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Trends and Future of Ultrafast Transistors and Terahertz Light Amplification by Stimulated Emission of Radiation Using Graphene

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1. Introduction

Graphene, a monolayer of sp2-bonded carbon atoms in a honeycomb crystal lattice, has attracted considerable attention due to its unique carrier transport and optelectronic properties [1-4]. When graphene is introduced to the field-effect transistors (FETs) as the channel material it will break through the limit on conventional planar transistor performance so that it could become a booster technology for making short-channel-free ultimately fast transistors [5]. On the other hand, the nonequilibrium carrier relaxation/recombination dynamics of optically pumped graphene will lead to the population inversion in the wide terahertz (THz) range under sufficiently high pumping intensity [6]. Such an active mechanism can be used for creating a graphene-based new type of THz laser. In this paper trends and future of graphene-based ultrafast transistors and THz lasers are discussed.

2. Graphene-Channel FETs (G-FETs)

Basic Properties

Considering the electronic properties of graphene, the giant mobility of massless electrons/holes and real two-dimensional electron/hole systems are of the superior advantages beyond any semiconductor materials. Thanks to the linear dispersion relation the density of states in graphene is proportional to the energy giving rise to extremely high saturation current density $>10^8$ A/cm^2 [7]. Furthermore, the saturation velocity of electrons and holes are quite high because no valley exists around the K and K' points and optical phonon energy is so high that the optical phonon scattering becomes weaker than those for conventional semiconductor materials [8].

Monolayer graphene shows an ambipolar behavior where electrons/holes coexist symmetrically against the Dirac point. Thus, formation of the bandgap is necessary to turn off the G-FETs. Patterning of monolayer graphene into a nanoribbon [9] and chiral stacking of monolayer graphene into bilayer or multiple layers under a vertical electric field [10] are typical options to open the bandgap.

State of the Arts

IBM has led the development of high frequency G-FETs, demonstrating a highest current-gain-cutoff frequency f_T of 100 GHz by using a 240-nm-gate epitaxial-G-FET [11]. 10-nm thick HfO_2 gate insulator is deposited on an ultrathin inert layer by atomic layer deposition (ALD). Recently a group of UCLA has demonstrated the record 300-GHz f_T performance by a 140-nm gate exfoliated G-FET featuring a dedicated Co2/Si composite nanowire gate wrapped with 5-nm thick Al2O3 insulator [12]. The source/drain electrodes are formed in a self-aligned manner, which is the key to minimize the parasitic access resistance that severely deteriorates the FET performance. Although such an acrobatic gate stack technique is premature out of the standard planar process technology the result has extended the high frequency performance of G-FETs.

Figure 1 plots f_T vs. L_g for various types of FETs. The original figure in Ref. [5] is modified with additional plots for the above-mentioned G-FETs. It is clearly seen that the real performance of G-FETs is just now on the same level as that for InP-based HEMTs and need more studies to demonstrate the superior performance expected from the original nature of graphene.

Future Subjects

First, crystal quality of graphene should be further improved. From the view point of a possible post Si-CMOS technology heteroepitacial graphene on a silicon substrate (GOS) [13] will be a promising method for graphene synthesis. So far back-gate and top-gate GOS FETs have been fabricated, demonstrating a high field effect mobility >6,000 cm^2/(Vs) [14, 15]. Second, the gate stack needs to be improved. Oxidized high-k dielectrics like HfO_2 and

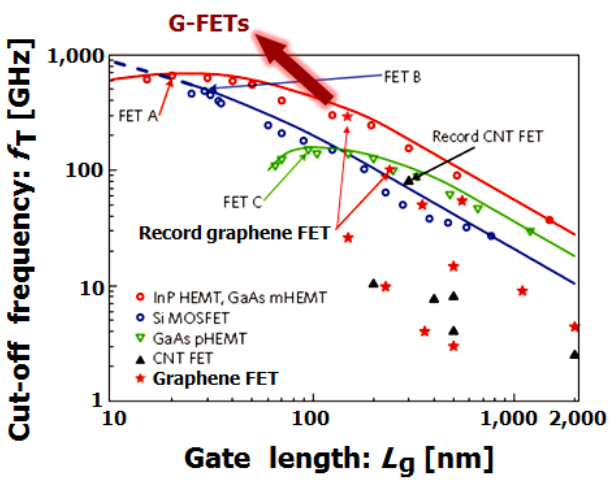


Fig. 1 Trends in f_T vs. L_g. Data for G-FETs are added in [5].

