

理論限界を超えたテラヘルツ波増幅

– 6G&7G超高速無線通信の可能性

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PHYSICAL REVIEW X

Open Access

Room-Temperature Amplification of Terahertz Radiation by Grating-Gate Graphene Structures

Stephane Boubanga-Tombet, Wojciech Knap, Deepika Yadav, Akira Satou, Dmytro B. But, Vyacheslav V. Popov, Ilya V. Gorbenko, Valentin Kachorovskii, and Talichi Otsuji
Phys. Rev. X **10**, 031004 – Published 6 July 2020



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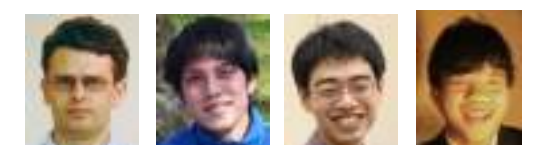
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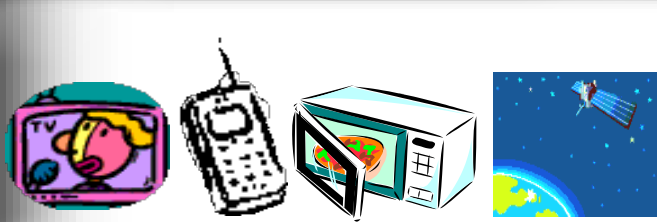
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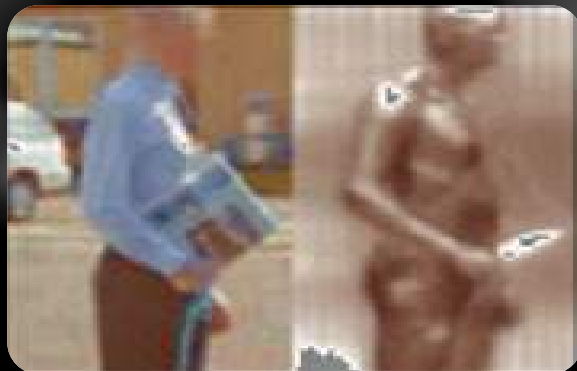
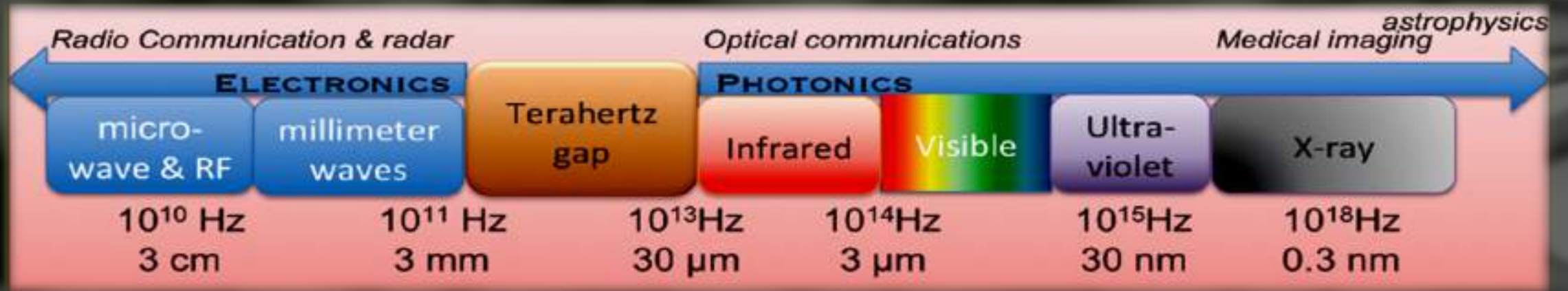
発表の内容

- 研究の背景と目的
- グラフェンの光電子物性
- グラフェンのテラヘルツ(THz)レーザー応用
- グラフェンプラズモンとその巨大THz利得増強作用
- グラフェンTHzレーザートランジスタの新しい展開
- まとめ

テラヘルツ波とは？



THz



テラヘルツ波が拓く超高速無線通信の世界

<https://medium.com/@augusto.tomas/its-5g-it-s-6g-it-s-7g-the-quantum-generation-c65771042b08> Finland's 6G visions for 2030.

MACHINE LEARNING
CYBER-SECURITY
EDGE ANALYTICS
SENSOR FUSION
BLOCKCHAIN

AUTONOMOUS HEALTH
BLOOD SAMPLE

SENSOR TO AI FUSION
AMBIENT SENSING INTELLIGENCE
SCANNING HEALTH INDICATORS
SMART CLOTHING AND ENVIRONMENT

45%

INDUSTRIAL FACE SCAN

CONTEXT MACHINE LEARNING
CYBER-IDENTITY
BIOMETRICS

BIO-CYBERNETIC IDENTITY
IDENTITY CRITICAL SERVICE ARCHITECTURES
SENSING-BASED MACHINE LEARNING



WATER INTERFERENCE
DATA PATTERNS ANALYSIS
STREAM ANALYSIS

AUTONOMOUS PORT

AUTONOMOUS
LOGISTICS OF PEOPLE AND
SWARM-BASED OPERATIONS
COLLABORATIVE MO



NOTIFICATION REMOTE MEETING

WIRELESS COMMUNICATION

PERSONALIZED SURFACES
PRINTED ELECTRONICS FUSED WITH IOT
AND WIRELESS SERVICES OFFERING
CONTEXTUAL APPLICATIONS

CONSENT MANAGEMENT
CONTEXT PROCESSING
EDGE COMPUTING



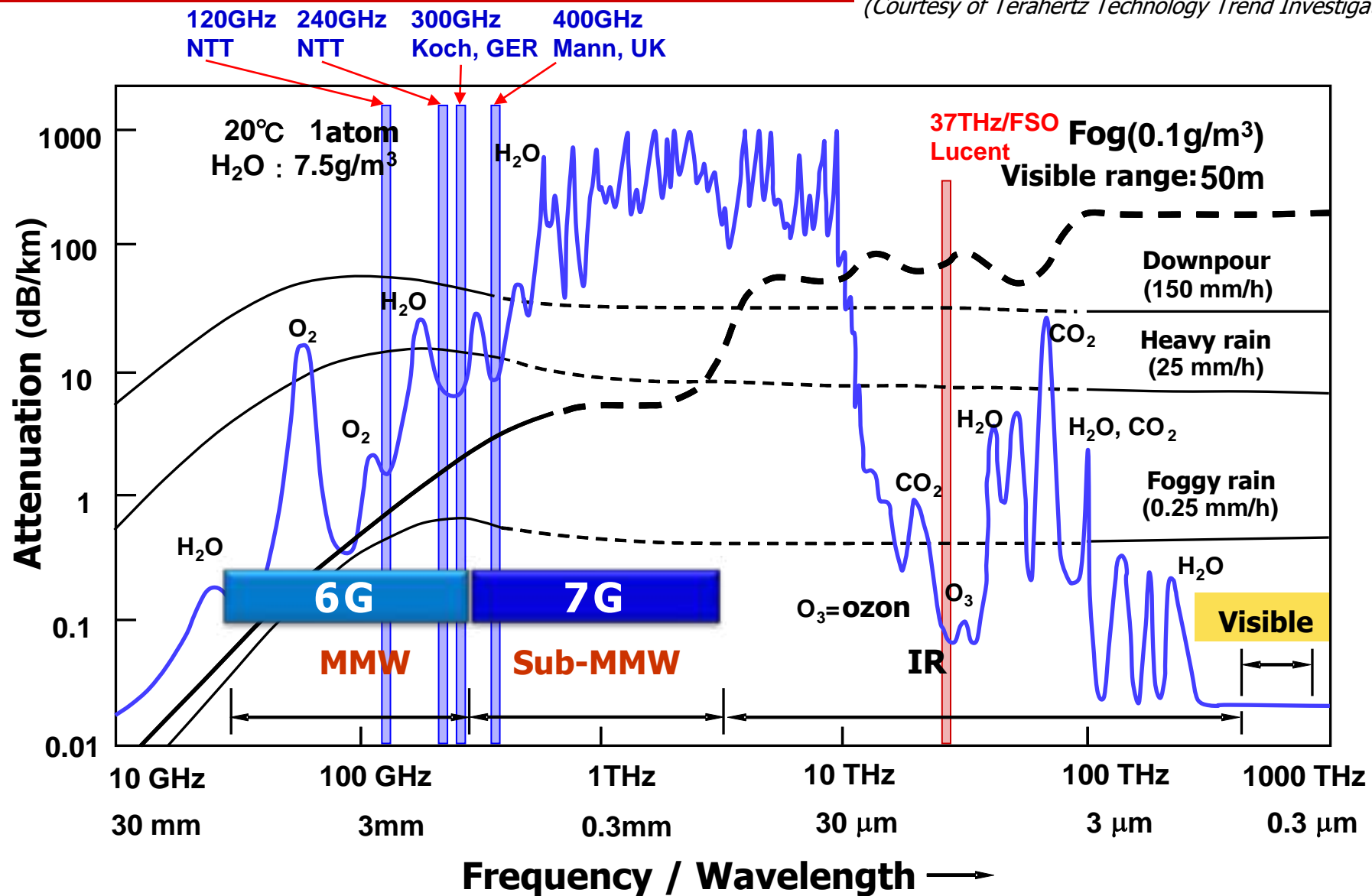
MOBILITY AS A SERVICE
OBJECTS AND INFRASTRUCTURE COMMUNICATE
AUTONOMOUS SAFETY MANAGEMENT
LOGISTICS GUIDANCE

SMART MATERIALS
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INNOVATION
WATG
THIS BOY
MADE IN
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2496
101%

大気中の電磁波吸収と通信応用の可能性

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



サブTHz高速無線通信実現の課題

T. Nagatsuma et al., Opt. Express 21, 23736 (2013).

8K Ultra-HDTV

- Available in 2020
- Scanning lines >4000
- Uncompressed at 72Gbps
- Carrier freq. ~1000GHz

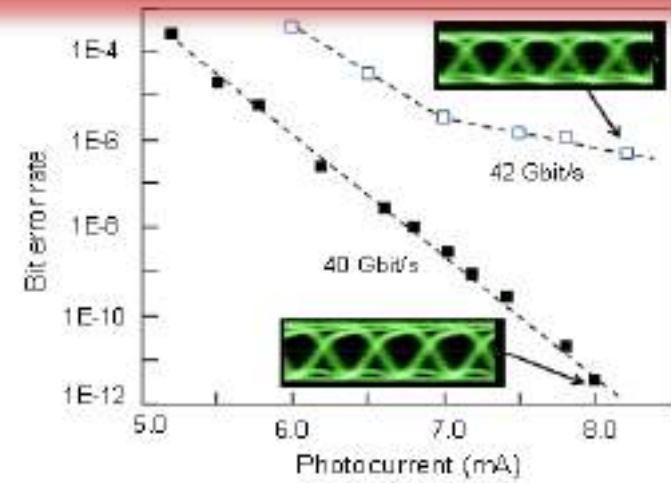
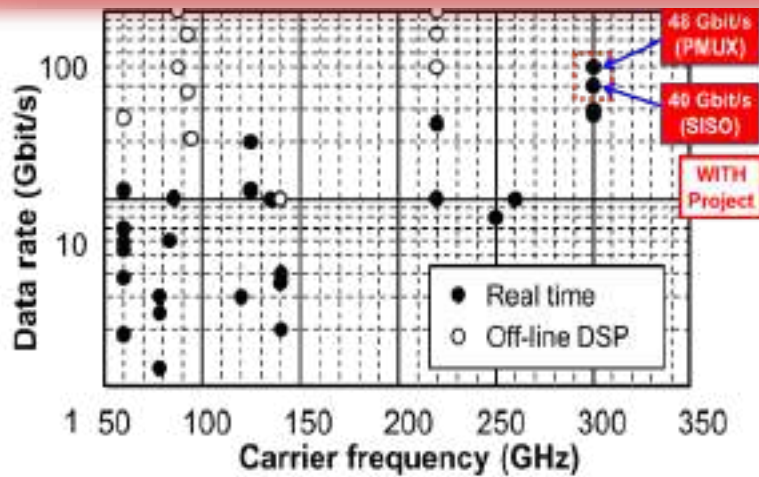


300 GHz帯で48 Gbit/s 無線伝送に成功

しかし、伝送距離はたったの 1 m !

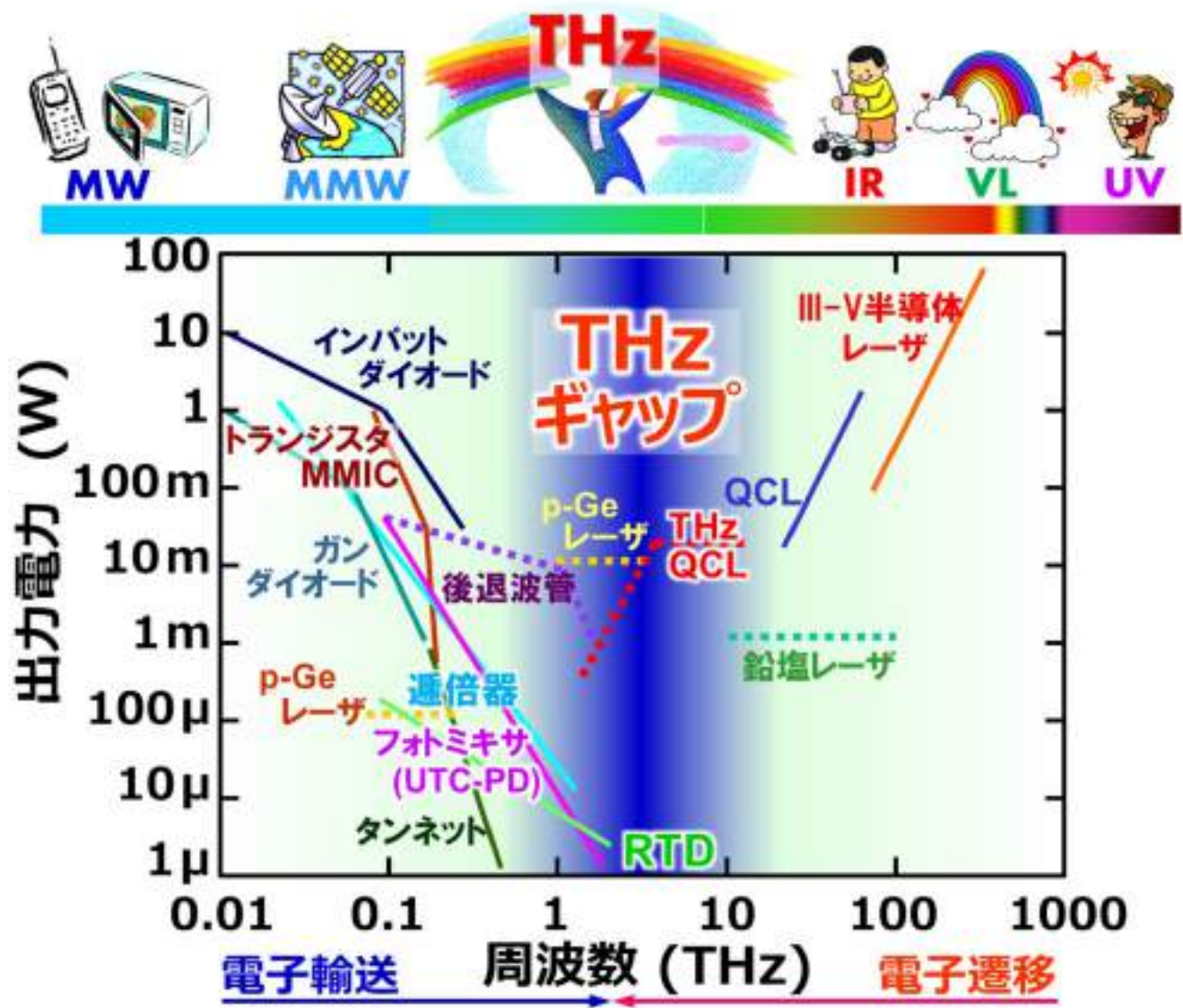


実用的な超高速THz無線の実現には
光源の高出力・高周波化と検出器の高感度化が不可欠！



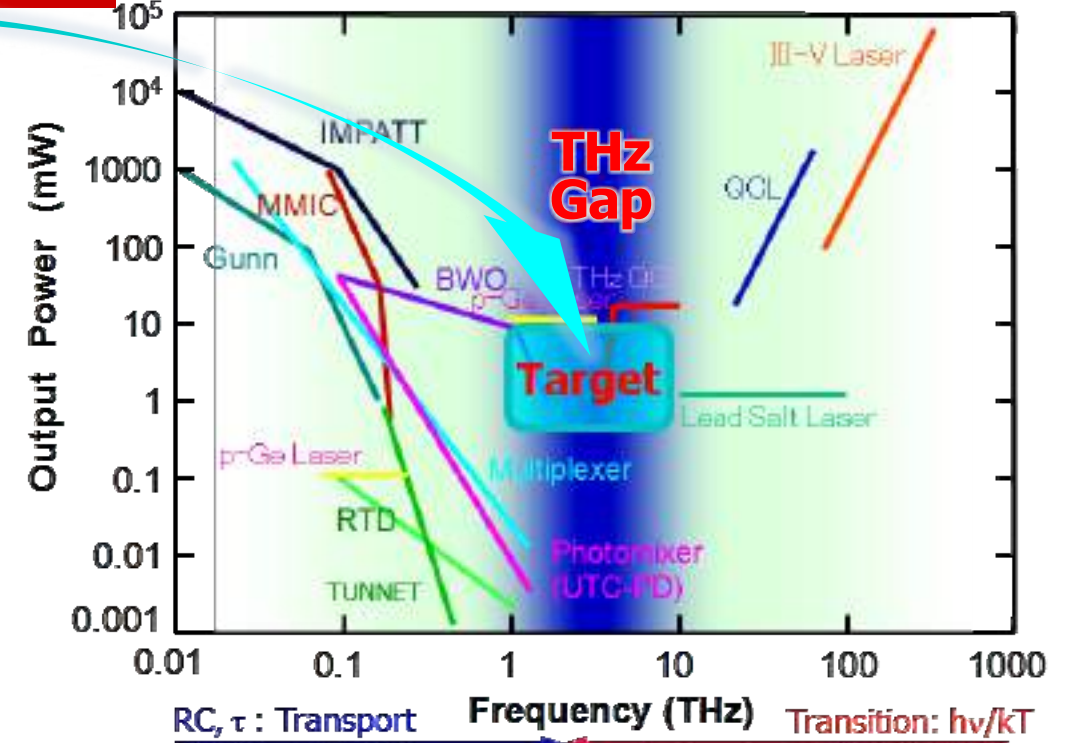
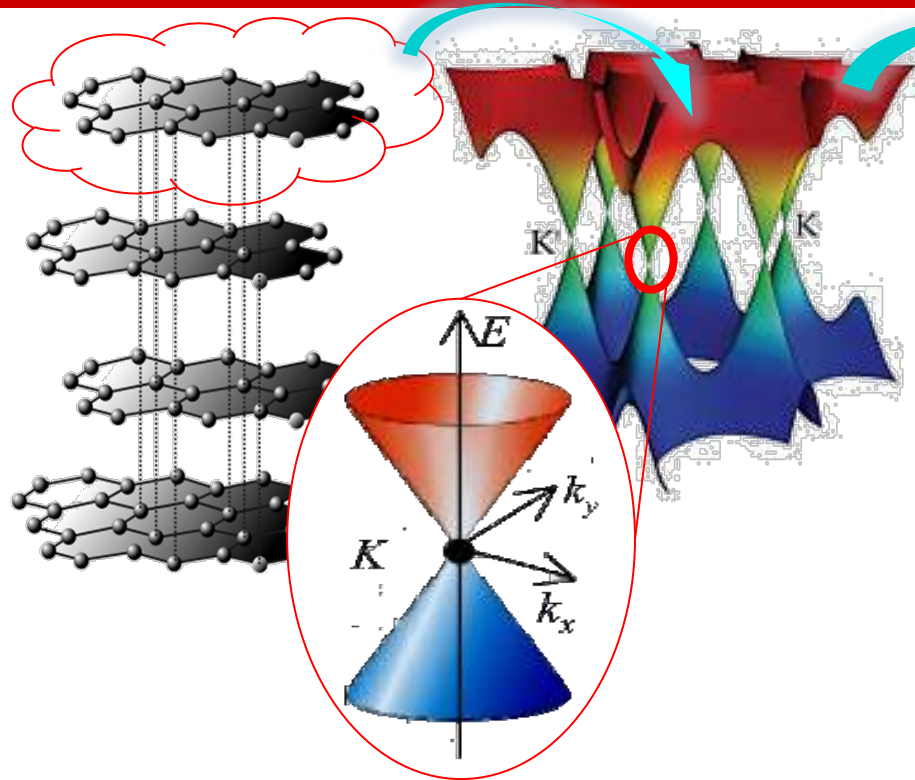
THzギャップ

M. Tonouchi, Nature Photon. 1, 97-105 (2007).



THzギャップを新材料グラフェンで克服する！

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).



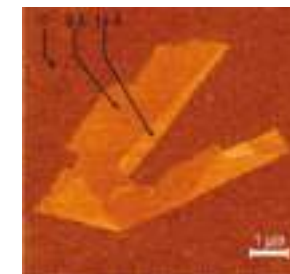
- Mono-layer of sp^2 bonded carbon atoms in a honeycomb lattice.
- Massless Dirac Fermions obey linear dispersion relation at K & K' points.
- High carrier mobility $\mu > 200,000 \text{ cm}^2/\text{Vs}$ at RT. (cf. InGaAs: $\mu \sim 12,000 \text{ cm}^2/\text{Vs}$)

グラフェンの製膜方法

■ Peeling from HOPG (highly oriented pyrolytic graphite)

- Highest mobility obtained
- 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

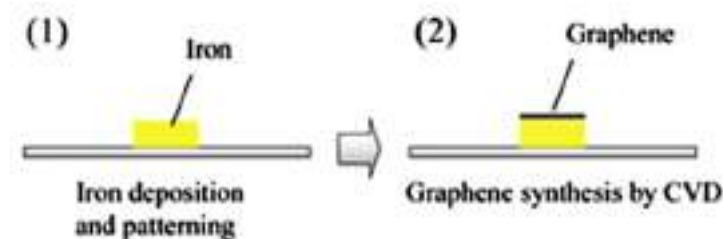
W.A. de Heer et al., Solid State Commun. 143, 92 (2007).
M. Suemitsu and H. Fukidome, J. Phys. D 43, 374012 (2010).



■ CVD growth on metallic catalyst and transferring substrate

- Cu, Ni, Fe, Co etc.. at low temperature 650 – 1000 °C
- Large area, quality being improved
- Epitaxial CVD graphene now available
- Transfer process mandatory

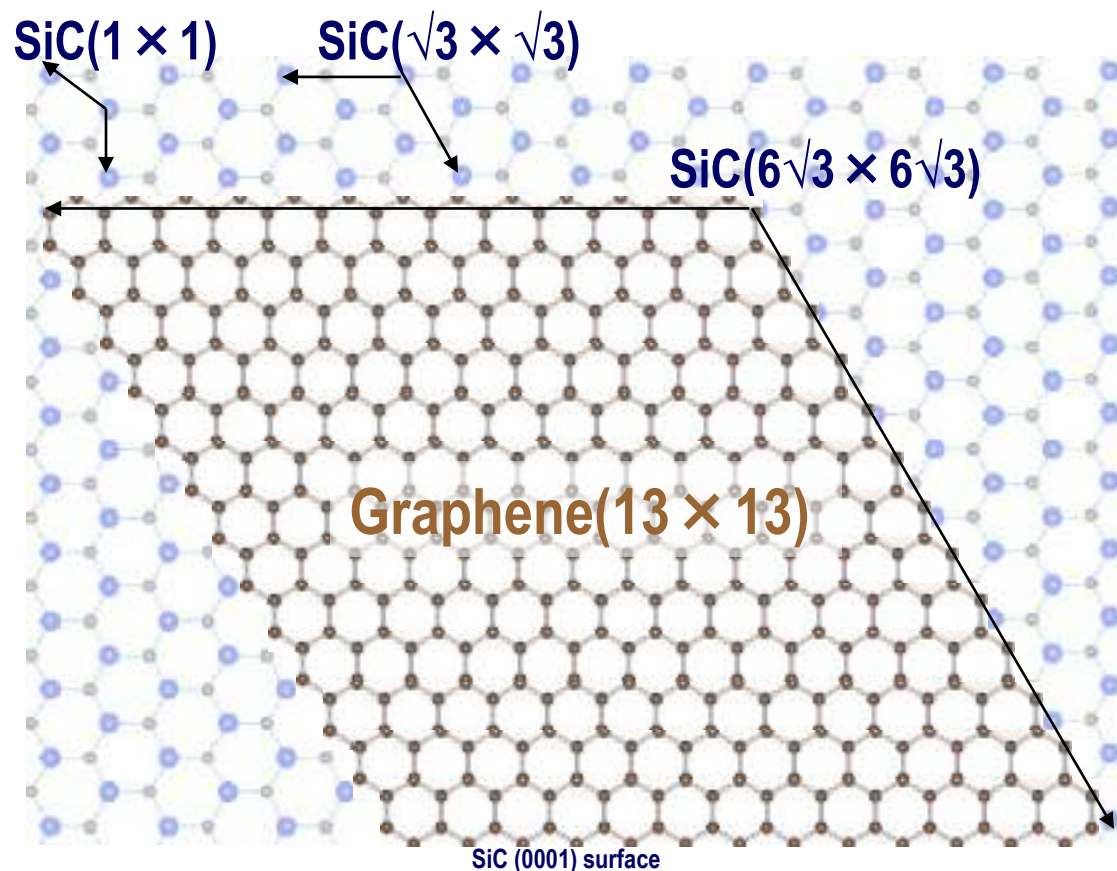
J. Bae et al, Nature Nanotech. 5, 574 (2010).
H. Ago et al., ACS Nano 4, 7404 (2010).



熱分解法によるH-SiC基板からのエピタキシャルグラフェン製膜

*van Bommel et al. Surf. Sci. 48, 463 (1975).
C. Berger et al. Science 312, 1191 (2006).*

By annealing a hexagonal 6H-SiC substrate at a high temperature in vacuum, the surface changes to graphene.

