TILA

Tiny Integrated Laser

小型集積レーザー
コンソーシアム

マイクロ固体フォトニクス研究会
第２回レーザー学会「小型集積レーザー」専門委員会
第２回科学技術交流財団「ジャイアントン・マイクロフォトニクス」研究会
自然科学研究機構　分子科学研究所、愛知県岡崎市内
Sept. 22, 2021

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

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 Taiichi Otsuji

Phys. Rev. X **10**, 031004 – Published 6 July 2020

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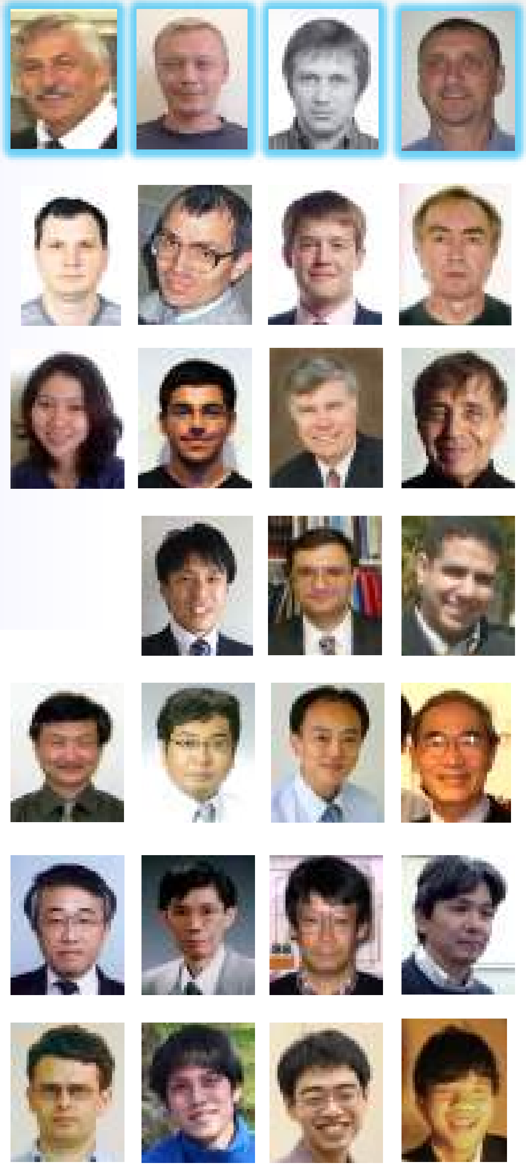
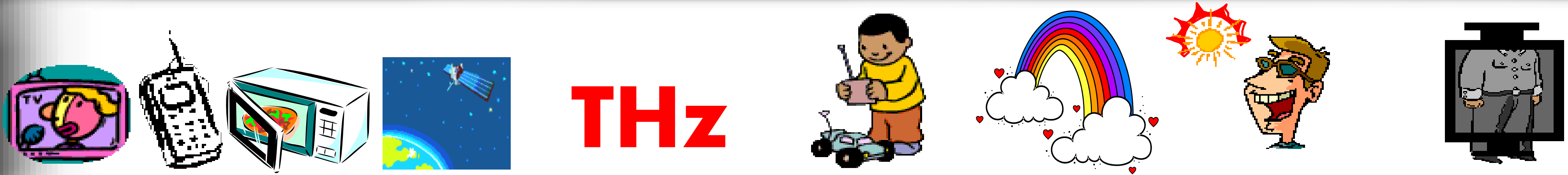
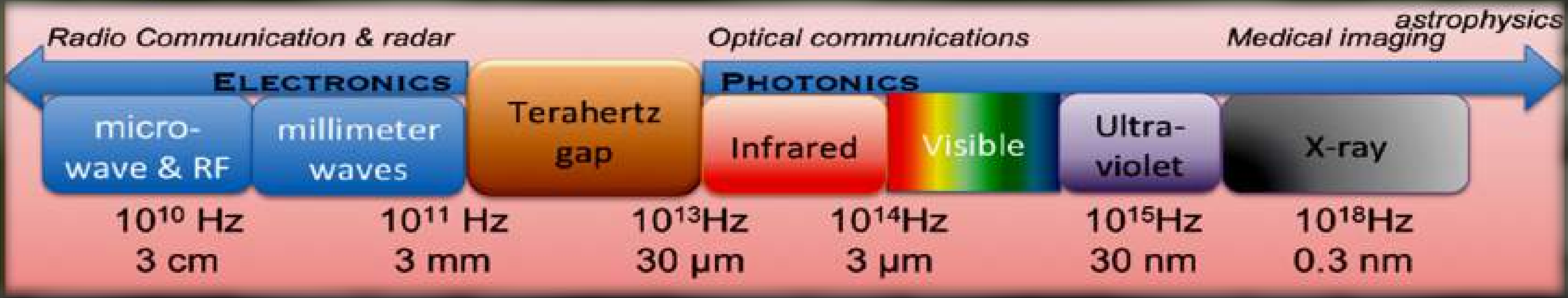


発表の内容

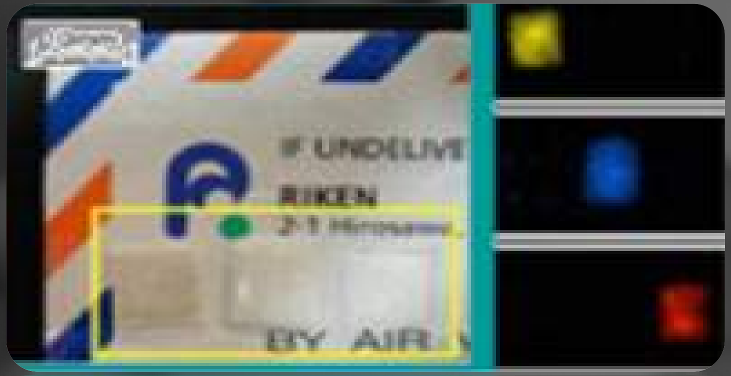
- 研究の背景と目的
- グラフェンの光電子物性
- グラフェンのテラヘルツ(THz)レーザー応用
- グラフェンプラズモンとその巨大THz利得増強作用
- グラフェンTHzレーザートランジスタの新しい展開
- まとめ

テラヘルツ波とは？


TV
THz


Radio Communication & radar
Optical communications
Medical imaging
astrophysics
ELECTRONICS
PHOTONICS
micro-wave & RF
millimeter waves
Terahertz gap
Infrared
Visible
Ultra-violet
X-ray
10^10 Hz 3 cm
10^11 Hz 3 mm
10^13Hz 30 µm
10^14Hz 3 µm
10^15Hz 30 nm
10^18Hz 0.3 nm


Ubiquitous ICT
Hello!
Bonduel!


BY AIR

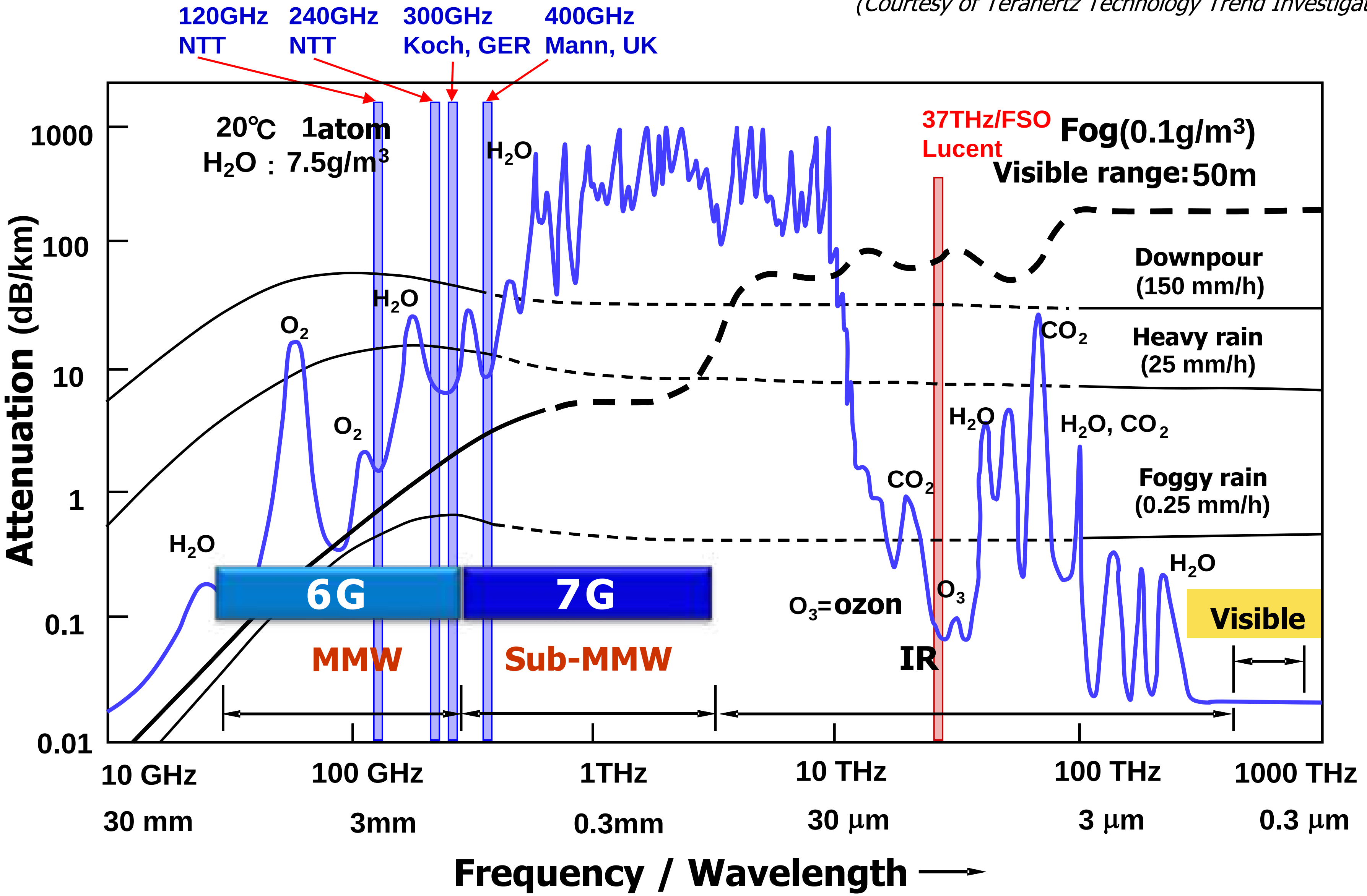
テラヘルツ波が拓く超高速無線通信の世界

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

(IEEE Spectrum May 2018.)

大気の電磁波吸収と通信応用の可能性

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



JST-ANR SICORP (2010~2013) の成果

サブTHz高速無線通信実現の課題

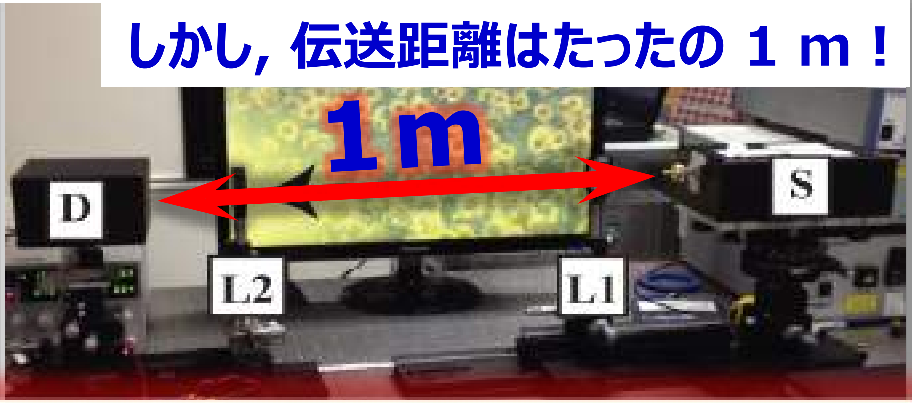
T. Nagatsuma et al., **Opt. Express 21**, 23736 (2013).

8K Ultra-HDTV

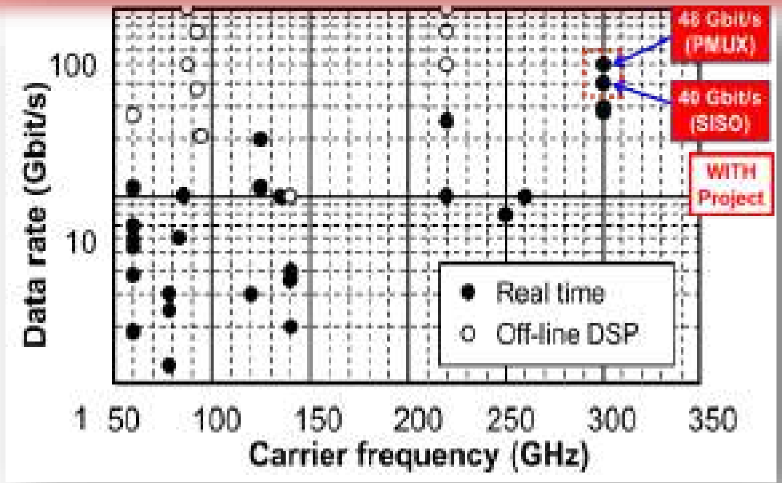
- Available in 2020
- Scanning lines >4000
- Uncompressed at 72Gbps
- Carrier freq. ~1000GHz

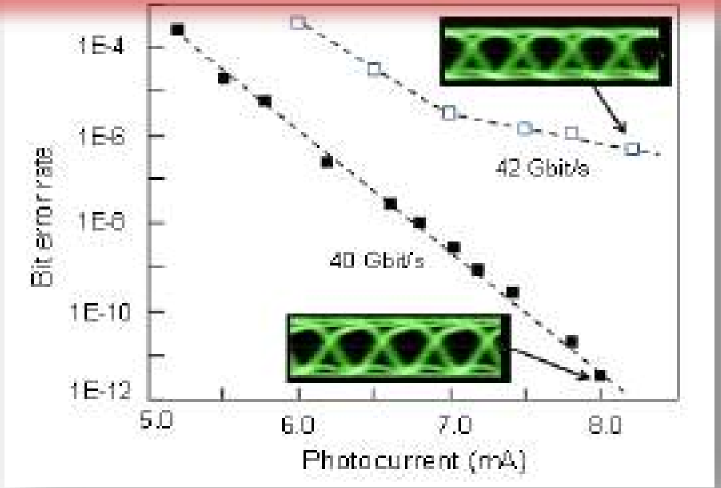
300 GHz帯で48 Gbit/s 無線伝送に成功

しかし, 伝送距離はたったの 1 m！



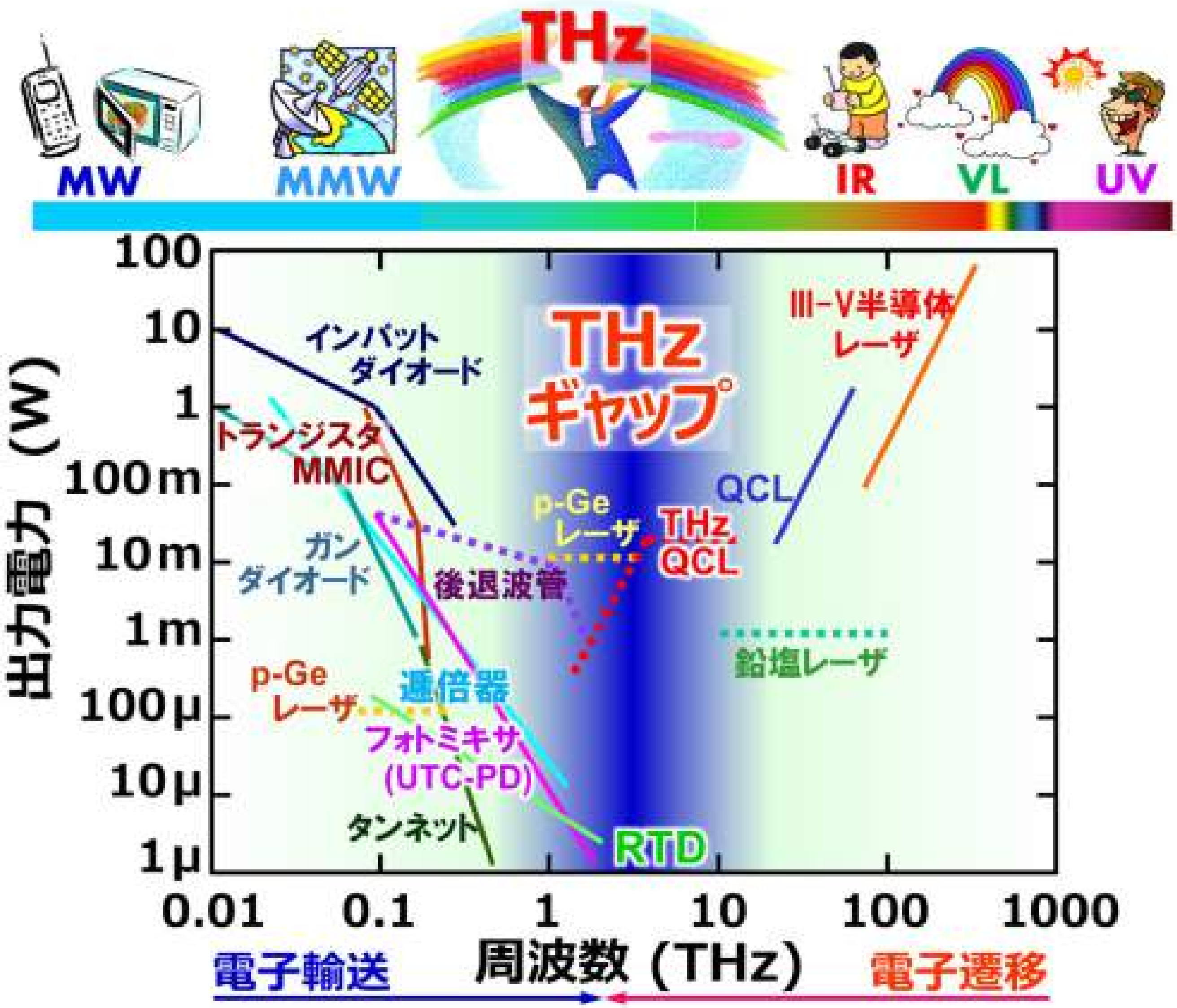
実用的な超高速THz無線の実現には
光源の高出力・高周波化と検出器の高感度化が不可欠！





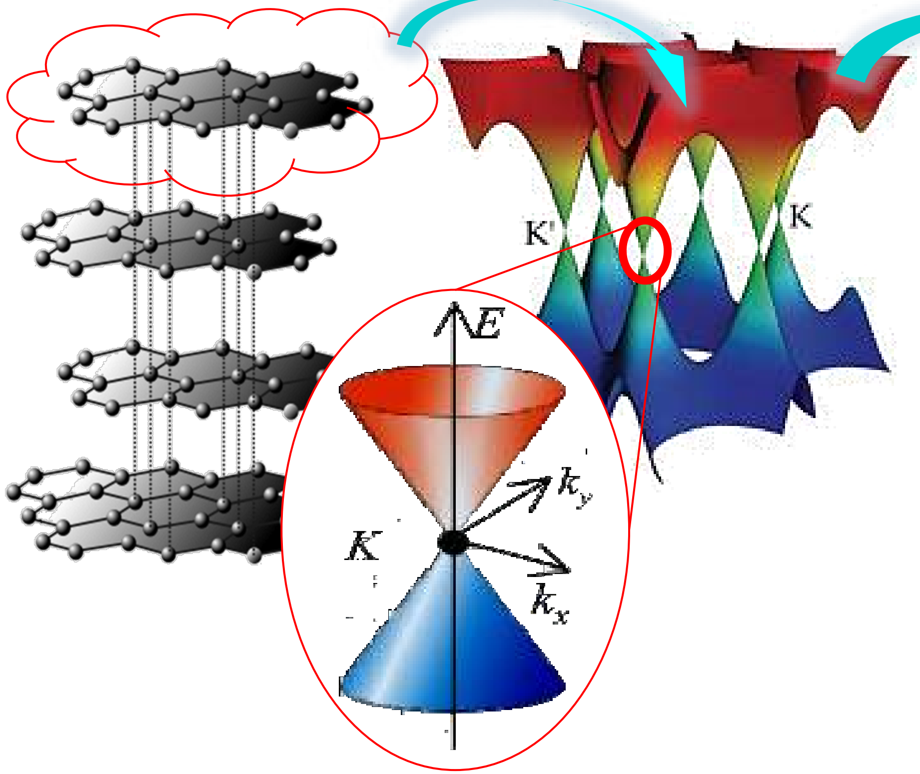
THzギャップ

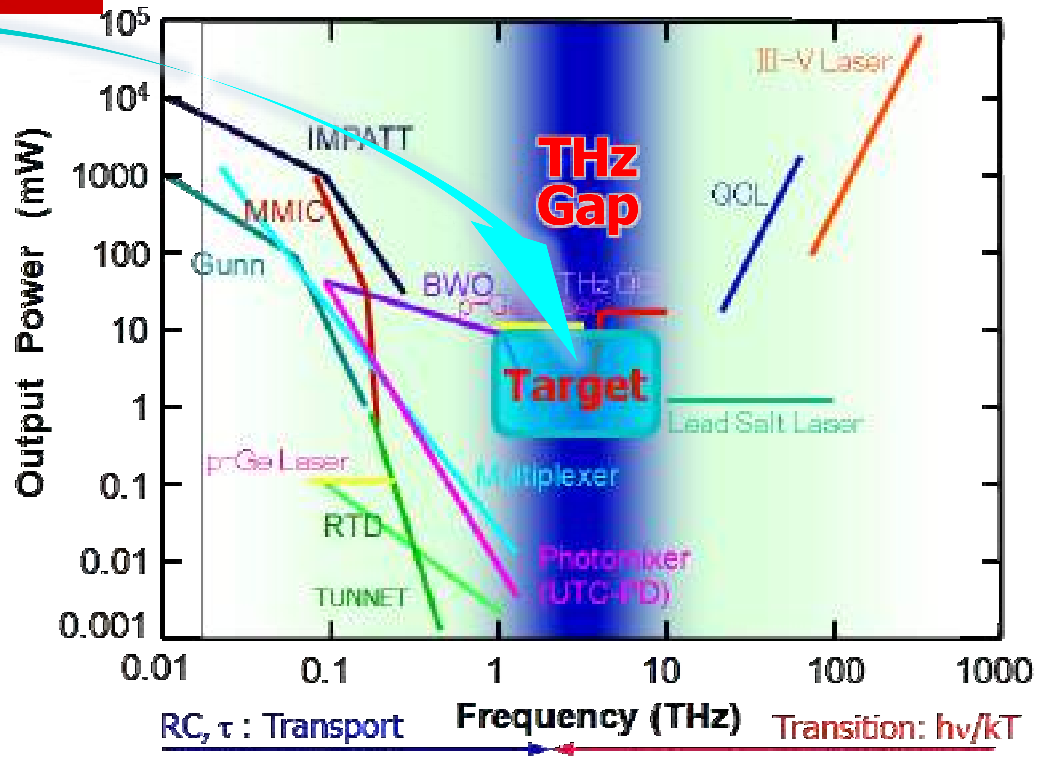
M. Tonouchi, **Nature Photon.** 1, 97-105 (2007).



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).



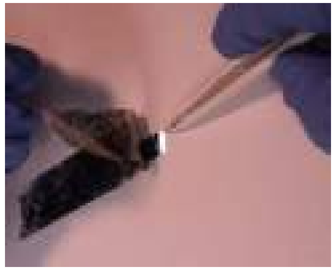


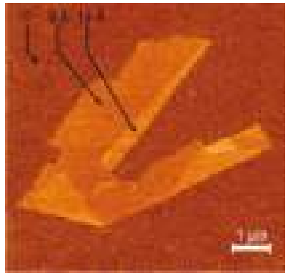
- **Mono-layer of sp² bonded carbon atoms in a honeycomb lattice.**
- **Massless Dirac Fermions obey linear dispersion relation at K & K′ points.**
- **High carrier mobility μ >200,000 cm²/Vs at RT.** **(*cf.* InGaAs: μ ~ 12,000 cm²/Vs)**

グラフェンの製膜方法

- **Peeling from HOPG (highly oriented pyrolytic graphite)**
  - **Highest mobility obtained**
  - **Reproducibility is challenging**

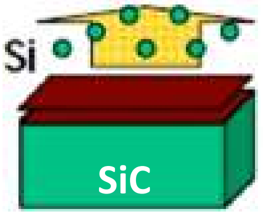
  *A. Geim and K. Novoselov, **Nat. Mat. 6**, 184 (2007).*





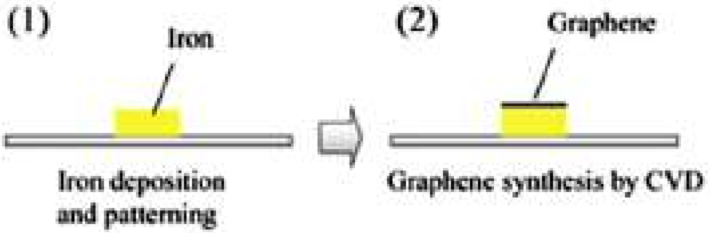
- **Epitaxial graphene: thermal decomposition of hexagonal SiC**
  - **Process temperature rather high ~1000**
  - **Better mobility than CVD growth**

  *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**

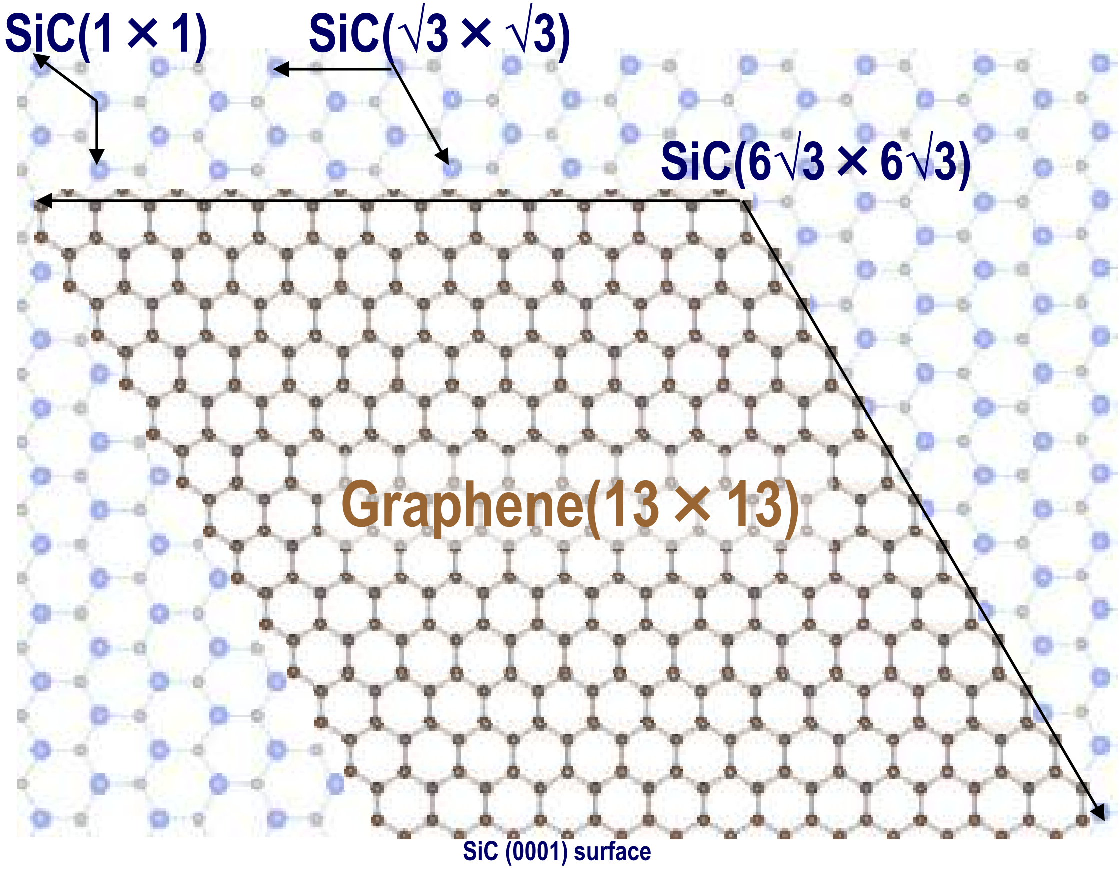
  *J. Bae et al, **Nature Nanotech. 5**, 574 (2010).*
  *H. Ago et al., **ACS Nano 4**, 7404 (2010).*

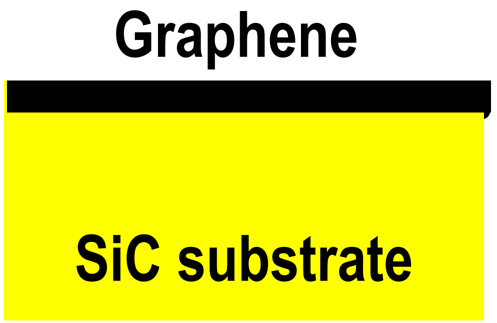


熱分解法によるH-SiC基板からのエピタキシャルグラフェン製膜

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

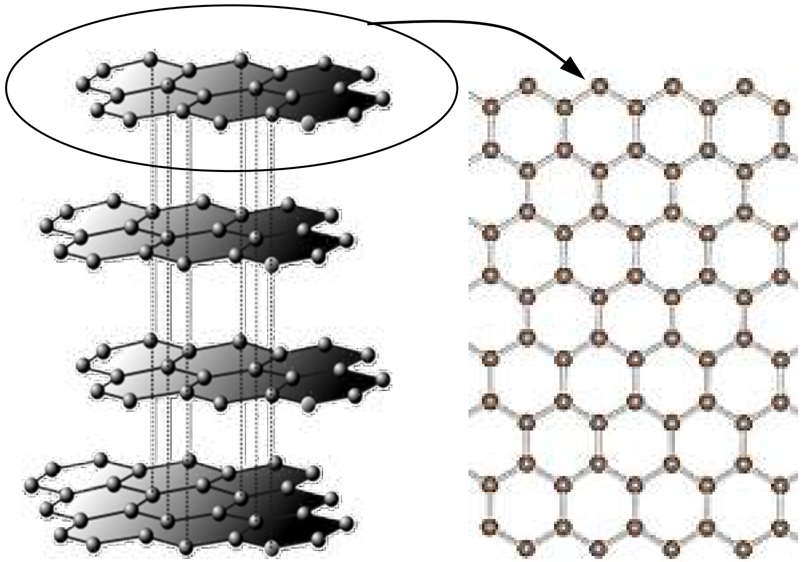
By annealing a hexagonal 6H-SiC substrate at a high temperature in vacuum, the surface changes to graphene.

