

Bound States and Tomasch Oscillations in TI-SC Heterostructures



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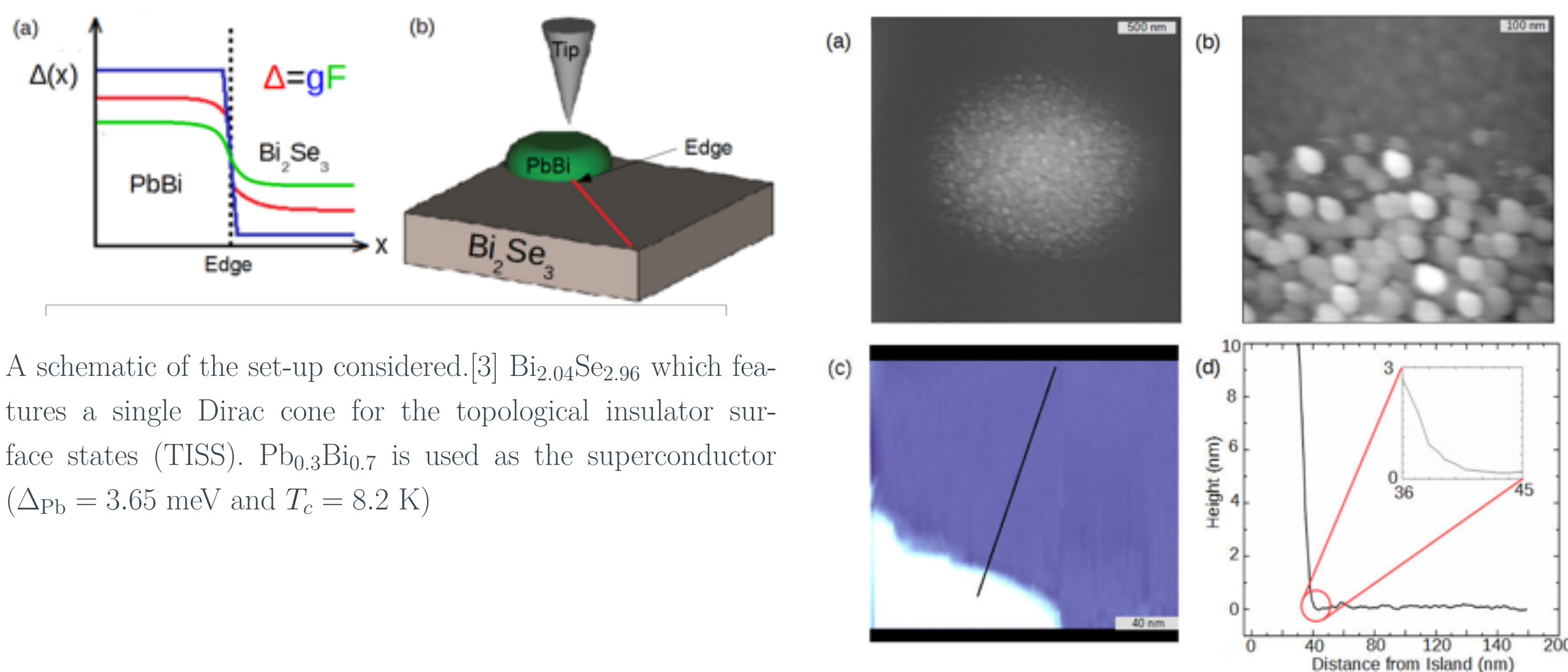
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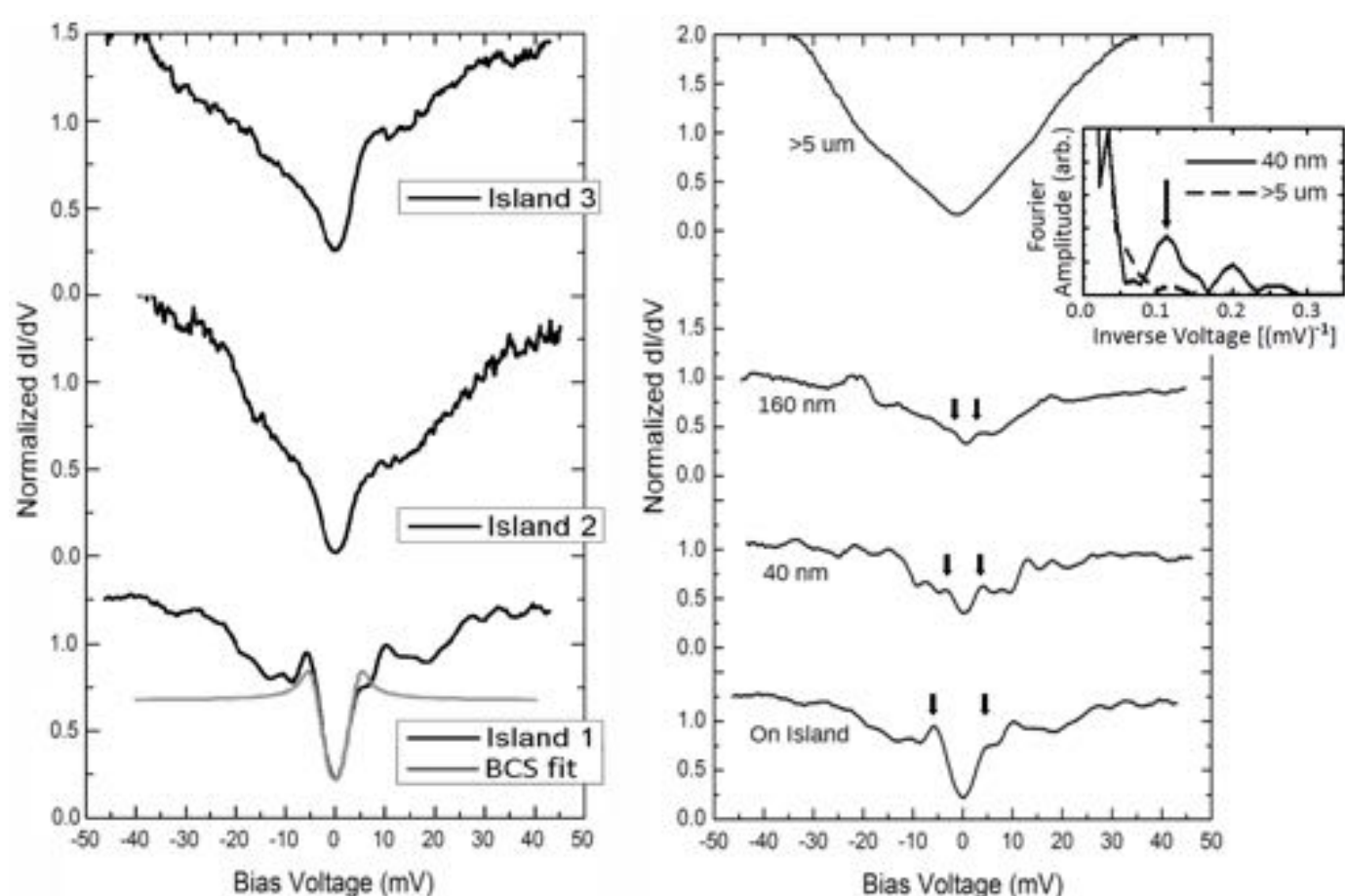
Abstract

