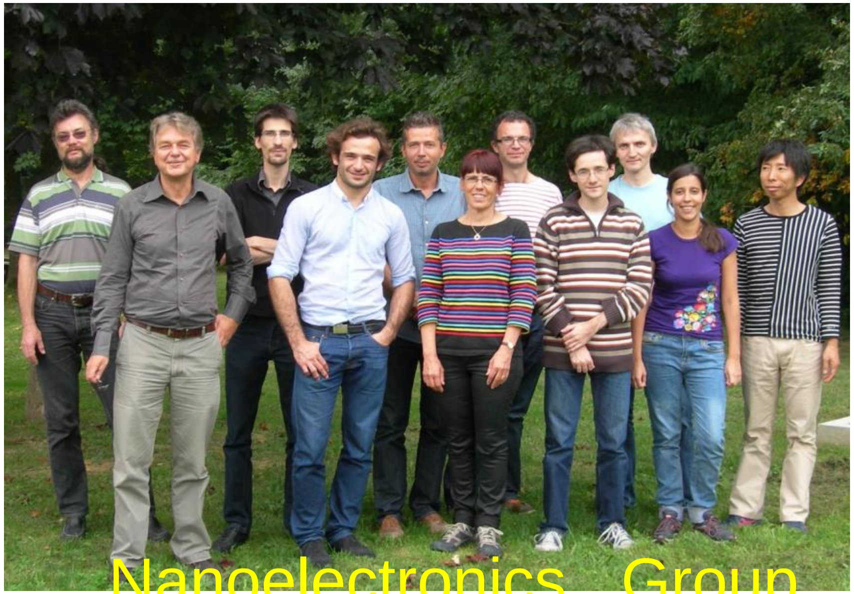
ERC Advanced Grant MeQuaNo

Edge Magnetoplasmons in Graphene in the Quantum Hall Regime

D. C. Glattli CEA Saclay ,France

collab. NTT Atsugi, Jpn

N. Kumada (NTT Atsugi Jpn, visitor CEA)
H. Hibino (NTT Atsugi, Jpn)
M. Hashisaka (Tokyo Inst. Techn. Jpn)
I. Petkovic (post-doc, now at Yale)
F.I.B. Williams (visitor from Un.Budapest)
L. Serkovic (Post-doc, now in Mexico)
Keyan Bennaceur (PhD now @ McGill Un.)
Preden Roulleau (CEA Saclay)
P. Roche (CEA Saclay)
F. Portier (CEA Saclay)
D. C. Glattli (CEA Saclay)



Nanoelectronics Group

electronflying qubits (levitons), electron interferometer, quantum shot noise, electron quantum state tomography Graphene.,

Plasmons and/in Graphene

fast rising field

Koppens, F.H.L., Chang, D.E. and de Abajo, F.J.G. Nano Letters 11, 3370-3377 (2011).
Fei, Z. et al. Infrared nanoscopy of Dirac plasmons at the graphene-SiO2 interface.
Nano Lett. 11, 4701-4705 (2011).

Ju, L. et al. Graphene plasmonics for tunable terahertz metamaterials.
Nature Nanotechnol. 6, 630-634 (2011).

Chen, J. et al. Optical nano-imaging of gate-tunable graphene plasmons.
Nature 487 77-81 (2012).

Fei, Z. et al. Gate-tuning of graphene plasmons revealed by infrared nano-imaging.
Nature 487 82-85 (2012).

L. Vicarelli, M. S. Vitiello, D. Coquillat, A. Lombardo, A. C. Ferrari, W. Knap, M. Polini,
V. Pellegrini & A. Tredicucci,
Graphene field-effect transistors as room-temperature terahertz detectors,
Nature Materials 11, 865–871 (2012)

Ryzhii V. Terahertz plasma waves in gated graphene heterostructures.
Jpn. J. Appl. Phys. 45, L923–L925 (2006)