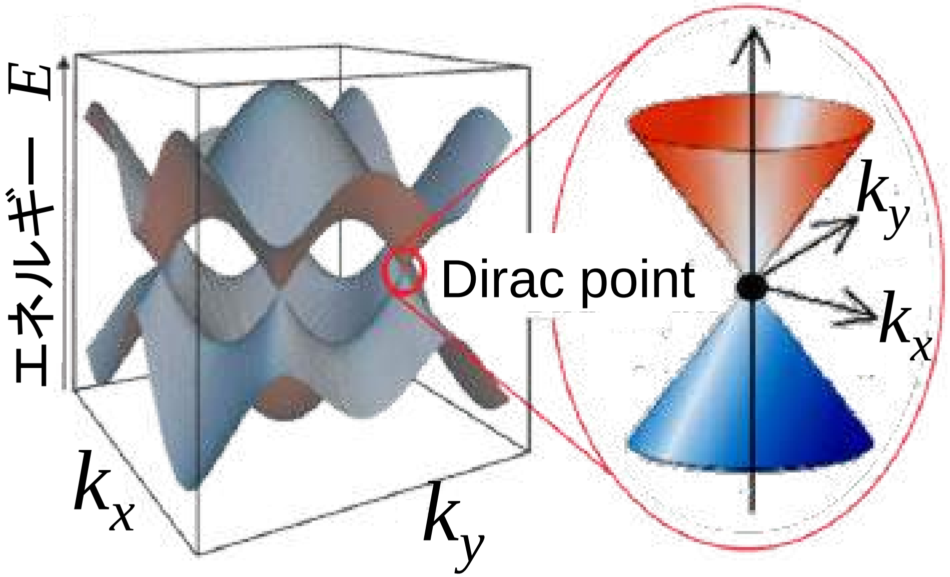


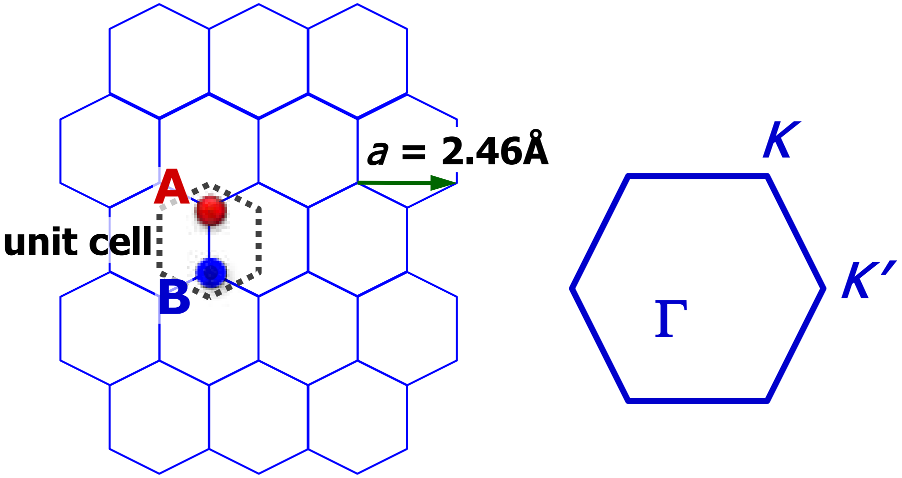


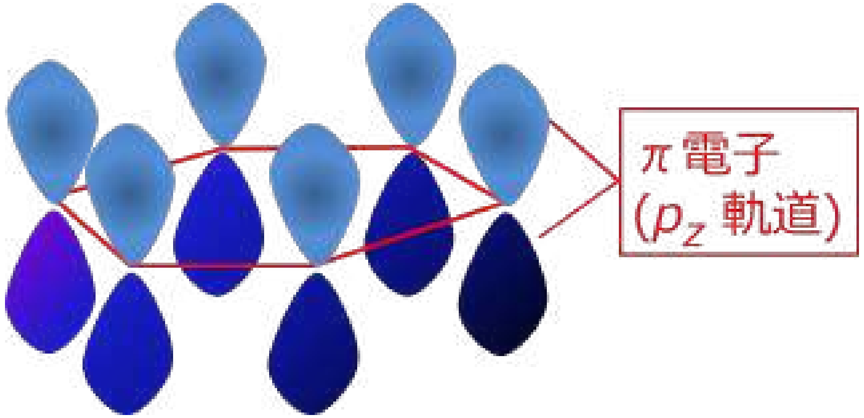
● : Si atom
• : C atom

グラフェンの結晶構造とバンド構造



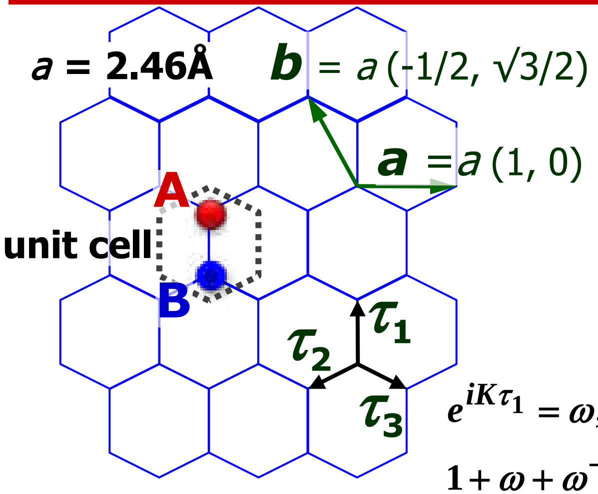


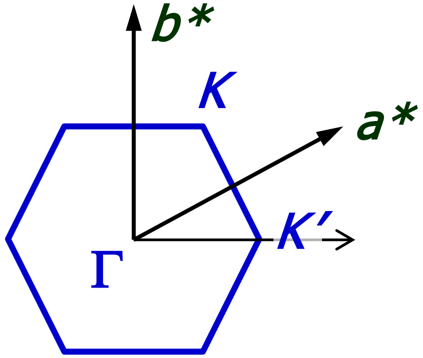




Energy Band Structures in Graphene

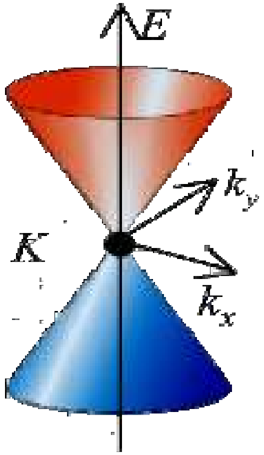
T. Ando , ***JPSJ 74***, 777 (2005).

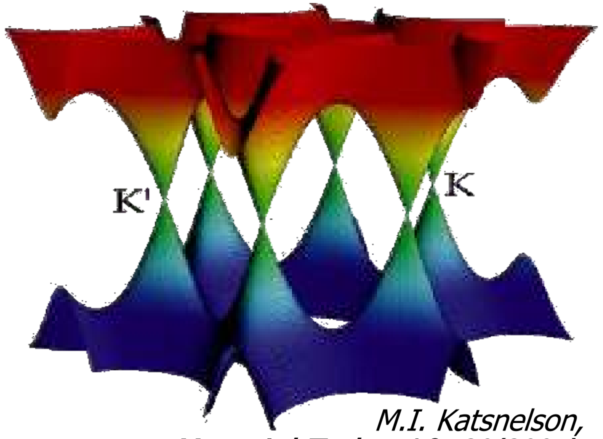




$$e^{iK\tau_1}=\omega,\quad e^{iK\tau_2}=\omega^{-1},\quad e^{iK\tau_3}=1$$

$$1+\omega+\omega^{-1}=0$$





M.I. Katsnelson, *Material Today 10*, 20(2007).

π band electron:

$$\psi(\mathbf{r})=\sum_{R_A}\psi_A(R_A)\phi(r-R_A)+\sum_{R_B}\psi_B(R_B)\phi(r-R_B)$$

$$=\sum_{R_A}f_A(k)e^{ik\cdot R_A}\phi(r-R_A)+\sum_{R_B}f_B(k)e^{ik\cdot R_B}\phi(r-R_B)$$

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

Tight-Binding Approx.:

$$\varepsilon\psi_A(\mathbf{R}_A)=-\gamma_0\sum_{l=1}^{3}\psi_B(\mathbf{R}_A-\tau_l)$$

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

Hamiltonian:

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

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

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

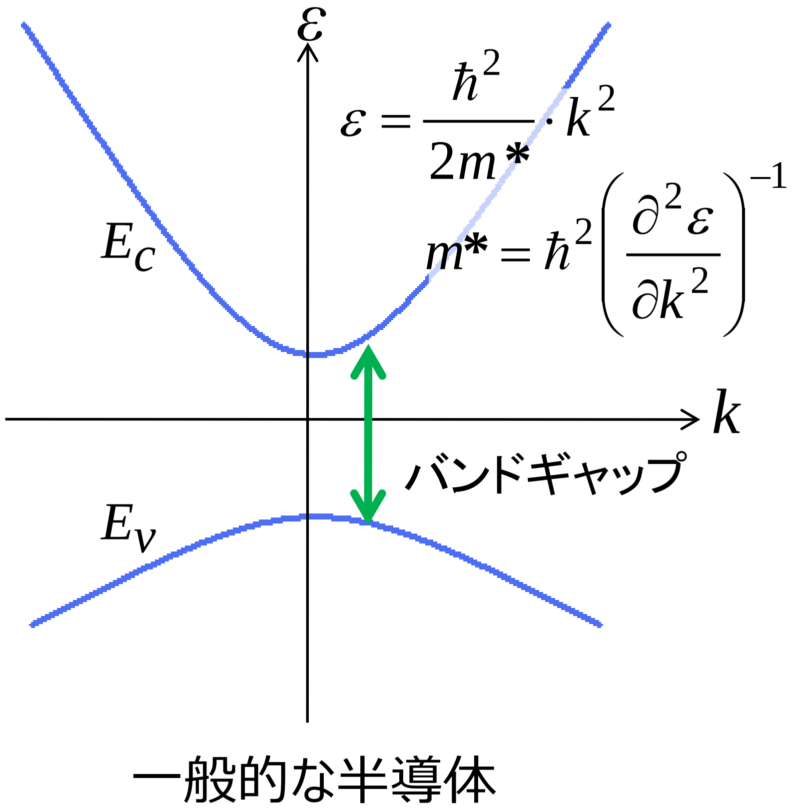
$$\frac{\sqrt{3}}{2}a\gamma_0\begin{pmatrix}0 & k_x-ik_y\\ k_x+ik_y & 0\end{pmatrix}\begin{pmatrix}\bar{f}_A(\mathbf{k})\\ \bar{f}_B(\mathbf{k})\end{pmatrix}=\varepsilon\begin{pmatrix}\bar{f}_A(\mathbf{k})\\ \bar{f}_B(\mathbf{k})\end{pmatrix}$$

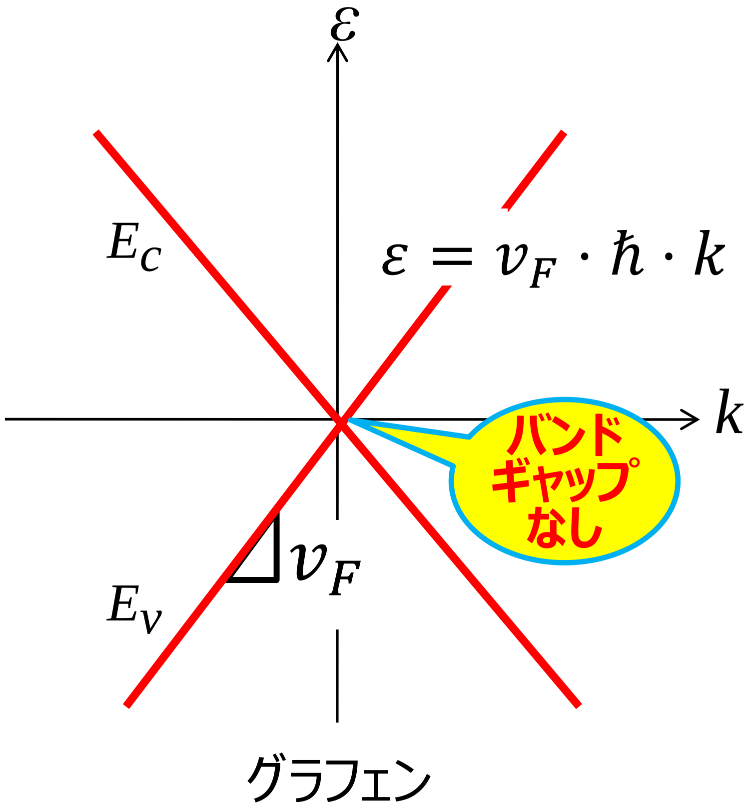
Eigenvalues:

$$\det(\varepsilon\boldsymbol{I}-\boldsymbol{H})=0 \;\Rightarrow\; \varepsilon=E(k)=\pm v_F\hbar|k|$$

$$v_F\approx10^8\ \mathrm{cm/s}$$

グラフェンのバンド構造





- 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 ⇒ 有効質量 $m^* = 0$
- 電子とホールの輸送特性が完全に対象

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

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

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

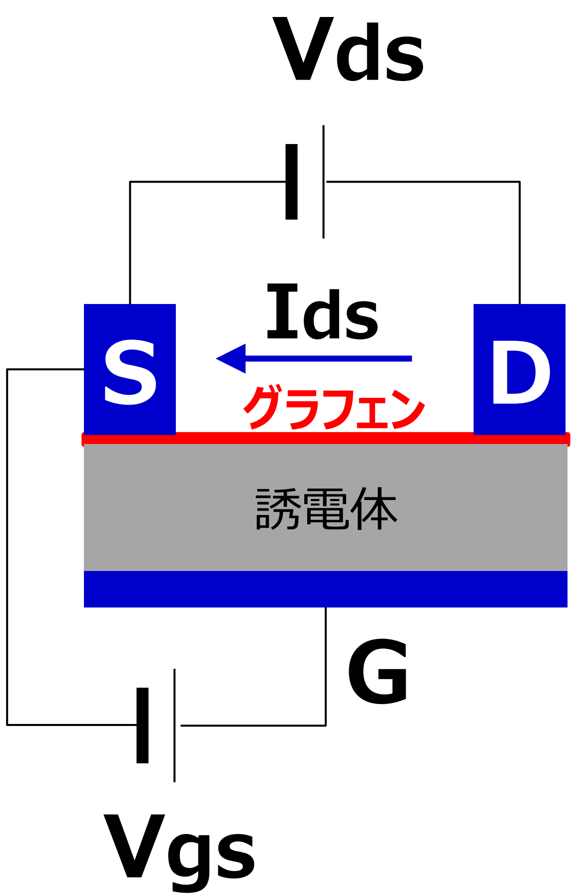
$$m \Leftrightarrow \frac{p}{v_F} = \frac{\varepsilon}{v_F^2}$$

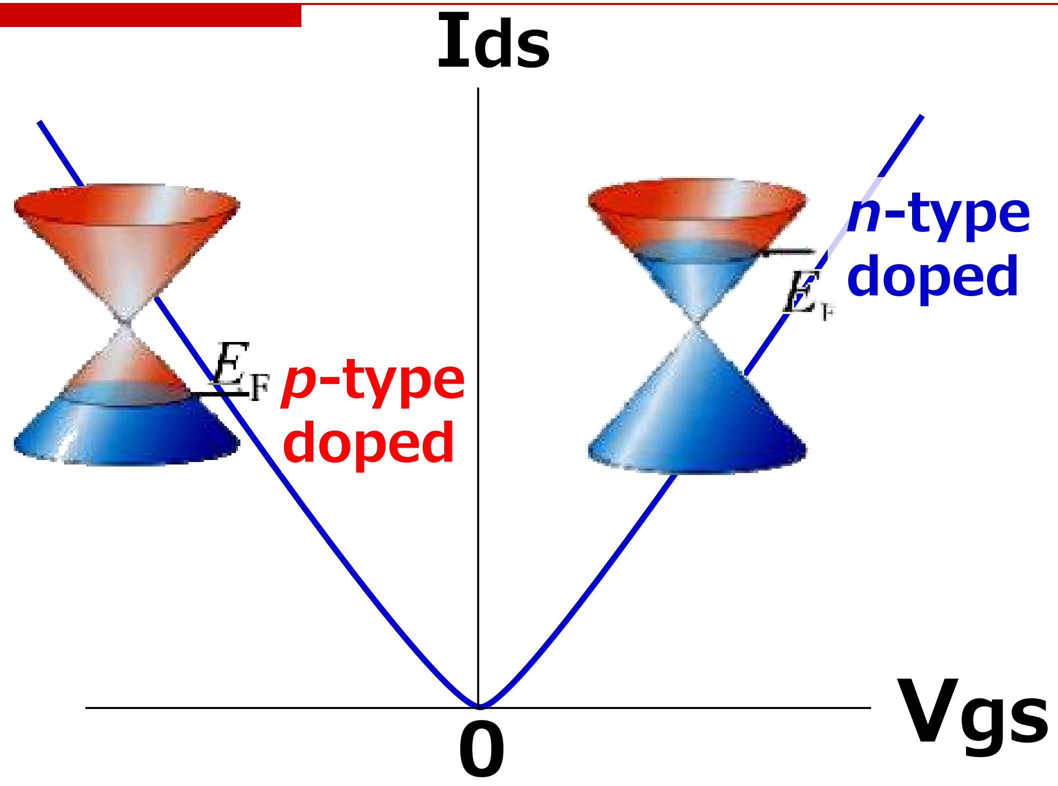
$$\Rightarrow \mu = \frac{e {v_F}^2 \tau}{\varepsilon_F}$$

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

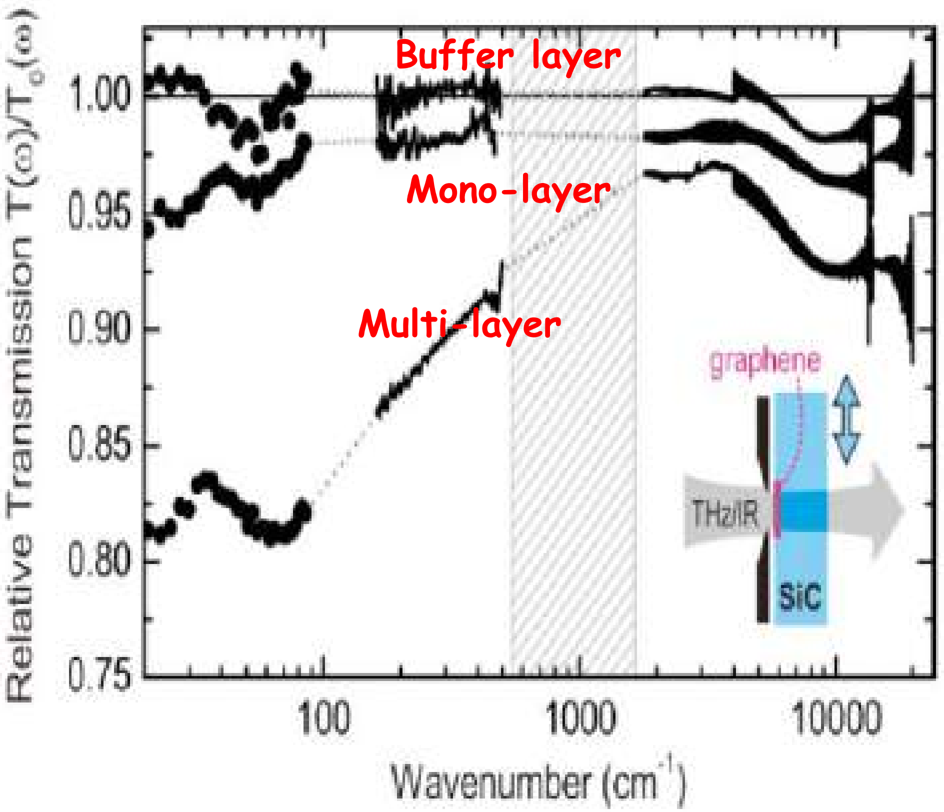




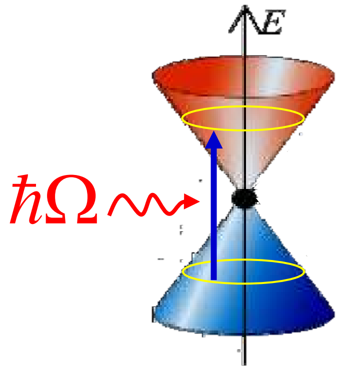
- バンドギャップがないため、
  しきい値以上のVgsでは電子が
  しきい値以下のVgsでは正孔が
  誘起され、オフできない！

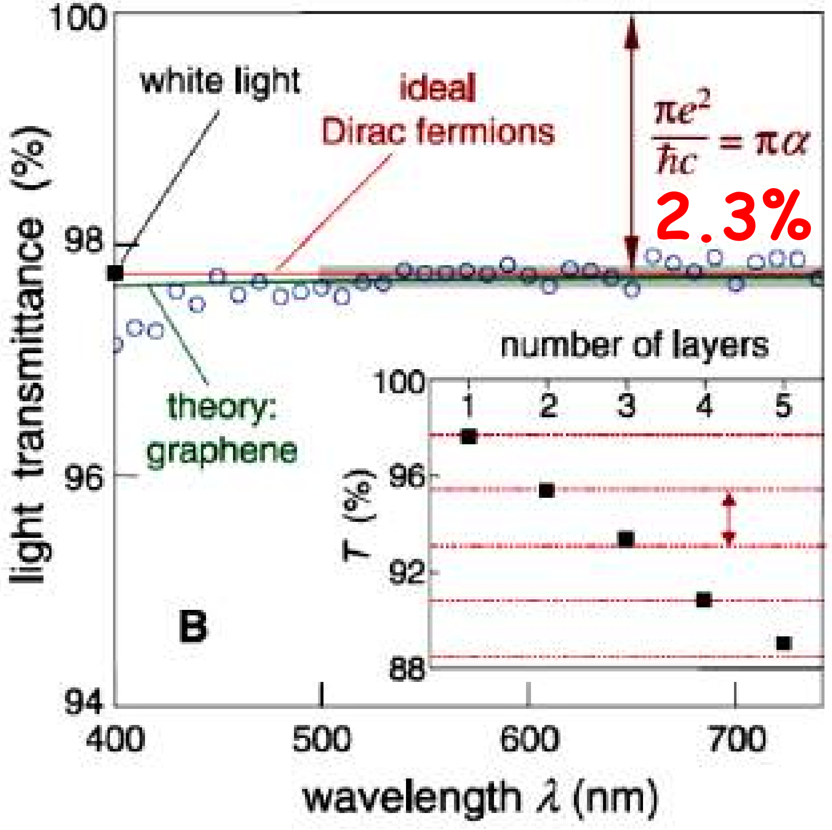
グラフェンの超広帯域＆フラットなバンド間光学吸収

Photon absorption in Graphene via interband transition is
- **flat over the linear dispersive energy range**
- **limited to ~2.3%/layer by $\pi e^2/\hbar c$!**



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



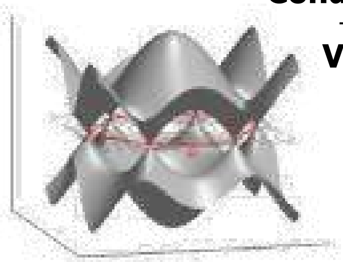


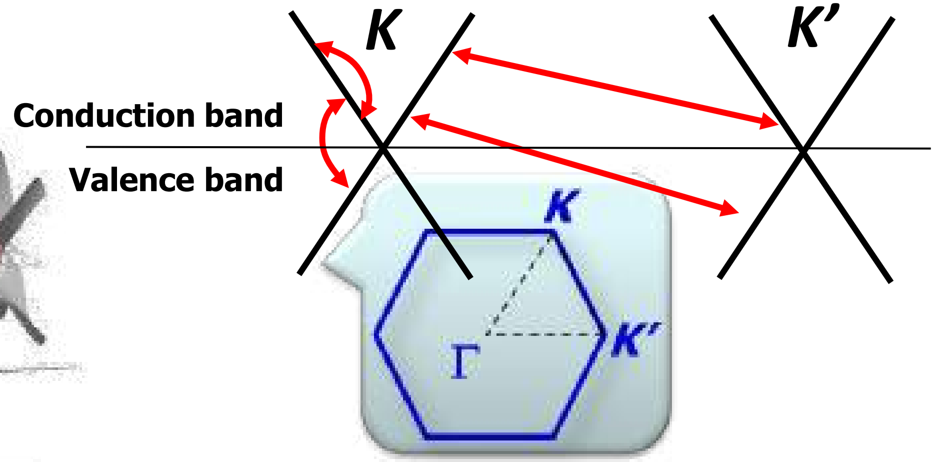
R.R. Nair et al., ***Science* 320**, 1308 (2008).

グラフェンのフォノン物性

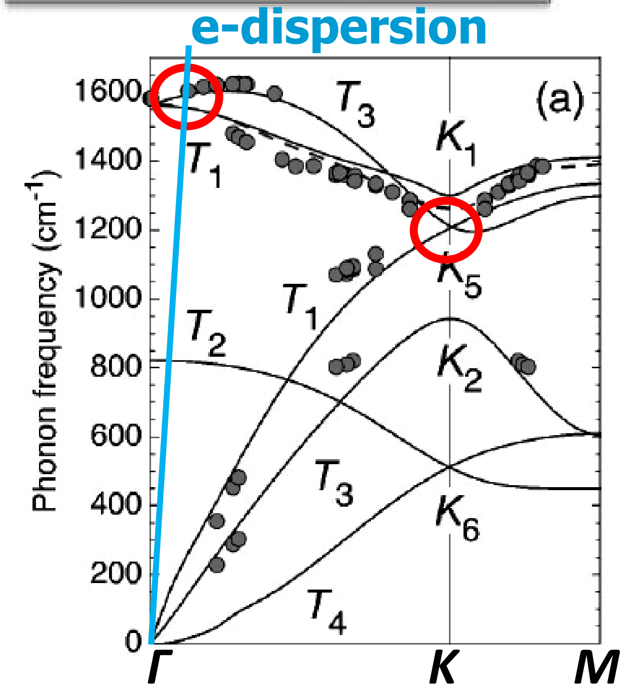
Carriers interact with:

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





Phonon dispersion



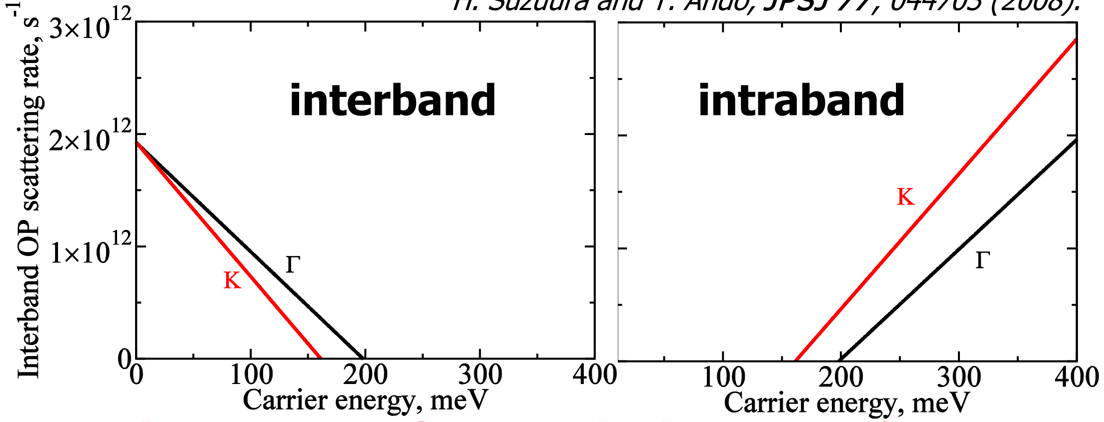
J. Maultzsch, *PRB 70*, 155403 (2004).

