Supplementary Material to the article «Correlation Coulomb Gap in Magnetotunneling Between Graphene Layers»

Sample description

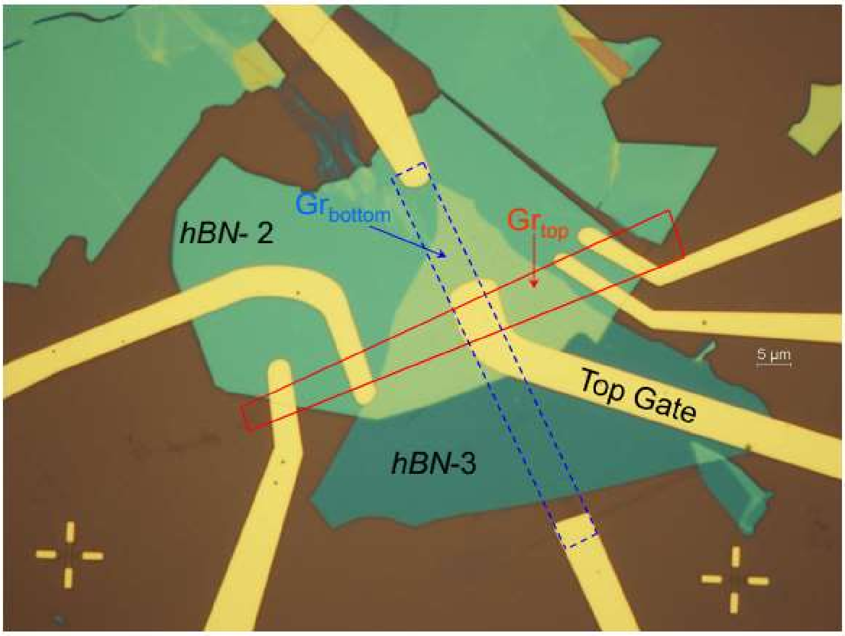

Fig. 1S

The figure Fig. 1S shows an optical micrograph of the sample, in which the positions of the upper and lower graphene monolayers are circled in red and blue dashed lines, respectively, and also shows the BN-2 tunnel barrier and the BN-3 gate dielectric. Our sample was a vertical van der Waals heterostructure obtained by mechanical separation and transfer of graphene and hBN layers. The following layers were sequentially deposited on a highly doped Si substrate with an upper SiO2 layer 300 nm thick: hBN 30 nm thick (BN1), graphene monolayer (Gr2), hBN 4 monolayers (BN2), graphene monolayer (Gr1), and hBN 15 nm thick. (BN3). Contacts to the graphene layers and the upper gate metallization were fabricated using electron lithography and Ti / Au deposition. Conducting graphene layers Gr1 and Gr2 were fabricated in the form of a cruciform structure separated at the intersection by the BN2 tunnel barrier, which made it possible to measure the tunneling conductivity by the four-probe method. The angular lattice mismatch of the Gr1 and Gr2 layers was about 2 degrees and the area of their intersection was 25 µm2.

