Emission and Detection of Terahertz Radiation Using Two-Dimensional Electrons in III-V Semiconductors and Graphene

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***Abstract*— Recent advances in emission and detection of terahertz radiation using two-dimensional (2D) electron systems in III-V semiconductors and graphene. 2D plasmon resonance is first presented to demonstrate intense broadband terahertz emission and detection from InGaP/InGaAs/GaAs and InAlAs/InGaAs/InP material systems. The device structure is based on a high-electron mobility transistor and incorporates the author's original asymmetrically interdigitated dual-grating gates. Second topic focuses on graphene, a monolayer carbon-atomic honeycomb lattice crystal, exhibiting peculiar carrier transport and optical properties owing to massless and gapless energy spectrum. Theoretical and experimental studies toward the creation of graphene terahertz injection lasers are described.**

***Index Terms*—compound semiconductors, detectors, graphene, lasers, plasmons, terahertz**

I. Introduction

In the research of modern terahertz (THz) electronics, development of compact, tunable and coherent sources and detectors operating in the THz regime is one of the hottest issues [1]. Two-dimensional (2D) plasmons in semiconductor nano-heterostructures like electron channels in high-electron mobility transistors (HEMT's) have attracted much attention due to their nature of promoting emission and detection of THz electromagnetic radiation [2, 3]. On the other hand, graphene, a monolayer carbon-atomic honeycomb lattice crystal, has attracted attention due to its peculiar carrier transport properties owing to the massless and gapless energy spectrum [4]. Optical and/or injection pumping of graphene can exhibit negative-dynamic conductivity in the THz spectral range [5, 6], which may bring new types of THz lasers. This paper reviews recent advances in emission and detection of terahertz radiation from 2D electron systems in III-V semiconductor and graphene nano-heterostructures.

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II. THz Emission and Detection Using 2D Plasmons

A. THz Emission from 2D Plasmons in HEMTs

We have proposed our original 2D-plasmon-resonant micro-chip emitter as a new terahertz light source [7-10]. The structure is based on a HEMT and featured with interdigitated dual-grating gates (Fig. 1). The dual grating gates can alternately modulate the 2D electron densities to periodically distribute the plasmonic cavities (~100-nm width in microns distance) along the channel, acting as an antenna [7]. Under pertinent drain-source dc bias conditions, dc electron drift flows may promote the instability owing to the periodic modulation of electron drift velocities [11], resulting in self-oscillation with characteristic frequencies in the terahertz regime. The device was fabricated using InGaP/InGaAs/GaAs and/or InAl/InGaAs/InP material systems [8-10]. So far a broadband THz emission ranging from 1 to ~6 THz has been obtained reflecting multimode of coherent/incoherent plasmons [2], for which oblique modes [12], hot plasmons, and chirped plasmon modes [8] are of the major causes. The DGG-HEMT THz emitter can work for terahertz spectroscopic and imaging applications as an incoherent broadband terahertz microchip source, demonstrating fine identification of water vapor

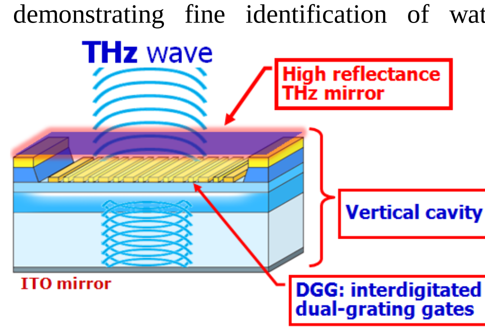


Fig. 1. Schematic and SEM images of a DGG-HEMT with a vertical cavity.

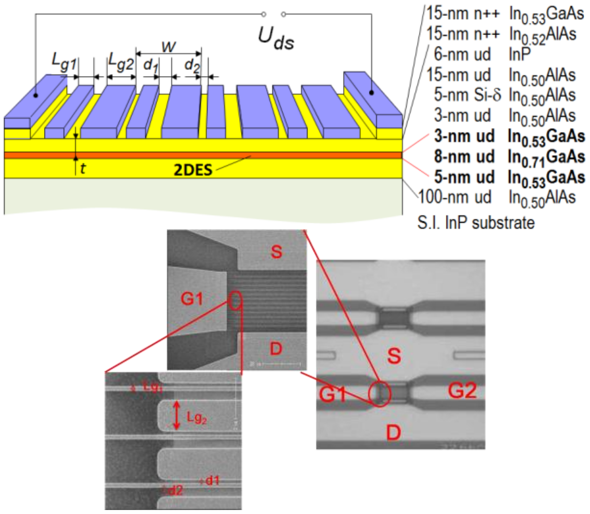


Fig. 2. Schematic view and SEM images of an A-DGG HEMT THz detector. L_{g1} = 200 nm, L_{g2} = 400 nm, d_1 = 200 nm, d_2 = 400 nm.