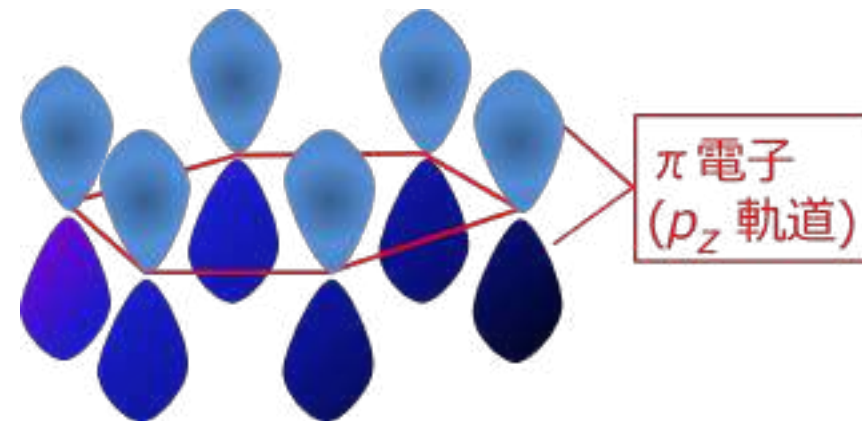
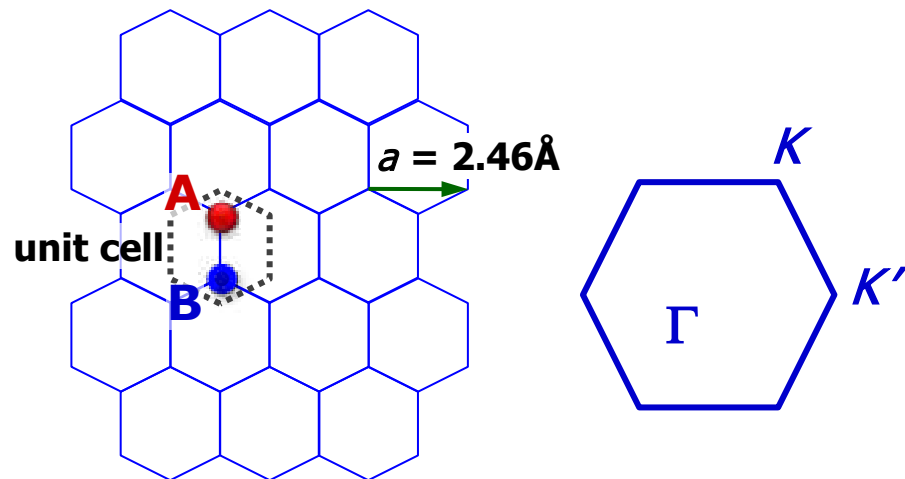
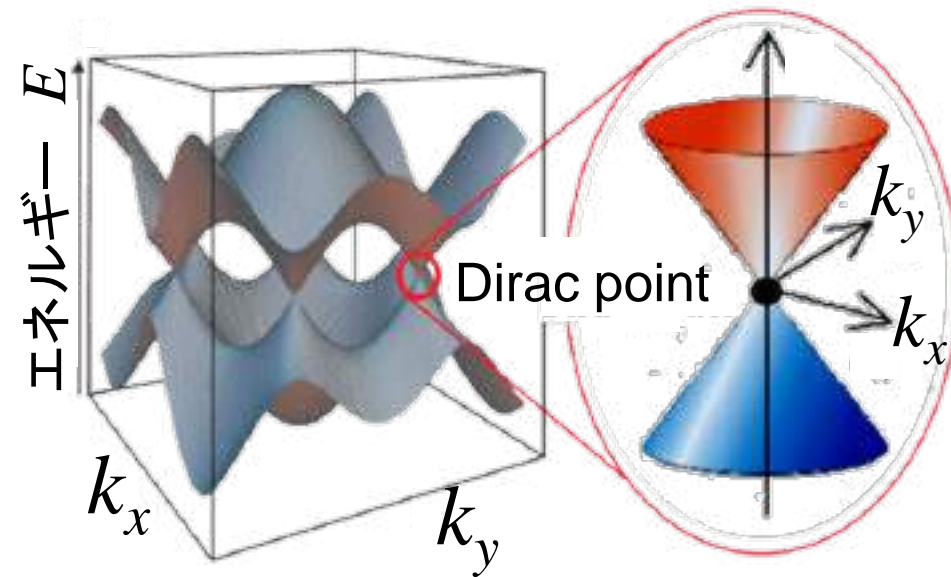
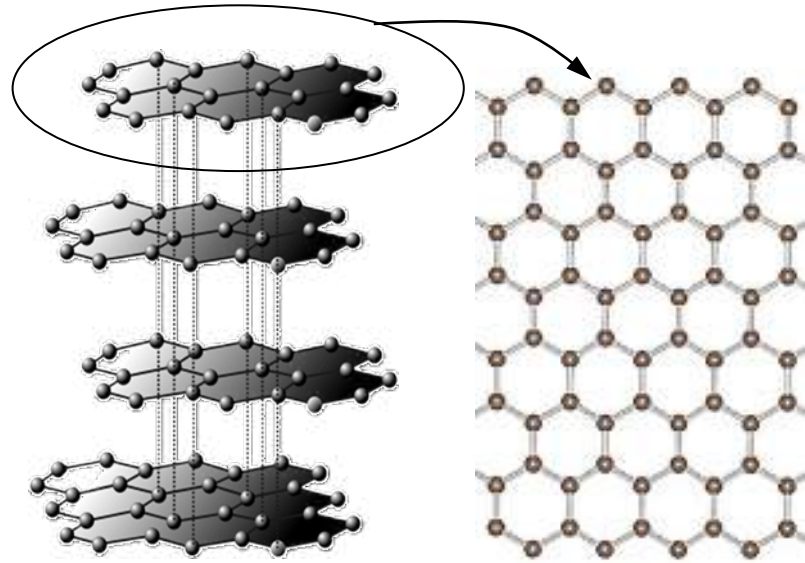


Graphene

SiC substrate

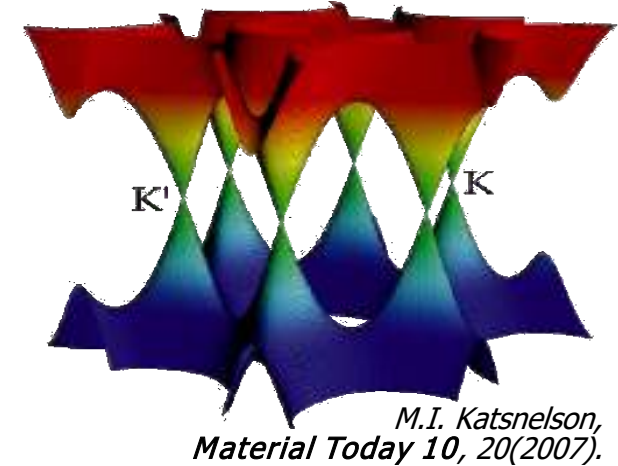
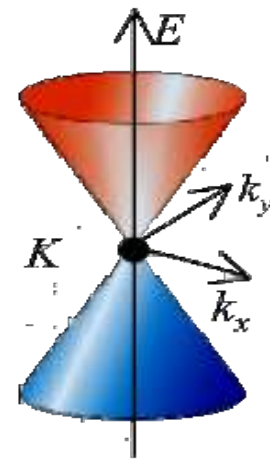
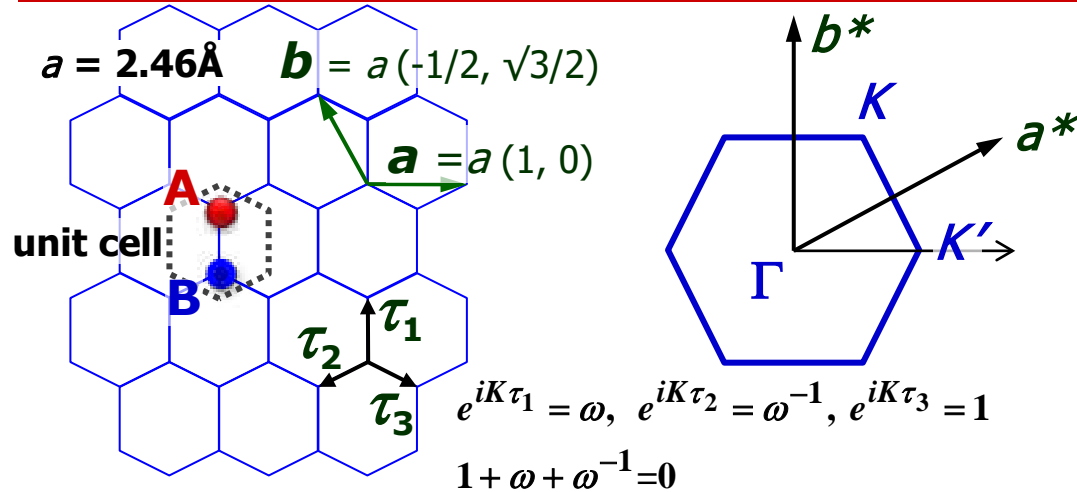
- : Si atom
- : C atom

グラフェンの結晶構造とバンド構造



Energy Band Structures in Graphene

T. Ando, JPSJ 74, 777 (2005).



π band electron:

$$\begin{aligned} \psi(\mathbf{r}) &= \sum_{\mathbf{R}_A} \psi_A(\mathbf{R}_A) \phi(\mathbf{r} - \mathbf{R}_A) + \sum_{\mathbf{R}_B} \psi_B(\mathbf{R}_B) \phi(\mathbf{r} - \mathbf{R}_B) \\ &= \sum_{\mathbf{R}_A} f_A(\mathbf{k}) e^{i\mathbf{k} \cdot \mathbf{R}_A} \phi(\mathbf{r} - \mathbf{R}_A) + \sum_{\mathbf{R}_B} f_B(\mathbf{k}) e^{i\mathbf{k} \cdot \mathbf{R}_B} \phi(\mathbf{r} - \mathbf{R}_B) \end{aligned}$$

$\phi(\mathbf{r})$: p_z orbital wavefunction around Γ

Tight-Binding Approx.:

$$\begin{aligned} \varepsilon \psi_A(\mathbf{R}_A) &= -\gamma_0 \sum_{l=1}^3 \psi_B(\mathbf{R}_A - \tau_l) \\ \varepsilon \psi_B(\mathbf{R}_B) &= -\gamma_0 \sum_{l=1}^3 \psi_A(\mathbf{R}_B + \tau_l) \end{aligned}$$

Hamiltonian:

$$\begin{pmatrix} 0 & h_{AB}(\mathbf{k}) \\ h_{AB}(\mathbf{k})^* & 0 \end{pmatrix} \begin{pmatrix} f_A(\mathbf{k}) \\ f_B(\mathbf{k}) \end{pmatrix} = \varepsilon \begin{pmatrix} f_A(\mathbf{k}) \\ f_B(\mathbf{k}) \end{pmatrix}$$

$$h_{AB}(\mathbf{k}) = -\gamma_0 \sum_{l=1}^3 e^{-i\mathbf{k} \cdot \tau_l} \approx -i\omega^{-1} \frac{\sqrt{3}}{2} a\gamma_0 (k_x - ik_y) \Big|_{\mathbf{k} \approx \mathbf{K}, \mathbf{K}'}$$

$$f_A(\mathbf{K} + \mathbf{k}) = \bar{f}_A(\mathbf{k}), \quad f_B(\mathbf{K} + \mathbf{k}) = i\omega \bar{f}_B(\mathbf{k})$$

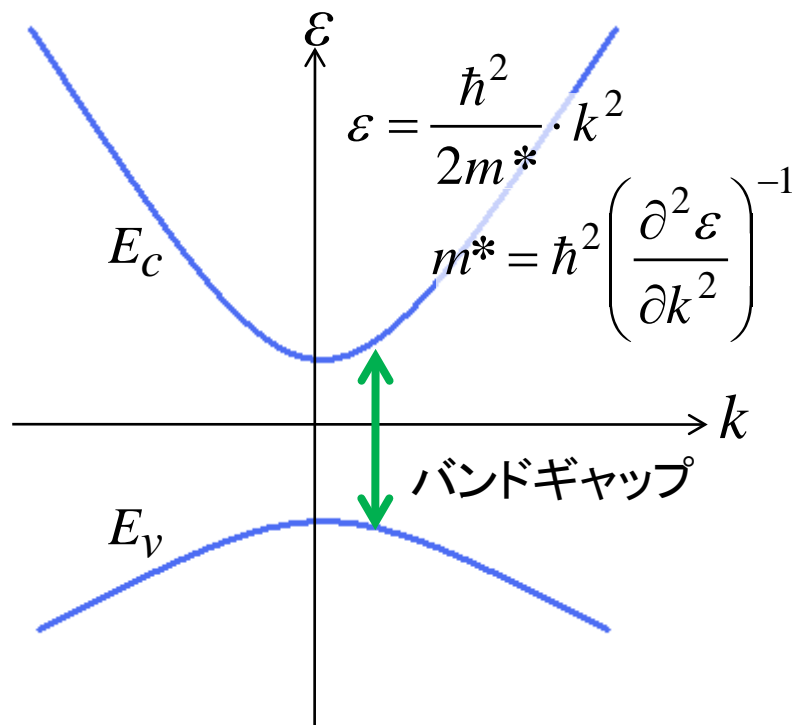
$$\frac{\sqrt{3}}{2} a\gamma_0 \begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix} \begin{pmatrix} \bar{f}_A(\mathbf{k}) \\ \bar{f}_B(\mathbf{k}) \end{pmatrix} = \varepsilon \begin{pmatrix} \bar{f}_A(\mathbf{k}) \\ \bar{f}_B(\mathbf{k}) \end{pmatrix}$$

Eigenvalues:

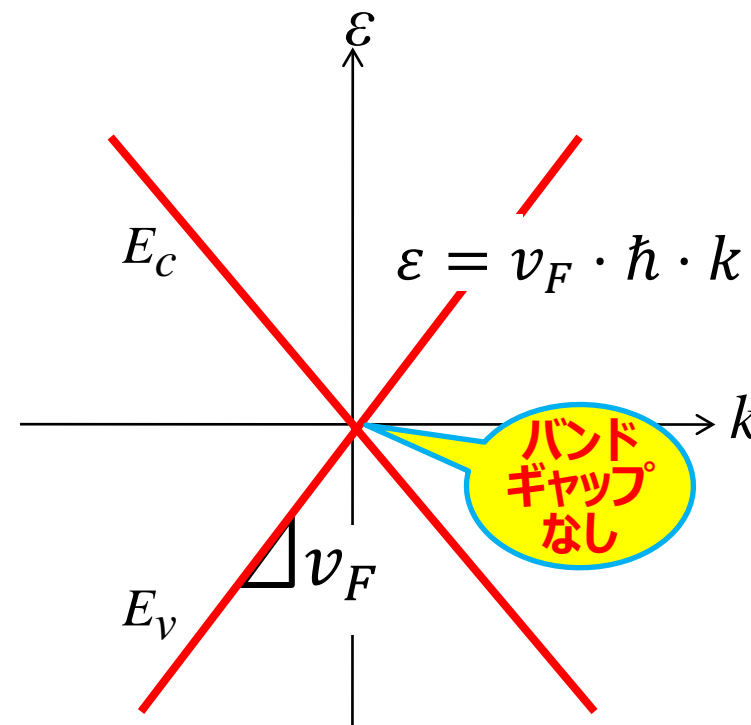
$$\varepsilon = E(\mathbf{k}) = \pm v_F \hbar |\mathbf{k}|$$

$$\det(\varepsilon \mathbf{I} - \mathbf{H}) = 0 \rightarrow v_F \approx 10^8 \text{ cm/s}$$

グラフェンのバンド構造



一般的な半導体



グラフェン

- バンドギャップが存在しない ($\hbar = h/2\pi$)
- バンドが線形分散 \Rightarrow 有効質量 $m^* = 0$
- 電子とホールが完全に対象

グラフェンの巨大キャリア移動度

通常の半導体中の電子の運動

有効質量のある電子

$$F = m_e^* \cdot \frac{dv}{dt} = -e \cdot E - \frac{m_e^* \cdot v}{\tau}$$

(τ : lifetime)

定常状態:

$$v = -\frac{e \cdot \tau}{m_e^*} E = -\mu E$$

↑
移動度

μ の比較 (cm²/(Vs))

Si:	300
GaAs:	6,700
Graphene:	>200,000

グラフェン内の電子の運動

$$\varepsilon = \frac{p^2}{2m} \Leftrightarrow \varepsilon = v_F p$$

$$\frac{\partial \varepsilon}{\partial p} = \frac{p}{m} \Leftrightarrow v_F$$

$$m \Leftrightarrow \frac{p}{v_F} = \frac{\varepsilon}{v_F^2}$$

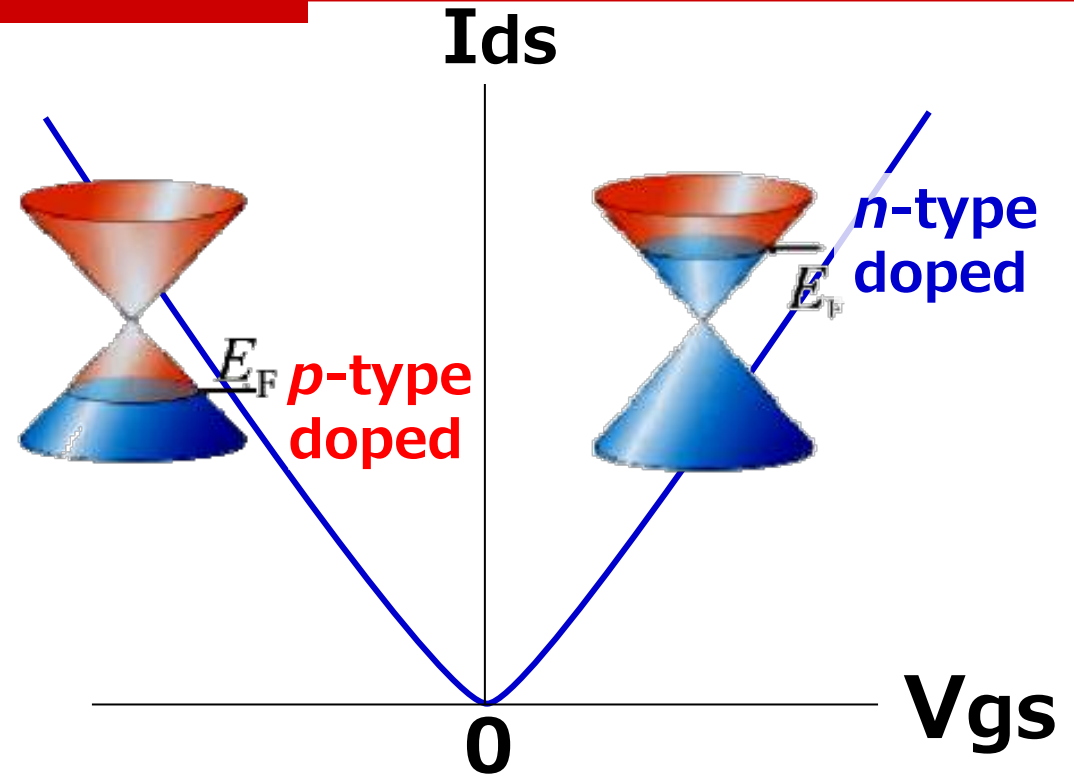
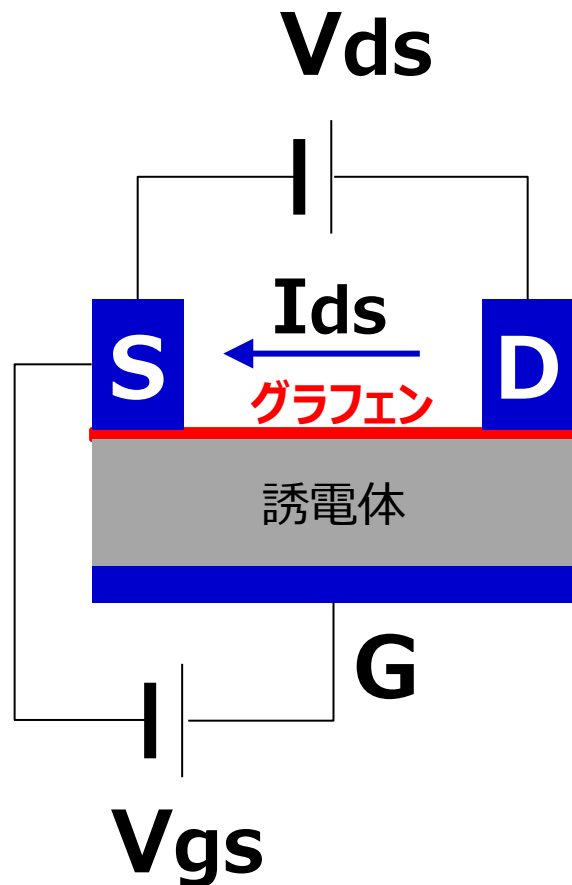
$$\Rightarrow \mu = \frac{e v_F^2 \tau}{\varepsilon_F}$$

グラフェンでは有効質量 m^* がゼロ、さらに散乱が弱いので、平均寿命 τ が大きい。



移動度 μ は非常に大きな値となる

グラフェン特有のアンバイポーラ特性

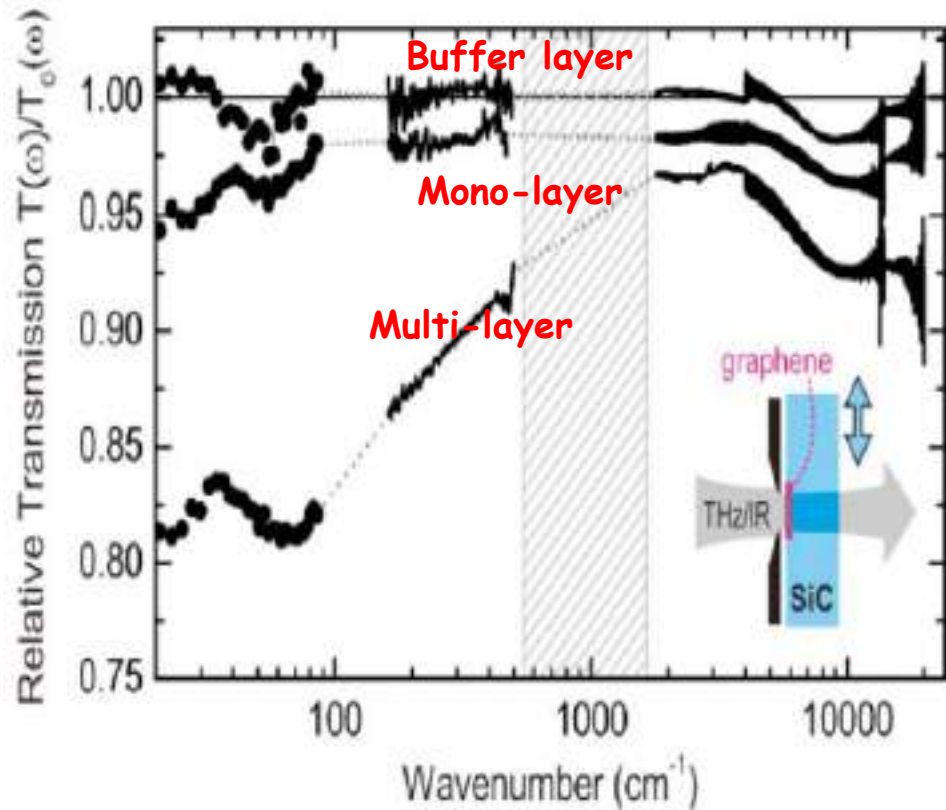


- バンドギャップがないため、しきい値以上のVgsでは電子がしきい値以下のVgsでは正孔が誘起され、オフできない！

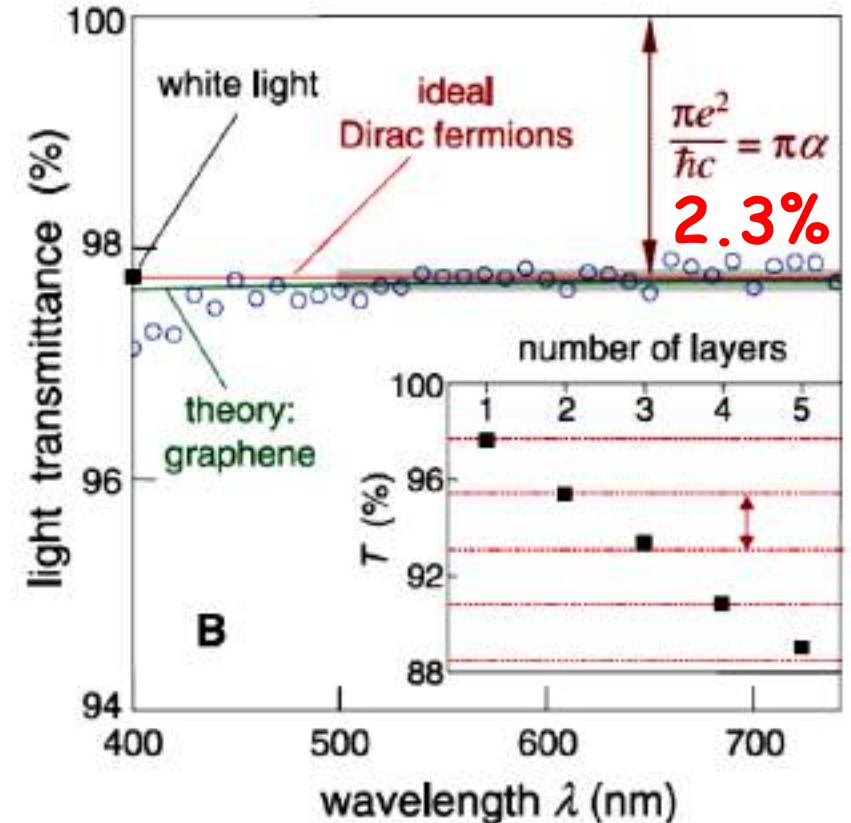
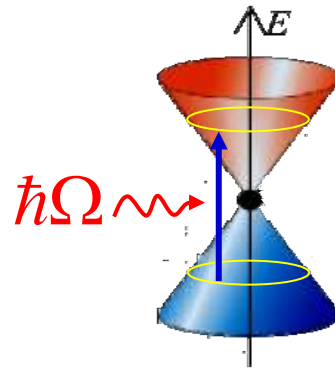
グラフェンの超広帯域&フラットなバンド間光学吸収

Photon absorption in Graphene via interband transition is

- flat over the linear dispersive energy range
- limited to $\sim 2.3\%$ /layer by $\pi e^2/\hbar c$!



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

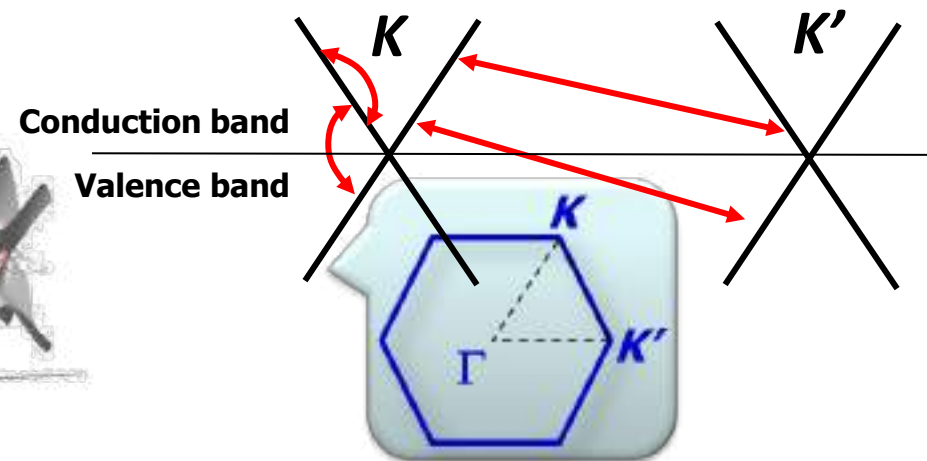
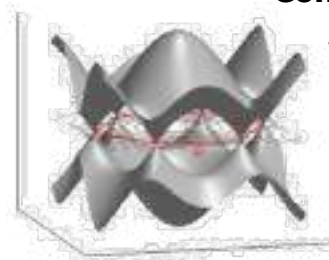


R.R. Nair et al., *Science* 320, 1308 (2008).

