FINAL REPORT

Novel Behavior of Ferromagnet/Superconductor Hybrid Systems

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This DOE-funded project lasted from September, 2006 through May 31, 2016. By any objective measure, it was very successful. Fifteen refereed papers were published on this DOE-funded work, including three in Physical Review Letters and one in Nature Physics. One of the three PRL's has been cited over 200 times, and is considered by most workers in the field to represent the most convincing experimental demonstration that spin-triplet supercurrent can appear in Josephson junctions containing ferromagnetic materials, even when the superconducting electrodes are conventional, spin-singlet superconductors. Two years ago the PI was invited to write a chapter in a forthcoming special issue of Philosophical Transactions A. (Unfortunately, the issue has not yet been published, even though the original deadline of June, 2015 was met.) The PI has given invited talks on this work at 24 international conferences, including most recently a semi-plenary talk at the Joint European Magnetics Symposia (JEMS-2016) held in Glasgow, Scotland. As a result of the work produced under DOE support, the PI is now considered to be one of leading experts in the world in the area of superconducting/ferromagnetic hybrid systems.

Below is a brief summary of the most important achievements of this project. (Citation counts are from the ISI Science Citation Index.)

- Exploration of supercurrent through Josephson junctions containing a weak ferromagnet alloy with thicknesses up to 100 nm – much thicker than previously achieved: Phys. Rev. B **79**, 094523 (2009), **cited 43 times**.
- Demonstration that using a synthetic antiferromagnet (SAF) successfully cancels the internal magnetic flux in large-area Josephson junctions, enabling one to observe supercurrent in junctions containing strong ferromagnetic materials such as Co: Phys. Rev. B **80**, 020506(R) (2009), **cited 21 times**.
- Observation of spin-triplet supercurrent in Josephson junctions containing strong ferromagnetic materials: Phys. Rev. Lett. **104**, 137002 (2010), **cited 224 times**.
- Observation of several oscillations in the sign of the proximity-induced density of states corrections as a function of ferromagnetic layer thickness, observed by tunneling: Phys. Rev. B **84**, 020510(R) (2011), **cited 15 times**.
- A study of the area-dependence of the critical current in ferromagnetic Josephson junctions revealed some patterns that are not thoroughly understood: Phys. Rev. B **85**, 214522 (2012), **cited 11 times**.
- Observation of a large enhancement of the spin-triplet supercurrent by optimization of the ferromagnetic layer magnetizations: Phys. Rev. Lett. **108**, 127002 (2012), **cited 57 times.**
- Demonstration of spin-triplet supercurrent in Josephson junctions using a middle ferromagnetic layer with perpendicular magnetic anisotropy: Phys. Rev. B **86**, 224506 (2012), **cited 19 times**.
- Demonstration of amplitude control of spin-triplet supercurrent by rotating the orientation of one of three magnetic layers in micron-scale Josephson junctions: Phys. Rev. Lett. **116**, 077001 (2016), not yet cited.
- Demonstration that the ground-state phase difference across a Josephson junction can be controllably switched between zero and pi by rotating one of two ferromagnetic layers in the junction while keeping the other fixed (partial DOE support): Nature Physics **12**, 564 (2016), **cited 1 time**.

The following graduate students were supported mostly from this DOE grant while carrying out their PhD research. They have all graduated and have gone on to jobs in academia, industry, or national labs.

- Trupti Khaire, graduated 2010
- Mazin Khasawneh, graduated 2010
- Yixing Wang, graduated 2013
- Eric Gingrich (partial DOE support), graduated 2014
- William Martinez, graduated 2015

In addition, fourteen undergraduate students participated in DOE-funded research during the duration of the grant.

The discovery of spin-triplet supercurrent in ferromagnetic Josephson junctions has spurred several writers to name a new subfield of condensed matter physics: “superconducting spintronics.” Under DOE support (and more recent IARPA support), we have played a major role in the appearance of this new field, and we hope to be able to make further contributions to its development in the near future.