Edge *vs* bulk plasmons

BULK

$$\omega \sim n^{1/4} \sim V_G^{1/4}$$

non chiral

weak gate dependence

damped < inverse relaxation time (~THz)
THz to Infrared domain

EDGE

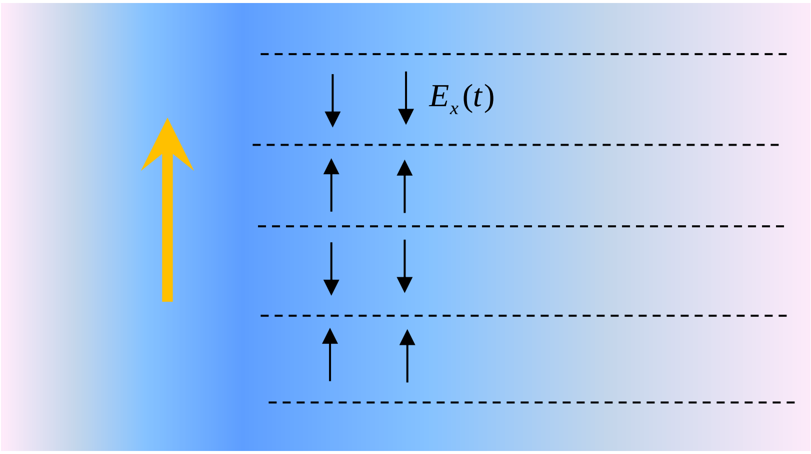
$$\omega \sim n \sim V_G$$

chiral

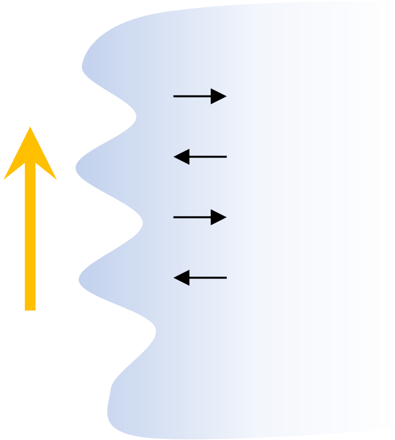
reversible with gate or field

weakly damped on Hall plateaus
GHz to THz domain

possibility of chiral plasmonics
(gated rf-isolators, circulators,…)

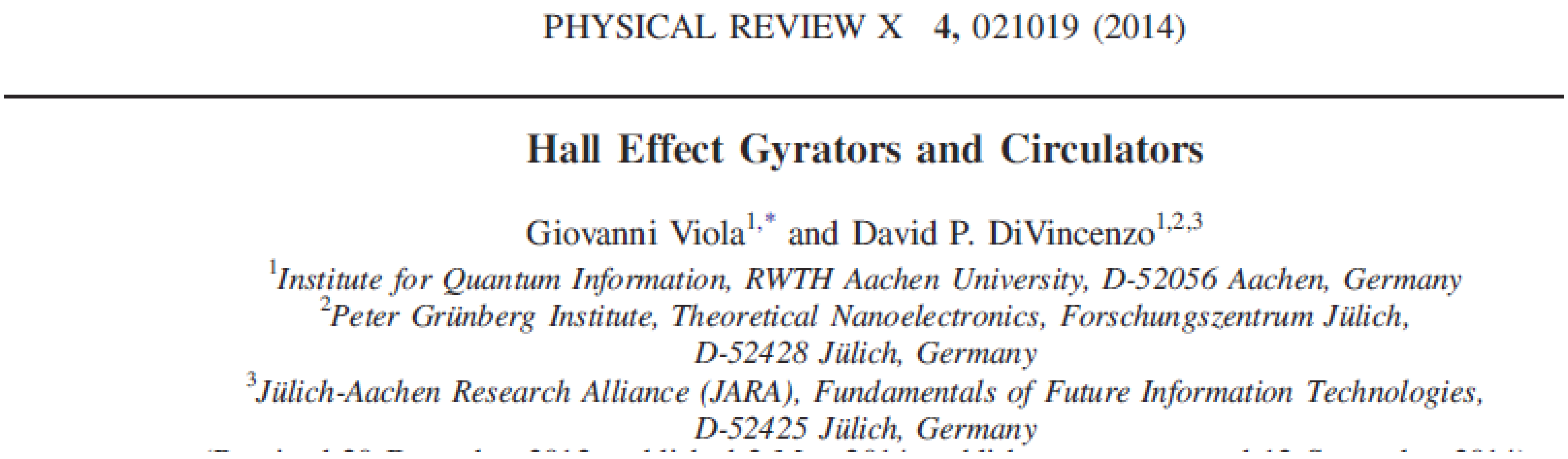


bulk



boundary

Edge magneto-plasmons applications



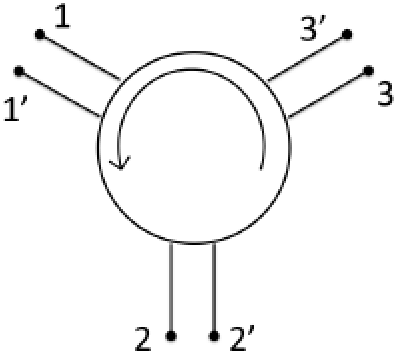
PHYSICAL REVIEW X **4**, 021019 (2014)

