The Role of Substrate in the Photoresponse of Graphene Transistors

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Abstract: Recent experiments on graphene phototransistors, composed of a graphene channel back-gated by an un-doped 6H-SiC (see Fig. 1), have demonstrated impressive photo-responsivity (> 1A/W) [1,3]. Despite several experimental reports and significant potential for commercial application, the theoretical basis of this high sensitivity is not fully understood. Here we use detailed computational modeling to demonstrate that the extraordinary photosensitivity arises from the electrostatic doping of graphene due to surface accumulation of photo-generated carriers in the substrate. We find that further optimization of substrate mobility, lifetime, and, bandgap may substantially improve photosensitivity as well as the gain-bandwidth of photo-detection.

Physical Original of Photosensitivity: The photo-sensitivity of graphene phototransistor arises from an unusual interaction of vertical charge transport in the substrate coupled to lateral charge transport in graphene. The two-dimensional (2D) charge transport in the substrate was simulated in a semi-classical drift-diffusion simulator PADRE developed at Bell Labs [4]. The charge transfer from the substrate to graphene is phenomenologically modeled as an interface transfer flux, *i.e.*, $J_{tr} = qn_{itf}\, v_{inj}$, where n_{itf} and v_{inj} are the photogenerated carrier density and injection velocity at graphene/substrate interface, respectively. J_{tr} defines the boundary condition to the drift-diffusion transport inside the substrate and physically depends on the properties of the interface. In particular, we find that, $v_{inj} \ll v_{th}$, the thermal velocity, presumably due to formation of thin-oxide layer before graphene is deposited. With $v_{inj} \ll v_{th}$, high density of photo-generated carriers accumulate at the graphene/substrate interface, leading to electrostatic modulation (and significant photosensitivity) of the graphene channel. As an illustrative example, Fig. 1(b) shows an energy band diagram perpendicular to the channel. A back gate voltage (V_{bg}) creates an electric field (ε) in the substrate, which separates the photogenerated carriers to opposite contacts. An interfacial barrier at the graphene/SiC interface results in carrier accumulation, see Figs. 1 (c) and (d) for V_{bg}=20V and −20V, respectively. The lateral charge profiles in Fig. 2, plotted as a function of V_{bg}, show how the accumulated charge electrostatically dopes the graphene and shifts the Dirac point (E_{Dirac}) away from Fermi level (E_F).

Substrate Dependence: SiC is expensive; Can graphene phototransistor with Si substrate offer comparable performance? Fig. 3 shows the doping modulation ($E_{Dirac} - E_F$) with Si vs. SiC being used as photo-absorber. Under dark, Si-device shows a stronger modulation compared to SiC, since the lower bandgap energy for Si allows a higher carrier injection from metal which subsequently accumulate at graphene/substrate interface. Under light, both materials show a similar behavior. Fig. 4 shows the dependence of graphene doping under illumination on mobility (μ) and carrier lifetime (τ) of the substrate. As τ or μ is increased, the drift length ($l_{drift} = \mu \times \tau \times \varepsilon$) of carriers is also increased and more number of photogenerated carriers can accumulate at graphene/substrate interface to electrostatically modulate the potential of graphene. Similarly, Fig. 5 illustrates the dependence of graphene doping on photon wavelengths for Si and SiC as photo-absorber. The smaller band gap of Si allows absorption of lower photon energy (higher wavelength) as compared to SiC; thus, Si may have improved bandwidth. Finally, Fig. 6 shows the dependence of graphene resistance on substrate material properties. The greater l_{drift} (higher μ and τ) allows more photogenerated carriers to reach at graphene/substrate interface hence increasing graphene doping and lowering its resistance (R).

Summary: In this paper, we have explained the origin of extraordinary photosensitivity of graphene phototransistor and that even if SiC is replaced by much cheaper Si substrate, the performance may not be compromised. In either case, improved material quality (higher $\mu\tau$ product) improves sensitivity; ultimately the sensitivity may be dictated by system application, rather than device limits.

References:

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[3] Foxe, Michael, *et al*, *IEEE Trans. Nanotech.*, 11.3 (2012) [4] M. Pinto *et al,* https://nanohub.org/resources/padre

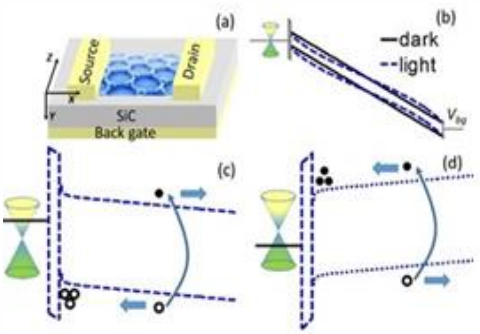

Fig. 1. (a) 3-D Illustration of graphene phototransistor. A single layer graphene forms the channel between source/drain metals and substrate is used as photo-absorber. (b) Energy band diagram under metal near the graphene/substrate interface. (c,d) Energy band diagram along Y for V_{bg} = ± 20V. The holes or electrons accumulate at graphene/substrate interface make graphene n or p-type

