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Challenges to Create Graphene-Based Terahertz/Infrared Lasers

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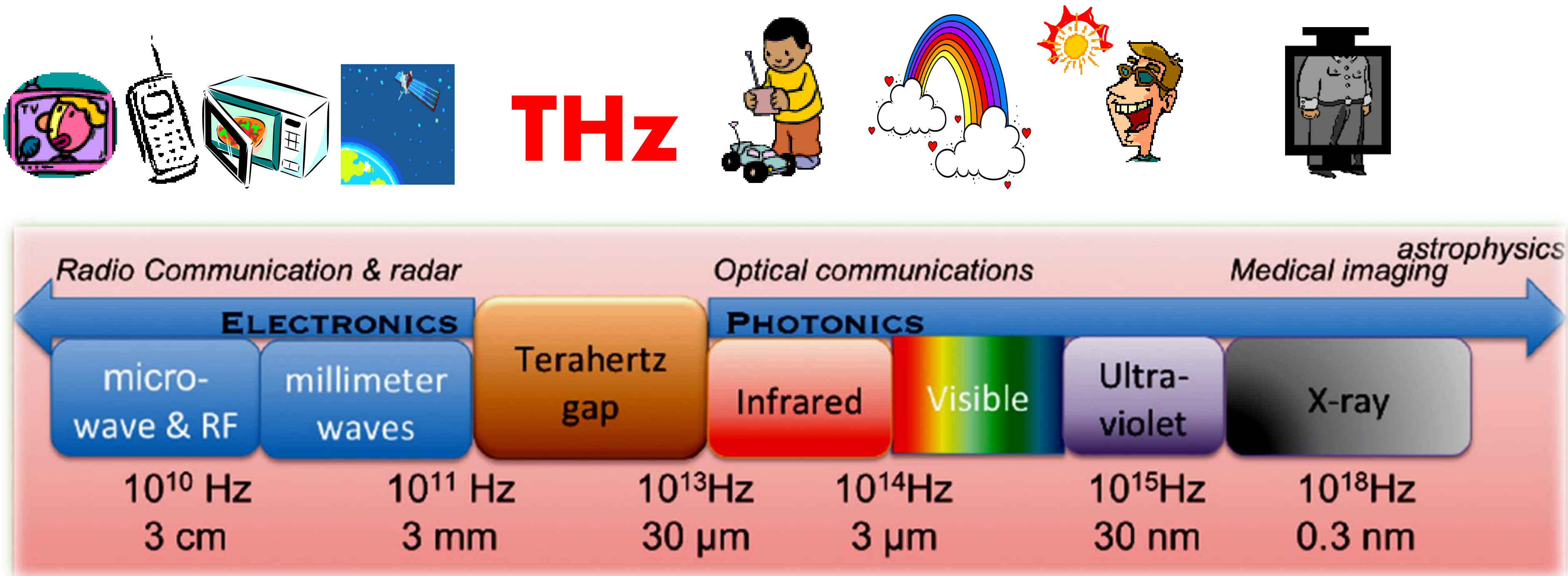
Outline

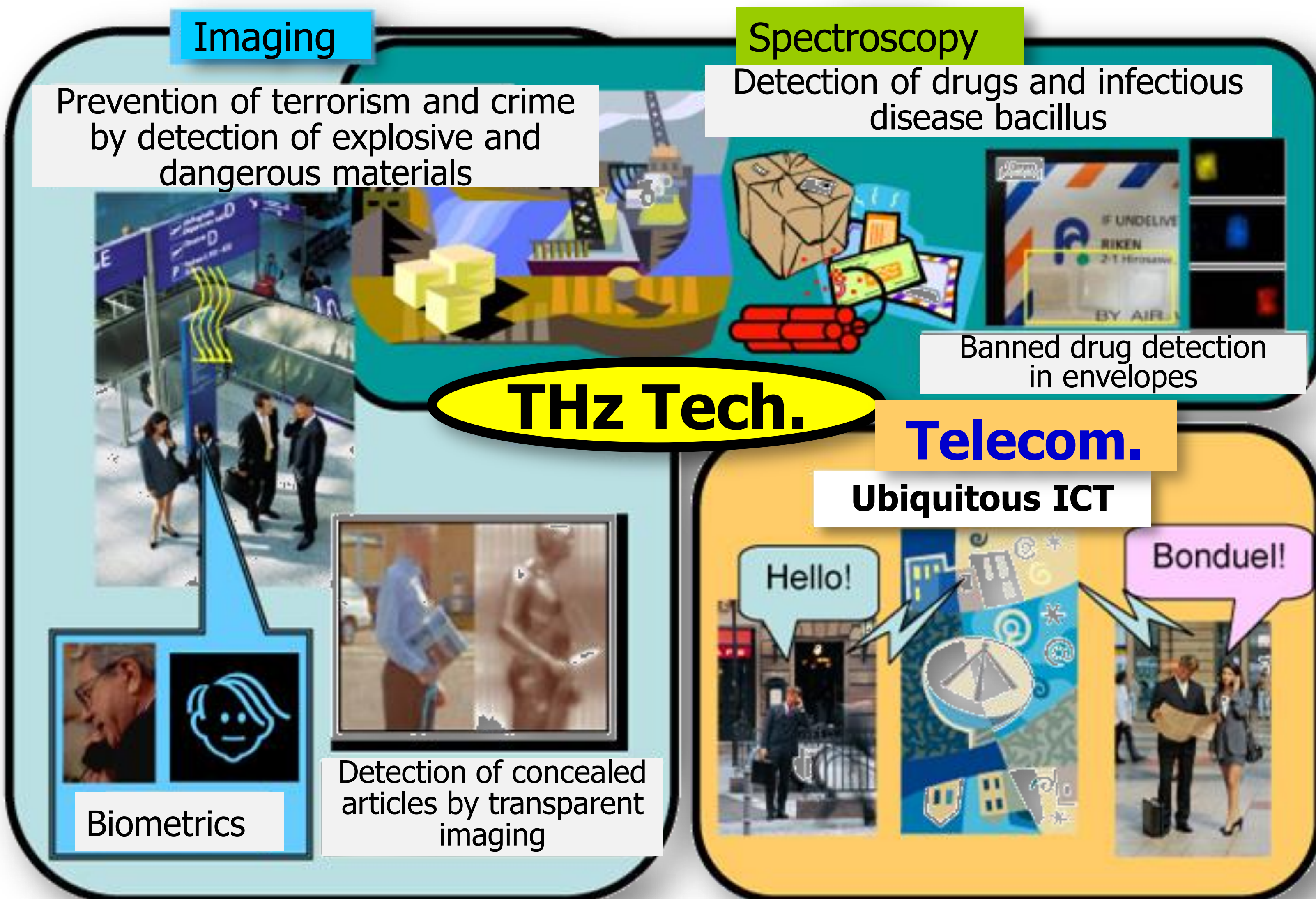
- Introduction and motivation
- Ultrafast carrier relaxation dynamics and THz/IR gain in optically/electrically pumped graphene
- Carrier heating & cooling effect in optical & injection pumping
- Graphene current-injection lasers
- Graphene active plasmonics for giant gain
- Summary

Where is "Terahertz"?



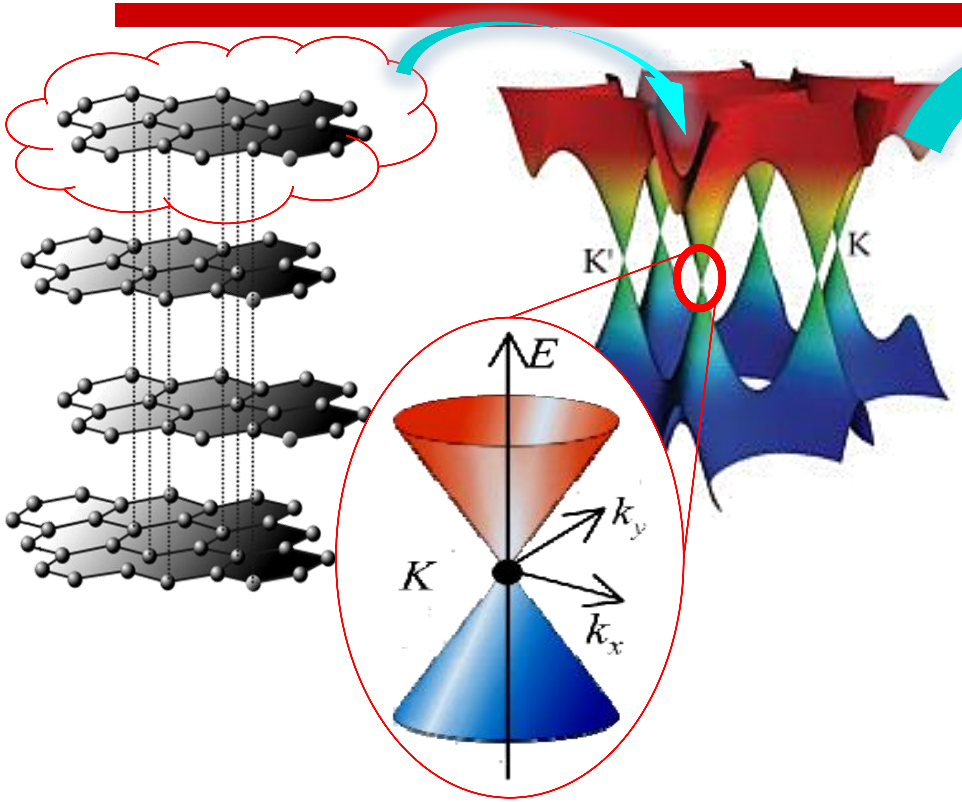
Promising Applications for Terahertz ICTs

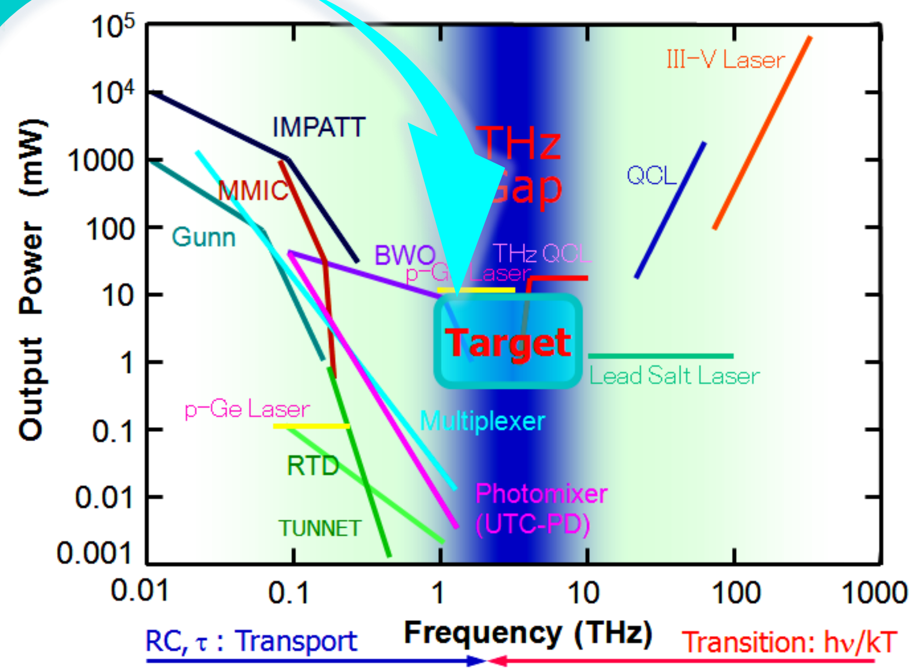
(Courtesy of Terahertz Technology Trend Investigation Committee, MIC, Japan)



Graphene can Bridge over the THz Gap!

P. R. Wallace, ***PR 71***, 622 (1947).
K.S. Novoselov et al., ***Science 306***, 666 (2004).
K.S. Novoselov et al., ***Nature 438***, 197(2005).
Y. Zhang et al., ***Nature 438***, 201(2005).
M.I.Katsnelson, ***Mat.Today 10***, 29 (2007).



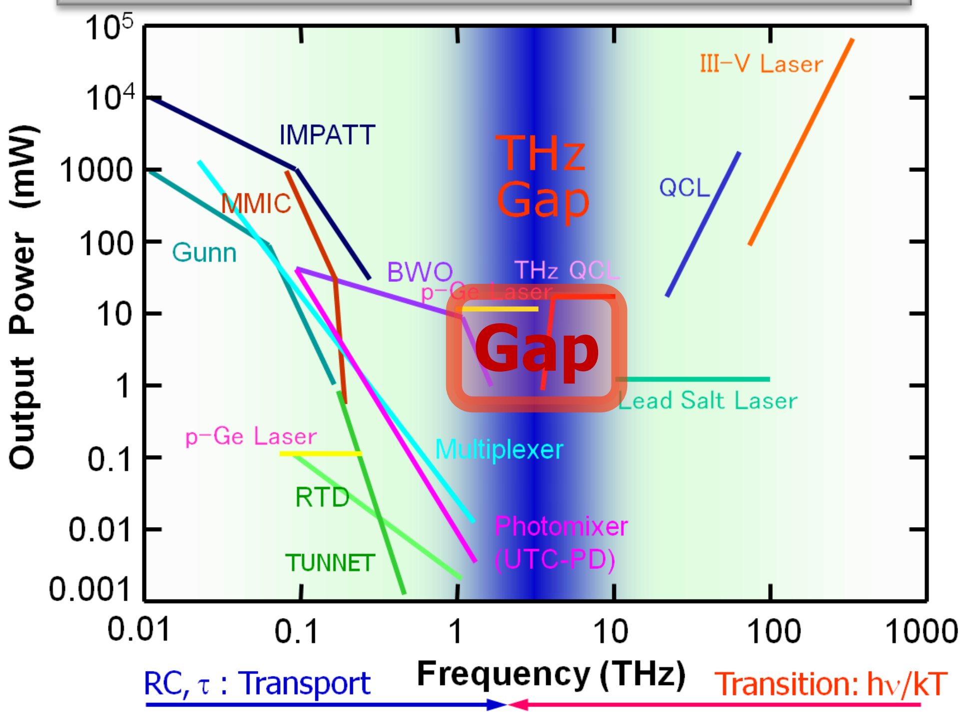


- **Mono- or few layers of sp² bonded carbon atoms in a honeycomb lattice.**
- **Massless Dirac Fermions obey linear dispersion relation at K & K' points.**
- **High carrier mobility μ >200,000 cm²/Vs at RT. (*cf.* InGaAs: μ ~ 12,000 cm²/Vs)**

Due to its unique transport properties, graphene is suitable for implementation in photonic devices.

