Plasmonic Enhancement of Graphene Heterostructure based Terahertz Detectors

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Outline

- Introduction and Motivation
- Optoelectronic Properties of Graphene
- Optically Pumped THz Lasers
- Current Injection THz Lasers
- Double Graphene Layer Structures
- Plasmonic Enhancement
- Summary

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<u>Carbon structures (carbon allotropies). What is graphene?</u>



Multiple disoriented non-Bernal stacked graphene Layer structure – Absolutely New Material for Optoelectronics!!!

Synthesis of Graphene

Peeling from HOPG (highly oriented pyrolytic graphite)

Highest mobility obtained

nature

- Reproducibility is challenging
 - A. Geim and K. Novoselov, Nat. Mat. 6, 184 (2007).

Epitaxial graphene: thermal decomposition of hexagonal SiC

- Process temperature rather high ~1000
- Better mobility than CVD growth W.A. de Heer et al., Solid State Commun. 143, 92 (2007). M. Suemitsu and H. Fukidome, J. Phys. D 43, 374012 (2010).

CVD growth on metallic catalyst and transferring substrate













Why graphene attracted attention of researchers?

?

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($\epsilon = \pm v_F p$, where $v_F \approx 10^8$ cm/s).

Zero Band gap



Linear (rather than quadratic) dispersion

Just a nonolayer thick material

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Ultra-Broadband Flat Optical Response Due to Gapless/Linear Energy Spectra



H. Choi et al., APL 94, 172102 (2009).

R.R. Nair et al., Science 320, 1308 (2008).

Bandgap Engineering for Graphene



Does absorphion coefficient of graphene depend on frequency?

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No, it is frequency independent



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Carrier Relaxation Dynamics after Optical Pumping and Population Inversion at RT

Major carrier scatterings

Intraband optical-phonon (OP) scattering

- **Energy relaxation (100** fs ~ 1 ps)
- **Interband OP scattering**

Carrier-carrier (CC) scattering

> Energy relaxation & Recombination (1~10 ps)

> Quasi-equilibration (10~100 fs)

Distribution function



Experiments suggest CC scattering is dominant at room temperature and/or strong excitation.

D. Sun et al., **PRL 101,** 157402 (**2008**). P.A. George et al., **Nano Lett. 8**, 4248 (**2008**). J. Dawlaty et al., **APL 92,** 042116 (**2008**). M. Breusing et al., **PRL 102**, 086809 (**2009**).

Observation of Threshold Behavior, ¹⁶ Proving Stimulated THz Emission & Gain

Details with new data TBP at W4B.3 16:00~



What is the Minimum Lasing Frequency?



Hindering effects on stimulated emission mechanism

Recombination Processes

Population inversion is suppressed in the active region, for energies $>\hbar\omega_0/2$, while recombination is weak in the passive region, $<\hbar\omega_0$

Long-Range Disorder

Separation of e-h pairs due to random potential increases the averaged min concentration for the population inversion condition

Small Active Volume

Since ~3 A thickness of graphene, active volume (and an output power) can be increased using large-area (or long) samples

Losses in Resonator

Losses of metal (or heavily-doped) resonators in QCL ~50 cm⁻¹; a dielectric waveguide (e.g. Si-fiber) can be used as resonator

Methods of e-h pairs excitation

Electrical injection through pn-junction

Optical pumping with lateral diffusion

Pulse optical excitation

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Toward the Creation of Graphene²⁰ Current-Injection THz Lasers



Benchmarking GRL over QCL & Raman-L

Laser type Figure of merits	QCL	Graphene-L		Raman-L
	Injection pump	Injection pump	Optical pump	Optical pump
Mechanism	ISB	IB		SRS
Quantum efficiency	~N of QCs	~ 1		low
Pumping efficiency	high	high	low @IR or moderate @THz (CO ₂)	very low
Gain/volume	low	high (large & & emission by plasmon modes)		very low
Freq. range	down to 1.5 THz at lowered temp.	down to 1 THz at elevated temp.		down to 1 THz at elevated temp.
Operating temp.	low	could be high		could be high
Heat spread	×	Ο		×
Linewidth	very narrow	could be narrow by plasmon instability		narrow
Fabrication	complex SLs with MBE	easy epi with MBE		easy bulky,fiber
Size	compact	compact		large

Is it possible to get lasing from graphene?

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Yes, optical and injection pumping can be achieved

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Double-GL structures and their features



- (1) Voltage control of electron and hole densities and interband and intraband absorption of radiation
- (2) Inter-GL tunneling, including resonant tunneling, negative differential conductivity
- (3) Plasma oscillations in double-GL structures – each GL serves as the gate for another GL!