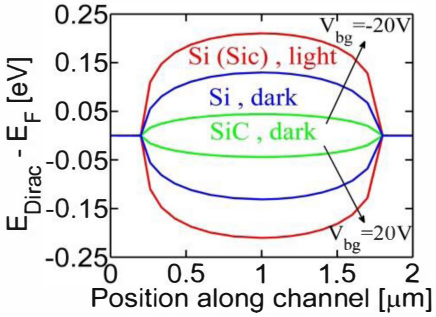

Fig. 3. E_{Dirac} - E_F for Graphene phototransistor along the channel for Si and SiC as photo-absorbers. Under dark, more charges accumulate at graphene/substrate interface for Si due to low energy barrier that prevents injection of carriers to flow into substrate from metal contact. Under illumination, behavior of both substrates remains same.

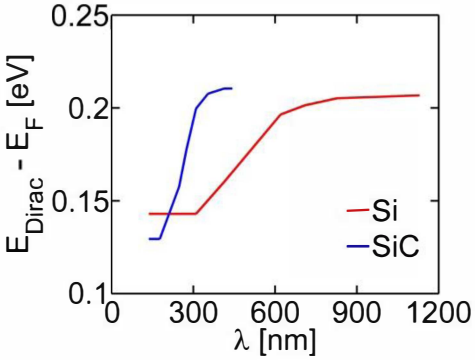

Fig. 5. E_{Dirac} – E_F under illumination for Si and SiC based graphene phototransistors. The smaller band gap of Si can absorb light having smaller photon energy as compared to SiC that can absorb photons having greater energy.

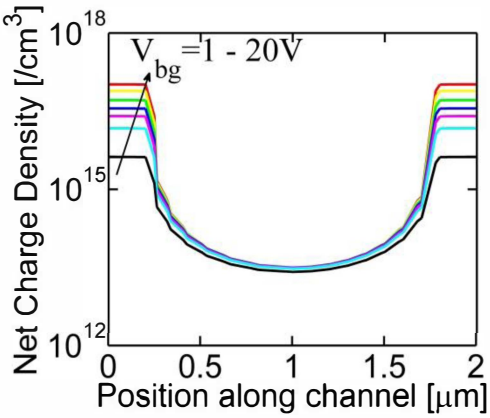

Fig. 2. Net concentration of the accumulated carriers along the position of channel in graphene at different V_{bg} for v_{inj}<<v_{th}. The higher charge concentration for higher voltage is due to the increased collection of photogenerated carriers at graphene/substrate interface as the drift length increase at higher $V_{bg.}$

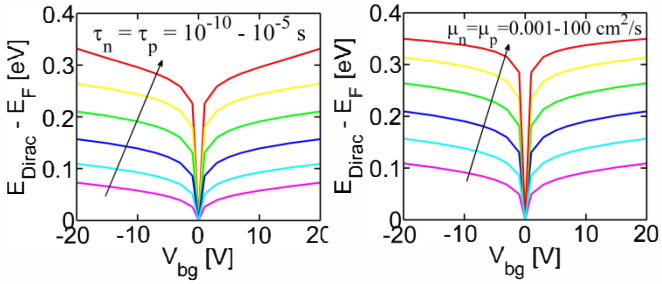

Fig. 4. Dependence of E_{Dirac} - E_F under illumination on minority carrier lifetime (τ) and mobility (μ). As τ or μ is increased, more and more carriers accumulate at graphene/SiC interface to make graphene doped and vice versa.

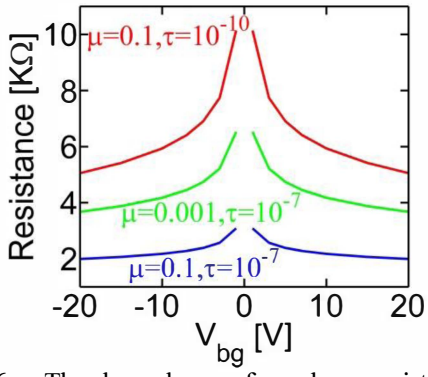

Fig. 6. The dependence of graphene resistance on μ and τ under illumination for v_{inj}<<$v_{th.}$ As l_{drift} of carriers is increased, more carriers can accumulate at graphene/substrate interface hence modulating the graphene doping and lower resistance.