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 Bi₂Se₃. 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 of states in these systems.

Heterostructures



Experimental Results



We will compare this to two models.

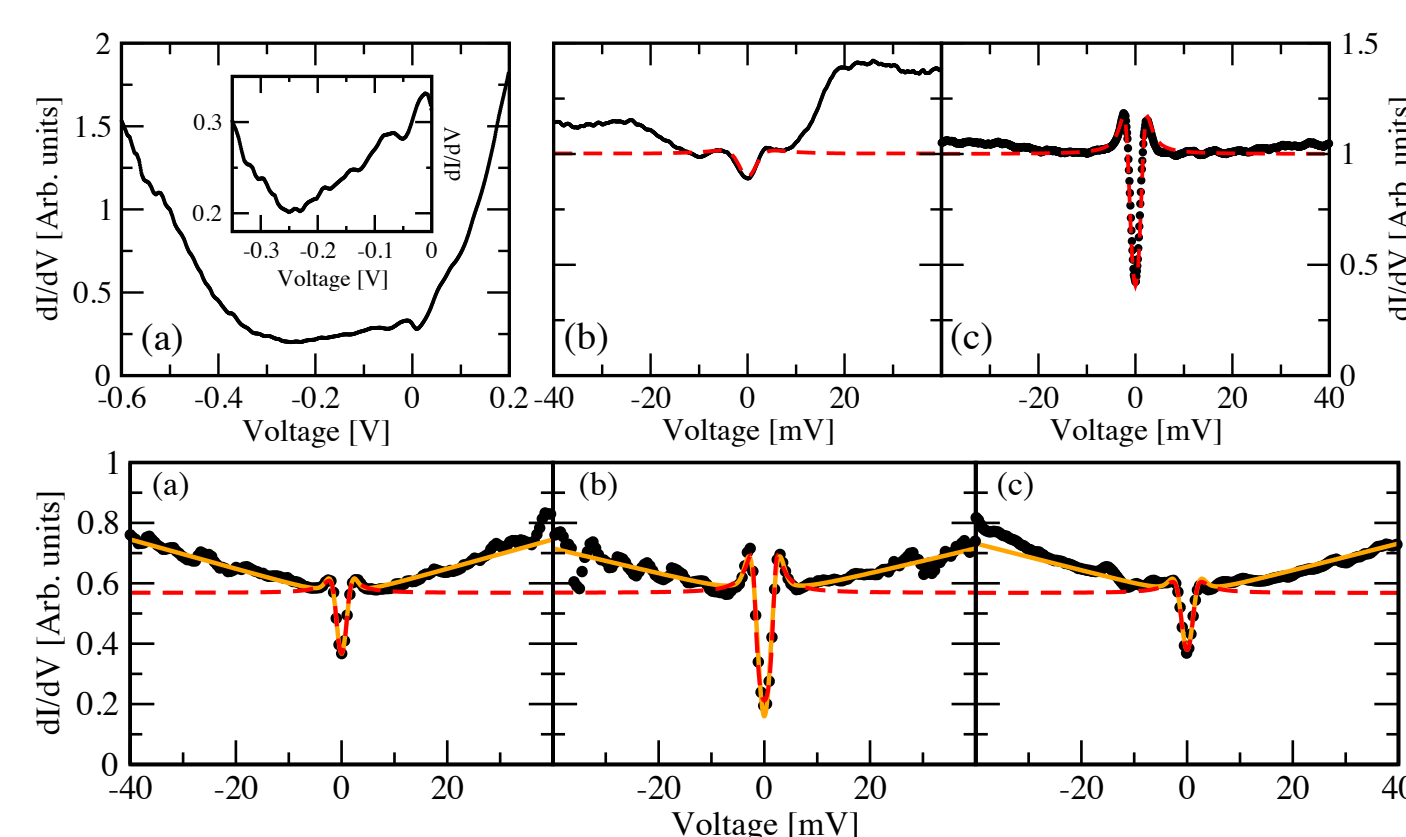
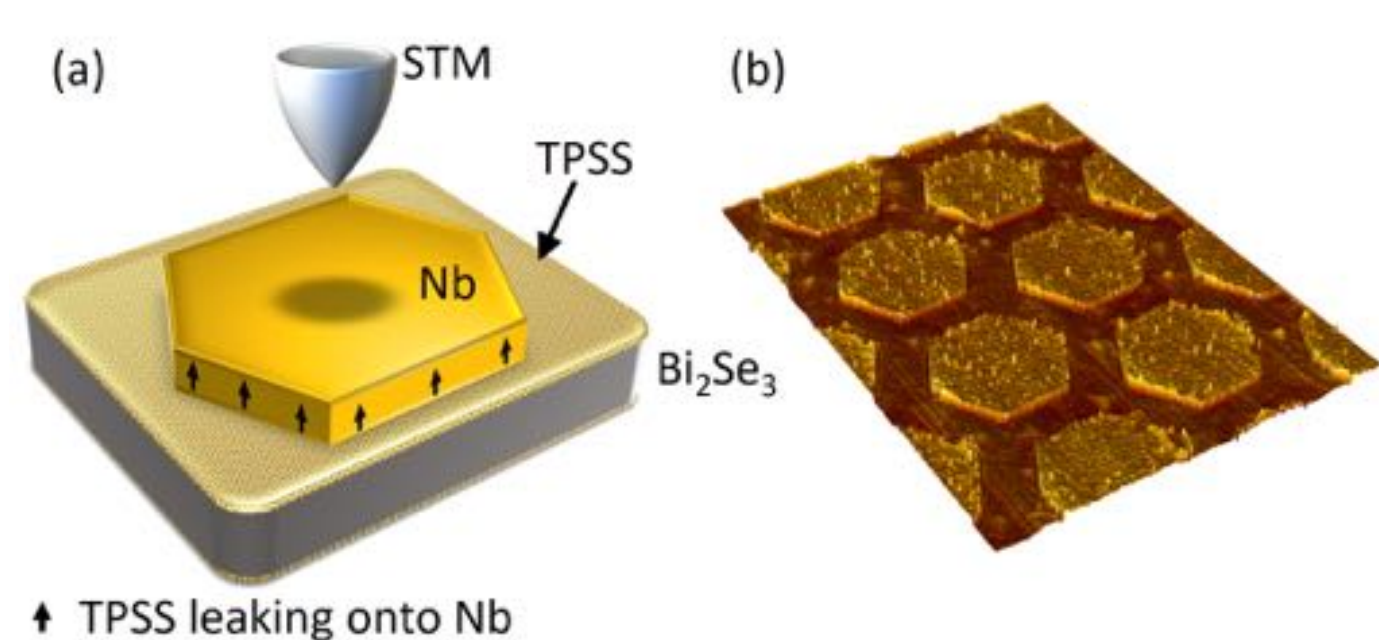
- Check a disorder model using Usadel equation to rule out that the effect is due to trivial surface states.
- In the clean limit we solve a model for the topological surface states.

