Bound States and Tomasch Oscillations in TI-SC Heterostructures

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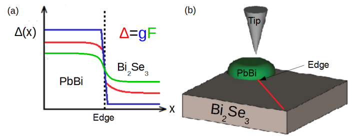
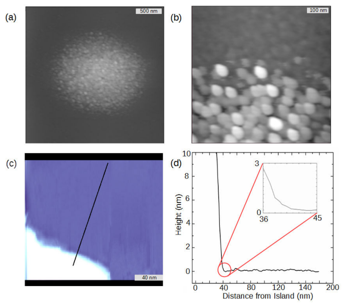
Abstract

Tomasch oscillations occur in systems where there is a spatial variation in the electron-electron interactions which give rise to the superconducting pairing potential.[1, 2] For example they can occur in states bound within superconducting junctions or islands. Here we report on Tomasch-like oscillations which have been found to occur in Superconducting-Topological Insulator structures.[3] In particular in superconducting islands deposited on top of the topological insulator Bi_2Se_3. We go on to consider their existence in junctions formed from Topological Insulators, or topological insulator surface states, and superconductors by calculating the local density fo states in these systems.

Heterostructures

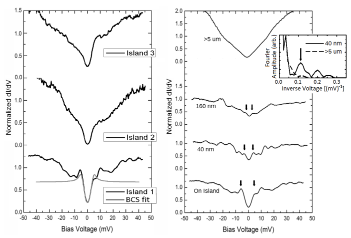


A schematic of the set-up considered.[3] $Bi_{2.04}Se_{2.96}$ which features a single Dirac cone for the topological insulator surface states (TISS). $Pb_{0.3}Bi_{0.7}$ is used as the superconductor ($\Delta_{\mathrm{Pb}} = 3.65$ meV and $T_c = 8.2$ K)



AFM and STM topographs demonstrating the structure of these islands. The PbBi dots appear to be comprised of many 20-100 nm radius droplets grown on top of and around one another. (c) is an STM topograph showing the edge of one of such droplet formations, along with the respective height profile in (d).[3]

Experimental Results



The right panel represents dI/dV curves measured at 4.2 K taken at various distances from a PbBi island. The LDoS displays clear signature of the induced superconducting gap. Another notable feature of the presented data is visible oscillations, the frequency of oscillations is visible in the Fourier transforms shown in the inset. The left panel represents dI/dV curves measured on different islands at nominally the same conditions. Above the gap one can see not only oscillations but also traces of the Dirac cone at higher energies.[3]

We will compare this to two models.

- Check a disorder model using Usadel equation to rule out that the effect is due to trivial surface states.
- In the clean limit we solve a model for the topological surface states.

Inverse Proximity Effect

To understand the TISS leaking into the superconductor we write a phenomenological model:

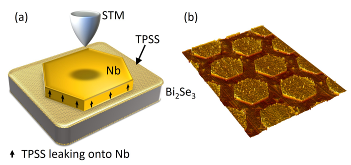
$$H = \boxed{H_{\mathrm{metal}} + H_{\mathrm{BCS}}} + \boxed{H_{\mathrm{TISS}}} + \boxed{H_{\mathrm{coupling}}}$$

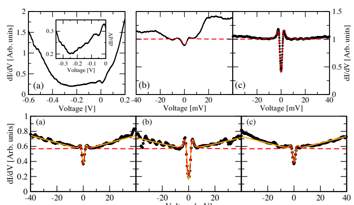
Niobium Island

Dirac states leaked into Nb

Local spin independent coupling

We can compare this to experiments done on superconducting Nb islands:





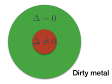
Local density of states measurements[4]. In the lower panels:

- Black dots are experimental results
- Red lines are BCS fits
- Orange lines are our phenomenological model

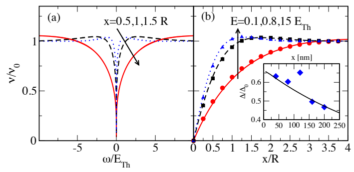
Theory for Diffusive Limit

Usadel equation for a circular geometry describing a superconducting island of radius R surrounded by an infinite normal system. In the normal region:

$$\frac{\partial^2\theta}{\partial x^2} + \frac{1}{x}\frac{\partial\theta}{\partial x} + \frac{i\omega}{E_{\mathrm{Th}}}\sin\theta = 0$$



- $x = r/R$
- Thouless energy: $E_{\mathrm{Th}} = v_F l/2R^2$
- l is mean free path
- v_F is Fermi velocity



The inset shows a comparison between the gap found experimentally (blue diamonds) and the theory (solid line)[3]

Superconducting coherence length for disordered surface states is in the range of $\xi = \sqrt{v_F l/\Delta} \sim 200$ nm. However, in order to fit the inset in (b) a Thouless scale orders of magnitude out is required, and no oscillatory features can be reproduced.

