MEASUREMENT Application note

Topological insulator Josephson junctions

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Introduction

In a topological insulator (TI), the electronic structure of the bulk reveals a unique topology that leads to the formation of conducting surface states with intriguing properties.

The topological protection of the surface states and the possible emergence of Majorana fermions in superconductor/TI hybrid devices make these materials a leading candidate for use as a robust platform for future fault-tolerant quantum computation.

The main challenge in creating these structures lies in the fabrication of an electrically transparent interface between the conventional superconductor and the topological insulator. A Josephson junction, formed by two closely spaced superconducting electrodes separated by a gap of less than 100 nm, can be used as a measure of the quality of the electrical interface. At low temperatures the superconducting electrodes induce superconductivity in the topological insulator by the proximity effect, with a finite Josephson current observed across a sufficiently narrow gap.

Triton and **Nanonis Tramea**

Equipment used

Oxford Instruments **Triton 200** dilution refrigerator
Nanonis Tramea with lock-in module
Keithley 2450 Source meter
NF LI-75A preamplifier
Tabor 9200 high-voltage amplifier

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Experimental set-up

For our experiment, Josephson junctions are fabricated using electron beam lithography and the deposition of high quality aluminium on an ultra-thin flake of the topological insulator $BiSbTeSe_2$ (BSTS2), which has bulk-insulating properties.

The device was installed on the mixing chamber of an Oxford Instruments **Triton 200** dilution refrigerator and measured at a temperature of less than 8 mK. Using a superconducting solenoid magnet installed on the Oxford Instruments **Triton**, magnetic fields of up to 6.8 mT were applied during these experiments. The magnetic field was driven with a **Keithley 2450** current source via the **Nanonis Tramea** external devices module. A maximum current of 100 mA was applied to the superconducting magnet of the dilution refrigerator. The current was changed slowly with a maximum rate of 0.5 mA/s. DC bias sweeps were performed every mA whilst keeping the current fixed.

In order to distinguish between a supercurrent through the bulk and that through the surface, we perform gating of the device by using a back-gate voltage applied to the back side of the Si/SiO_2 substrate.

The size of the critical current of the fabricated Josephson junction is obtained from the IV-characteristics of the device. A four terminal resistance measurement is performed by applying a biased AC current ($I = I_{DC} + I_{AC}$) and measuring the voltage drop with the lock-in amplifier module of **Nanonis Tramea**.

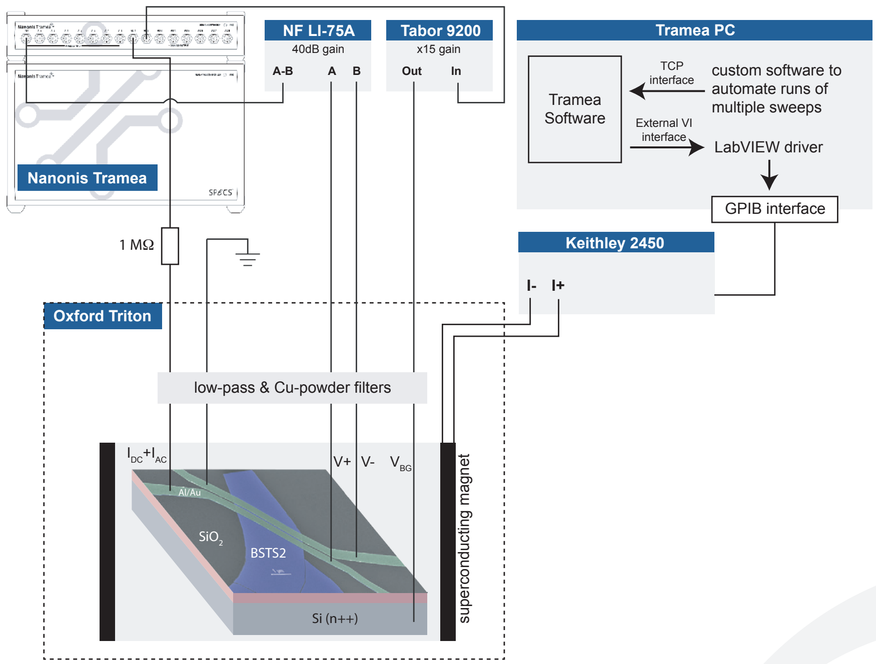

Figure 1. Schematic of the measurement setup.

Experimental results

The differential resistance of the device was measured whilst stepping the DC current biases from 0 to 0.3 μA in 121 steps. As the magnitude of the voltage to be measured using the **Nanonis Tramea** was in the range of 10 nV up to a few μV, a preamplifier was used. Each bias sweep took 9 seconds and the magnetic field was driven with a **Keithley 2450** current source via the **Nanonis Tramea** external devices module.