Hall Effect Gyrators and Circulators

Giovanni Viola[1,*] and David P. DiVincenzo[1,2,3]
[1]*Institute for Quantum Information, RWTH Aachen University, D-52056 Aachen, Germany*
[2]*Peter Grünberg Institute, Theoretical Nanoelectronics, Forschungszentrum Jülich,*
D-52428 Jülich, Germany
[3]*Jülich-Aachen Research Alliance (JARA), Fundamentals of Future Information Technologies,*
D-52425 Jülich, Germany

possibility of chiral plasmonics
(gated rf-isolators, circulators,…)

$$S = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}.$$



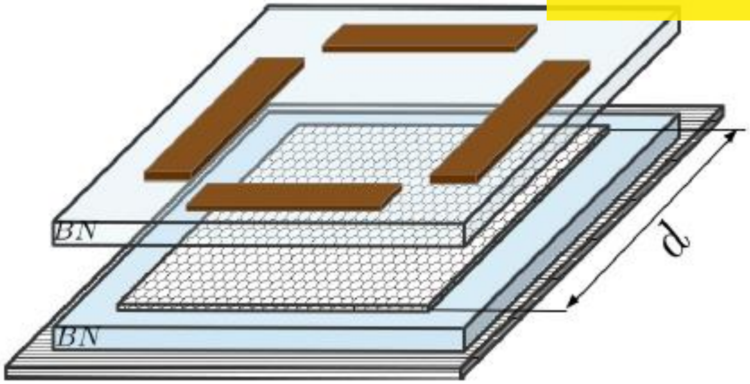


FIG. 15. An exploded view of a sandwich structure, based on the capabilities recently reported in [62]. A graphene flake is encapsulated between two layers of insulating boron nitride (BN). Four edge electrodes grown above the structure as shown could serve as the four capacitive contacts of the two-port gyrator.

Graphene:
B = 2 Tesla, T=300K

$\mu \sim 10^4$ V cm^{-2} s^{-1}

Hall angle > 45°

enough for low loss circulator

dynamics mediated by Edge Magneto-plasmons

Outline

- Introduction
  - what are edge magnetoplasmons (EMP)?
  - classical
  - quantum (QH regime)

- EMP in graphene

- Experiment I (exfoliated graphene 40um perimeter)
  - evidence for chiral propagation
  - velocity of EMP mode
  - carrier drift velocity

- Experiment II (SiC graphene 200um /1mm perimeter)
  - check EMP dispersion relation
  - measure damping of EMPs

- Conclusion and Perspectives

2D plasmons

3D

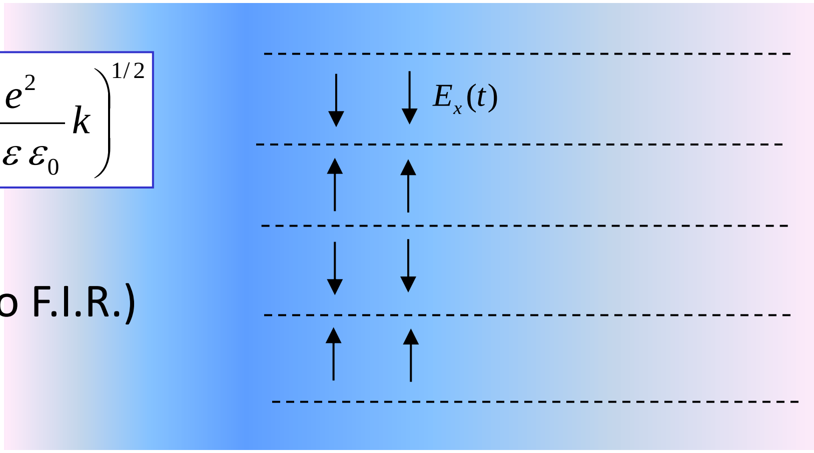
$$\boxed{\omega_P(k)=\left(\frac{n_{3D}e^2}{m\varepsilon\varepsilon_0}\right)^{1/2}}$$

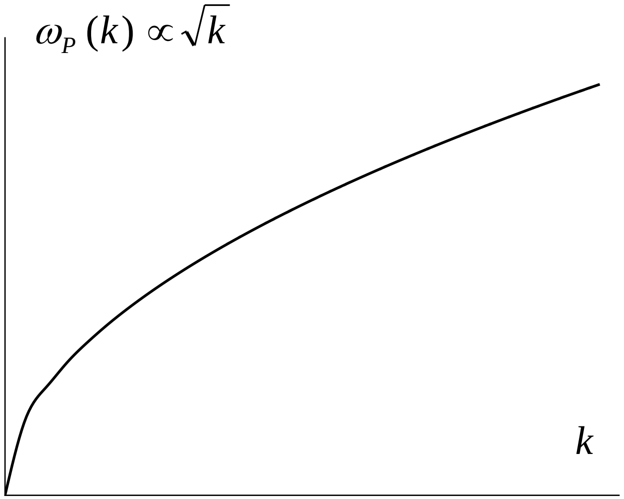
(IR to U.V. range)

2D

$$\boxed{\omega_P(k)=\left(\frac{n_s e^2}{2m\varepsilon\varepsilon_0}k\right)^{1/2}}$$

(microwave to F.I.R.)