グラフェンのフォノン物性

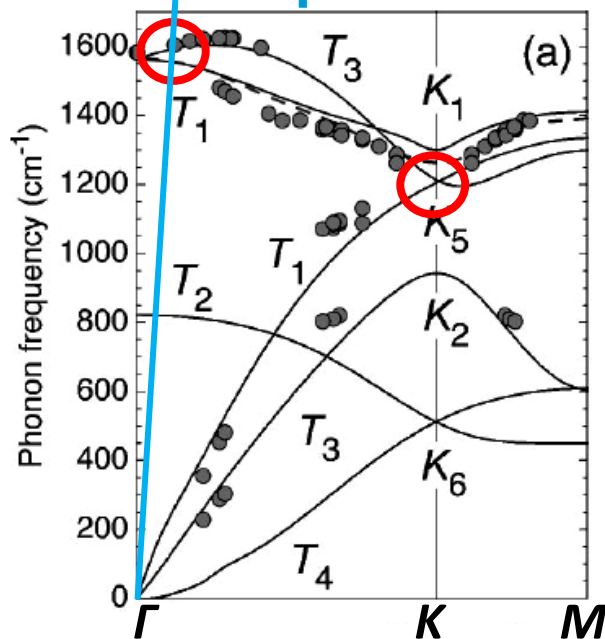
Carriers interact with:

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



Phonon dispersion

e-dispersion



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

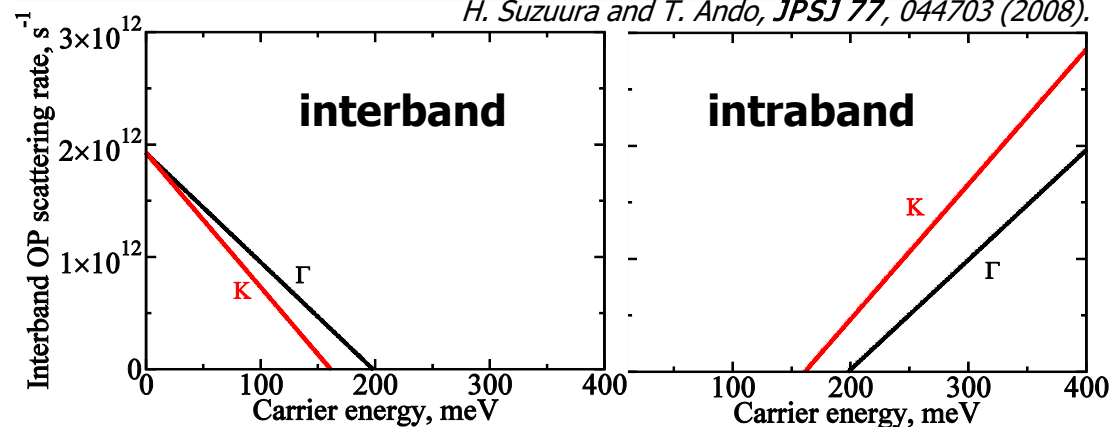
Scattering rates

$$W_{A,inter/tra}^{(\pm)}(lk, lk') = \frac{2\pi}{\hbar} |\langle lk' | H_{A,inter/tra} | lk \rangle|^2 \cdot \delta(k - k' \pm \omega / v_F)$$

$$= \frac{1}{\tau_{A,inter/tra}^{(\pm)}}$$

Transition probability density from state k to k'

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



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

発表の内容

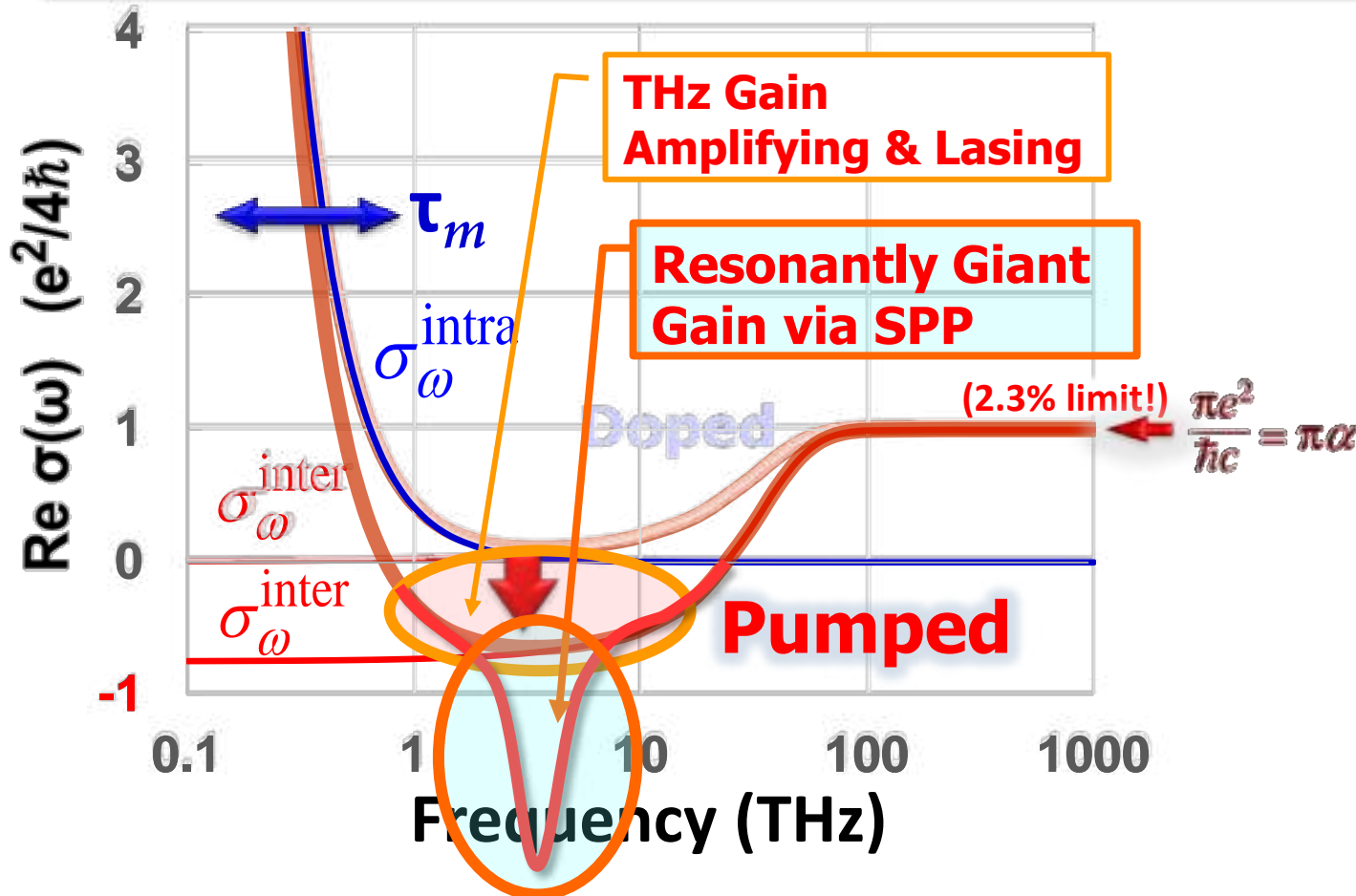
- 研究の背景と目的
- グラフェンの光電子物性
- **グラフェンのテラヘルツ(THz)レーザー応用**
- グラフェンプラズモンとその巨大THz利得増強作用
- グラフェンTHzレーザートランジスタの新しい展開
- まとめ

グラフェンの光学導電率

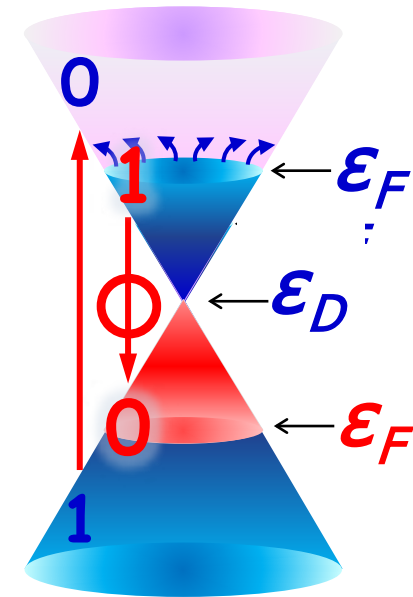


L.A. Falkovsky & S.S. Pershoguba *PRB* 76, 153410 (2007).

$$\text{Re } \sigma_{\omega} \approx \frac{e^2 (\ln 2 + \varepsilon_F / 2k_B T)}{\pi \hbar} \frac{k_B T \tau_m}{\hbar (1 + \omega^2 \tau_m^2)} + \frac{e^2}{4\hbar} (f_e(-\hbar\omega/2) - f_e(\hbar\omega/2)) \begin{cases} > 0: \text{Loss} \\ < 0: \text{GAIN} \end{cases}$$



V.Ryzhii, M.Ryzhii, T.Otsuji, *JAP* 101, 083114 (2007).
A. Satou, F.T. Vasko, V. Ryzhii, *PRB* 78, 115431 (2008).



A.A. Dubinov et al., *J. Phys.: Condens. Matter* 23 145302 (2011).
S. Boubanga Tombet et al., *PRB* 85, 035443 (2012).
T. Watanabe et al., *New J. Phys.* 15, 075003 (2013).

Maxwell方程式に見る導電率の意味： 負性導電率は利得を与える！

$$\begin{aligned} \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} &= 0 \\ \nabla \cdot \mathbf{D} &= \rho \\ \nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} &= \mathbf{j} \end{aligned}$$

$$\text{rot } \mathbf{H} = \varepsilon \frac{\partial \mathbf{E}}{\partial t} + \sigma \mathbf{E}$$

$$\Rightarrow (-i\omega\varepsilon + \sigma)\mathbf{E} = -i\omega \left(\varepsilon + i\frac{\sigma}{\omega} \right) \mathbf{E}$$

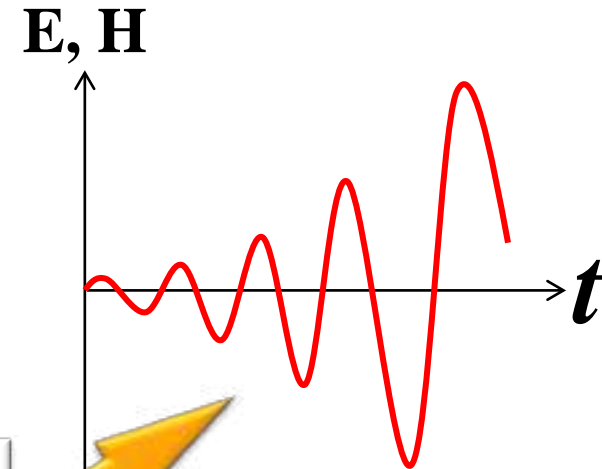
$$\equiv -i\omega \tilde{\varepsilon} \mathbf{E} = -i\omega(\varepsilon' + i\varepsilon'')\mathbf{E}$$

$$\varepsilon'' \equiv \text{Im}(\varepsilon) = \sigma / \omega$$

$$\omega = \frac{c}{\sqrt{\varepsilon' + i\varepsilon''}} \cdot k \equiv \omega' - i\omega''(\sigma)$$

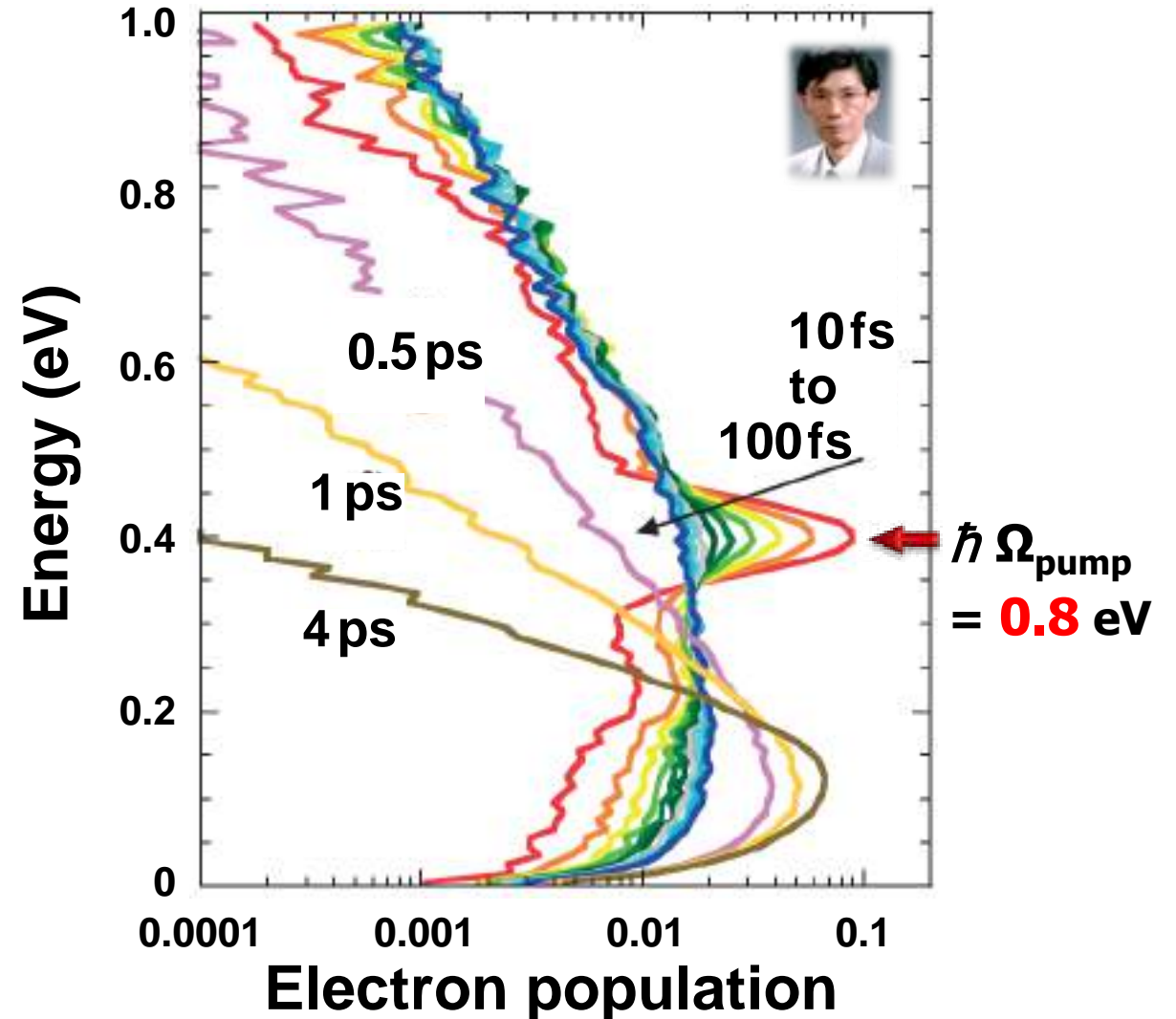
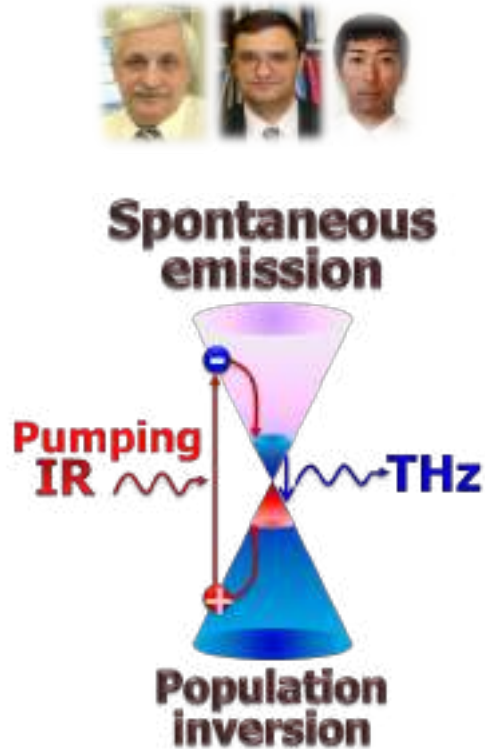
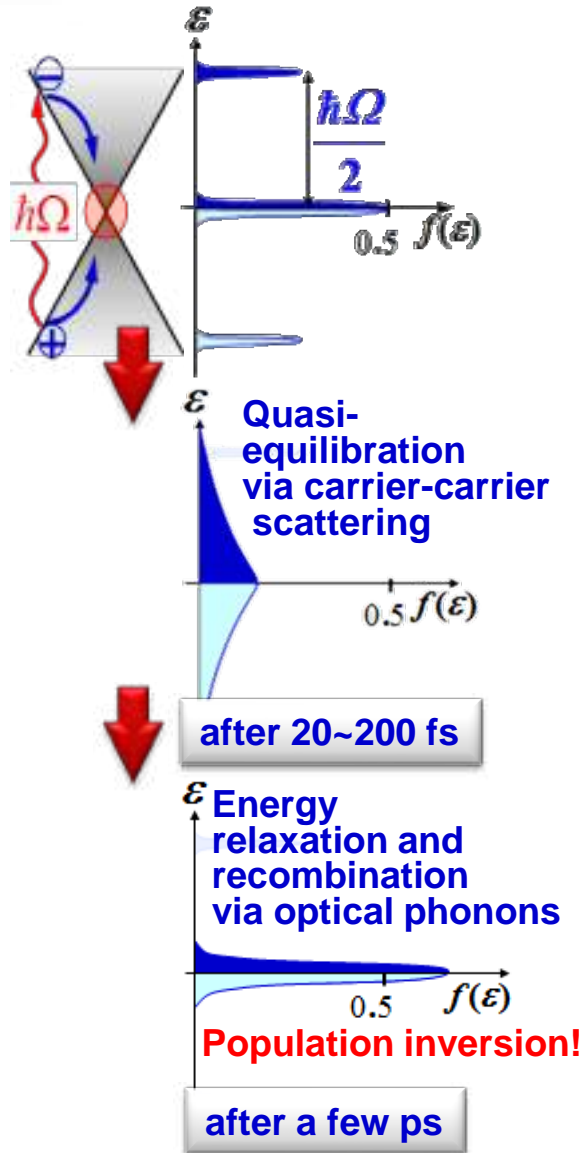
$$\sigma < 0 \Rightarrow \omega''(\sigma) < 0 \Rightarrow e^{-i\omega t} = e^{-i\omega' t} \cdot e^{+|\omega''|t}$$

$$\sigma > 0 \Rightarrow \omega''(\sigma) > 0 \Rightarrow e^{-i\omega t} = e^{-i\omega' t} \cdot e^{-|\omega''|t}$$



光学励起グラフェンの非平衡キャリア緩和過程

V.Ryzhii, M.Ryzhii, T.Otsuji, *JAP* **101**, 083114 (2007).
 A. Satou, F.T. Vasko, V. Ryzhii, *PRB* **78**, 115431 (2008).
 E. Sano, *APEX* **4**, 085101 (2011).

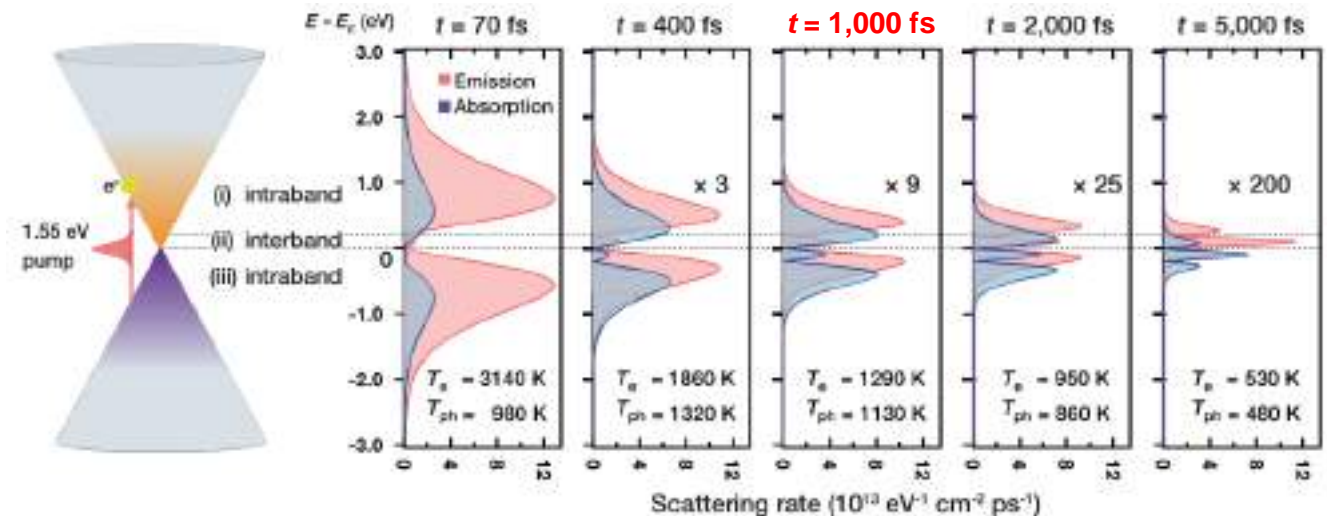
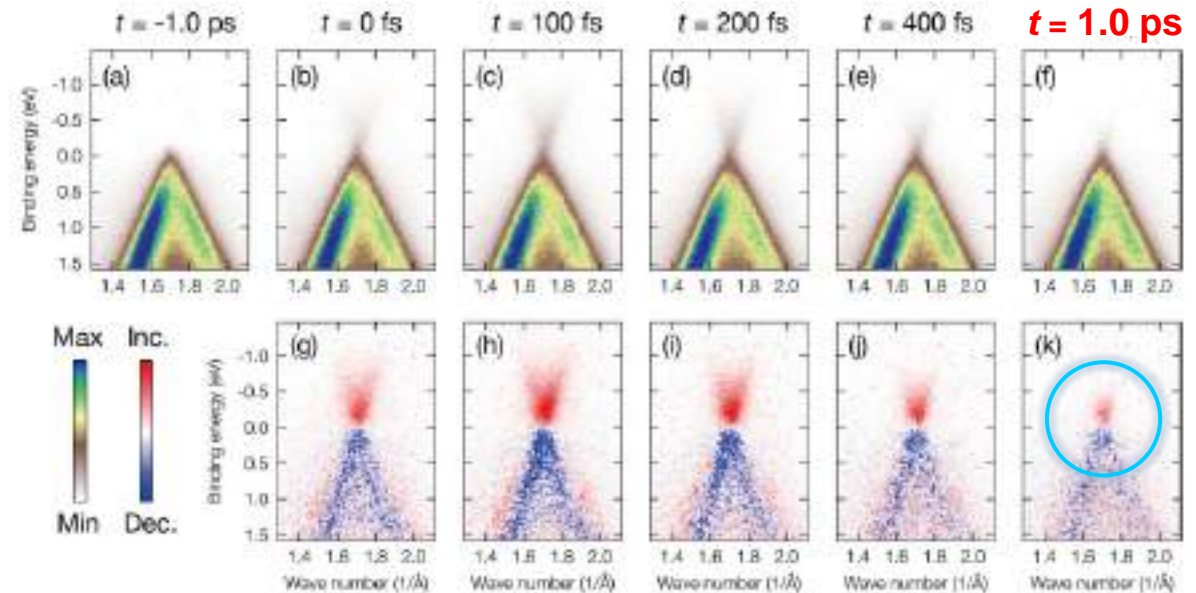


時間&角度分解X線光電子分光：T-ARPESで 光学励起グラフェンの反転分布形成を実証

T. Someya, H. Fukidome et al. I. Matsuda, PRB 95, 165303 (2017).



- Epi-graphene on 4H-SiC
- $\mu \sim 100,000 \text{ cm}^2/\text{Vs}$
- Time- & Angle-resolved photoemission microscopy
- Even for rather high pump energy 1.55eV
- Population inversion is maintained in ps time scale !
- Auger scattering well-suppressed !

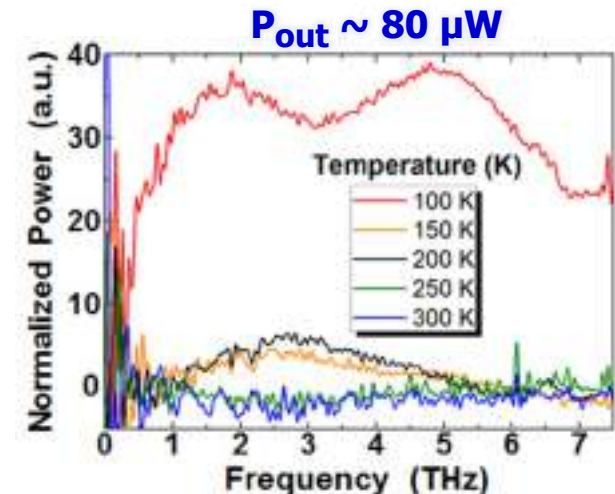
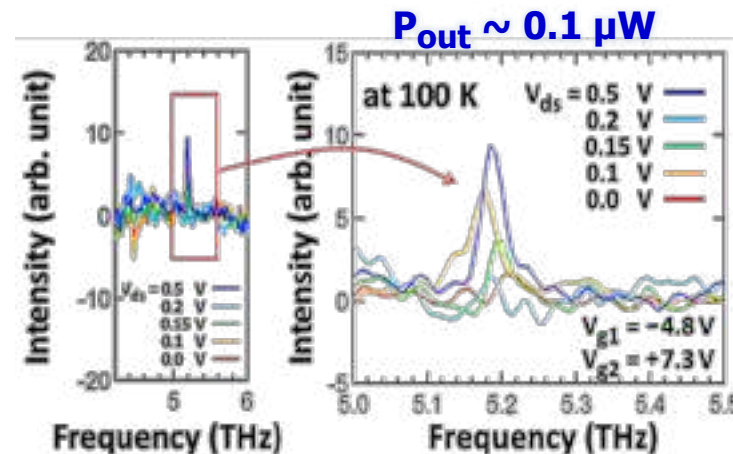
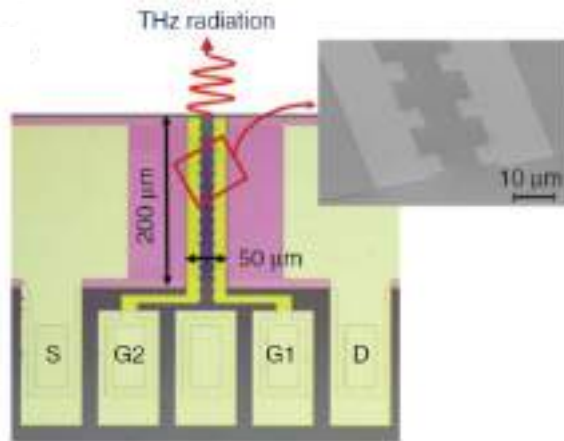
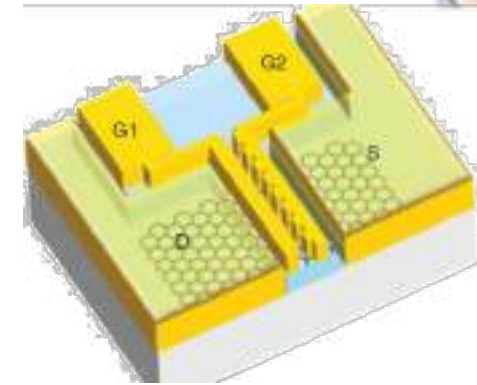
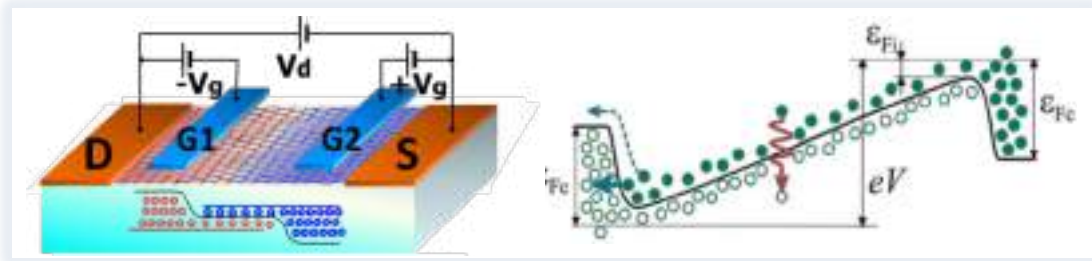




Research article

Deepika Yadav, Gen Tamamushi, Takayuki Watanabe, Junki Mitsushio, Youssef Tobah, Kenta Sugawara, Alexander A. Dubinov, Akira Satou, Maxim Ryzhii, Victor Ryzhii and Taiichi Otsuji*

Terahertz light-emitting graphene-channel transistor toward single-mode lasing

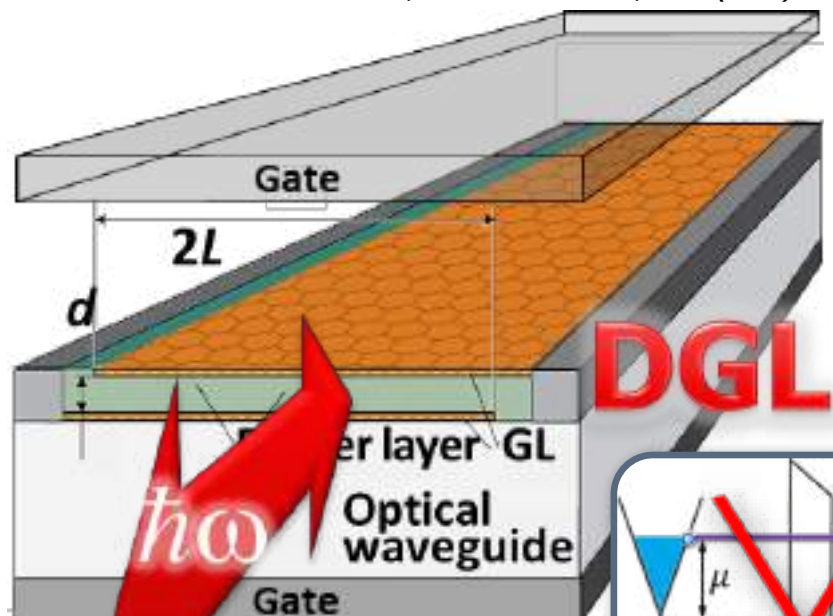


ゲート制御DGLにおけるフォトンアシスト共鳴トンネル効果とそのTHz利得発現



L. Britnell et al., Nature Comm. 4, 1794 (2013).

V. Ryzhii, A.A. Dubinov, T. Otsuji et al., Opt. Exp. 21, 31569 (2013).
V. Ryzhii, A. Dubinov, V.Ya. Aleshkin, M. Ryzhii, T. Otsuji, APL 103, 163507 (2013).