Idea for Graphene THz/IR Lasers

Current status of THz sources

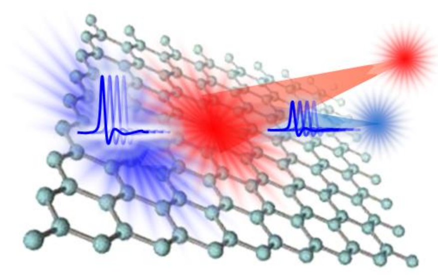


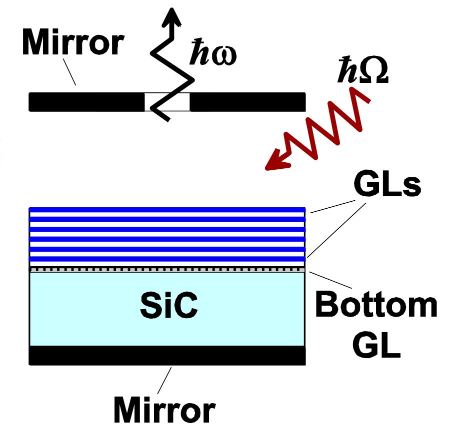
(Courtesy of Terahertz Technology Trend Investigation Committee, MIC, Japan)

- **QCLs only work at cryogenic temperatures.**
- **Need powerful, compact, room-temperature operating THz sources for imaging and communications.**

Proposal of graphene THz lasers

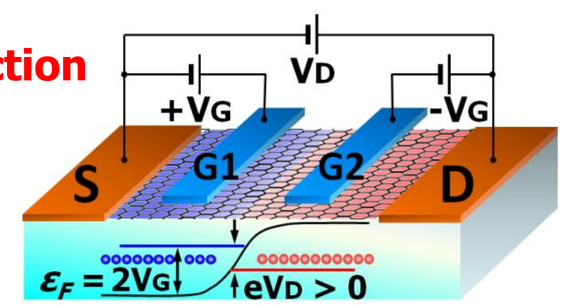
Optical pumping





*V.Ryzhii, M.Ryzhii, T.Otsuji, **JAP 101**, 083114 (2007).*

Current injection



*M. Ryzhii and V. Ryzhii, **JJAP 46**, L151 (2007).*
*V. Ryzhii, M. Ryzhii, V. Mitin, T. Otsuji, **JAP 110**, 094503 (2011).*

Popul… umping
-Ideas… rs

JOURNAL OF APPLIED PHYSICS **101**, 083114 (2007)

Negative dynamic conductivity of graphene with optical pumping

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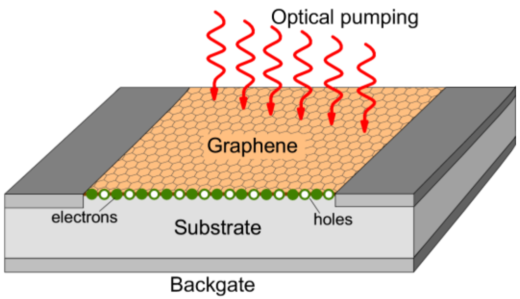
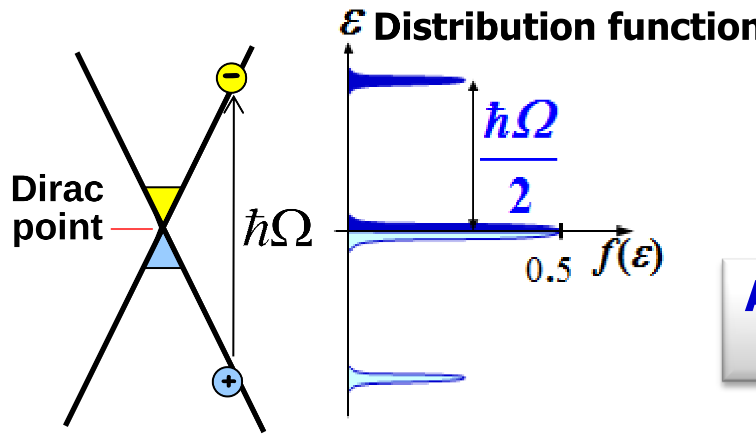
(Received 30 January 2007; accepted 8 February 2007; published online 26 April 2007)

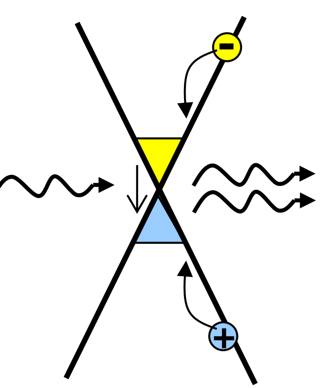
*V. Ryzhii, M. Ryzhii, and T. Otsuji, **JAP 101**, 083114 (2007).*
*V. Ryzhii, et al., **JAP 106**, 084507 (2009).*

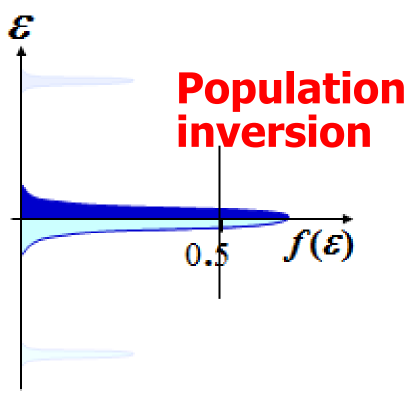
Optical pumping of intrinsic graphene





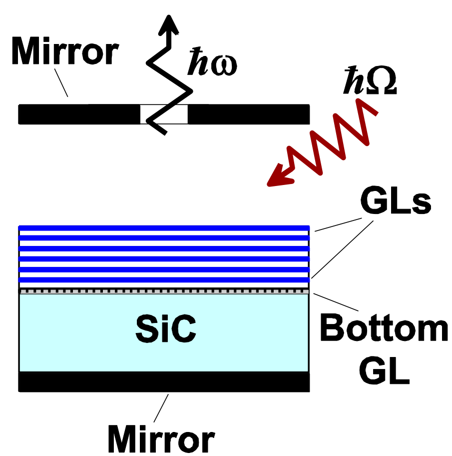
Population inversion in THz (low-energy) region





1-10 THz = 4-40 meV

Cavity structure



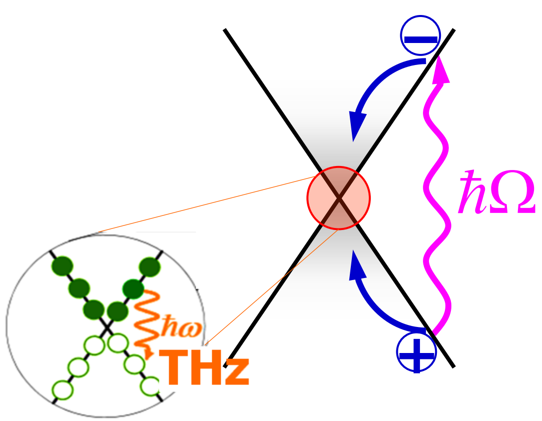
Optical pumping
⇓
Relaxation by OPs
⇓
Accumulation of carriers near the Dirac point
⇓
Population inversion
$1 - f_e - f_h = 1 - 2f < 0$
⇓
Gain for THz waves + resonant cavity
⇓
THz laser!

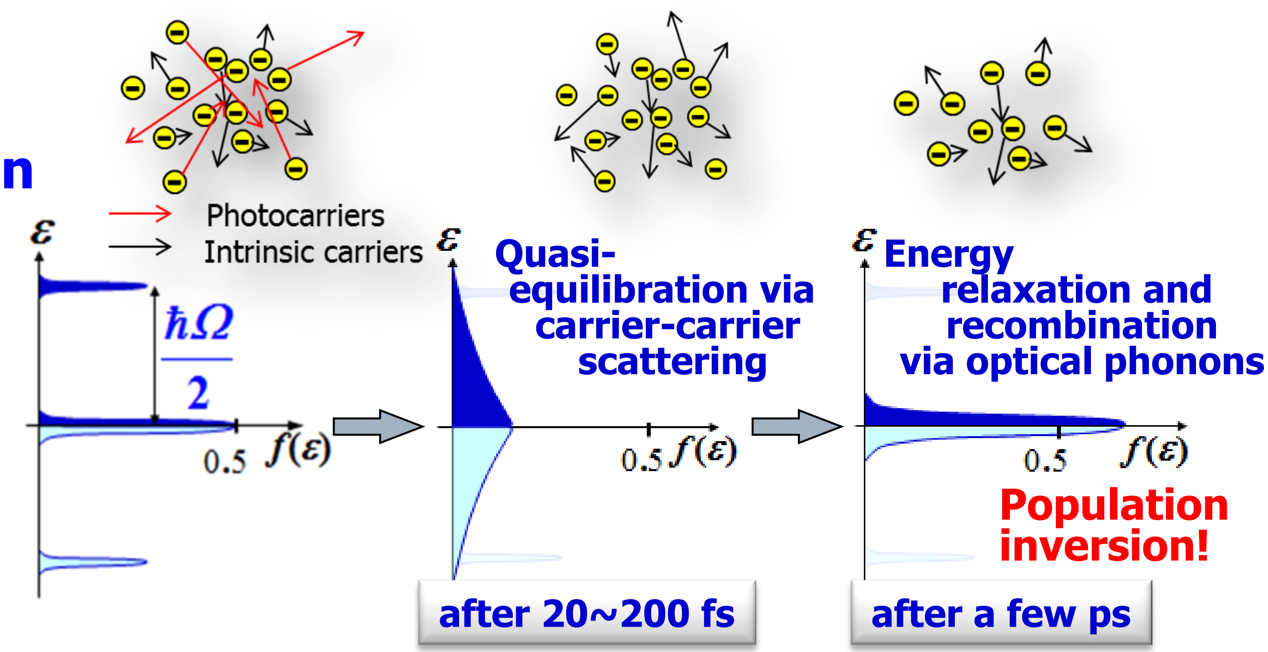
Carrier Relaxation Dynamics after Optical Pumping and Population Inversion at RT

Major carrier scatterings

Carrier-carrier (CC)	⇨	Quasi-equilibration (20~200 fs)
Intraband optical phonon (OP)	⇨	Energy relaxation (100 fs ~ a few ps)
Interband OP	⇨	Energy relaxation & Recombination (1~10 ps)
Auger-type	⇨	Recombination & Impact ionization (10 fs ~1 ps)

Distribution function

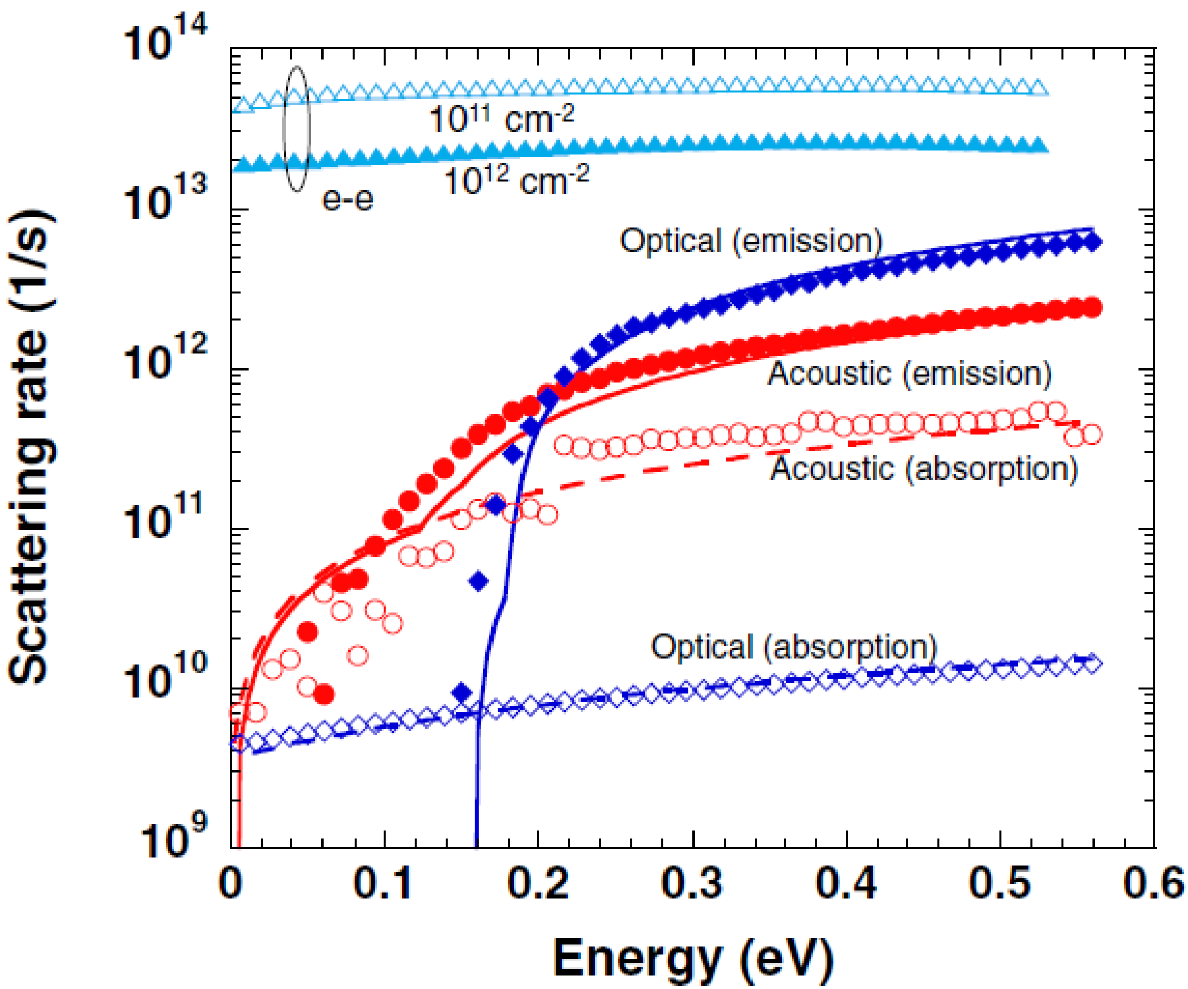




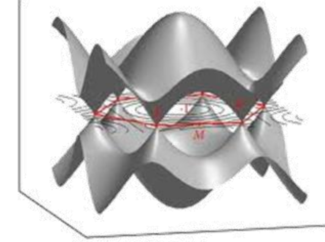
D. Sun et al., ***PRL 101****, 157402 (2008).*
P.A. George et al., ***Nano Lett. 8****, 4248 (2008).*
J. Dawlaty et al., ***APL 92****, 042116 (2008).*
M. Breusing et al., ***PRL 102****, 086809 (2009).*
T. Winzer and E. Malic, ***PRB 85****, 241404(R) (2012).*

Scattering Rates for Intrinsic Graphene Obtained by MC Simulation

*E. Sano, **JJAP 50**, 090205 (2011).*
X. Li et al., arXiv:1005.2631v1 (2010).
*V. Perebeinos and Ph. Avouris, **PRB 81**, 195442 (2010).*

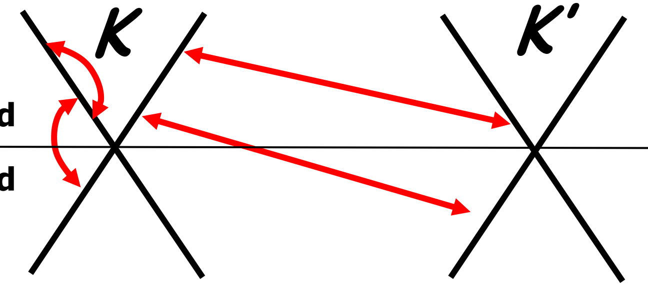


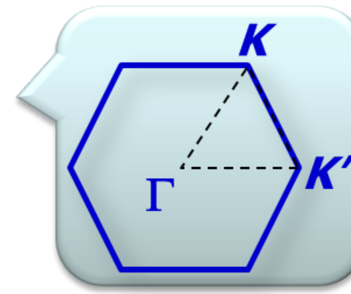
Optical Phonons in Graphene



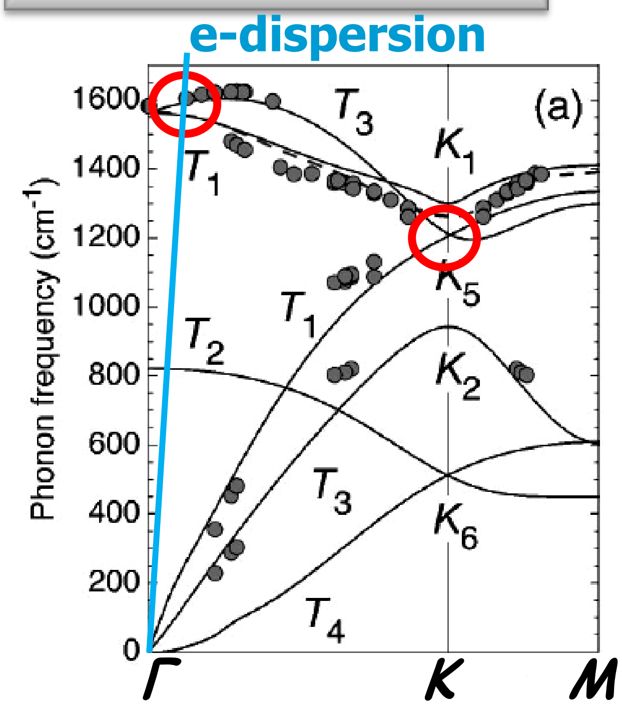
Carriers interact with:

- Optical Phonons at Γ (Γ-LO&TO)
  - Intravalley & Intraband/Interband
- Optical Phonons at K (K-TO)
  - Intervalley & Intraband/Interband





Phonon dispersion



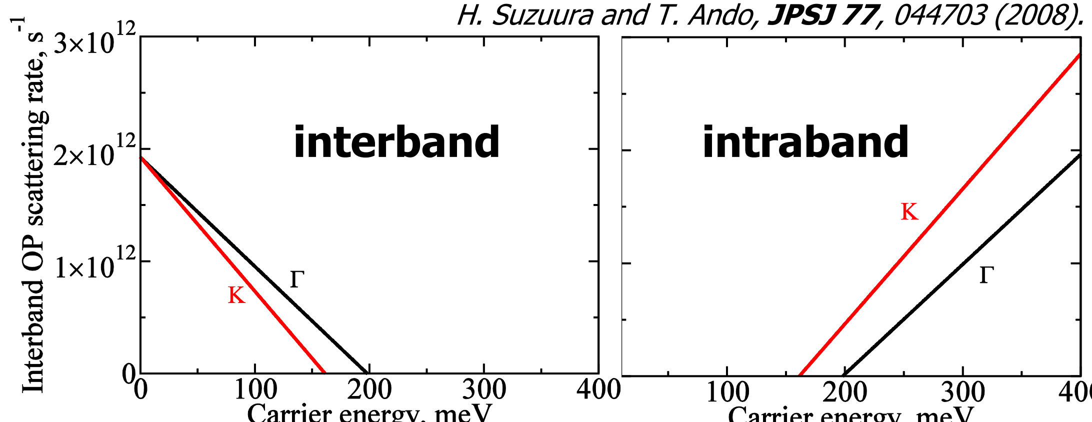
J. Maultzsch, ***PRB 70***, 155403 (2004).

