

# Electron Diffusion in Electrodynamic Response of Graphene

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## Abstract

Carrier transport in graphene always occurs in electrostatic equilibrium due to the low density of states (DOS) near the charge neutral point (Dirac point), and the carrier response is assumed to respond instantaneously to relatively slow environmental fluctuations [1-4]. However, in the presence of environmental fluctuations that introduce changes on the timescale of the electrodynamic response time, graphene cannot be assumed to respond instantaneously. A lag in the graphene response can degrade the efficiency of carrier transport relative to electrostatic equilibrium conditions. In this work, we investigate the carrier diffusion induced by a non-uniform carrier concentration and measure the diffusion time in graphene. For the first time, the electron diffusion times were measured from the electrodynamic response of a single-layer graphene field-effect transistor (SLG-FET). The application of a negative gate voltage ( $V_G$ ) electrostatically introduced a local excess of electron density into the graphene channel, and diffusion from the high-concentration region to the low-concentration region was characterized by measuring the time evolution of the drain current ( $I_D$ ). In a dark environment, the electron diffusion times in graphene were inversely proportional to the temperature. Electron diffusion required a relatively long diffusion time (4 s) to achieve electrostatic equilibrium at low temperatures (100 K); however, the extra energy provided by the photons makes carriers diffuse fast under illuminated conditions, indicating the presence of a strong photoresponse in graphene.

A back-gate SLG-FET was fabricated, in which the SLG was synthesized via metal-catalyzed chemical vapor deposition (CVD) and its Dirac point was located at the  $V_G$  of 160 V. An electrodynamic theory of electron diffusion was proposed. For a  $V_G$  of zero, the Fermi level of graphene in the channel is equilibrated with the source and drain. The electrodynamic response of graphene, however, is characterized by an instantaneous downward shift in the Fermi level with the Dirac point energy, upon application of a positive  $V_G$ , thereby producing a temporary shortage of electrons in the channel. The drift of electrons moving from the source to the drain rapidly compensates for this shortage of electrons, and the Fermi level shifts back to the electrostatic equilibrium. For comparison purposes, the Fermi level instantaneously shifted to higher values upon formation of a temporary excess of electrons under the application of a negative  $V_G$ . The extra electrons diffused toward the source and drain to restore the Fermi level to electrostatic equilibrium.

The carrier diffusion induced by the excess electrons under a negative  $V_G$  showed a strong photoresponse under illumination conditions. This response contrasted with the absence of a photoresponse under electron shortage conditions produced under a positive  $V_G$ . The absence of carrier diffusion under laser illumination substituted a slow transition, with a transition time of 0.25 s under dark conditions, with a fast transition, with a transition time of 0.04 s under illumination conditions. All the electrons in the channel then become “hot” under laser illumination (655 nm wavelength) due to the introduction of additional kinetic energy (1.89 eV) provided by the photons. In this case, the distribution of electrons in the channel corresponded to a non-equilibrium state where no electrodynamic disturbances were present in the Fermi level and the electron diffusion in the channel ceased.

The carrier diffusion time, which was defined as the time required to equilibrate the Fermi level after disruption by the application of  $V_G$ , was obtained from the time evolution of  $I_D$ . The diffusion time under a negative  $V_G$  increased significantly to 4 s at 100 K from less than 1 s at room temperature. As a comparison, the time evolution of the channel current under a positive  $V_G$  did not vary significantly with temperature. The time evolution of the normalized  $I_D$  at  $V_G = -40$  V was obtained for various temperatures. The diffusion time as a function of temperature was calculated, which was inversely proportional to the temperature, in agreement with the diffusion theory.

In summary, for the first time, electron diffusion in graphene was measured based on the electrodynamic response of an SLG-FET. We measured the electron diffusion time from the time evolution of the channel current. The photoresponse and temperature dependence of the channel current were also measured. Electron diffusion with a relatively long diffusion time reduced the channel current under dark conditions. In contrast, the electron diffusion was absent under photo illumination

conditions, resulting in a strong photoresponse in graphene. The diffusion time was inversely proportional to the temperature, in agreement with the theory. Because the electron diffusion properties in graphene could be easily controlled through the temperature and light illumination conditions, these findings may be applicable to the development of future electronics and photo-electronic devices based on graphene. The effects are particularly useful in high-frequency device applications.

## References

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