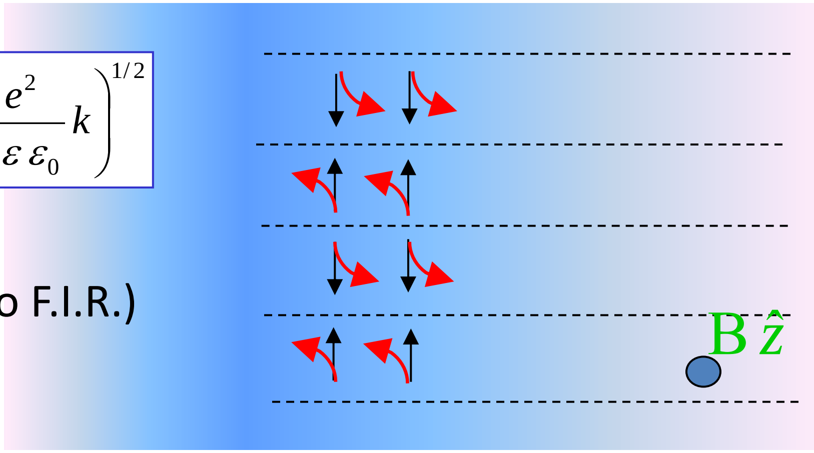
2D magneto-plasmons

3D $$\omega_P(k) = \left(\frac{n_{3D}\, e^2}{m\, \varepsilon\, \varepsilon_0} \right)^{1/2}$$

(IR to U.V. range)

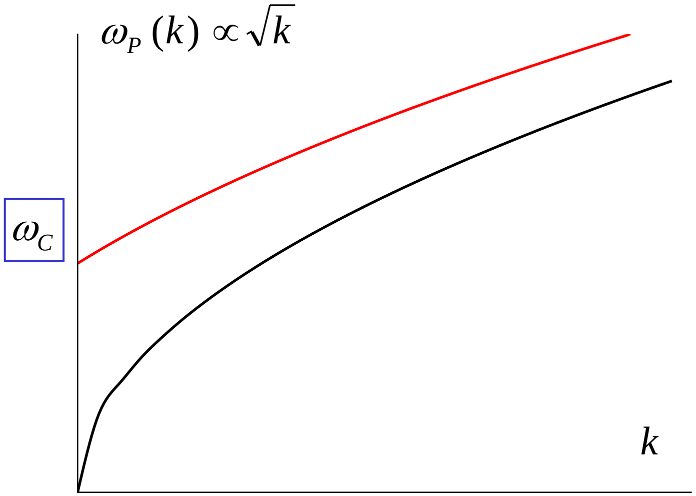
2D $$\omega_P(k) = \left(\frac{n_s\, e^2}{2\, m\, \varepsilon\, \varepsilon_0} k \right)^{1/2}$$

(microwave to F.I.R.)



