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SUPPLEMENTARY INFORMATION

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Microscopic Polarization in Bilayer Graphene

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Supplementary Material

I. Numerical Data Analysis of Landau Levels

The low energy band structure of graphene consists of four bands; two bands meet at the charge neutrality point, and two higher energy bands related to the $\boldsymbol{A}_2$-$\boldsymbol{B}_1$ dimer bonds are offset by the interlayer energy γ_1[1]. We adopt a two-band model, which includes only the lowest energy bands, to quantitatively analyze the LLs spectra[2,3]. The analysis of LLs is limited to the low energy regime (less than 150 meV), which meets the requirement of the two-band model; $E < \gamma_1 = 0.377$ eV. We have found that this simple two-band model gives results within 5 % of those from the full four-band model[4]. Thus, the introduced error for using the simpler model is less than our experimental uncertainties. The simple analytic expression for the LL energies is derived from the two-band model as given by Eq. 1 in the main text, which we use to fit the LLs spectra with the potential energy asymmetry, ΔU and Fermi velocity, v_F as free parameters.

Figure S1a shows the individual dI/dV spectrum obtained for the P1 electron puddle at $V_g = 33$ V. Up to nine Landau levels are observed over the displayed spectra range in Fig. S1a. A fit of the LL energies with Eq. 1 yields an energy asymmetry, ΔU = (-34.8 ± 2.4) meV [5], and Fermi velocity of v_F = (1.00 ± 0.01) × 10^6 m s^{-1} as shown in Fig. 3d in the main text.

The band gaps qualitatively follow the separation between $LL_{(0,+);(1,+)}$ and $LL_{(2,+);(2,-)}$. We plot in Fig. S1b the difference in LL energies between $LL_{(2,+);(2,-)}$ - $LL_{(0,+);(1,+)}$, which can be obtained directly from the gate maps (Fig. 3c). It is clear that the determined energy asymmetries from the fitting of the LLs with Eq. 1 (Fig. S1c, d) match the overall trend seen in the difference between LLs. Additionally, we have confirmed that using the Fermi velocity as a variable fit parameter only weakly affects the gap determination as demonstrated in Fig. S1c, d. Using the velocity as a fitting parameter, however, we observe a few percent variation in Fermi velocity as displayed in Fig. S1e, which can be ascribed to the velocity renormalization effects due to electron-electron interactions[6].

References:

1. McCann, E. & Fal'ko, V.I. Landau-Level Degeneracy and Quantum Hall Effect in a Graphite Bilayer. *Phys. Rev. Lett.* **96**, 086805 (2006).
2. Shizuya, K. Pseudo-zero-mode Landau levels and collective excitations in bilayer graphene. *Phys. Rev. B* **79**, 165402 (2009).
3. McCann, E. Asymmetry gap in the electronic band structure of bilayer graphene. *Phys. Rev. B* **74**, 161403 (2006).
4. Pereira, J.M., Peeters, F.M. & Vasilopoulos, P. Landau levels and oscillator strength in a biased bilayer of graphene. *Phys. Rev. B* **76**, 115419 (2007).
5. All uncertainties reported represent one standard deviation in the measured quantity.
6. Roldán, R., López-Sancho, M.P. & Guinea, F. Effect of electron-electron interaction on the Fermi surface topology of doped graphene. *Phys. Rev. B* **77**, 115410 (2008).

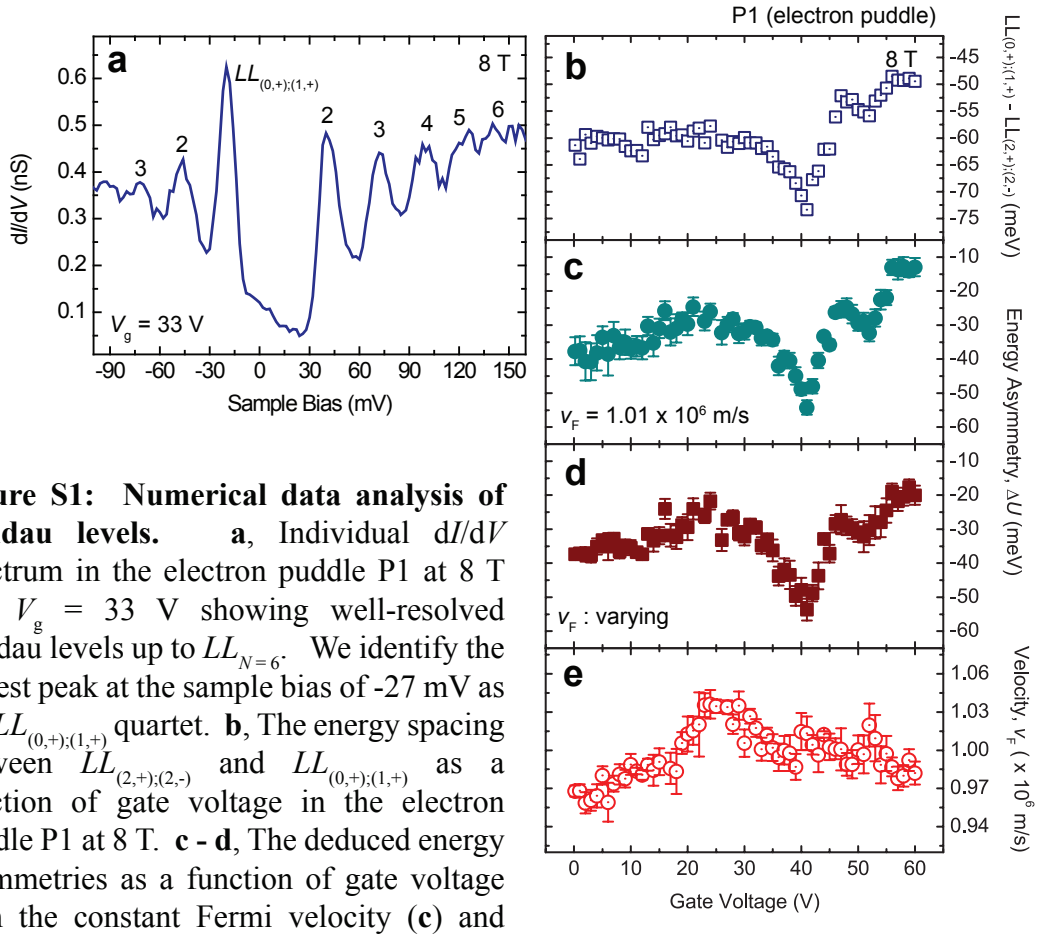

Figure S1: Numerical data analysis of Landau levels. **a**, Individual dI/dV spectrum in the electron puddle P1 at 8 T and V_g = 33 V showing well-resolved Landau levels up to $LL_{N=6}$. We identify the largest peak at the sample bias of -27 mV as the $LL_{(0,+);(1,+)}$ quartet. **b**, The energy spacing between $LL_{(2,+);(2,-)}$ and $LL_{(0,+);(1,+)}$ as a function of gate voltage in the electron puddle P1 at 8 T. **c - d**, The deduced energy asymmetries as a function of gate voltage with the constant Fermi velocity (**c**) and with the Fermi velocity as a fitting parameter (**d**). The band gaps follow the evolution of LL spacing displayed in **b**. **e**, The extracted Fermi velocity variation as a function of gate voltage from the LL fitting. The velocity renormalization, manifested by a few percent variations in magnitude does not affect the main features of bilayer energy asymmetry (Fig. S1**c**, **d**). Error bars one standard deviation,in (**c**) - (**e**).