Lattice models for Josephson junctions and graphene superlattices

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Title: Lattice models for Josephson junctions and graphene superlattices
Issue Date: 2018-06-27

Summary

In this thesis we study quantum transport phenomena on the nanometer scale, in two classes of materials: topological insulators with induced superconductivity and graphene superlattices. Both topics are motivated by recent experimental developments: the first topic arose from the search for Majorana fermions in a quantum spin Hall insulator, the second topic arose from the search for massive Dirac fermions in the Kekulé band structure of graphene on a copper substrate.

The first two chapters address the experimental observation in Delft of an h/e-periodic component in the magnetic-field dependence of the critical supercurrent in a Josephson junction formed out of a quantum spin Hall insulator. This doubled Fraunhofer periodicity is suggestive of the appearance of Majorana zero-modes in the junction, however the theory presented in Chapter 2 indicates a more mundane explanation. Using a network model of an edge-conducting Josephson junction, we demonstrate that the existence of a conducting channel along the normal-superconductor interface can explain the coexistence of h/e and $h/2e$ Fraunhofer periodicities — without requiring any contribution from Majorana fermions.

In the next Chapter 3 we describe our collaboration with the experimentalists in Delft to test our theory against new experimental data. We take into account the details of the experimental setup, which lead to partial screening of the normal part of the Josephson junction from the gate electrode. Using a realistic tight-binding model, we could explain the observations along the lines of the theory of the preceding chapter.

In Chapter 4 we continue our study of Josephson junctions in a different system, the conducting surface of a three-dimensional topological insulator. The circular Fermi surface of free electrons has a square deformation, which as we have found strongly influences the lattice of magnetic vortices. Unlike the one-dimensional array of Josephson vortices of pre-

vious studies, we find a fully two-dimensional vortex lattice. We predict that this vortex lattice leads to observable effects in the decay rate of the Fraunhofer oscillations. The lattice might also be directly measurable using scanning tunneling microscopy.

In Chapter 5 we turn to the second topic of our thesis, the superlattice of a carbon monolayer (graphene) on an epitaxial substrate. Experiments on a graphene/copper superlattice had observed a periodic modulation of the potential with a structure that resembles the Kekulé dimerization of a benzene ring. The conclusion from the published experiments was that this modulation converts the massless Dirac fermions of graphene into massive electrons, by opening a band gap at the Dirac point. We have found that the physics of this problem is different: the electrons remain massless, but the superlattice potential introduces a coupling between the valley degree of freedom and the momentum. This valley-momentum locking could be useful in so-called valleytronics applications.