Graphene-based Josephson Triode

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There has been a growing interest to the materials with broken time-reversal and inversion symmetry, which can support non-reciprocal superconducting currents [1]. This search for an intrinsic superconducting diode has so far resulted in devices that typically show a few percent difference between the magnitudes of the supercurrent flowing in the positive and negative directions. We show that required time-reversal symmetry breaking can be achieved in multiterminal Josephson junctions [2], resulting in supercurrent rectification approaching 100%.

In our samples, several superconducting leads (left, right, and bottom: L, R, and B) are coupled via gate-tunable graphene Josephson junctions. The state of one of the junctions, e.g. between the left and bottom contacts (LB) can be controlled by the non-dissipative current flowing in the right contact, I_R. The phase difference induced by the control current creates the required time-reversal symmetry breaking. At zero control current, the controlled junction demonstrates a symmetric I-V curve, which becomes progressively asymmetric as the control current is tuned (Figure 1). At $I_R = – 100$ nA, the supercurrent exists for the positive direction of I_L and is equal to zero for the negative direction; the rectification is complete.

The observed asymmetry of the supercurrent can be used to rectify a square wave applied to the junction, in a way a conventional diode rectifies AC current. Figure 2 demonstrates the voltage across the LB junction, upon application of a square wave current I_L. Setting the control current $I_R = \pm 50$ nA, either the positive or the negative part of the waveform yields zero V_{LB}, while the part of the waveform with the opposite I_L results in finite voltage. For comparison, at zero control current, the LB junction remains superconducting throughout the same range of I_L.

We speculate that the three-terminal junctions considered here, to which we refer as "Josephson triodes", may potentially find application in cryogenic microwave engineering, such as superconducting quantum information processing.

[1] F. Ando *et al.*, Nature **584,** 373 (2020). https://doi.org/10.1038/s41586-020-2590-4.

[2] A.W. Draelos *et al.*, Nano Lett. **19,** 1039 (2019). https://doi.org/10.1021/acs.nanolett.8b04330.

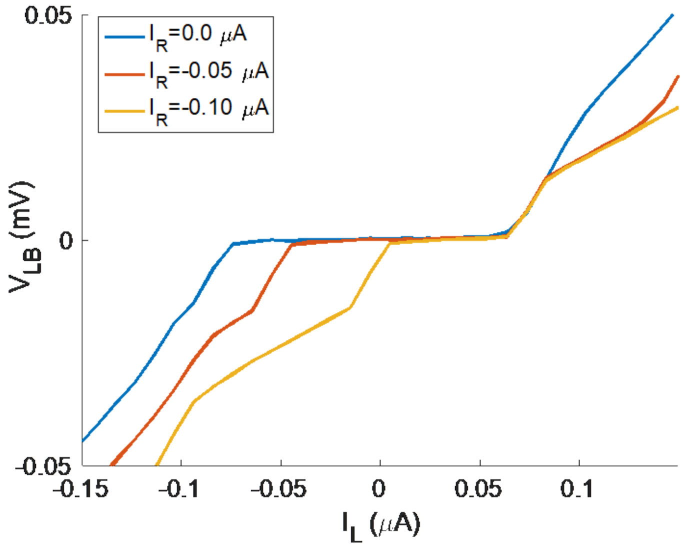

Fig.1: I-V curves of the left-bottom junction as a function of the control supercurrent flowing in the right contact. .

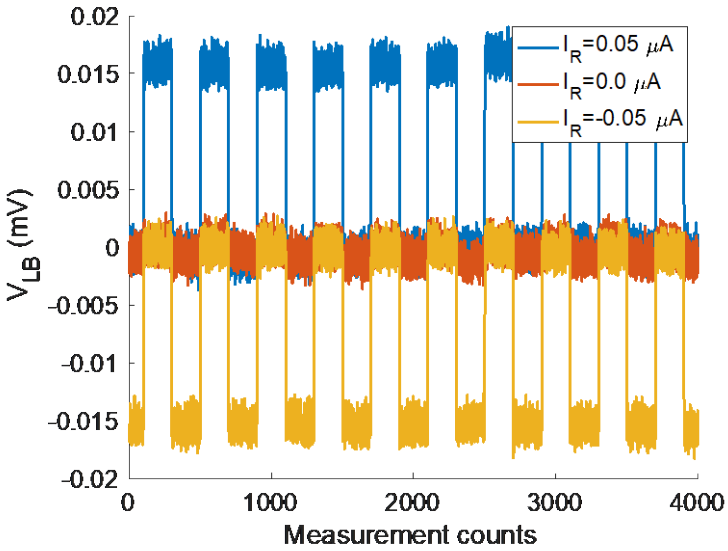

Fig.2: Voltage in the left-bottom junction as a function of time, while a square wave current is applied to the same junction. Depending on the current in the right (control) junction, the voltage across the controlled junction is zero (corresponding to the supercurrent) either for the positive (yellow), or negative (blue), or both directions (red) of the square wave. .