Microscopic theory of plasmon-enabled resonant terahertz detection in bilayer graphene

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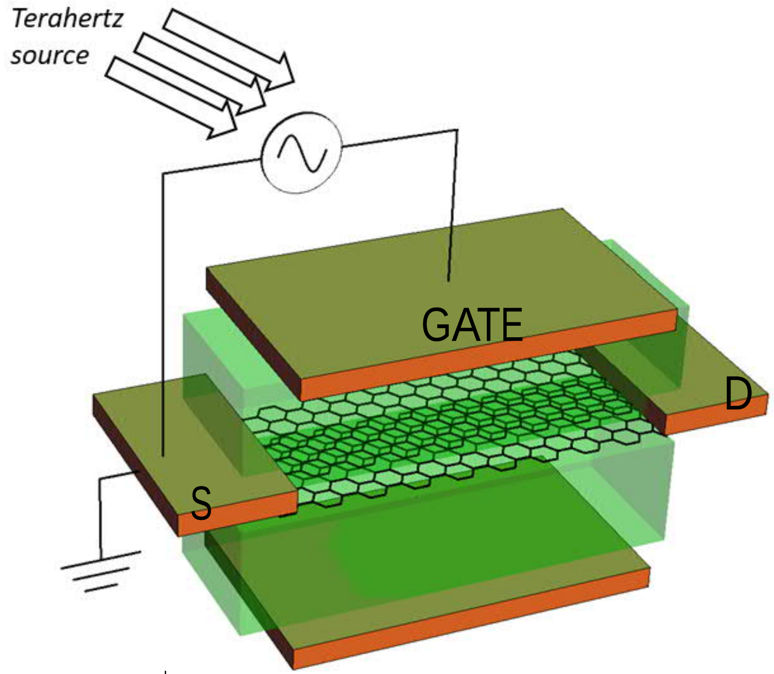
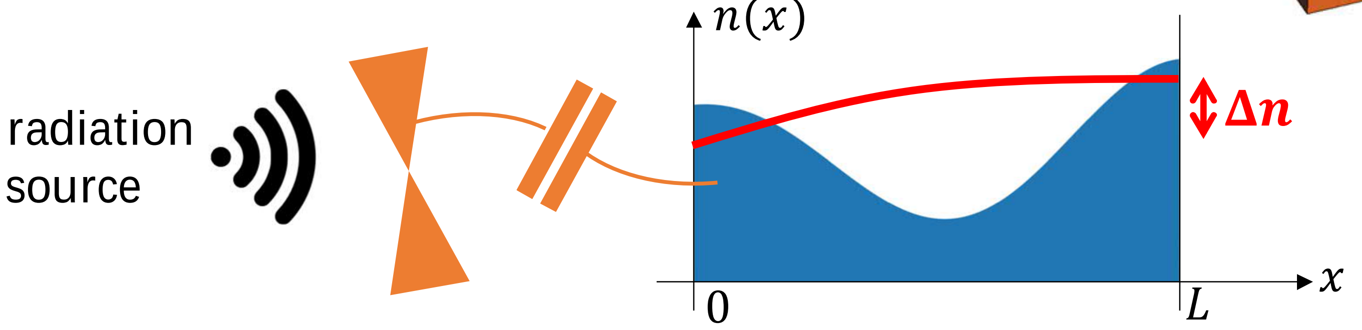
Plasma-wave based photodetection



- FET: capacitive coupling between antenna and carrier density
- Plasma waves oscillate between source and drain as in a Fabry-Pérot



- Hydrodynamic nonlinearity ⇒

DC source-drain photovoltage (*rectification*)

First proposed: M. Dyakonov and M. Shur, IEEE Trans. Electron. Devices 43, 380 (1996)