Scattering rates

$$W^{(\pm)}_{\mathrm{A},inter/tra}(l\mathbf{k},l\mathbf{k}')=\frac{2\pi}{\hbar}\left|\langle l\mathbf{k}'|H_{\mathrm{A},inter/tra}|l\mathbf{k}\rangle\right|^2 \cdot\delta(k-k'\pm\omega/v_F)$$

$$\frac{1}{\tau^{(\pm)}_{\mathrm{A},inter/tra}}=\sum_{\mathbf{k}'}W^{(\pm)}_{\mathrm{A},inter/tra}(l\mathbf{k},l\mathbf{k}')$$

H. Suzuura and T. Ando, ***JPSJ 77***, 044703 (2008).



■ **Time scale of OP emission: 300 fs ~ 3 ps**

Theoretical Study of Graphene Under Pulse Excitation

*A. Satou, T. Otsuji, and V. Ryzhii, **JJAP 50**, 070116 (2011).*
*H. Suzuura and T. Ando, **J. Phys. Soc. Jpn. 77** 044703 (2008).*

Rate equations for relaxation of quasi-Fermi level and carrier temperature

$\Sigma = \Sigma(\varepsilon_F(t), T_c(t))$ Carrier concentration

$E = E(\varepsilon_F(t), T_c(t))$ Energy density

$$\frac{d\Sigma}{dt} = \frac{1}{\pi^2}\sum_{i=\Gamma,K}\int d\mathbf{k}\left[(1-f_{\hbar\omega_i - v_w\hbar k})(1-f_{v_w\hbar k})/\tau^{(+)}_{i\mathrm{O,inter}} - f_{v_w\hbar k} f_{\hbar\omega_i - v_w\hbar k}/\tau^{(-)}_{i\mathrm{O,inter}}\right]$$

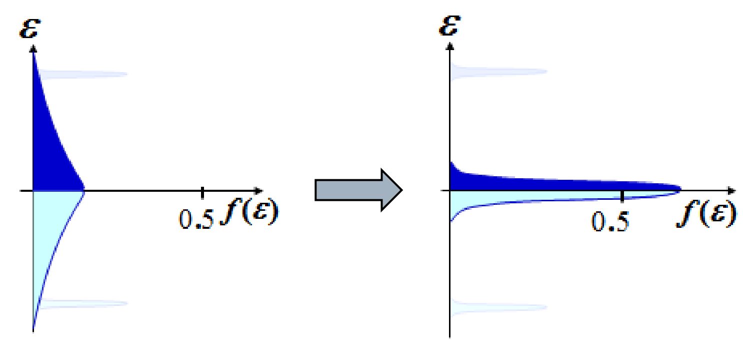
$$\frac{dE}{dt} = \frac{1}{\pi^2}\sum_{i=\Gamma,K}\int d\mathbf{k}\, v_w\hbar k\left[(1-f_{\hbar\omega_i - v_w\hbar k})(1-f_{v_w\hbar k})/\tau^{(+)}_{i\mathrm{O,inter}} - f_{v_w\hbar k} f_{\hbar\omega_i - v_w\hbar k}/\tau^{(-)}_{i\mathrm{O,inter}}\right]$$
$$+\frac{1}{\pi^2}\sum_{i=\Gamma,K}\int d\mathbf{k}\,\hbar\omega_i\left[f_{v_w\hbar k}(1-f_{v_w\hbar k+\hbar\omega_i})/\tau^{(+)}_{i\mathrm{O,intra}} - f_{v_w\hbar k}(1-f_{v_w\hbar k-\hbar\omega_i})/\tau^{(-)}_{i\mathrm{O,intra}}\right]$$

$\tau^{(\pm)}_{i\mathrm{O,inter}}, \tau^{(\pm)}_{i\mathrm{O,intra}}$ Relaxation time for interband and intraband OP ("+" for absorption and "-" for emission; i= K, Γ)

Quasi-Fermi distribution caused by CC scattering

$$f_{v_w\hbar k} = \frac{1}{\exp[(v_W\hbar k - \varepsilon_F)/k_B T_c] + 1}$$

with $\varepsilon_F = \varepsilon_F(t), \quad T_c = T_c(t)$



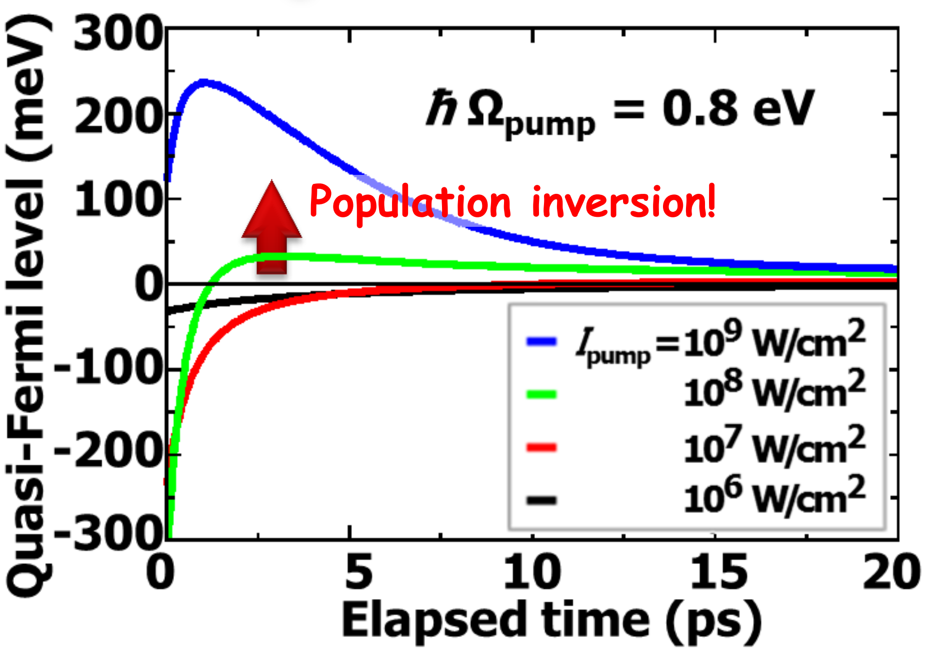
Relaxation of Quasi-Fermi Level and Carrier Temperature

A. Satou, T. Otsuji, and V. Ryzhii, ***JJAP 50***, 070116 (2011).

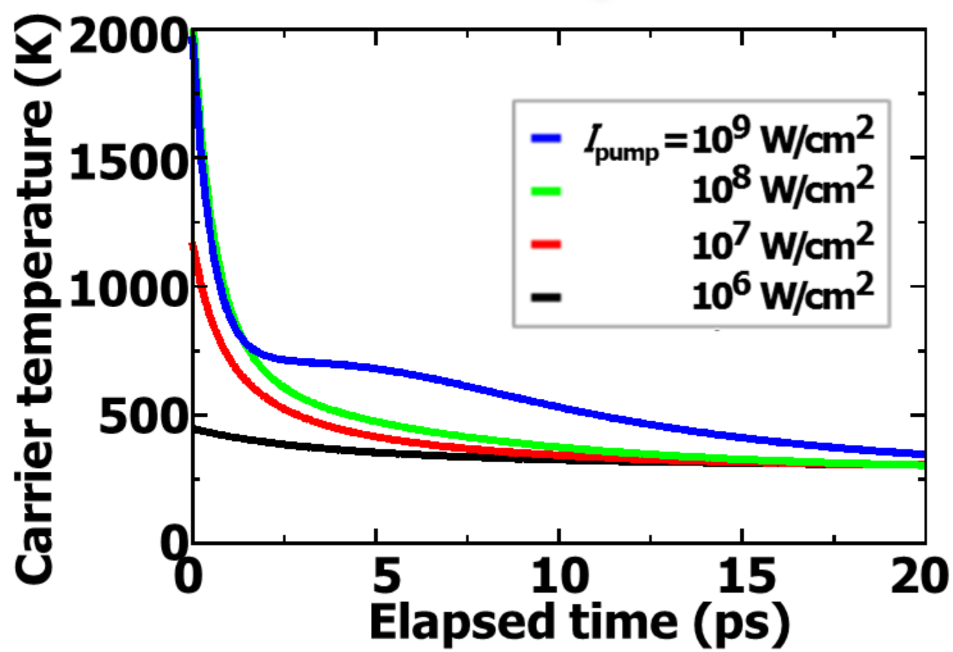
Δt **Pulse width = 80 fs**

I_{pump} **Peak intensity**

Quasi-Fermi level



Carrier temperature

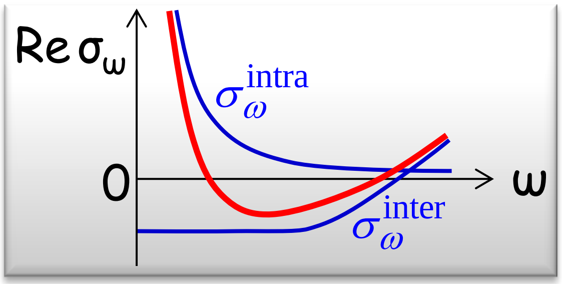


■ **Population inversion occurs with a threshold of pumping intensity!**

Time-Dependent Dynamic Conductivity

T. Otsuji et al., **J. Phys. D 45**, 303001 (2012).

Dynamic conductivity

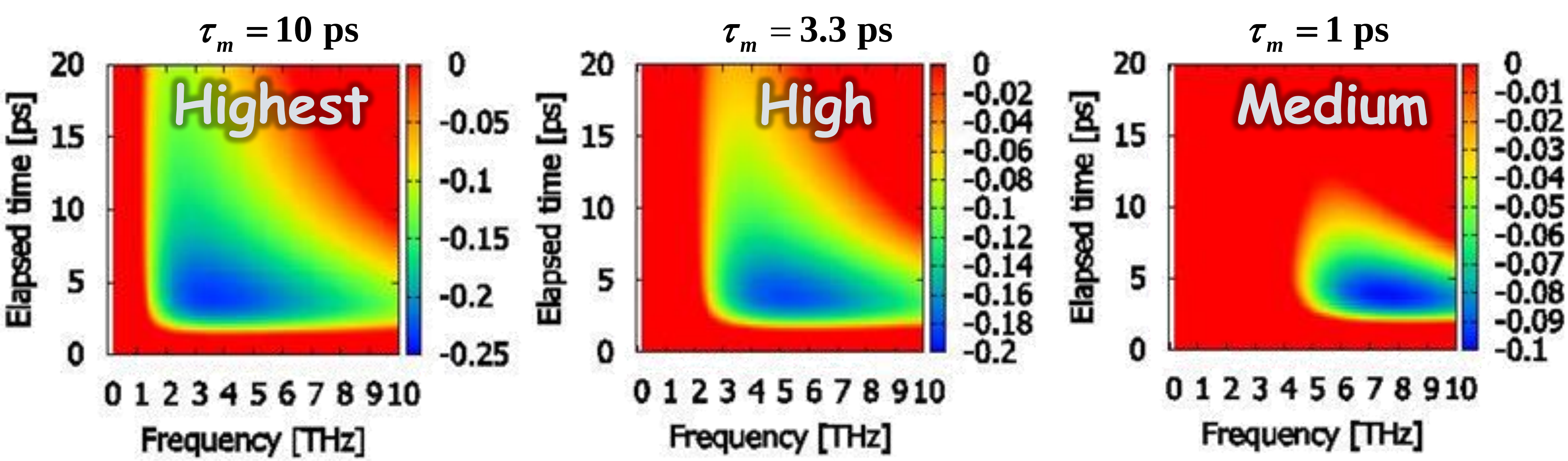


$$\mathrm{Re}\,\sigma_\omega = \mathrm{Re}\,\sigma_\omega^{\mathrm{inter}} + \mathrm{Re}\,\sigma_\omega^{\mathrm{intra}}$$

$$\approx \frac{e^2}{4\hbar}(1-2f_{\hbar\omega}) + \frac{(\ln 2 + \varepsilon_F/2k_BT)e^2}{\pi\hbar}\frac{k_BT\tau}{\hbar(1+\omega^2\tau^2)}$$

$$\approx \frac{e^2}{4\hbar}\tanh\left(\frac{\hbar\omega - 2\varepsilon_F}{4k_BT}\right) + \frac{(\ln 2 + \varepsilon_F/2k_BT)e^2}{\pi\hbar}\frac{k_BT\tau}{\hbar(1+\omega^2\tau^2)}$$

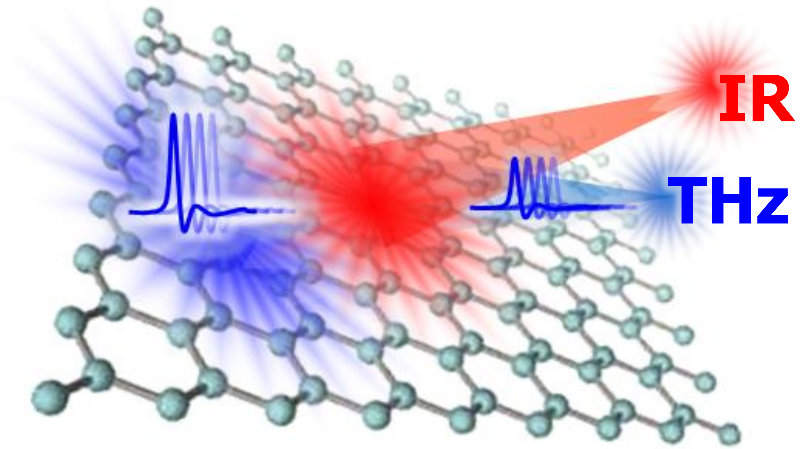
(intra) = Drude absorption

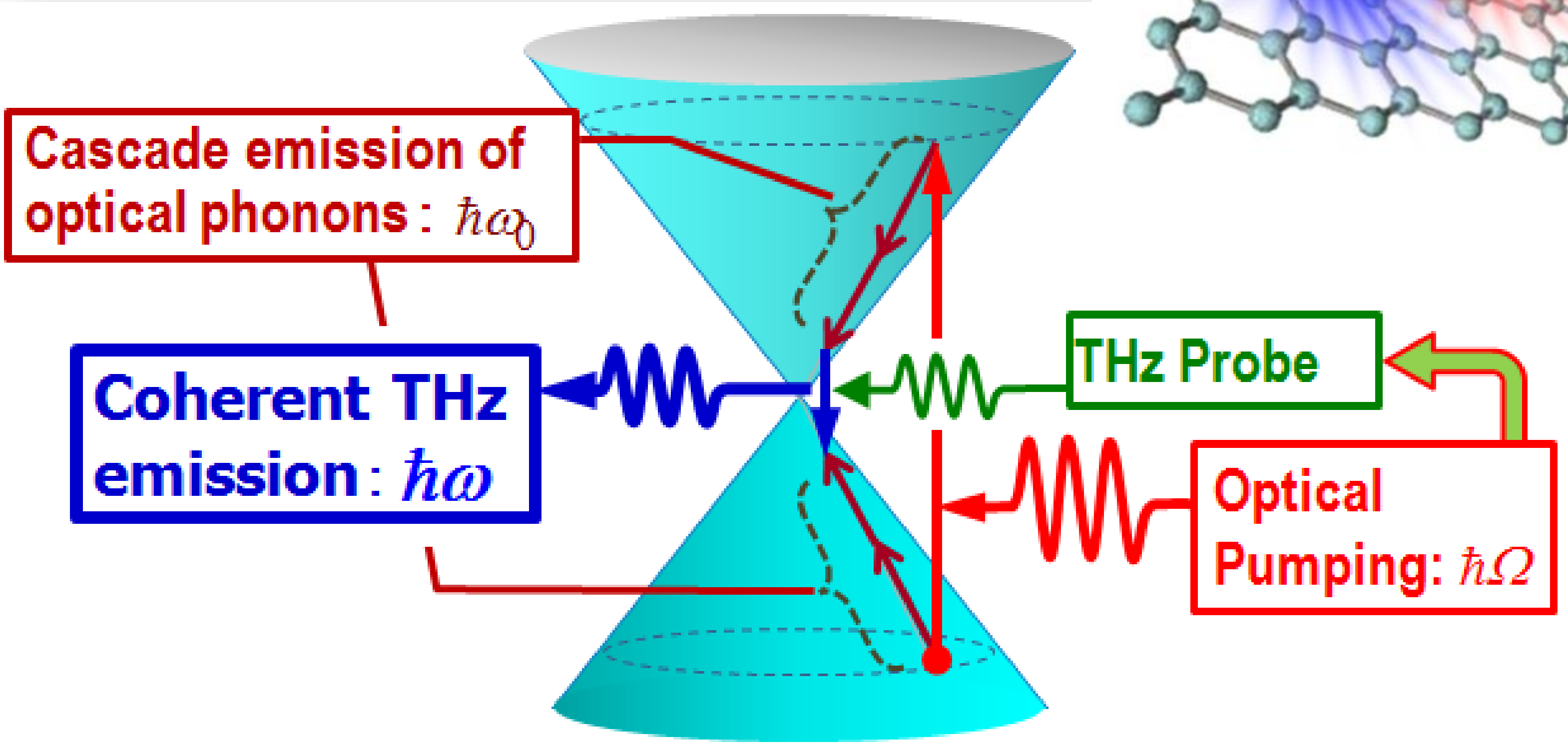


- **Longer relaxation time, larger and broader NDC**

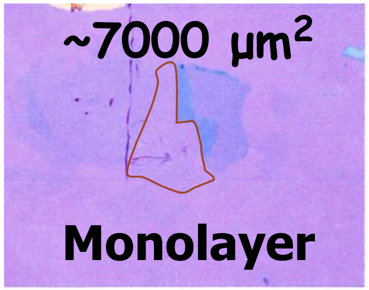
$I_{pump} = 10^8\ \mathrm{W/cm^2}$
80 fs FWHM

