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Scanning Tunneling Spectroscopic Studies of Topological Matter of Graphene and Topological Insulators

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We report novel properties derived from scanning tunnelling spectroscopic (STS) studies of Dirac fermions in graphene [1,2] and the surface state (SS) of strong topological insulators (STI) of Bi_2Se_3 [2,3], pure $(Bi_{0.5}Sb_{0.5})_2Te_3$ and Cr-doped $(Bi_{0.5}Sb_{0.5})_2Te_3$. For monolayer graphene grown on Cu by chemical vapour deposition (CVD), strain-induced scalar and gauge potentials are manifested by the charging effects and the tunnelling conductance peaks at quantized energies, respectively. Additionally, spontaneous time-reversal symmetry breaking is evidenced by the alternating anti-localization and localization spectra associated with the zero-mode of two sublattices while global time-reversal symmetry is preserved under pseudo-magnetic fields. We also observe pseudo-field induced conductance peaks at quantized energies that correspond to Landau levels of integers of $n = 0, \pm1, \pm2, \pm3, \pm4$... and fractional values of $n = 0, \pm1/3, \pm2/3, \pm4/3, \pm5/3$... The latter cannot be explained by non-interacting Dirac fermion pictures in graphene. [1,2] We conjecture that meta-stable $(\sqrt{3}\times\sqrt{3})$ superlattices as a result of the Clar's aromatic sextet rule may be responsible for the appearance of conductance peaks at fractional quantized energies that corresponds to fractional densities of mobile Dirac fermions relative to the total Dirac fermions. While the appearance of strain-induced pseudo-magnetic fields and charging effects can be useful for nano-scale strain engineering of novel devices, it also contributes to significant reduction of the electronic mobility. We have recently succeeded in growing large sheets of monolayer graphene on Cu at room temperature, which is promising for significant strain reduction and higher electronic mobility.

For the surface state of three-dimensional (3D) STI's, we investigate Bi_2Se_3 epitaxial films on Si (111) and pure and Cr-doped $(Bi_{0.5}Sb_{0.5})_2Te_3$ heterostructures on GaAs (111) grown by molecular beam epitaxy (MBE). In Bi_2Se_3, our STS studies revealed spatially localized unitary impurity resonances with sensitive dependence on the energy difference between the

Fermi level and the Dirac point are observed for samples thicker than 6 quintuple layers (QL). These findings are characteristic of the SS of a STI and are direct manifestation of strong topological protection against impurities. [2,3] For Bi_2Se_3 thinner than 6-QL, STS studies revealed opening of an energy gap in the SS due to overlaps of wave functions between the surface and interface layers. [2] Similarly, for the 4QL pure $(Bi_{0.5}Sb_{0.5})_2Te_3$ sample, a surface gap ~ (0.25±0.08) eV was observed. In contrast, for 8QL pure $(Bi_{0.5}Sb_{0.5})_2Te_3$ on 8QL Cr-doped $(Bi_{0.5}Sb_{0.5})_2Te_3$, the surface of the pure $(Bi_{0.5}Sb_{0.5})_2Te_3$ revealed ungapped spectra characteristics of massless Dirac fermions near the Dirac point (~ –0.18 eV) and electron doping. On the other hand, for 4QL pure $(Bi_{0.5}Sb_{0.5})_2Te_3$ on 8QL Cr-doped $(Bi_{0.5}Sb_{0.5})_2Te_3$, bulk Hall effect measurements exhibited the anomalous Hall effect (AHE) that is characteristic of the occurrence of ferromagnetism, and the Curie temperature was estimated to be ~ 7 K. The effect of bulk ferromagnetism on the SS of $(Bi_{0.5}Sb_{0.5})_2Te_3$ based on STS studies will be reported.

References:

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[3] M. L. Teague *et al.*, Solid State Comm. **83**, 132509 (2012).