Equilibrium tunneling conductivity map at B = 12T in coordinates V_{tg} - V_{bg}

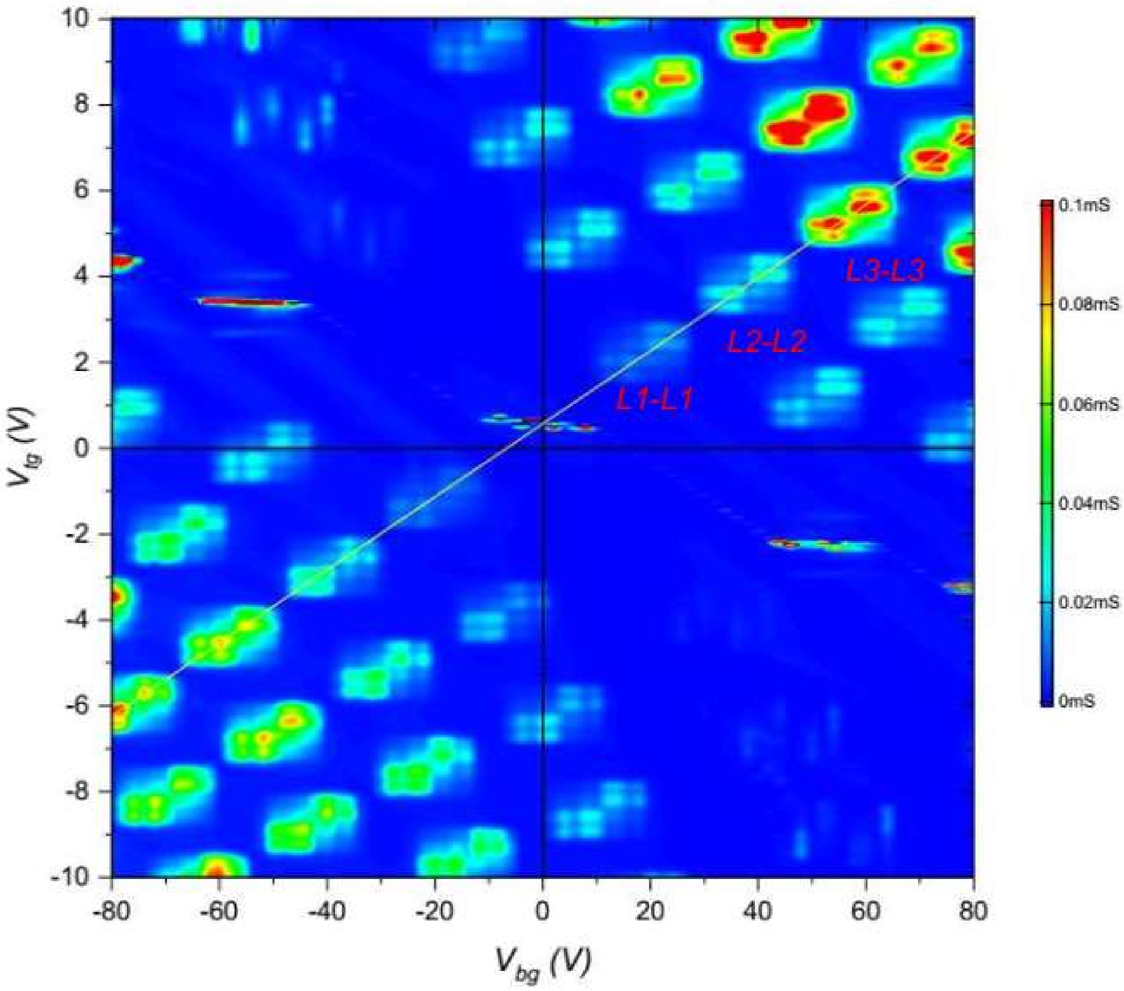

Fig. 2S

Fig. 2S shows an experimental map of tunneling conductivity in a magnetic field B = 12T perpendicular to the plane of the graphene layers at a temperature of T = 2K. Measurements of dI / dV_{bias}-$V_{top\ gate}$ characteristics in wide intervals of $V_{top\ gate}$ and $V_{back\ gate}$ allowed us to construct such three-dimensional maps of equilibrium tunneling conductivity, visualizing the entire spectrum of tunnel junctions available to us. The step $V_{bottom\ gate}$ during card measurements was 1 V, which corresponded to 161 curves, and the actual intervals of gate voltages were limited by the possibility of breakdown of the structure. Each light (red / green) area on the map corresponds to high tunneling conductivity and reflects a specific transition between the Landau levels with specific numbers N_T and N_B in the upper and lower layers. Each resonance in the narrow-window regime is generated by a transition between a specific pair of Landau levels with the same energy in different layers. The lower left part of the card at negative voltages $V_{bottom\ gate}$ and $V_{top\ gate}$ refers to the situation when only hole Landau levels (N_T<0 and N_B<0) are filled in the lower and upper layers and tunnel junctions occur exclusively between them, while the upper right part corresponds to the condition $N_T > 0$ and $N_B > 0$, when tunneling occurs between electronic Landau levels. The upper left and lower right regions refer to mixed situations of tunneling between hole and electron Landau levels in layers. The amplitudes of such electron-hole transitions, as can be seen, are significantly less than the electron-electron and hole-hole ones. At B = 12T, the three-dimensional map of the equilibrium tunneling conductivity is a series consisting of groups of similar features with the same type of symmetry, each of which reflects the splitting of pairs of Landau levels between which tunneling occurs. In other words, visually, each "hill" of the map with increasing magnetic field is divided into four symmetrically located hills of a smaller size.

