Supplementary Information for

Observation of hydrodynamic plasmons and energy waves in graphene

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S1. Full-wave electromagnetic simulations of micro-ribbon absorption

The graphene micro-ribbon absorption in our experiment can be calculated using full-wave electromagnetic simulations (FDTD solutions, Lumerical Inc.). Our simulated structure consists of the waveguide (Perfect electric conductor), the graphene micro-ribbon, hBN ($\epsilon_{xx} = \epsilon_{yy} = 4.8, \epsilon_{zz} = 4.4$), and the SiO_2 substrate ($\epsilon = 3.6$) shown in Fig. S1. A mode source is used to excite the terahertz wave in the waveguide, and the transmission is collected by a frequency domain monitor. We also simulate the terahertz transmission without graphene and use the result as a reference to obtain the micro-ribbon absorption.

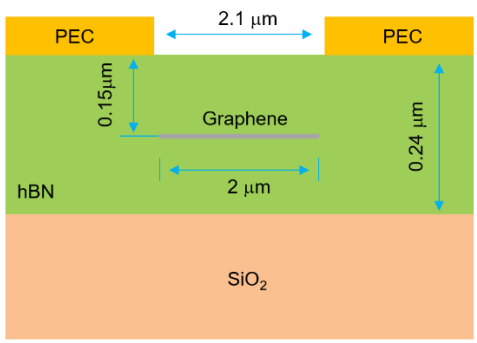

Fig. S1 | Graphene micro-ribbon modeled in the full-wave electromagnetic simulations.

In the simulations, we treat graphene as a two dimensional surface with local conductivity[1]

$$\sigma = D_Z\pi^{-1}({\tau_{ee}}^{-1} + {\tau_d}^{-1} - i2\pi f)^{-1} + D_F\pi^{-1}({\tau_d}^{-1} - i2\pi f)^{-1}.$$

Here D_z and D_F are the Drude weights of the zero and finite momentum modes, respectively. ${\tau_{ee}}^{-1}$ and ${\tau_d}^{-1}$ are the electron and disorder scattering rates given by[2]

$${\tau_{ee}}^{-1} = \alpha k_B T_e/\hbar,$$

$${\tau_d}^{-1} = \frac{\pi^4 n_{imp}}{27\hbar\xi(3)}\left(\frac{e^2}{4\pi\epsilon_0\epsilon}\right)^2\frac{1}{k_B T_e}.$$

Here α is a dimensionless constant, $\xi(3) \approx 1.202$, n_{imp} is the impurity density, and ϵ is the effective dielectric constant of the medium. We use $\alpha = 0.2$ according to Ref. 1, and assume that $n_{imp} = 2 \times 10^9 \mathrm{cm}^{-2}$ and $\epsilon = 4$ for graphene encapsulated in hBN. The Drude weight of the finite momentum mode is

$$D_F = \frac{\pi(neV_F)^2}{W},$$

where ne is the charge density, V_F is the Fermi velocity, and W is the enthalpy density:

$$W = \frac{3(k_B T_e)^3}{\pi(\hbar V_F)^2}\int_0^\infty \tilde{k}^2\left(\frac{1}{e^{\tilde{k}-\frac{\mu}{k_B T_e}}+1} + \frac{1}{e^{\tilde{k}+\frac{\mu}{k_B T_e}}+1}\right)d\tilde{k}.$$

Here μ is the chemical potential determined by the charge density and temperature, and k_B is the Boltzmann constant. The Drude weight of the zero-momentum mode is $D_Z = D_{gr} - D_F$, where

$$D_{gr} = 2\frac{e^2}{\hbar^2}k_B T_e \log\left[2\cosh\left(\frac{\mu}{2k_B T_e}\right)\right]$$

is the total Drude weight of graphene.

To compare the simulation results with the experimental observations, we convert the graphene charge density in the simulation to gate voltage using the parallel-plate capacitor model. The capacitance per unit area is $C = \epsilon_0 \varepsilon_{hBN}/d$, where $\varepsilon_{hBN} = 3.76$ and $d = 90$ nm is the hBN thickness determined by the atomic force microscope (AFM) image (Fig. S2). The gate voltage $\mathrm{V_G}$ is obtained using $\mathrm{n} = \mathrm{C} \times (\mathrm{V_G} - \mathrm{V_{CNP}})$, where $\mathrm{V_{CNP}} = -0.1\ V$ is the experimentally determined gate voltage of the charge neutrality point.