Proof-of-Concept Experiment: Optical Pumping/THz Probing Graphene



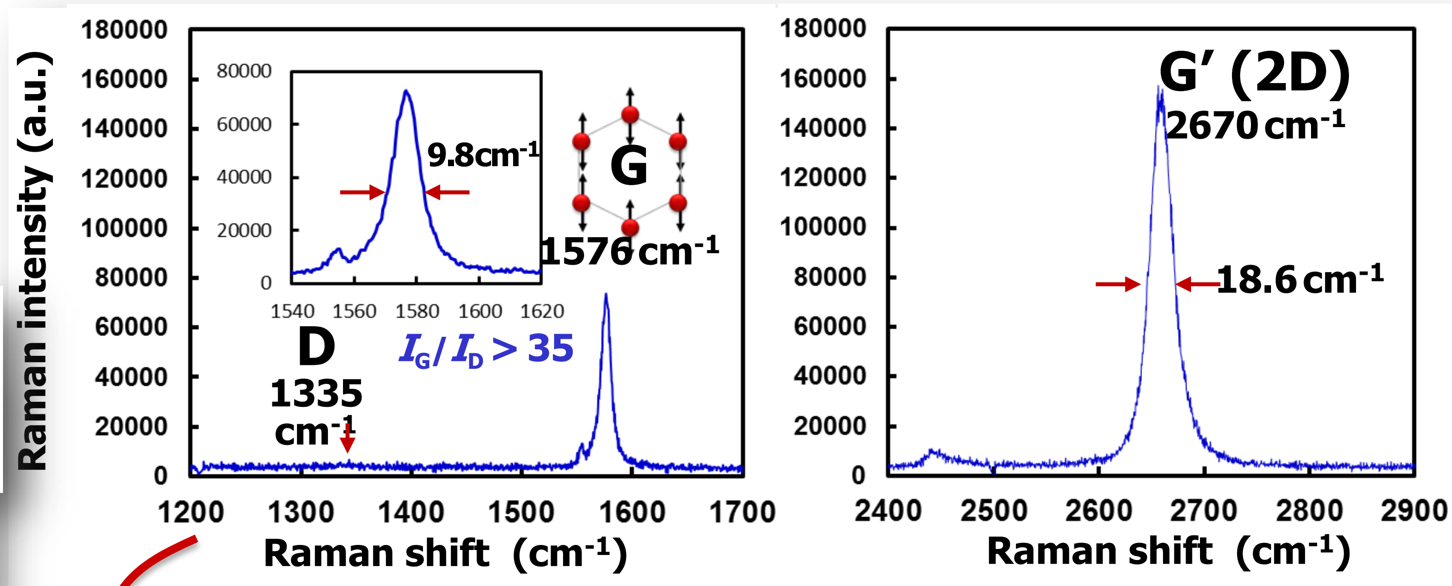


Exfoliated Monolayer Graphene/SiO_2/Si

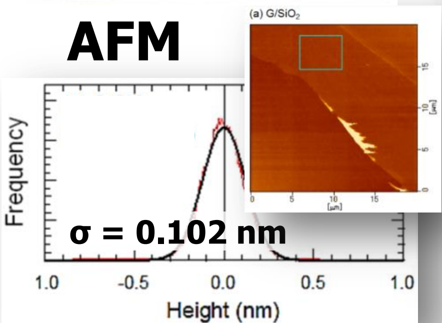


Raman

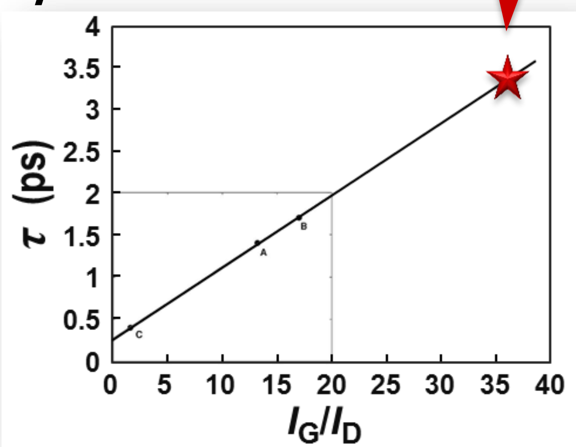
T. Otsuji et al., **J. Phys. D 45**, 303001 (2012).



AFM

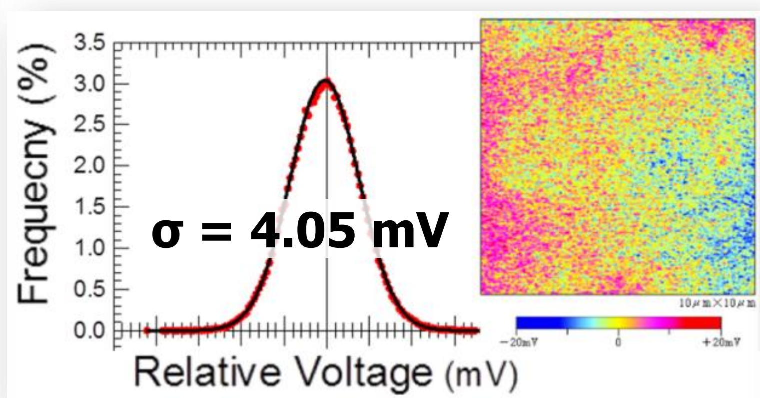


e/h life time

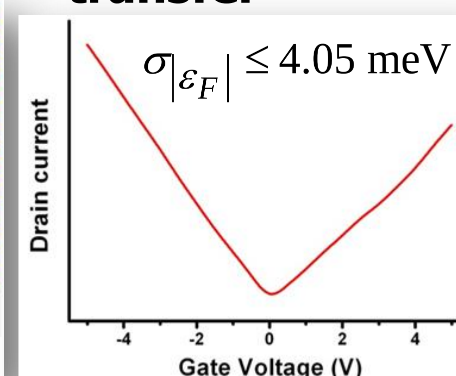


J.M. Dawlaty et al., **APL 92**, 042116 (2008)

KFM



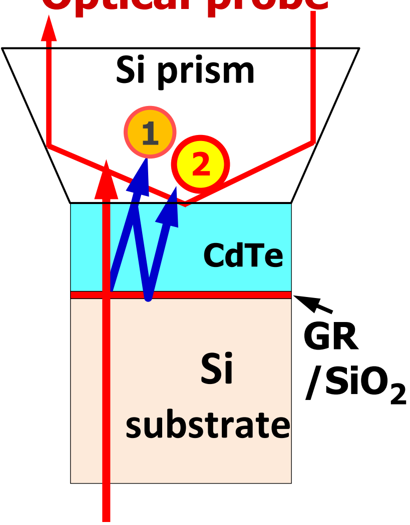
Back-gated transfer

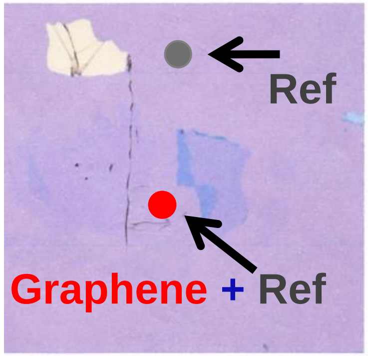


S. Boubanga Tombet et al., **PRB 85**, 035443 (2012).

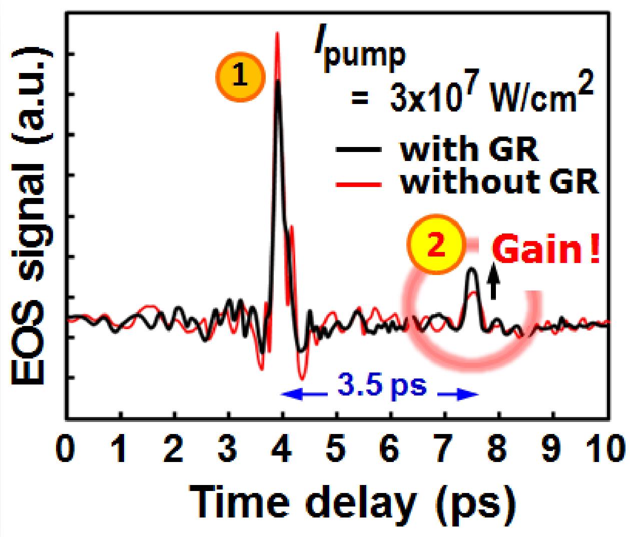
Observation of Threshold Behavior, Proving Stimulated THz Emission & Gain

S. Boubanga Tombet et al., ***PRB 85***, *035443 (2012).*

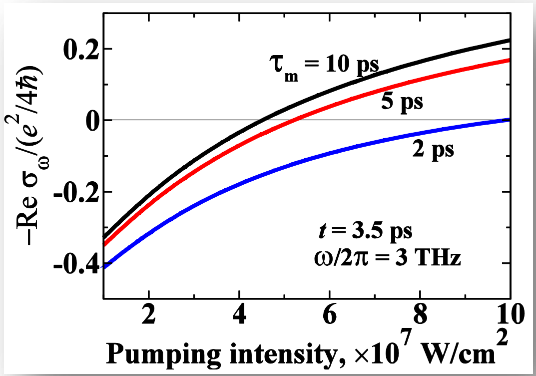


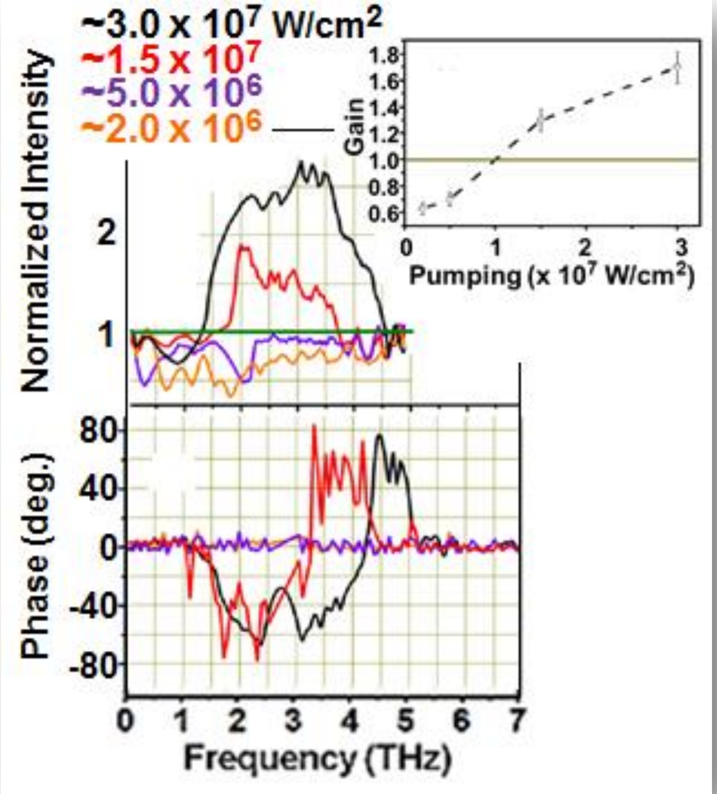


Experimental result



Theoretical result

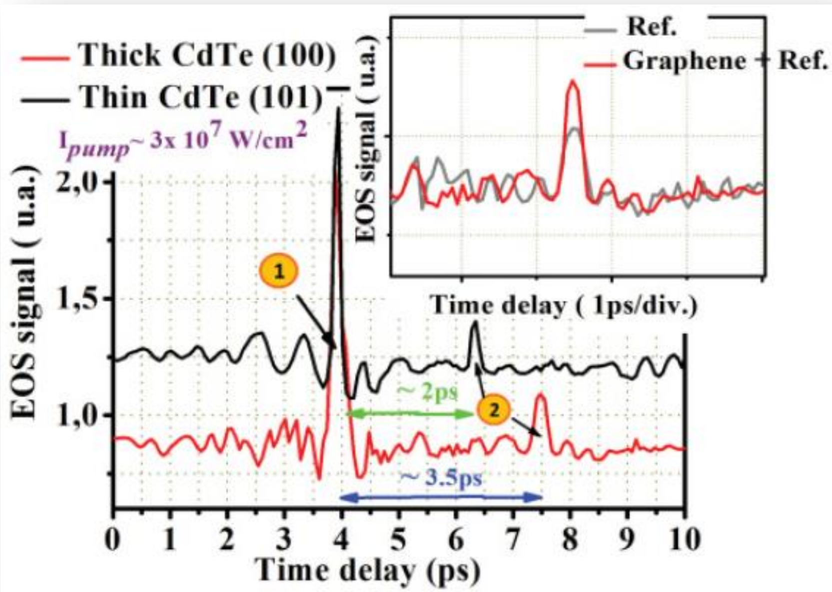


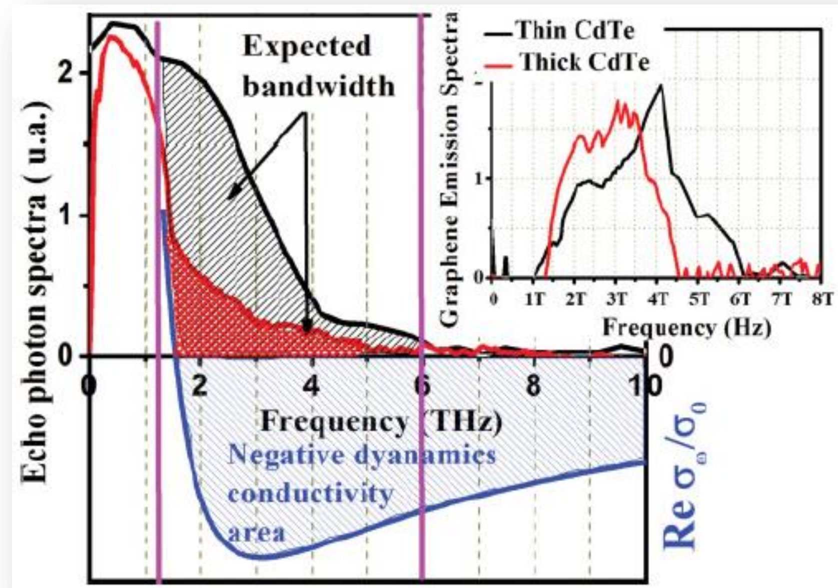


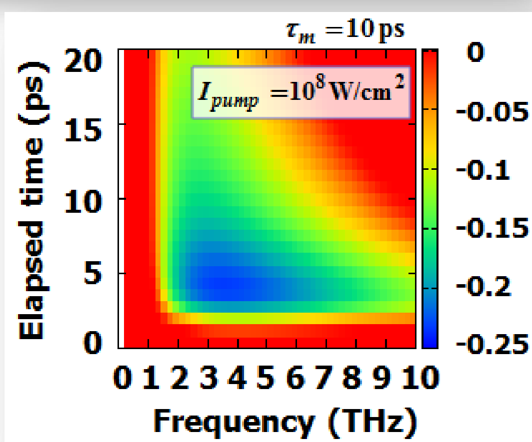
- Threshold behavior
- Normal dispersion
- ☞ Proving the THz gain!