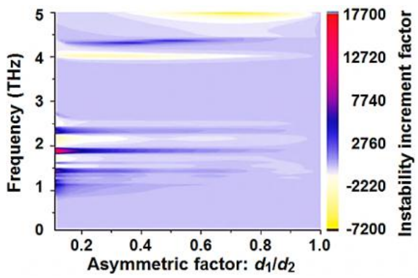


Fig. 3. Simulated relative instability-increment factors for an A-DGG HEMT as a function of the asymmetric factor d_1/d_2. L_{g1} = 200 nm, L_{g2} = 1.6 µm, $d_1 + d_2$ = 600 nm, W = 2.4 µm. Electron density under the gate G2 is 2.5×10^{11} cm^{-2} whereas that is 2.5×10^{12} cm^{-2} under the gate G1.

absorptions as well as finger prints of sugar groups [9].

In order to realize coherent monochromatic THz emission we introduced our original asymmetric DGG (A-DGG) structure (Fig. 2) [13] and an improved resonant-enhanced high-Q vertical cavity structure [7]. In the A-DGG structure the DGG is implemented with asymmetric inter-finger spaces, which originates a strong asymmetric field distribution for a unit section of the DGG periodic structure, resulting in promotion of the Dyakonov-Shur-type instability [2, 13]. We expect so called 'giant' plasmon instability as a result of cooperative effects between these two instability mechanisms, accelerating the injection locking operation (Fig. 3). Preliminary trial of the emission spectral measurement is now undergoing using fabricated InAl/InGaAs/InP A-DGG-HEMTs. Very sharp resonant-type monochromatic emission is expected.

B. *THz Detection Using 2D Plasmons in HEMTs*

The possibility of the THz detection in a HEMT structure is due to the nonlinearity of the 2D plasmon dynamics, which lead to the rectification of the THz radiation. As a result, a photoresponse appears as a dc voltage between source and drain in proportion to the radiation intensity (photovoltaic effect) [3]. Depending on the quality factor of the 2D plasmon cavity, which is characterized by the product of incoming THz angular frequency ω and electron momentum relaxation time τ, the detection operation is categorized in the "resonant" mode ($\omega\tau > 1$) or "non-resonant" mode ($\omega\tau < 1$) [3, 14].

We have demonstrated so far several THz imaging experiments using standard single-gate (SG) HEMTs [14, 15] as well as DGG-HEMTs [16]. Typical result is shown in Fig. 4; the image of the tea leaves that are invisible and hidden in an aluminum-coated plastic package is clearly seen [15], confirming the potentiality of the plasmonic HEMTs as a powerful THz detector.

In order to improve the detector responsivity, pertinent antenna structure should be introduced. A smart design of a narrow band antenna has been proposed in [17] where the SG electrode is designed as a dipole antenna, demonstrating an excellent responsivity 1 KV/W at 1 THz at 300K. The obtained responsivity exceeds that for Schottky barrier diodes.

In terms of broadband antennae, log-periodic or log-spiral as well as grating-gate (GG) are frequently utilized. The DGG structure [7] is an improved type derived from the GG type but still suffers from low responsivity. Our original A-DGG structure can surpass this critical limit [13] because the unit cell of the A-DGG structure can create strong build-in asymmetric field. The THz photoresponse dramatically increases when the parts of 2D channel under the fingers of one of the two sub-gratings are depleted. The InAlAs/InGaAs/InP A-DGG HEMTs (Fig. 2) demonstrate a record-breaking responsivity of 2.2 kV/W and an excellent noise equivalent power of 15 pW/Hz$^{0.5}$ at 1 THz at 300K (Fig. 5) [18]. A fairly high responsivity (>0.5 kV/W) is also maintained over the frequencies beyond 2 THz. All these values are, to the authors' knowledge, the best ever reported at these frequencies.