Scattering rates

$$W^{(\pm)}_{A,inter/tra}(l\mathbf{k},l\mathbf{k}')=\frac{2\pi}{\hbar}\left|\langle l\mathbf{k}'|H_{A,inter/tra}|l\mathbf{k}\rangle\right|^2\cdot\delta(k-k'\pm\omega/v_F)=\frac{1}{\tau^{(\pm)}_{A,inter/tra}}$$

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

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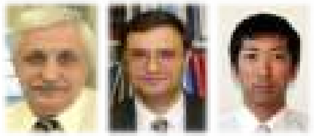
- グラフェンプラズモンとその巨大THz利得増強作用
- グラフェンTHzレーザートランジスタの新しい展開
- まとめ

TOHOKU UNIVERSITY RIEC

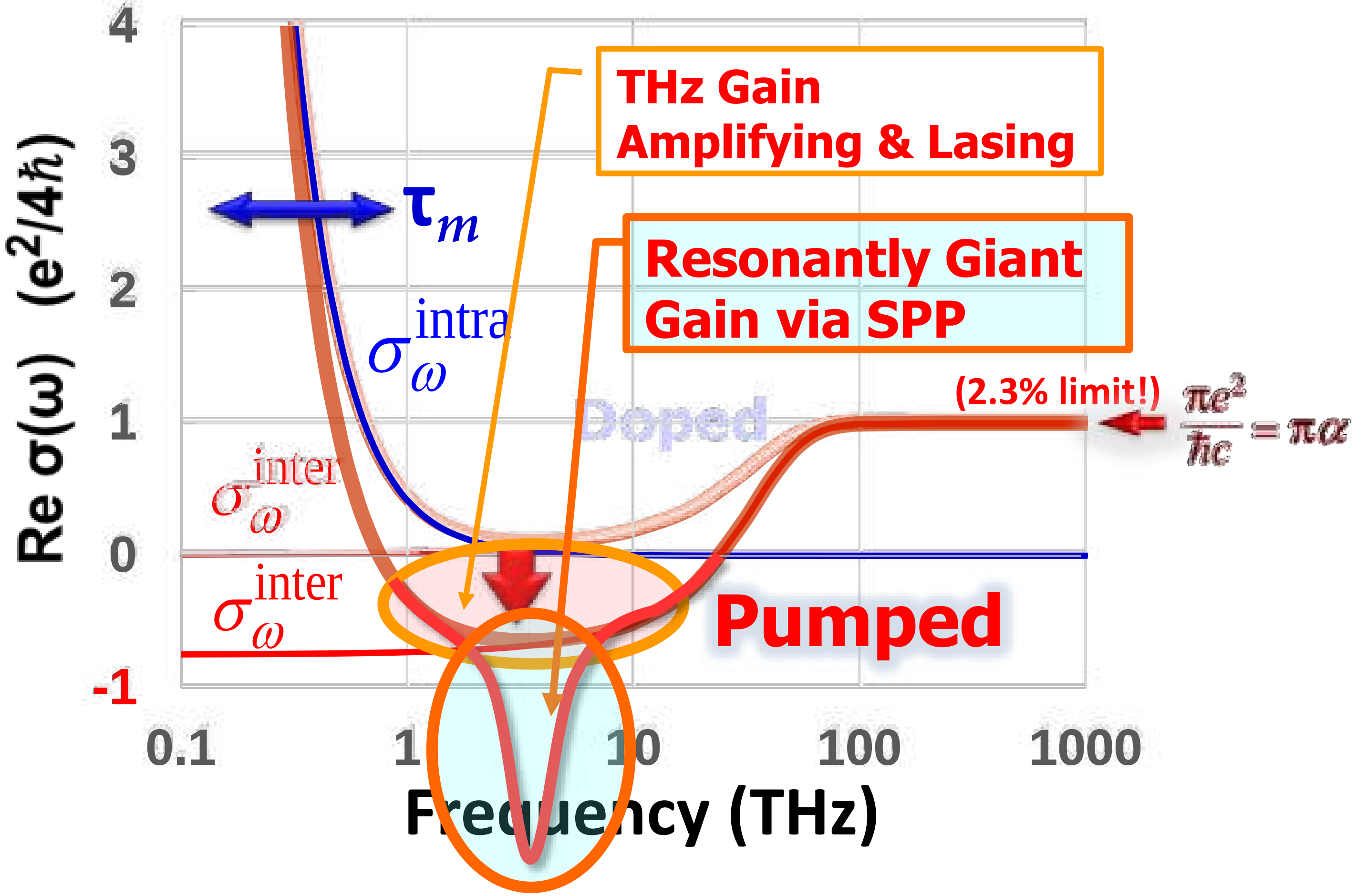
グラフェンの光学導電率

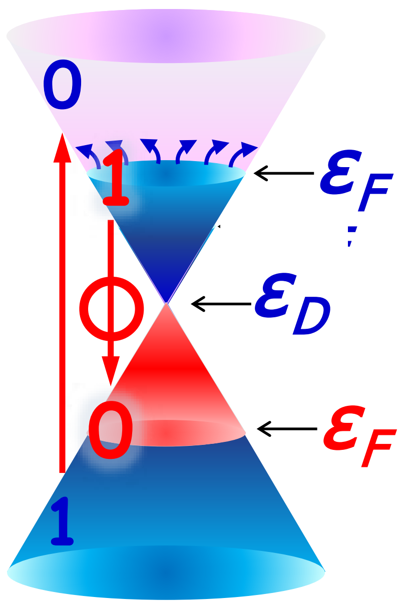


L.A. Falkovsky & S.S. Pershoguba ***PRB* 76**, *153410 (2007).*

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

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





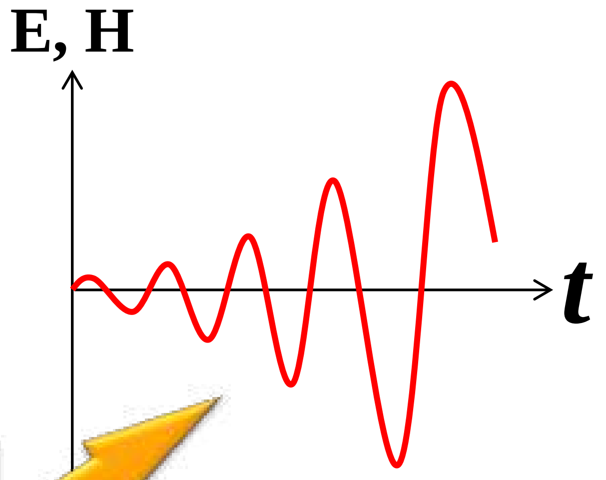
A.A. Dubinov et al., ***J. Phys.: Condens. Matter 23** 145302 (2011).*
S. Boubanga Tombet et al., ***PRB 85**, 035443 (2012).*
T. Watanabe et al., ***New J. Phys. 15**, 075003 (2013).*

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！

$$\nabla\cdot\boldsymbol{B}=0$$
$$\nabla\times\boldsymbol{E}+\frac{\partial\boldsymbol{B}}{\partial t}=\boldsymbol{0}$$
$$\nabla\cdot\boldsymbol{D}=\rho$$
$$\nabla\times\boldsymbol{H}-\frac{\partial\boldsymbol{D}}{\partial t}=\boldsymbol{j}$$

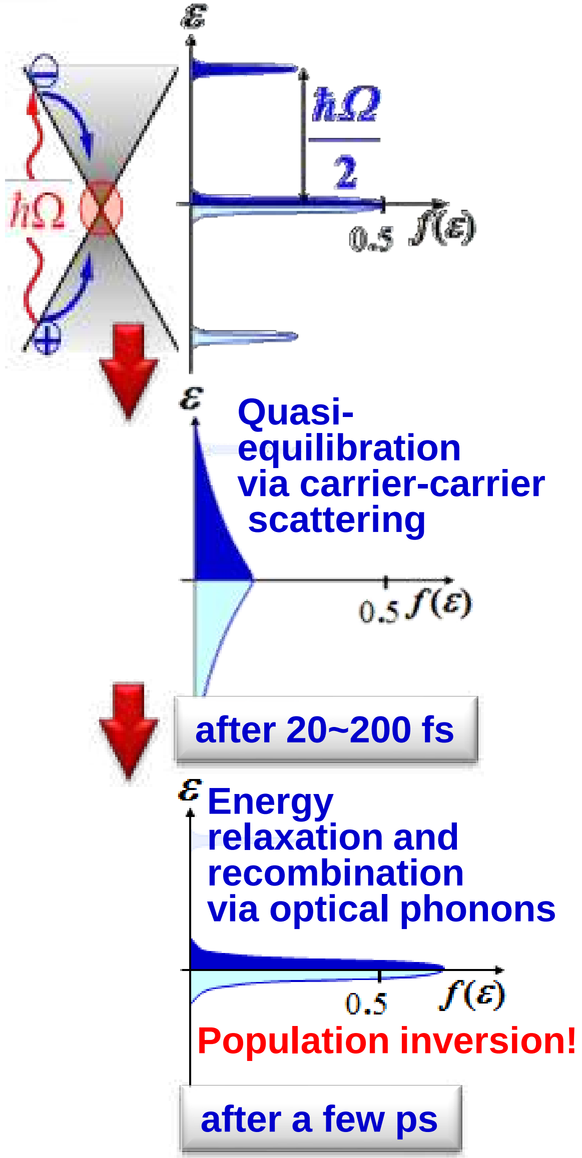
$$\mathrm{rot}\,\mathbf{H}=\varepsilon\frac{\partial\mathbf{E}}{\partial t}+\sigma\mathbf{E}$$
$$\Rightarrow(-i\omega\varepsilon+\sigma)\mathbf{E}=-i\omega\left(\varepsilon+i\frac{\sigma}{\omega}\right)\mathbf{E}$$
$$\equiv-i\omega\tilde{\varepsilon}\mathbf{E}=-i\omega(\varepsilon'+i\varepsilon'')\mathbf{E}$$
$$\varepsilon''\equiv\mathrm{Im}(\varepsilon)=\sigma/\omega$$

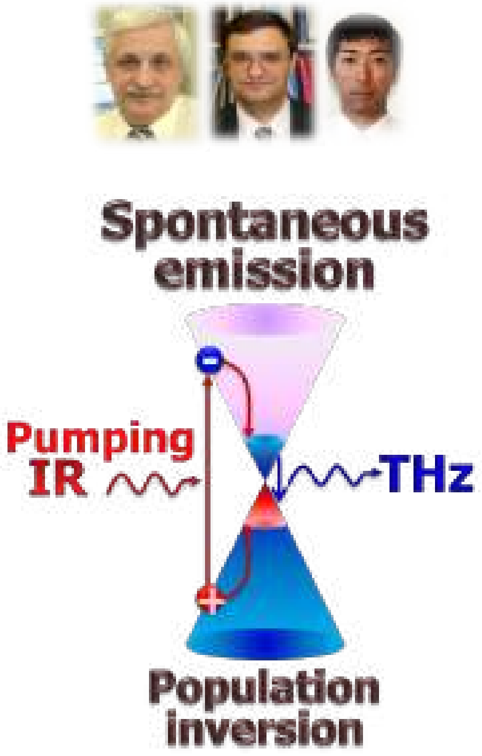
$$\omega=\frac{c}{\sqrt{\varepsilon'+i\varepsilon''}}\cdot k\equiv\omega'-i\omega''(\sigma)$$
$$\sigma<0\ \Rightarrow\ \omega''(\sigma)<0\ \Rightarrow\ e^{-i\omega t}=e^{-i\omega' t}\cdot e^{+|\omega''|t}$$
$$\sigma>0\ \Rightarrow\ \omega''(\sigma)>0\ \Rightarrow\ e^{-i\omega t}=e^{-i\omega' t}\cdot e^{-|\omega''|t}$$

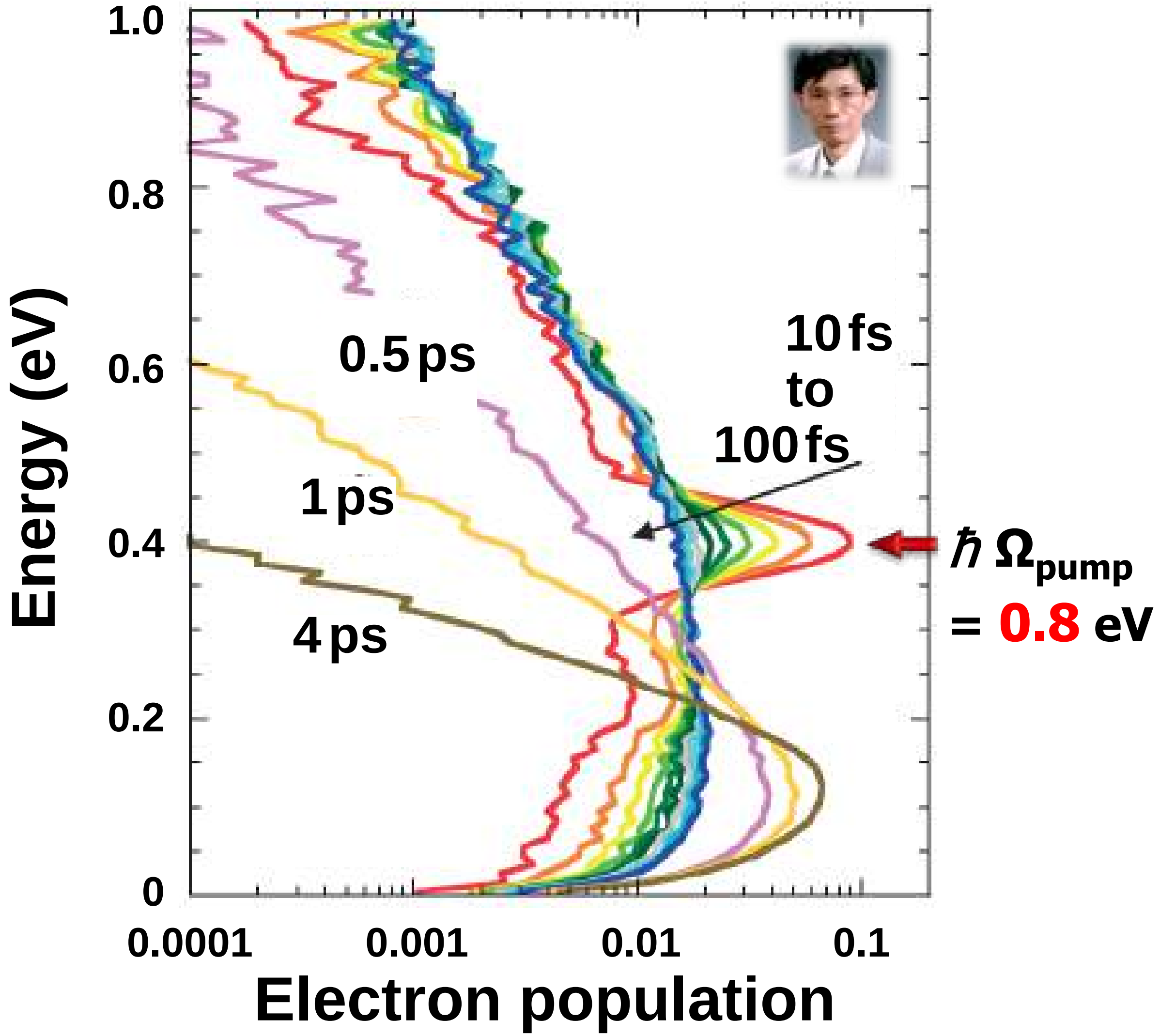


光学励起グラフェンの非平衡キャリア緩和過程

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).

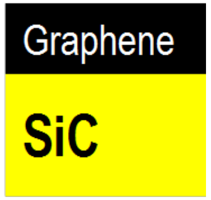


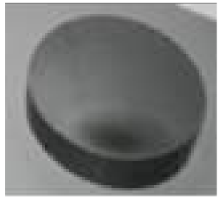


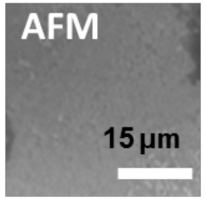


時間＆角度分解X線光電子分光：T- ARPESで光学励起グラフェンの反転分布形成を実証

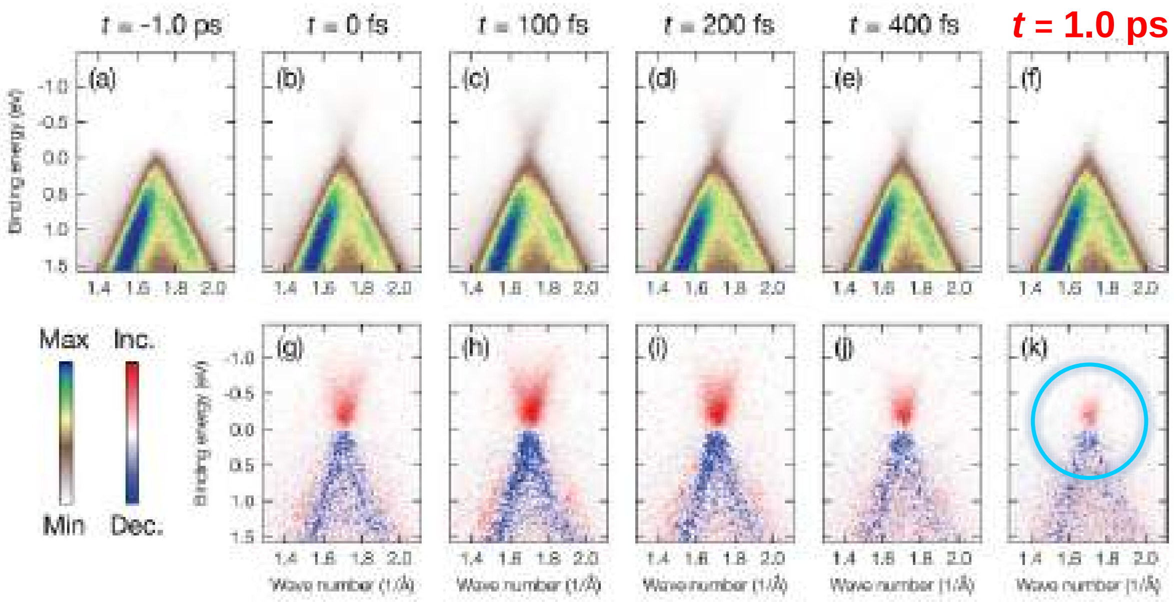
T. Someya, H. Fukidome et al. I. Matsuda, **PRB 95**, 165303 (2017).

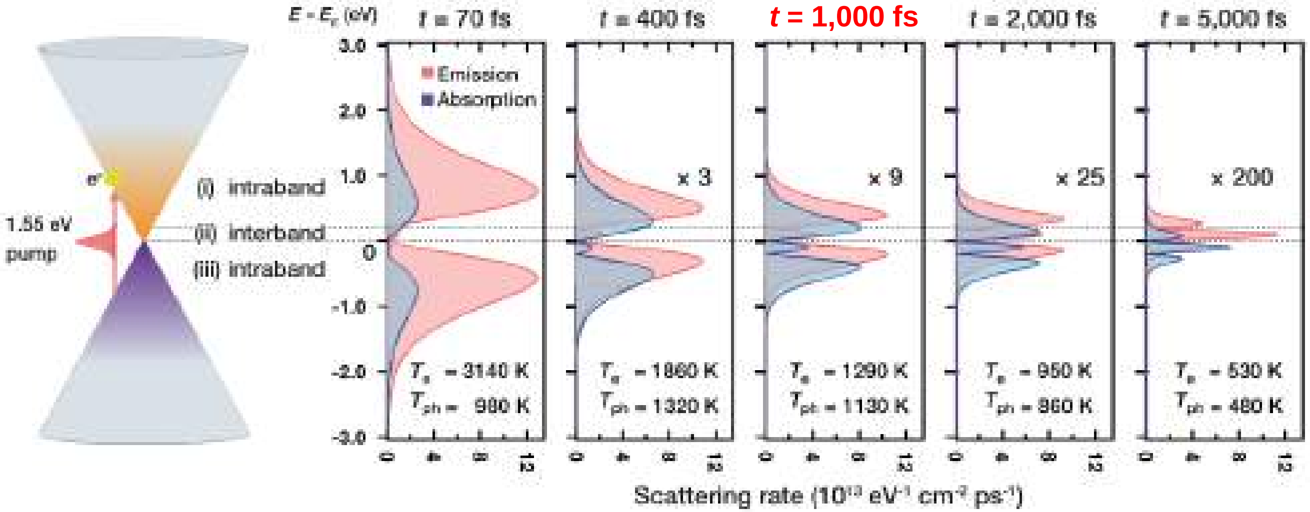






- **Epi-graphene on 4H-SiC**
- **μ ~ 100,000 cm^2/Vs**
- **Time- & Angle-resolved photoemission microscopy**
- **Even for rather high pump energy 1.55eV**
- **Population inversion is maintained in ps time scale !**
- **Auger scattering well-suppressed !**



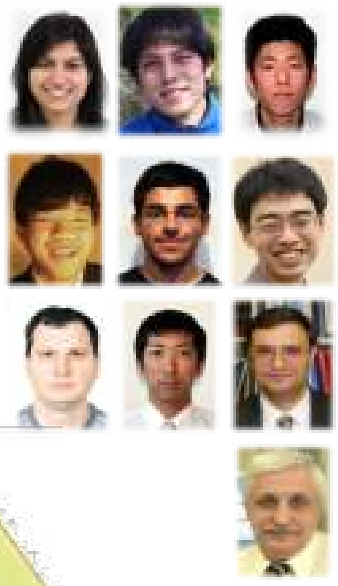


グラフェンによるテラヘルツレーザー発振に初めて成功！

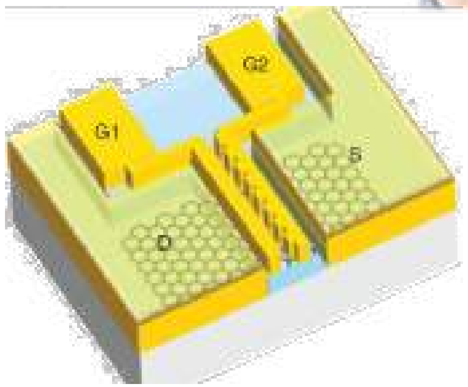
DE GRUYTER
NANOPHOTONICS
DE GRUYTER Nanophotonics 2018; 7(4): 741–752

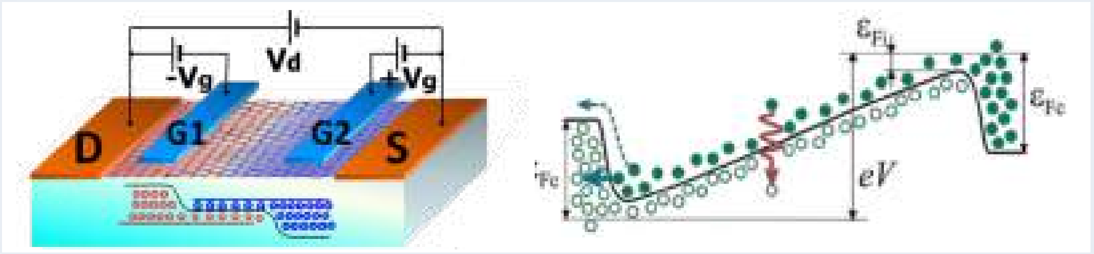
Research article

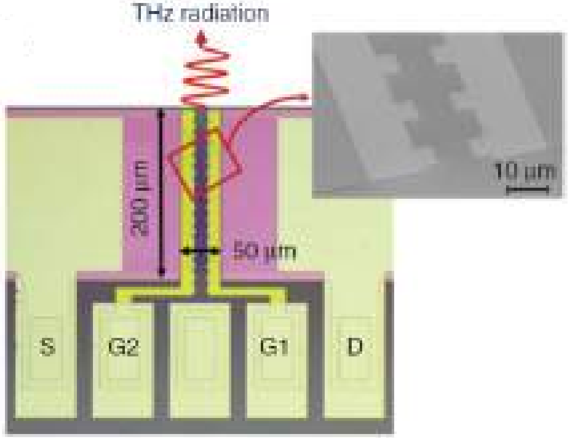
Deepika Yadav, Gen Tamamushi, Takayuki Watanabe, Junki Mitsushio, Youssef Tobah, Kenta Sugawara, Alexander A. Dubinov, Akira Satou, Maxim Ryzhii, Victor Ryzhii and Taiichi Otsuji*

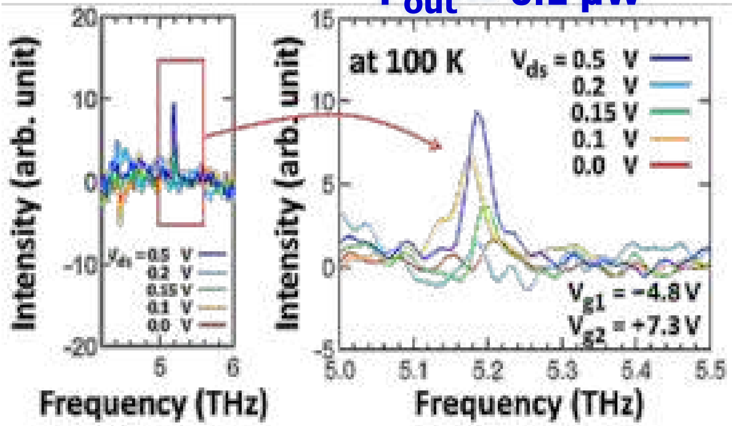


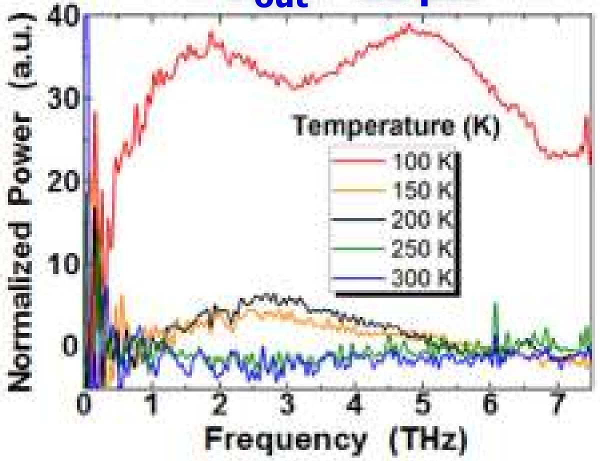
Terahertz light-emitting graphene-channel transistor toward single-mode lasing







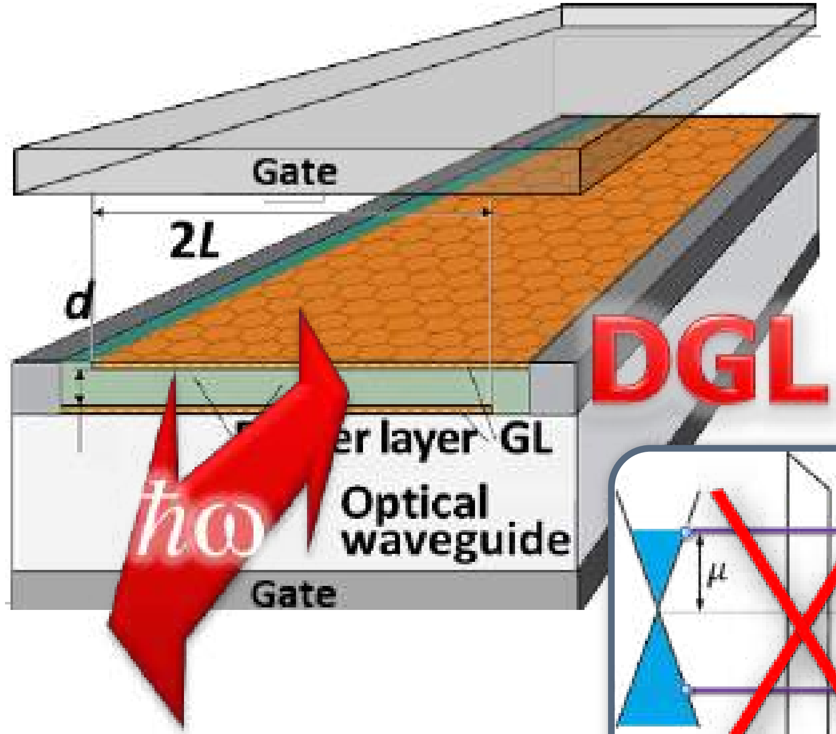


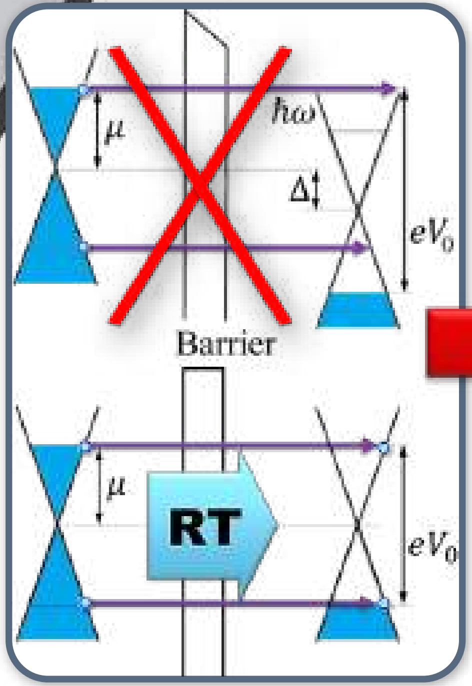


ゲート制御DGLにおけるフォトンアシスト共鳴トンネル効果とそのTHz利得発現

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

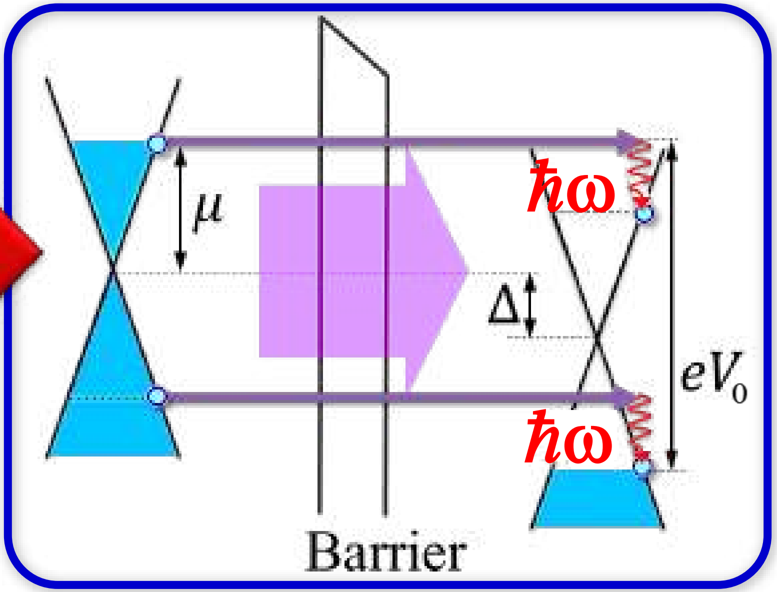
V. Ryzhii, A.A. Dubinov, T. Otsuji et al., **Opt. Exp. 21**, 31569 (2013).
V. Ryzhii, A. Dubinov, V.Ya. Aleshkin, M. Ryzhii, T. Otsuji, **APL 103**, 163507 (2013).