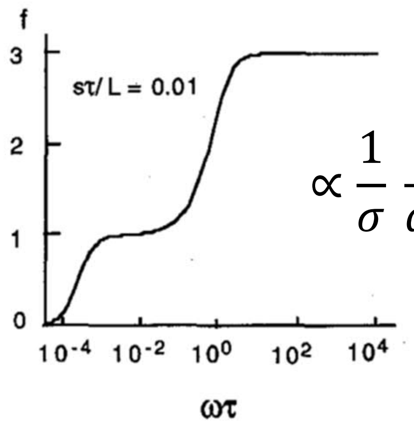
Plasma-wave based photodetection

- Impurities damp plasma waves and the photovoltage is broadband
- If e-e collision rate much larger than damping rate, the photovoltage is resonant at multiples of ω_P

diffusive

⇓

broadband

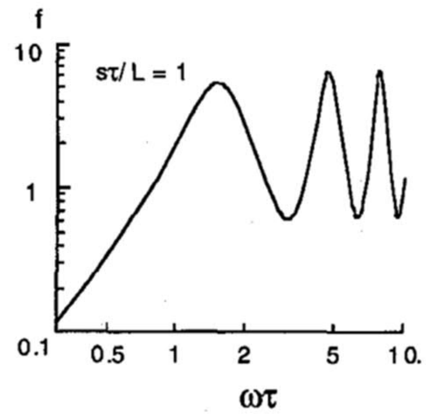


$$\propto \frac{1}{\sigma}\frac{d\sigma}{dV_G}$$

collisional ballistic

⇓

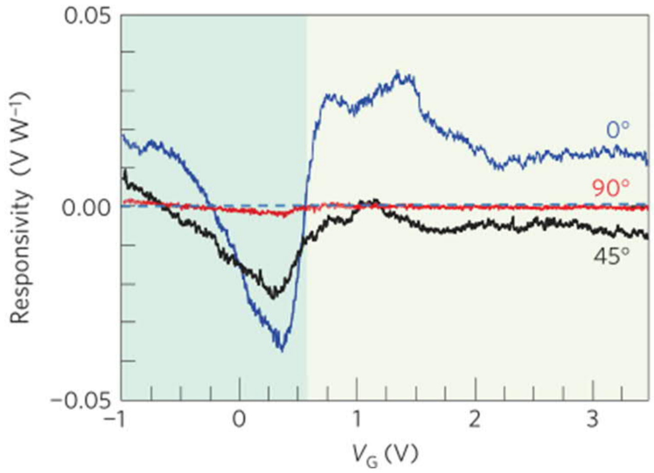
resonant

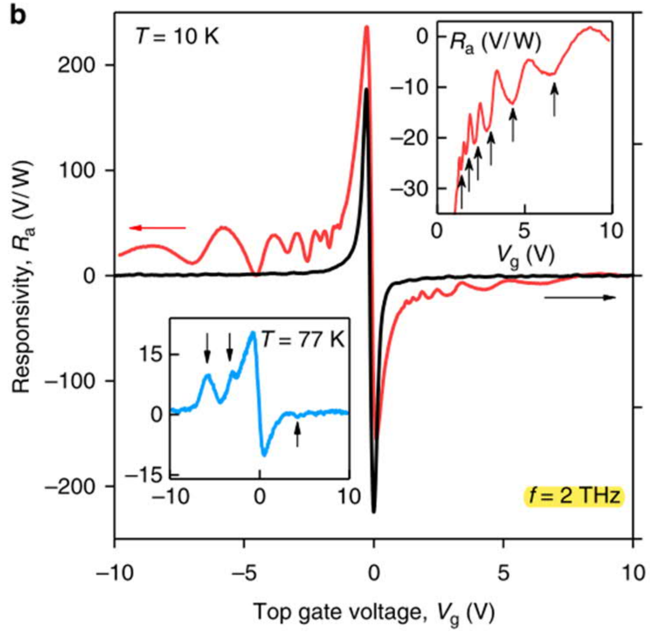


Review: W. Knap *et al.*, J. Infrared Milli Terahz Waves **30**, 1319 (2009)

Resonant plasma-waves in encapsulated bilayer graphene

- Particularly relevant in the THz (10^{12}Hz) range where room temperature photodetectors are scarce
- Graphene supports *tunable* plasma waves in the THz – mid IR range
- Bilayer graphene features higher quality factors
  L. Vicarelli *et al.*, Nat. Mater. **11**, 865 (2012)
  D. Spirito *et al.*, Appl. Phys. Lett. **104**, 061111 (2014)
- Resonant photovoltage measured in hBN-encapsulated bilayer graphene
  D.A. Bandurin *et al.*, Nat. Commun. **9**, 5392 (2018)





