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Terahertz Light Emission and Lasing in Graphene-based van der Waals 2D Heterostructures

Graphene has attracted considerable attention due to its massless and gapless energy spectrum. Optical and/or injection pumping of graphene can enable negative-dynamic conductivity in the terahertz (THz) spectral range, which may lead to new types of THz lasers [1,2]. In the graphene structures with p-i-n junctions, the injected electrons and holes have relatively low energies compared with those in optical pumping, so that the effect of carrier cooling can be rather pronounced, providing a significant advantage of the injection pumping in realization of graphene THz lasers [3]. This paper reviews recent advances in THz light emission and lasing in graphene-based van der Waals (vdW) 2D heterostructures.

We designed and fabricated our original distributed-feedback dual-gate graphene-channel field-effect transistor (DFB-DG-GFET) [4,5]. The DG-GFET structure serves carrier population inversion in the lateral p-i-n junctions under complementary dual-gate ($V_{g1,2}$) biased and forward drain-source (V_d) biased conditions, promoting spontaneous broadband incoherent THz light emission. The tooth-brash-shaped DG forms the DFB cavity having the fundamental mode at 4.96 THz, which can transcend the incoherent broadband LED to the single-mode lasing action. Numerical analysis indicates that the modal gain and the Q factor strongly depend on the graphene carrier momentum relaxation time τ, suggesting, for example, a single-mode emission at 5.0 THz when $\tau = 2$ whereas a broadband emission over 1 to 8 THz when $\tau = 7$ ps. The GFET channel consists of a few layer (non-Bernal) highest-quality epitaxial graphene [6], providing an intrinsic field-effect mobility exceeding 100,000 $\mathrm{cm^2/Vs}$ [7]. Fourier-transform far-infrared spectroscopy using a 4.2K-cooled Si bolometer revealed the THz emission spectra for the fabricated samples under population inversion conditions; one sample exhibited a broadband light-emitting-diode (LED) like intense (~10~100 μW) amplified spontaneous emission in a 1-7-THz range [4] and the other sample did a weak (~0.1~1μW) single mode lasing at 5.2 THz [5] both at 100K. They showed peculiar non-monotonic threshold behaviors with respect to V_d.

To increase the operating temperature and lasing radiation intensity, further enhancement of the THz gain and the cavity Q factor are mandatory. Introduction of the graphene plasmonics [8] in vdW 2D heterostructures is the key to realize room-temperature intense THz lasing. Asymmetric dual-grating-gate meta-surface structures may promote plasmonic superradiance [9] and/or plasmonic instabilities [11], giving rise to giant THz gain enhancement at plasmonic resonant frequencies. Further improvement will be given by a gated double-graphene-layer (G-DGL) nanocapacitor vdW 2D heterostructures [12]. In the DGL a thin tunnel barrier layer is sandwiched by outer graphene layers at both sides. By applying a pertinent gate bias voltage, THz photon emission, whose energy coincides with the band offset between the GLs, can assist the inter-GL resonant tunneling, leading to giant gain enhancement [12]. Preliminary experimental results demonstrate the occurrence of THz photon emission in the G-DGL [13]. The DGL can excite symmetric optical and anti-symmetric acoustic coupled plasmon modes in the GLs. The latter mode can modulate the band-offset between the GL, giving rise to modulation of the inter-GL-layer resonant tunneling. This can dramatically enhance the THz gain [14].

In conclusion, we experimentally observed broadband spontaneous light emission and single-mode lasing in the THz range at 100K from the DFB-DG-GFET structure. Exploitation of the graphene plasmonics in vdW 2D heterostructures will be the key to realize room-temperature intense THz lasing.

