Lateral Photo-Dember Effect in Graphene

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Abstract: The photocurrent at graphene/metal junctions under femtosecond laser excitation is found to have its polarity fully determined by asymmetry in the electron-hole mobility; this suggests the existence of unexpected lateral photo-Dember effect in graphene.

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1. Introduction

The photo-Dember effect arises from the asymmetric diffusivity of photoexcited electrons and holes, which creates a transient spatial charge distribution and thus induces an electric field [1,2]. Conventionally, a strong photo-Dember effect is only observed in semiconductors such as GaAs and InAs, which have a large asymmetry between the electron and hole mobilities. The photo-Dember effect has long been considered to be extremely unlikely in graphene due to the electron-hole symmetry in the band structure. However, here we report the observation of unusual photocurrent generation close to the graphene-metal contact edge under the excitation of femtosecond laser pulses. In contrast to excitation with a Continuous Wave (CW) laser, the ultrafast photocurrent is determined by the electron-hole mobility asymmetry, which implies the existence of a lateral photo-Dember effect induced by hot carrier dynamics.

Contrary to conventional wisdom, the unusual properties of graphene can compensate for the small electron-hole mobility difference, leading to a strong lateral photo-Dember field. This can be underscored with the following key properties. First, 2D spatial confinement enables efficient lateral diffusion of hot carriers. Second, the low electronic specific heat capacity in graphene favours a high carrier temperature. This, combined with high carrier mobility, enhances the diffusion speed of hot carriers, as given by the Einstein relation $D = \mu k_B T / (2\pi q)$, where $D$ is the diffusion coefficient, $\mu$ the excited charge mobility, $T$ the temperature, and $k_B$ the Boltzmann constant. The high carrier temperature is the key to magnifying the small difference between electron and hole mobilities. Third, strong light coupling within the single atomic layer results in high photocarrier density in graphene. Taken together, the photo-Dember effect can account for an important mechanism for photocurrent generation in graphene devices, which also suggests a new type of terahertz source based on 2D nanomaterials.

2. Gate-dependent photocurrent measurement on devices with mobility asymmetry

![Graphs](FTu4B.3.pdf)

(a-b) Gate-dependent photocurrent generated by femtosecond laser excitation of device A and device B, respectively. (c-d) Gate-dependent photocurrent generated by CW laser excitation of device A and device B, respectively.

We employ a scanning photocurrent technique to probe spatially the photocurrent generation from graphene transistors [3]. In particular, we have fabricated 15 devices with different electron and hole mobilities. Results from two representative graphene devices, devices A and B, are demonstrated here. Device A has slightly higher hole mobility than electron mobility ($\mu_e = 1095 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$; $\mu_h = 1289 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$), while device B shows the opposite behavior ($\mu_e = 820 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$; $\mu_h = 611 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$), as extracted from gate-dependent resistance measurements. The small asymmetry of the electron/hole mobility is a consequence of the unequal impurity scattering between electrons and holes in each fabricated device.
We then explore the photoresponse of these devices with femtosecond laser excitation under short-circuit conditions. Fig. 1 (a-b) show the gate-dependent photocurrent when the laser is focused at the graphene/metal contact edge. We observe three important features. First, the polarity of the photocurrent is independent of the gate voltage, which cannot be explained by the mechanism of the photovoltaic effect. Second, the polarity of the photocurrent from device B is completely opposite to that of device A. Third, regardless of the photocurrent polarity, the magnitude of the photocurrent peaks near the Dirac point gate voltage, and decreases with the doping. We emphasize that, all 15 devices we fabricated show the same features as the two representative devices.

To compare with the hot carrier photocurrent generated by femtosecond laser, we also conduct control experiments using a CW laser. As shown in Fig. 1 (c-d), the photocurrent of all devices exhibits polarity reversal as the gate voltage flips sign, in agreement with the photovoltaic effect at the metal/graphene interface. The dramatic difference between femtosecond and CW excitation indicates the important role of hot carrier dynamics in the photocurrent generation.

3. Simulation of the lateral photo-Dember effect near the graphene/metal contact edge

We simulate the hot carrier dynamics by modelling the drift-diffusion equations [4]:

\[
\frac{\partial n_i}{\partial t} = G \pm \mu_i \frac{\partial (n_i E)}{\partial x} + D_i \frac{\partial^2 n_i}{\partial x^2} - \frac{n_i}{\tau} \quad \text{with} \quad \frac{\partial (n_e - n_h)}{\partial x} = \frac{q(n_e - n_h)}{\varepsilon}
\]

where \(n_i\) is the photoexcited carrier density (\(i = e, h\) represent electron and hole, respectively), and \(E\) is the electric field. \(G\) is the photocarrier generation term. The diffusion coefficient \(D_i\) is related to mobility \(\mu_i\) via the Einstein relation. We assume the hot carrier lifetime \(\tau=1.5\) ps, \(\mu_e=2000\) cm\(^2\)V\(^{-1}\)s\(^{-1}\), \(\mu_h=16000\) cm\(^2\)V\(^{-1}\)s\(^{-1}\). For simplicity, we assume that hot carriers diffuse in-plane and only in the direction perpendicular to the metal edge due to the sharp carrier gradient. Fig. 2 (a) demonstrates the simulated time-dependent electric field. Interestingly, the asymmetric carrier distribution close to the graphene/metal contact builds up a strong photo-Dember field. The peak electric field can reach 50 kVcm\(^{-1}\) under 26 pJ pulse excitation.

Our simulation also indicates that the field strength increases super-linearly with the pulse energy \((E \propto P^{1.13})\), as shown in Fig. 2 (b). This predicted nonlinear behavior is confirmed by the power-dependent photocurrent measurement shown in Fig. 2 (c). The measured photocurrent grows super-linearly in the low pulse energy region, and becomes sub-linear under strong excitation due to Pauli blocking. The super-linear region can be well fit by \(I \propto P^{1.13}\), as shown by the inset of Fig. 2 (c). The consistency between the simulation and the experiments provides good evidence of the formation of lateral photo-Dember field close to the graphene/metal contact edge.

Fig. 2. (a) Simulation of the spatial and temporal evolution of the lateral photo-Dember electric field after the pulse laser excitation (26 pJ). The positive position corresponds to unmasked graphene area, while the negative position corresponds to the graphene area blocked by metal. (b) Simulation of the power-dependent electric field under different electron-hole mobility. The inset shows the carrier temperature. (c) Experimental measurement of the power-dependent photocurrent under pulse excitation. The inset shows the zoom-in view in the low power region.

4. References