$$\omega_{MP}(k) = \left(\omega_P(k)^2 + \omega_C{}^2 \right)^{1/2}$$

$$\omega_C = \frac{eB}{m}$$



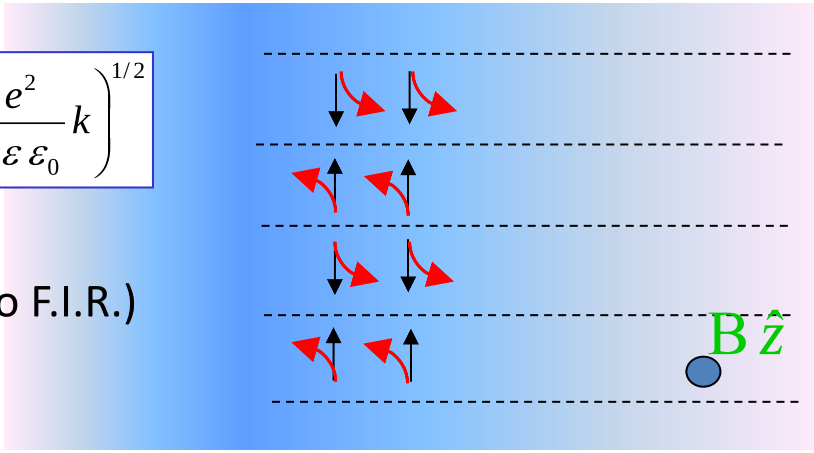
2D magneto-plasmons

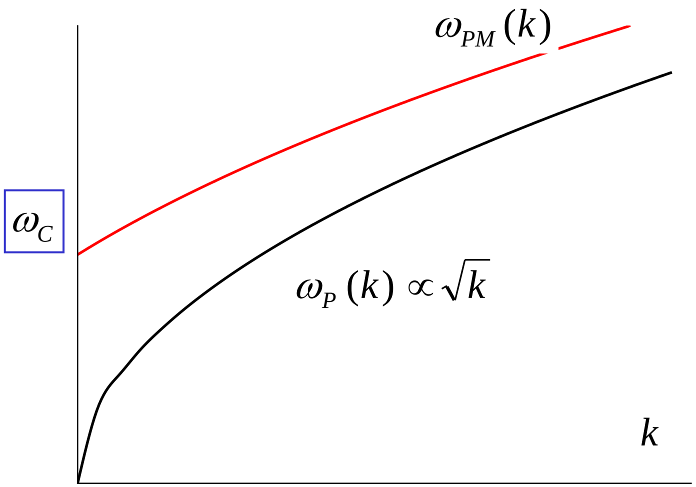
3D $\boxed{\omega_P(k) = \left(\frac{n_{3D}\, e^2}{m\,\varepsilon\,\varepsilon_0}\right)^{1/2}}$

(IR to U.V. range)

2D $\boxed{\omega_P(k) = \left(\frac{n_s\, e^2}{2\,m\,\varepsilon\,\varepsilon_0}\, k\right)^{1/2}}$

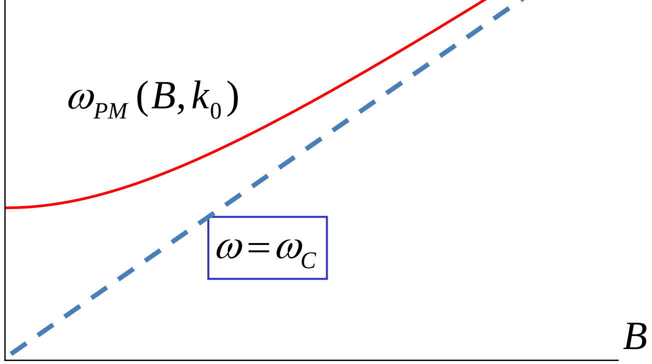
(microwave to F.I.R.)





$$\omega_{MP}(k) = \left(\omega_P(k)^2 + \omega_C{}^2\right)^{1/2}$$

$$\omega_C = \frac{eB}{m}$$



Edge Magneto-Plasmons (EMP)

3D

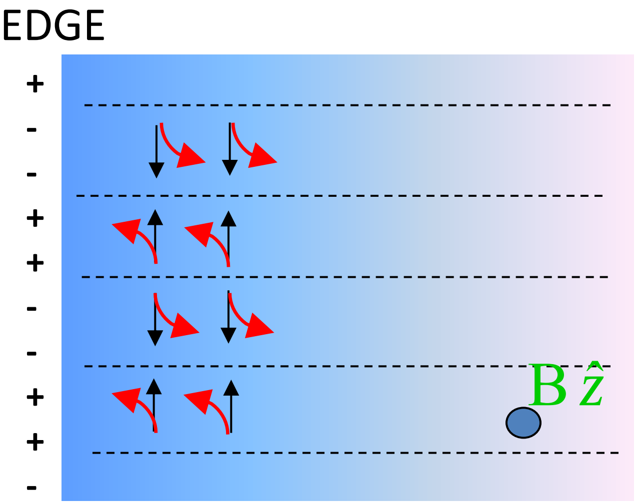
$$\boxed{\omega_P(k)=\left(\frac{n_{3D}\,e^2}{m\,\varepsilon\,\varepsilon_0}\right)^{1/2}}$$

(IR to U.V. range)

2D

$$\boxed{\omega_P(k)=\left(\frac{n_s\,e^2}{2\,m\,\varepsilon\,\varepsilon_0}\,k\right)^{1/2}}$$

(microwave to F.I.R.)