LabVIEW software was written to control the **Tramea** via the TCP interface to run several sweeps automatically to check for reproducibility. A gate voltage of up to 80 V was applied to the device using a **Tabor 9200** high-voltage amplifier with a fixed gain (x 15) connected to one of the ± 10V outputs of the Nanonis Tramea.

The measurements were repeated with both positive and negative bias current and with opposite magnetic field directions. The results were fully symmetric (Figure 2) and the shape of the observed oscillations gives insight into the microscopic details of the Josephson junction.

The critical current changes as a function of an applied magnetic field and a Fraunhofer pattern is observed. This pattern was measured using Nanonis Tramea in the setup shown schematically in Figure 1.

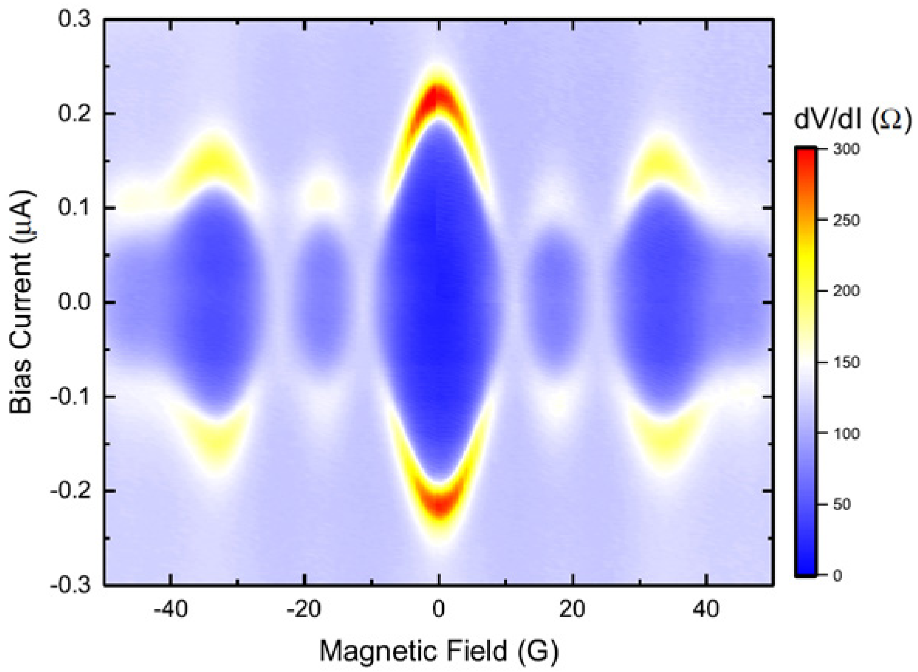

Figure 2: Fraunhofer pattern of a topological insulator Josephson junction measured using **Nanonis Tramea**.

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Conclusion

In summary, topological-insulator-based superconducting devices have been fabricated and at cryogenic temperatures a Fraunhofer pattern of the Josephson junction measured, providing insight into the microscopic details of the junction.

The full data set for either a positive or negative magnetic field and bias current was acquired in 20 minutes with **Nanonis Tramea**. Previously the same data taken with conventional lock-in amplifiers and **LabVIEW** controlled instrumentation typically took several hours to obtain. Using **Nanonis Tramea**, faster data acquisition was possible due to the rapid processing rate and the precise control of settling and averaging times.

Further reading
"Anomalous Fraunhofer patterns in gated Josephson junctions based on the bulk-insulating topological insulator $BiSbTeSe_2$", Subhamoy Ghatak, Oliver Breunig, Fan Yang, Zhiwei Wang, Alexey A. Taskin, Yoichi Ando - Nano Letters 2018 18 (8), 5124-5131, https://pubs.acs.org/doi/full/10.1021/acs.nanolett.8b02029.

About **Triton** and **Nanonis Tramea**

The ultra low temperatures and high magnetic fields provided by the **Triton** dilution refrigerator make it a key research tool in revealing the quantum properties of many materials of interest. The **Triton** systems already lead the way in experiment-readiness with high-density RF and DC wiring capability, unique sample exchange mechanisms, and unbeatable superconducting magnet integration. SPECS' **Nanonis Tramea** QTMS is a natural complementary partner to the **Triton**, with its fast, multi-channel, multi-functional capability. The system enables quantum measurements to be carried out on a variety of samples, as shown in this application note.

Nanonis Tramea multifunctional, low noise, low drift and high resolution electronics.

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