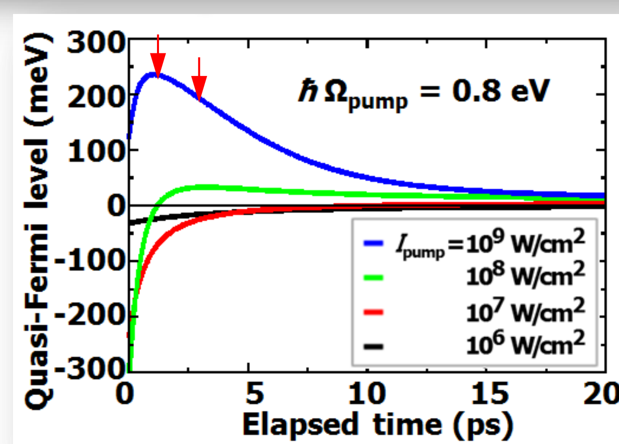
Narrower Emission Spectra at a Longer Probe Delay, Reflecting Equilibration

S. Boubanga Tombet et al., ***PRB 85***, 035443 (2012).



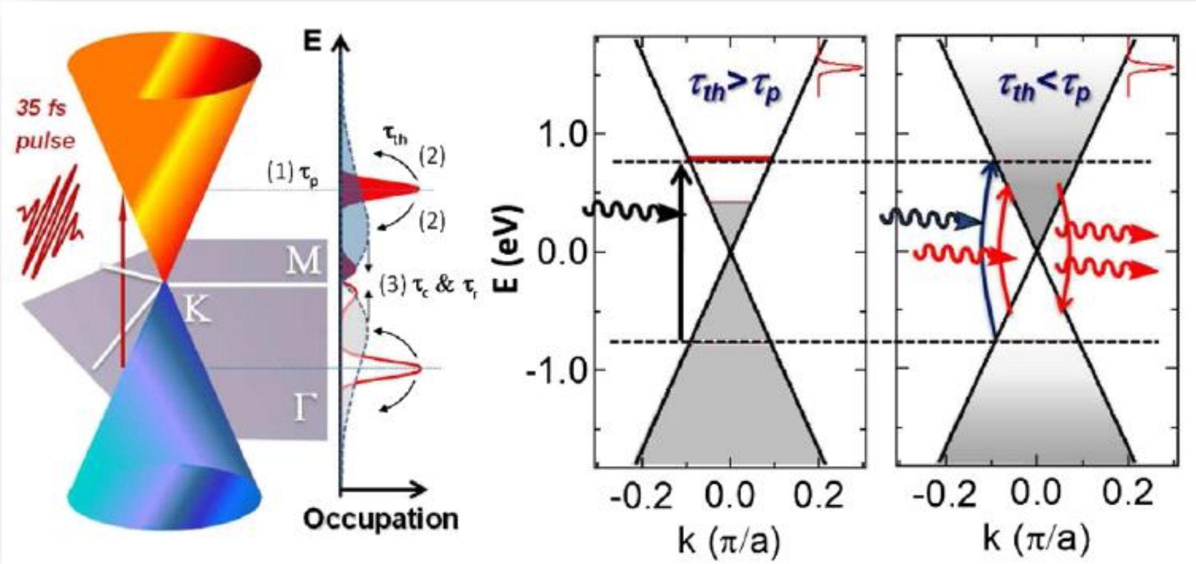


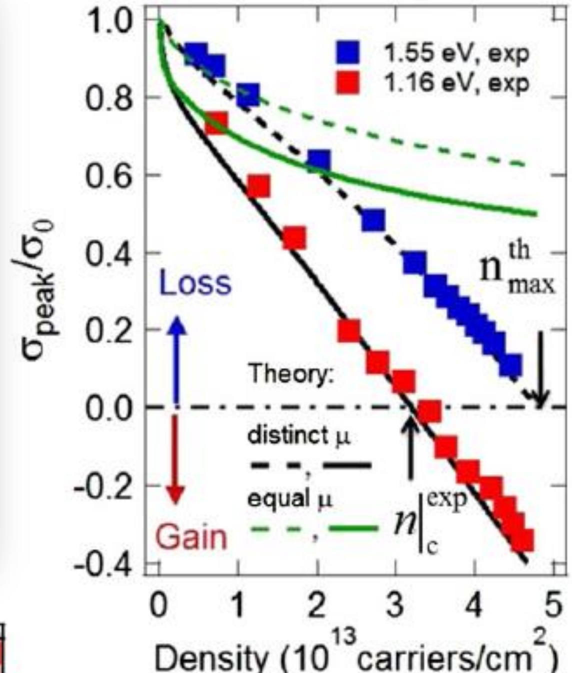


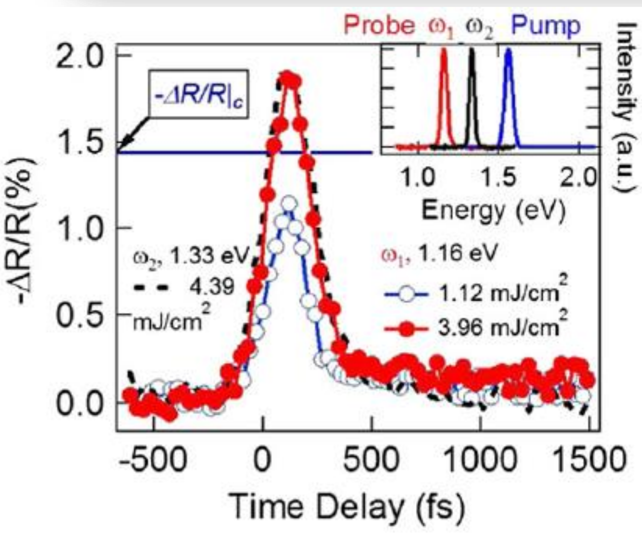


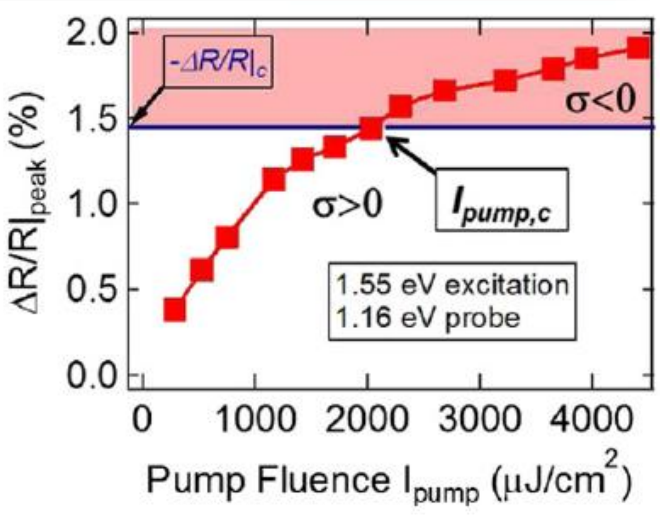
Observation of IR Stimulated Emission in fs Regime before Quasi-Equilibration

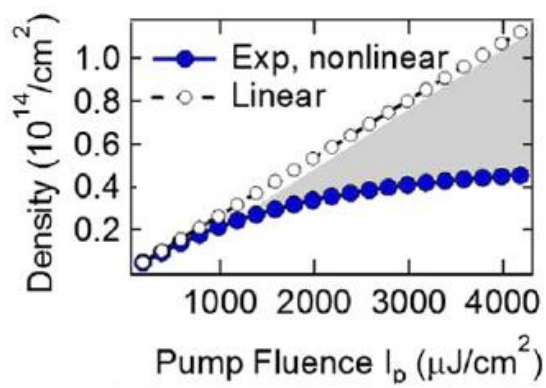
*T. Li et al., **PRL 108**, 167401 (2012).*









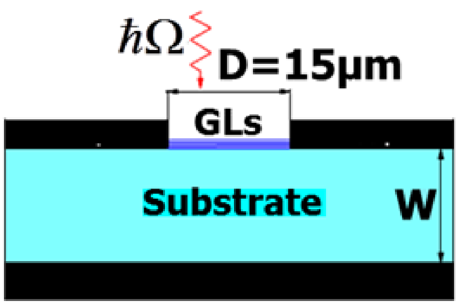


Gain Profile of MGL Laser Calculated for Slot-Line Waveguides

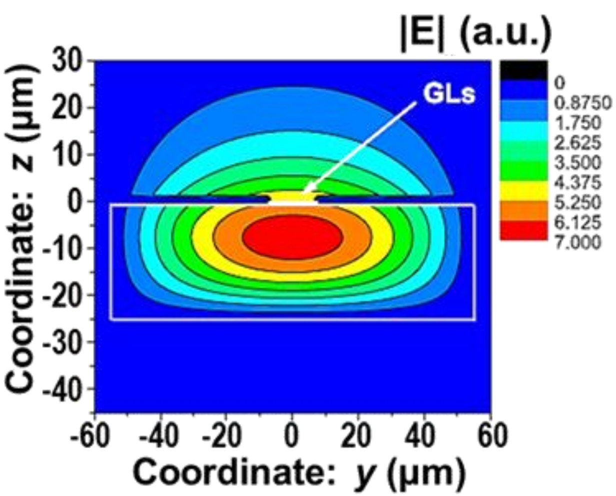
JOURNAL OF APPLIED PHYSICS 107, 054505 (2010)

Terahertz lasers based on optically pumped multiple graphene structures with slot-line and dielectric waveguides

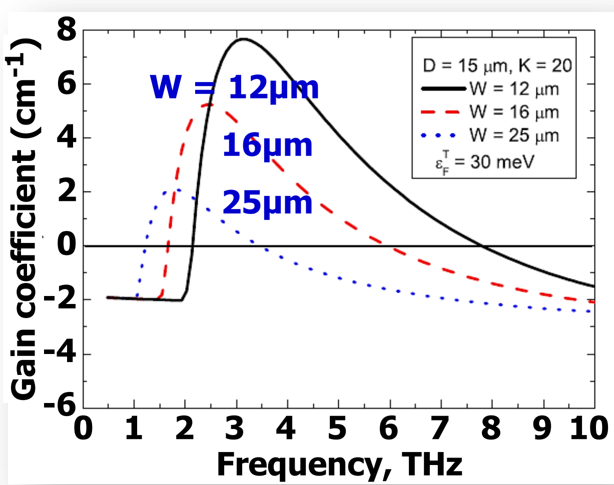
V. Ryzhii,[1,2,a)] A. A. Dubinov,[1,3] T. Otsuji,[2,4] V. Mitin,[5] and M. S. Shur[6]



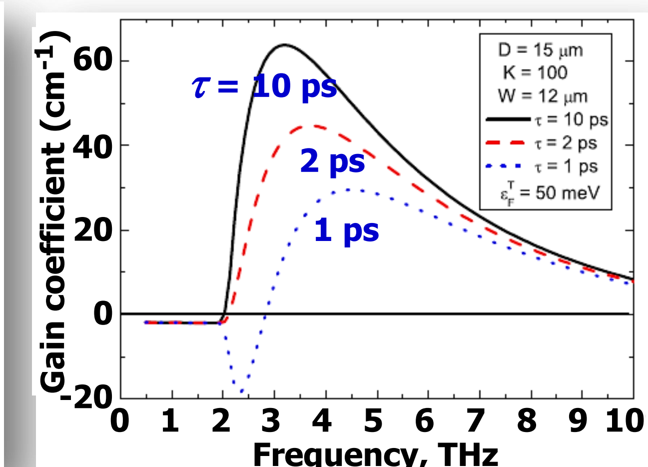
$$g_\omega = \frac{4\pi \,\mathrm{Re}\, \sigma_\omega}{c\sqrt{\eta_S}}\Gamma_\omega - \alpha_\omega, \quad \Gamma_\omega = \frac{\int_{-D/2}^{D/2} |E_\omega(y,0)|^2 dy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |E_\omega(y,z)|^2 dy dz}$$



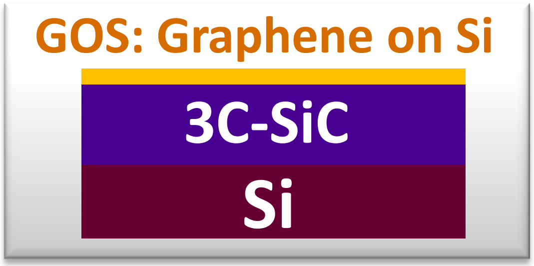
20GLs, ε_F=30meV, τ=10ps



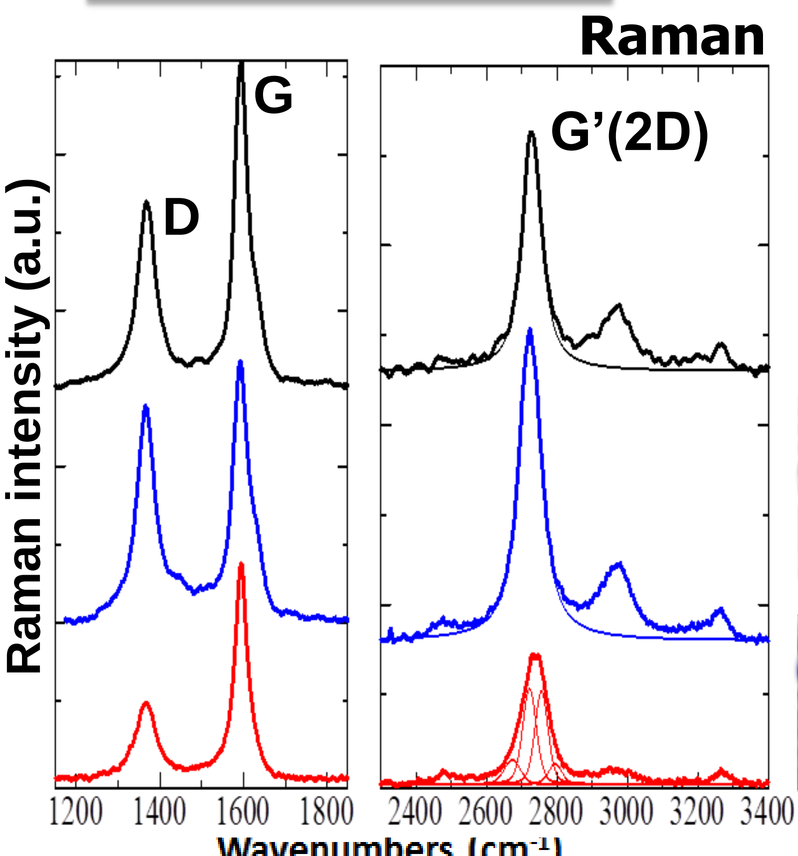
100GLs, ε_F=50meV, W=12μm



MLG: Epitaxial Graphene on SiC/Si can Control the GR-Layer Stacking



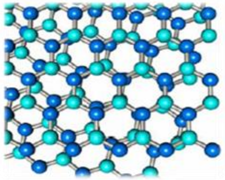
H. Fukidome et al., ***J. Mat. Chem. 21***, *17242 (2011).*
M. Suemitsu and H. Fukidome, ***J. Phys. D 43***, *374012 (2010).*
M. Suemitsu et al., ***e-J. Surface Sci. Nano****. **7** 311 (2009).*



On SiC(100)/Si(100)

SiC(110)/Si(110)

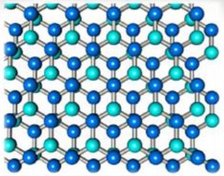
☛ Turbostratic Non-Bernal



- **Multilayer of monolayer GR**
- **High power applications**
- **THz photonic applications**

On SiC(111)/SiC(111)