Band diagrams of laser/PD structures with (a) photoemission-assisted inter-GL and (b) photo-absorption-assisted inter-GL radiative transistions





Simulated frequency dependence of the THz gain for the D-GL inter-GL transition laser for different band-offset energies between the Dirac points and of the THz gain for the D-GL intra-GL transition laser for different Fermi energies in GLs: (a) L = 5µm and W = 5µm, and (b) L = 15µm and W = 5µm. (c) Simulated spatial distributions of the photon electric field components in the TM mode in the DGL inter-GL transition laser.

What is an advantage of a double graphene layer structure?

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One of advantages is resonant tunneling at a controlled frequency of absorption and/or emission

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2D Plasmons in Graphene

тоноки





V. Ryzhii, T. Otsuji, M. Ryzhii, V. Leiman, S. O. Yurchenko, V. Mitin, M. S. Shur, J. Appl. Phys. **112**, 104507 (2012)

<u>Responsivity vs signal frequency at different plasma and collision</u>



 $V_0 = 0.5 V$, $R_V = 10^4 - 10^5 V/W$ Dependence of normalized responsivity R_V/\overline{R}_V versus bias voltage swing $(V_0 - V_t)/\Delta V_t$.n at different signal frequency ω near the zeroth plasma resonance (upper panel) and near the first plasma resonance (lower panel).

V. Ryzhii, A. Satou, T. Otsuji, M. Ryzhii, V. Mitin, M. S. Shur, J. Phys. D: Appl. Phys. (2013)



V. Ryzhii, T. Otsujj, M. Ryzhii, and M. S. Shur, J. Phys. D: Appl. Phys. (2012)



$$R_{\omega} = \left(\frac{\pi e^2}{c\hbar}\right) \frac{8e|z_{u,l}|^2 \gamma}{[\hbar^2(\omega - \omega_{max})^2 + \gamma^2]} \left(\Sigma_i + \frac{\kappa\Delta}{4\pi e^2 d}\right) \theta$$
$$\frac{\Delta}{e} = V + V_0 - \sqrt{2VV_0 + V_0^2 + V_t^2}$$
$$\hbar\omega \simeq -\Delta + \hbar\omega_{dep} = \hbar\omega_{max}$$

The DLG-PD responsivity R_{ω} versus the photon energy $\hbar \omega$ calculated for different voltages *V*

$$R_{\omega_{max}} = \left(\frac{e\kappa d}{c\hbar}\right) \left(\frac{\hbar\omega_{dep}}{\gamma}\right)\theta$$

This shows the dependencies of photon energy $\hbar \omega_{max}$ and responsivity maximum $R_{\omega max}$ on the applied voltage *V* calculated for different thicknesses of the inter-GL barrier layer *d*. A marked shift in the responsivity maxima with varying bias voltage enables the DGL-PD spectrum voltage tuning.





This shows the dependency of the responsivity maximum $R_{\omega max}$ on the electron and hole density Σ_i and different bias voltages *V* and thicknesses *d*. The maximum of the DGL-PD responsivity markedly depends on electrical doping determined by the gate voltage V_{α}



$$\begin{aligned} R_{\omega}^{pin} \simeq \left(\frac{\pi e^2}{c\hbar}\right) \frac{eg^{pin}}{\hbar\omega}, \ R_{\omega}^{qwip} \simeq \left(\frac{e}{\hbar\omega}\right) \sigma_i \Sigma_i \ g^{qwip}\theta \\ \\ \frac{R_{\omega_{max}}}{R_{\omega_{max}}^{pin}} \simeq \frac{\hbar^2 \omega_{max} \omega_{dep}\theta}{\varepsilon_d \gamma \ g^{pin}}, \ \frac{R_{\omega_{max}}}{R_{\omega_{max}}^{qwip}} \simeq \frac{\hbar^2 \omega_{max} \omega_{dep}}{\varepsilon_i \gamma \ g^{qwip}} \\ \\ \varepsilon_d = 2\pi \ e^2/\kappa \ d \qquad \varepsilon_i = c\hbar\sigma_i \Sigma_i/\kappa \ d. \end{aligned}$$

This shows the ratios of DGL-PD and QWIP responsivity versus photon energy $\hbar\omega_{max}$ for different electron and hole densities Σ_i and thicknesses of the inter-GL barrier layer, d



A graphene plasmonic heterostructure for THz lasers and detection

Enhanced THz Responsibilies via PA-RT & Plasmon Resonances in DGLs



Observed THz Gain Exceeding the e²/4ħ Limit by Orders 39



Do plasmonics add frequency selectivity?

Do plasmonics add frequency selectivity?

2D plasmons in graphene enhance the lightmatter interaction.



Concepts of THz & IR devices based on graphene structures were reviewed.

Optically pumped graphene can generate in a wide THz range.

Current injection G-Lasers, implementing in dual gate G-FETs, have a great advantage to dramatically decrease the equivalent pumping photon energy, resulting in NDC at rather low injection currents.