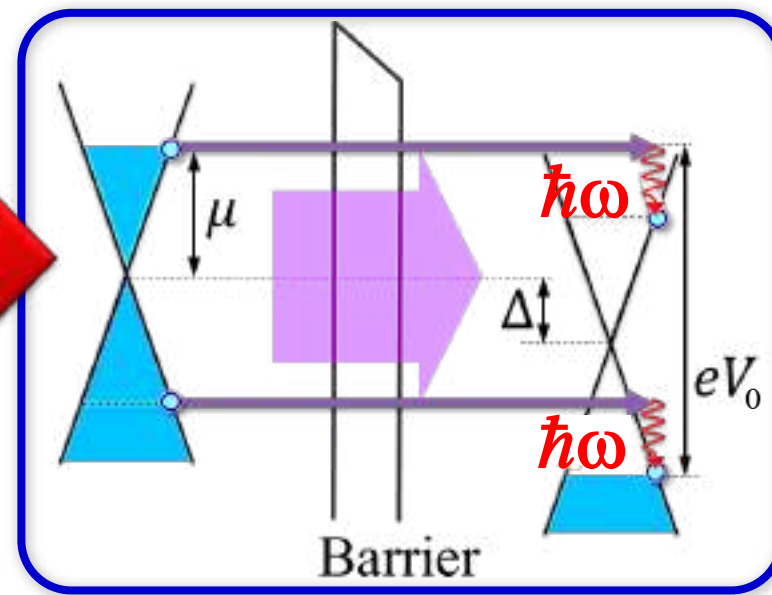
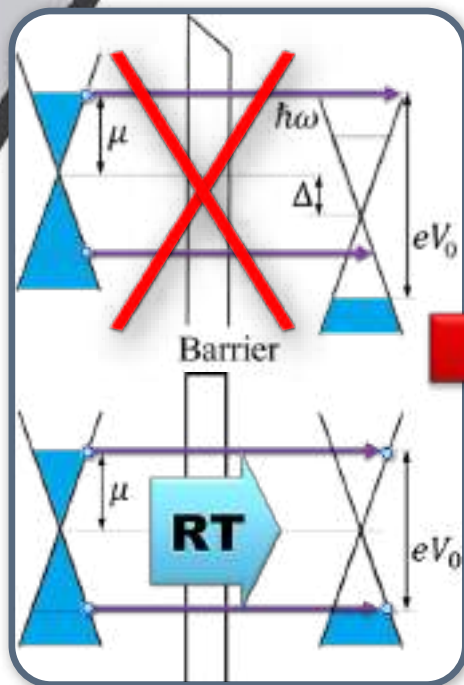


DGL

Tunable Resonant THz Photon Emission



Photo-Emission-Assisted Resonant Tunneling

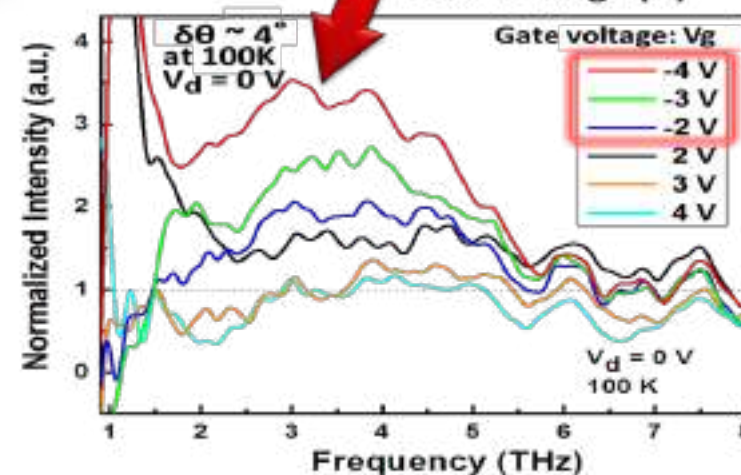
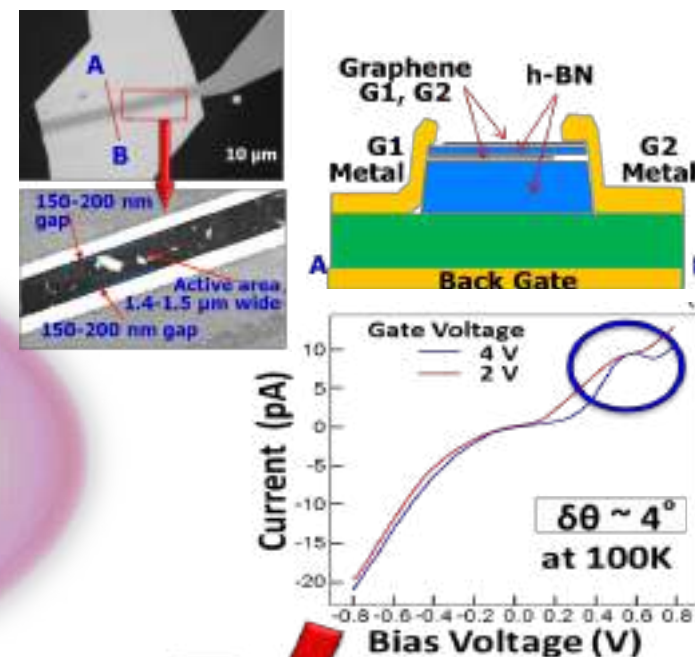
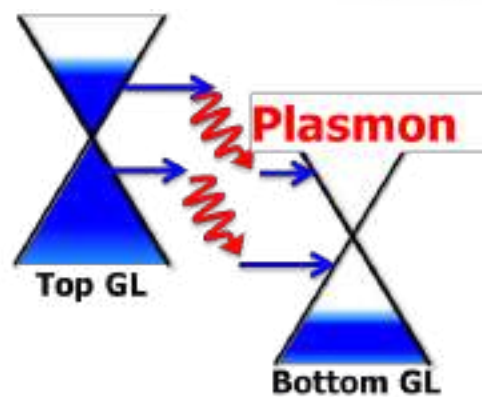
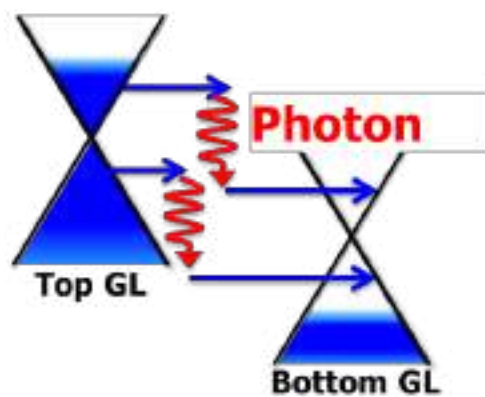
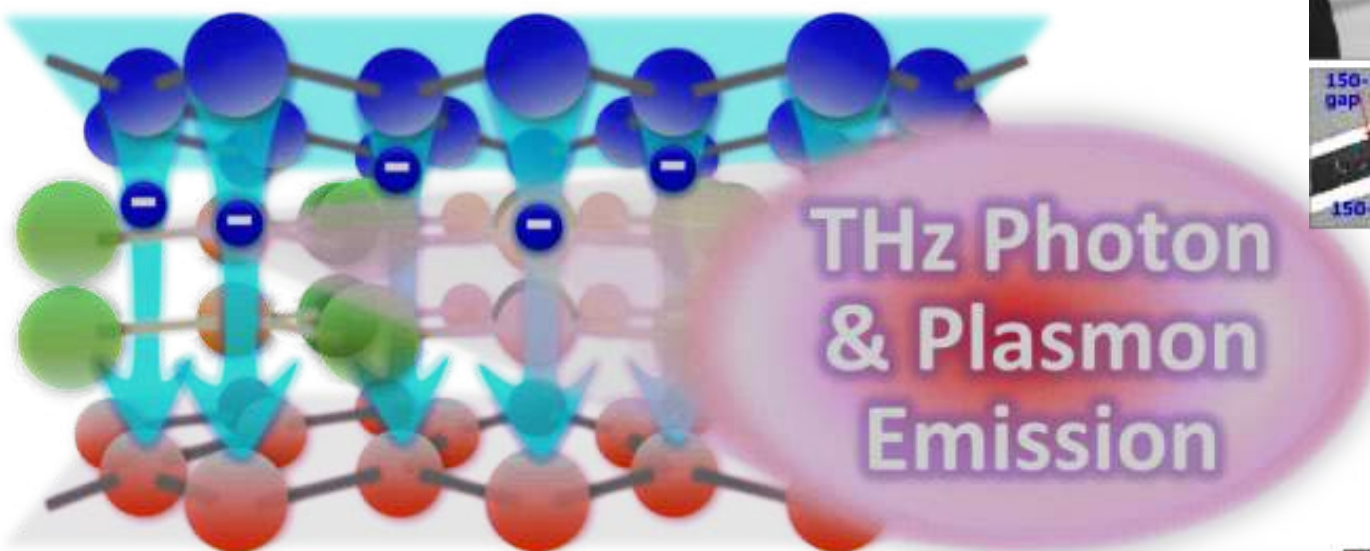


グラフェン二重層ファンデルワールスヘテロ接合 室温高強度THzレーザーの実現に向けて！



D. Yadav et al., 2D Mater. 3, 045009 (2016).

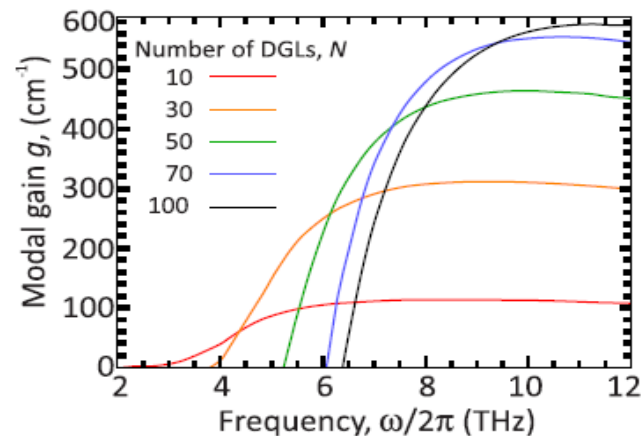
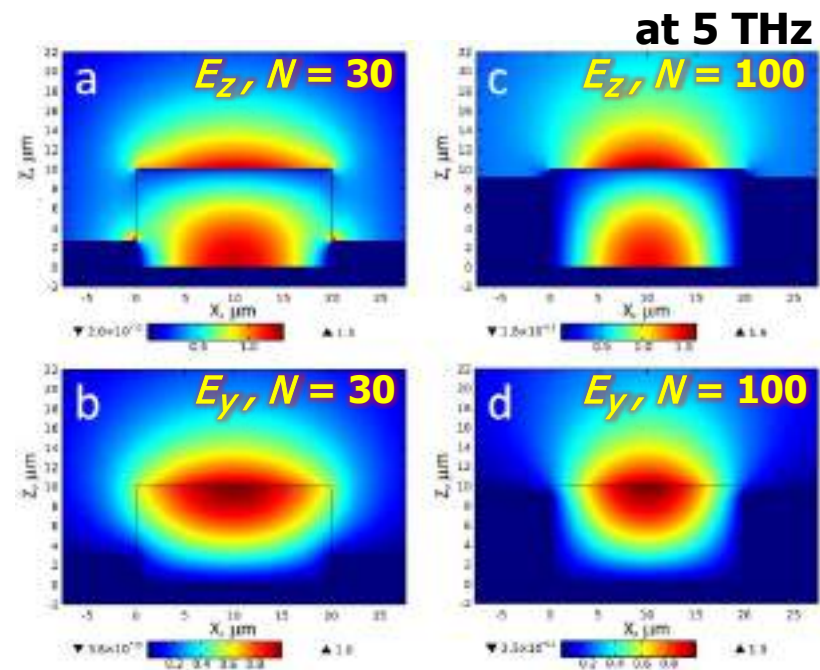
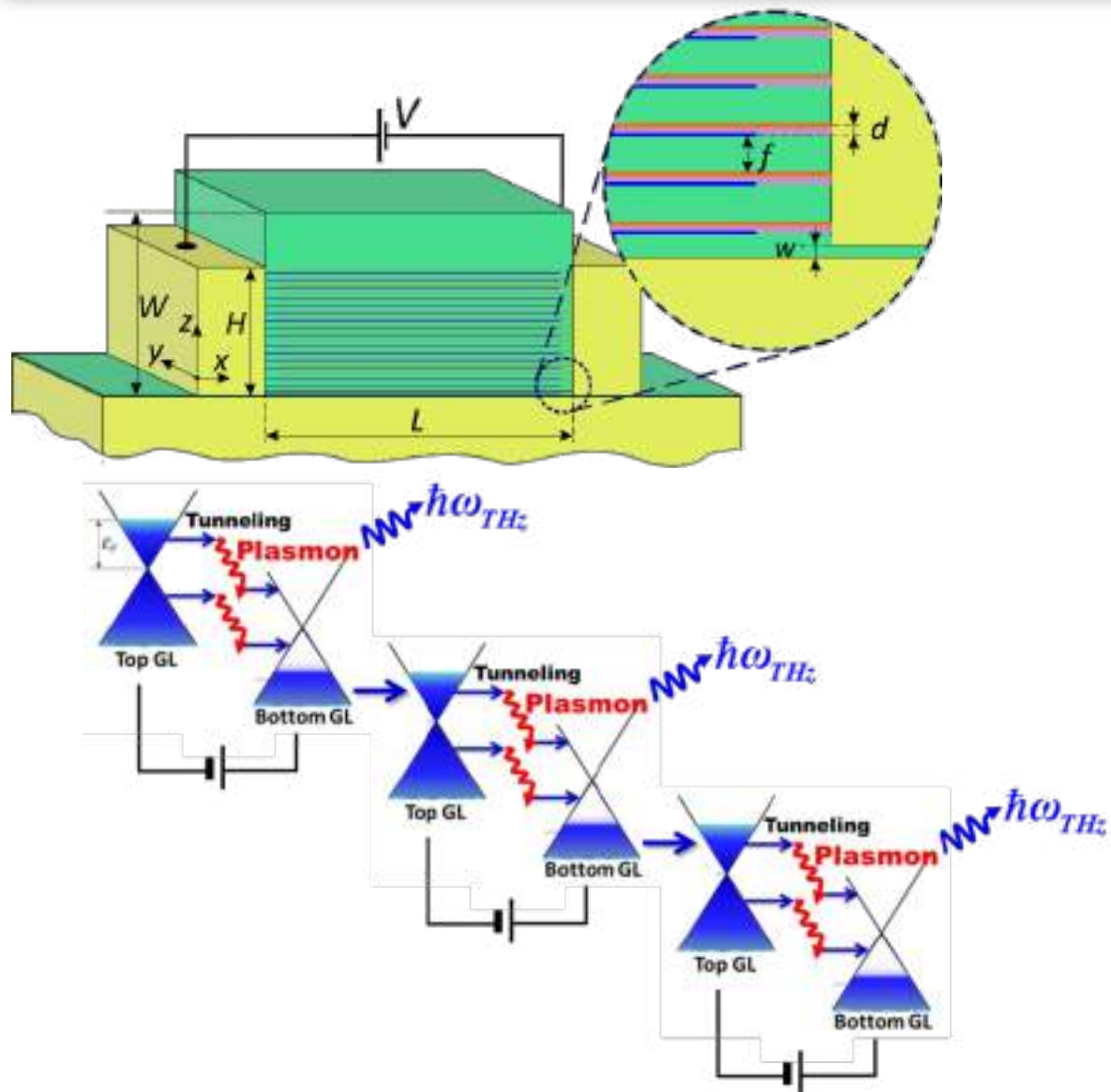
科研費：基盤研究(S) 二次元原子薄膜ヘテロ接合の創製と
その新原理テラヘルツ光電子デバイス応用 (H28~R02)



DGL積層構造による 新原理グラフェンTHz量子カスケードレーザー



A.A. Dubinov et al., *Opt. Exp.* 24, 29603 (2016).



発表の内容

- 研究の背景と目的
- グラフェンの光電子物性
- グラフェンのテラヘルツ(THz)レーザー応用
- **グラフェンプラズモンとその巨大THz利得増強作用**
- グラフェンTHzレーザートランジスタの新しい展開
- まとめ

グラフェンプラズモンの電場増強作用



V. Ryzhii, A. Satou, T. Otsuji, *JAP* **101**, 024509 (2007).
 E.H. Hwang and S. Das Sarma, *PRB* **75**, 205418 (2007).
 A.N. Grigorenko et al., *Nature Photon.* **6**, 749–58 (2012).
 D. Svintsov et al., *JAP* **111**, 083715 (2012).

Normal semiconductors

ungated 2D $\omega = \sqrt{\frac{e^2 n}{2\epsilon m}} k$

gated 2D $\omega = \sqrt{\frac{e^2 n d}{\epsilon m}} \cdot k \propto k d^{1/2} V_g^{1/2}$

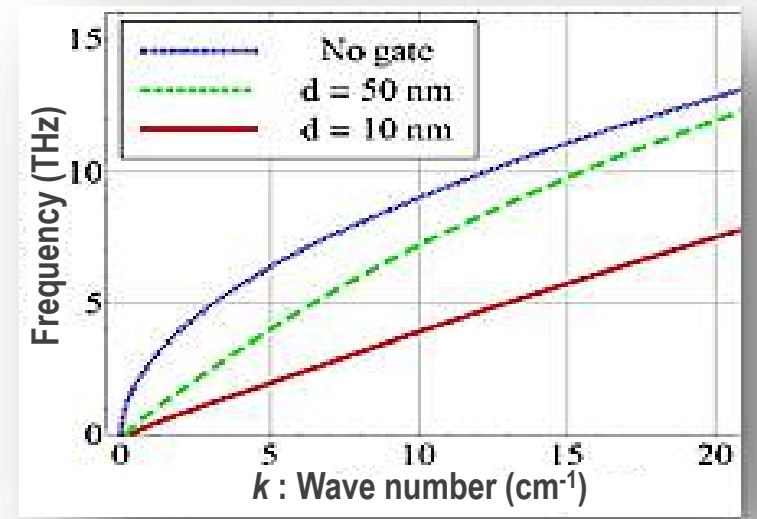
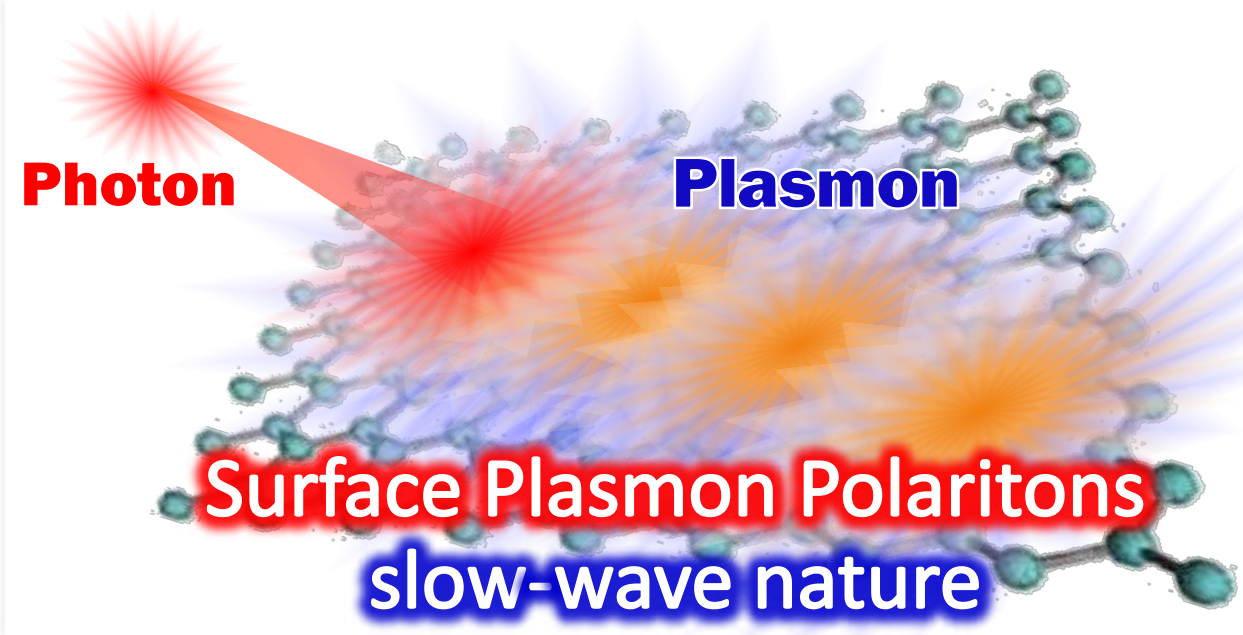


Gated graphene

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

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

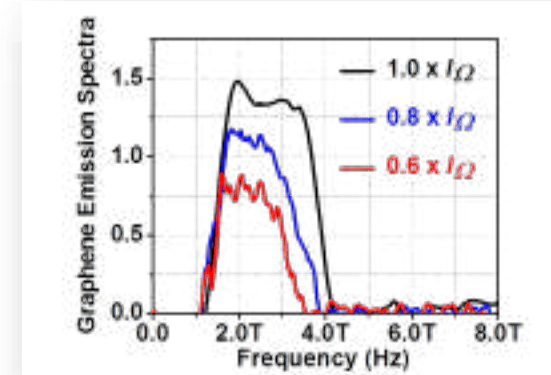
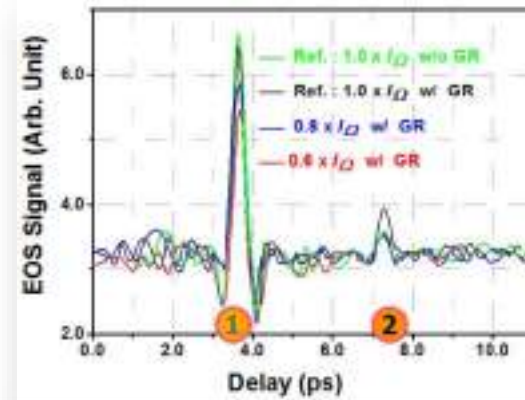
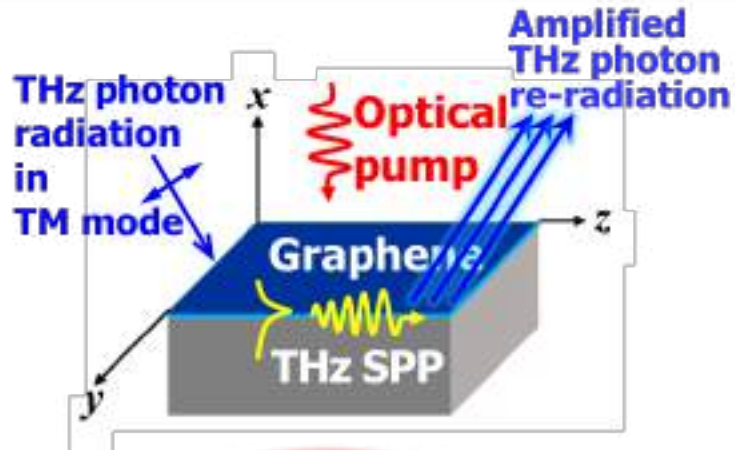
$$\epsilon_F = \hbar v_F \sqrt{\frac{\epsilon V_g}{2ed}} \begin{cases} \ll k_B T \\ \gg k_B T \end{cases}$$

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


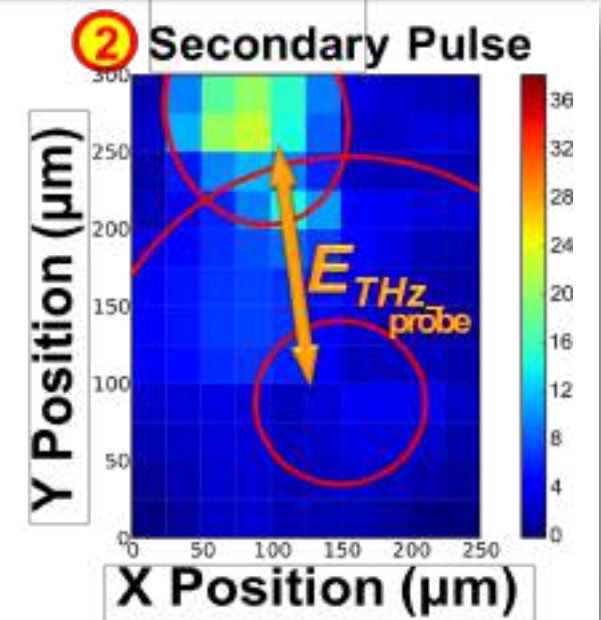
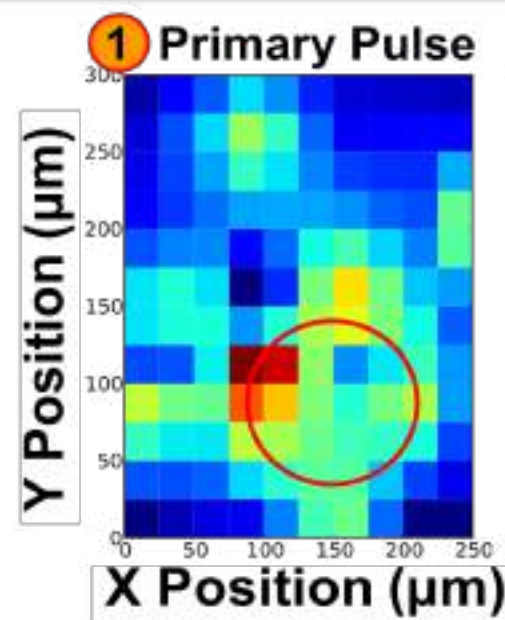
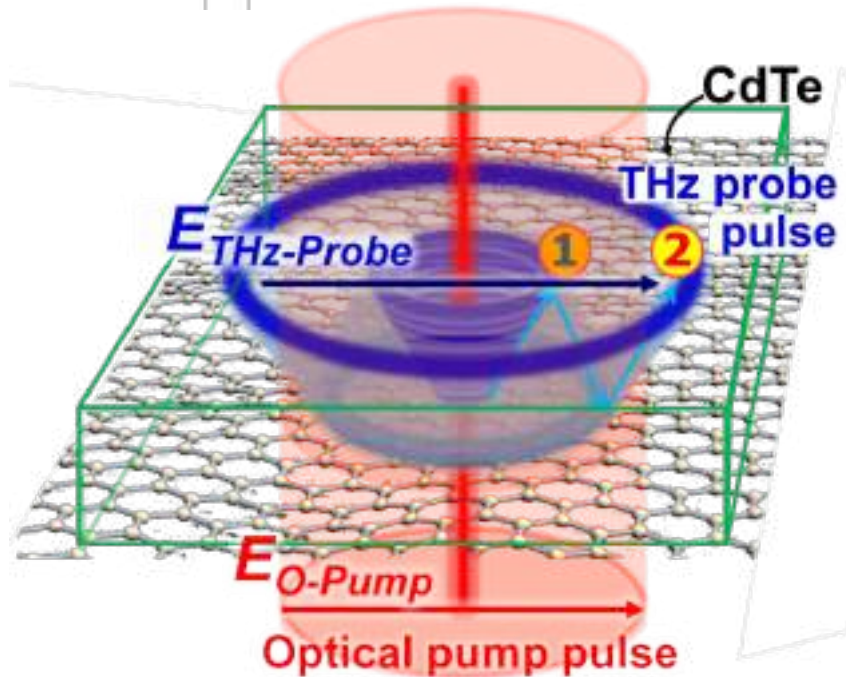
光学励起グラフェンのプラズモンポラリトンによる 巨大THz利得増強効果の実証



T. Watanabe et al., *New J. Phys.* 15, 075003 (2013).
S. Boubanga Tombet et al., *PRB* 85, 035443 (2012).



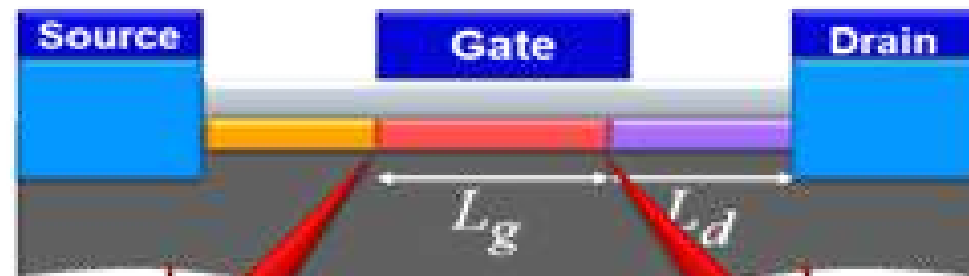
Spatial Distributions of the Pulse Intensities



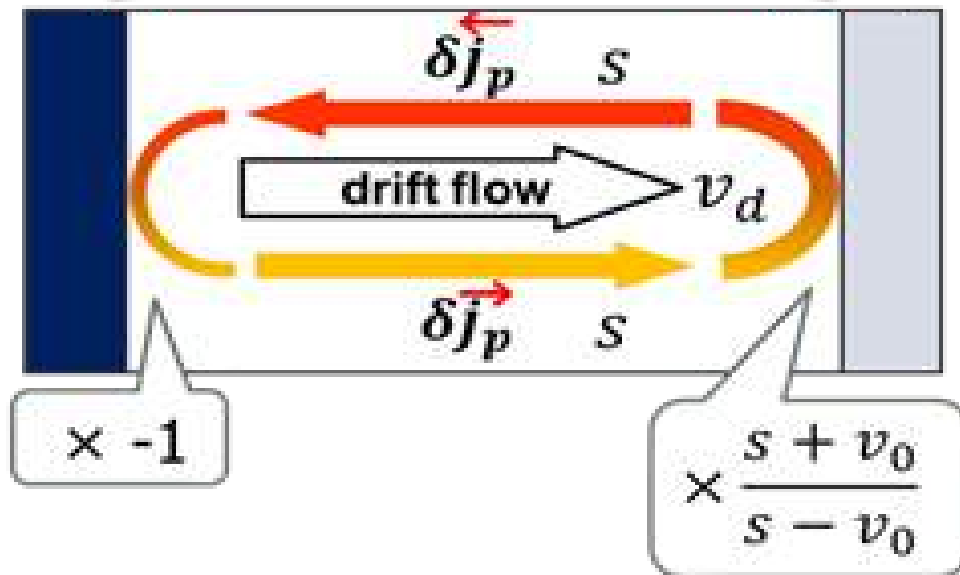
プラズモンのもう一つの物理： Dyakonov-Shur型プラズモン不安定性



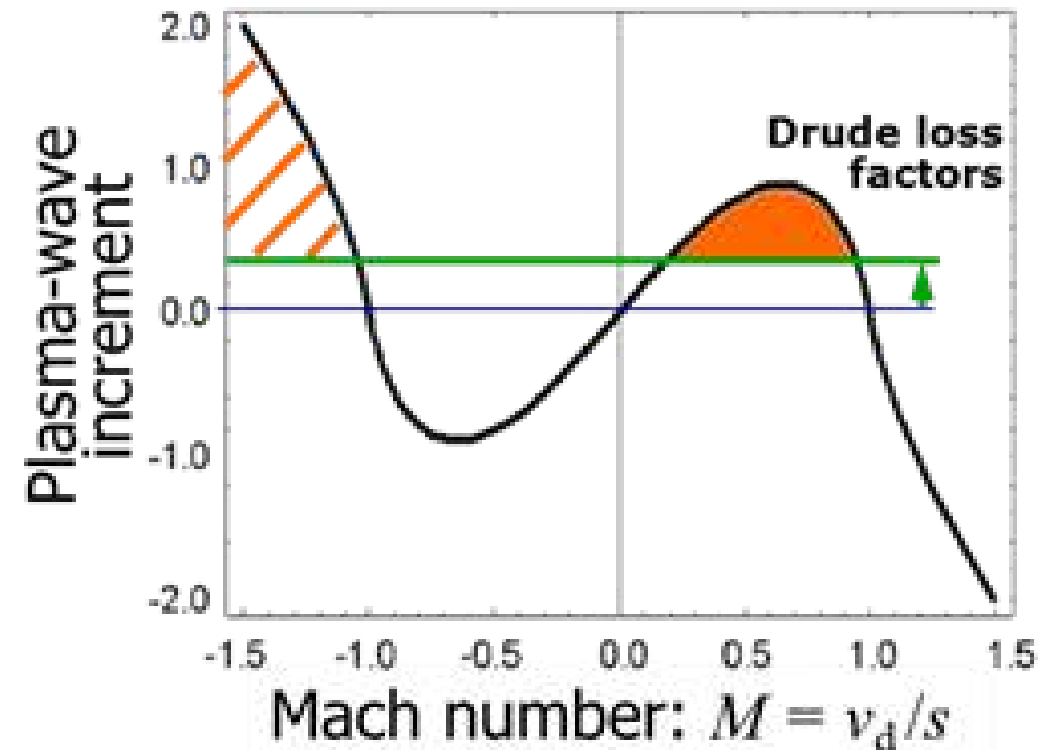
M. Dyakonov and M. Shur, *Phys. Rev. Lett.* 71, 2465–2468 (1993).