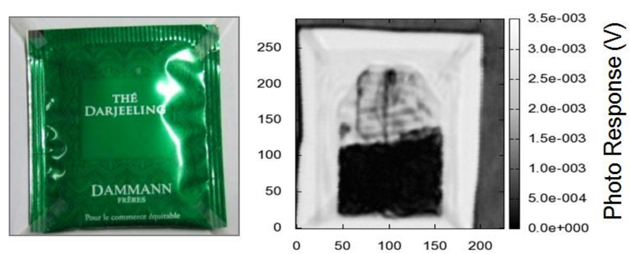


Fig. 4. Terahertz imaging for a tea bag. Left: photo image, right: THz image.

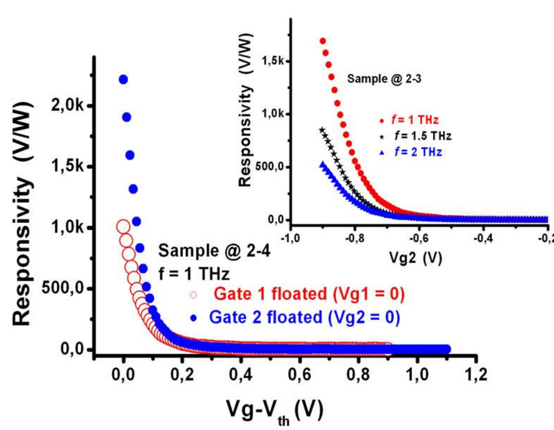


Fig. 5. Measured responsivity of fabricated A-DGG HEMTs at 300K [18].

III. THz Light Amplification by Stimulated Emission in Graphene

A. Carrier Dynamics in Optically Pumped Graphene

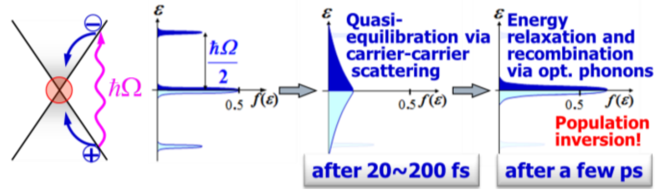
Carrier relaxation dynamics at relatively high temperatures in optically pumped graphene is shown in Fig. 6. When the photogenerated electrons and holes are heated, collective excitations due to the carrier-carrier scattering, e.g., intraband plasmons should have a dominant roll to perform an ultrafast carrier quasi-equilibration (Fig. 6(b)) [19]. Then carriers at high-energy tails of their distributions emit the optical phonons, cooling themselves and accumulating around the Dirac points (Fig. 6(c)). We numerically simulated the temporal evolution of the quasi-Fermi energy and carrier temperature after impulsive pumping with 0.8-eV photon energy [20]. As shown in Fig. 7, due to a fast intraband relaxation (ps or less) and relatively slow interband recombination (>>1ps) of photoelectrons/holes, the population inversion is obtainable under a sufficiently high pumping intensity > 10^7 W/cm^2 [20].

B. Observation of Amplified Stimulated THz Emission

We conducted THz time domain spectroscopy for fs-laser pumped graphene samples and showed that graphene amplifies an incoming terahertz field [21, 22]. An exfoliated monolayer-graphene/SiO_2/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 electrooptic sensor [22]. A single 80-fs, 1550-nm, 4-mW, 20-MHz fiber laser was used for optical pump and probe signals as well as generating the THz probe beam. The THz probe pulse double-reflect to stimulate the THz emission in graphene, which is detected as a THz photon echo signal (marked with number "2" in Fig. 8(a)) [22]. Figure 8(b) shows the measured temporal response. The secondary pulse, the THz photon echo signal, obtained with graphene (GR) is more intense compared with that obtained without graphene. When the pumping intensity weakens below 1 x 10^7 W/cm^2 a threshold like behavior can be seen in Fig. 8(c), testifying to the light amplification by stimulated emission of THz radiation. A Lorentzian-like normal dispersion around the gain peak also provides a manifestation of the occurrence of amplification attributed to stimulated emission of photocarriers in the inverted states. If the gain medium of graphene is installed in a pertinent cavity, it will lead to a new type of THz lasers [23].