Tunable Resonant THz Photon Emission

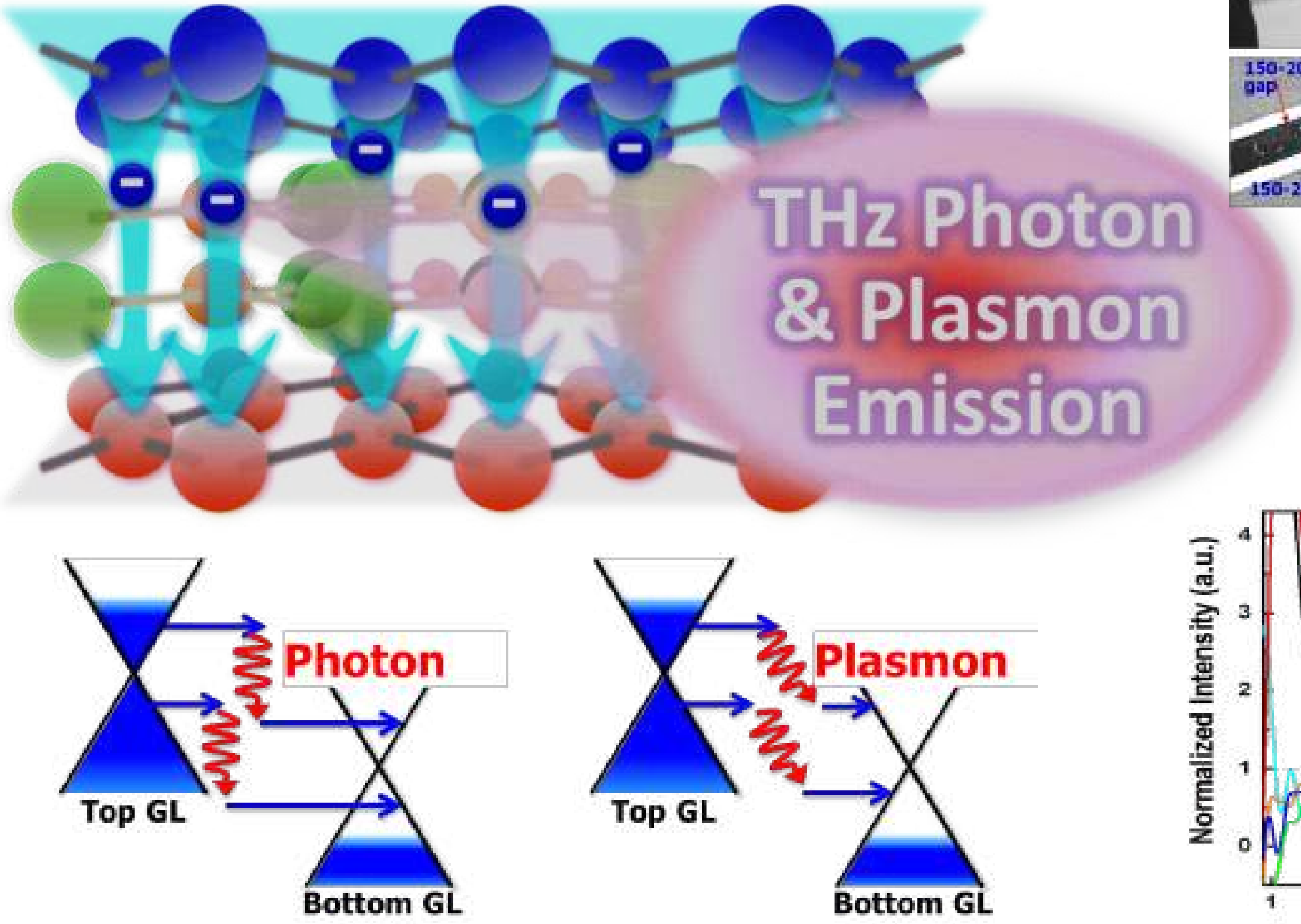
Photo-Emission-Assisted Resonant Tunneling

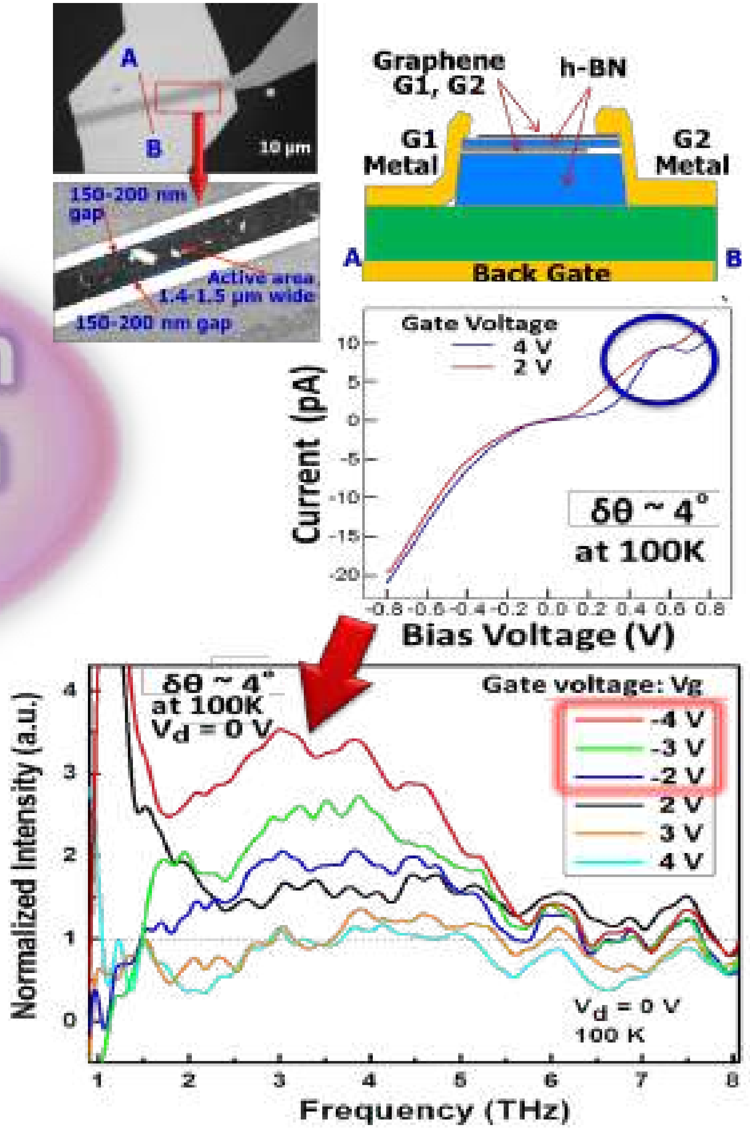


グラフェン二重層ファンデルワールスヘテロ接合室温高強度THzレーザーの実現に向けて！

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

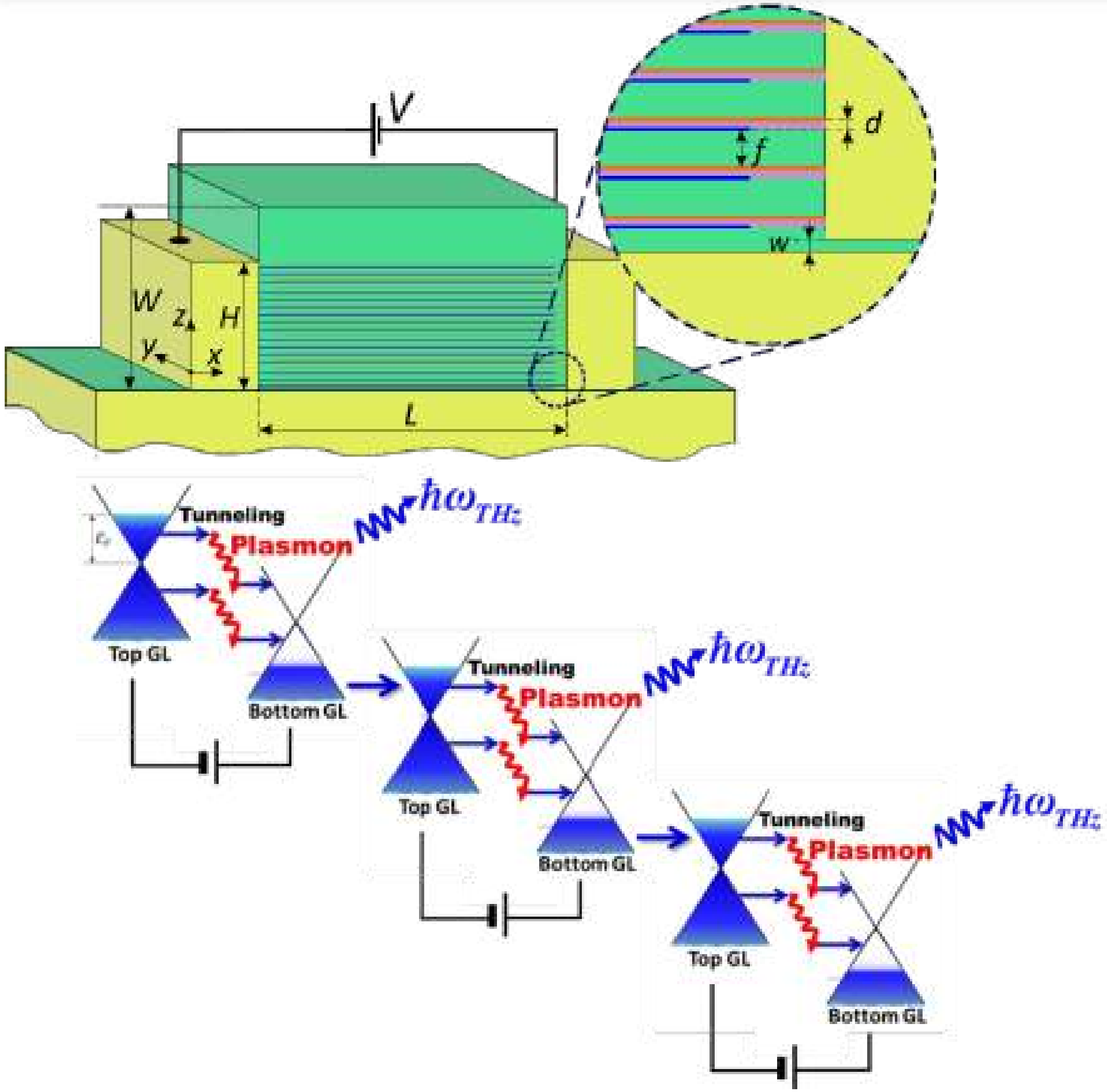
科研費：基盤研究(S) 二次元原子薄膜ヘテロ接合の創製とその新原理テラヘルツ光電子デバイス応用 (H28~R02)



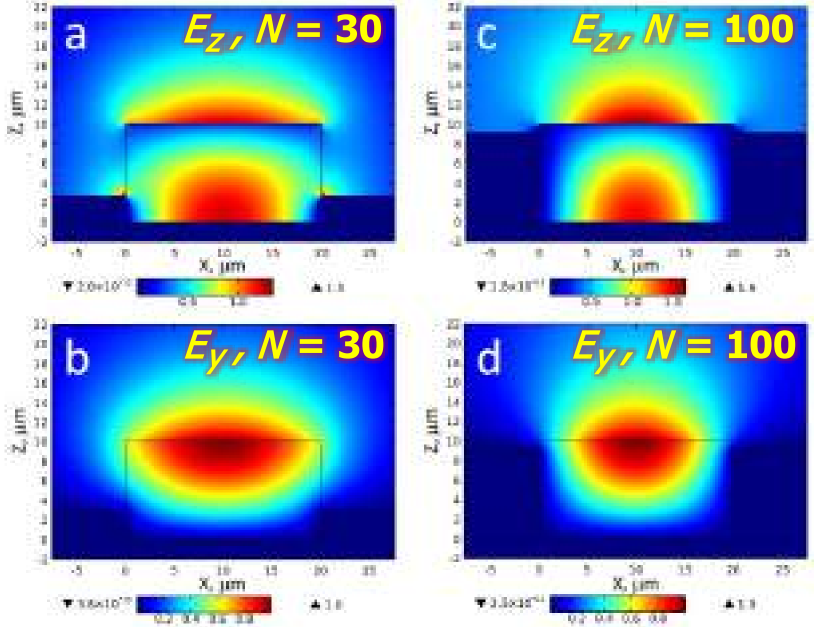


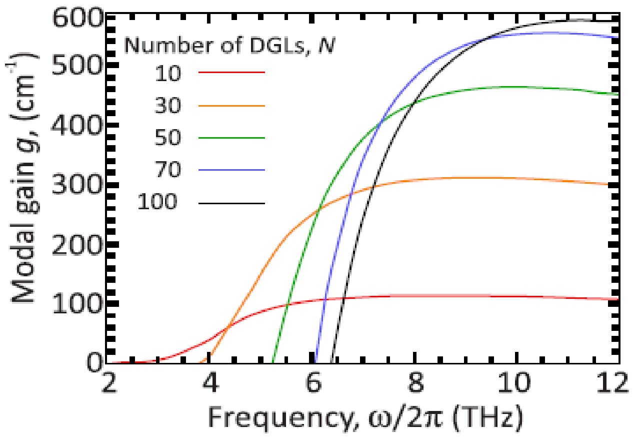
DGL積層構造による新原理グラフェンTHz量子カスケードレーザー

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



at 5 THz





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

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

gated 2D

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

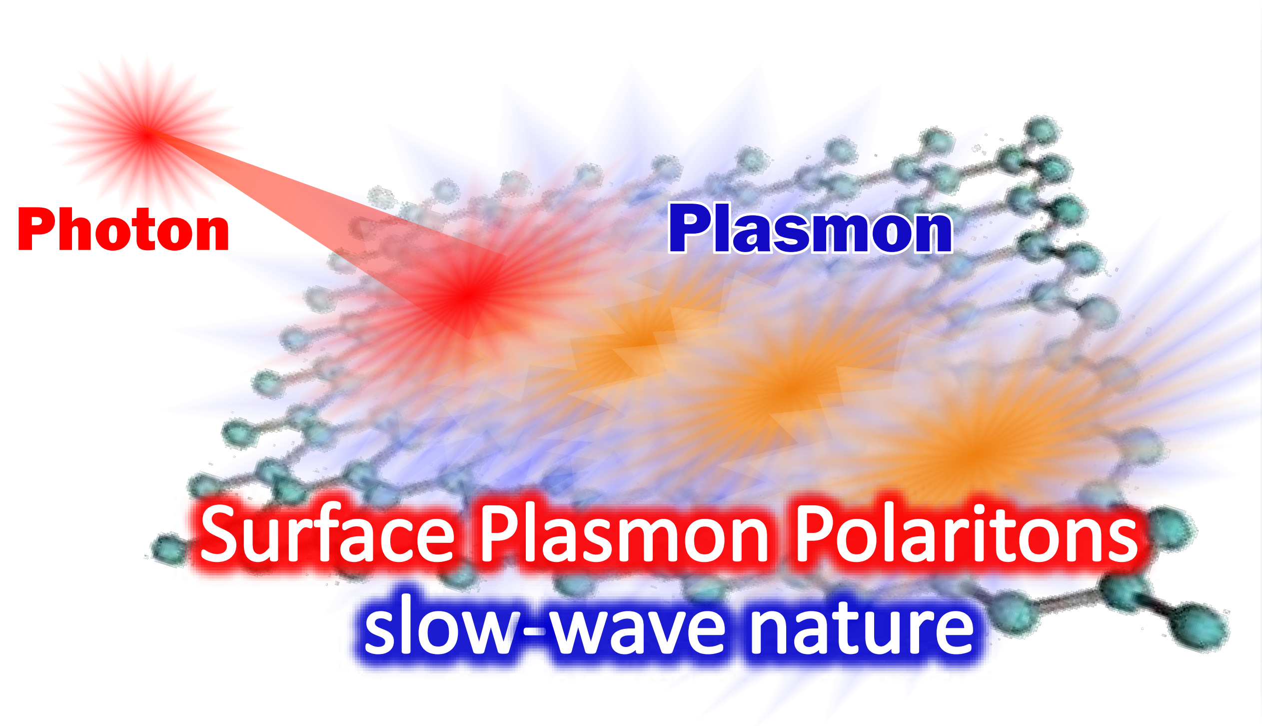
Gated graphene

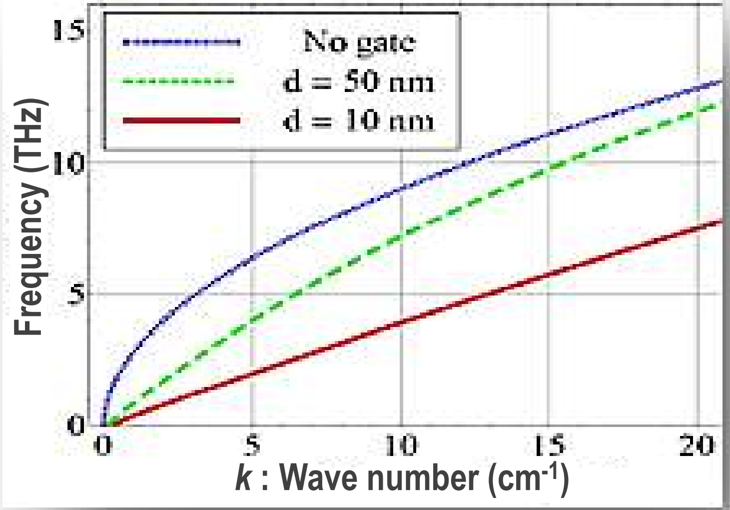
$(s > \upsilon_F,\ |k|^{-1} \gg d)$

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

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

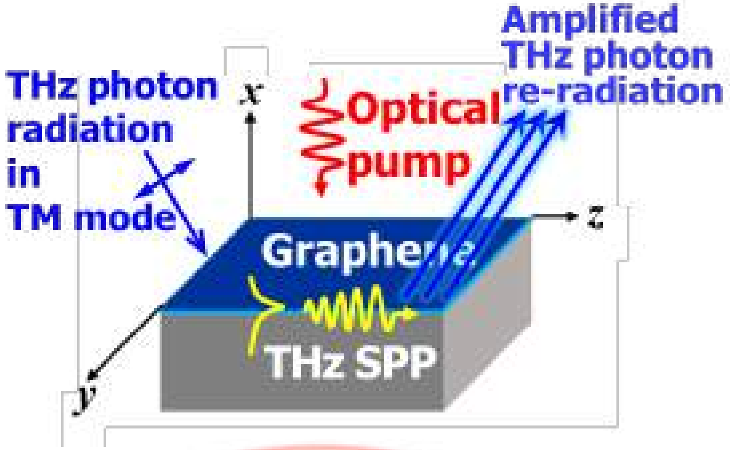
$$\omega = ks \approx k \upsilon_F \sqrt{\frac{\alpha}{2}} \propto k \upsilon_F d^{1/4} V_g^{1/4}$$

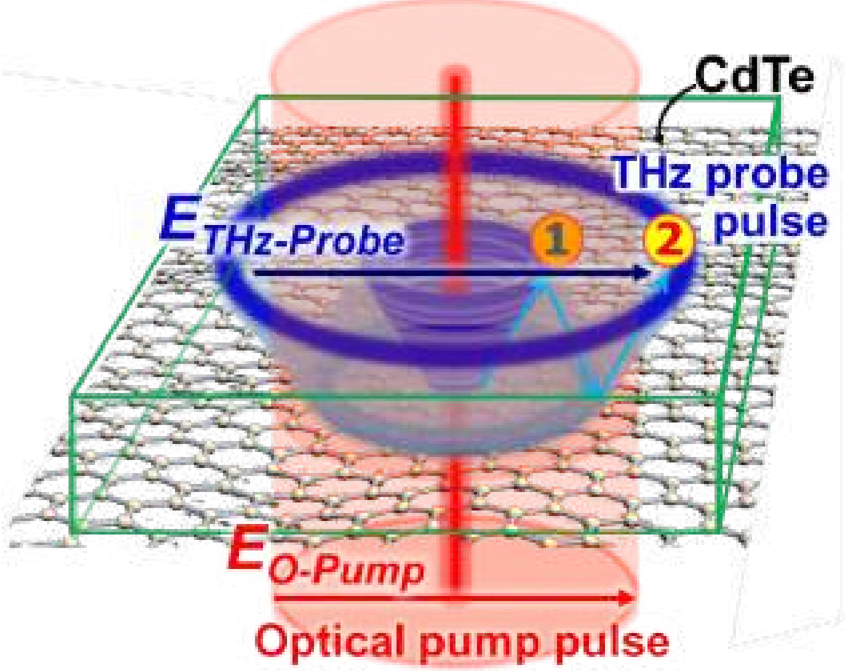


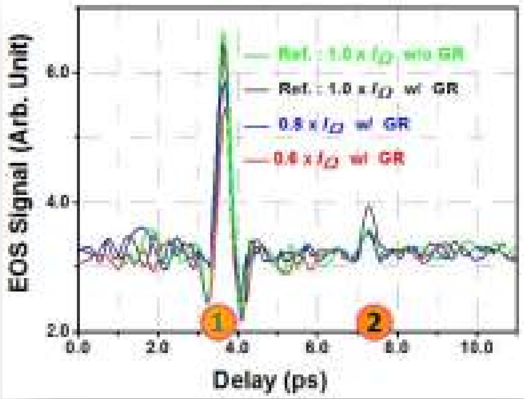


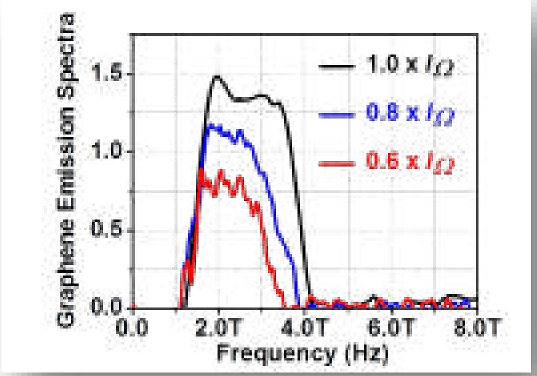
光学励起グラフェンのプラズモンポラリトンによる巨大THz利得増強効果の実証

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

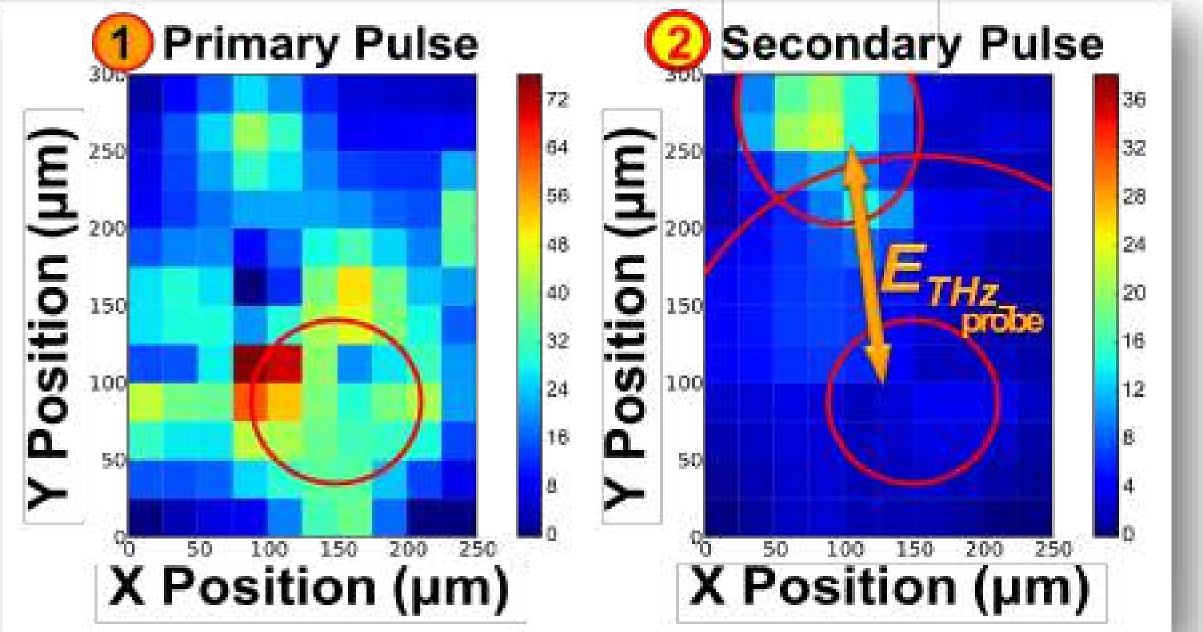




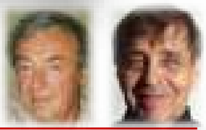




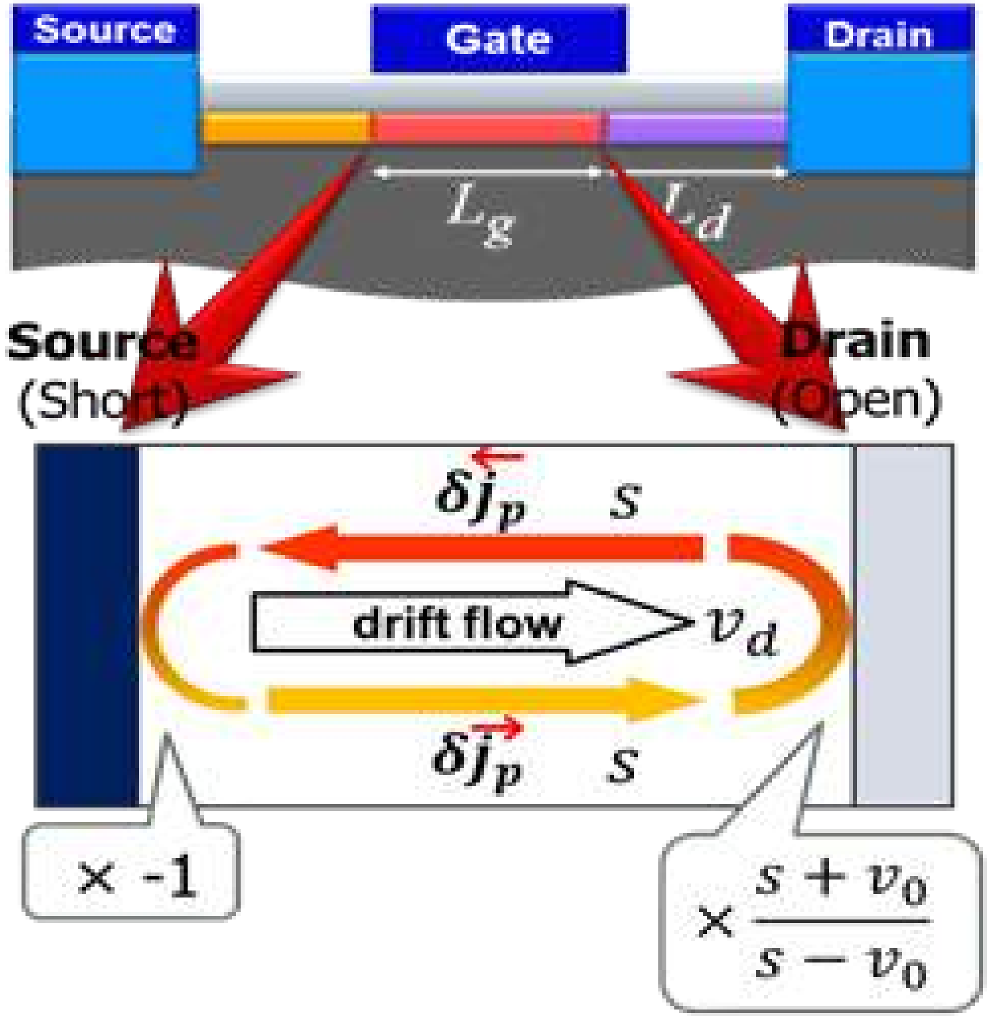
Spatial Distributions of the Pulse Intensities



