1. GRANT:

DE-SC0008630, Purdue University

2. TITLE:

"Engineering topologically protected superconducting states ", PI Prof. Leonid P. Rokhinson

3. DATE OF REPORT:

January 25, 2022

4. SUPPORTED PERSONNEL:

graduate students:
- Ananthesh Surandesh, expected graduation Fall 2022
- Zhong Wan, graduated Spring 2018
- Ying Wang, graduated Summer 2021

postdoctoral associates:
- Dr. Alexander Kazakov, partial support during 2018-2019
- Dr. Tailung Wu, partial support during 2018

5. PUBLICATIONS SINCE 2018 PROGRAM RENEWAL (ACKNOWLEDGE DOE DE-SC0008630 SUPPORT):

- Morteza Kayyalha, Aleksandr Kazakov, Ireneusz Miotkowski, Sergei Khlebnikov, Leonid P. Rokhinson, Yong P. Chen, *"Highly skewed current–phase relation in superconductor–topological insulator–superconductor Josephson junctions"* **npj Quantum Materials**, **5** 7 (2020)
- Michele Kotiuga, Zhen Zhang, Jiarui Li, Fanny Rodolakis, Hua Zhou, Ronny Sutarto, Feizhou He, Qi Wang, Yifei Sun, Ying Wang, Neda Alsadat Aghamiri, Steven Bennett Hancock, Leonid P. Rokhinson, David P. Landau, Yohannes Abate, John W. Freeland, Riccardo Comin, Shriram Ramanathan, and Karin M. Rabe, "Carrier localization in perovskite nickelates from oxygen vacancies" **PNAS** article 201910490 (2019)
- Morteza Kayyalha, Mehdi Kargarian, Aleksandr Kazakov, Ireneusz Miotkowski, Victor M. Galitski, Victor M. Yakovenko, Leonid P. Rokhinson, Yong P. Chen, *"Anomalous low-temperature enhancement of supercurrent in topological-insulator nanoribbon Josephson junctions: evidence for low-energy Andreev bound states"* **Phys. Rev. Lett. 122**, 047003 (2019)
- Tailung Wu, Zhong Wan, Aleksandr Kazakov, Ying Wang, George Simion, Jingcheng Liang, Kenneth W. West, Kirk Baldwin, Loren N. Pfeiffer, Yuli Lyanda-Geller, and Leonid P. Rokhinson, *"Formation of helical domain walls in the fractional quantum Hall regime as a step toward realization of high-order non-Abelian excitations"* **Phys. Rev. B 97**, 245304 (2018)
- Luis A. Jauregui, Morteza Kayyalha, Aleksander Kazakov, Ireneusz Miotkowski, Leonid P. Rokhinson, Yong P. Chen, *"Gate-tunable supercurrent and multiple Andreev reflections in a superconductor-topological insulator nanoribbon-superconductor hybrid device"*, **Appl. Phys. Lett. 112**, 093105 (2018).

6. SUMMARY OF THE WORK PERFORMED TOWARD PROPOSAL OBJECTIVES.

Objective #1 *Development of ballistic Josephson junctions toward Abelian protected qubits.* In this work we develop Josephson junctions with highly unharmonic current-phase relation. Combination of several JJ with large second harmonic is a potential route to topologically protected qubits without yet-to-be-discovered non-Abelian excitations. Along this objective we developed highly transparent superconductor-topological insulator contacts where multiple Andreev reflection is observed (APL 2018), studied low-energy in-gap states in topological insulator-based Josephson junctions and discovered unexpected enhancement of critical supercurrent beyond Bardeen-Cooper-Schriffer model (PRL 2019), and, finally, reported ballistic SC-TI-SC

Josephson junction with the most skewed (unharmonic) current-phase relation with the second harmonic reaching 40% (42% is theoretical maximum), (npj Quantum Materials 2020). These Josephson junctions can be used as building blocks to form Kitaev-Ioffe rhombi topological qubit.

Objective #2 *Development of the parafermion-supporting platform: investigation of a charge transport in helical domain walls in the fractional quantum Hall state* $\nu = 2/3$ Along the lines of this objective we demonstrated formation of a single helical domain wall with fractionalized excitations in the fractional quantum Hall state $\nu = 2/3$ (PRB 2018). Careful study of electron transport through these new object show that a naïve model of two counter-propagating $\nu = 1/3$ edge states with opposite spin overestimates measured conductance by a factor of 10, and, in collaboration with theory colleagues, a detailed mesoscopic theory based on the Luttenger liquid approach has been developed (Proc. SPIE 2021). Detailed comparison of theory and experiment reveals formation of complex helical state with counter-propagating charge, spin and neutral modes which, coupled to a conventional superconductor, should result in a topological superconducting state with fractionalized high-order non-Abelian excitations (Nat. Comm. 2021). The latter part of this work was supported by NSF(experiment) and DOE(theory).

Objective #3 *Fabrication of circular/elliptical nanowires with built-in charge sensors, detection of topological boundaries in curved nanowires and Majorana braiding in connected structures.* This was the most intensively pursued objective, yet we discovered that almost every assumption which was built into the design and based on previously published results has to be revised and re-evaluated. First, we discovered that in circular and elliptical devices in-plane field creates connected superconducting pathes that results in the formation of two equally-probable states with different winding number (in all previously studied rings the higher winding number states are exponentially suppressed). Careful studies of straight nanowires fabricated from InAs/Al heterostructures revealed unexpected critical current non-reciprocity in the presence of in-plane magnetic field. Re-examination of an old (late '90s) theory which "predicted" such effect led to a conclusion that the theoretical work was plain incorrect and another mechanism should be at play. In collaboration with two theoreticians we examined several models which may lead to the appearance on non-reciprocity in InAs/Al heterostructures and found formation of Josephson vortices between Al and proximatized InAs as a most plausible scenario. If our understanding is correct, it would prevent observation of Majorana fermions in InAs/Al heterostructures, which is one of the leading platforms pursued by several groups including Microsoft Quantum. Considering importance of these conclusions it took us longer than usual to write a manuscript, a draft is currently in the latest stages of preparation and will be submitted to a publication soon. The summary of the results will be presented at the 2022 APS March Meeting.