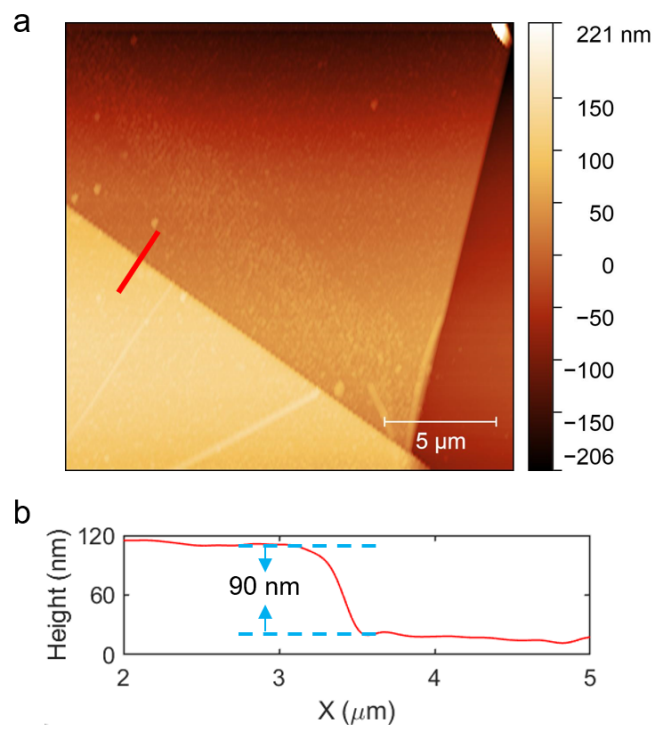

Fig. S2 | Topography of the micro-ribbon device. (a) 2D plot of the sample edge area. (b) Line cut across the spacer hBN edge indicated by red line in a.

S2. Hydrodynamic plasmons in graphene micro-ribbon near charge neutrality

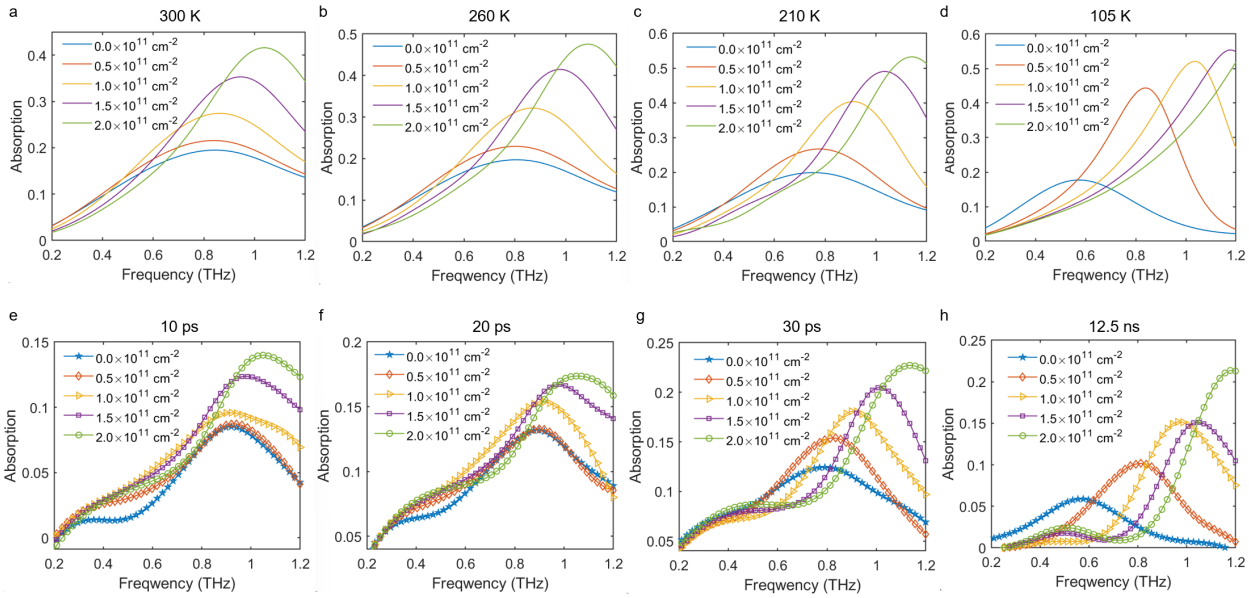

Fig. S3 | Line cuts of the absorption spectra at selected carrier densities from Fig. 2a-d and g-j in the manuscript.

S3. Graphene micro-ribbon absorption in a second device

We studied the THz absorption of graphene micro-ribbon in a second device of similar design. The bipolar plasmon shows similar temperature dependence on the electron temperature, and the demon response becomes clear at high enough electron temperature.

