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Tunneling conductance in normal-insulator-superconductor junctions of silicene

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A B S T R A C T

We theoretically investigate the transport properties of a normal-insulator-superconductor (NIS) junction of silicene in the thin barrier limit. Similar to graphene the tunneling conductance in such NIS structure exhibits an oscillatory behavior as a function of the strength of the barrier in the insulating region. However, unlike in graphene, the tunneling conductance in silicene can be controlled by an external electric field owing to its buckled structure. We also demonstrate the change in behavior of the tunneling conductance across the NIS junction as we change the chemical potential in the normal silicene region. In addition, at high doping levels in the normal region, the period of oscillation of the tunneling conductance as a function of the barrier strength changes from $\pi/2$ to π with the variation of doping in the superconducting region of silicene.

1. Introduction

One of the most active research field in condensed matter physics since the last decade has been the study of Dirac fermions in graphene [1,2] and topological insulator [3,4], and others. The low energy spectrum of these 2D materials satisfies massless and aslo massive Dirac equation. The relativistic band structure of the Dirac fermions has lead to tremendous interest in graphene and others 2D exotic materials in terms of possible application (e.g spintronics [5,6] due to intrinsic spin-orbit coupling (SOC)) as well as from the point of view of fundamental physics.

Very recently, a silicon analogue of graphene, silicene has been attracting a lot of attention both theoretically and experimentally [7–11], due to the possibility of new applications, given its compatibility with silicon based electronics. Unlike graphene, silicene does not have a planar structure; instead the buckled structure of silicene manifests itself as a spin-orbit coupling resulting in a band gap at the Dirac point [8]. More interestingly, it has been reported earlier that such band gap is tunable by an external electric field applied perpendicular to the silicene sheet [12,13]. This opens up the possibility of realizing silicene based electronics and very recently a silicene based transistor has been experimentally realized [14].

In recent times, it has been realized that topologically non-trivial phases arise in silicene, tuned by the external electric field only [13,15,16]. Graphene and silicene have similar band structures and the low energy spectrum of both are described by the relativistic Dirac equation *i.e.*, both have the Dirac cone band structure around the two valleys represented by the momenta $\mathbf{K}$ and $\mathbf{K}'$. However, the important difference between graphene and silicene is that the SOC in silicene is much stronger than in graphene [8,13,17] which causes the Dirac fermions in silicene to become massive. Furthermore, due to the buckled structure in silicene, the two sub-lattices respond differently to an externally applied electric field resulting in electrically tunable Dirac mass term [13]. Such tunability allows for the mass gap to be closed at some critical value of the electric field and then reopened. Hence, the phases on the two sides of the critical electric field where the gap is closed are different, with one of them being topologically trivial and the other being

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topologically non-trivial [13,15,16]. As a result, silicene under the right circumstances can be a quantum spin hall insulator with topologically protected edge states [15,18,19]. The tunability of band gap leads to a very special kind of transport study in different type of silicene-based junction [20–22] and also the experimental realisation [14], while not yet achievable, are commonly influencable future spintronic research.

The advent of superconductivity in graphene and certain topological insulators via the proximity effect has led to an upsurge of interest in this area [3,23]. Although, to the best of our knowledge, no experimental evidence of proximity induced superconductivity in silicene has been reported so far. Nevertheless, the behavior of Andreev reflection (AR) and crossed Andreev reflection (CAR) in a normal-superconductor (NS) and normal-superconductor-normal (NSN) junctions of silicene have been theoretically investigated [20], wherein the superconductivity in silicene has been assumed to arise from the proximty effect. Recently, studies on heat transport [22] in NIS type of junction and current transport in ferromagnetic-superconducting [24,25] and ferromagnetic-superconducting-ferromagnetic junctions have been reported [24].