The local density of states is

$$\nu(x,\omega) = \nu_0 \Re\cos[\theta(x,\omega)]$$

In a linearised regime, for $x \gg 1$,

$$\theta(x,\omega) = \theta_0(\omega)\frac{K_0(x\sqrt{i\omega/E_{\mathrm{Th}}})}{K_0(\sqrt{i\omega/E_{\mathrm{Th}}})}$$

$K_0(z)$ is the modified Bessel function

$\theta_0 = \cos^{-1}(\nu_{\mathrm{BCS}}/\nu_0)$

Typical values for Bi_2Se_3 surface states are

- $v_F \simeq 5 \times 10^5$ m/s
- $l \simeq 80$ nm
- $R \simeq 500$

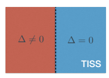
Theory for TISS Model

Proximity effect relevant for TISS described by Gor'kov's equation:

$$\begin{pmatrix} i\omega_n - H & i\sigma^y\Delta_x \\ -i\sigma^y\Delta_x^\dagger & -i\omega_n - H^* \end{pmatrix}\begin{pmatrix} G_{n,k_y}(x,x') \\ F_{n,k_y}^\dagger(x,x') \end{pmatrix} = \begin{pmatrix} \delta(x-x') \\ 0 \end{pmatrix}$$

with a Hamiltonian

$$H^{(*)} = v_{Fx}\begin{pmatrix} 0 & \pm\hat{k}_x - ik_y \\ \pm\hat{k}_x + ik_y & 0 \end{pmatrix}$$



Assuming a perfect interface the local density of states is

$$\nu(x,\omega) = -\frac{1}{\pi}\Im\int_{-\infty}^{+\infty}\frac{dk_y}{2\pi}\mathrm{Tr}\left[G_{n,k_y}^{T,S}(x,x)\right]_{i\omega_n \to \omega + i\delta}$$

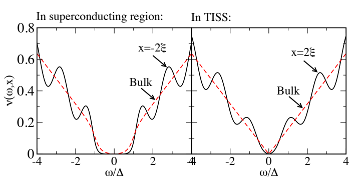
resulting in

$$\nu(x,\omega) = \frac{|\omega|\Theta(|\omega|-\Delta_x)}{2\pi v_{Fx}^2}\left[1 - J_0\left(\frac{2x\sqrt{\omega^2-\Delta_x^2}}{v_{Fx}}\right)\right]$$

J_0 is the Bessel function of the first kind

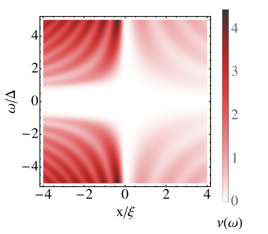
Displays Friedel-like oscillations induced in the LDoS in the normal side of the junction. The energy scale of these oscillations, $v_{FT}/2x$, are of the same order of magnitude as those we see experimentally

On the superconducting side it implies oscillatory LDoS with Tomasch-like functional dependence on energy and position, which physically originates from quasiparticle scattering as induced by a nonuniform superconducting order parameter



The local density of states, in arbitrary units, as a function of energy for the topological insulator system with $\Delta = 1$ and $v_{FT} = 2v_{FS} = 1$. A phenomenological damping of magnitude $\Gamma = 0.25\Delta$ is included. The position is measured in units of the superconducting coherence length $\xi = v_{FS}/\Delta$.[3]

Proximity effect in topological insulator surface states[3]



References

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[2] T. Wolfram, "Tomasch oscillations in the density of states of superconducting films," Physical Review, vol. 170, pp. 481–490, jun 1968.

[3] I. M. Dayton, N. Sedlmayr, V. Ramirez, T. C. Chasapis, R. Loloee, M. G. Kanatzidis, A. Levchenko, and S. H. Tessmer, "Scanning tunneling microscopy of superconducting topological surface states in Bi2Se3," Physical Review B, vol. 93, p. 220506, jun 2016.

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