Inverse Proximity Effect

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

$$H = \underbrace{H_{\text{metal}} + H_{\text{BCS}}}_{\text{Niobium Island}} + \underbrace{H_{\text{TISS}}}_{\text{Dirac states leaked into Nb}} + \underbrace{H_{\text{coupling}}}_{\text{Local spin independent coupling}}$$

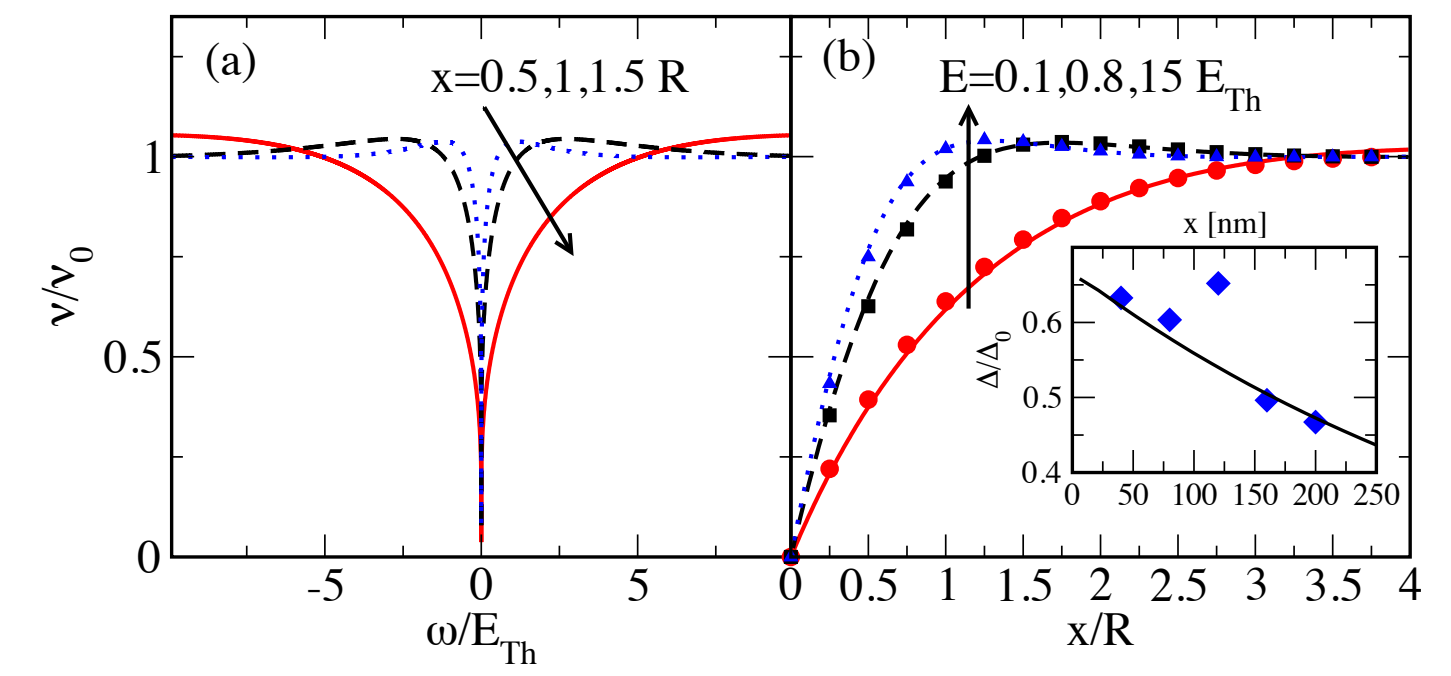
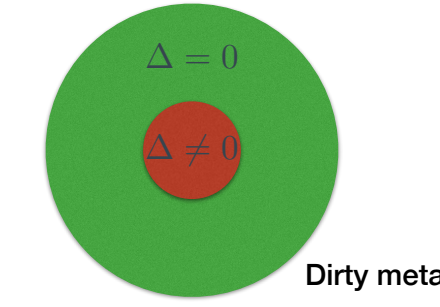
We can compare this to experiments done on superconducting Nb islands:



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:

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



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

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

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

$K_0(z)$ is the modified Bessel function

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

Typical values for Bi₂Se₃ surface states are

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

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

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

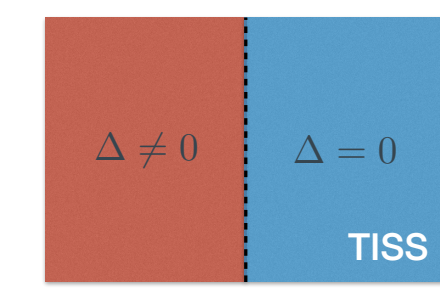
Theory for TISS Model

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

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

with a Hamiltonian

$$H^{(*)} = v_F x \begin{pmatrix} 0 & \pm \hat{k}_x - i k_y \\ \pm \hat{k}_x + i k_y & 0 \end{pmatrix}$$



Assuming a perfect interface the local density of states is

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

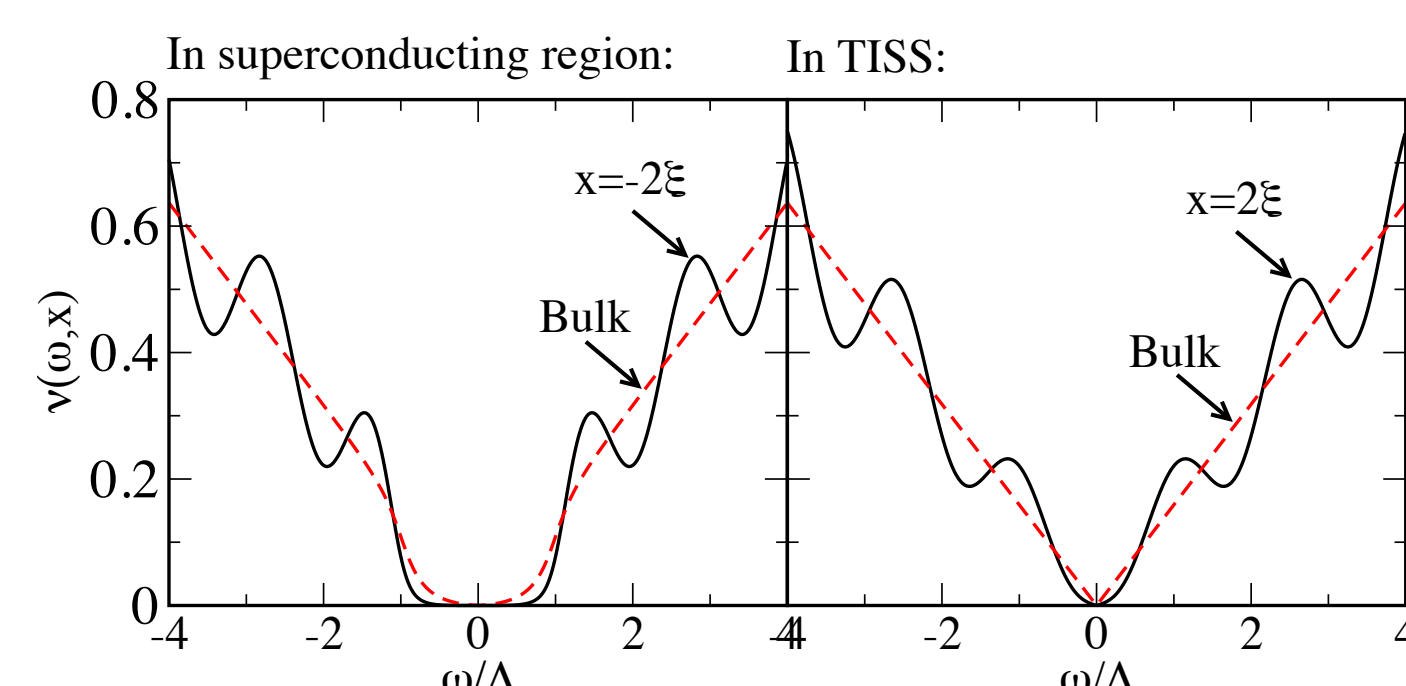
resulting in

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