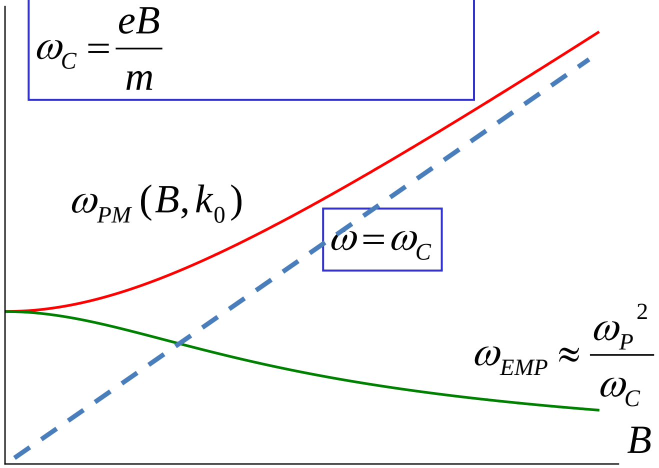
a charged line concentrates on the edge

wave exponentially decreases from the edge to the bulk

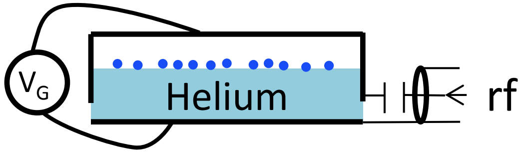
$$\boxed{\omega_{EMP}(k)\approx\frac{\omega_P(k)^2}{\omega_C}}$$

$$\omega_{MP}(k)=\left(\omega_P(k)^2+\omega_C{}^2\right)^{1/2}$$

$$\omega_C=\frac{eB}{m}$$



Edge Magneto-Plasmons (EMP) are classical



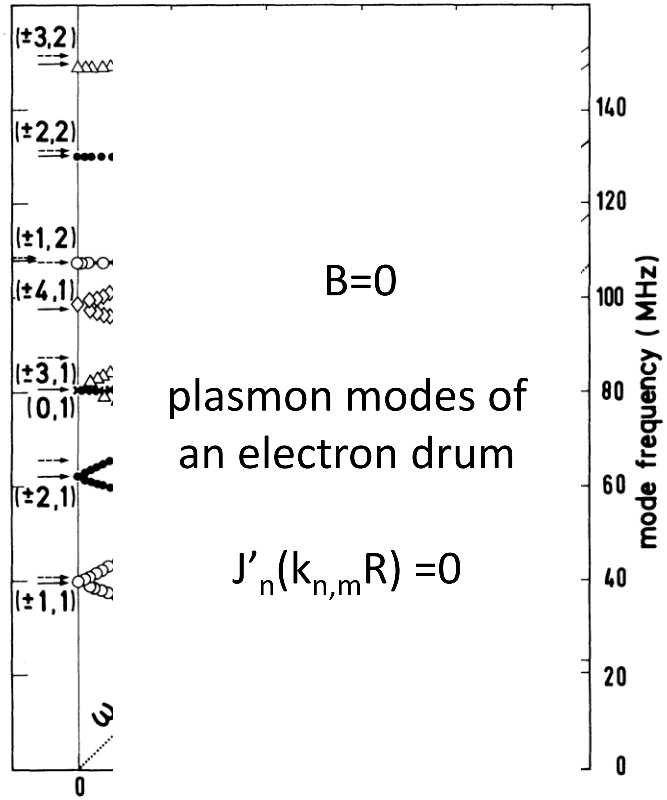
2D electrons
on Helium liq.

$$n_s = 10^8\ \mathrm{cm}^{-2}$$

$$\mu \approx 100\,\mathrm{x}\,10^6\ \mathrm{cm}^2\ \mathrm{V}^{-1}\ \mathrm{s}^{-1}$$

$$E_F\ 0.2\,\mathrm{K} \approx kT$$

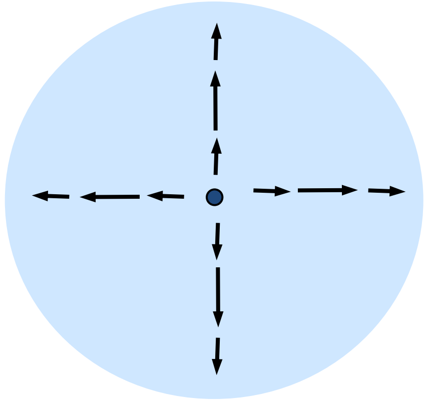
$$\boxed{\omega_P(k) = \left(\frac{n_s e^2}{2 m \varepsilon \varepsilon_0} k\right)^{1/2}}$$



