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Origins of Nonlocal Resistance in Multiterminal Graphene: Spin Hall and Valley Hall vs. Other Competing Effects

The recent experimental observation [1] of nonlocal voltage near the Dirac point (DP) several microns away from the nominal current path in multiterminal graphene devices with adatom-induced spin-orbit coupling, or in multiterminal graphene on hexagonal boron nitride (G/hBN) heterostructures, has been interpreted as the result of direct and inverse spin Hall effect or direct and inverse valley Hall effect (VHE) [2], respectively. However, subsequent experiments [3] reproducing the nonlocal signal in graphene with adatoms have also demonstrated its insensitivity to the applied in-plane magnetic field, thereby suggesting its disconnect with SHE physics or any other spin-related mechanism. The theoretical interpretation [2] of nonlocal signal in G/hBN heterostructures in terms of topological valley currents carried by the Fermi sea states just beneath the presumed gap opened in graphene due to inversion symmetry breaking does not explain the long-standing puzzle of why the highly insulating state of G/hBN is rarely observed [1,4]. Furthermore, using Landauer-Büttiker (LB) theory, as a rigorous quantum transport approach employed over the past three decades to obtain observable nonlocal voltage and the corresponding nonlocal resistance, we obtain zero nonlocal signal in the same geometry used in experiments [2] (where the channel connecting the two crossbars is much longer that its width) and for the same simplistic Hamiltonian which gives (not directly observable) quantized VH conductivity characterizing chargeless topological valley currents. In this talk, I will show how to resolve these puzzles by using first-principles derived Hamiltonians of graphene with adatoms or G/hBN heterostructures coupled with numerically exact calculations of the nonlocal resistance based on the multiterminal LB formula [5,6]. In the case of multiterminal graphene with adatoms, we find several background mechanisms which generate nonlocal resistance even when spin-orbit coupling is switched off [5]. We also propose (Fig. 1) a specific device geometry where nonlocal resistance due to the SHE can be isolated by diminishing background mechanisms [5]. In the case of multiterminal G/hBN heterostructure, we demonstrate the key role played by the Fermi surface edge states and the corresponding edge currents (which were missed in previous theoretical analysis based on too simplistic Hamiltonian) which explain *both* the nonlocal resistance and metallic-like resistivity observed in experiments [1] while being in full accord with the very recent Josephson interferometry-based imaging of the spatial profile of edge supercurrents in Gr/hBN wires [4].

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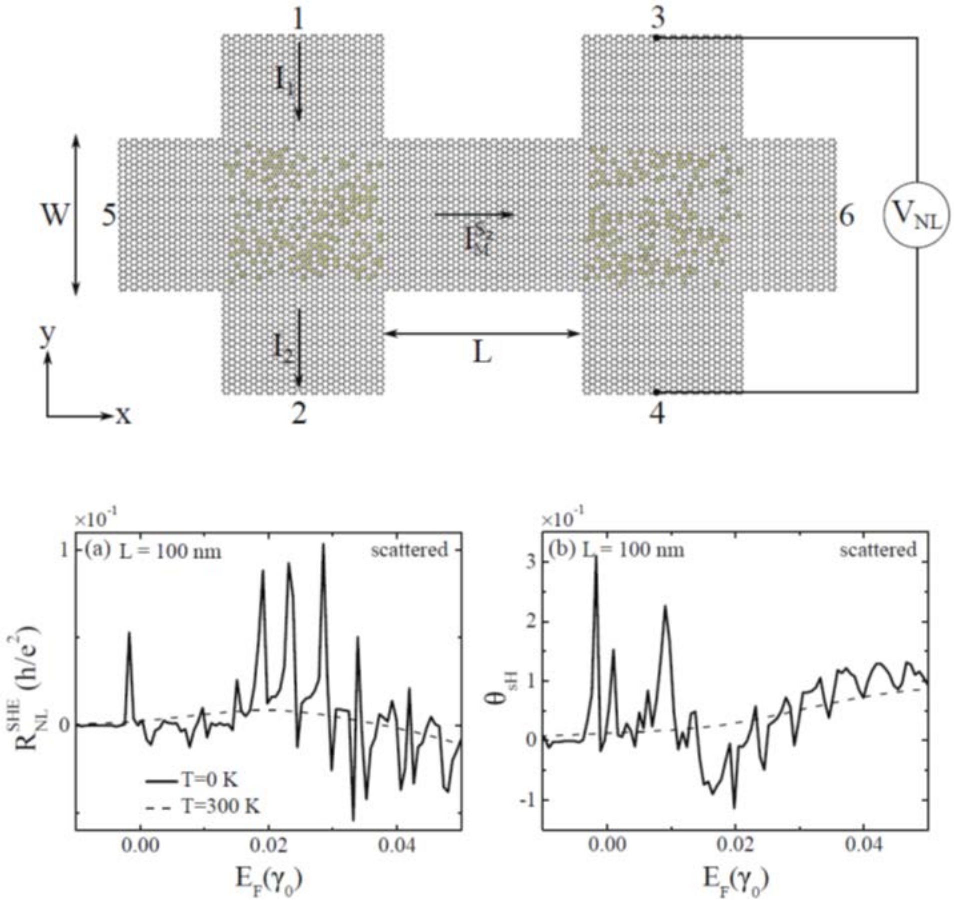

Figure 1: Top panels shows schematic view of our proposal [5] for a six-terminal graphene geometry where adatoms (yellow circles), locally inducing strong spin-orbit coupling on the honeycomb lattice of carbon atoms (black circles), are removed from the channel connecting the two crossbars in order to isolate contribution to the nonlocal resistance due to solely direct (in the first crossbar) and inverse (in the second crossbar) SHE. The is verified by numerically exact calculations [5] in the bottom panel where the nonlocal resistance in (a) near the DP (at E_F=0) is in *one-to-one correspondence* with the peak in the spin Hall angle at the same energy in (b).