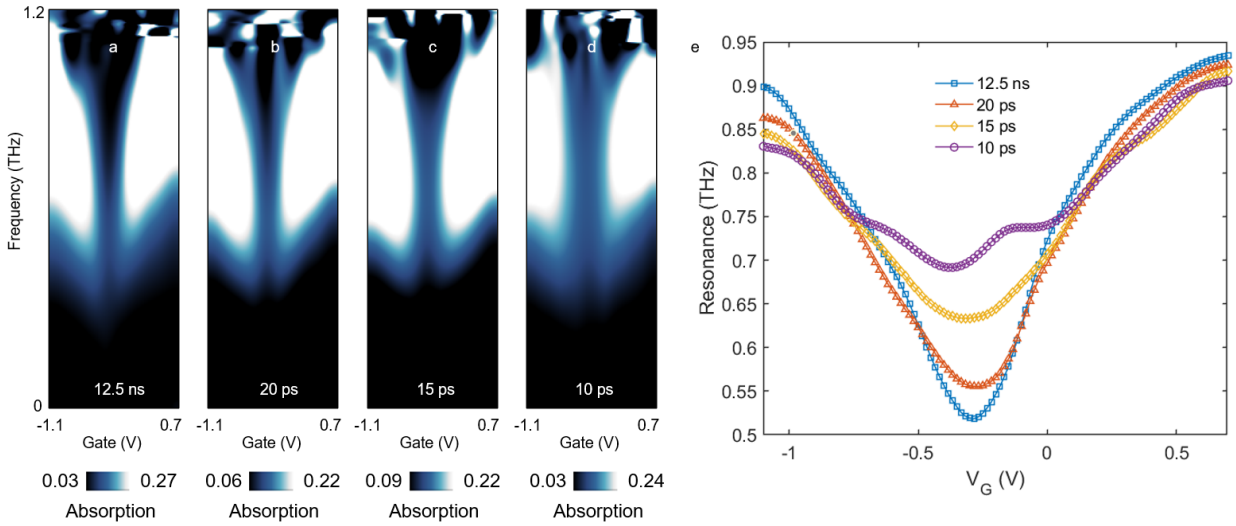

Fig. S4 | Graphene micro-ribbon absorption spectra in a second device. Measured graphene micro-ribbon absorption spectra at (a) 12.5 ns, (b) 20 ps, (c) 15 ps, and (d) 10 ps after the pump pulse. (e) Dispersion of hydrodynamic bipolar plasmons extracted from (a)-(d).

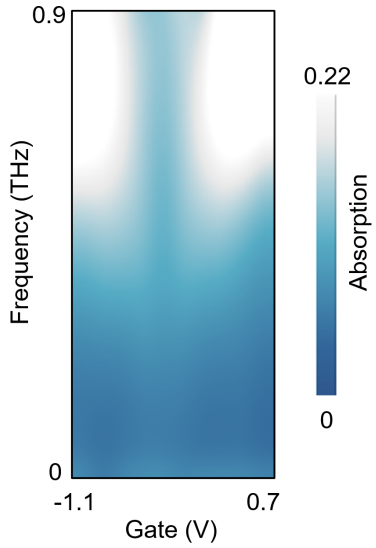

Fig. S5 | Demon mode in graphene micro-ribbon near charge neutrality. Measured graphene micro-ribbon absorption spectra at 10 ps after the pump pulse. The color bar is scaled for better visualization of the low-frequency feature.

S4. Transport measurement of the graphene device for demon propagation

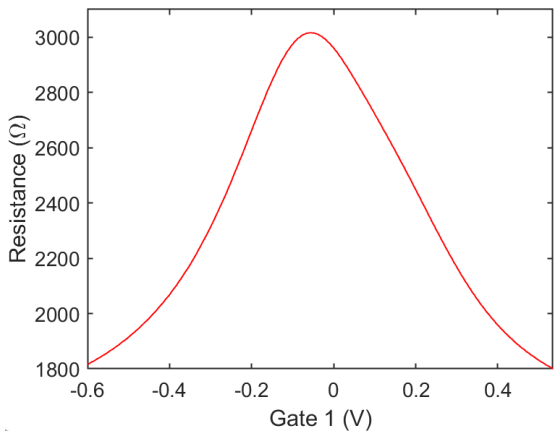

Fig. S6 | Transport measurement of the graphene device in Fig. 4 and 5 in the manuscript. The charge neutrality point is at $V_{Gate\ 1} = -0.06$ V.

References:

1 Sun, Z., Basov, D. N. & Fogler, M. M. Universal linear and nonlinear electrodynamics of a Dirac fluid. *Proceedings of the National Academy of Sciences* **115**, 3285-3289 (2018).

2 Müller, M., Fritz, L. & Sachdev, S. Quantum-critical relativistic magnetotransport in graphene. *Physical Review B* **78**, 115406 (2008).