Source (Short) Drain (Open)



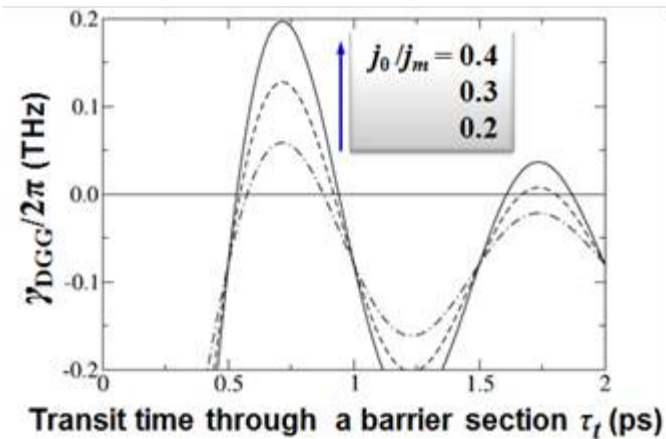
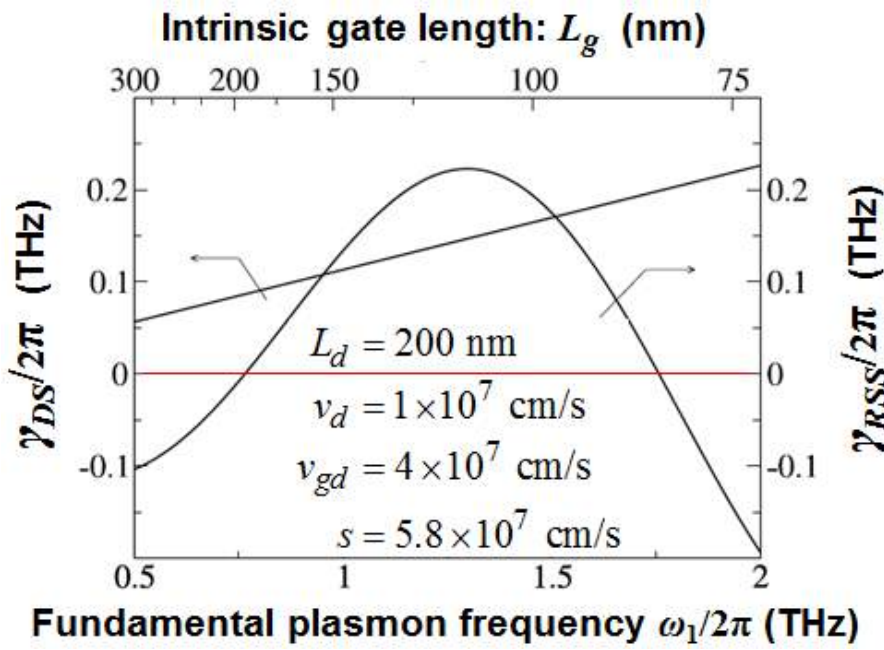
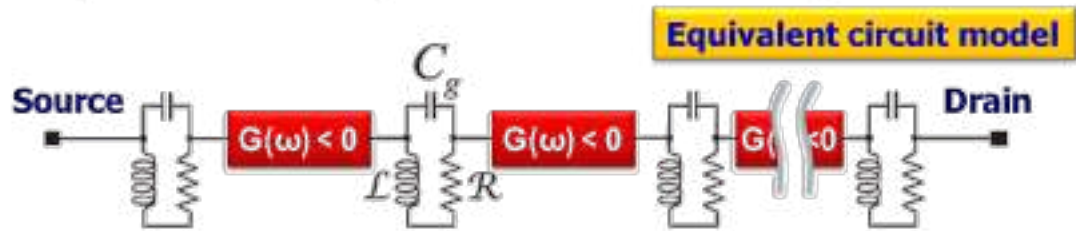
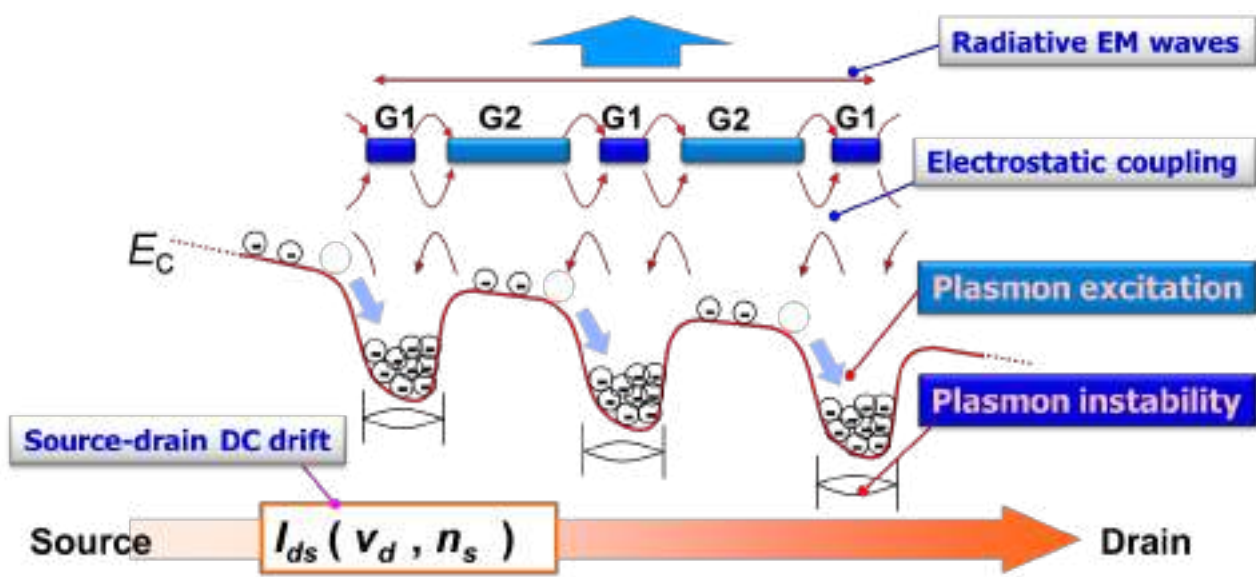
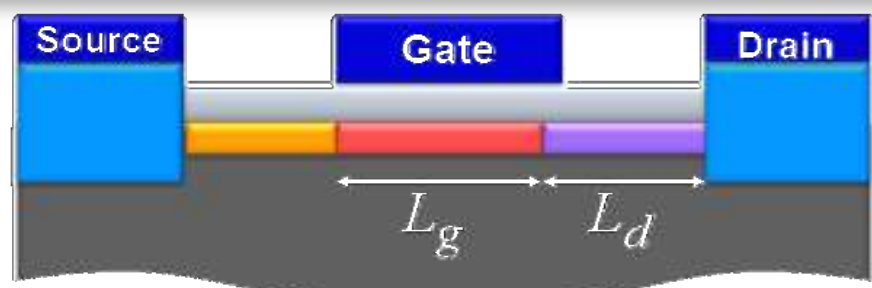
$$\therefore \frac{\delta n}{\delta n} = \frac{\delta V_g}{\delta V_g} = \frac{s + v_d}{s - v_d} > 1 \Rightarrow \text{Gain!!}$$



Ryzhii-Satou-Shur型 プラズモン不安定性

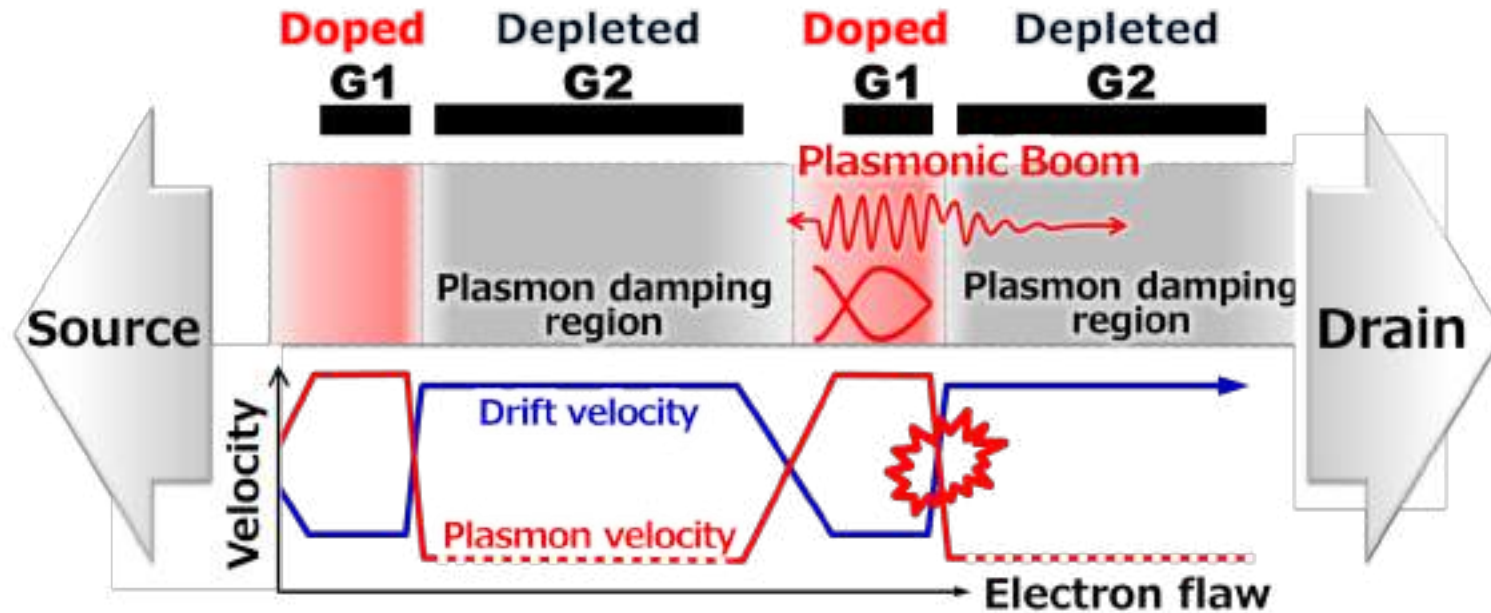
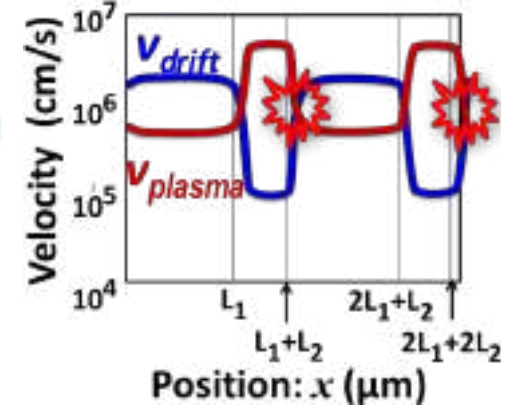
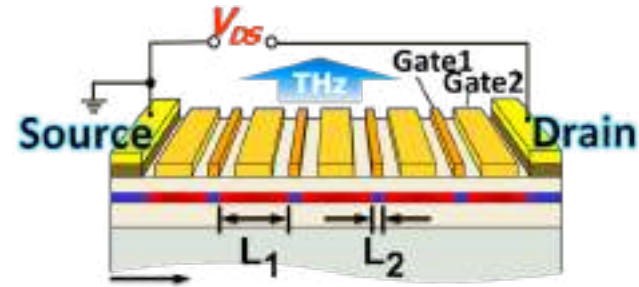


Ryzhii, V., Satou, A. & Shur, M.S. *IEICE T. E89*, 1012 (2006).
 Ryzhii, V., Satou, A., Ryzhii, M., Otsuji, T. & Shur, M.S. *JPCM* 20, 384207 (2008).





第3の不安定性：プラズモニックブームの可能性

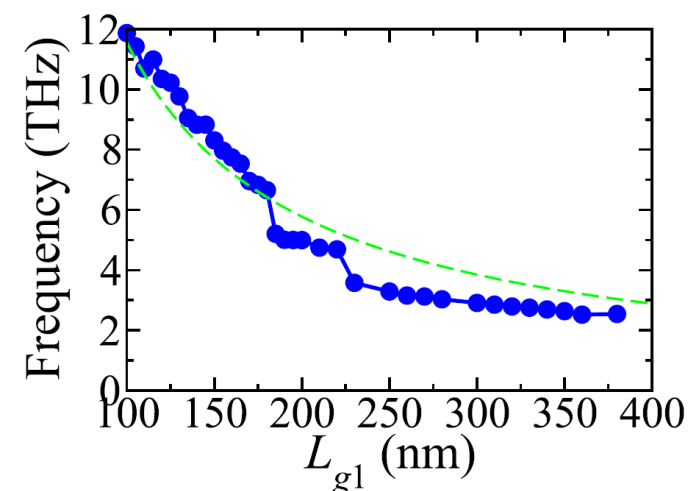
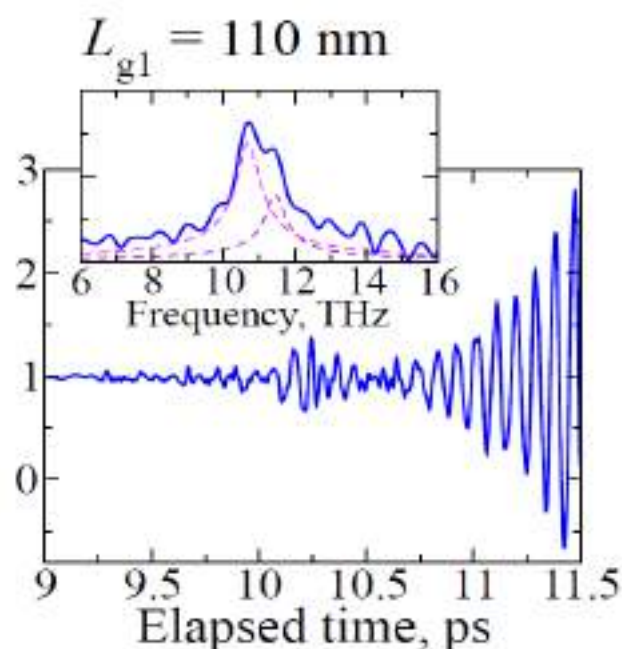
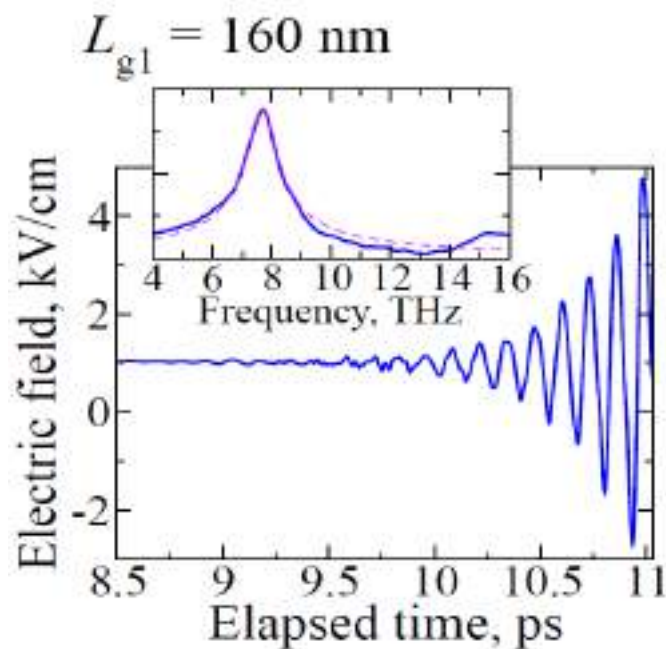
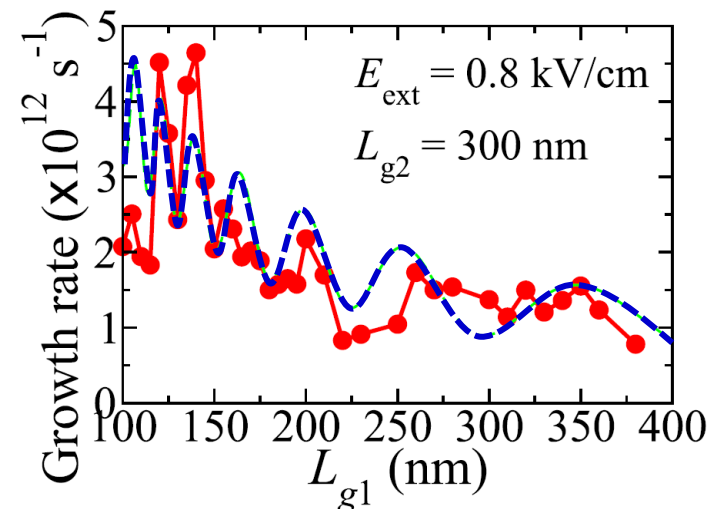
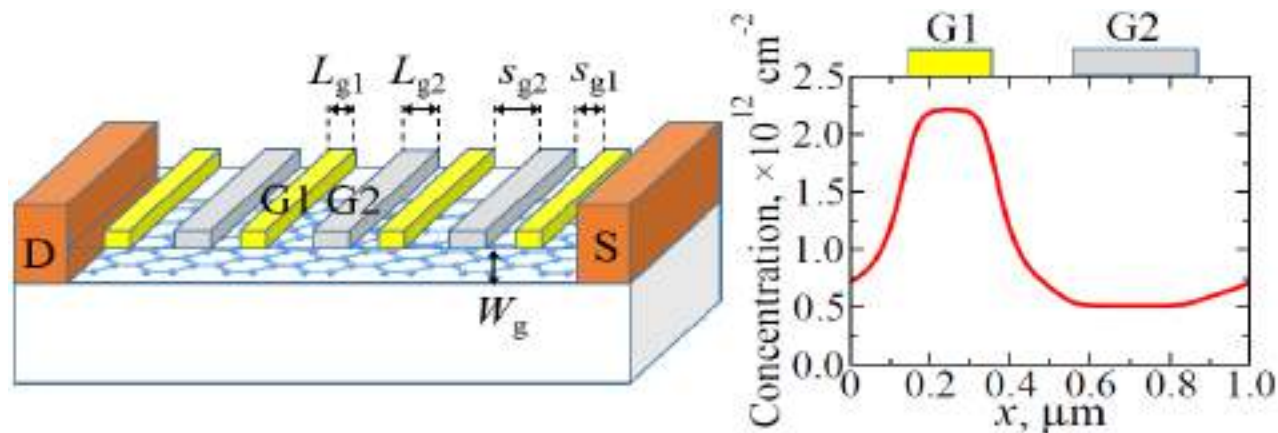


S. Mikhailov, *PRB* **58**, 1517 (1998).
 G.R. Aizin, J. Mikalopa, and M. Shur, *PRB* **93**, 195315 (2016).
 D. Svintsov, *PRB* **97**, 121405(R) (2018).
 T. Otsuji et al., *unpublished*.

グラフェンメタ表面におけるプラズモン不安定性に伴うTHz自励発振現象



Y. Koseki, V. Ryzhii, T. Otsuji, V.V. Popov, A. Satou, *PRB* **93**, 245408 (2016).



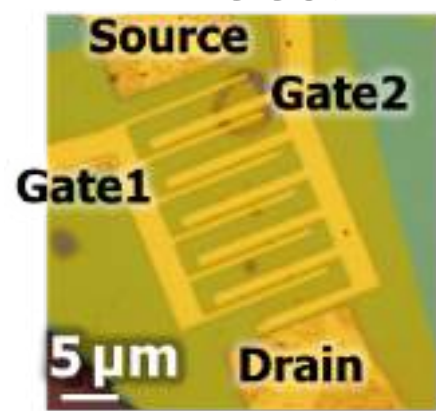
非対称二重回折格子ゲートADGG-GFET



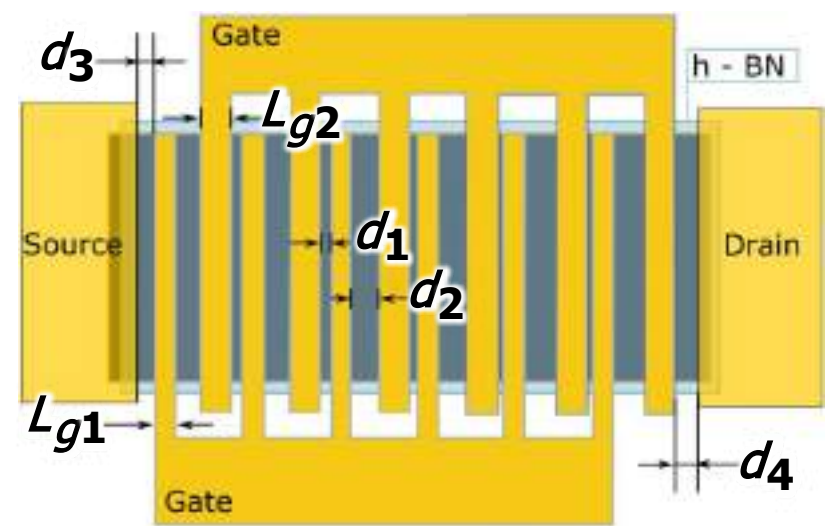
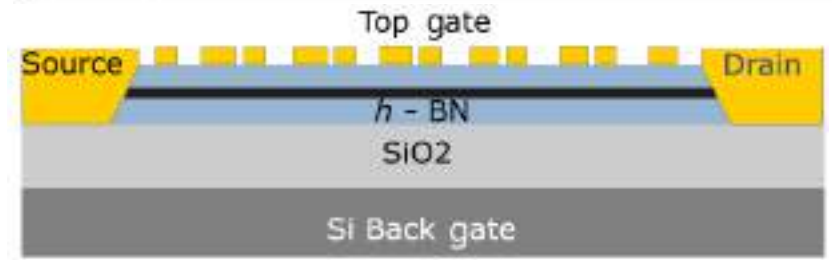
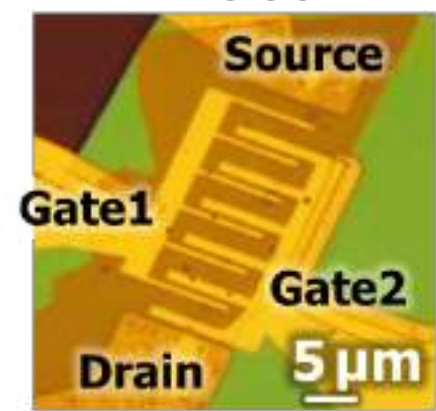
S. Boubanga-Tombet et al., Phys. Rev. X 10, 031004 (2020).

Cavity	C1	C2	C3	C4
Structure or sample	A-DGG3.1	A-DGG3.2	A-DGG3.1	A-DGG3.2
Thickness of top <i>h</i> -BN layer (nm)	32	20	32	20
CNP (V)	+0.15	-0.12	+0.10	-0.06
Biased cavity length (μm)	0.5	0.75	1.0	1.5
Total channel length (μm)	26.5	24.0	26.5	24.0
d_1 and d_2 (μm)	0.5 and 2.0	0.5 and 1.0	0.5 and 2.0	0.5 and 1.0
Channel width (average) (μm)	4.9	1.325	4.9	1.325
d_3 and d_4 (μm)	2.0 and 0.5	1.0 and 0.5	2.0 and 0.5	1.0 and 0.5

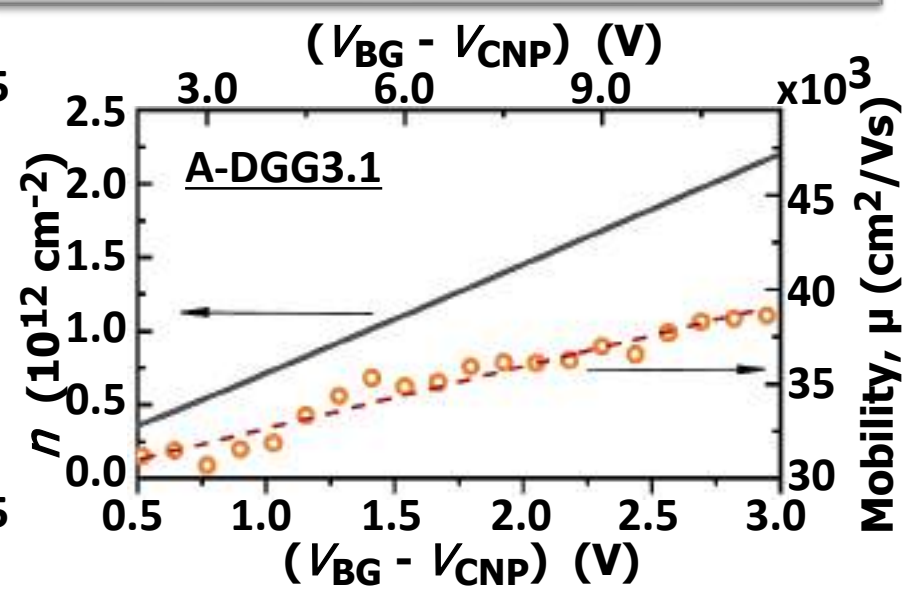
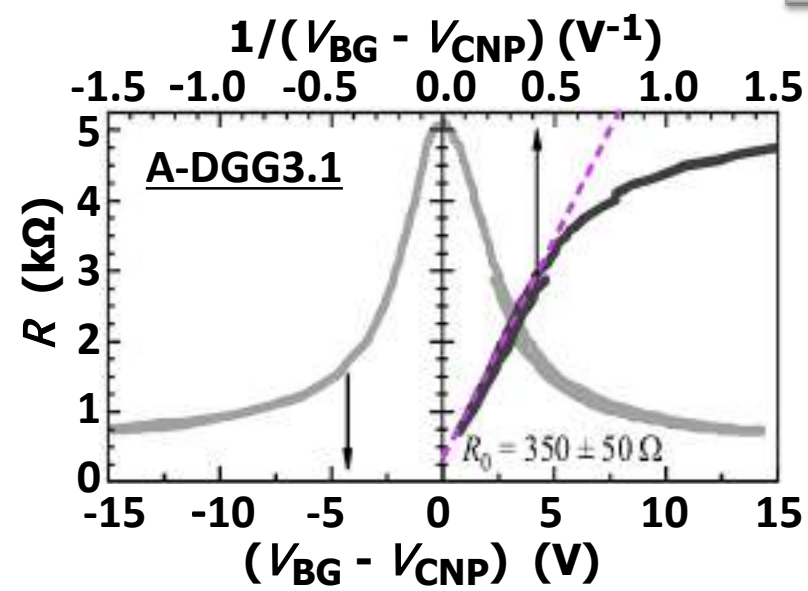
A-DGG3.1