☛ AB stacking

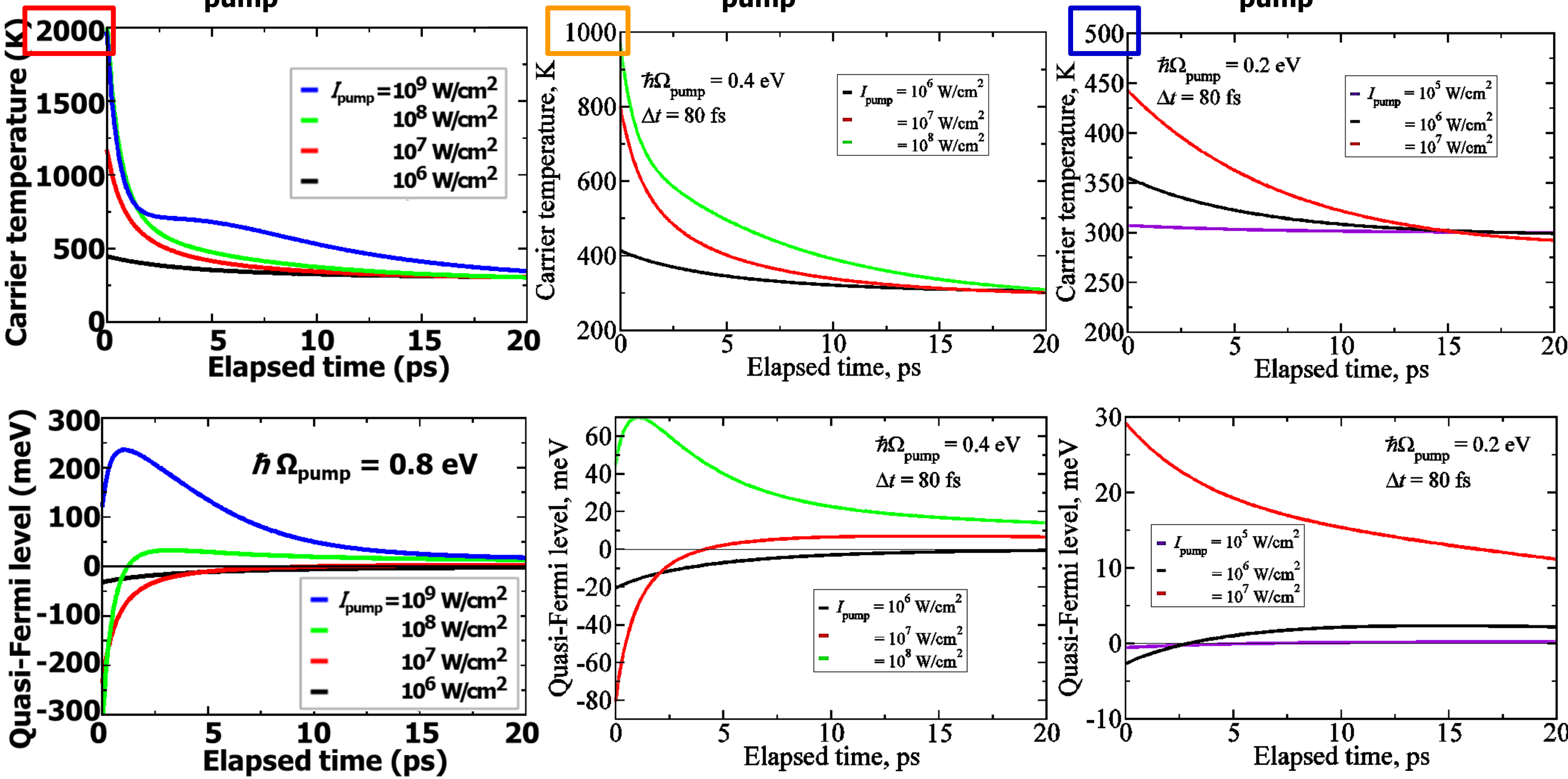


- **High on/off ratio**
- **Transistor & logic ICs**

Pumping Photon Energy vs. T_c & ε_F - Impulsive Pumping

T. Otsuji et al., ***IEEE T. THz. Sci. Tech. 3***, 63 (2013).

$\hbar\Omega_{pump}$ = 0.8 eV | $\hbar\Omega_{pump}$ = 0.4 eV | $\hbar\Omega_{pump}$ = 0.2 eV



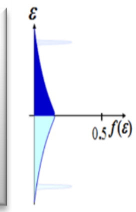
Effects of Optical-Phonon Decay τ_0^{decay} & Effective Pumping Photon Energy Ω_0

*V. Ryzhii, M. Ryzhii, V. Mitin, A. Satou, and T. Otsuji, **JJAP 50**, 094001 (2011).*

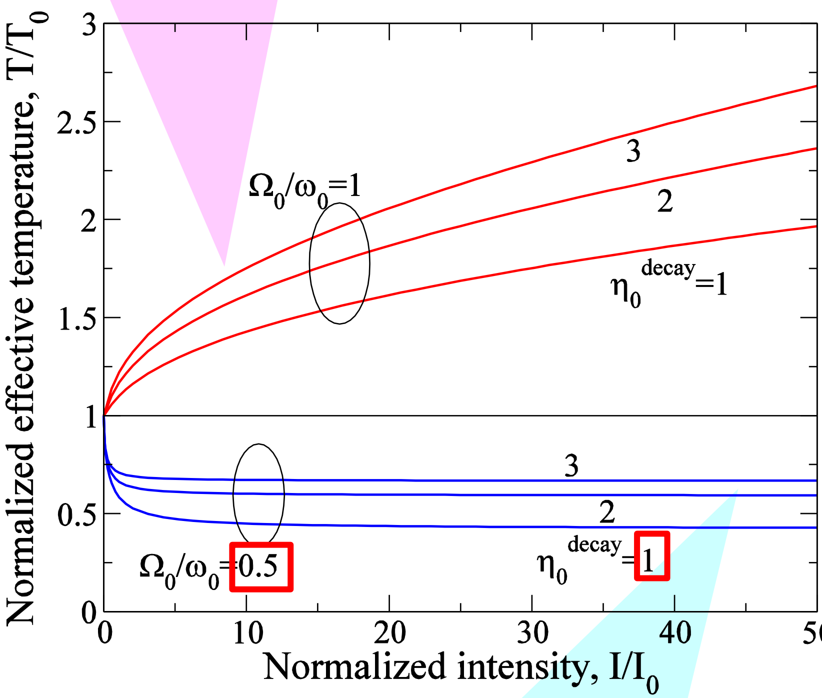
Thermal conductivity^{-1} ∝ $\eta_0^{decay} = \tau_0^{decay} / \tau_0^{inter}$

Effective pumping photon energy

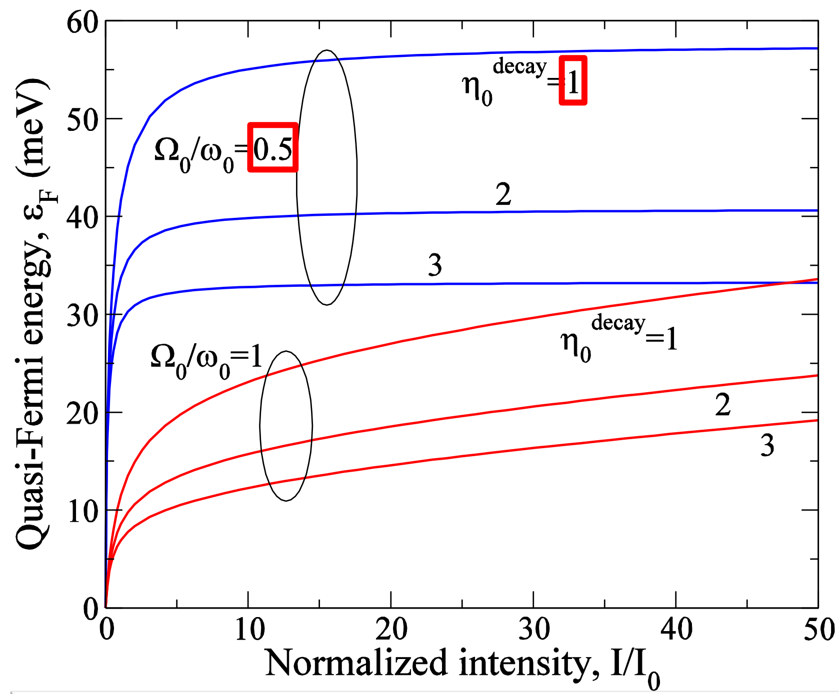
$$\Omega_0 = \Omega - \frac{2K\omega_0}{1 + K\tau_{op}/\tau_{cc}} \quad (K = 1, 2, ..)$$



Heating of electron-hole plasma



Cooling of electron-hole plasma



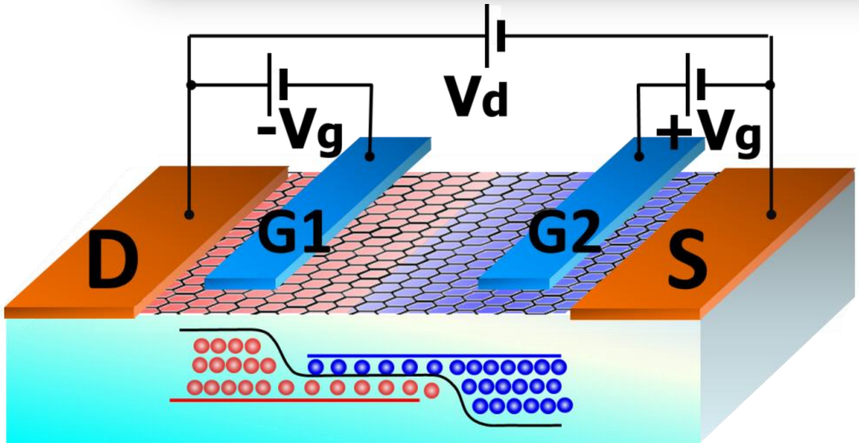
ε_F can be elevated by:
- **cooling carriers**
- **lowering pumping photon energy**

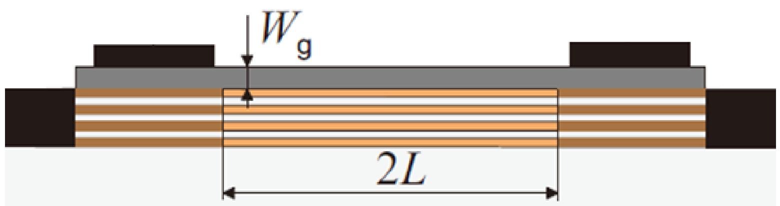
JOURNAL OF APPLIED PHYSICS 110, 094503 (2011)

Toward the creation of terahertz graphene injection laser

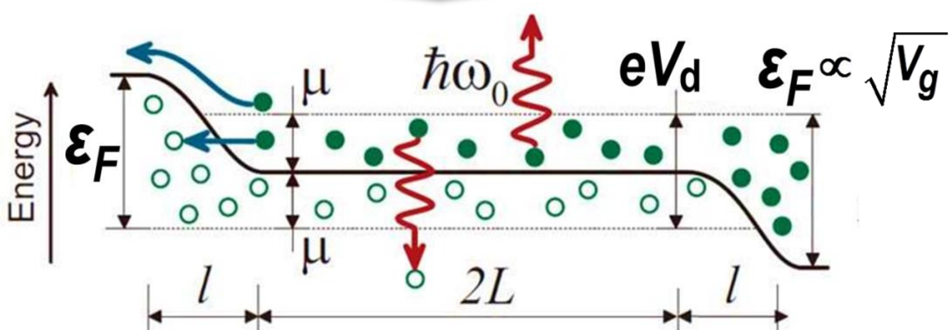
V. Ryzhii,[1,a)] M. Ryzhii,[1] V. Mitin,[2] and T. Otsuji[3]

M. Ryzhii and V. Ryzhii, ***JJAP 46****, L151 (2007).*





Sufficiently long i-section is the key to minimize I_{tt}!



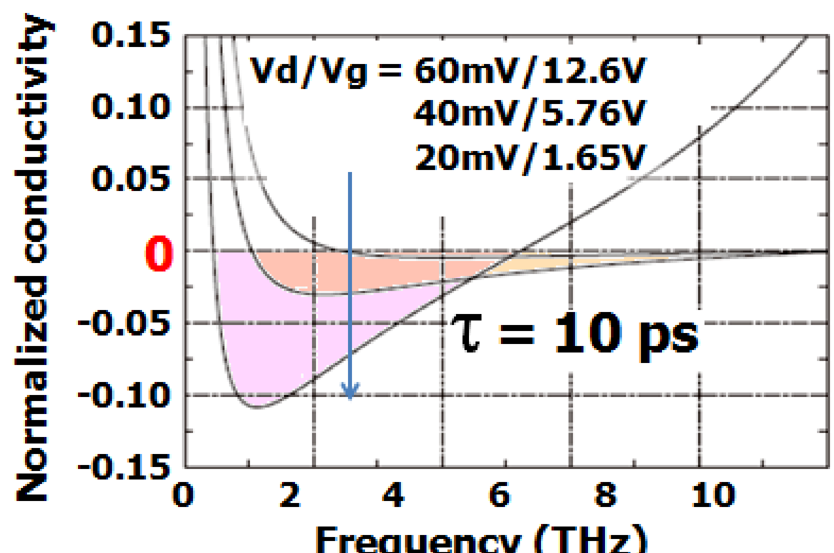
- Parameters
  - $+V_G$ / $-V_G$ $\Rightarrow$ η, I_{th}
  - V_D $\Rightarrow$ λ at G_{max}
  - L $\Rightarrow$ $\eta > 0$

η : injection efficiency = $(I_{inject} - I_{tt})/I_{inject}$

I_{inject} : injection current

I_{tt} : tunneling & thermionic leakage current

I_{th} : threshold current



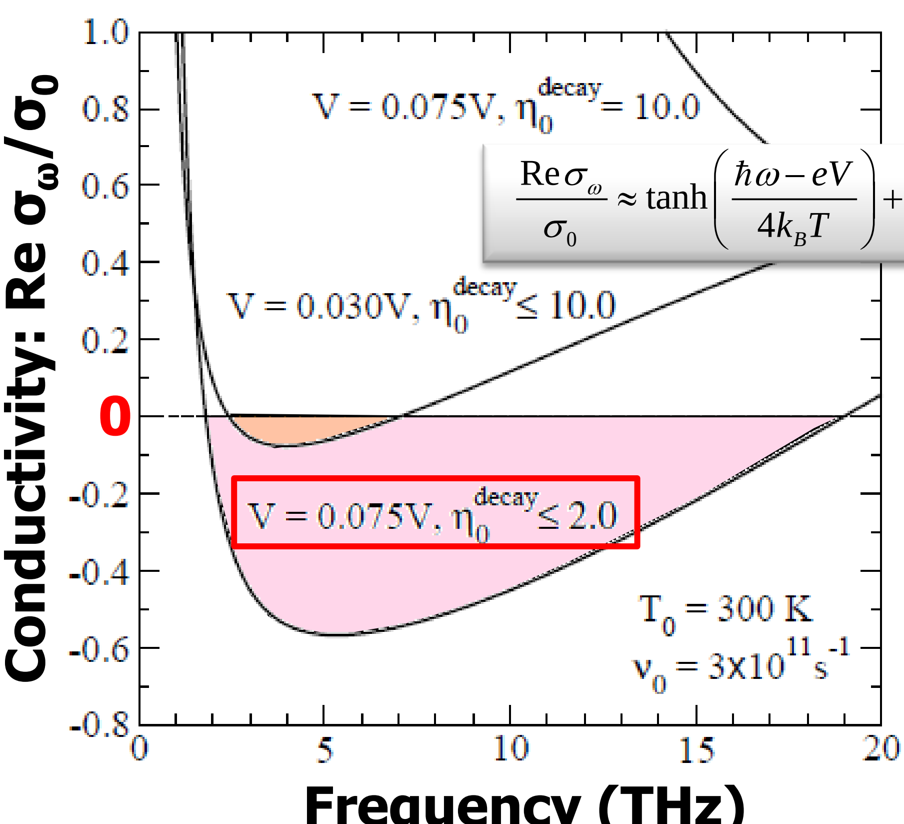
Negative Dynamic Conductivity at Different τ and η_0^{decay} at RT

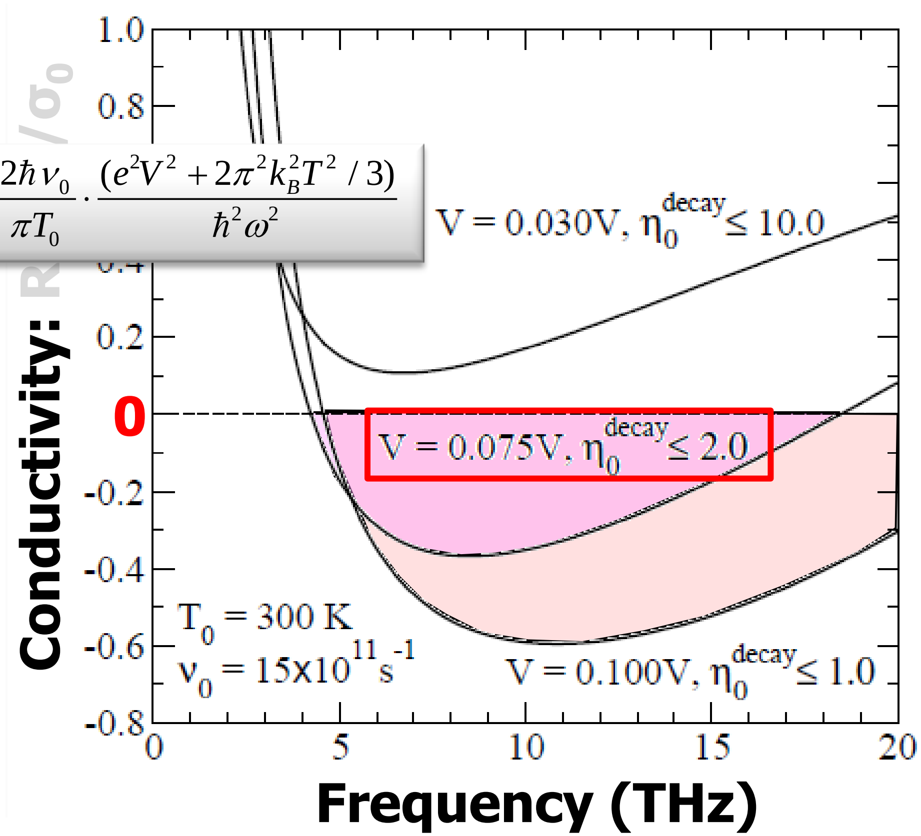
*V. Ryzhii, M. Ryzhii, V. Mitin, and T. Otsuji, **JAP 110**, 094503 (2011).*