Double graphene layer structure is a promising engineered material.

2D plasmons in graphene enhance the light-matter interaction.

As preliminary experimental results ehow, the presented devices are realistic: they can exhibit very high performance



Introduction:

Population Inversion in Optically Pumped Graphene Original Idea for GR-THz Lasers





Range of negative dynamic conductivity (at sufficiently strong optical pumping) – Interband transitions vs intraband (Drude absorption)

Population Inversion of e-h Pairs, **Negative Absorption, and Lasing**

Limitations of continuous scheme (heating by optical phonons, non-radiative recombination, etc.) may be resolved under transient regime of pumping

Model for transient regime of lasing

Population inversion with quasi-Fermi energy $\varepsilon_{\rm F}$ takes place during t_{p} . $_{eq} < t < t_{rec}$, where t_{p-eq} duration of pumping and subsequent emission of optical phonons

 \Box Unstable mode with population N_{ot} $\sim \exp(t/t_{rad})$ propagates along resonator of length *L* during time ~ t_{rad} \Box Minimal length $L > c / \sqrt{\kappa t_{rad}}$

 \Box If $t_{rad} \sim 10$ ps (see below), one obtains L > 0.5 mm

□ Output power ~10 - 100 pW per pulse because an active volume is very small



Sketch of graphene (red) in resonator under pulse optical pumping with mid-IR output

Introduction: Femtosecond Population Inversion in Heavily-Doped Graphene



(a) Schematics of ultrafast optical interband excitations.

(b) Dispersion of our electron-doped graphene, monolayers (μ=0.4 eV) illustrating state filling (left) and band filling (right) that leads to stimulated emission from a broadband, inverted population (red arrow). Also shown together is the pump pulse spectrum.



(a) Ultrafast $\Delta R/R$ at 1.55 eV pump, 1.16 eV probe, at 1116 and 3960 µJ/cm², and 1.33 eV probe, at 4390 µJ/cm², respectively. Blue arrow marks $\Delta R/R/_c$ =-1.4582% for zero conductivity. Shown together are the pump and probe spectra. (b) The peak transient reflectivity as function of the pump fluence. (c) The extracted transient fermion density at 40 fs (blue dots), as explained in the text, which is significantly lower than $A_0 I_p = \hbar \omega$ obtained from the universal conductivity (open circles), as illustrated in shadow area. (d) Theory (lines) vs experimental values (rectangles) for nondegenerate (red) and degenerate (blue) transient conductivity at 40 fs. Shown together (lines) are two model simulations with the single (green) or distinct (black) chemical potentials. [Phys. Rev. Lett. 108, 167401 (2012)]



(a) I_{sampling} for excitation positions starting at the graphene–metal interface in steps of 2 µm (from bottom to top) along the dotted line in Fig. b. Data are offset for clarity. The parameters are $E_{\text{laser}} = 1.59 \text{ eV}$, $P_{\text{laser}} = 800 \text{ µW}$, $V_{\text{sd}} = 0 \text{ V}$, and T = 300 K.

(b) Time-resolved I_{sampling} at T = 77 K for the same parameters as in (a). The position y (right) refers to the dotted line in Fig. b.

(c) Corresponding fast-Fourier-transformation of I_{sampling} as displayed in (a).

<u>Introduction:</u> Time-resolved photocurrents and THz generation in suspended graphene



(a) Suspended graphene onto a coplanar stripline circuit. A pump laser pulse focused onto the graphene-sheet generates the time-integrated photocurrent I_{photo} . Scale bar, 20 µm. (b) Spatially resolved scan of I_{photo} . Parameters are $E_{laser} = 1.6 \text{ eV}$, $P_{laser} = 200 \text{ µW}$, $V_{sd} = 0 \text{ V}$. (c) Single line-sweep of I_{photo} along the dotted line in (b).

(d) The time-resolved photocurrent response I_{sampling} is measured at the field probe, located ~0.3 mm away from the graphene. The probe laser pulse (red circle) triggers the read-out of I_{sampling} . All measurements at T=300 K (Nature Comm. 3, 646, 2012)

Photon-Assisted Resonant Tunneling Enabling Novel THz Functionalities



Double-GL structures resonant tunneling



Operation principle: -THz input signals result in inter-GL nonlinear tunneling or thermionic current

-Rectified component of this current – output signal

-Excitation of plasma oscillations leads to resonant increase in inter-GL current and output signal



Resonant inter-GL tunneling promotes high detector responsivity!!!

Each GL serves as a gate for another GL!!! V. Ryzhii, T. Otsuji, M. Ryzhii, V. Mitin and M. S. Shur, J. Phys. D: Appl. Phys. (2012) V. Ryzhii, A. Satou, T. Otsuji, M. Ryzhii, V. Mitin, M. S. Shur, J. Phys. D: Appl. Phys. (2013)