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Abstract

In this thesis, transport phenomena of Dirac Fermions are theoretically studied. We study graphene and a three-dimensional (3D) topological insulator. The electronic structure forms four degenerated pseudo-spin Dirac cones and a non-degenerated single Dirac cone in graphene and on a two-dimensional (2D) surface of a 3D topological insulator, respectively. The conductivity, the susceptibility and the Hall conductivity for graphene with long-ranged impurities, and the Hall conductivity for a 2D surface of a 3D topological insulator with short-ranged impurities are calculated within a self-consistent Born approximation. These results exhibit intriguing behaviors caused by the singularity of the Dirac point.

In graphene, we analytically derive an expression of the conductivity, the susceptibility and the Hall conductivity with long-ranged impurities of any spatially smooth function. We then calculate these quantities numerically for Gaussian impurities and for charged impurities with Thomas-Fermi screening. These numerical calculations are massive because the Green's function and the vertex corrections strongly depend on the wave vector. We find that the minimum conductivity at the Dirac point remains universal in the clean limit, but becomes non-universal with increasing scattering strength for Gaussian impurities. We also find that the minimum conductivity approaches the universal value when the potential range d gets short, which agrees with the previous study of the conductivity for the short-ranged impurities. For charged impurities, the resulting conductivity increases in proportion to the electron concentration. The minimum conductivity for charged impurities is almost independent of impurity concentration, but its value is larger than that expected from the previous theory for the short-ranged impurities. This result for charged impurities is in good agreement with experiments.

The susceptibility in graphene without impurities have been known to show a delta-functional peak at the Dirac point. Our result for Gaussian impurities shows broadening of the susceptibility peak by impurities. This broadening comes from a hybridization of states with those at the Dirac point. We show that this broadening rapidly decays in the Fermi-energy region where the density of states converges to the clean limit. For charged impurities, the susceptibility exhibits a double-peak structure as a function of the Fermi energy at zero temperature. The double peak structure is due to the rapid decrease in effective scattering strength with the increase of the Fermi level.

For the weak-field Hall conductivity, we analytically calculate the Hall conductivity in clean limit for long-ranged impurities based on the self-consistent Born approximation. This analytic formula, derived in the clean limit, reproduces the results for the Boltzmann transport theory in the case of short-ranged impurities, but becomes different in the long-ranged case. Explicit numerical calculations are also performed for impurities with a Gaussian potential with range d, showing that the Hall conductivity as well as the density of states and the diagonal conductivity becomes universal when the energy is scaled by 1/d. Results for the charged impurities are qualitatively in good agreement with the Boltzmann results, but deviate when covered by materials with large dielectric constant.

We also calculate the Hall conductivity for a 2D surface of a 3D topological insulator where the surface band forms a single Dirac cone. In this study, we treat the system with short-ranged impurities, which have not been studied. In this case, the Hall conductivity can be calculated by analytic calculation, unlike the system with long-ranged impurities. For a single Dirac cone, both the electronic orbital motion and the Zeeman splitting term contribute to the Hall conductivity. The contribution from the electronic orbital motion almost agrees with the Hall conductivity in graphene with short-ranged impurities, apart from a trivial overall factor. On the other hand, the contribution from the Zeeman splitting term survives only in a single Dirac cone, but not in graphene. The contribution from the

Zeeman splitting term is symmetric as a function of Fermi energy. It has a sharp peak at the Dirac point, and it decreases for the high-energy region. We confirm that the contribution from Zeeman term agrees with that derived from the semi-classical theory, when we assume the energy-independent broadening model and ignore the vertex corrections. Since the orbital contribution is antisymmetric with respect to the Dirac point and the Zeeman contribution is symmetric, the total weak-field Hall conductivity is neither symmetric nor antisymmetric around the Dirac point.