Excellent quality of GR with $\nu_0 = 3E^{11} s^{-1}$ ($\tau = 3.3$ ps)

Less quality of GR with $\nu_0 = 15E^{11} s^{-1}$ ($\tau = 0.6$ ps)

$$\frac{\mathrm{Re}\,\sigma_\omega}{\sigma_0} \approx \tanh\left(\frac{\hbar\omega - eV}{4k_BT}\right) + \frac{2\hbar\nu_0}{\pi T_0}\cdot\frac{(e^2V^2 + 2\pi^2k_B^2T^2/3)}{\hbar^2\omega^2}$$

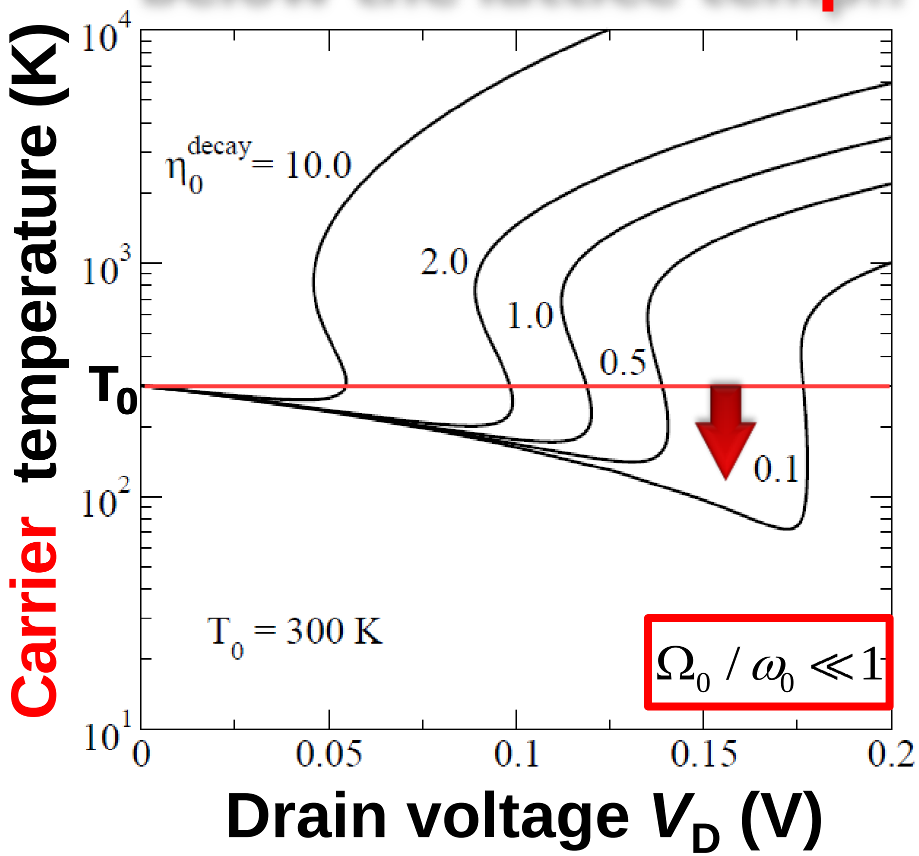




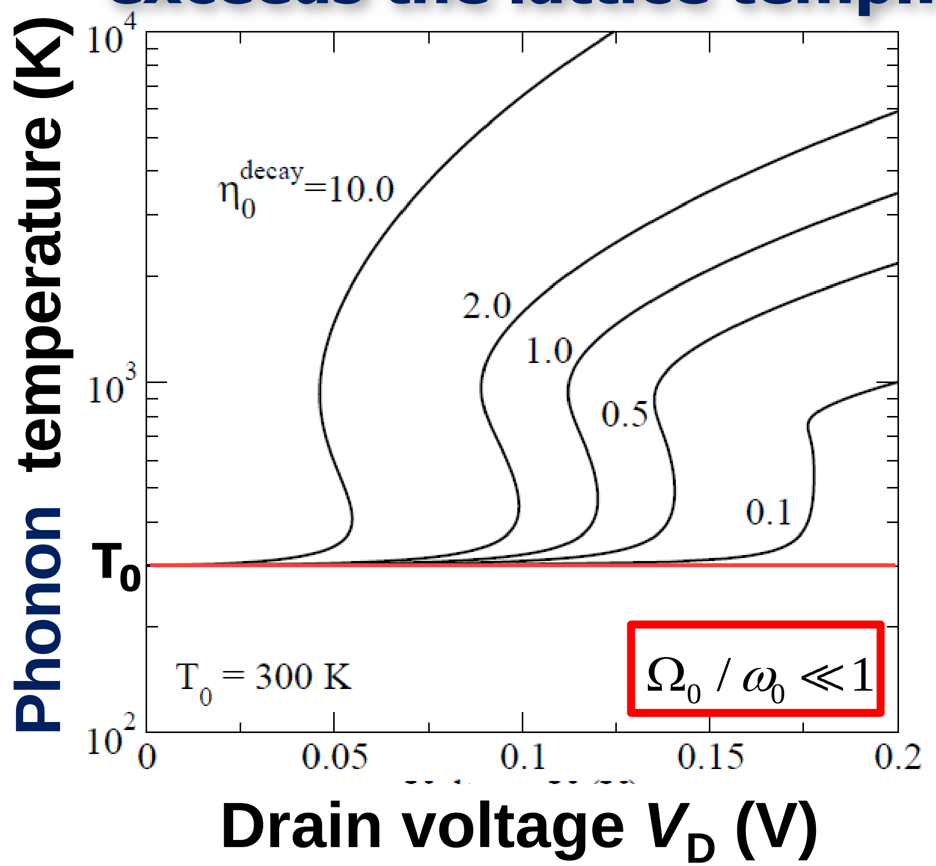
Advantage of Current Injection: Carrier Over-Cooling Effect even at RT

*V. Ryzhii, M. Ryzhii, V. Mitin, and T. Otsuji, **JAP 110**, 094503 (2011).*

Carrier temp. can be below the lattice temp.!



Phonon temp. always exceeds the lattice temp.!



2D Plasmon Dispersions in Graphene

V. Ryzhii, A. Satou, T. Otsuji, ***JAP* 101**, 024509 (2007).
V. Popov, , T.Y. Bagaeva, T. Otsuji, V. Ryzhii, ***PRB* 81**, 073404 (2010).
V. Ryzhii, M. Ryzhii, V. Mitin, A. Satou, T. Otsuji, ***JJAP* 50**, 094001 (2011).

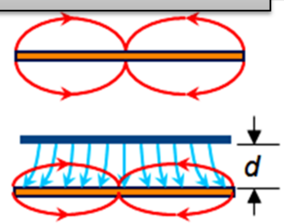
Normal semiconductors

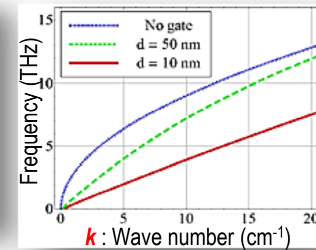
ungated 2D

$$\omega = \sqrt{\frac{e^2 n}{2\varepsilon m}k}$$

gated 2D

$$\omega = \sqrt{\frac{e^2 nd}{\varepsilon m}}\cdot k \propto k d^{1/2} V_g^{1/2}$$





Gated graphene

$(s > v_F,\ |k|^{-1} \gg d)$

$$\omega = ks \approx k\sqrt{\frac{4\ln 2\, e^2 d k_B T}{\varepsilon \hbar^2}} \propto k d^{1/2} T^{1/2}$$

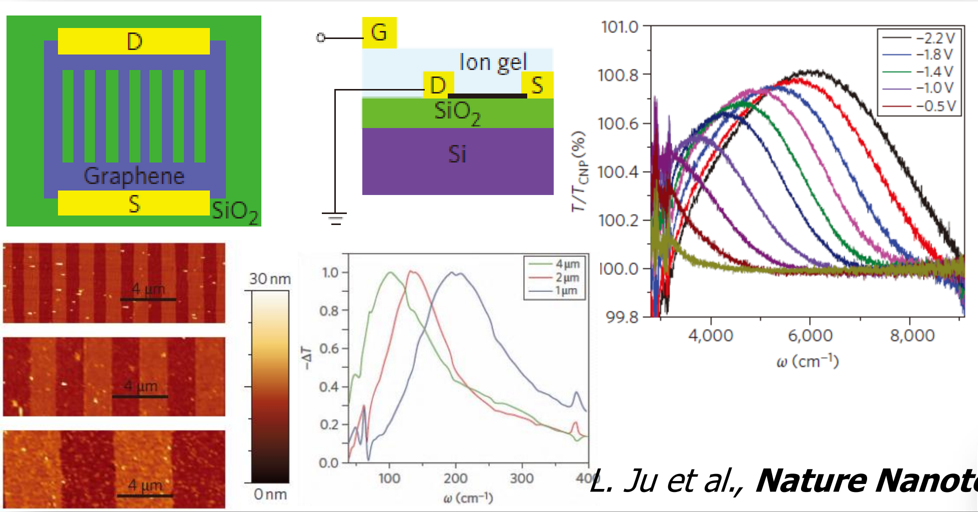
$$\varepsilon_F = \hbar v_F \sqrt{\varepsilon V_g / 2ed}\ \begin{cases} \ll k_B T \\ \gg k_B T \end{cases}$$

$$\omega = ks \approx k v_F \sqrt{\frac{\alpha}{2}} \propto k v_F d^{1/4} V_g^{1/4}$$

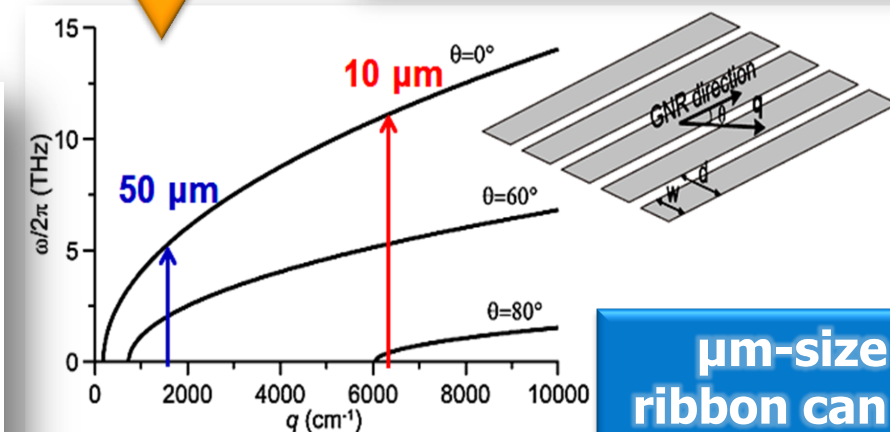
Gated graphene ribbon array

$$\tilde{\omega}_p = \omega_p - i\gamma = \sqrt{\frac{4\pi e^2 n}{\wp m^*}\,\frac{q\cos^2\theta}{1+\coth(qd)} - \frac{1}{4\tau^2}} - i\,\frac{1}{2\tau}$$

e : elementary charge, $\wp$: the permittivity
d : the period of the GRA
τ : the momentum relaxation time of electrons



L. Ju et al., ***Nature Nanotech.* 6**, 630 (2011).



µm-size ribbon can resonate in THz

Dispersions and the Damping of Graphene Plasmons

A. D. Svintsov, V. Vyurkov, S. Yurchenko, T. Otsuji, and V. Ryzhii, ***JAP 111***, 083715(2012).

Semi-classical Boltzmann's equations for Dirac Fermion

Electron: $$\frac{\partial f_e}{\partial t} + \upsilon_F \frac{\mathbf{p}}{p}\frac{\partial f_e}{\partial \mathbf{r}} + e\frac{\partial \varphi}{\partial \mathbf{r}}\frac{\partial f_e}{\partial \mathbf{p}} = St\{f_e, f_e\} + St\{f_e, f_h\} + St_i\{f_e\}$$

Hole: $$\frac{\partial f_h}{\partial t} + \upsilon_F \frac{\mathbf{p}}{p}\frac{\partial f_h}{\partial \mathbf{r}} - e\frac{\partial \varphi}{\partial \mathbf{r}}\frac{\partial f_h}{\partial \mathbf{p}} = St\{f_h, f_h\} + St\{f_h, f_e\} + St_i\{f_h\}$$

Collision integrals: inter-carrier, disorder

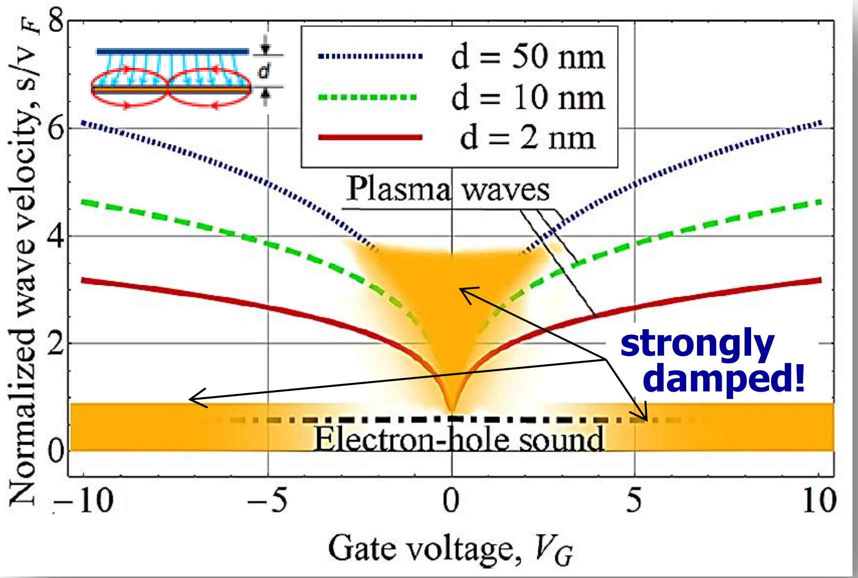
Continuity equations:

$$\frac{\partial \Sigma_e}{\partial t} + \frac{\partial \Sigma_e \mathbf{V}_e}{\partial \mathbf{r}} = 0, \quad \frac{\partial \Sigma_h}{\partial t} + \frac{\partial \Sigma_h \mathbf{V}_h}{\partial \mathbf{r}} = 0.$$

Hydrodynamic Euler equations:

Electron: $$\frac{3}{2}\frac{\partial}{\partial t}\frac{\langle p_e\rangle \mathbf{V}_e}{\upsilon_F} + \frac{\partial}{\partial \mathbf{r}}\frac{\upsilon_F\langle p_e\rangle}{2} - e\Sigma_e\frac{\partial \varphi}{\partial \mathbf{r}} = -\beta_e\mathbf{V}_e - \beta_{eh}(\mathbf{V}_e - \mathbf{V}_h),$$

Hole: $$\frac{3}{2}\frac{\partial}{\partial t}\frac{\langle p_h\rangle \mathbf{V}_e}{\upsilon_F} + \frac{\partial}{\partial \mathbf{r}}\frac{\upsilon_F\langle p_h\rangle}{2} + e\Sigma_h\frac{\partial \varphi}{\partial \mathbf{r}} = -\beta_h\mathbf{V}_h - \beta_{eh}(\mathbf{V}_h - \mathbf{V}_e).$$



Bipolar modes for intrinsic and photoexcited GR

e-h plasma waves: $$\omega_+ = -i\left(\frac{\nu}{2} + \frac{\nu_{eh}}{3}\right) + \sqrt{k^2\upsilon^2(1+2r)^2 - \left(\frac{\nu}{2} + \frac{\nu_{eh}}{3}\right)^2}$$

e-h sound waves: $$\omega_- = -i\frac{\nu}{2} + \sqrt{k^2\upsilon^2 - \left(\frac{\nu}{2}\right)^2}$$

strongly damped!

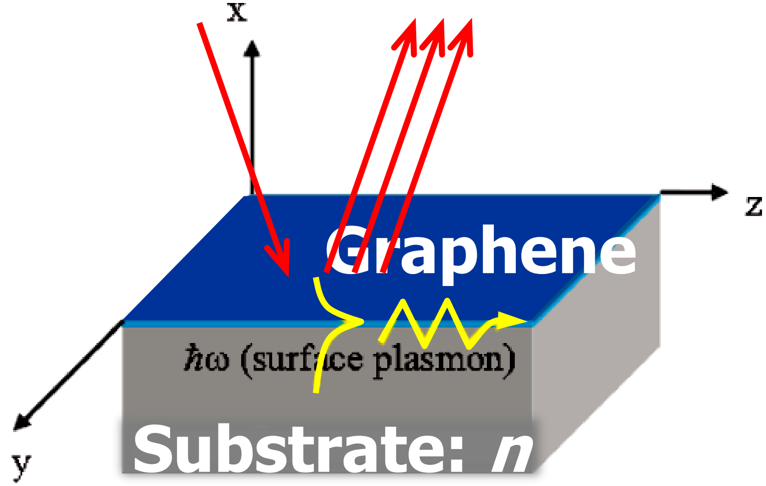
Unipolar modes for doped / gate-biased GR

Majority carriers: $$\omega_+ = -i\frac{\nu_e}{2} + \sqrt{k^2\upsilon_e^2(1+r_e) - \left(\frac{\nu_e}{2}\right)^2},$$

Minority carriers: $$\omega_- = -i\left(\frac{\nu_h}{2} + \frac{\nu_{eh}}{3}\right) + \sqrt{k^2\upsilon_h^2(1+2r_h)^2 - \left(\frac{\nu_h}{2} + \frac{\nu_{eh}}{3}\right)^2}.$$

Amplification of THz-SPPs along Population-Inverted-Graphene Waveguide

A. Dubinov, Y. Aleshkin, V. Mitin, T. Otsuji, V. Ryzhii, ***JPCM 23***, 145302 (2011).
F. Rana, ***IEEE T. NanoTechnol. 7***, 91 (2008).