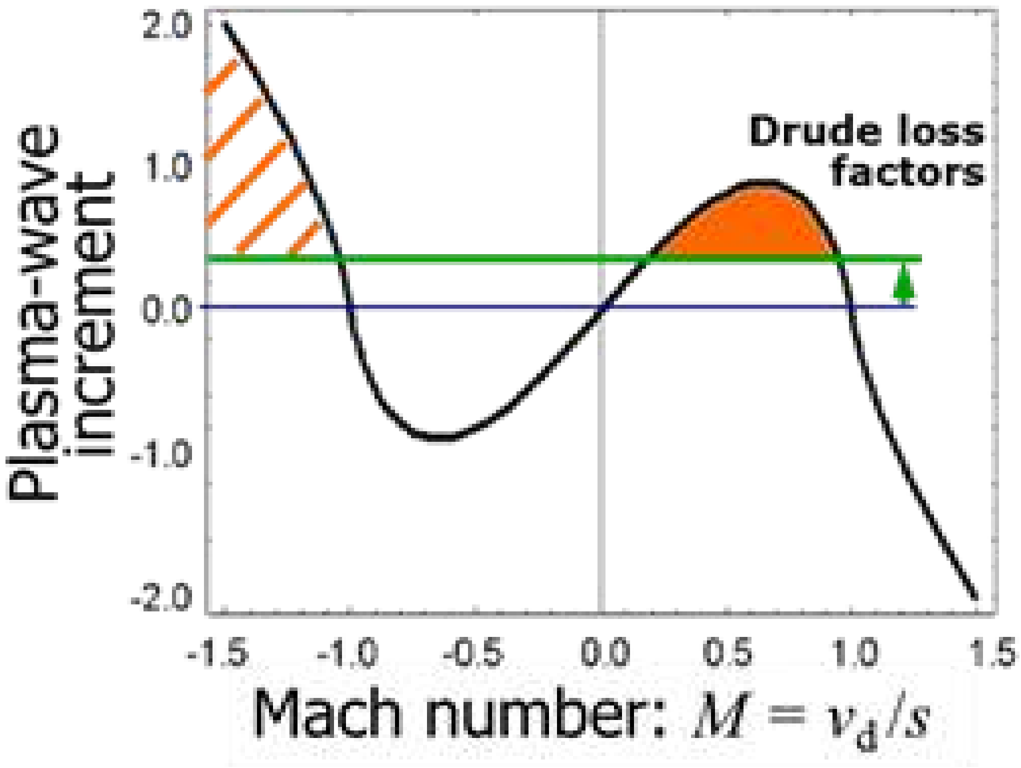
プラズモンのもう一つの物理：Dyakonov-Shur型プラズモン不安定性



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

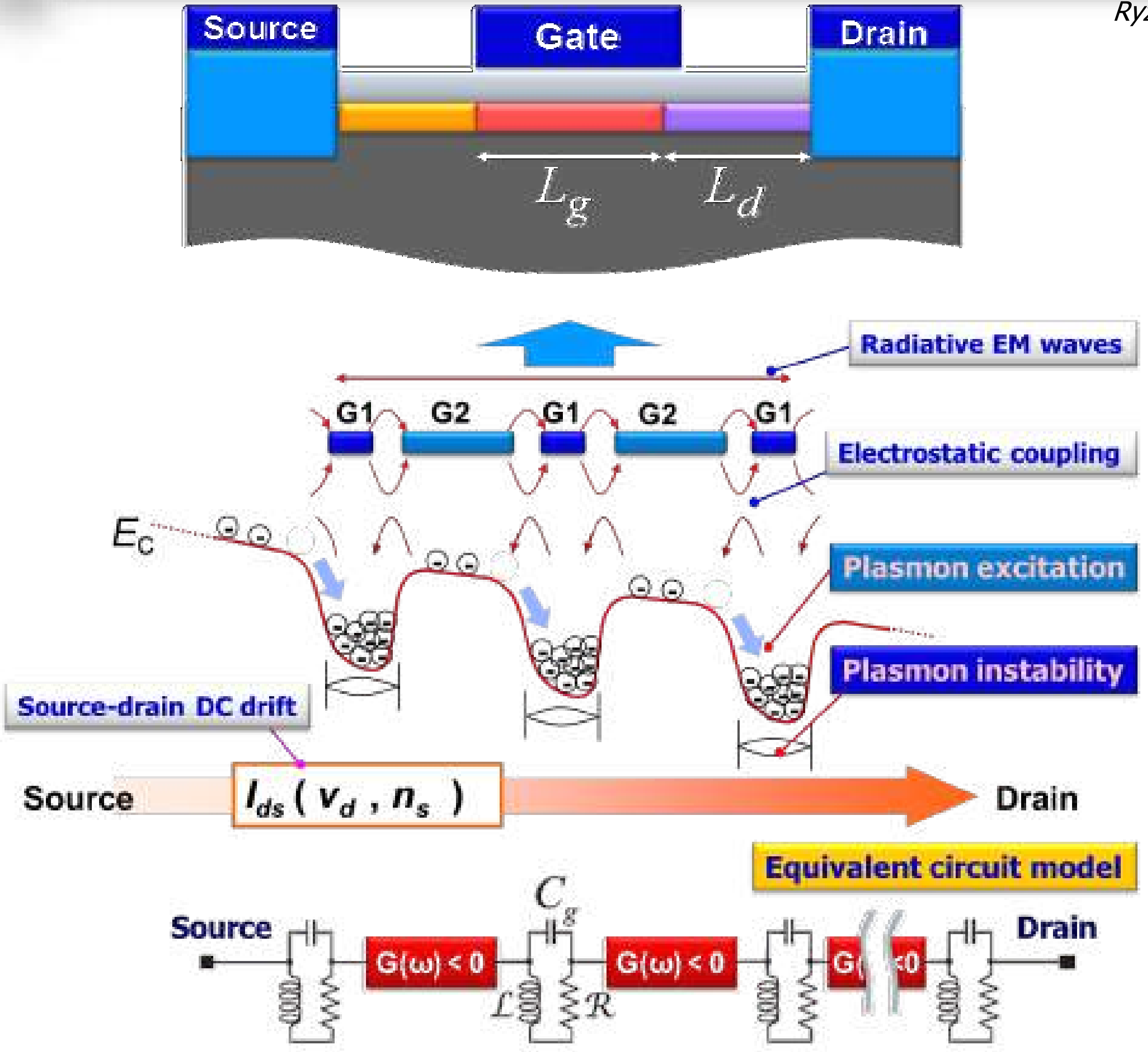


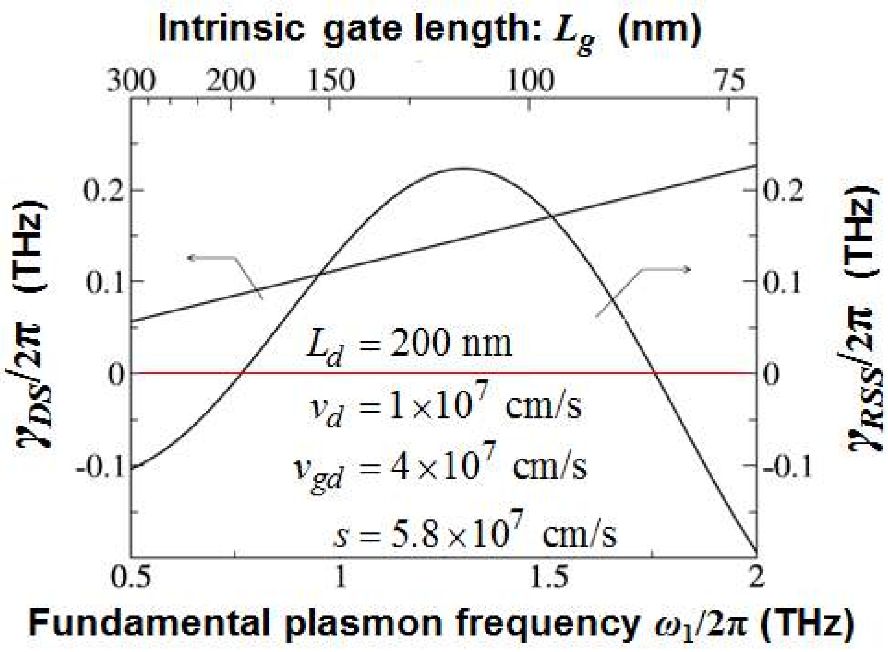
$$\therefore \frac{\delta \overleftarrow{n}}{\delta \overrightarrow{n}} = \frac{\delta \overleftarrow{V_g}}{\delta \overrightarrow{V_g}} = \frac{s+v_d}{s-v_d} > 1 \Rightarrow \textbf{Gain!!}$$

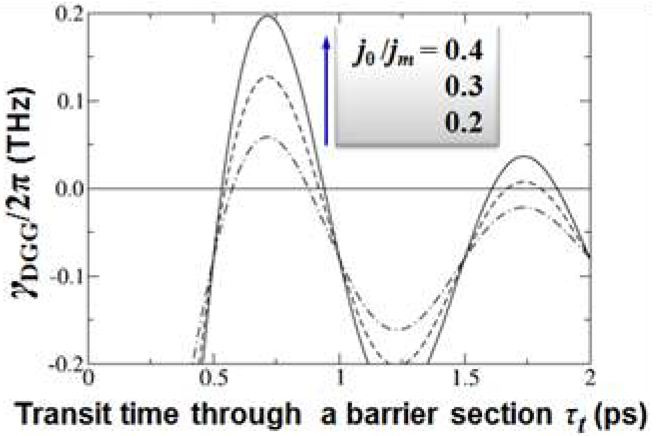


Ryzhii-Satou-Shur型 プラズモン不安定性

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).

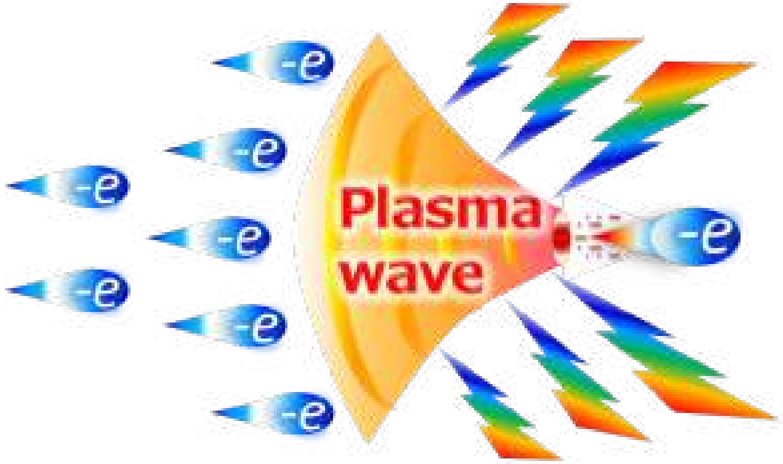


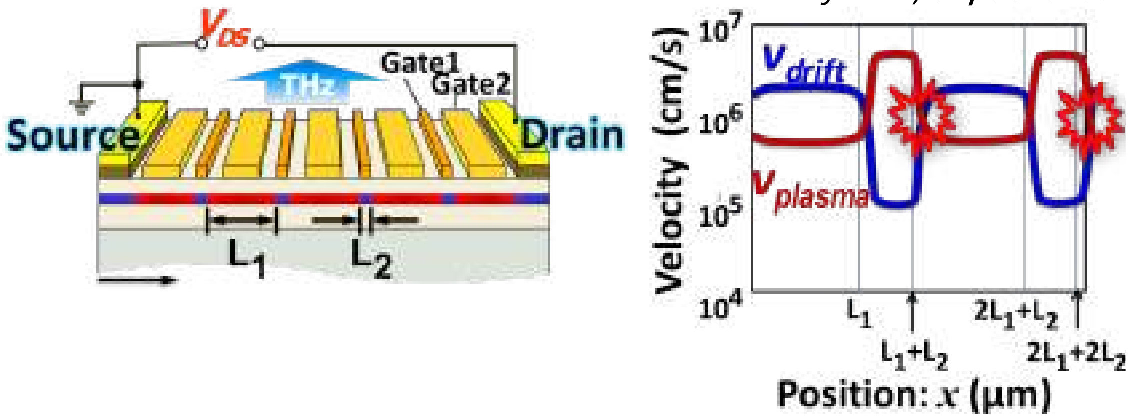


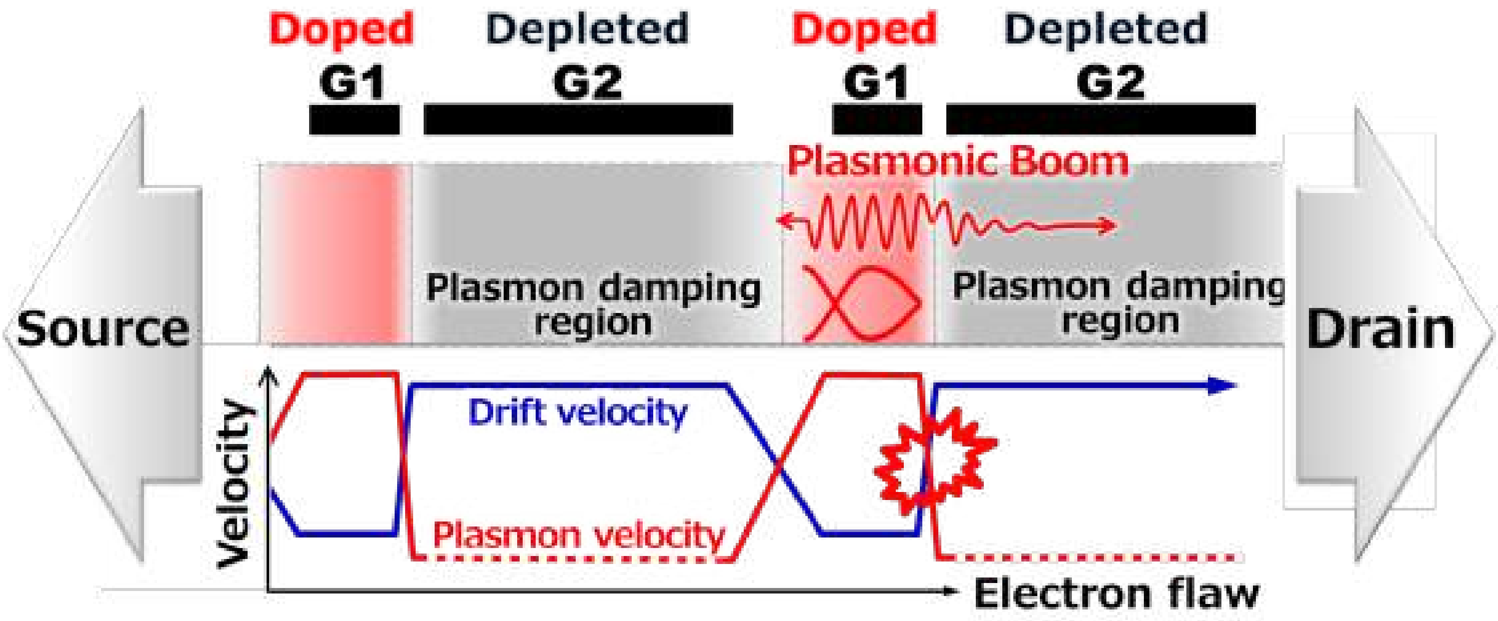


第3の不安定性：プラズモニックブームの可能性

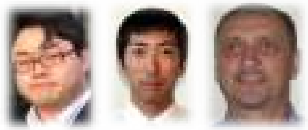
S. Mikhailov, **PRB 58**, 1517 (1998).
G.R. Aizin, J. Mikalopa, and M. Shur, **PRB 93**, 195315 (2016).
D. Svintsov, **PRB 97**, 121405(R) (2018).
T. Otsuji et al., **unpublished**.



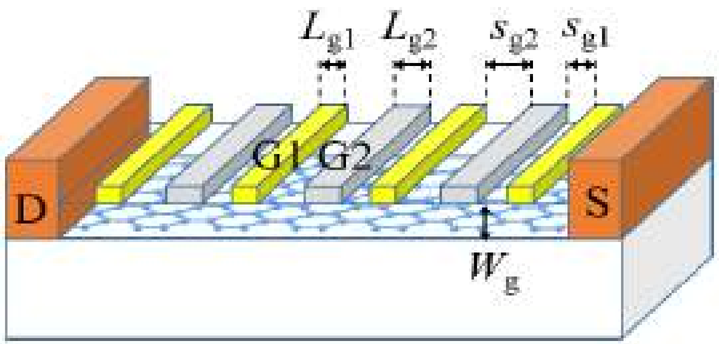


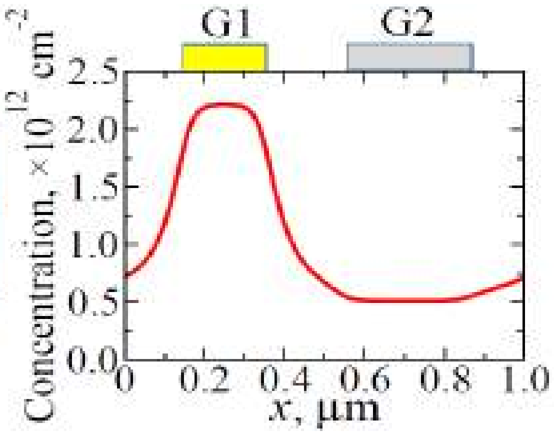


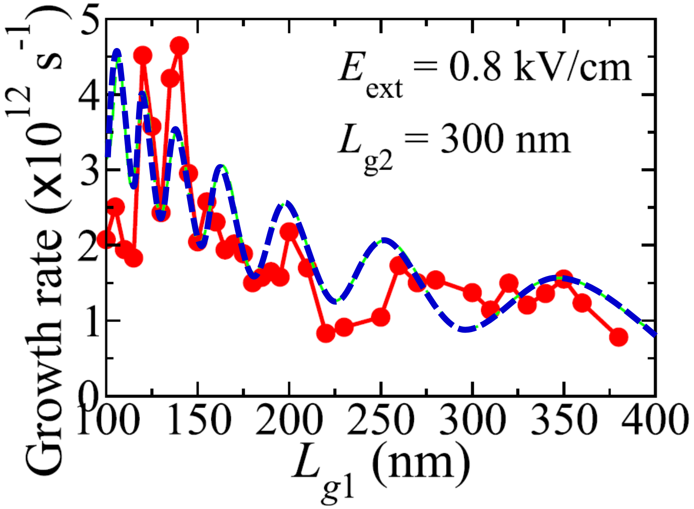
グラフェンメタ表面におけるプラズモン不安定性に伴うTHz自励発振現象

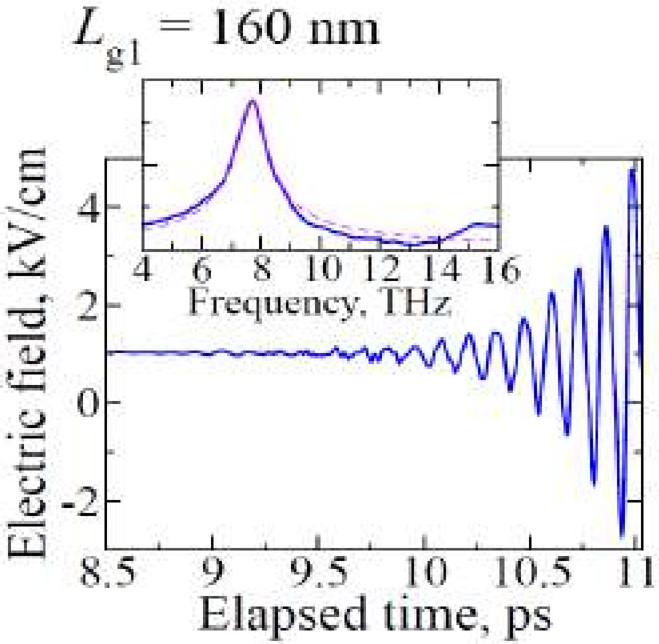


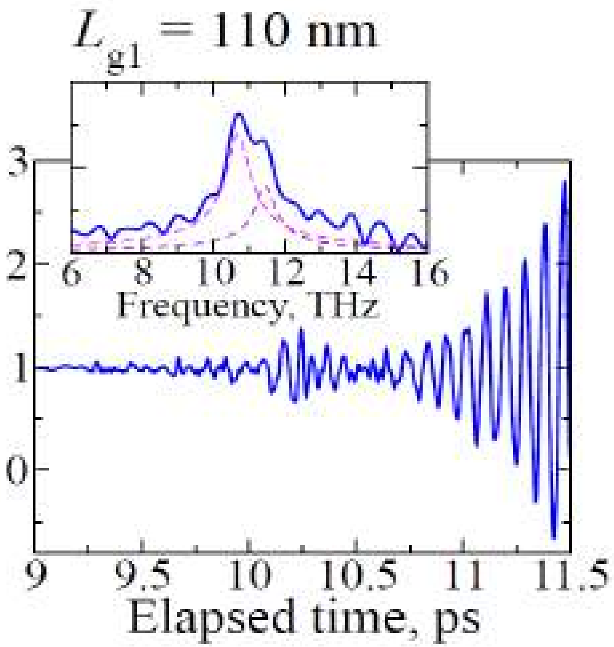
Y. Koseki, V. Ryzhii, T. Otsuji, V.V. Popov, A. Satou, **PRB 93**, 245408 (2016).

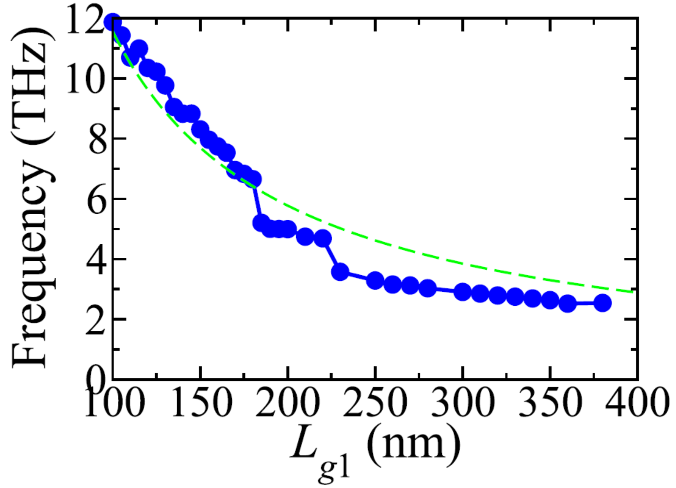








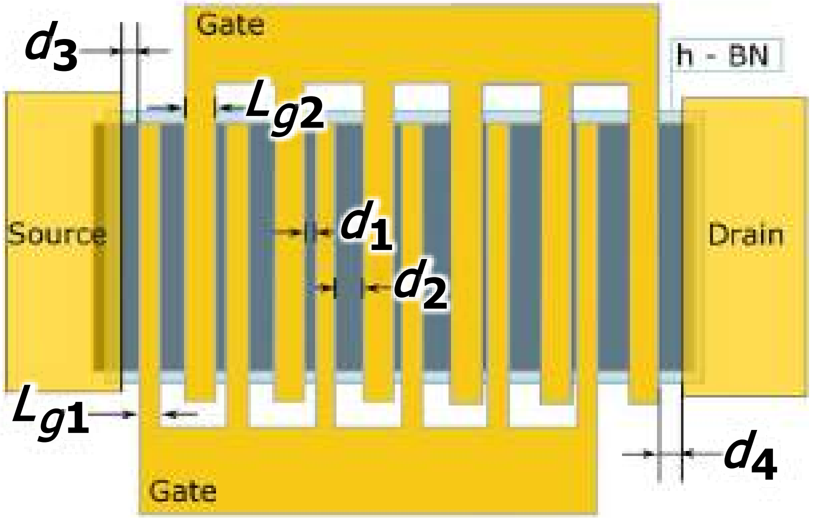




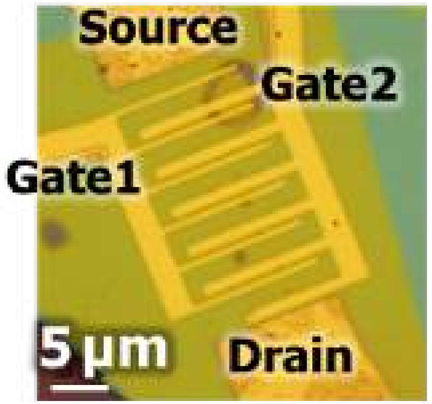
非対称二重回折格子ゲートADGG-GFET

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

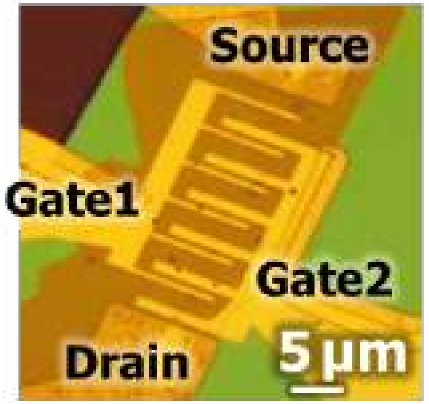
Cavity	C1	C2	C3	C4
Structure or sample	A-DGG3.1	A-DGG3.2	A-DGG3.1	A-DGG3.2
Thickness of top h-BN layer (nm)	32	20	32	20
CNP (V)	+0.15	−0.12	+0.10	−0.06
Biased cavity length (μm)	0.5	0.75	1.0	1.5
Total channel length (μm)	26.5	24.0	26.5	24.0
d_1 and d_2 (μm)	0.5 and 2.0	0.5 and 1.0	0.5 and 2.0	0.5 and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