In this article, we study the behavior of tunneling conductance (TC) in a normal-insulator-superconductor (NIS) junction of silicene where superconductivity in silicene is induced via the proximity effect. We model our NIS setup within the scattering matrix formalism [26–28] and obtain the external electric field controllable TC for thin barrier limit. Similar set up in graphene have been studied earlier in Refs. 29 and 30. However, TC based on silicene NIS structure has not yet been considered in the literature.

The remainder of this paper is organized as follows. In Sec. 2, we present our model for the silicene NIS structure and describe the scattering matrix formalism to compute the tunneling conductance. In Sec. 3, we present our results for the TC in the NIS set-up for the thin barrier case. Finally in Sec. 4, we summarize our results followed by the conclusions.

2. Model and method

In this section we set up the equations to investigate the transport properties of an NIS junction in a silicene sheet placed along the xy-plane (see Fig. 1). The $x \le -d$ region is the normal region (N), the insulating region (I) has a width d and occupies the $-d \le x \le 0$ region, while the superconducting region (S) occupies $x \ge 0$ region. In the N-region, a double-gate technique involving top and bottom gate can be implemented for generating electric-field and in addition p-type or n-type doping for controlling the doping levels. The insulating region requires a separate gate for tuning the barrier potential V_0. The superconductivity in $x \ge 0$ region is assumed to have been induced via the proximity effect where the external superconductor is considered to be of the s-wave type. Moreover, either the top-gates or p/n-type doping can be used for controlling the doping levels in the S-region.

The Silicene NIS junction is described by the Dirac Bogoliubov-de Gennes (DBdG) equation of the form

$$\begin{pmatrix} \widehat{H_\eta} & \Delta\hat{I} \\ \Delta^\dagger\hat{I} & -\widehat{H_\eta} \end{pmatrix} \Psi = E\Psi, \tag{1}$$

where E is the excitation energy, Δ is the proximity induced superconducting energy gap. The Hamiltonian $\hat{H}_\eta$ describes the low energy physics near each of the **K**, **K′** Dirac points and has the form [20],

$$H_\eta = \hbar v_F(\eta k_x\hat{\tau}_x - k_y\hat{\tau}_y) + (lE_Z - \eta\hat{\sigma}_z\lambda_{SO})\hat{\tau}_z - \mu_i\hat{1}, \tag{2}$$

where $\eta = +(-)$ corresponds to **K** (**K′**) valleys, v_F is the fermi velocity (in the following we will set $\hbar v_F = 1$), μ_i (i represents any of the N/I/S regions) is the chemical potential and λ_{SO} is the spin orbit term. The Pauli matrices $\hat{\sigma}$ and $\hat{\tau}$ act on the spin and sub-lattice space, respectively. The potential energy term lE_Z owes its origin to the buckled structure of the Silicene wherein the A and B sites occupy slightly different planes (separated by a distance of length l) and therefore acquire a potential difference when an external electric field E_Z is applied perpendicular to the plane. It turns out that at the critical electric field $E_Z^c = \lambda_{SO}/l$ each of the valleys become gapless with the gapless bands of one of the valley being up-spin polarised and the other down-spin polarised [13,21]. Away

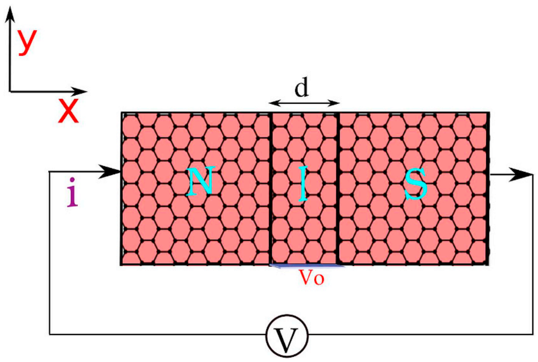

Fig. 1. Schematic of the silicene NIS junction on an xy−plane. N corresponds to the normal region, a barrier of height V_0 is applied in the I region (with width d) to make it insulating. Superconductivity is induced in the S region via the proximity effect. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)