Measurements of interlayer tunneling current while maintaining the equality of electron concentrations in graphene layers by controlling gate voltages.

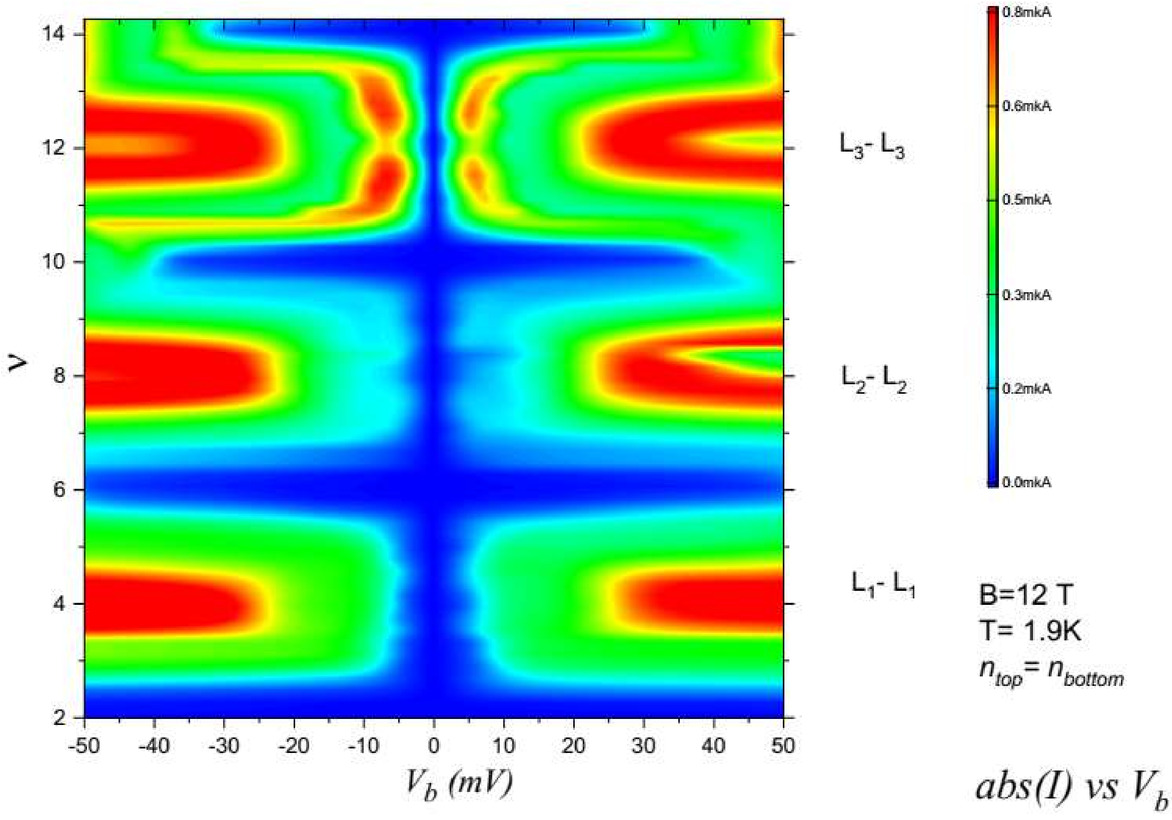

Fig. 3S

Fig.3S shows the I-V_b map at different ν under conditions of coincidence of the electron concentrations in the upper and lower graphene layers near zero bias, that is, $n_{top} = n_{bottom}$ at $V_b = 0$. We can see suppression of the tunneling current for transitions between the same Landau levels in the upper and lower graphene layers at ν = 2, 6, 10, 14.