A-DGG3.2



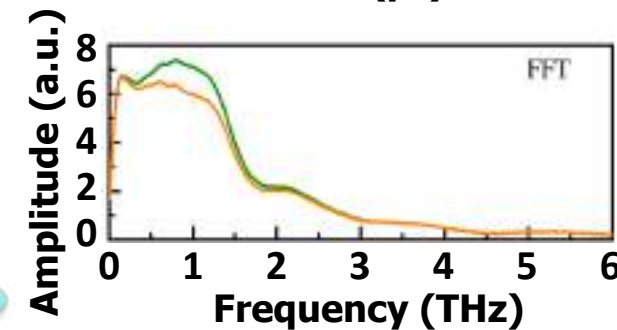
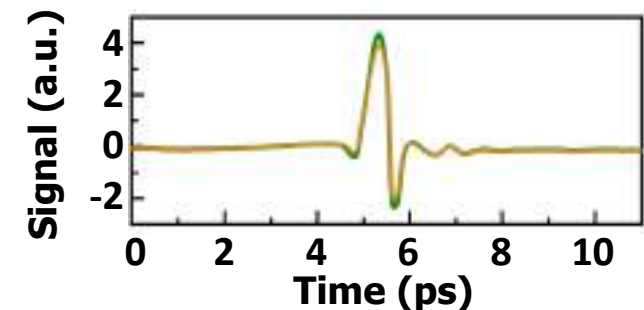
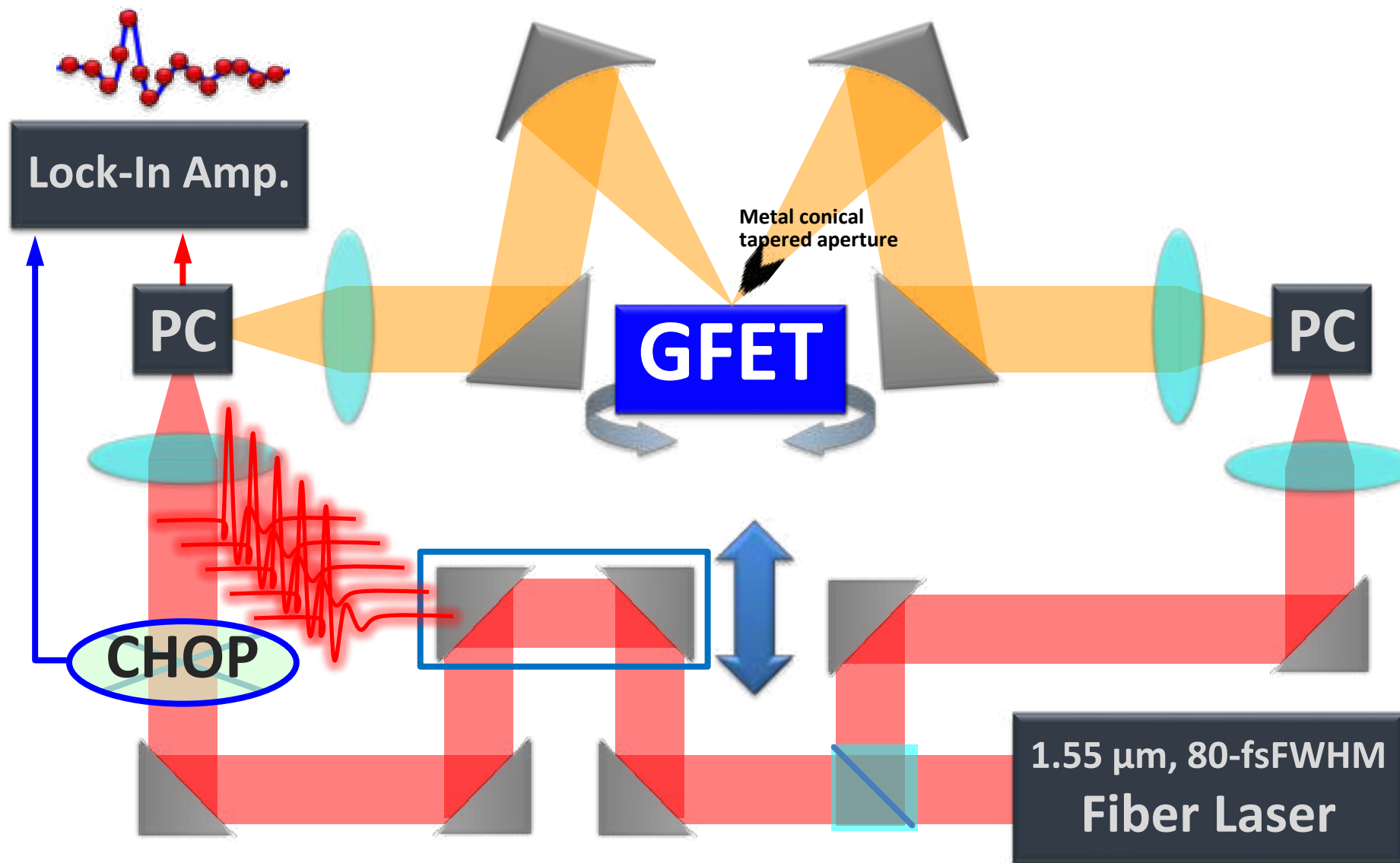
$30,000 \leq \mu \leq 40,000 \text{ cm}^2/\text{Vs}$



THz時間領域分光法による実験検証



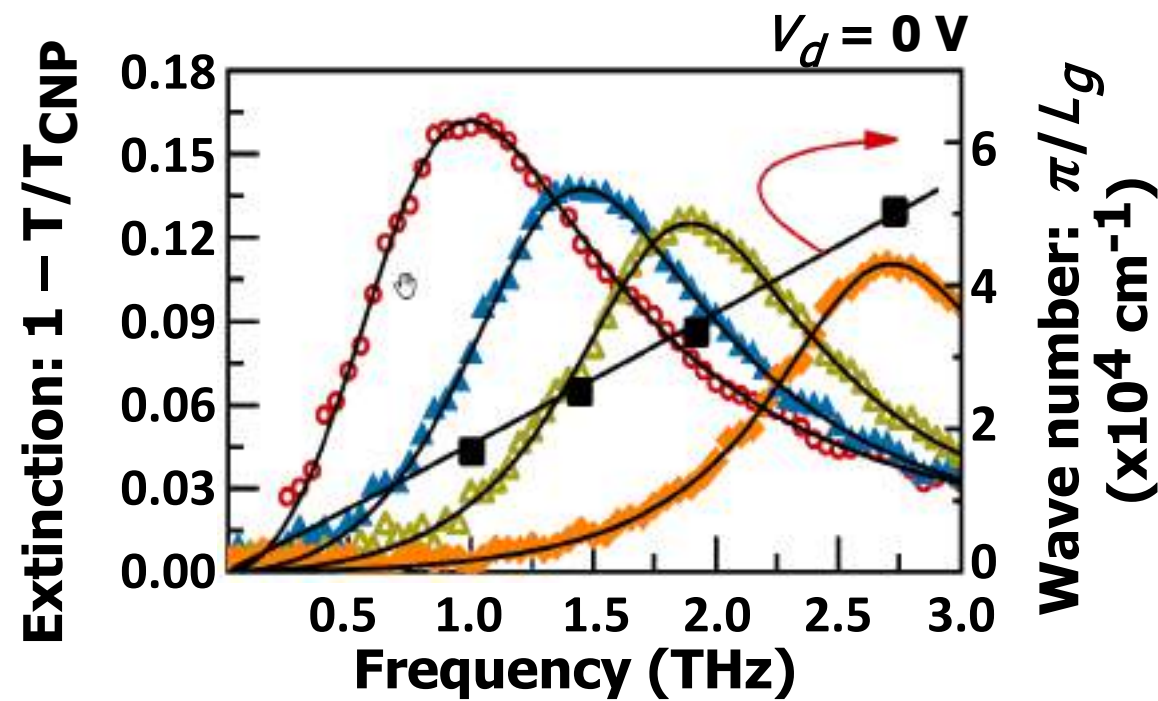
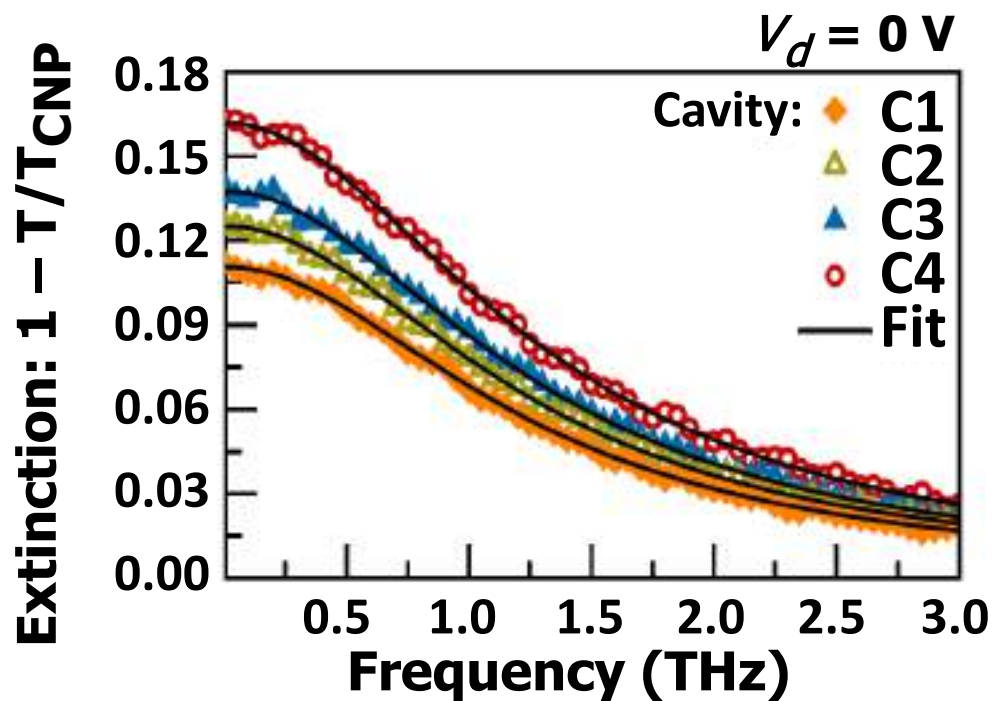
S. Boubanga-Tombet et al., Phys. Rev. X 10, 031004 (2020).





ドレイン無バイアス条件： 偏光敏感依存のTHz共鳴吸収特性

S. Boubanga-Tombet et al., Phys. Rev. X 10, 031004 (2020).

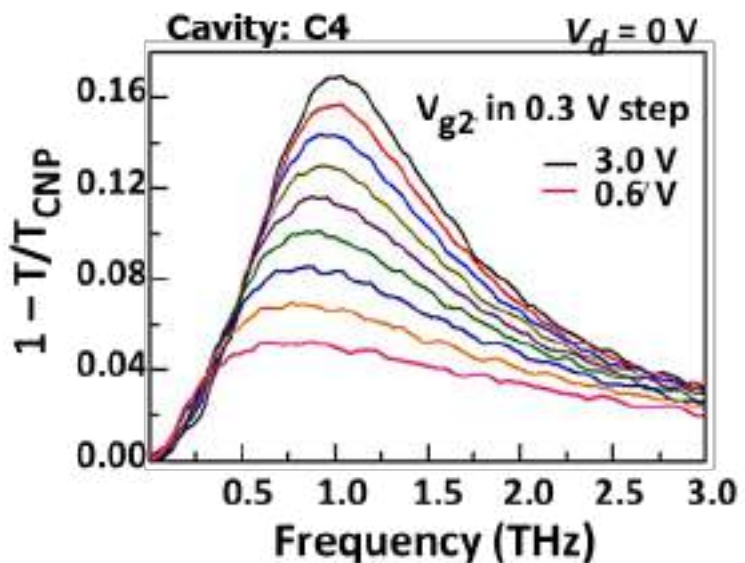
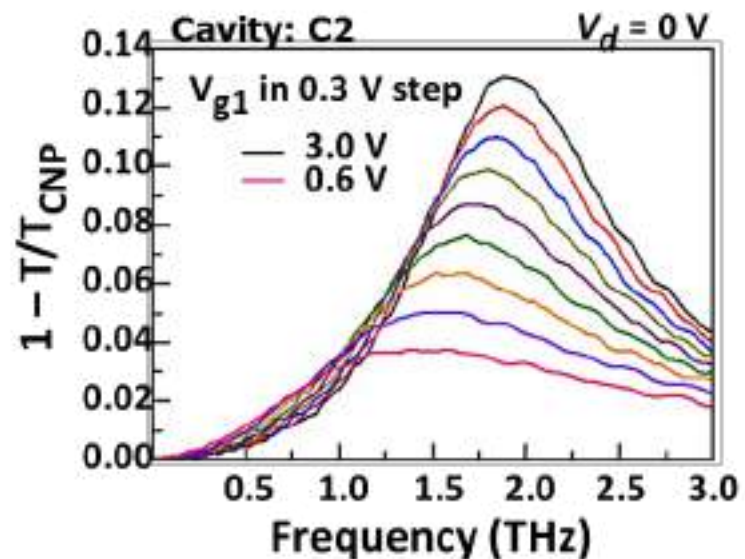




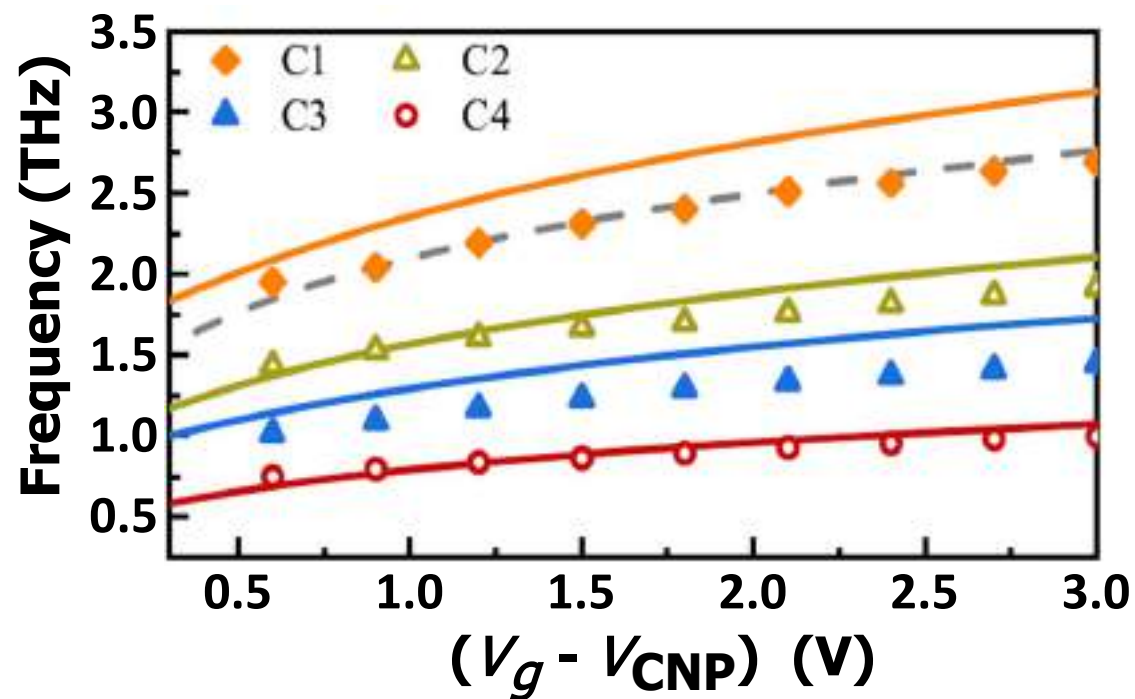
ゲートバイアス依存性： グラフェンプラズモンの分散理論とよく一致

S. Boubanga-Tombet et al., Phys. Rev. X 10, 031004 (2020).

A-DGG3.2



$$f \propto V_g^{1/4}$$

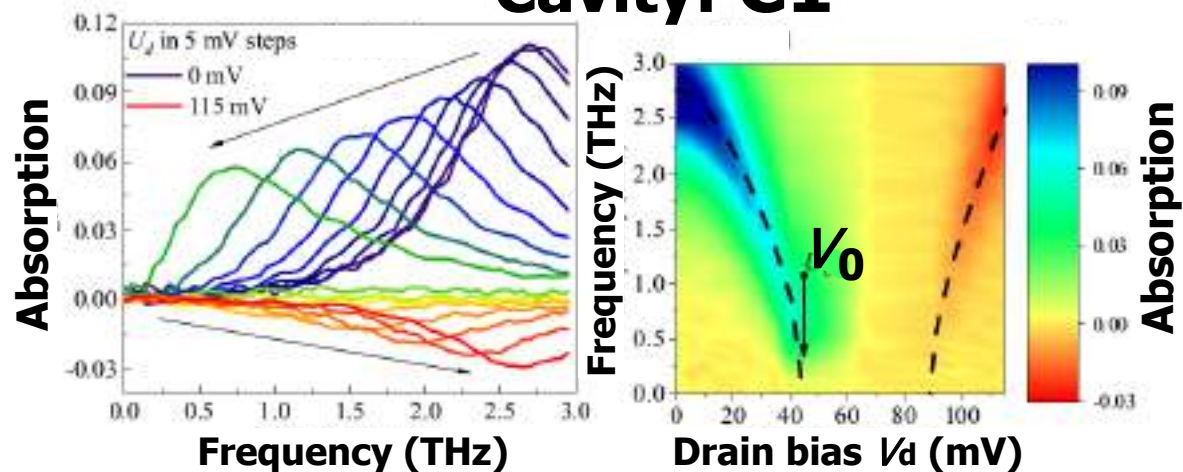


ドレインバイアス依存性： 共鳴吸収から共鳴増幅に反転！

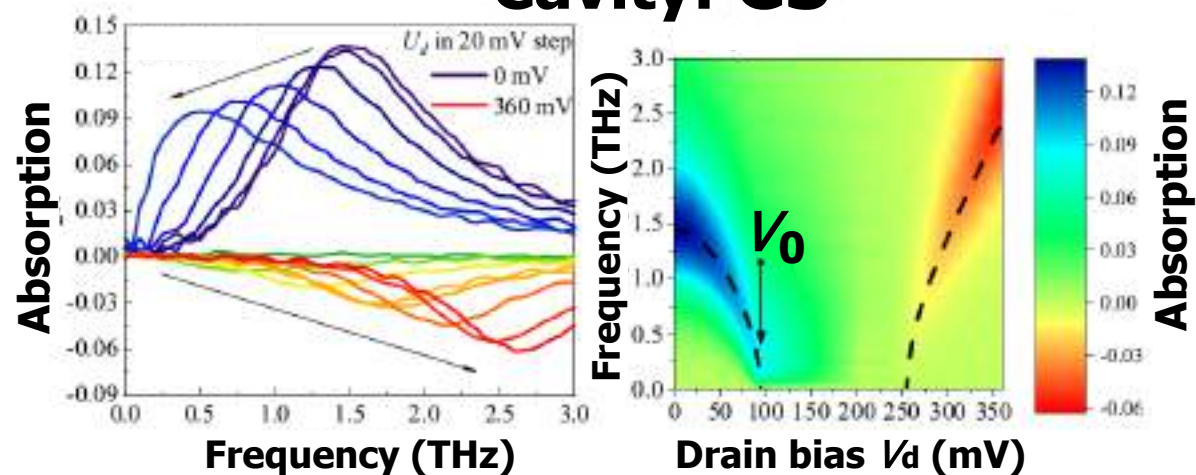


S. Boubanga-Tombet et al., Phys. Rev. X 10, 031004 (2020).

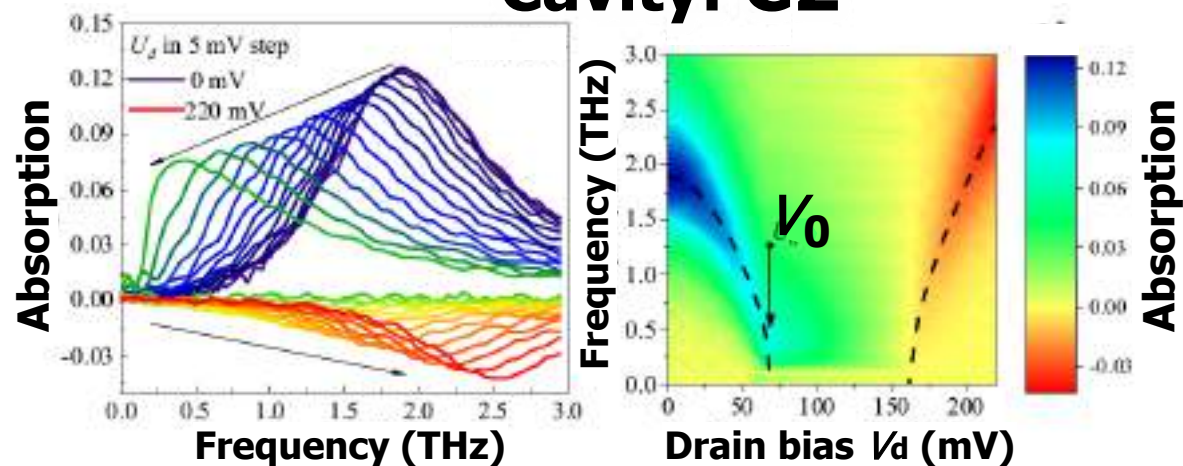
Cavity: C1



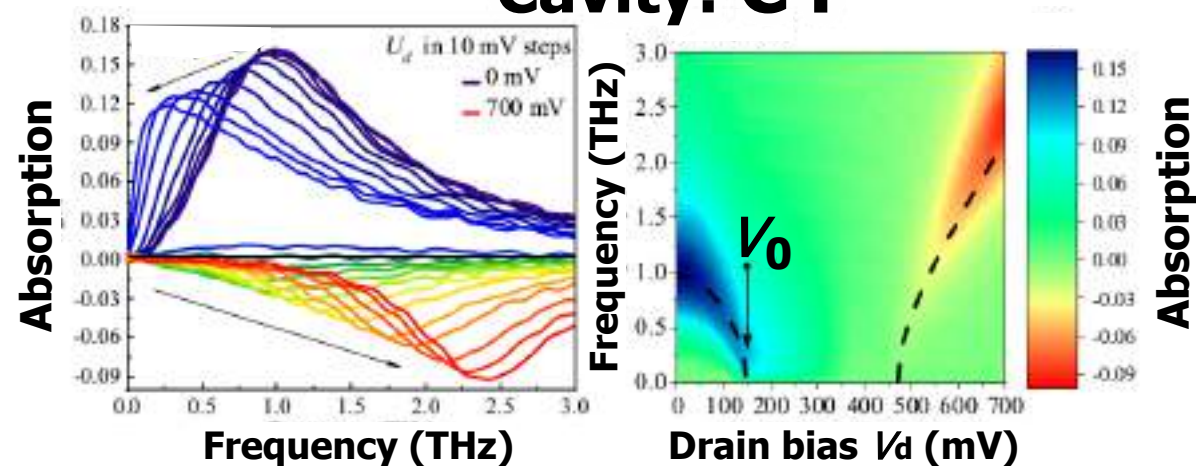
Cavity: C3



Cavity: C2



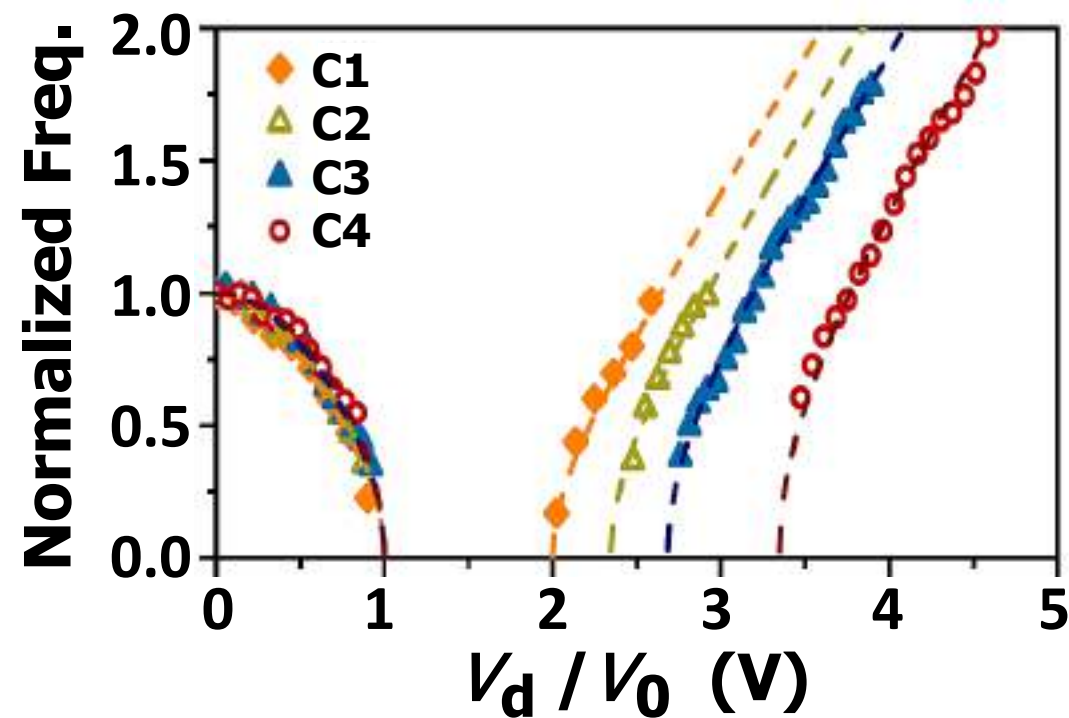
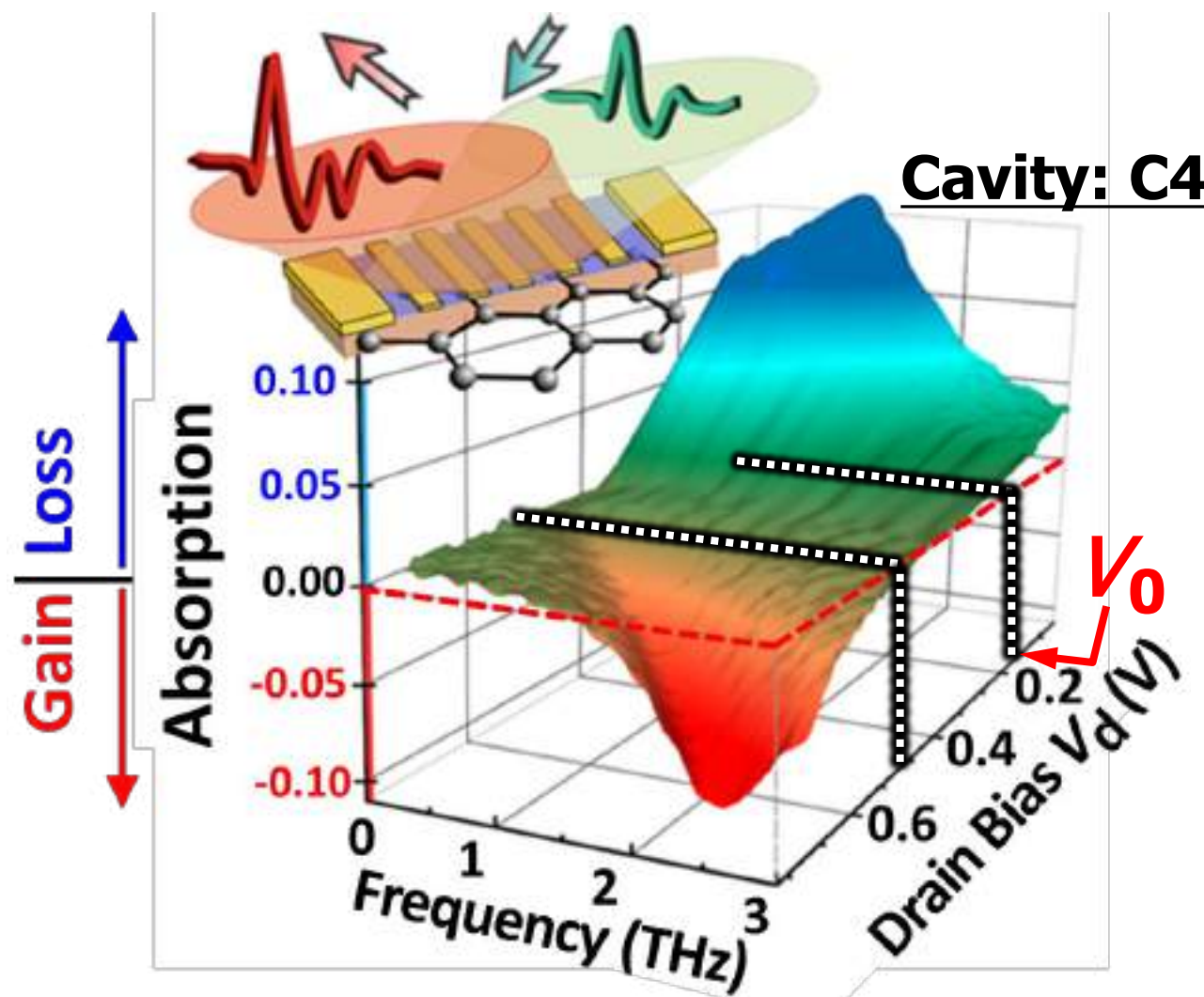
Cavity: C4



グラフェンの理論限界：“2.3%の壁”を超える THz電磁波の増幅に成功

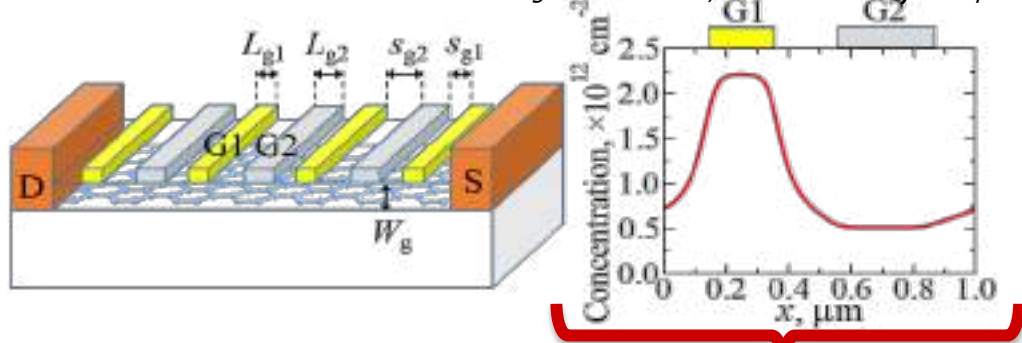


S. Boubanga-Tombet et al., Phys. Rev. X 10, 031004 (2020).



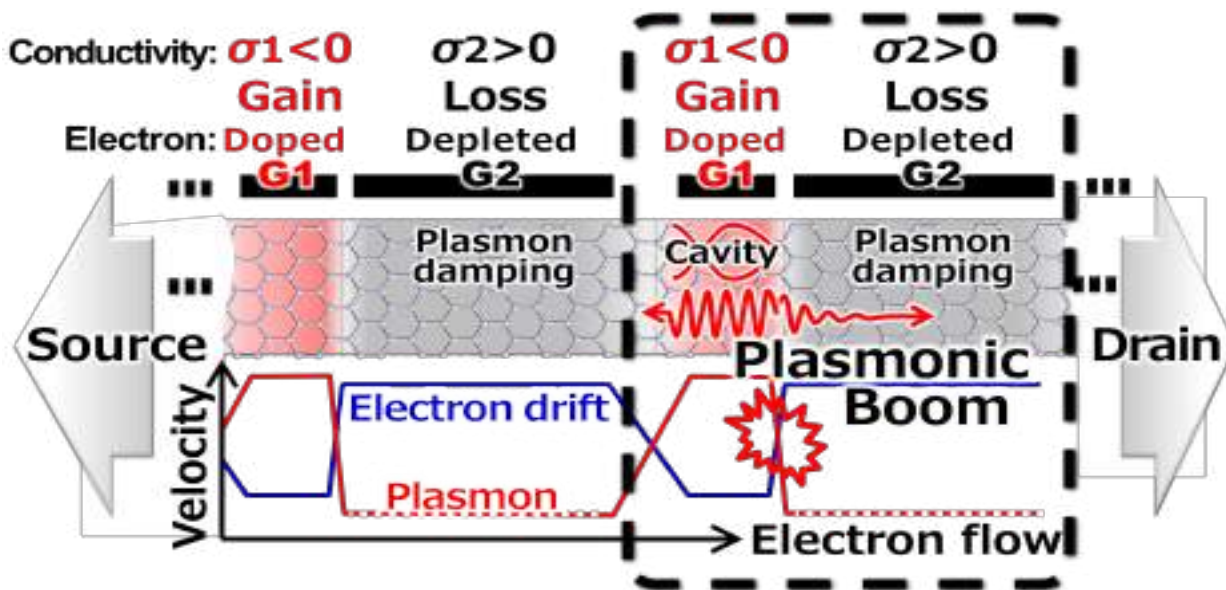
グラフェンDiracプラズモンの不安定性に由来した 自励発振 & 誘導増幅放出の発現

Y. Koseki et al., *Phys. Rev. B* **93**, 245408 (2016).
 S. Boubanga-Tombet et al., *Phys. Rev. X* **10**, 031004 (2020).
 S. Boubanga-Tombet et al., *Frontiers in Phys.* in press.