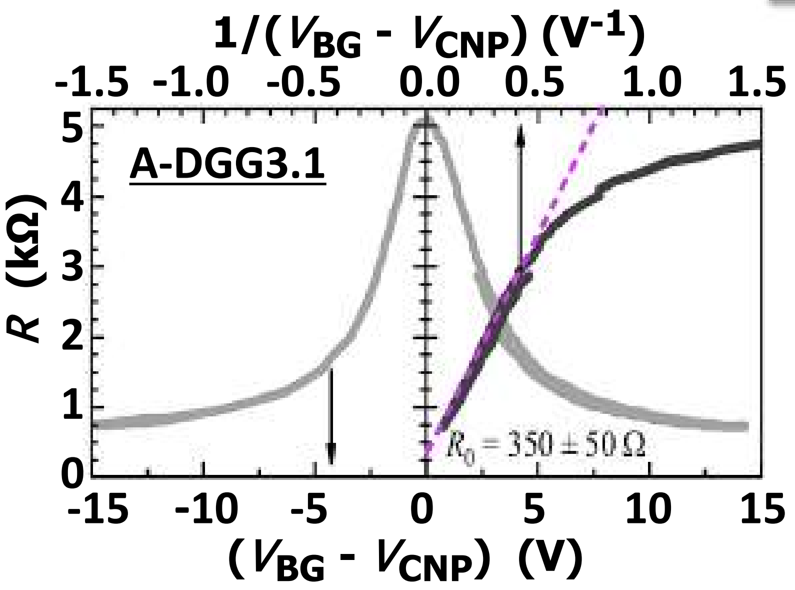
A-DGG3.1

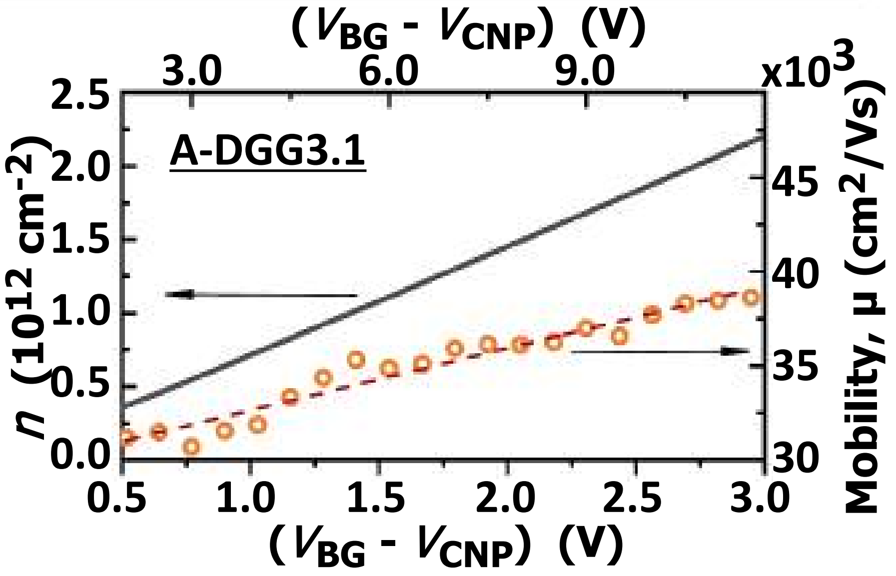


A-DGG3.2



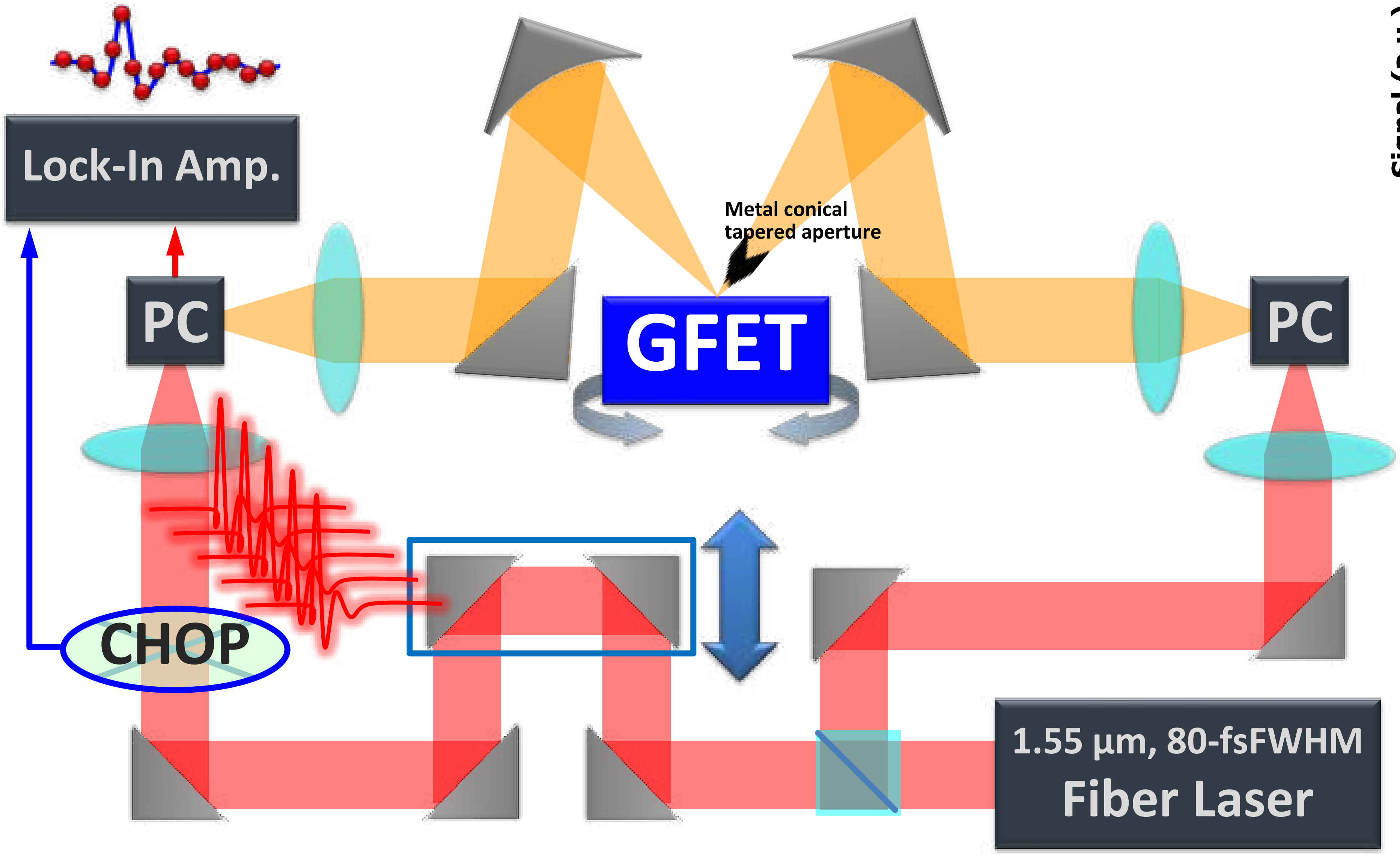
30,000 ≤ μ ≤ 40,000 cm²/Vs

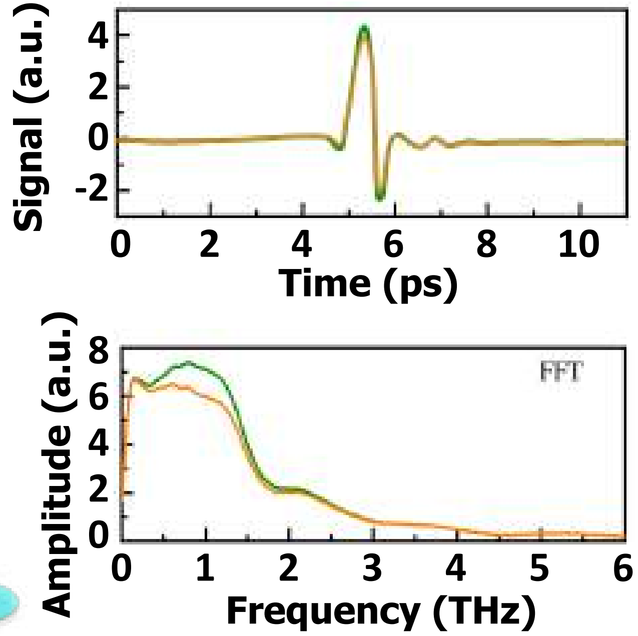




THz時間領域分光法による実験検証

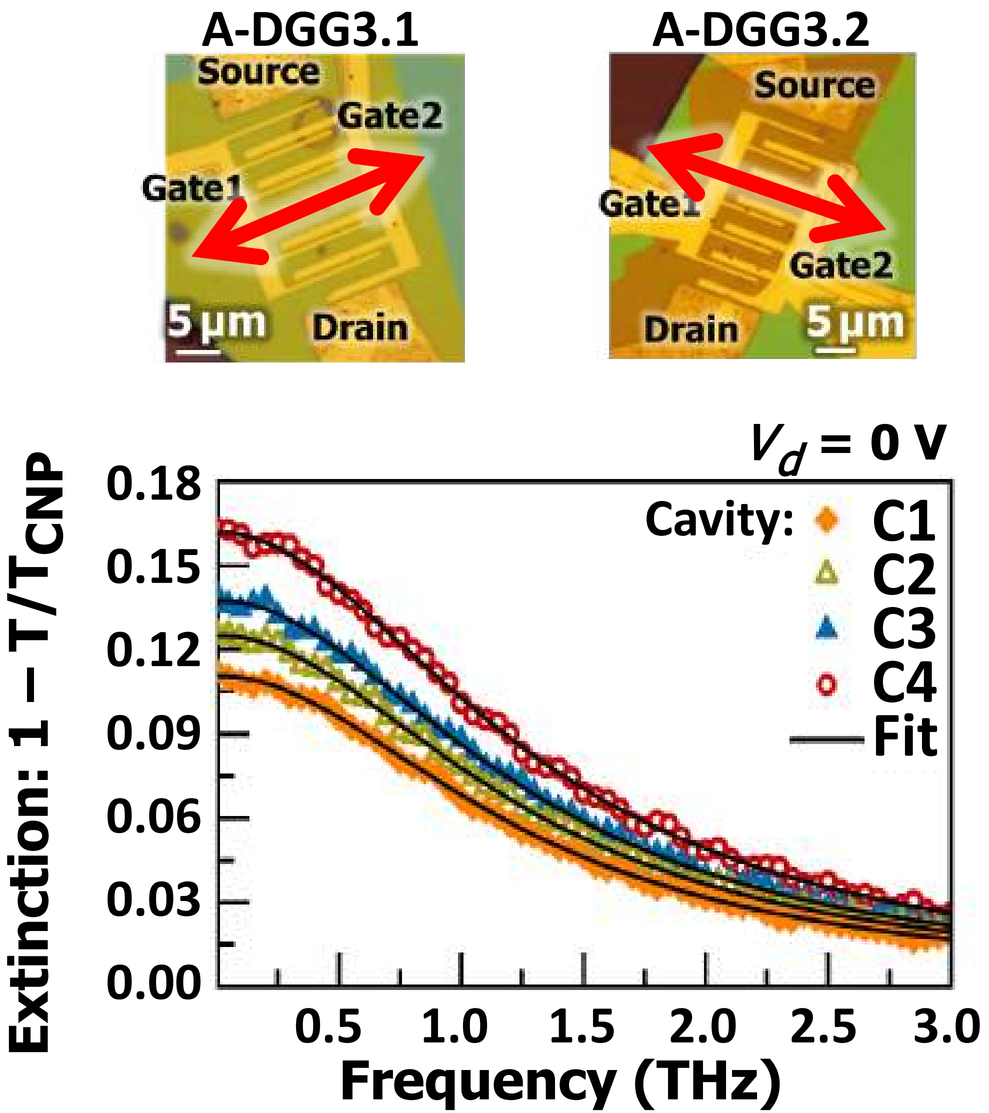
S. Boubanga-Tombet et al., *Phys. Rev. X* **10**, 031004 (2020).

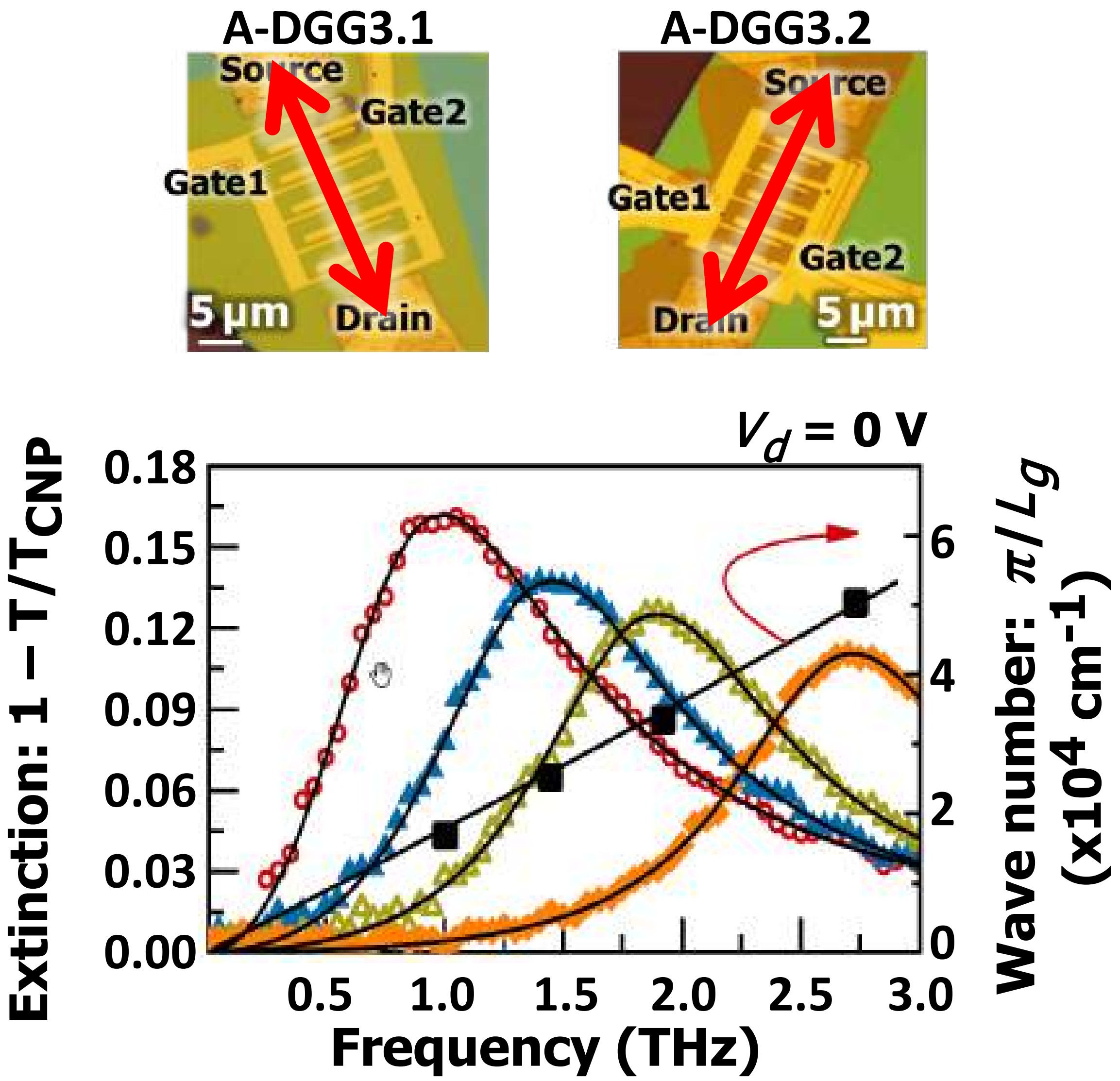




ドレイン無バイアス条件：偏光敏感依存のTHz共鳴吸収特性

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

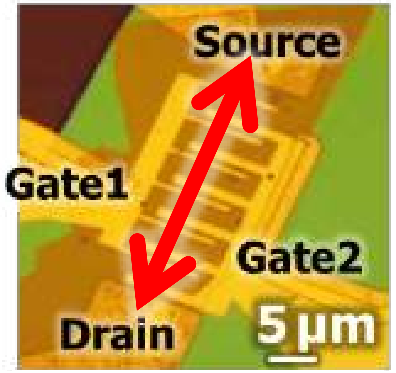


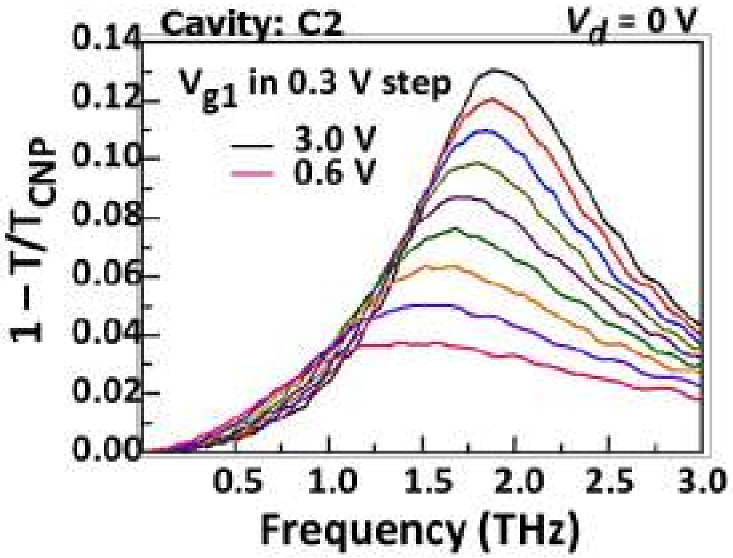


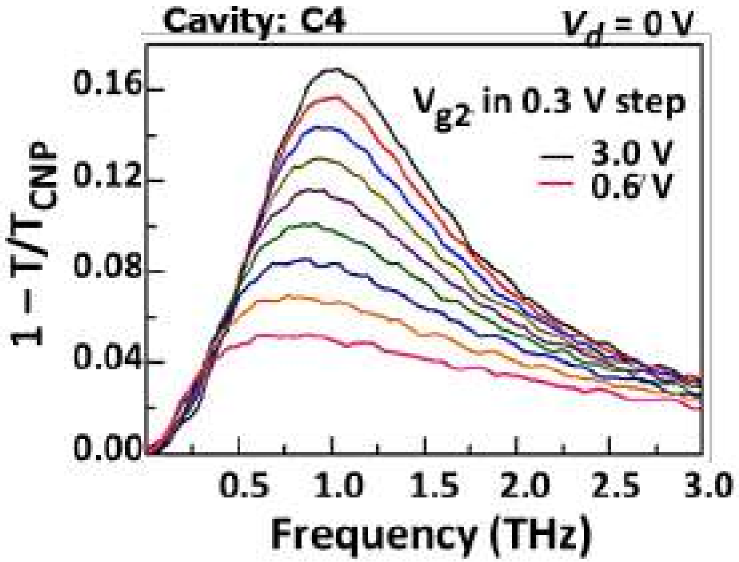
ゲートバイアス依存性：グラフェンプラズモンの分散理論とよく一致

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

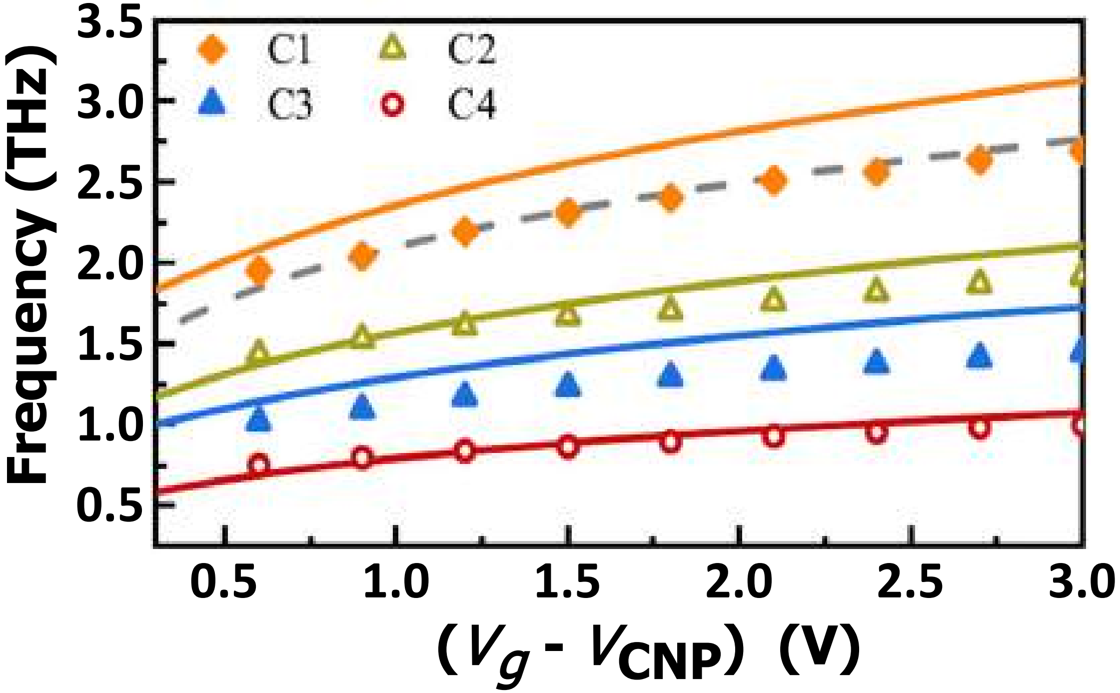
A-DGG3.2







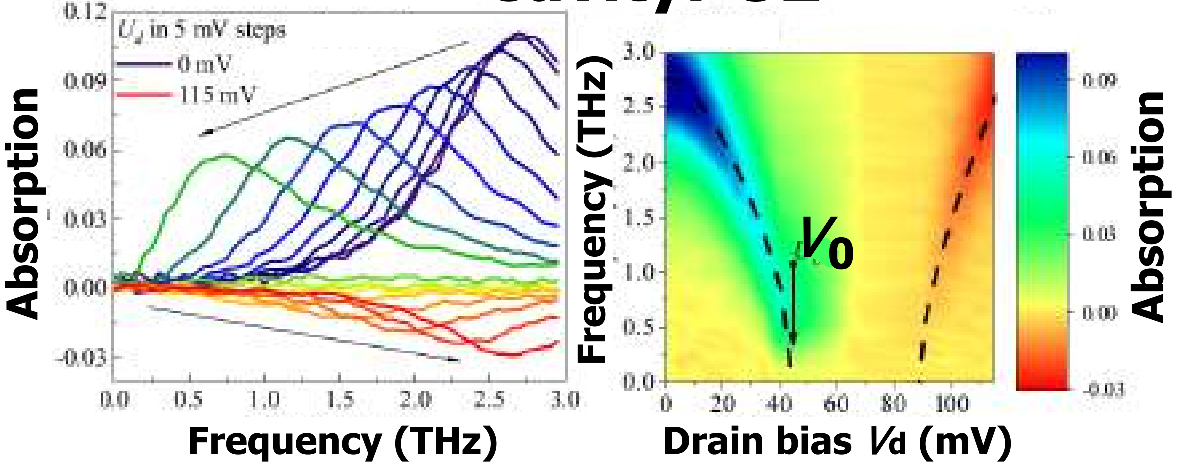
$$f \propto V_g^{1/4}$$



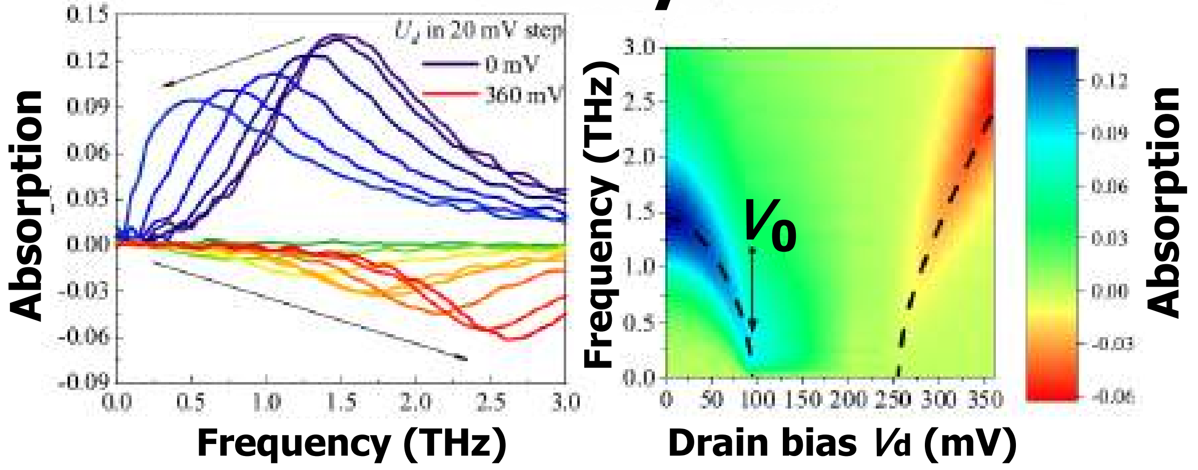
ドレインバイアス依存性：共鳴吸収から共鳴増幅に反転！

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

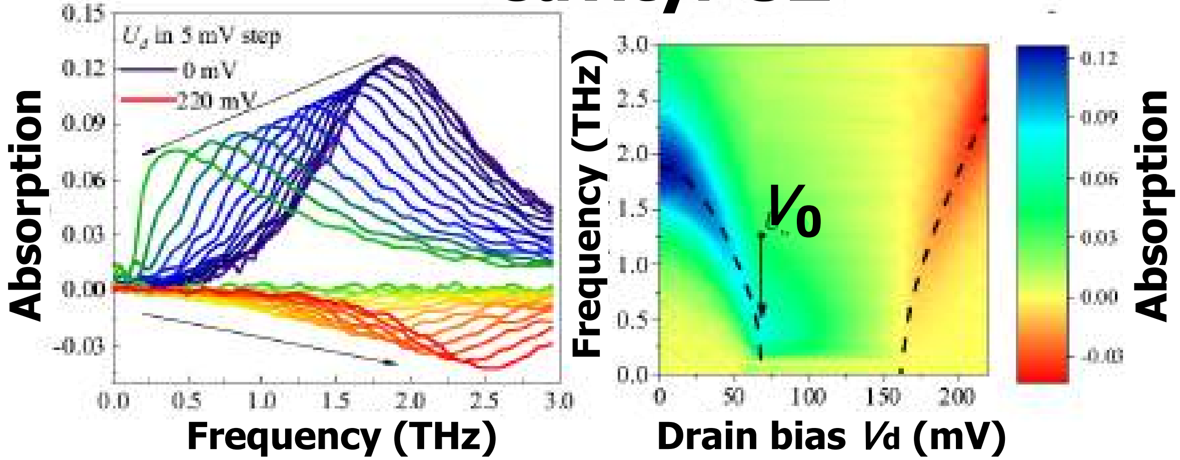
Cavity: C1



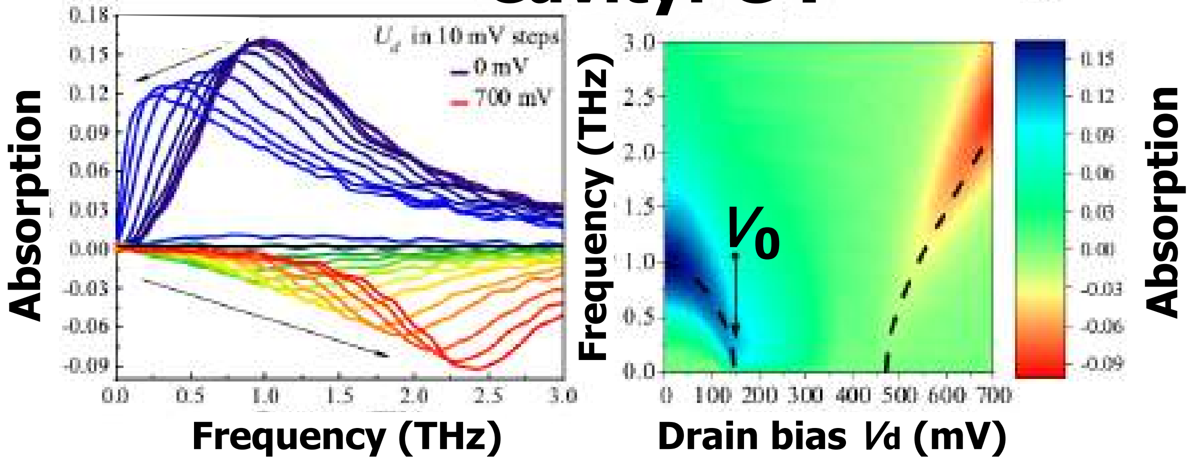
Cavity: C3



Cavity: C2

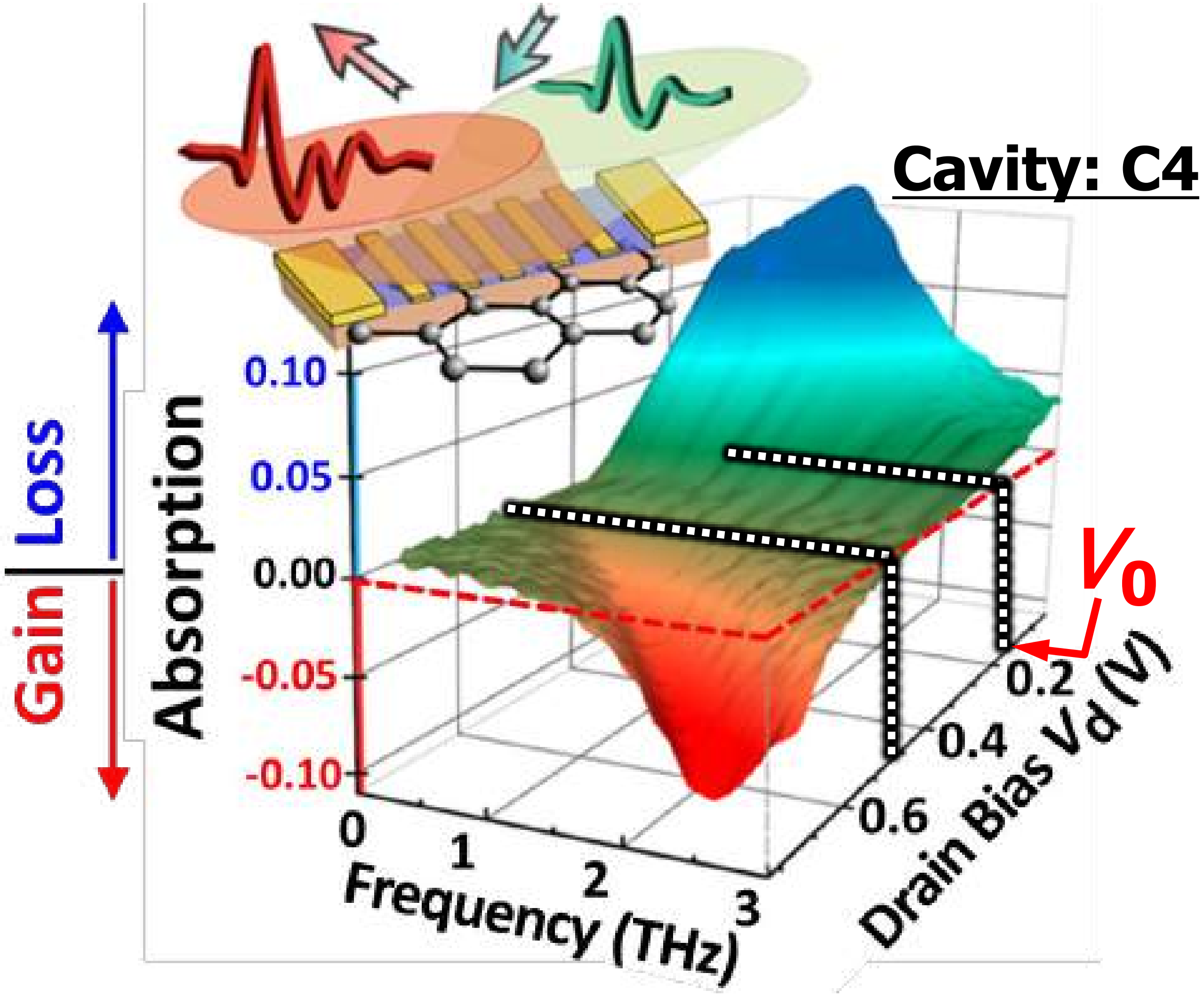


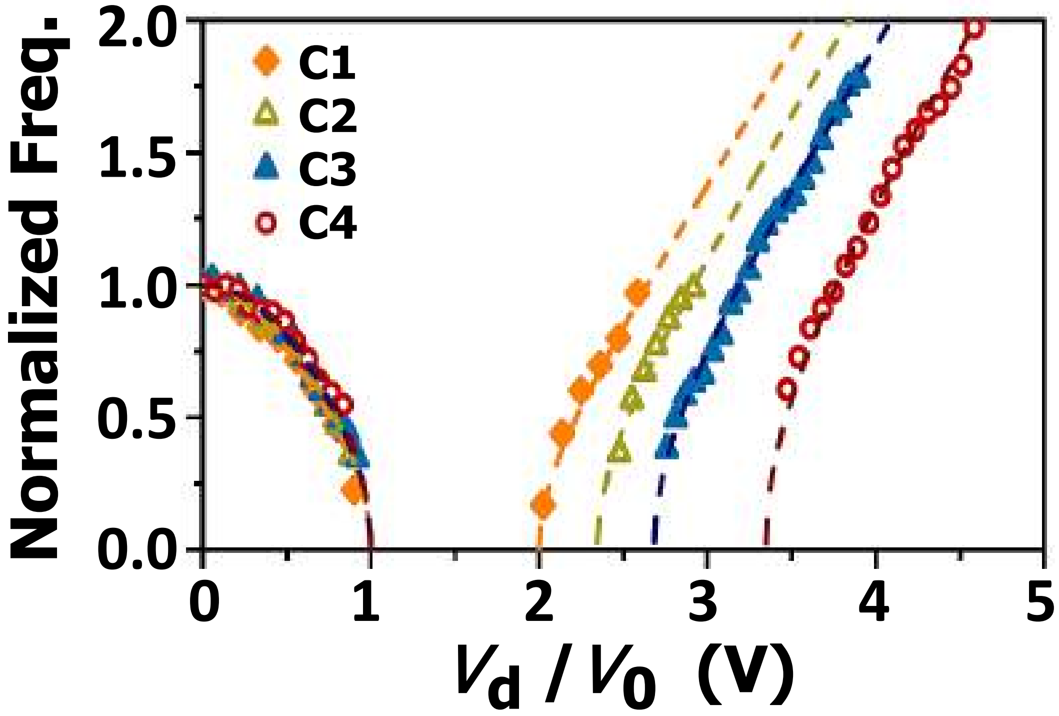
Cavity: C4



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).