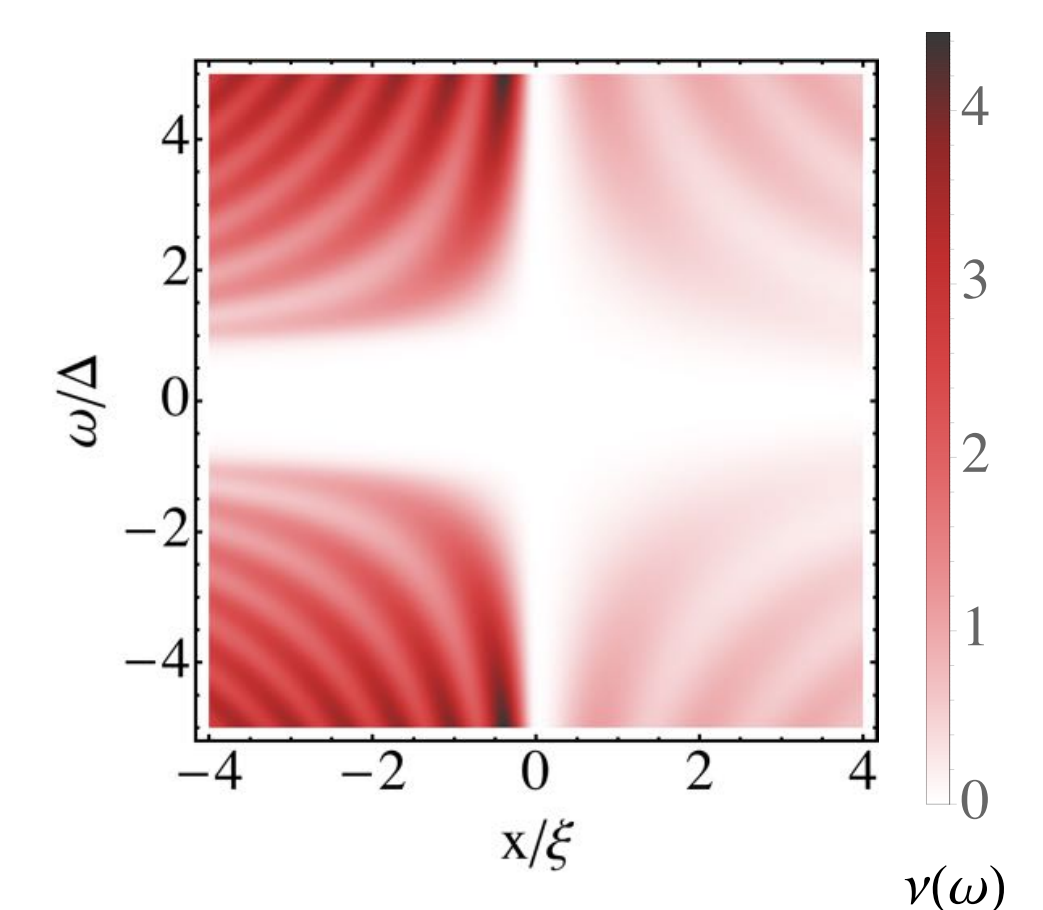
J_0 is the Bessel function of the first kind

Displays Friedel-like oscillations induced in the LDoS in the normal side of the junction. The energy scale of these oscillations, $v_F T / 2x$, 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



Proximity effect in topological insulator surface states[3]



The local density of states, in arbitrary units, as a function of energy for the topological insulator system with $\Delta = 1$ and $v_F T = 2v_{FS} = 1$. 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]

References

- [1] T. Wolfram and G. W. Lehman, "Theory of the tomasch effect," Physics Letters A, vol. 24, no. 2, pp. 101-102, 1967.
- [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. Chassapis, 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.
- [4] N. Sedlmayr, E. W. Goodwin, M. Gottschalk, I. M. Dayton, C. Zhang, E. Huemiller, R. Loloee, T. C. Chassapis, M. Sdeh, N. Koirala, G. Kanatzidis, S. Oh, D. J. V. Harlingen, A. Levchenko, and S. H. Tessmer, "Dirac surface states in superconductors: a dual topological proximity effect," arXiv preprint, p. 1805.12330, 2018.