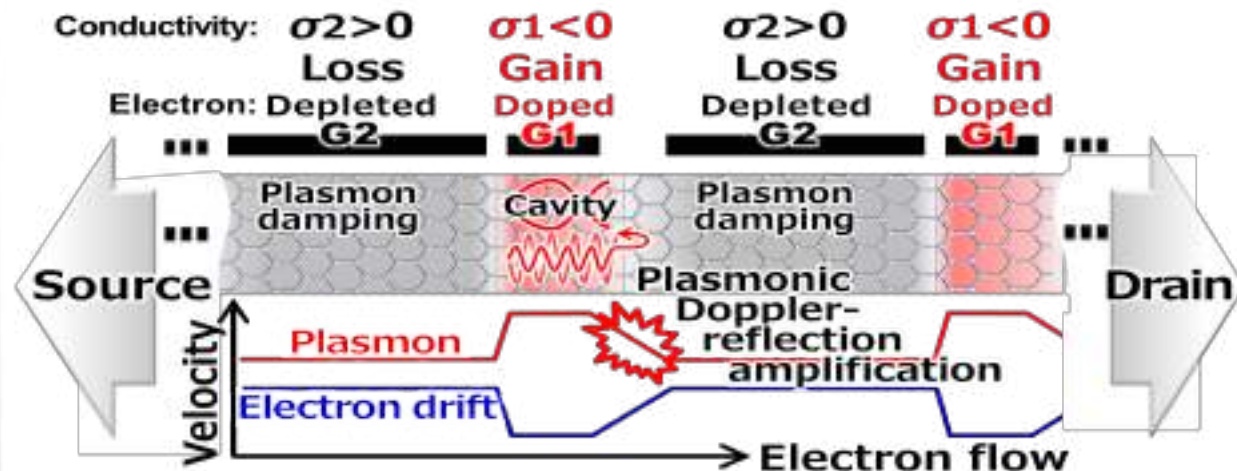
プラズモニックブーム型不安定性

G.R. Aizin, J. Mikalopas, M. Shur, *Phys. Rev. B* **93**, 195315 (2016).



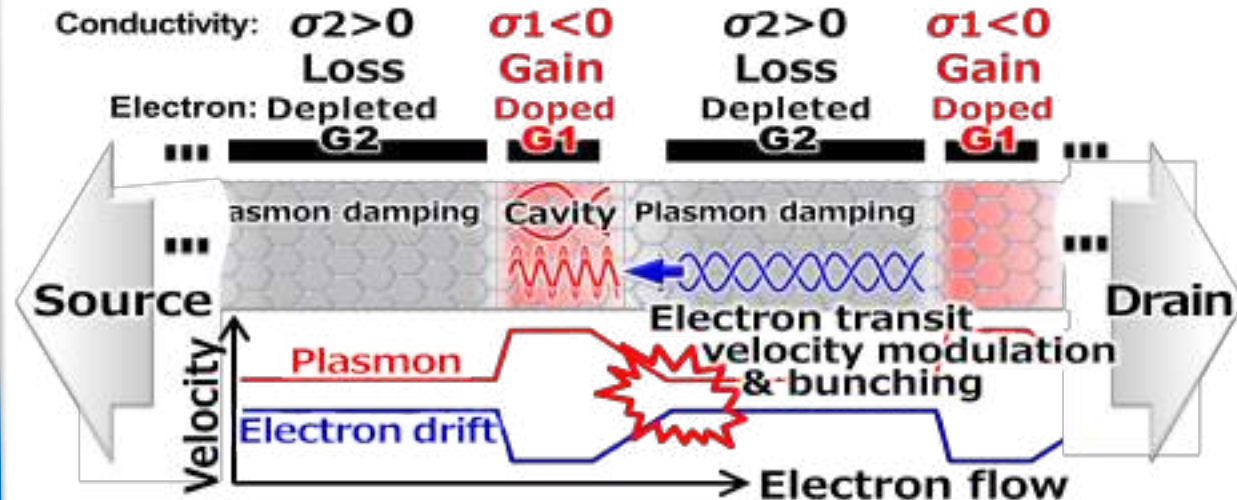
ドップラーシフト型不安定性

M. Dyakonov, M. Shur, *Phys. Rev. Lett.* **71**, 2465 (1993).



電子速度変調型不安定性

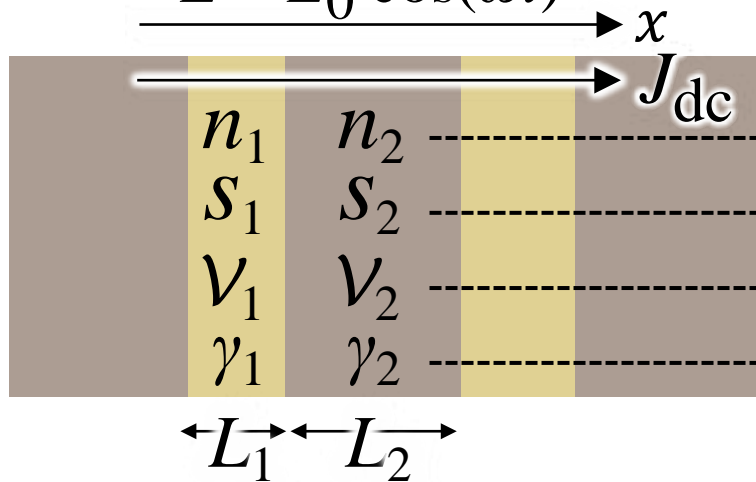
V. Ryzhii, A. Satou, M.S. Shur, *Phys. Status Solidi A* **202**, R113 (2005).



グラフェンプラズモン不安定性の新たな学理を発見 電子速度がプラズモン速度以下でも増幅が可能！



$$E = E_0 \cos(\omega t)$$



n_1 n_2 ——— Electron density
 S_1 S_2 ——— Plasma velocity
 V_1 V_2 ——— Drift velocity
 γ_1 γ_2 ——— Momentum relaxation rate

$\alpha = V_{1,2}/S_{1,2}$

Experiments: S. Boubanga-Tombet et al., *arXiv*. 1801.04518.

Theory: A. V. Chaplik, *Sov. Phys. JETP* **35**, 395 (1972).

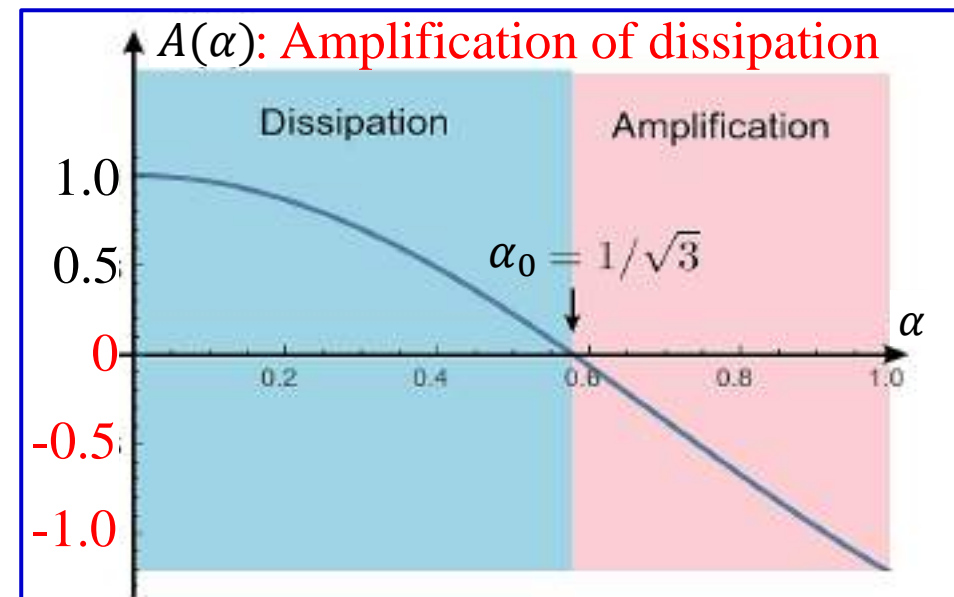
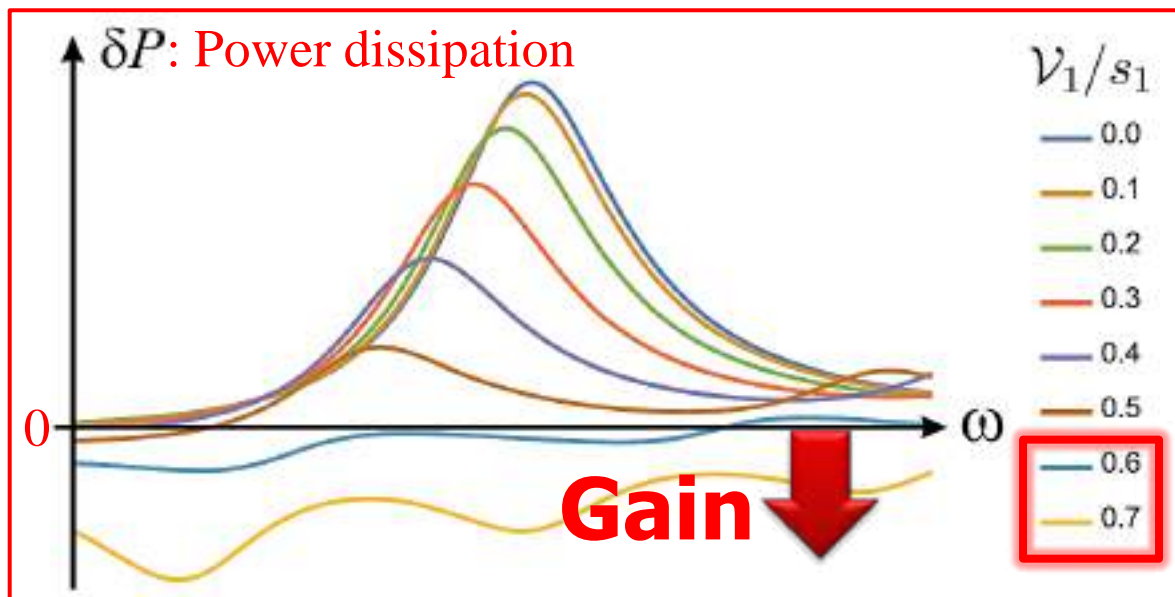
Y. Koseki et al., *PRB* **93**, 245408 (2016).

S. Mikhailov, *PRB* **58**, 1517 (1998).

M. Dyakonov and M. Shur, *PRL* **71**, 2465 (1993).

$$\left(v_1 \frac{\partial}{\partial x} - i\omega + \gamma_1 \right) \delta v_1 + s_1^2 \frac{\partial \delta n_1}{\partial x} = \frac{eE_0}{2m},$$

$$\left(v_1 \frac{\partial}{\partial x} - i\omega \right) \delta n_1 + \frac{\partial \delta v_1}{\partial x} = 0.$$



発表の内容

- 研究の背景と目的
- グラフェンの光電子物性
- グラフェンのテラヘルツ(THz)レーザー応用
- グラフェンプラズモンとその巨大THz利得増強作用
- **グラフェンTHzレーザートランジスタの新しい展開**
- まとめ

PT 対称性操作による電磁波伝搬制御の誕生

C.M. Bender, S. Boettcher, *Phys. Rev. Lett.* **80**, 5243–5246 (1998).
 M.-A. Miri, and A. Alu, *Science* **363**, eaar7709 (2019).

Symmetry of:

Parity $\mathbf{r} \leftrightarrow -\mathbf{r}$, $\mathbf{k} \leftrightarrow -\mathbf{k}$, $\mathbf{p} \leftrightarrow -\mathbf{p}$

Time reversal $t \leftrightarrow -t$, $\omega \leftrightarrow -\omega$

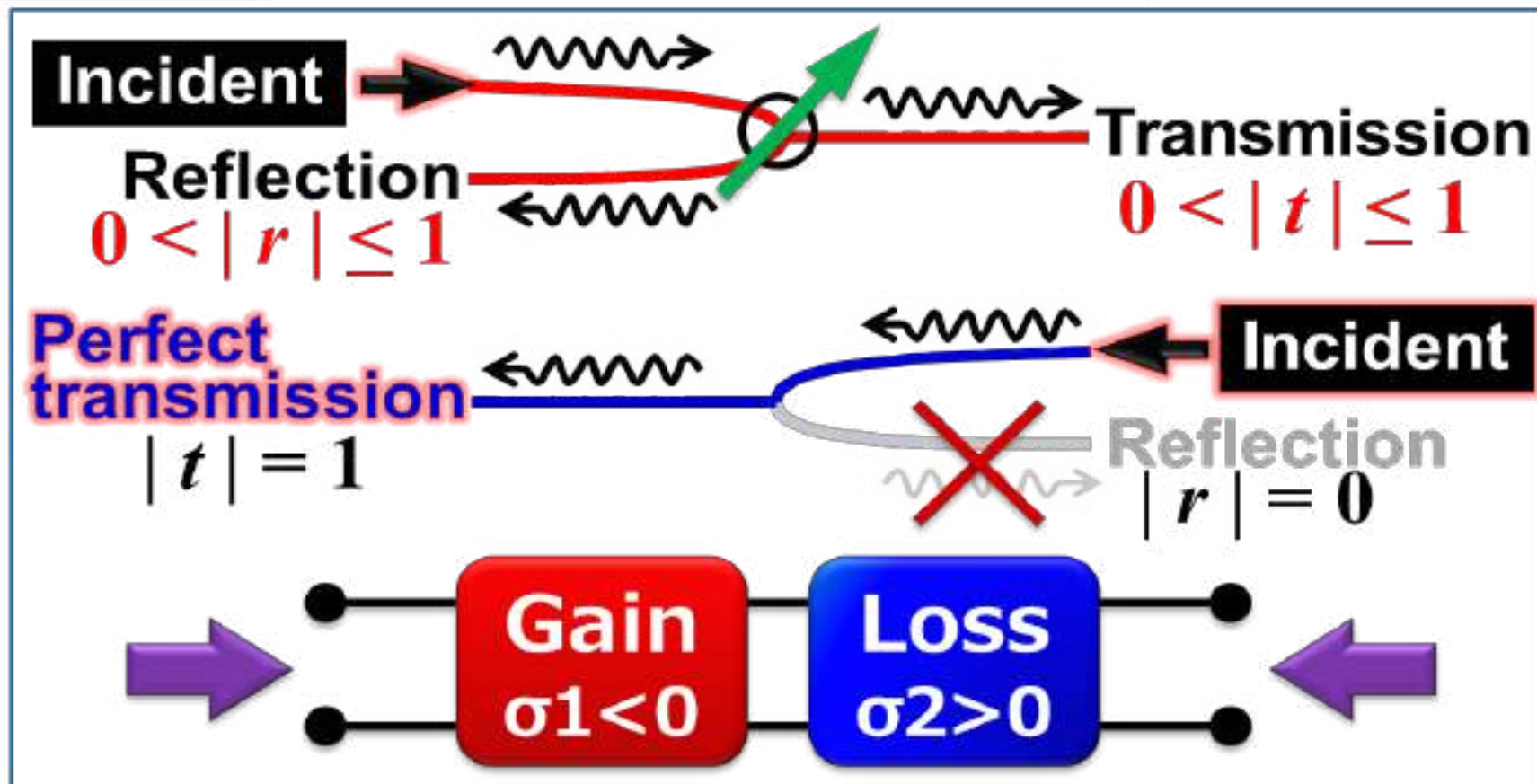
PT Symmetry

$|\sigma_1| = |\sigma_2|$

$\sigma \leftrightarrow -\sigma$

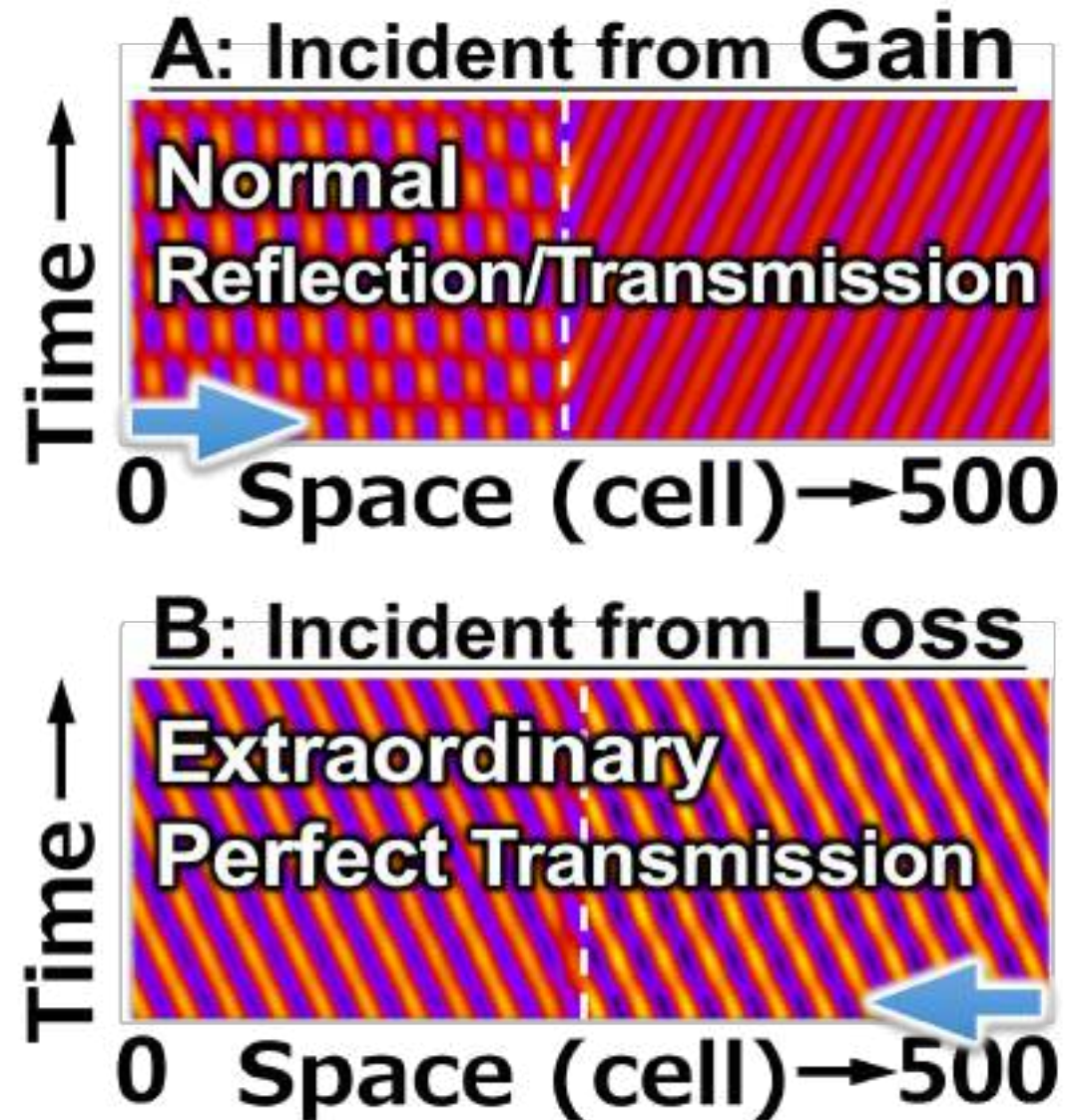
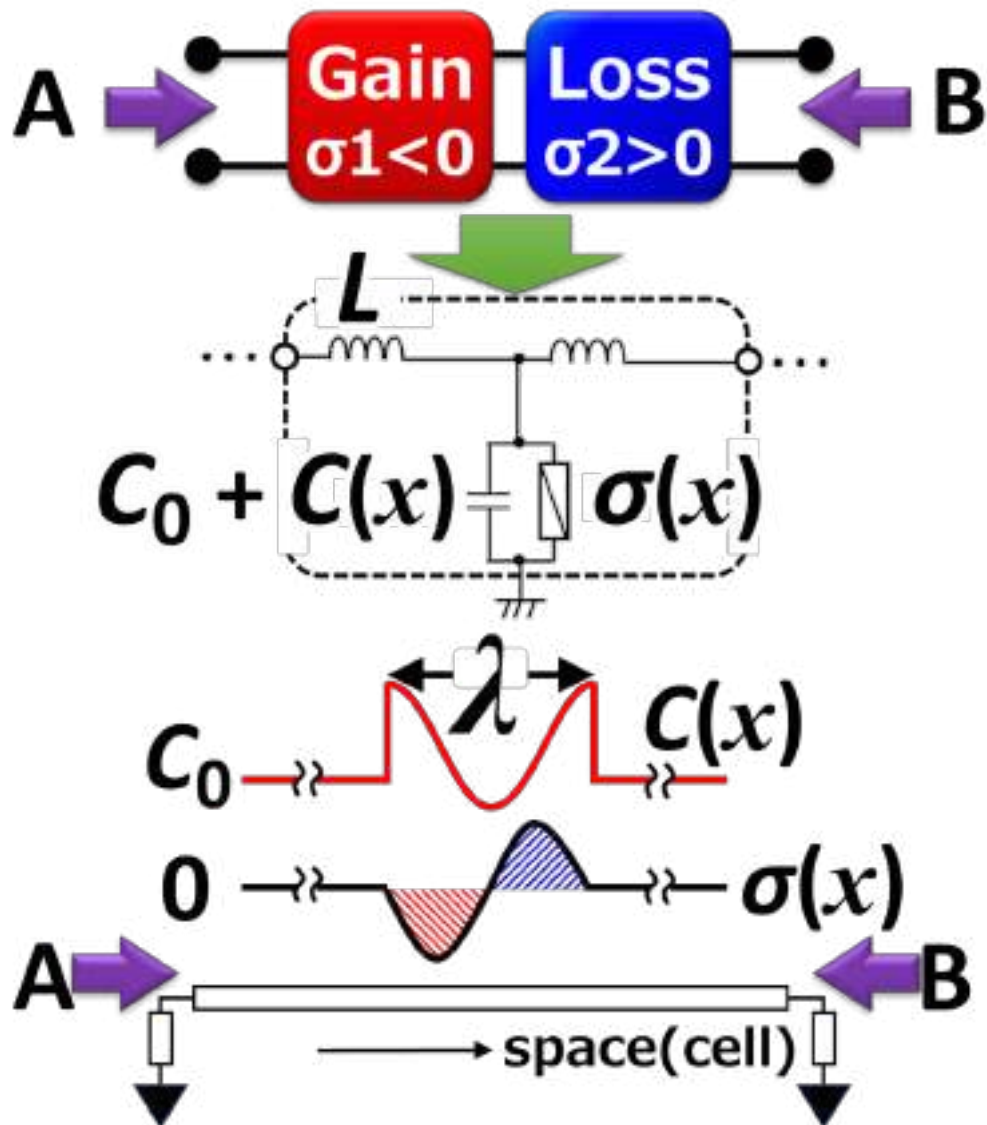


$$\omega = kc / \sqrt{\epsilon_r + i\sigma/\omega}$$

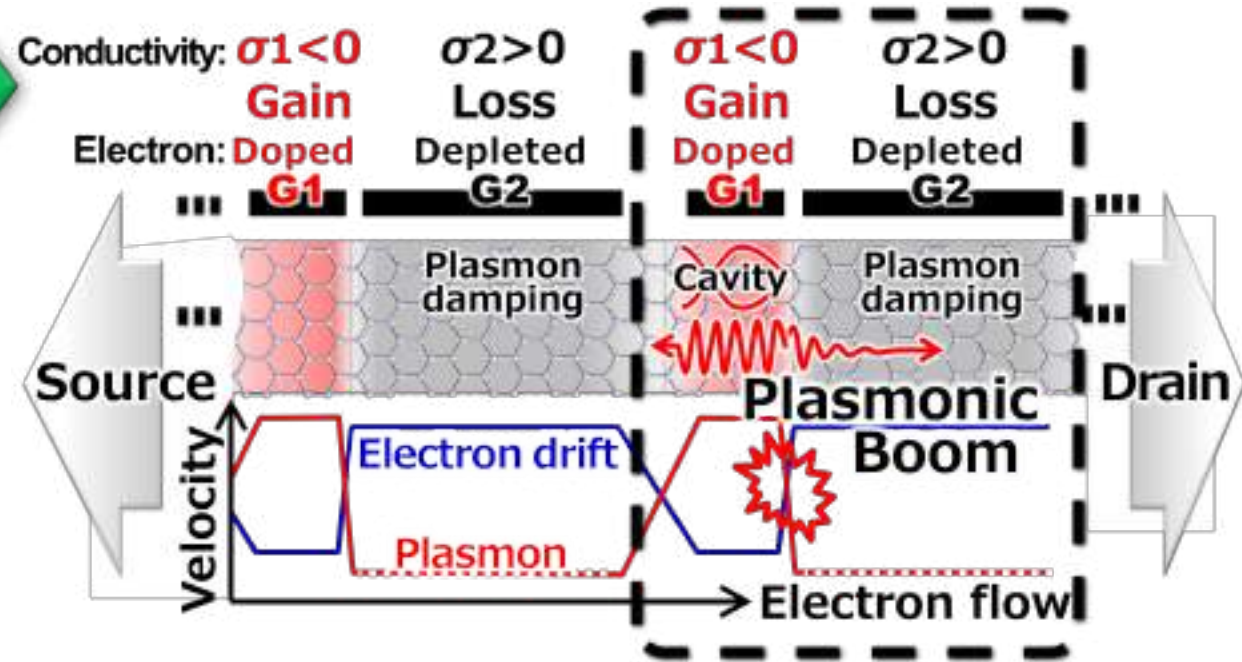
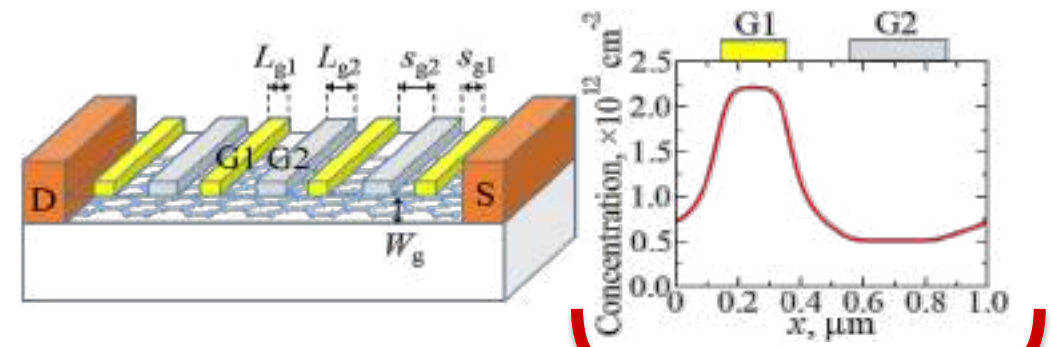
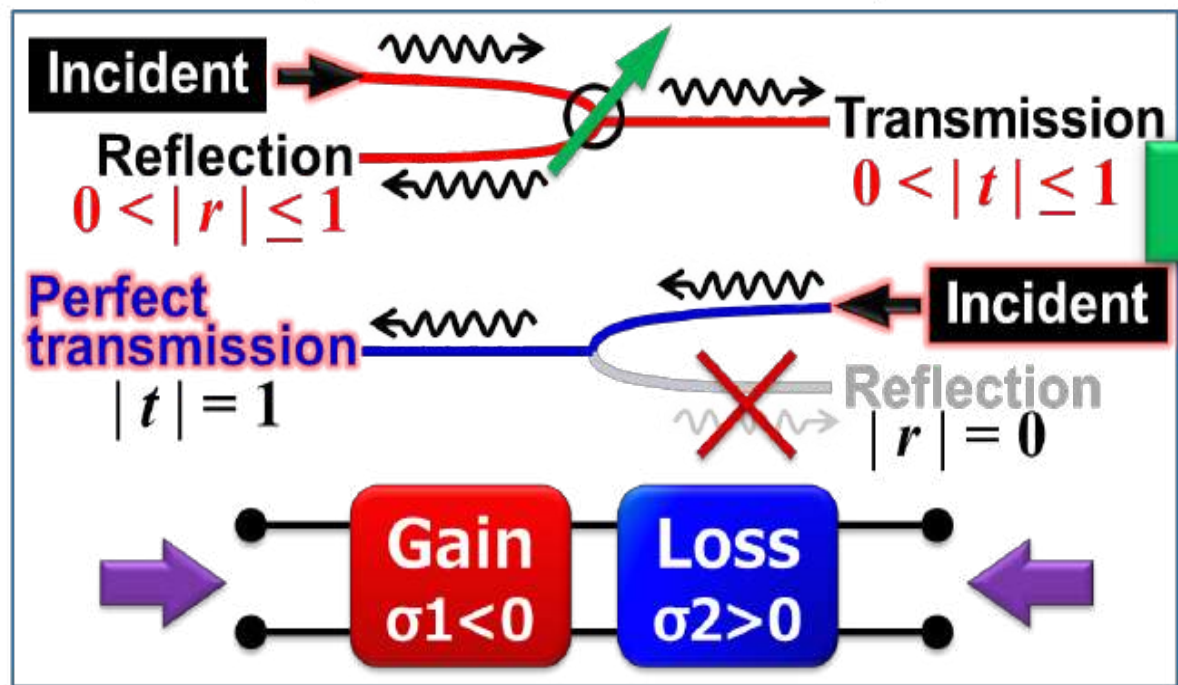