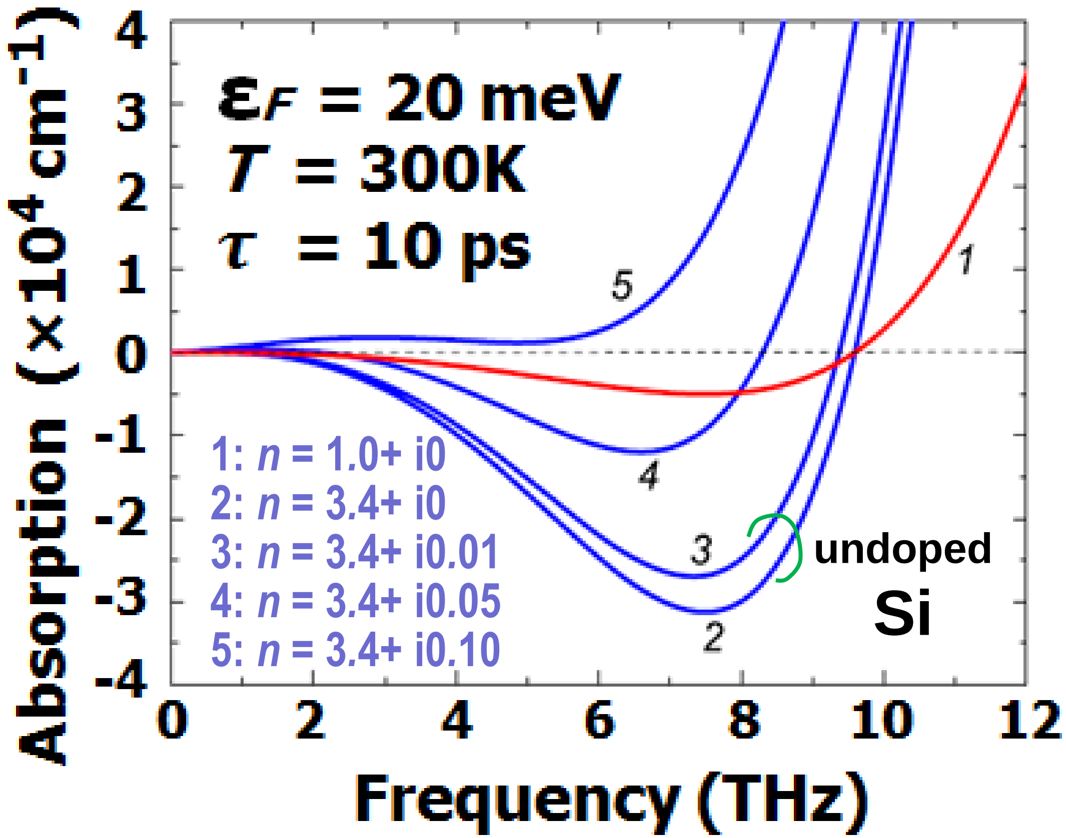


Complex propagation constant of the SPPs:

$$\rho = \sqrt{1 - \frac{c^2}{4\pi^2\sigma_\omega^2}}$$

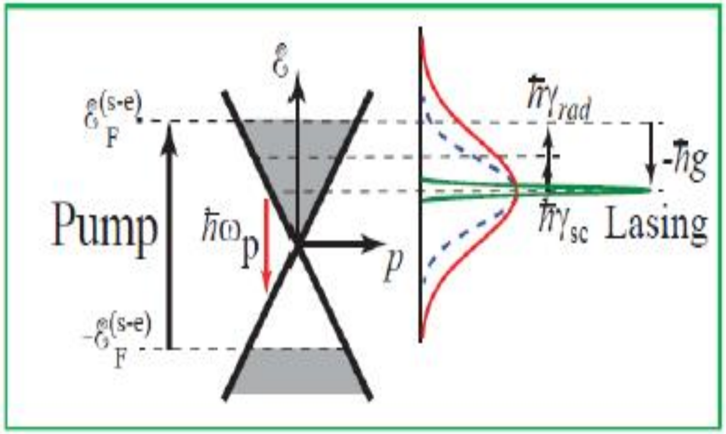
Absorption coefficient of SPPs:

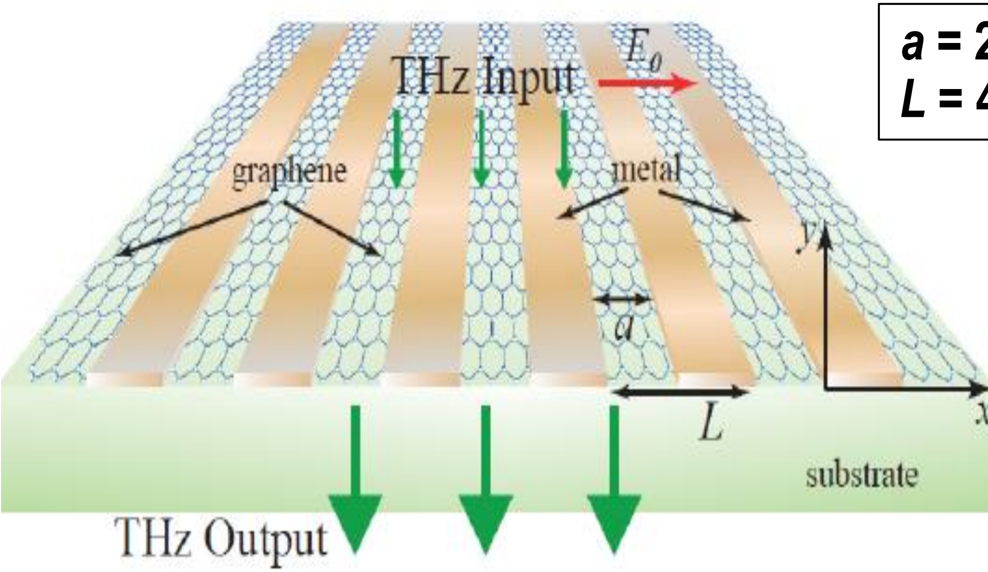
$$\alpha = \mathrm{Im}(q_z) = 2\mathrm{Im}(\rho\omega/c)$$



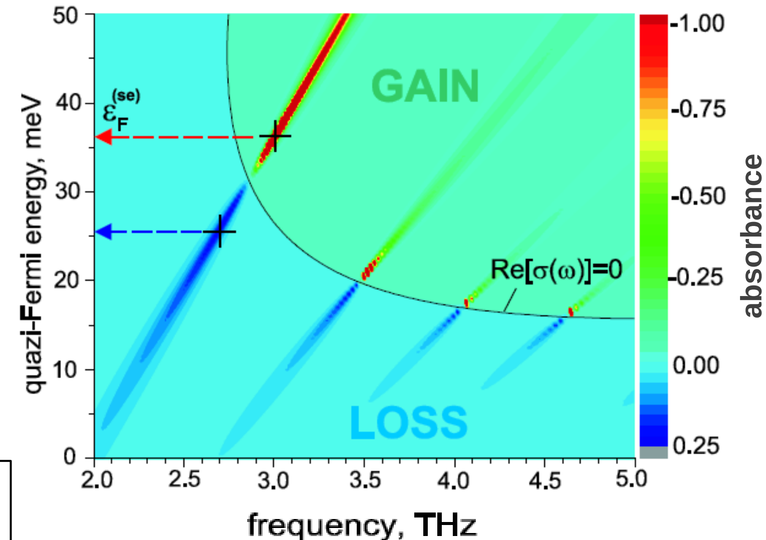
Plasmonic Terahertz Lasing from Nano-Patterned Graphene-Metal Array

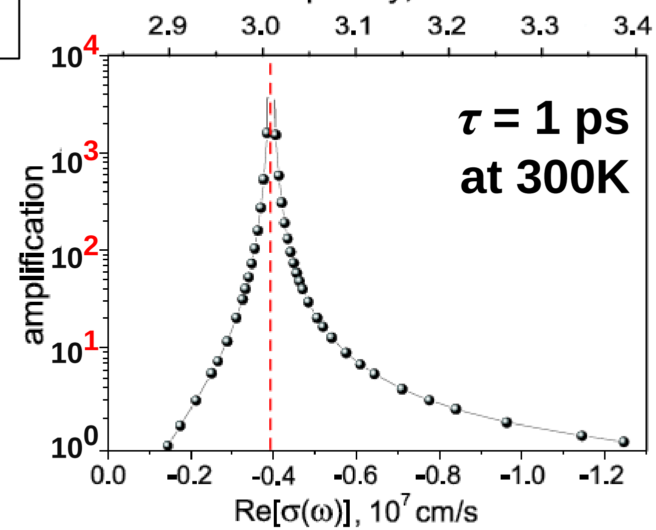
*V.V. Popov, O.V. Polischuk, A.R. Davoyan, V. Ryzhii, T. Otsuji, M.S. Shur, **PRB 86**, 195437 (2012).*





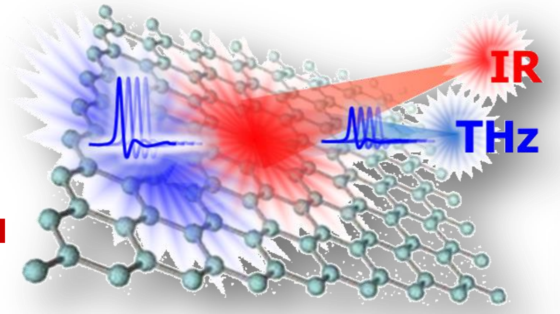
***a* = 2 μm**
***L* = 4 μm**

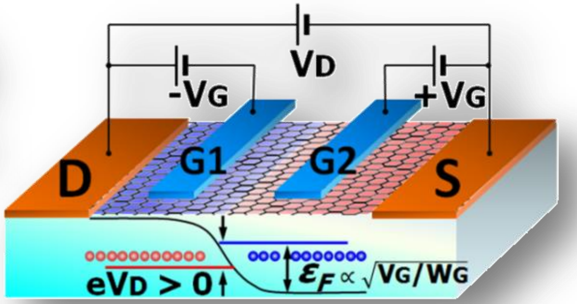




TOHOKU UNIVERSITY

Summary





1. Optically/Electrically pumped GR-THz/IR lasers.

2. Carrier heating can be suppressed by reducing the pumping photon energy.

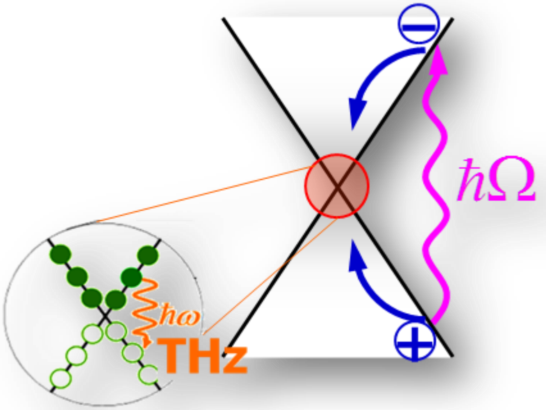
3. Current injection is the best-suited, providing a carrier over-cooling effect.

4. Dual-gate GR-FET is a possible GR-injection THz/IR laser structure.

5. Active plasmonic structures can greatly boost the THz/IR gain.

6. Advantages of graphene THz/IR injection lasers:

   - no need extra care for carrier depopulation.
   - low end of THz range at room temperatures.
   - integrated with simple epitaxy techniques.



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Applied Physics

Volume 45 Number 30 1 August 2012

Fast Track Communication

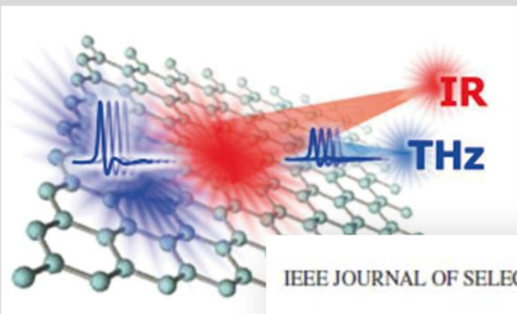
Double graphene-layer plasma resonances terahertz detector

V Ryzhii, T Otsuji, M Ryzhii and M S Shur

Topical review

Graphene-based devices in terahertz science and technology

T Otsuji, S A Boubanga Tombet, A Satou, H Fukidome, M Suemitsu, E Sano, V Popov, M Ryzhii and V Ryzhii



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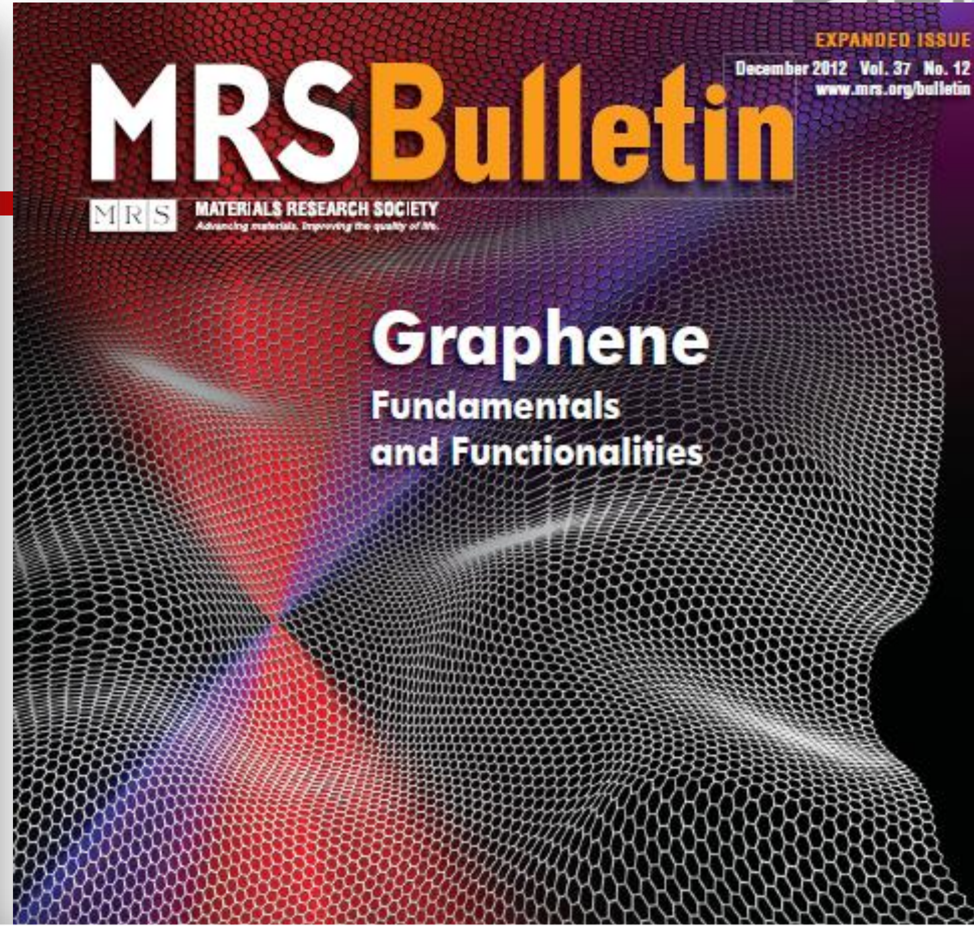

IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 19, NO. 1, JANUARY/FEBRUARY 2013 8400209

Terahertz-Wave Generation Using Graphene: Toward New Types of Terahertz Lasers

Taiichi Otsuji, *Member, IEEE*, Stephane Boubanga Tombet, Akira Satou, *Member, IEEE*, Maxim Ryzhii, *Senior Member, IEEE*, and Victor Ryzhii, *Fellow, IEEE*

(Invited Paper)

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Prof. Michael Shur

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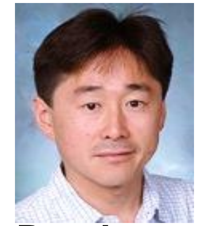
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