization measurements of epitaxial La_xEuO_{1-x} on an insulating $YAlO_3$ substrate. From this perspective, the statement in our paper was fully justified.

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First, let us emphasize that, in spite of possible disagreements on the specific details of the measurements, we recognize the high level of technical sophistication of the team of Ref. 1 and never questioned the relevance of their results overall. We did mention, however, as we believe correctly, certain advantages of our geometry,[2] compared to the work of Ref. 3. The authors of the Comment claim that in doing so we expressed "several misconceptions" about their work. We will address this issue and clarify our comments below. First, let us quote the statement from our paper, verbatim: "*in this work* (Ref. 3) *La-doped europium oxide films were epitaxially grown on* $YAlO_3$ substrate to measure the La_xEuO_{1-x} spin polarization. As $YAlO_3$ is not conductive, an arbitrarily chosen spreading resistance had to be introduced as an additional adjustable parameter. Similarly, significantly reduced value of the Nb superconducting gap 0.88 meV instead of 1.34 meV, the BCS Nb gap corresponding to the reported transition temperature of 8.5 K was used in order to fit the data." The first part of our comment reflects the fact that, while the main result of our paper was the determination of the spin polarization in polycrystalline EuO_{1-x} on a highly conductive Si substrate,[2] the main results of Ref. 3 was the spin-polarization measurements of epitaxial La_xEuO_{1-x} on an insulating $YAlO_3$ substrate. The choice of geometries was primarily determined by these different goals. Obviously, both the current perpendicular to the plane (CPP) geometry used by us and the lateral geometry used in Ref. 3, have their advantages and disadvantages and we certainly agree that, compared to the CPP geometry, lateral geometry would provide a better means to characterize La_xEuO_{1-x} independently. However, while growing epitaxial film on Si without a buffer layer is difficult,[4] our approach makes it possible to grow highly spin-polarized EuO film in direct contact with silicon substrate,[5] in the geometry that can be immediately useful for spin injection into Si, *and to measure the spin polarization in the same geometry.*

In the second part of the quoted paragraph we referred to the uncertainty in choosing of the so-called spreading resistance, R_c,[6] used as an *adjustable parameter*, as a part of the fitting procedure, in which the total of four adjustable parameters have been used. As it was stated in Ref. 3, the spreading resistance cannot be measured directly in their geometry because it partly originates from the contact itself.[7] What makes the situation even more difficult, however, is the fact that the value of the gap obtained in this procedure, which was also an adjustable parameter, is reduced compared to the bulk value. While we agree that it is not unreasonable to assume that large edge magnetic fields resulting from the in-plane magnetization of the La_xEuO_{1-x} film would suppress the superconducting order parameter Δ in Nb, *the exact degree* and *even the uniformity*[8] of this suppression is not known.[9] Therefore, while the use of spreading resistance is perfectly acceptable and, in fact, unavoidable in this geometry, the two parameters Δ *and* R_c are interdependent.[6] As it was demonstrated in Ref. 6, it is very easy to compensate for the uncertainty in the spreading resistance by the uncertainty in the gap, which would, in turn propagate into the determination of the spin-polarization values.

In our geometry, on the other hand, we have used the same modified[10] Blonder, Tinkham, and Klapwijk (BTK) model,[11] as in Ref. 3, but with only two variable parameters (Z and P), assuming no spreading resistance, as the resistance of the Si substrate (measured independently) and the Si/EuO interfacial resistances were small compared to the InSn/EuO contact resistance. While, indeed the Schottky barrier is always present at the interface between a metal and a semiconductor, its effects can be alleviated by using heavily doped silicon substrates, reducing the effective width of the Schottky barrier, as was done in Ref. 2. Importantly, the experimental conductance at and above the critical temperature within the relevant mV range *does not change*, see Figs. 3 and 4 of Ref. 2. It is only below the superconducting transition the resistance within the superconducting gap starts to deviate from its value outside the gap, finally becoming much larger at lower temperatures, a clear indication of the suppression of Andreev reflection. Suppose, though, that there is still some small temperature- and voltage-independent contribution of the Schottky barrier present in the *I-V* characteristics. In order to circumvent this potential problem, in addition to analyzing the conductance curves, we have implemented another technique (insensitive to the value of the Si/EuO interface resistance) following Ref. 12, wherein we have independently numerically fitted the temperature-dependent resistance data below the superconducting transition temperature to extract the P using the modified BTK model,[10] with the BCS value of the gap, with the correct temperature dependence (Fig. 5 of Ref. 2). The fact that the values of spin polarization obtained by both techniques coincide within the experimental error, allowed us to conclude that the possible impact of the Schottky barrier was negligible.

In summary, we believe, based on the information available in the original paper (Ref. 3), that our comments on the advantages of the CPP geometry for our specific materials system (EuO/Si) were justified. Most importantly, though, we would like to emphasize that both groups came to the same conclusion concerning the high spin-polarization value of EuO (Ref. 13) while utilizing different sample geometries and different underlying assumptions. The results, however, *are in agreement and are, therefore, independent of those underlying assumptions*, strongly indicating that EuO is a half-metal, which makes this interesting material a potential candidate for efficient spin injection in silicon.[2]

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[6] G. T. Woods, R. J. Soulen, I. I. Mazin, B. Nadgorny, M. S. Osofsky, J. Sanders, H. Srikanth, W. F. Egelhoff, and R. Datla, Phys. Rev. B **70**, 054416 (2004).

[7] While in their Comment it was stated that the values of the spreading resistance have been estimated using the known film geometry and conductance, this was not mentioned in Ref. 3.

[8] This nonuniformity can result in a variable gap across the junction; see, for example, J. G. Braden, J. S. Parker, P. Xiong, S. H. Chun, and N. Samarth, Phys. Rev. Lett. **91**, 056602 (2003).

[9] Related effects might also be attributed to the direct exchange interaction between Eu^{++} ions and Nb electrons, see, for example, X. Hao, J. S. Moodera, and R. Meservey, Phys. Rev. Lett. **67**, 1342 (1991).

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[11] G. E. Blonder, M. Tinkham, and T. M. Klapwijk, Phys. Rev. B **25**, 4515 (1982).

[12] J. Aumentado and V. Chandrasekhar, Phys. Rev. B **64**, 054505 (2001).

[13] We would also like to point out the strong similarities in the high quality of the XMCD data in Ref. 3, as well as that in Ref. 2.