伝送線路トイモデルによるPT 対称性の特異伝搬再現

K. Narahara and T. Otsuji, unpublished.

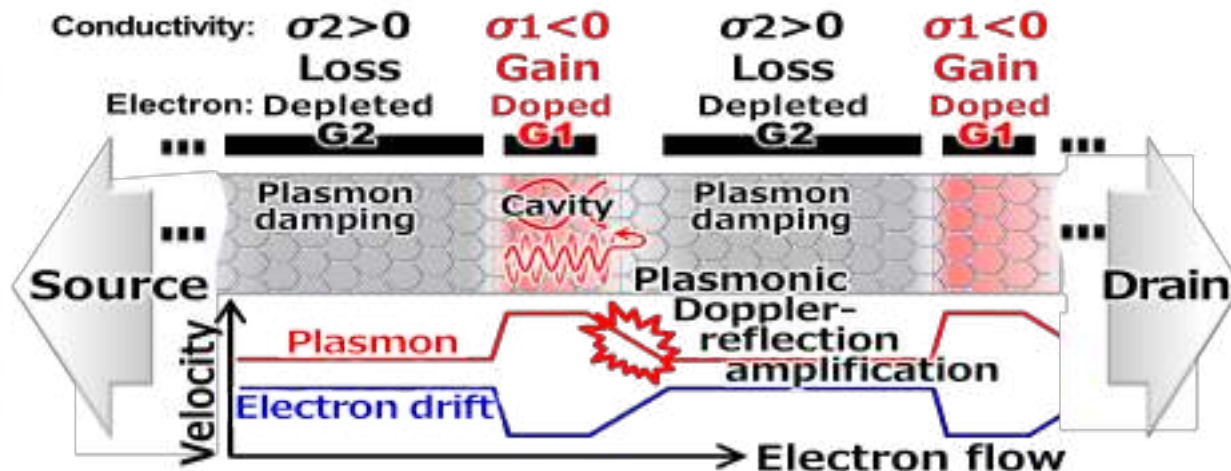


PT Symmetry
 $|\sigma_1| = |\sigma_2|$

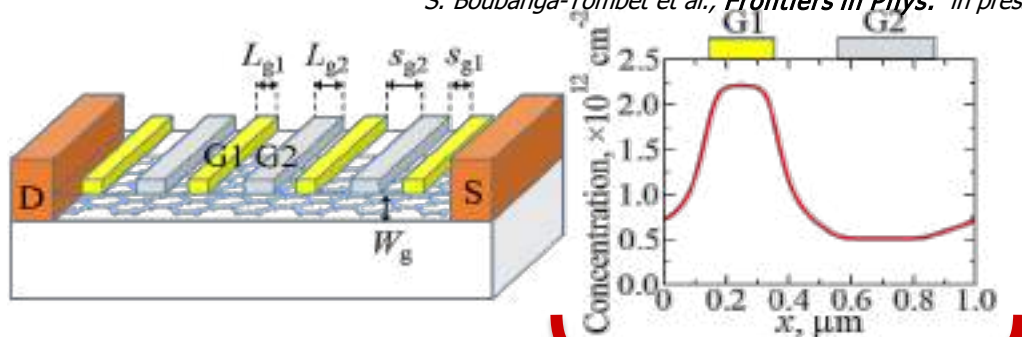


Doppler-Shift-Type Instability

M. Dyakonov, M. Shur, *Phys. Rev. Lett.* **71**, 2465 (1993).

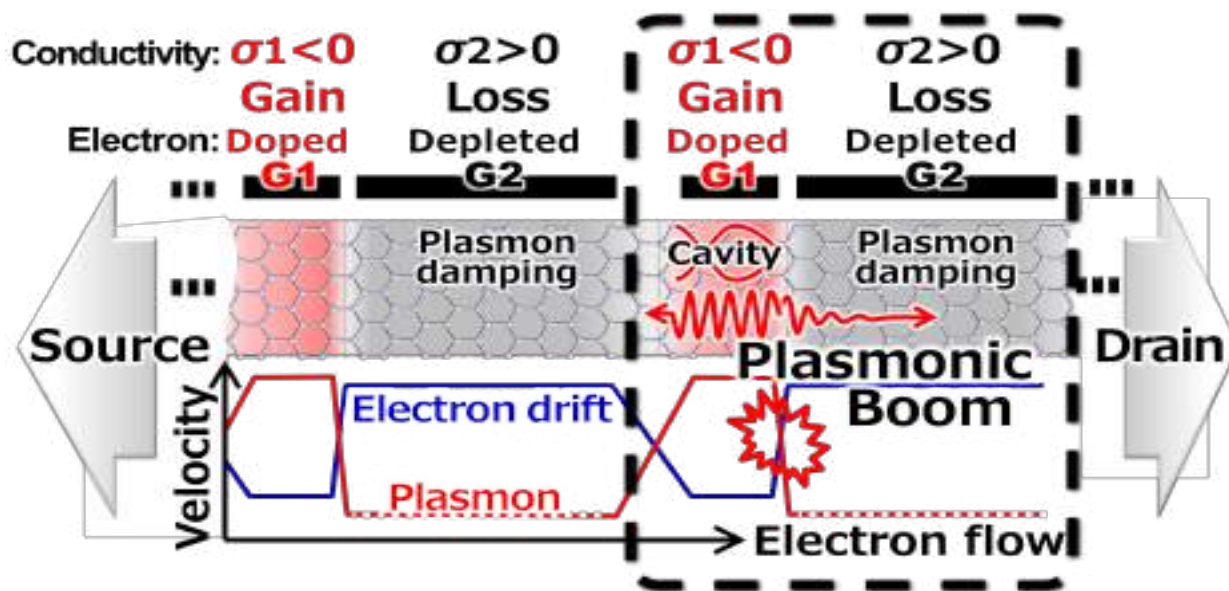


Y. Koseki et al., *Phys. Rev. B* **93**, 245408 (2016).
 S. Boubanga-Tombet et al., *Phys. Rev. X* **10**, 031004 (2020).
 S. Boubanga-Tombet et al., *Frontiers in Phys.* in press.



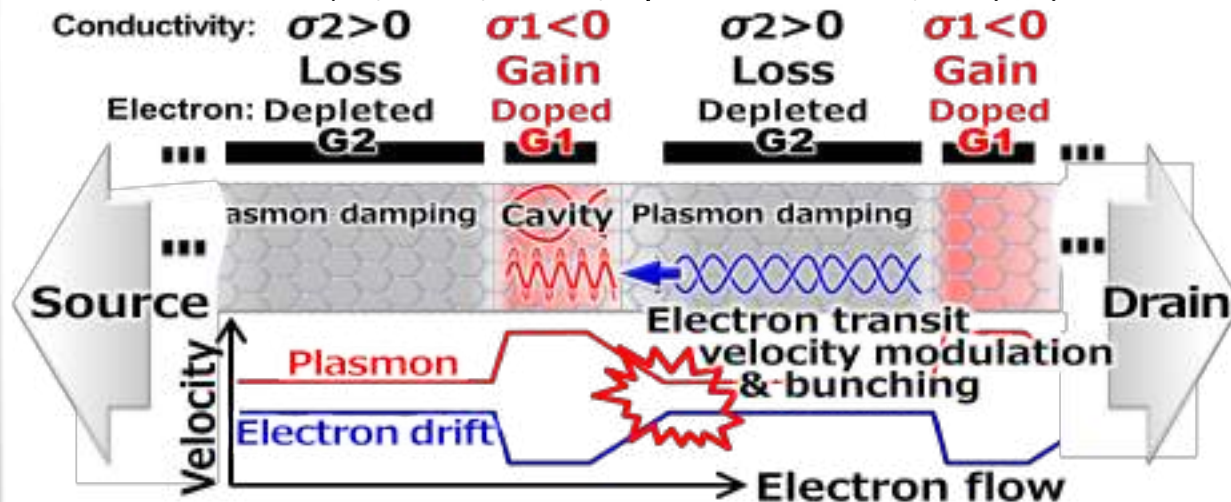
Plasmonic-Boom Instability

G.R. Aizin, J. Micalopas, M. Shur, *Phys. Rev. B* **93**, 195315 (2016).



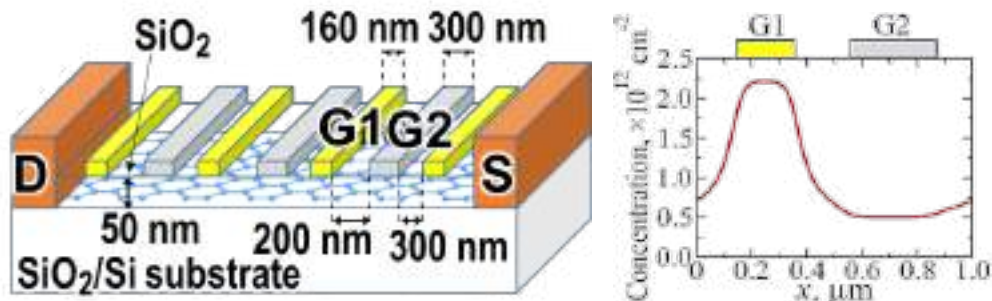
Electron-Transit-Type Instability

V. Ryzhii, A. Satou, M.S. Shur, *Phys. Status Solidi A* **202**, R113 (2005).



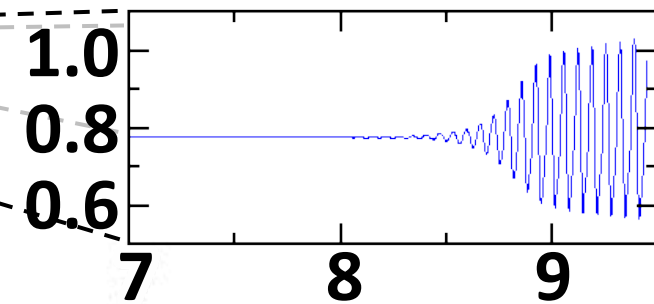
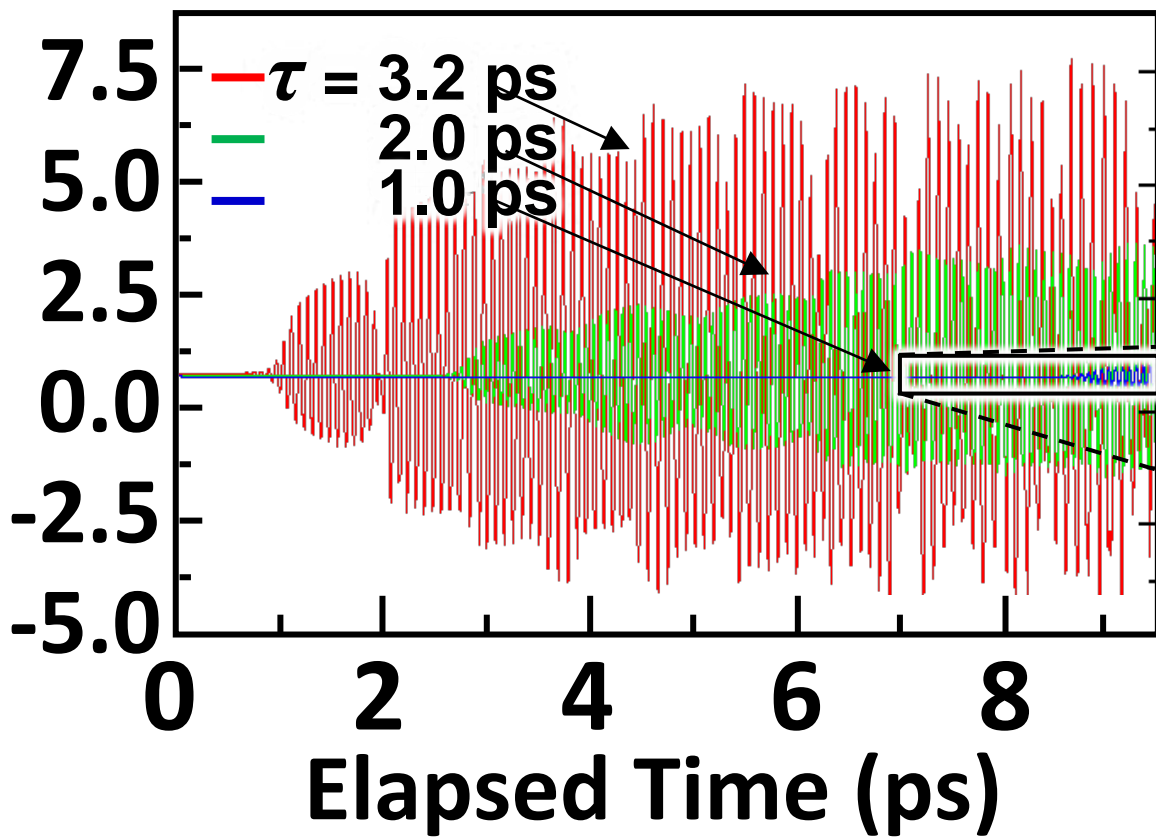
PT 対称性操作によるADGG-GDP不安定性制御とその 超高速レーザー発振直接変調制御の可能性

A. Satou, and T. Otsuji, unpublished.
B. Y. Koseki et al., *Phys. Rev. B* 93, 245408 (2016).



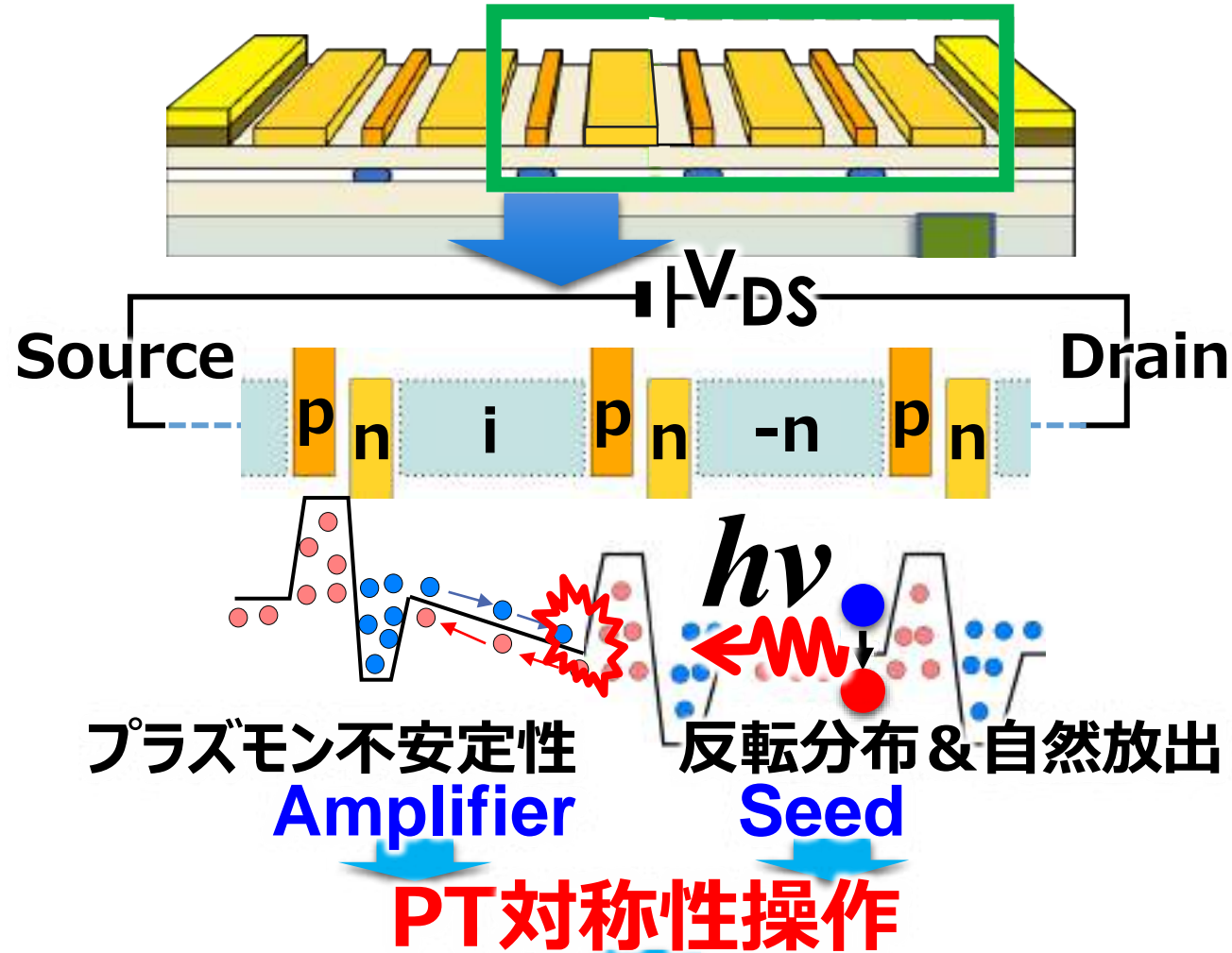
**100-Gbit/s-class
ultrafast data coding
for 6G & 7G
THz wireless comm's
is feasible!!!!**

Electric Field (kV/cm)



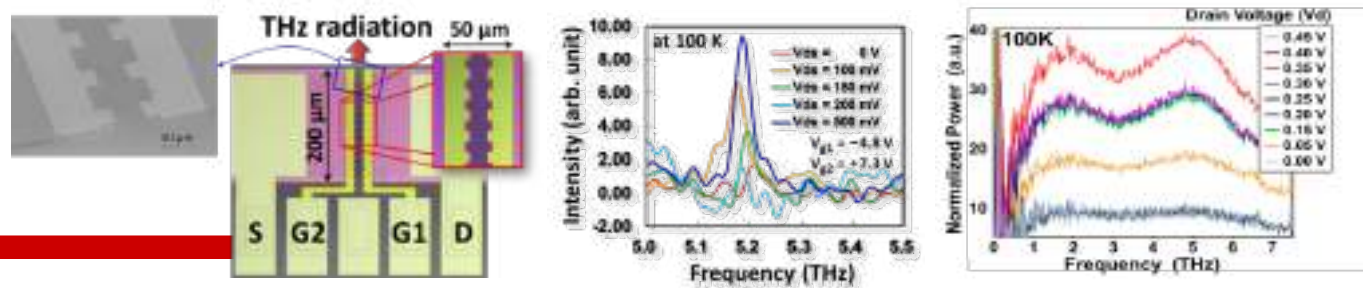
DGG-GDPメタ表面のPT対称性制御による グラフェンプラズモニックTHzレーザートランジスタの創出

T. Otsuji et al., unpublished.

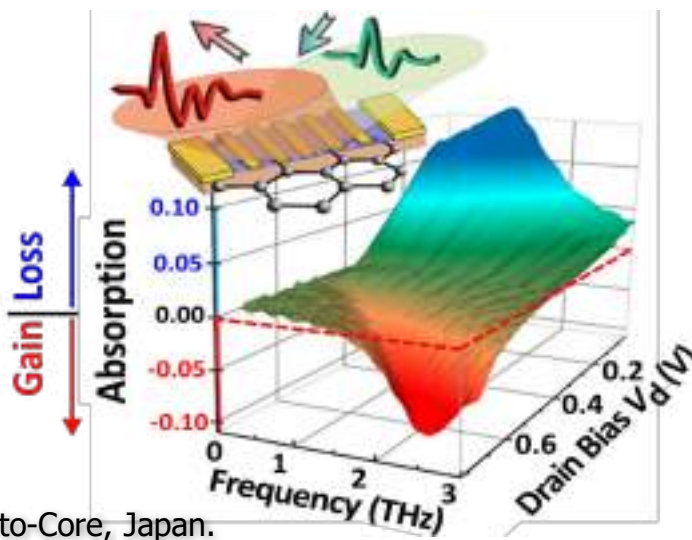
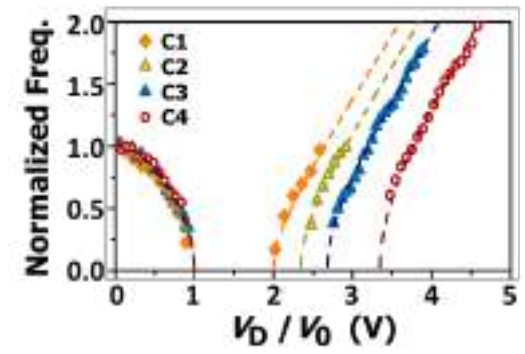
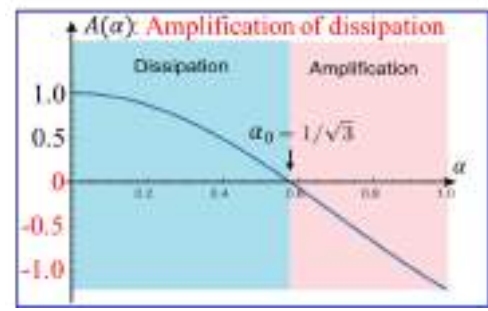
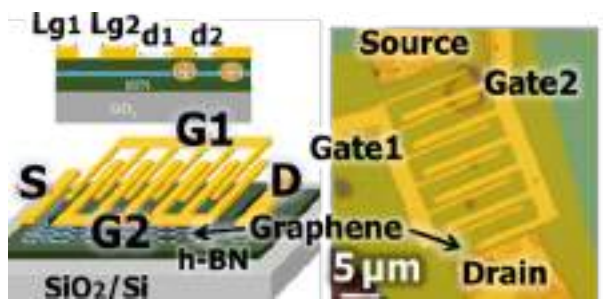


グラフェンプラズモニックTHzレーザートランジスタ

まとめ



- THzギャップ克服のために、グラフェンの2次元電子ガスに励起される“プラズモン”を新たなブレイクスルーとして導入した新原理テラヘルツ波増幅素子を提案した。
- 実験の結果、THz光子がグラフェン電子と直接相互作用して得られる量子効率限界を4倍以上も上回る最大9%の増幅利得を室温下で得ることに成功した。
- 次世代6G, 7G超高速無線通信実現に光明となる成果であり、室温・高強度・高速変調グラフェンプラズモニックTHzレーザートランジスタの実現に期待がかかる。



Financial Supports:

JSPS-KAKENHI (A#20K20349, EXP#21H04546, S#16H06361, SPR#2300008), JST-CREST, JSPS-Jpn-Russ, JSPS Core-to-Core, Japan.

A New Review Book Edition Collecting Original 52 Articles

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Prof. Junichiro Kono
Rice University, USA

"An attractive feature of the book is a well-substantiated physical analysis of possible device applications of graphene-based structures. This topic is a 'hot spot' in solid state device physics and condensed matter physics as well. The authors of the book are widely known to specialists in both of these areas."

Prof. Robert Suris
Member of the Russian Academy of Sciences, A. F. Ioffe Institute, Russia

"Devoted to the fascinating field of plasmonics and optoelectronics in the THz range, this book presents most important theoretical and experimental achievements and is a precious guide for researchers, engineers, and PhD students working on THz physics and technology related to graphene."

Prof. Wojciech Knap
Lab. Charles Coulomb, CNRS & University of Montpellier, France

Graphene demonstrates interesting electrical, optical, and optoelectronic properties. A number of other one-atom-thick material structures have been discovered and studied. Industrially applicable technologies for these structures are currently under active development. The material presented in the book is reviewed in the preface. Part 1 discusses the electronic and plasmonic properties of graphene and heterostructures based on graphene as well as detectors based on lateral transport. Parts 2 to 6 focus on the concepts of detectors and emitters with a special emphasis on plasmonic enhancement of those devices as well as on population inversion and lasing. The key advantage of the several detectors and emitters presented in the book is their ability to work at room temperature.

In spite of enormous research in the area of devices based on graphene, the number of extensive review publications on terahertz devices based on graphene is small. This review volume fills the gap. Researchers and engineers working in the fields of electronics and plasmonics can use it to learn about new concepts in the field of graphene devices and to understand the influence of plasmonics on device performance. The book can be also used as a required text for doctorate courses and as a supplementary material for postgraduate courses.



Vladimir Mitin is SUNY Distinguished Professor at the University of Buffalo, USA. He is a fellow of IEEE, SPIE, APS, AAAS, IoP, and Humboldt. He has authored or coauthored more than 270 papers in peer-reviewed journals, seven textbooks, and four monographs; his field of specialization is nanomaterials and nanodevices.



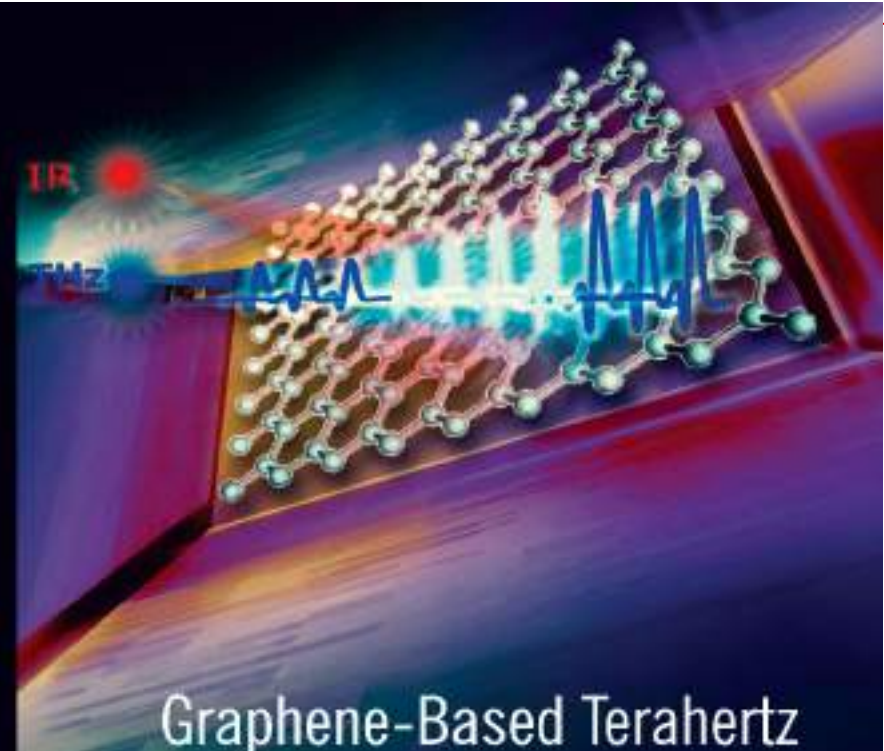
Taiichi Otsuji is a professor at the Research Institute of Electrical Communication, Tohoku University, Japan. He is a fellow of the IEEE, OSA, and JSAR. He has authored or coauthored 250 peer-reviewed journal papers and holds seven US patents. His current research interests include terahertz photonic/plasmonic nanodevices and systems.



Victor Ryzhii is a principal researcher at the Institute of Ultra-High-Frequency Semiconductor Electronics, Russia, and a visiting professor at the Research Institute of Electrical Communication, Tohoku University, Japan. He has authored or coauthored more than 400 research publications. Dr. Ryzhii has been a member of the Russian Academy of Sciences (since 1987) and is also an IEEE and APS fellow.

Graphene-Based Terahertz
Electronics and Plasmonics

Mitin | Otsuji | Ryzhii



Graphene-Based Terahertz Electronics and Plasmonics Detector and Emitter Concepts

edited by

Vladimir Mitin | Taiichi Otsuji | Victor Ryzhii

ご清聴をありがとうございました。