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Figures

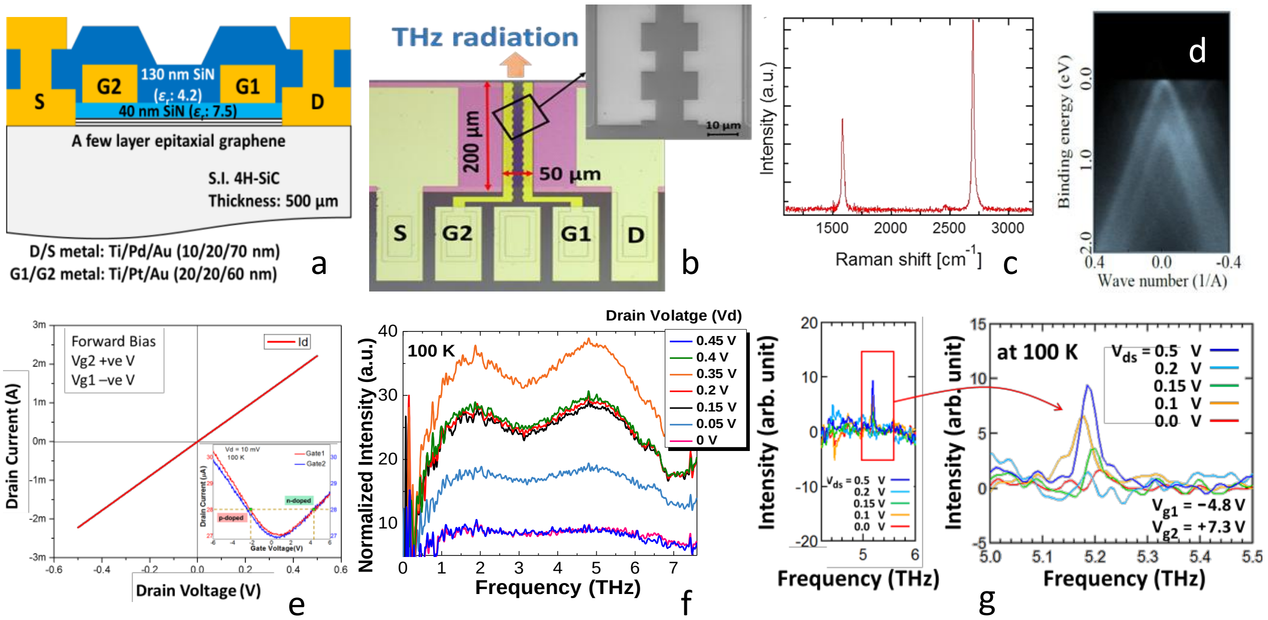

Figure 1: DFB-DG-GFET. (a) Cross-sectional view. (b) Micro-photo image. (c) Raman spectrum. (d) ARPES image. (e) dc current-voltage characteristics. (f) LED-like broadband THz emission. (g) Laser-like single-mode emission at 5.2 THz.

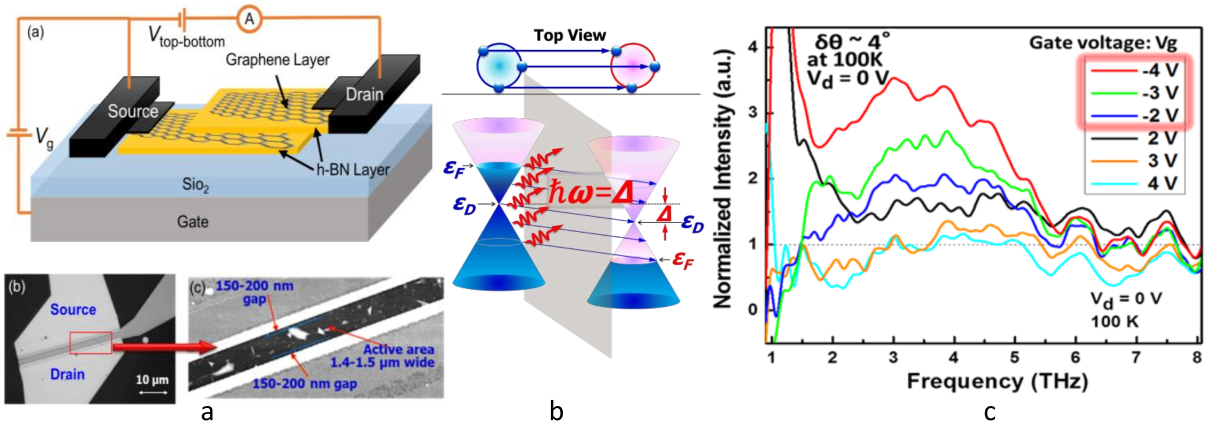

Figure 2: G-DGL vdW 2D heterostructure. (a) Bird’s view and micro-photo images. (b) PEA-RT: photo-emission-assisted inter-GL resonant tunneling. (c) Observation of THz emission via PEA-RT in a fabricated sample at 100K.