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What can we learn from the reported discovery of Majorana states?

InAs-Al Hybrid Devices Passing the Topological Gap Protocol
Authors: Microsoft Research
arXiv:2207.02472v2

Recommended with a Commentary by Anton Akhmerov, Kavli Institute of Nanoscience, Delft University of Technology

Conflict of interest disclosure: several of my former collaborators and colleagues are authors of the preprint; some of my current and former collaborators are partially funded by Microsoft Research; the preprint closely relates to my research, both past and ongoing. In formulating this opinion I did my best to only rely on what is stated in the preprint.

The Microsoft preprint is the latest development in the search for Majorana states in semiconductor-superconductor hybrid structures—a building block for protected qubits—that started with the visionary idea of Kitaev in 2000 [1]. At first glance, the new work satisfies a much higher standard of quality than what has been customary for the quantum transport community, and it is the main output of a collaboration of 127 researchers working in multiple locations across the globe. On the other hand, a retraction of an earlier visible result in the same line of research [2] ensured that the new works in the field are subject both to increased attention, and a higher degree of scrutiny. The evaluation of the new results by experts in the field ranges from an endorsement [3], to a dismissal [4]. In the following I will argue for another point of view: I believe that the work has high quality, but that the manuscript misses a lot of information for it to have scientific influence.

The main challenge in creating Majoranas is combining several ingredients that are not naturally compatible: semiconductors, superconductors, and strong magnetic fields. This needs to be done with an extremely high degree of quality control so that the resulting system is not dominated by disorder. Furthermore, almost every individual property of Majorana states can be mimicked by regular Andreev states in a disordered superconductor. The new work claims to address both of these problems. The authors report combining extensive material research with systematic and detailed numerical simulations. These two developments allow them to create a nanostructure likely to support Majorana states. To deal with the Majorana signatures not having high specificity, they develop the *topological gap protocol* [5]. This is an algorithm for an automated search of regions in the gate voltage and magnetic field parameter space, where Majorana states are likely to exist, and then verifying that these regions meet the required quality criteria. By applying the protocol to the numerical simulations, the authors observe no false positives given their selected quality thresholds. Based on this observation they bound the false positive rate to be $< 2\%$. When the protocol ‘clicks’ on three experimental samples, the authors conclude that these samples must contain Majorana states with an overwhelming probability.

Taking all the claims made in the preprint at face value still leaves years of work and conceptual development necessary to create qubits out of Majoranas. Firstly, the manuscript does not report the residual coupling between two zero energy resonances at the ends of the nanowire, nor does it show the symmetric part of the nonlocal conductance measurements that could be used to estimate this residual coupling. They do, however, state that the numerics estimates the Majorana localization length to be around 1 µm, and report the length of device A to be 3 µm. The 1/3 ratio between two length scales leaves only an order of magnitude energy scale for the qubit operation frequency, while this window must be exponentially broad for the qubit to benefit from the topological protection. In agreement with this observation, the manuscript also vaguely indicates that the numerics identified 10 µm as the desirable device length. I presume that the experiments were performed on shorter devices either because the longer devices become too inhomogeneous or because the nonlocal conductance measurements are not reliable enough in detecting transport over these longer distances. In addition to increasing the device size, one also needs to ensure that multiple neighboring wires function together: a single Majorana qubit requires 4 Majorana states or 2 nanowires similar to the ones measured. In the end, once one meets the fabrication and tuning yield requirement to combine multiple longer nanowires into a single working device, they need to add another completely unrelated bit of physics machinery: control over the device charge on a single electron level.

Turning to the study procedure described in the manuscript, I conclude that it introduced statistical biases that lead to overestimating the confidence in the final result. When describing numerical simulations, the manuscript states:

> The purpose of these simulations is not to establish qualitative similarities between simulated and measured data. The purpose of these simulations is to test the TGP on simulated devices in which we can compare the results of the TGP with a topological invariant.

In other words, the authors determine the false positive rate based on the numerical simulations, even though they do not establish quantitative statistical correspondence between the simulations and the measurements. Further, the manuscript does not state how the authors selected the protocol parameters. If the parameters were chosen by running the numerical simulations first, and then choosing the loosest criteria that still give no false positives, the procedure would bias the expected amount of false positives to be lower than the true one. On a more subtle note, the manuscript does not make a clear distinction between the total number of false positives and the false positive rate—the probability that a trivial sample would be identified as a topological one. The former depends on the rate of occurrence of negatives, the latter does not, and identifying one with the other is known as the base rate fallacy. Given the overall approach chosen by the authors, a possible statistically reliable way to perform this experiment would require the following steps:

1. Design a numerical model and demonstrate that the model properties reliably match the properties of real samples.

2. Fix the protocol parameters and assess its performance using a separate set of validation data.

3. Determine the likelihood that the samples passing the protocol are indeed topological.

I expect that the above gaps in the argumentation and the study design, while severe, are not insurmountable. On a technical level, the work appears to be of excellent quality both due to the amount of information collected, and the effort invested in systematic analysis of all relevant aspects of the problem. Given the combined expertise of the team, it is quite possible that even after correcting for the statistical biases, the measured devices will pass a quality test for Majorana states. However, another aspect of the manuscript prevents it from being useful to the broader scientific community. The description of what the authors have done is so vague that it does not allow any independent validity checks, nor can it inform follow-up research. For example, while the authors likely performed the highest quality numerical simulations of this type, the description of the numerical model stops at only naming the general building blocks that were used. The description of the devices is equally minimal. For example, the manuscript does not state what barrier layer or gate dielectric were used—the choices that were critical to the device performance, according to the work.

At face value, this work is far from a qubit. It does not (yet) clearly demonstrate the creation of Majorana states. It does not contain enough information to be reusable by others. It does, however, demonstrate an important idea. I believe that the overall spirit of the work is something that the condensed matter community can benefit from. It shows the ability to coordinate the effort of large teams with complementary expertise. It proves that a quantitative and rigorous analysis is possible even in the field of quantum transport. I applaud the approach followed by the Microsoft Research team, and I hope that our community will take this as an inspiration.

References

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