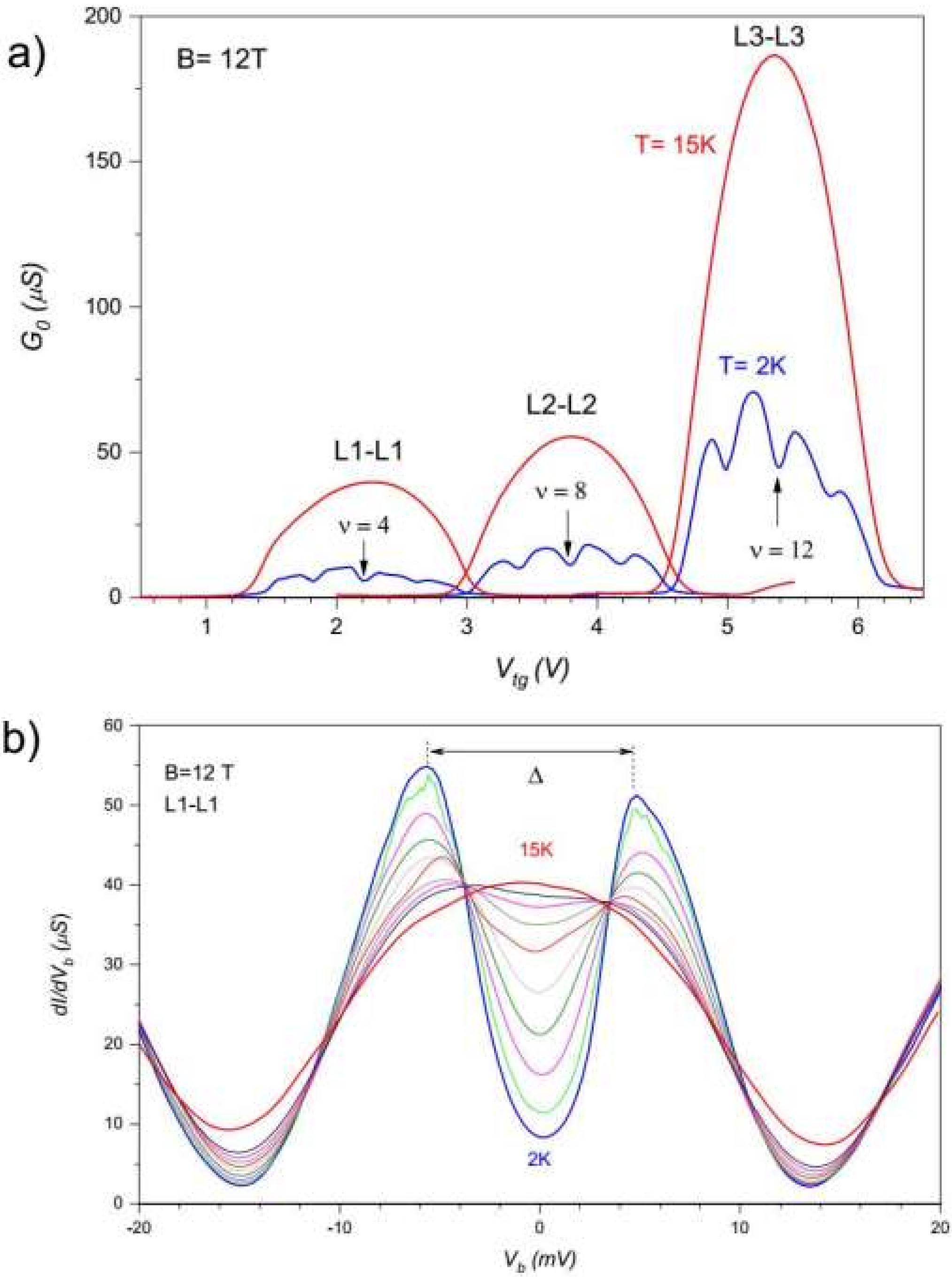

Fig. 4S

a) Dependences G_0 *vs* V_{tg} at T = 2K (blue curves) and T = 15K (red curves) at B = 12T for tunneling between L3-L3, L2-L2 and L1-L1 Landau levels.

b) $dI / dV_b - V_b$ dependences corresponding to tunneling between the L1-L1 Landau levels of the upper and lower graphene layers at temperatures of 2, 3, 4, 5, 6, 7, 8, 9, 10, and 15 K in a magnetic field B = 12T ; b) Dependence of G_0 at $\nu = 12$, B = 12T, corresponding to tunneling between the Landau levels L1-L1 of the upper and lower graphene layers, on the inverse temperature *1/T*.