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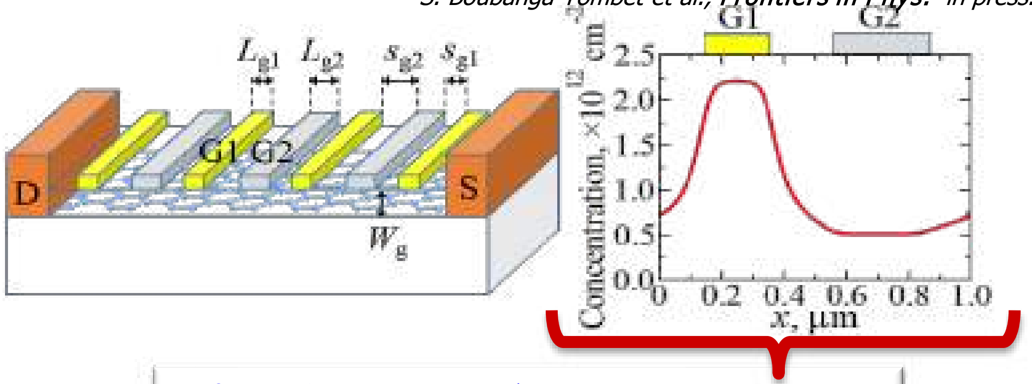
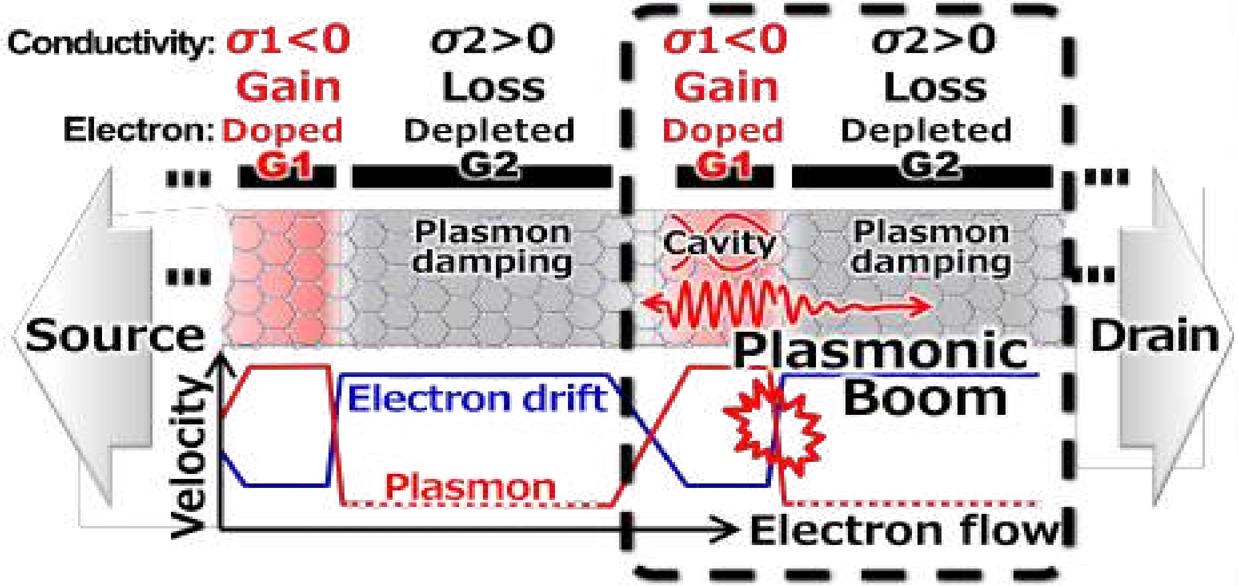
グラフェンDiracプラズモンの不安定性に由来した自励発振＆誘導増幅放出の発現

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.



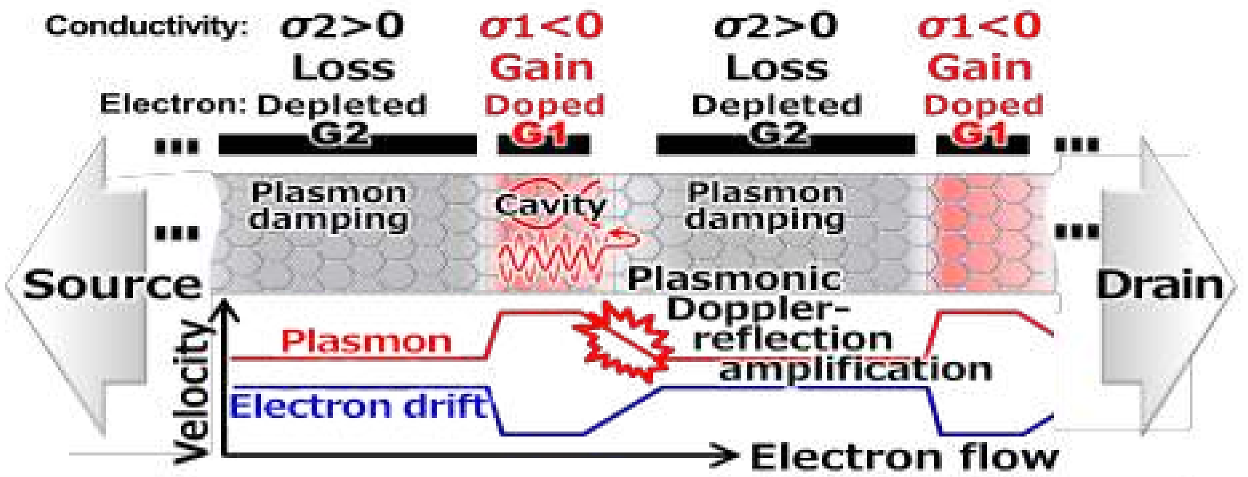
プラズモニックブーム型不安定性

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



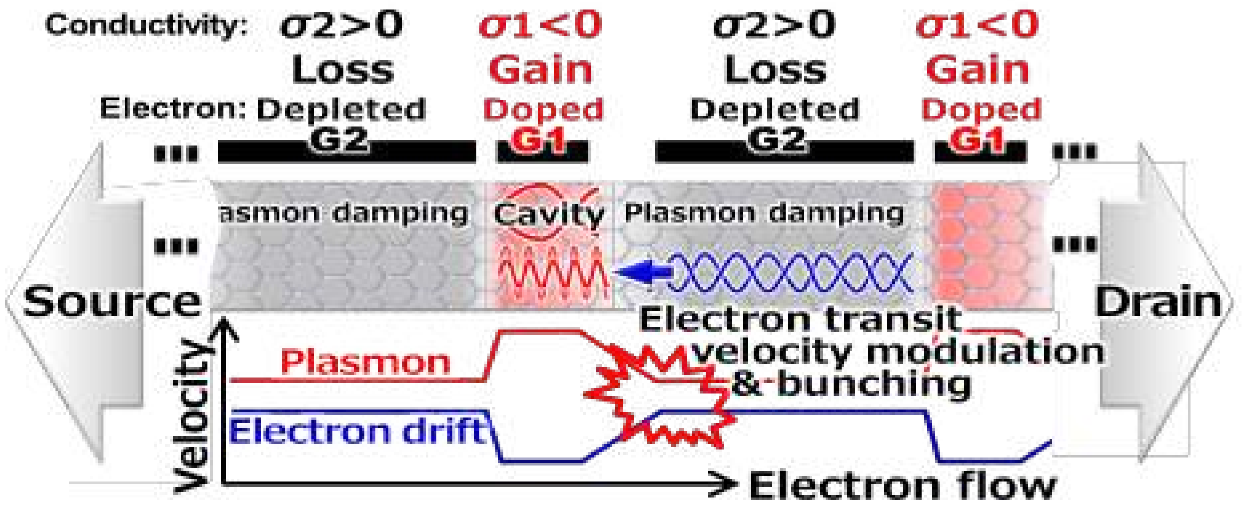
ドップラーシフト型不安定性

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



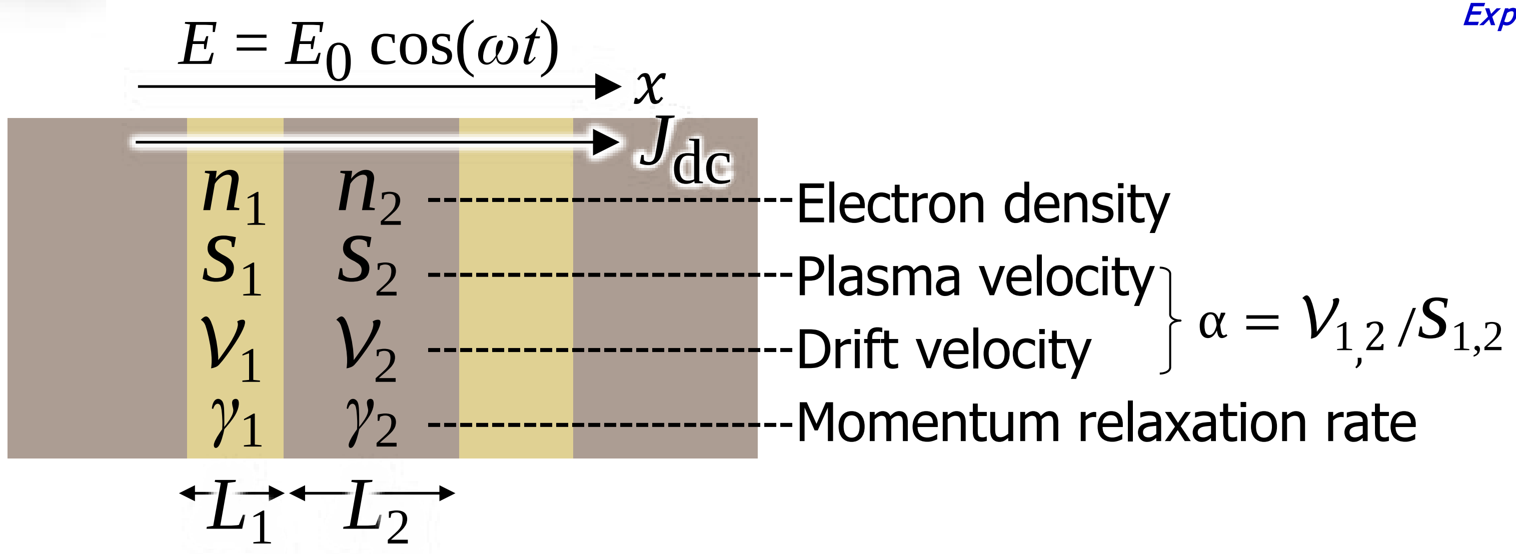
電子速度変調型不安定性

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



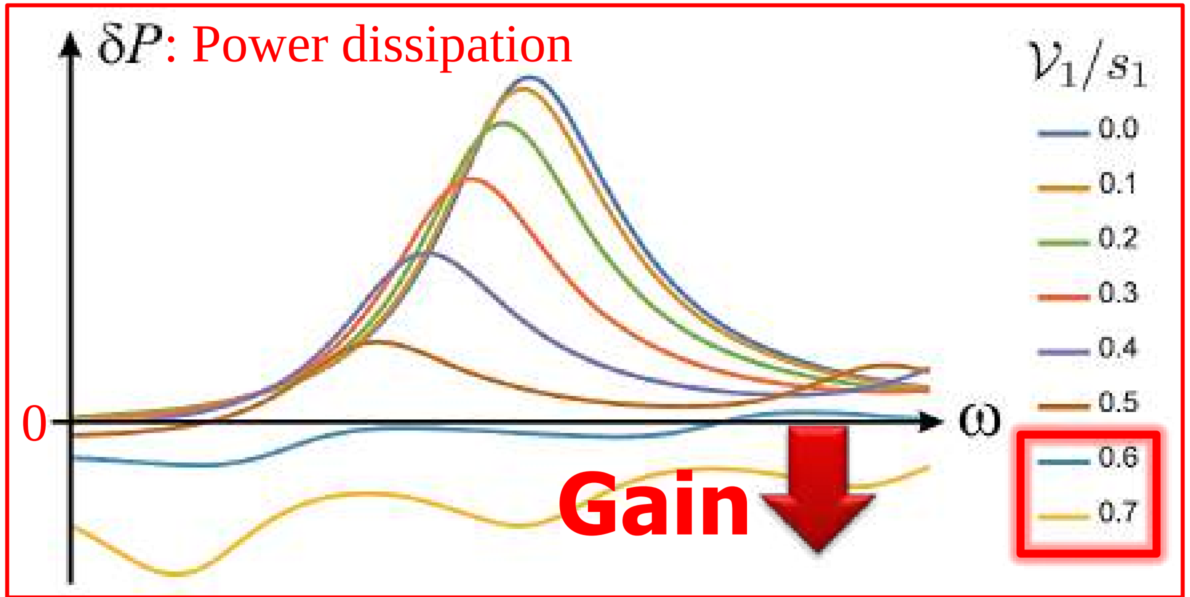
グラフェンプラズモン不安定性の新たな学理を発見
電子速度がプラズモン速度以下でも増幅が可能！

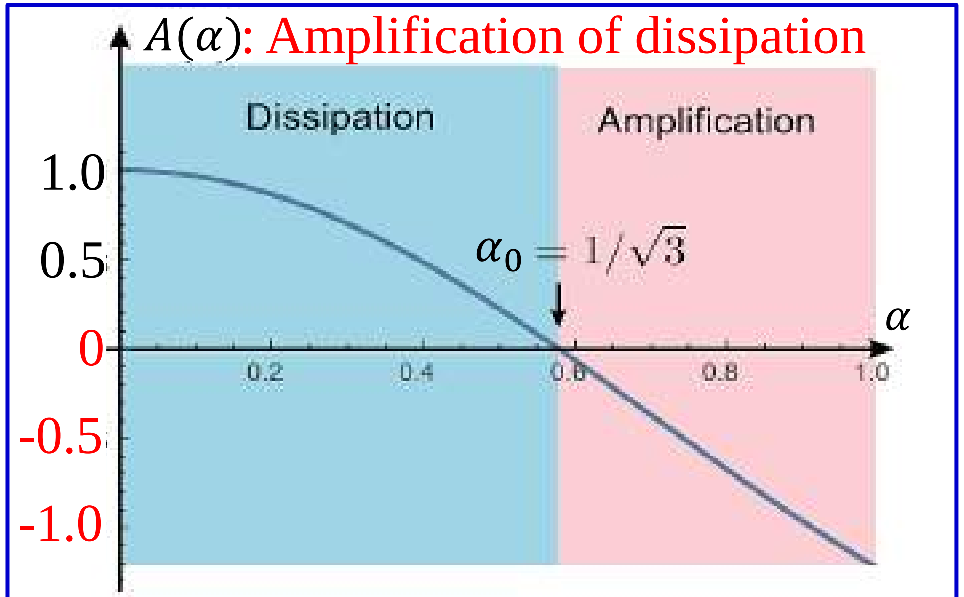
Experiments: S. Boubanga-Tombet et al., **arXiv**. 1801.04518.
Theory: A. V Chaplik, **Sov. Phys. JETP 35**, 395 (1972).
Y. Koseki et al., **PRB 93**, 245408 (2016).
S. Mikhailov, **PRB 58**, 1517 (1998).
M. Dyakonov and M. Shur, **PRL 71**, 2465 (1993).



$$\left(\mathcal{V}_1 \frac{\partial}{\partial x} - i\omega + \gamma_1\right)\delta v_1 + s_1^2 \frac{\partial \delta n_1}{\partial x} = \frac{eE_0}{2m},$$

$$\left(\mathcal{V}_1 \frac{\partial}{\partial x} - i\omega\right)\delta n_1 + \frac{\partial \delta v_1}{\partial x} = 0.$$





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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

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$\mathcal{PT}$ 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:

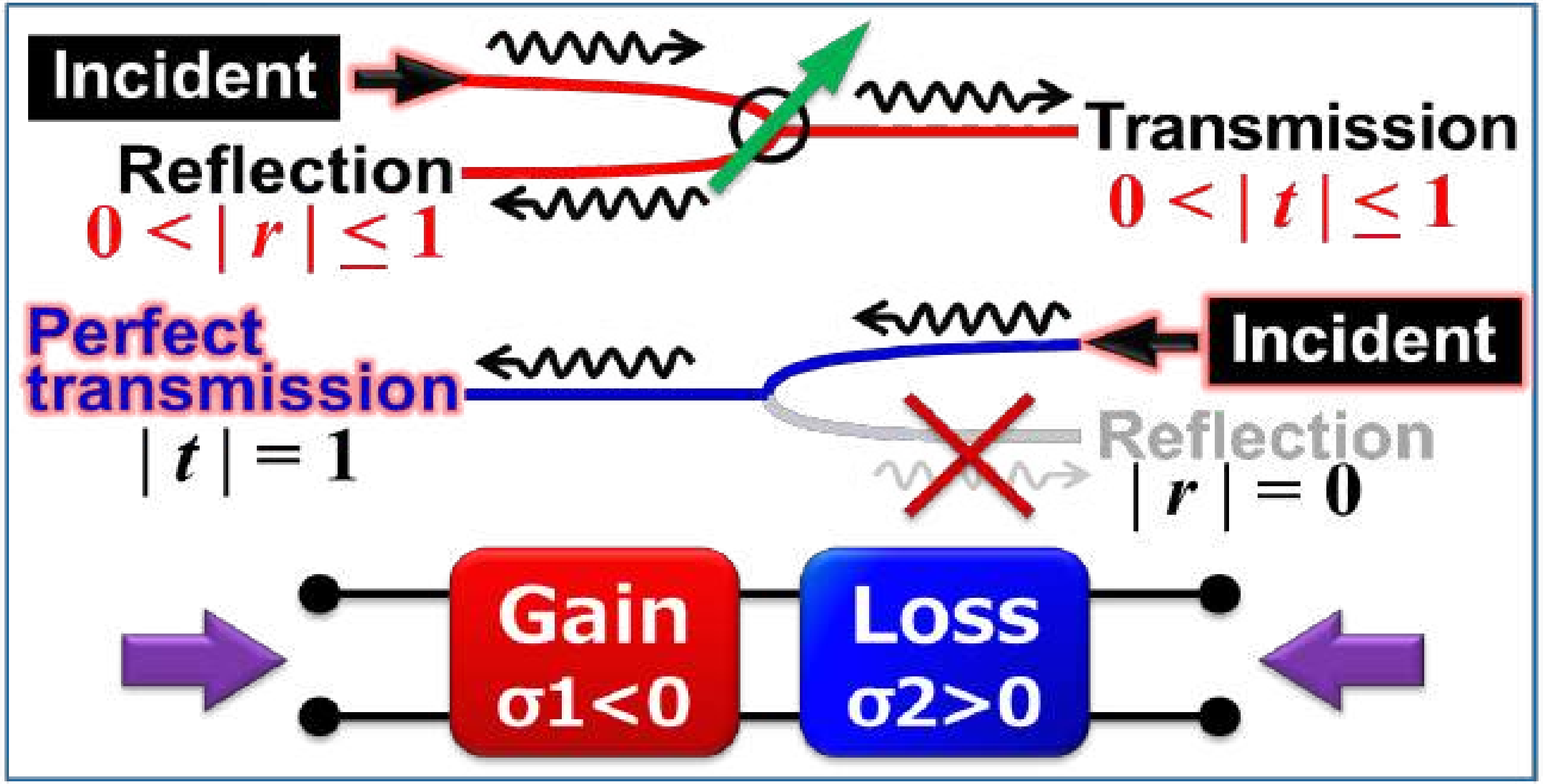
Parity ☞ **r ⇔ -r** , **k ⇔ -k** , **p ⇔ -p**

Time reversal ☞ ***t*** **⇔ -*t*** , **ω ⇔ -ω**

σ ⇔ -σ

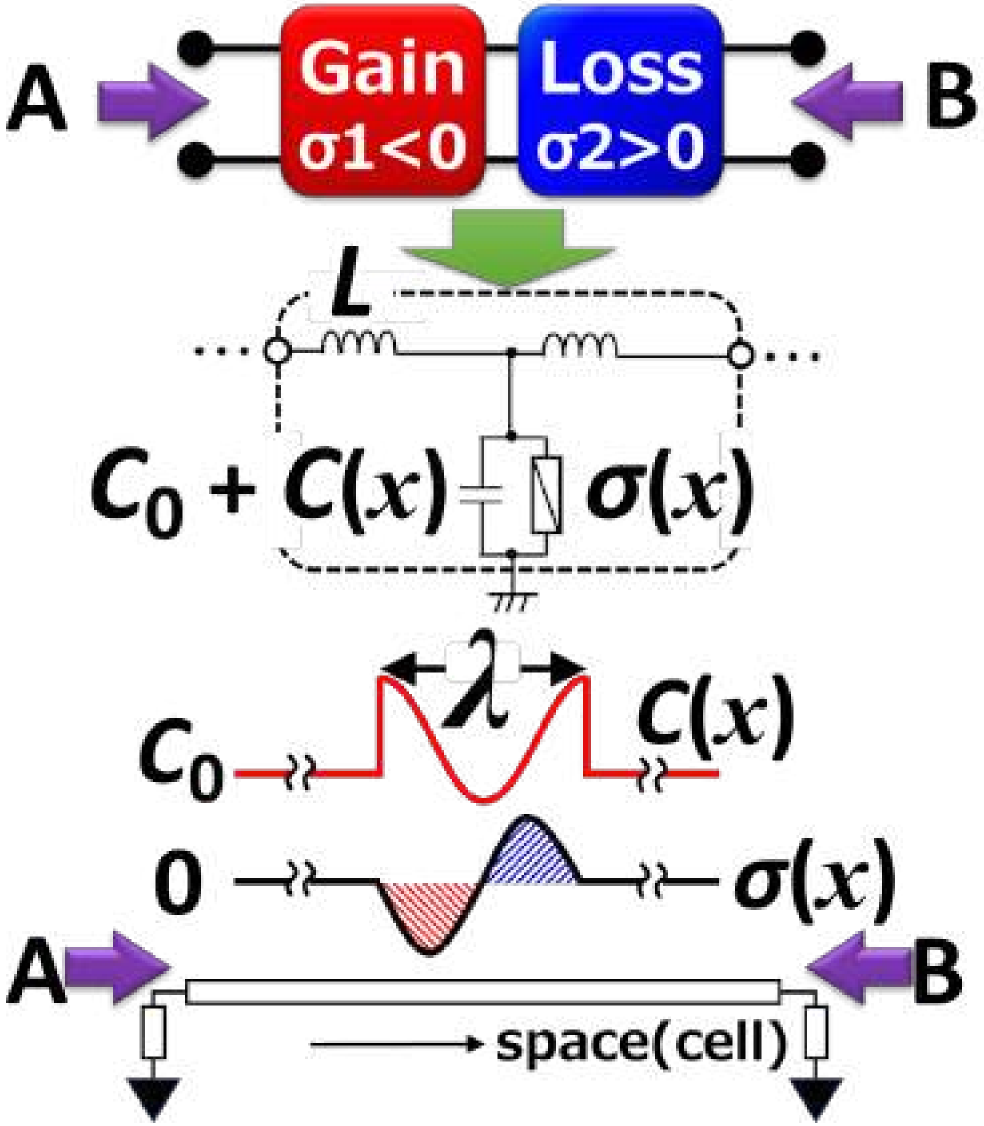
$$\omega = k\,c/\sqrt{\epsilon_r + i\sigma/\omega}$$