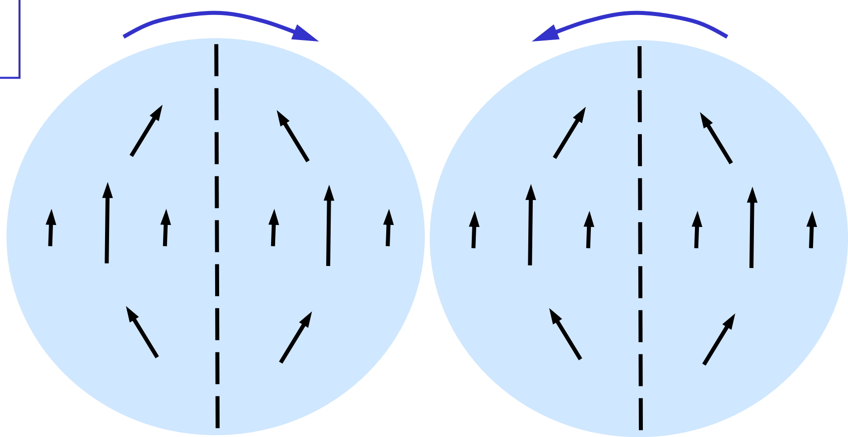
B=0

plasmon modes of
an electron drum

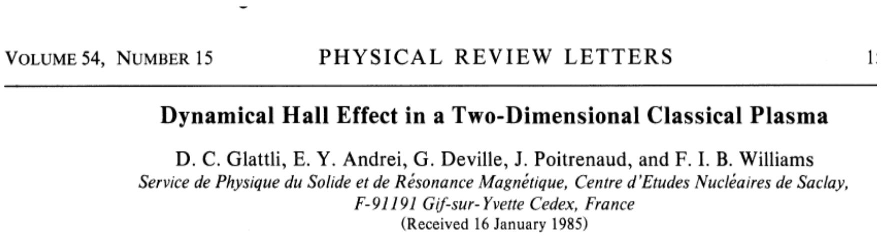
$J'_n(k_{n,m}R) = 0$



(radial)



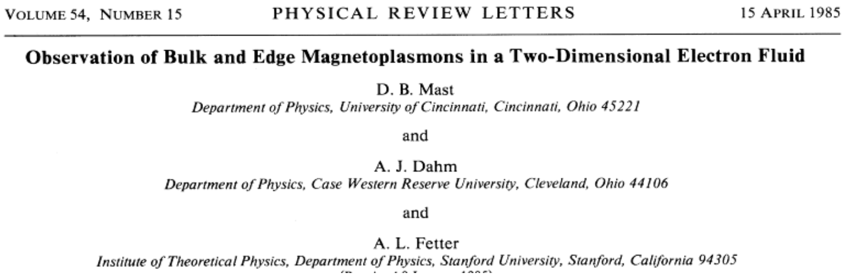
(azimuthal 1, +/- 1)



VOLUME 54, NUMBER 15 PHYSICAL REVIEW LETTERS 1

Dynamical Hall Effect in a Two-Dimensional Classical Plasma

D. C. Glattli, E. Y. Andrei, G. Deville, J. Poitrenaud, and F. I. B. Williams
Service de Physique du Solide et de Résonance Magnétique, Centre d'Etudes Nucléaires de Saclay,
F-91191 Gif-sur-Yvette Cedex, France
(Received 16 January 1985)