Al_2O_3 easily damage graphene. To prevent it, an ultrathin low-k noncovalent functionalization layer is introduced underneath them, severely degrading the dielectricity [12]. Recently carbonaceous gate stack using diamondlike carbon (DLC) and/or SiCN have been investigated to realize surface-state-free high performance gate stack technology [16]. Third, on/off current ratio must be improved. Recent works by IBM on a high on/off current ratio >100 from a bilayer G-FET [17] encourage us to proceed the way to the bandgap-engineered G-FETs.

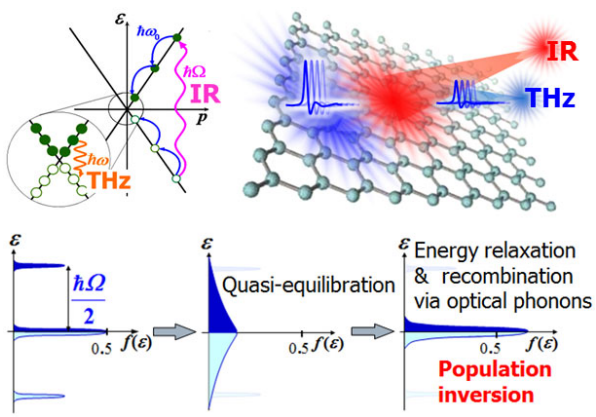
3. THz Light Amplification Using Graphene

Theory

Consider the carrier relaxation/recombination processes in optically pumped graphene as shown in Fig. 2. When the photogenerated electrons and holes are heated in case of room temperature environment and/or strong pumping, collective excitations due to the carrier-carrier scattering, e.g., intraband plasmons should have a dominant play to perform an ultrafast carrier redistribution along the energy (Fig. 2(b)). Then optical phonons are emitted by carriers on the high-energy tail of the electron and hole distributions, accumulating the nonequilibrium carriers around the Dirac points (Fig. 2(c)). Due to a fast intraband relaxation (ps or less) and relatively slow interband recombination (>>1ps) of photoelectrons/holes, one can obtain the population inversion under a sufficiently high pumping intensity [6].

Experiments

An exfoliated monolayer-graphene/SiO2/Si sample was placed on the stage and a 0.12-mm-thick CdTe (100) crystal was placed on the sample, acting as a THz probe pulse emitter as well as an electro-optic sensor. A single 80-fs, 1550-nm, 4-mW, 20-MHz fiber laser beam is split into two: one for optical pumping and generating the THz probe beam in the CdTel, and one for optical probing. The THz probe pulse double-reflect to stimulate the THz emission in graphene, which is detected as a THz photon echo signal [18]. Figure 3 shows the measured temporal response. The secondary pulse, the THz photon echo signal, obtained with graphene is more intense compared with that obtained without graphene. This indicates the graphene act as an



(a) (b) (c)

Fig. 2 Carrier dynamics in optically pumped graphene.

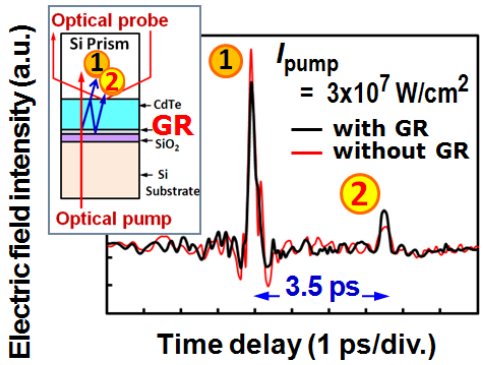


Fig. 3 Measured temporal profile. The secondary pulse is the THz photon echo transmitted and reflected through graphene.

amplifying medium. When the pumping intensity weakens below 1 x 10^7 W/cm^2 a threshold like behavior can be seen, testifying the occurrence of the negative conductivity and the THz light amplification by stimulated emission of radiation [19]. If the THz gain medium of graphene is installed into a pertinent THz cavity, it will lead to a new type of THz lasers [20].

4. Conclusions

The state-of-the-art technology of graphene-based ultrafast transistors and THz lasers were described. Issues and subjects for further advancement were also addressed.

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