Gate-tunable quantum pathways of massless Dirac fermions in high harmonic generation

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Under strong laser fields, electrons in solids radiate high-harmonic fields by travelling through quantum pathways in Bloch bands in the sub-laser-cycle timescales [1-3]. Imaging these pathways in the momentum space through the high-harmonic radiation can enable an all-optical ultrafast probe to observe coherent lightwave-driven processes and measure electronic structures as recently demonstrated for semiconductors. However, such demonstration has been largely limited for semimetals because the absence of the bandgap hinders the visualization of the exact pathways. In this study, by combining electrostatic control of chemical potentials with high harmonic generation (HHG) measurement, we image lightwave-driven quantum pathways of massless Dirac fermions in graphene [4]. Fig.1 shows schematic of chemical potential dependent HHG process in momentum space and polarization profile of gate-tunable HHG. For the charge-neutral case, current is generated simultaneously by the interband transition (black solid arrow), intraband transition along the x-direction (red solid arrow), and intraband transition along the y-direction (blue solid arrow). For the highly doped case, the interband transition (black dashed arrow) and connected intraband transitions (red and blue dashed lines) are blocked due to Pauli blocking. As VG decreases from 0.9 V to -1.5, the harmonic intensity is reduced by ~ 50 times while the polarization axis is rotated by 52.7 degrees.

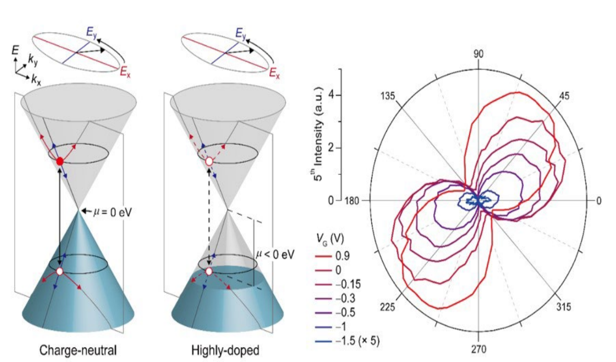

Fig. 1. Gate-tunable HHG in graphene under ε_{exc} = 0.3

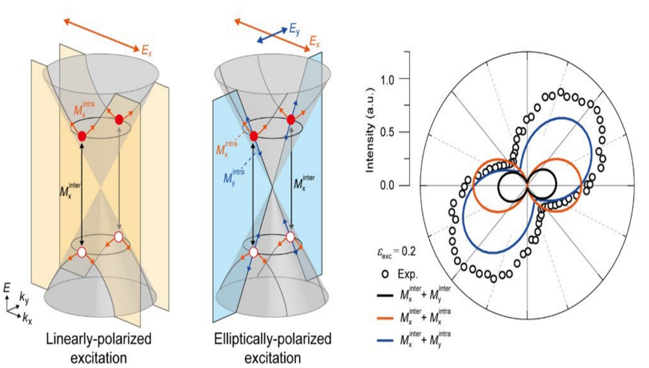

Fig. 2. Microscopic channels for carrier dynamics at the states on the k_y-axis and theoretical calculation of HHG from graphene.

Fig.2 demonstrates microscopic channels for carrier dynamics at the states on the k_y-axis and theoretical calculation of HHG from graphene. Under linearly-polarized excitation along the x-direction, the interband transition creates and recombine photo-excited electrons and holes Simultaneously, the intraband transition drives carriers along the k_x-direction. Under elliptically-polarized excitation, the intraband transition also drives carriers along the k_y-direction.

In this study, by combining electrostatic control of chemical potentials with high harmonic generation (HHG) measurement, we image lightwave-driven quantum pathways of massless Dirac fermions in graphene. Electrical modulation of HHG reveals quantum interference between the multi-photon interband excitation channels. In accordance with our theoretical calculations, we show that elliptically polarized laser fields efficiently drive massless Dirac fermions via an intricate coupling between the interband and intraband transitions. Our findings pave the way for strong-laser-field tomography of Dirac electrons in various quantum semimetals and their lightwave electronics with a gate control.

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