C. Toward the Creation of Graphene THz Injection Lasers

Optical pumping with rather high photon energy of the order of "~eV" significantly heats the carriers, which dramatically increases the pumping threshold, preventing from population inversion [24]. Hence, the pumping photon energy should be reduced to obtain a higher THz gain even at room temperature. In such a sense, current injection pumping is the best of solution to coupe with this issue because electrical pumping can serve any pumping energy below the order of "meV" when a p-i-n junction is formed like semiconductor laser diodes. Dual gate structure can make a p-i-n junction in the graphene channel as shown in Fig. 9 [6]. Gate biasing controls the injection level, whereas the drain bias controls the lasing gain profiles (photon energy and gain). To minimize undesired tunneling current that lowers the injection efficiency the distance between the dual gate electrodes must be sufficiently long [6, 25]. The structure- and material-dependent characteristics have been theoretically



(a) (b) (c)

Fig. 6. Carrier dynamics in optically pumped graphene.

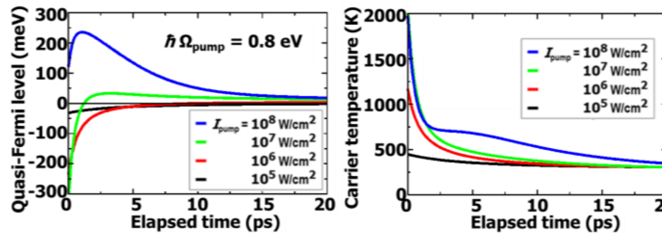
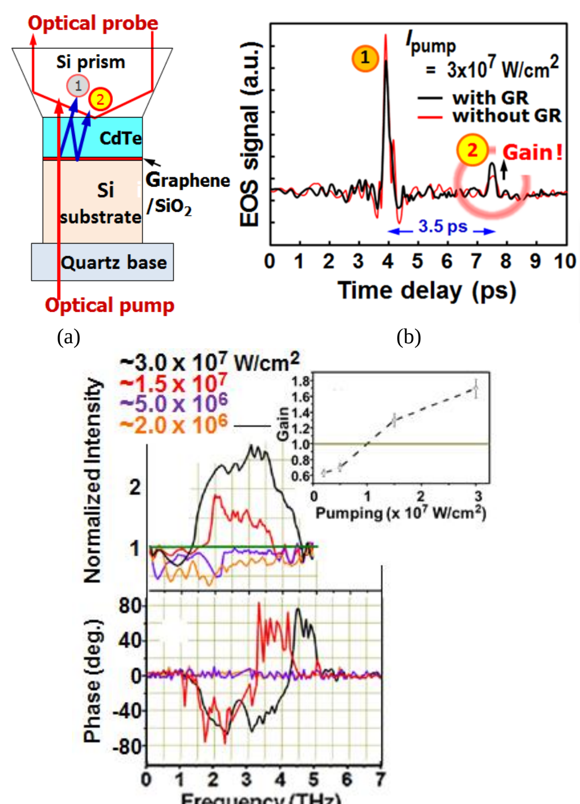


Fig. 7. Numerically simulated time evolution of the quasi-Fermi level (left) and carrier temperature (right) of monolayer graphene after impulsive pumping [20].



(c)

Fig. 8. THz time-domain spectroscopy for 80-fs infrared-laser pumped graphene. (a) pump and probe geometry, (b) temporal response of the THz probe pulse with the photon-echo signal, (c) Fourier spectra normalized to the one without graphene and gain vs. pumping intensity [22].

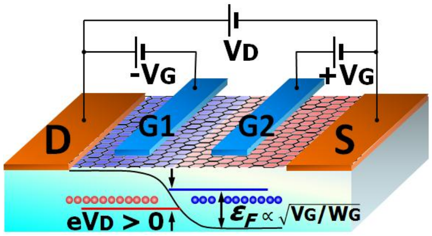


Fig. 9. Schematic for a graphene THz injection laser implemented in a dual-gate graphene-channel FET structure.

revealed in [25]. Recent development in epitaxial graphene synthesis technology enables multiple-layer stacking with keeping the monolayer graphene property, increasing the quantum efficiency in proportion to the number of the multiple graphene layers [26]. Waveguiding the THz emitted waves with less attenuation is another key issue. We theoretically discover the amplification of surface plasmon-polariton when traveling along the graphene-channel waveguide under population inversion [27]. These new findings can help create a new type of room-temperature operating graphene THz lasers.

IV. Conclusion

Recent advances in emission and detection of THz radiation from 2D electrons in III-V semiconductors and graphene were reviewed. 2D plasmon resonance in HEMT structures as well as ultrafast non-equilibrium dynamics of massless electrons/ holes in graphene are promising mechanisms for making new types of practical THz sources and detectors.

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