Terahertz Source with Graphene p–n Junction

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Abstract—**The gate-controlled graphene with two top gates shows that the positive gate voltage can move the Fermi level to higher energy towards conduction band, whereas the negative gate voltage will move the Fermi level to lower energy towards valence band to form graphene p-n junction. The band gap between the n-type graphene and the p-type graphene can be tuned from 0eV. When the induced n-type Fermi level is bigger than 2.15meV, it is possible to radiate terahertz photon if the electrons in n-type graphene are injected to p-type graphene to recombine with holes under a forward bias.**

I. INTRODUCTION

TERAHERTZ technology has wide application prospect in many fields, but the lack of high power terahertz sources which have simple structure and work at room temperature limits its development. There are conventional approaches for terahertz wave generation, such as microwave upconversion, tube sources, photon-mixing, optically-pumped gas lasers, p-doped Ge lasers and free electron lasers. Nevertheless, the conventional terahertz sources are not user-friendly (either bulky, complicated, power-hungry, or inefficient). Terahertz quantum cascade lasers are promising coherent terahertz sources, but they cannot be operated at room temperature. Clearly, there is a pressing and continuing need for the development of compact, easily-operable, high-performance solid-state terahertz sources. The mono-layer of graphene offers unique and new opportunities for the design and development of terahertz and electro-optic devices.

Graphene is regarded as a direct zero bandgap semiconductor. It has bipolar field effect, i.e. the Fermi level can be changed by the gate voltage to form n-type or p-type graphene rather than doping [1]. The band gap between the n-type graphene and the p-type graphene can be tuned from 0eV because of the zero band gap feature of intrinsic graphene.

Terahertz photon energy is very small compared to the band gap of most commonly-available semiconductors. The zero band gap is advantageous in terms of terahertz wave generation because a small effective band gap could be created by turning the Fermi energy level in a gate-controlled graphene p-n junction. We have fabricated and measured the graphene device with two top gates [2]. The measurement results show that the external gate biases can effectively induce a p-n junction in the graphene layer. It is therefore possible to employ this gate-controlled graphene based p-n junction for terahertz wave generation.

II. RESULTS

As shown in Fig. 1, the positive gate voltage V_{GS1} applied to the top gate TG1 will move the Fermi energy of this top gate area of graphene to higher energy towards the conduction band. Conversely, negative gate voltage V_{GS2} applied to the top gate TG2 will move Fermi energy of this top gate area of graphene to lower energy towards the valence band.

For n-type graphene, extra electrons are induced by electrostatic field and are accumulated in the graphene layer, resulting in population inversion. When the forward bias gets to a certain value, the electrons of high energy level move to the p-type graphene as shown in Fig. 1, and recombine with the holes in p-type graphene to generate terahertz photons. In spite of carrier losses due to Auger recombination and other mechanisms, electrons could be injected to the p-graphene region through ballistic transport [3], leading to electron-hole radiation recombination.

The induced charge-carrier density is given by $n = \varepsilon_0 \varepsilon_r V_g / te$, where ε_0 is the vacuum permittivity, ε_r is the relative dielectric constant, e is the electron charge, t is the thickness of the dielectric layer, and V_g is the gate voltage. The dielectric in Fig. 1 is 60 nm thick layer of Al_2O_3 (ε_r =6.5). The maximum gate voltage is 8V [3]. Hence, the charge-carrier density n=4.8×10^{12}cm^{-2}, shifts the Fermi energy $E_F = \mathrm{sgn}(n)\hbar v_F \sqrt{\pi|n|}$ =0.2eV accordingly [1], where v_F = 0.8 × 10^6 m/s, is the Fermi velocity. For example, terahertz photons at 1 THz frequency correspond to about 4.3 meV energy. Therefore the induced n-type Fermi level is elevated by 2.15meV. If the gate voltage is 0.9mV, it is possible to radiate 1 THz photon if the electrons in n-type graphene are injected to p-type graphene to recombine with holes under a forward bias.

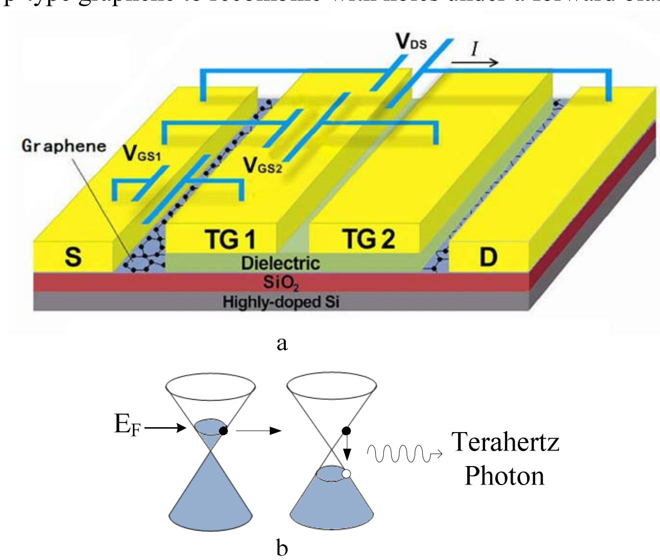

Fig. 2. *a* The schematic configuration of the gate-controlled graphene device with two top gates. *b* The terahertz photon emission by the electron-hole recombination

Hence the induced band gap in graphene would be sufficient for terahertz wave generation.

III. SUMMARY

The electrostatic field induces the charge-carrier density of graphene to form n-type or p-type graphene, which creates graphene p-n junction. When the Fermi energy difference between the two types of graphene corresponds to the terahertz energy, the electrons in n-type graphene recombine with holes in p-type graphene under a forward bias to radiate terahertz photons. As the p-n junction configuration presented in the paper, when the gate voltage is 0.9mV, the frequency of terahertz photon will be 1THz.

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