Goal

Bilayer graphene

microscopic quantum degrees of freedom

⇕

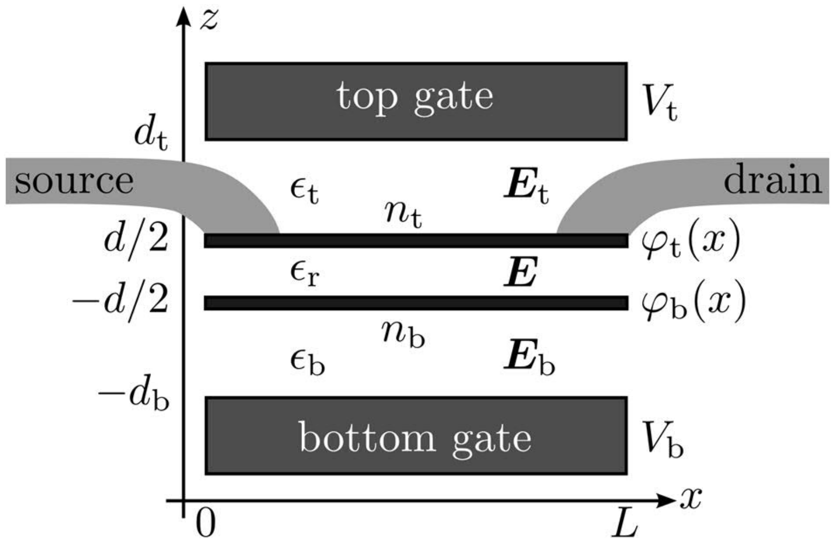
effects of coupling ?

⇕

Plasma waves

macroscopic classical collective mode

Theory of plasma-wave propagation in bilayer graphene I



Potential asymmetry:

$$\Delta(x) = -e[\varphi_t(x) - \varphi_b(x)]$$

Two-band Hamiltonian:

$$H(x) = \begin{pmatrix} 0 & -\frac{(p_x - i\,p_y)^2}{2m} \\ -\frac{(p_x + i\,p_y)^2}{2m} & 0 \end{pmatrix} - \frac{\Delta(x)}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Screening in the local-capacitance approximation:

$$n_b(x) - n_t(x) = \frac{C_b}{e} U_b(x) - \frac{C_t}{e} U_t(x) - 2\frac{C_r}{e}\frac{\Delta(x)}{e}$$

Theory of plasma-wave propagation in bilayer graphene II

Electron distribution:

$$f_{\lambda k}(x) = 1/e^{\beta[\varepsilon_{\lambda k} - \hbar v(x) k - \mu(x)]} + 1$$

Effective constitutive equation of the model:

$$0 = n(x)\frac{C_t - C_b}{C_t + C_b} + \frac{V_t - V_b}{e}\frac{2C_b C_t}{C_t + C_b}$$
$$-2\frac{\Delta(x)}{e^2}\frac{C_b C_r + C_b C_t + C_r C_t}{C_t + C_b}$$
$$+\frac{n_\perp}{2\gamma_1}\Delta(x)\ln\left(\frac{|n(x)|}{2n_\perp} + \frac{1}{2}\sqrt{\left[\frac{n(x)}{n_\perp}\right]^2 + \left[\frac{\Delta(x)}{2\gamma_1}\right]^2}\right)$$

Limit of large asymmetry:

$$C_r \Delta(x) = -e(V_t - V_b) C_{series}$$

Theory of plasma-wave propagation in bilayer graphene III

nonlinear couplings between drift velocity and charge density fluctuations

Continuity equation:

$$\partial_t n(x,t) + \partial_x[n(x,t)v(x,t)] = 0$$

Euler equation:

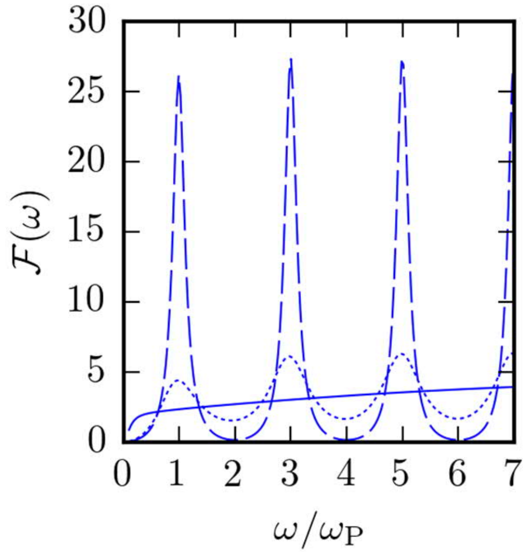
$$0 = \gamma(x,t)[\partial_t v(x,t) + v(x,t)\partial_x v(x,t)] + \frac{e}{m}\frac{n_e(x,t) - n_h(x,t)}{n(x,t)}\partial_x U(x,t) + \frac{1}{mn(x,t)}\partial_x P(x,t) + v(x,t)\partial_t \gamma(x,t) + v(x,t)^2 \partial_x \gamma(x,t) + \frac{1}{\tau}\gamma(x,t)v(x,t)$$

Relative pressure variation:

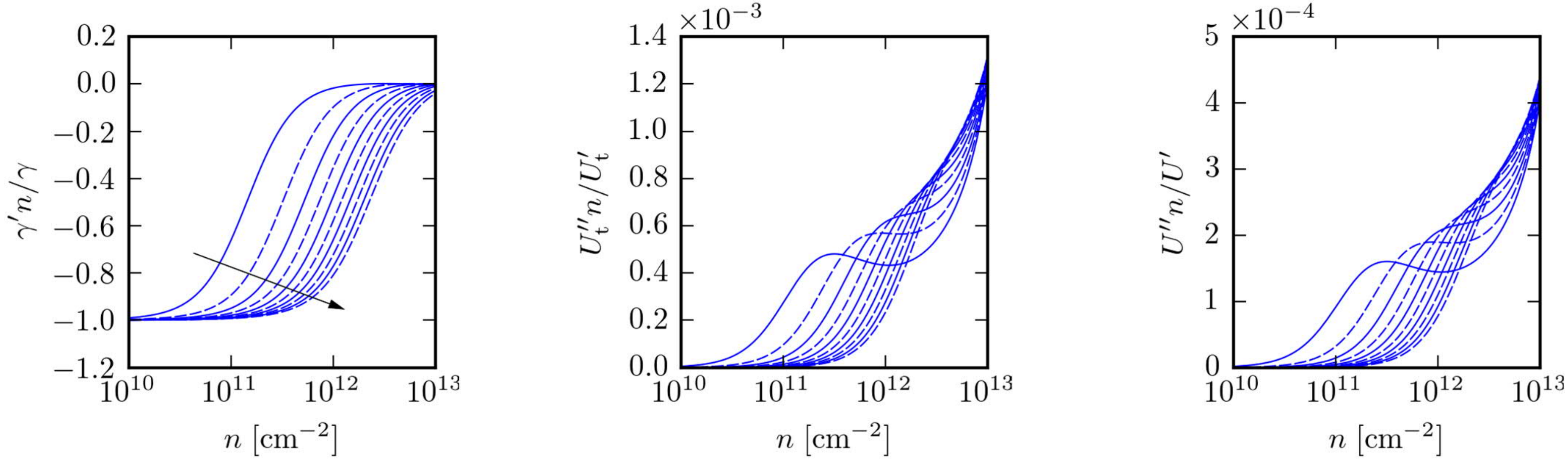
$$\gamma(x,t) = \sqrt{1 + \left[\frac{m\Delta(x,t)}{\hbar\pi n(x,t)}\right]^2}$$

Momentum-relaxing collision rate: $1/\tau$

Results and Conclusions



$$\mathcal{F}(\omega) \propto 1 - \frac{\gamma' n}{\gamma} - \frac{U_t'' n}{U_t'} + \frac{U'' n}{U'}$$



<u>More details:</u> A.T. *et al.,* Phys. Rev. B **103**, 085426 (2021)