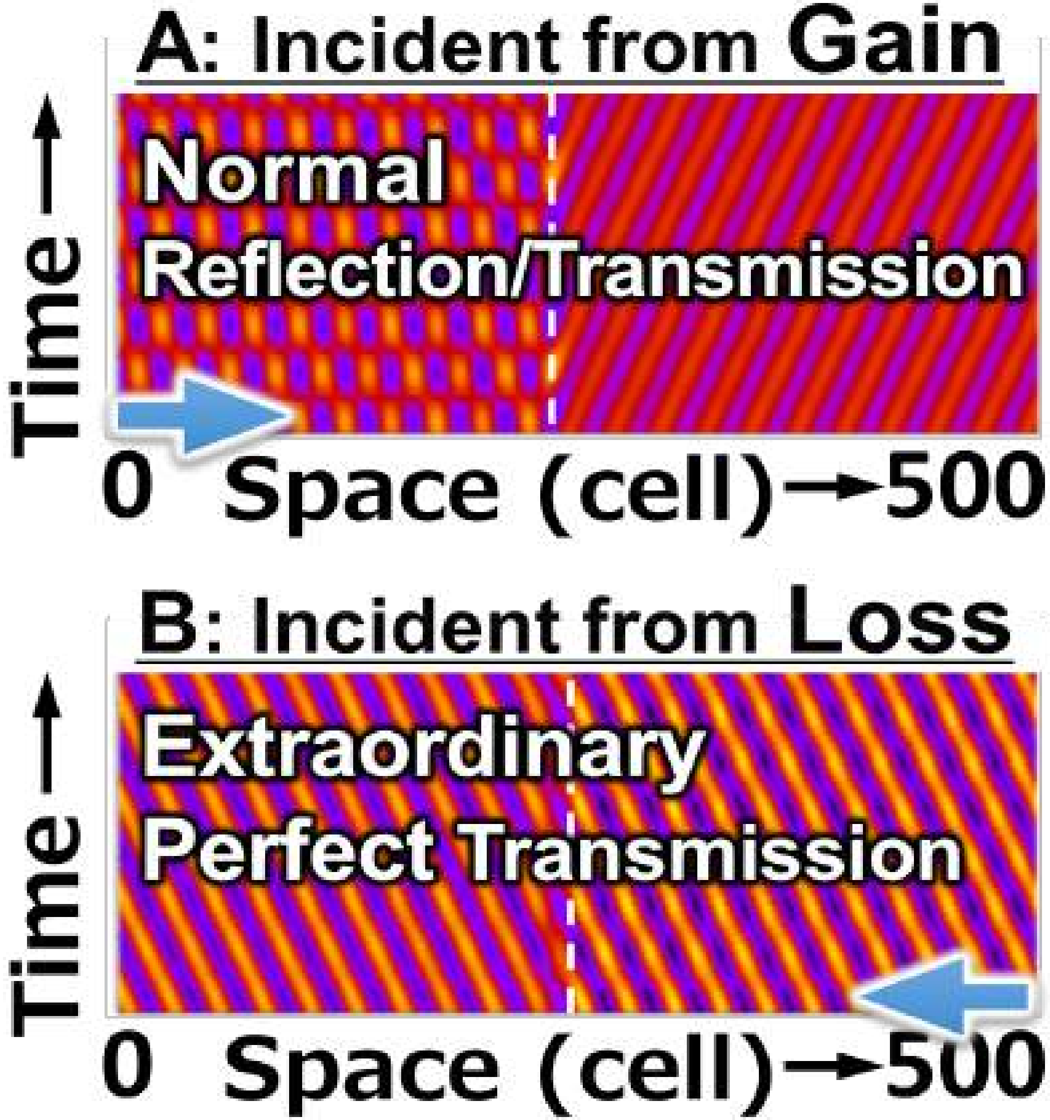
$\mathcal{PT}$ Symmetry
|σ1| = |σ2|



伝送線路トイモデルによる$\mathcal{PT}$ 対称性の特異伝搬再現

K. Narahara and T. Otsuji, ***unpublished***.

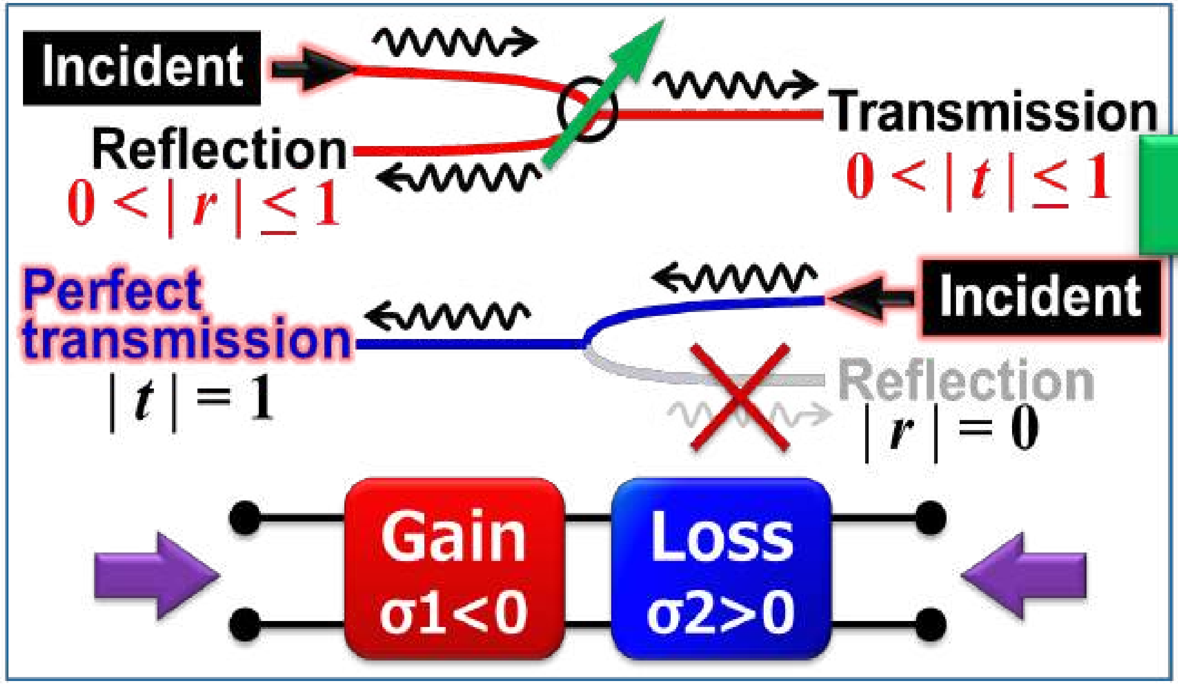


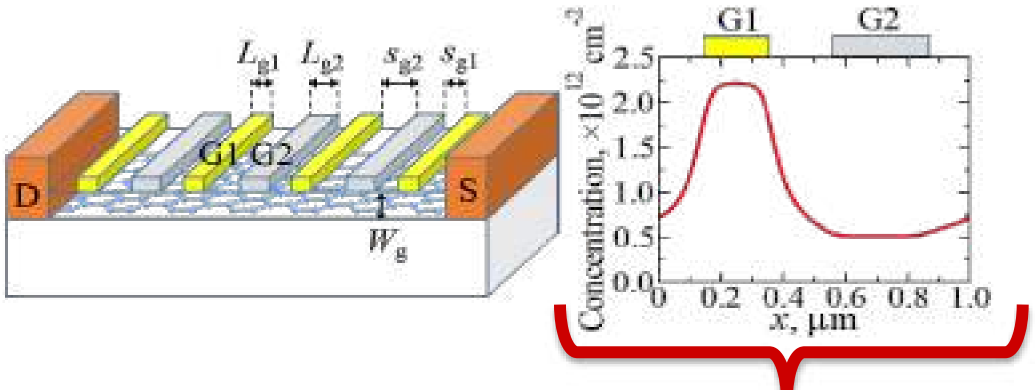


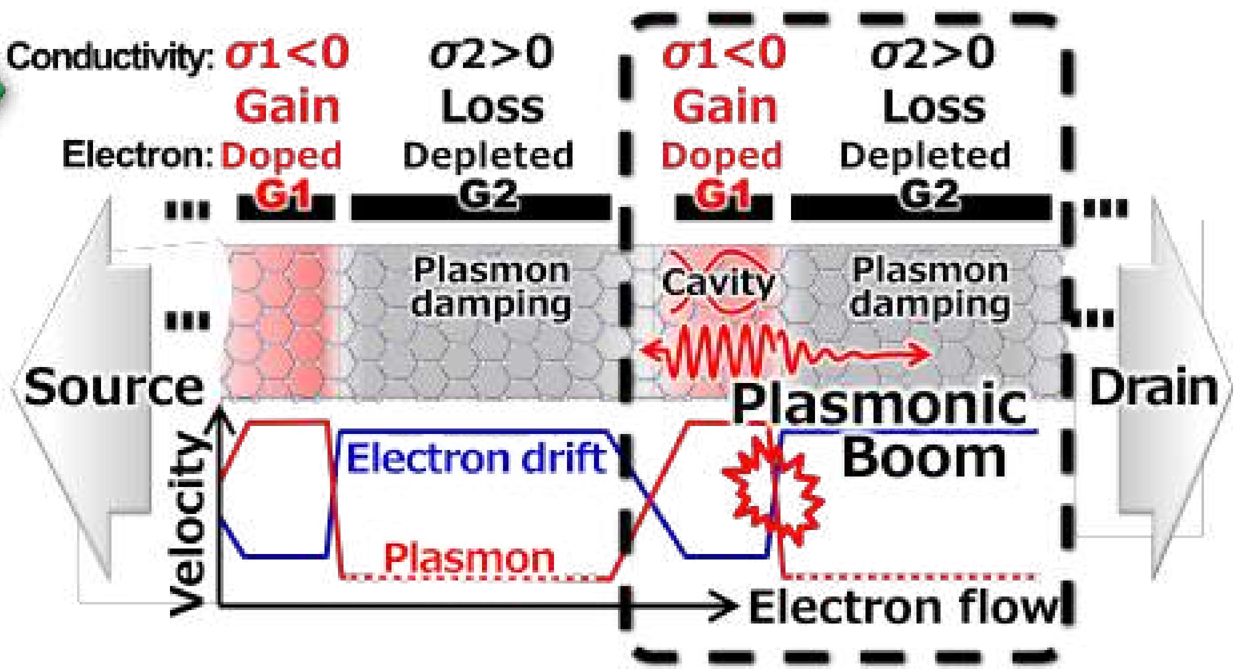
グラフェンDiracプラズモン(GDP)-DGGメタ表面への $\mathcal{PT}$ 対称性の実装

T. Otsuji, *unpublished.*

$\mathcal{PT}$ Symmetry
|σ1| = |σ2|



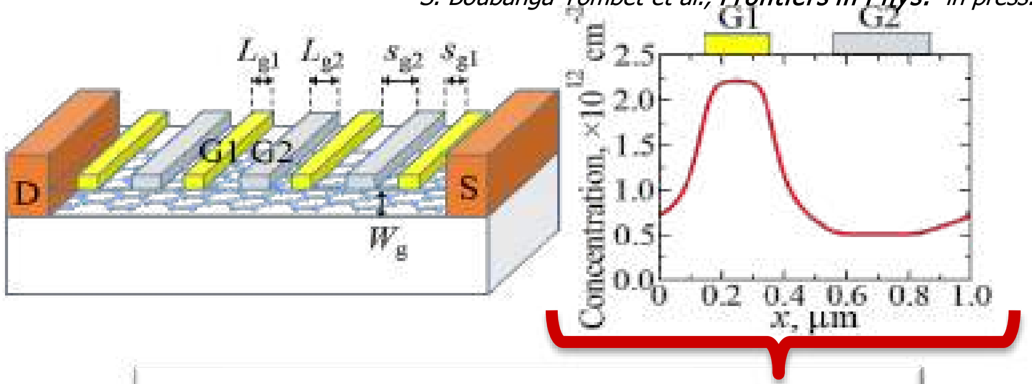




𝒫𝒯 対称性操作によるDGG-GDPの不安定性制御

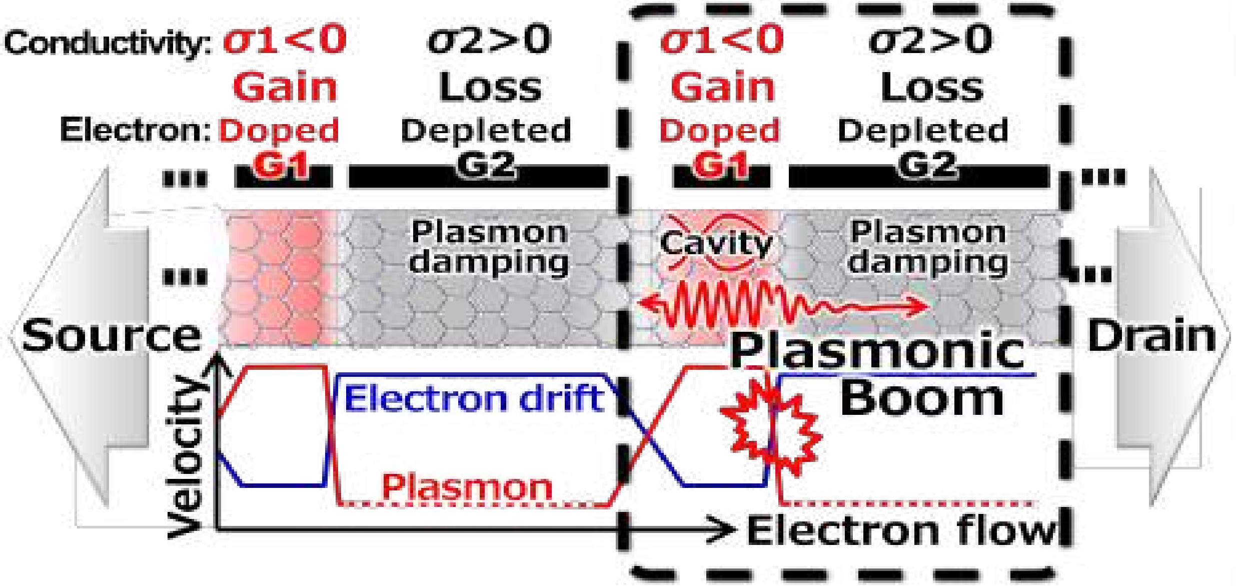
T. Otsuji, *unpublished.*

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.



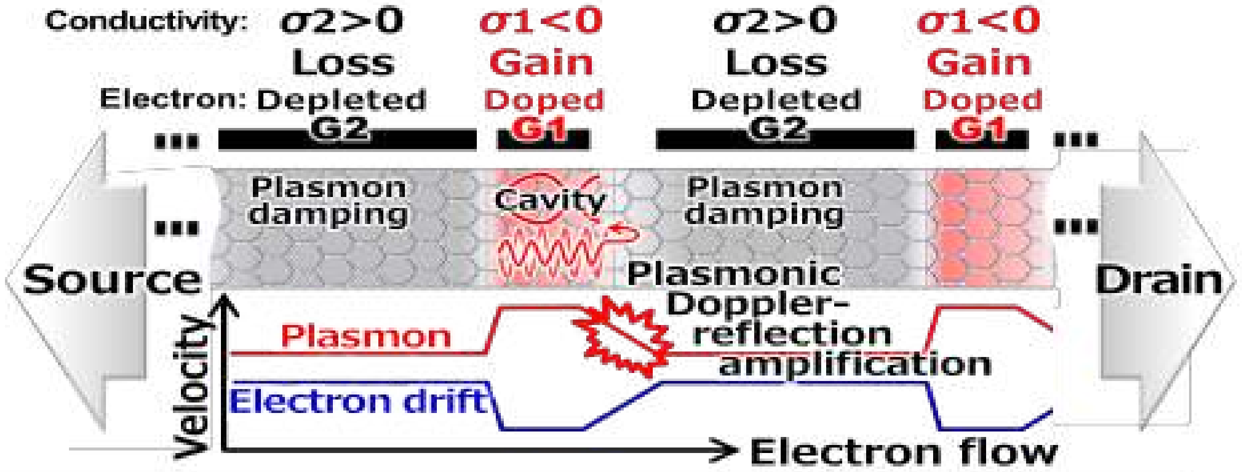
Plasmonic-Boom Instability

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



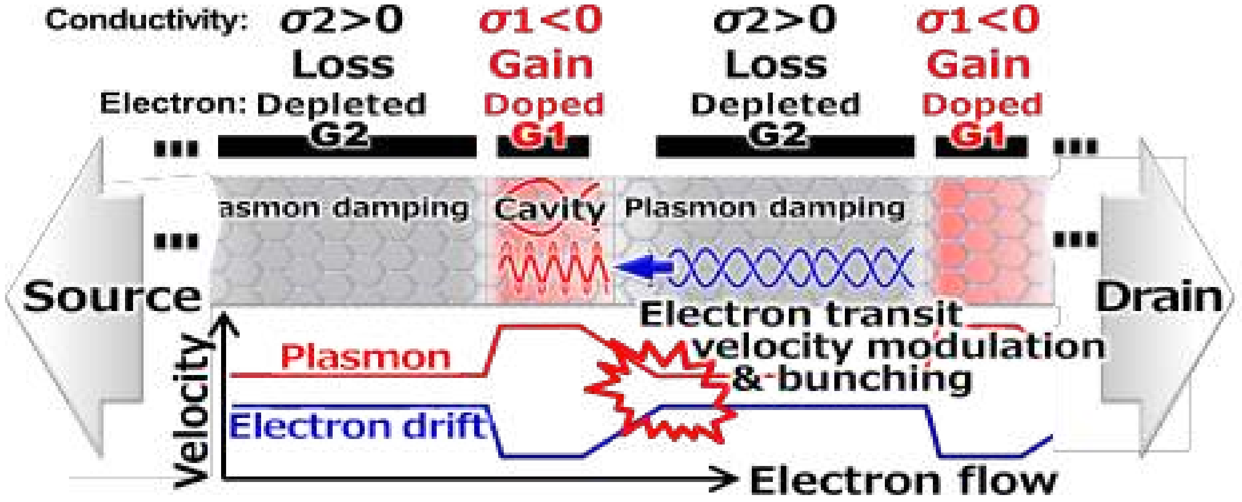
Doppler-Shift-Type Instability

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



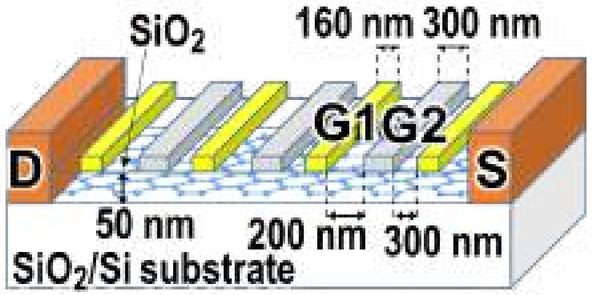
Electron-Transit-Type Instability

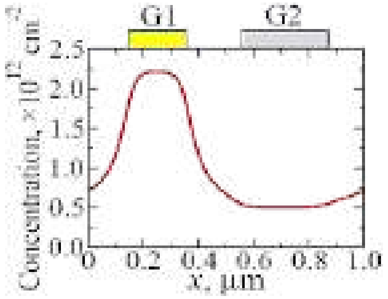
V. Ryzhii, A. Satou, M.S. Shur, **Phys. Status Solidi A 202**, R113 (2005).



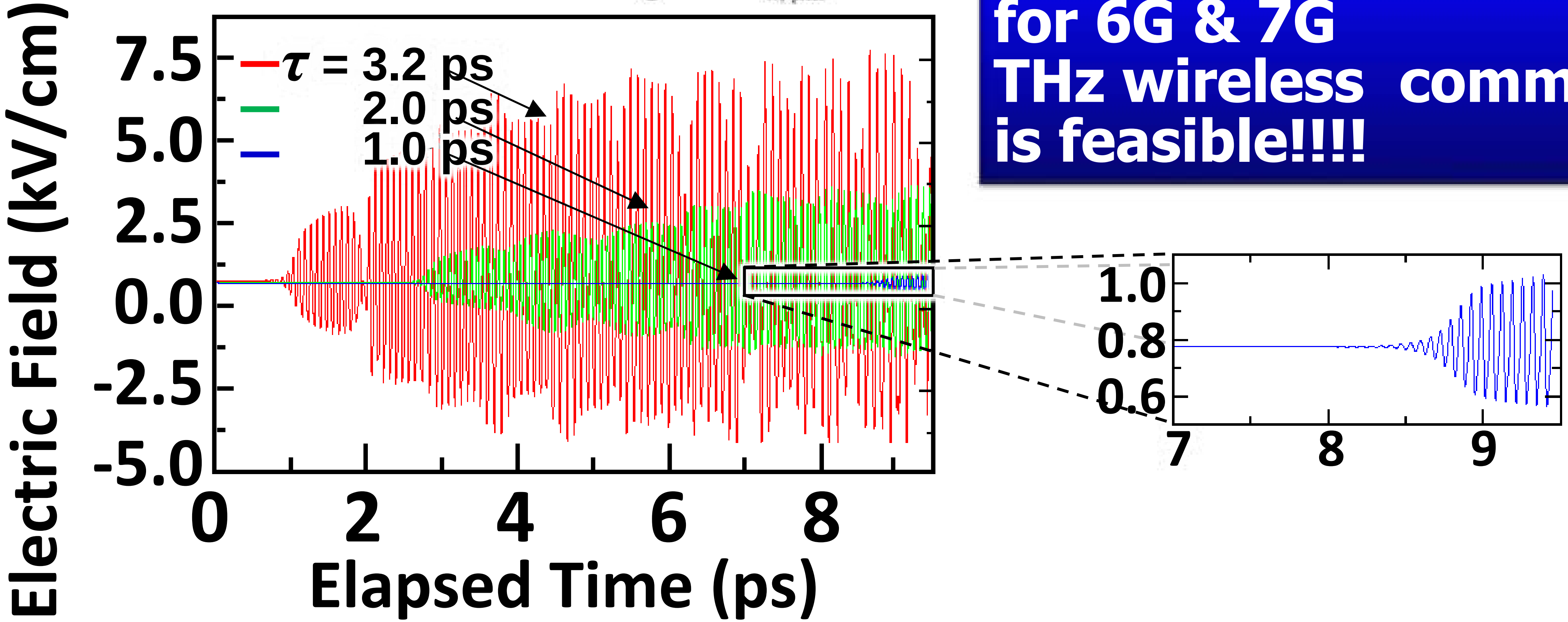
$\mathcal{PT}$ 対称性操作によるADGG-GDP不安定性制御とその超高速レーザー発振直接変調制御の可能性

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



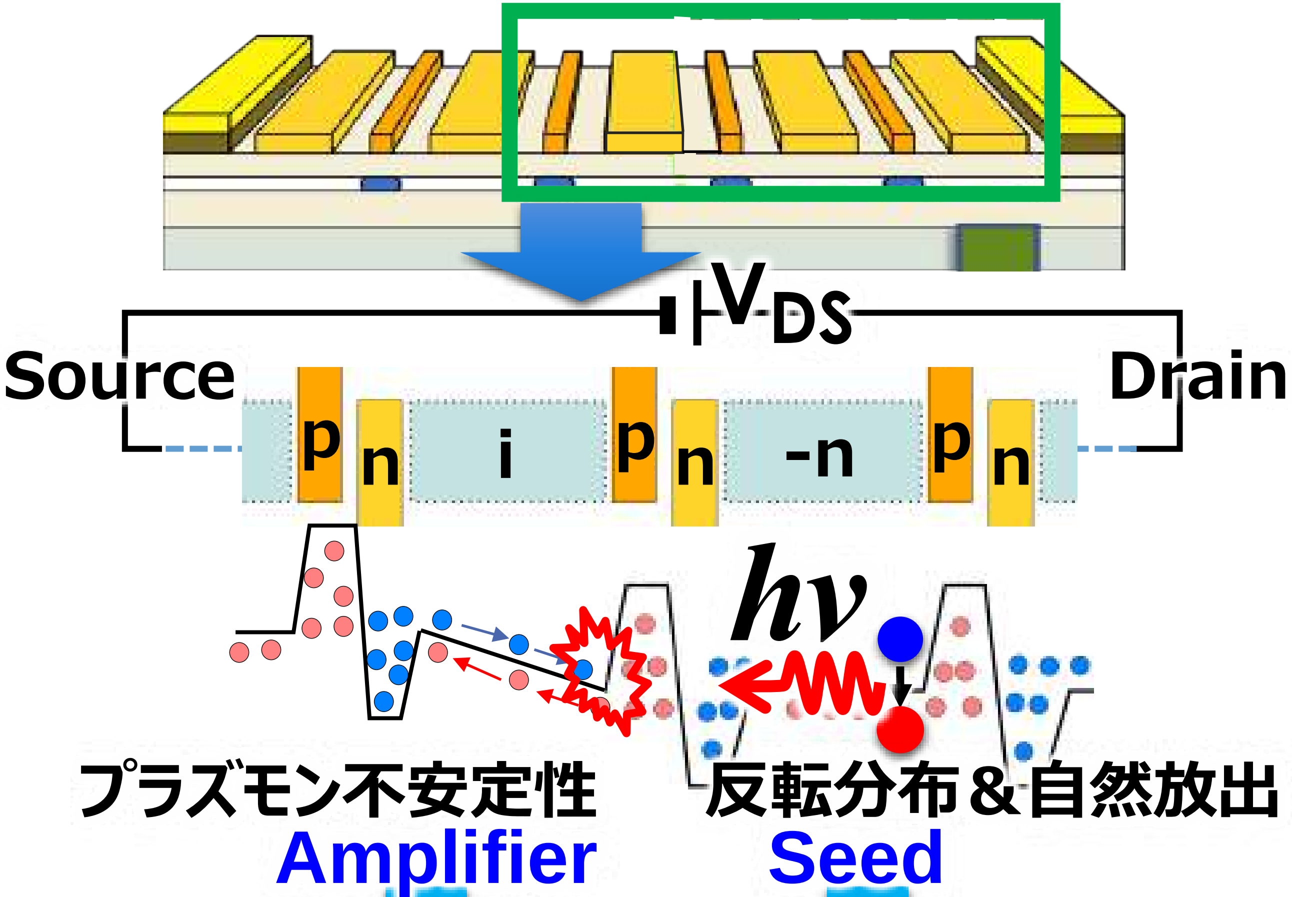


100-Gbit/s-class ultrafast data coding for 6G & 7G THz wireless comm's is feasible!!!!



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

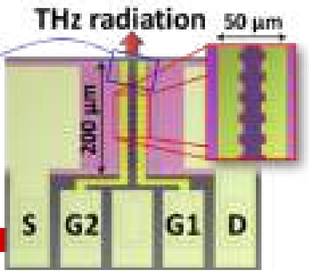
T. Otsuji et al., *unpublished.*

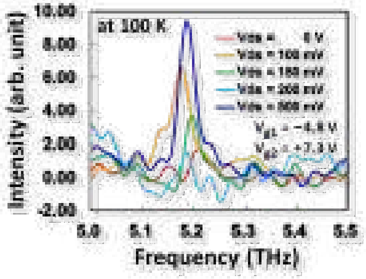


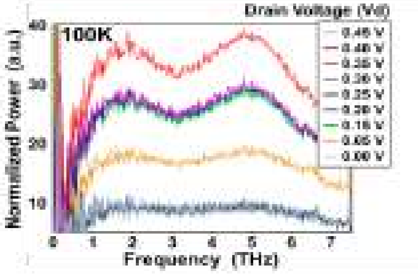
PT対称性操作

グラフェンプラズモニックTHzレーザートランジスタ

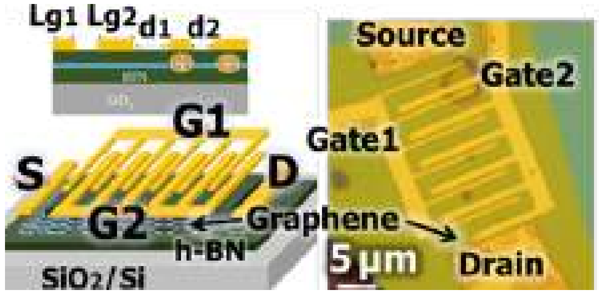
まとめ

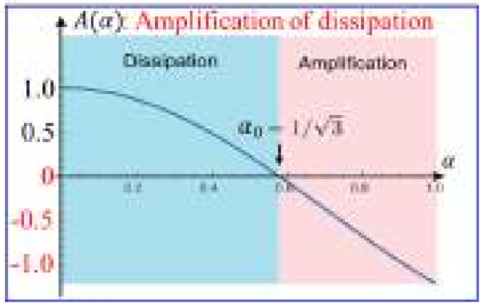



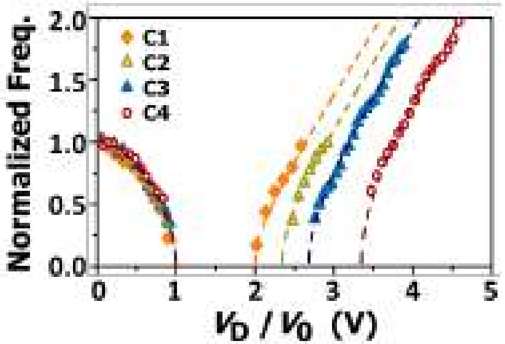


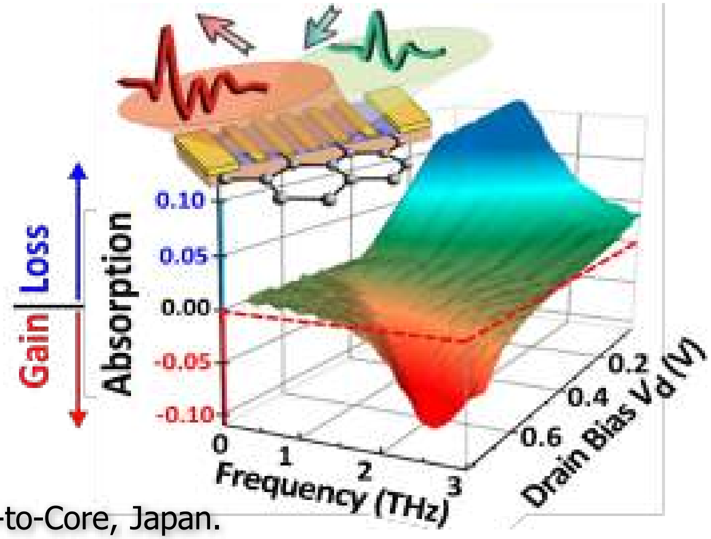


- THzギャップ克服のために、グラフェンの２次元電子ガスに励起される“プラズモン”を新たなブレークスルーとして導入した新原理テラヘルツ波増幅素子を提案した。
- 実験の結果、THzフォトンがグラフェン電子と直接相互作用して得られる量子効率限界を４倍以上も上回る最大９％の増幅利得を室温下で得ることに成功した。
- 次世代６G, 7G超高速無線通信実現に光明となる成果であり、室温・高強度・高速変調グラフェンプラズモニックTHzレーザートランジスタの実現に期待がかかる。









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

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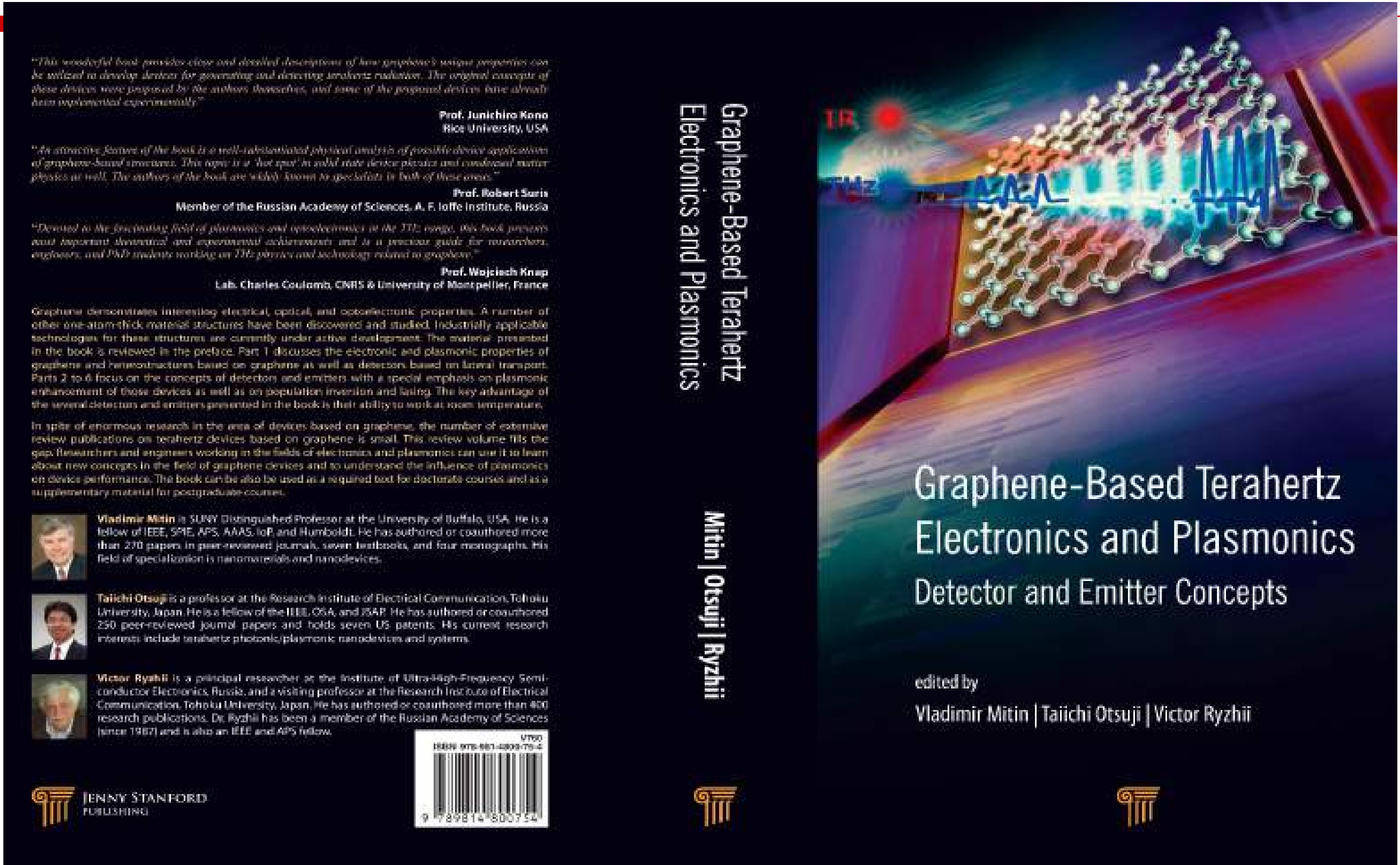

ご清聴をありがとうございました。