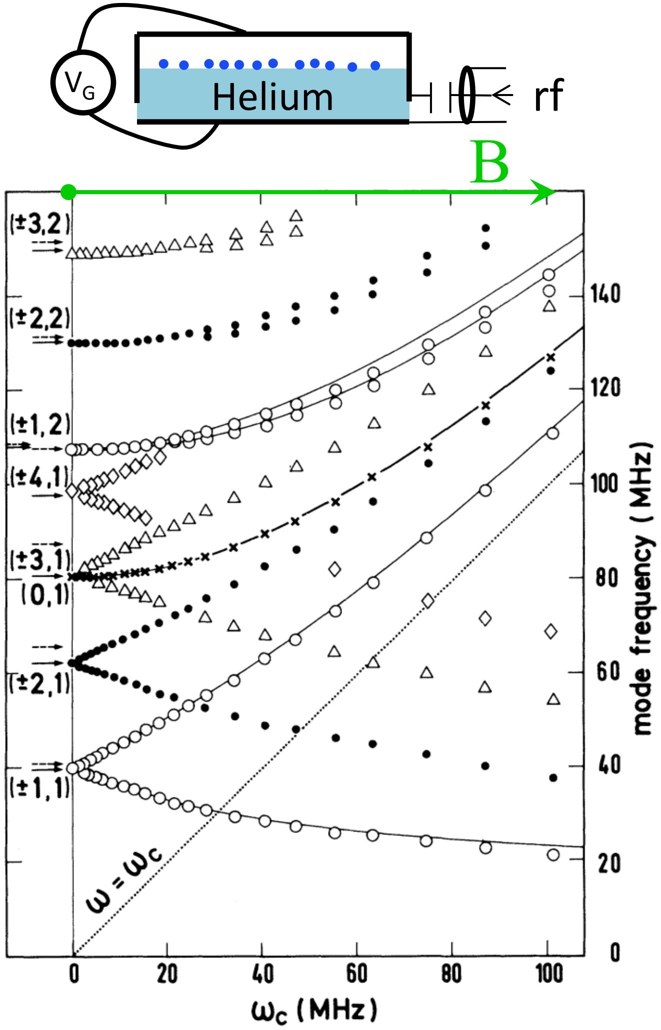


VOLUME 54, NUMBER 15 PHYSICAL REVIEW LETTERS 15 APRIL 1985

Observation of Bulk and Edge Magnetoplasmons in a Two-Dimensional Electron Fluid

D. B. Mast
Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221
and
A. J. Dahm
Department of Physics, Case Western Reserve University, Cleveland, Ohio 44106
and
A. L. Fetter
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305

Edge Magneto-Plasmons (EMP) are classical



2D electrons
on Helium liq.

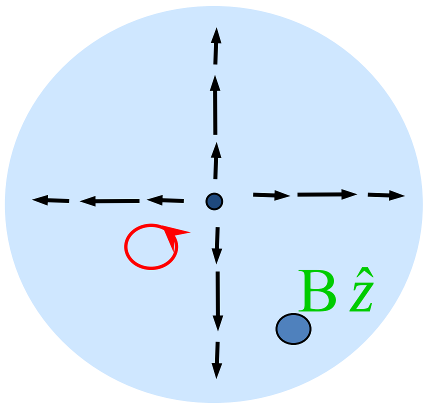
$$n_s = 10^8\ \text{cm}^{-2}$$

$$\mu \approx 100 \times 10^6\ \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$$

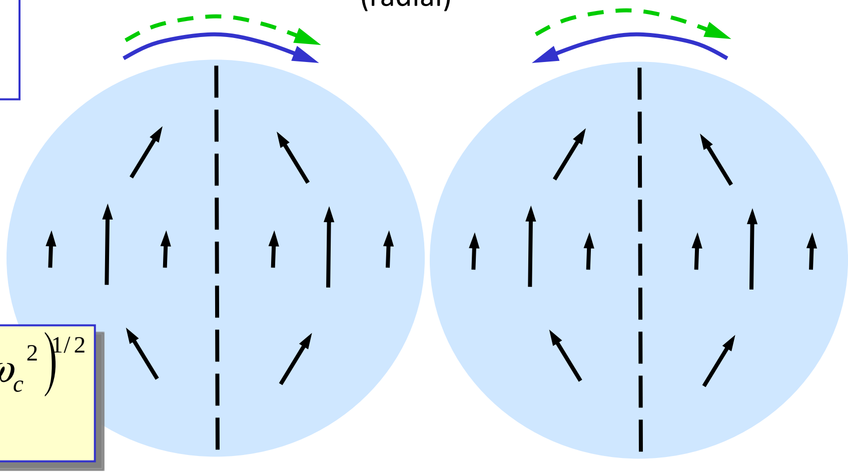
$$E_F\ 0.2\ \text{K} \approx kT$$

$$\omega_P(k) = \left(\frac{n_s e^2}{2m\varepsilon\varepsilon_0}k\right)^{1/2}$$

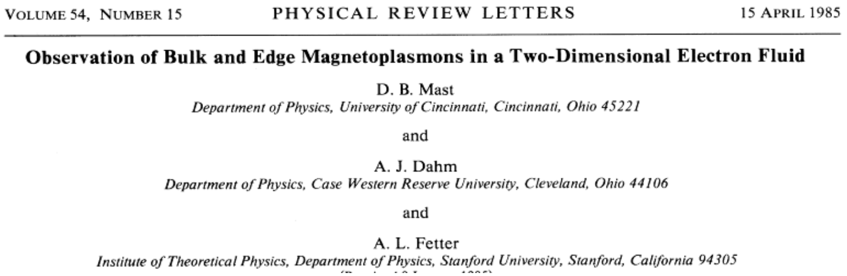
$$\omega_{MP}^{\ bulk} = \left(\omega_P(k)^2 + \omega_c^{\ 2}\right)^{1/2}$$



(radial)



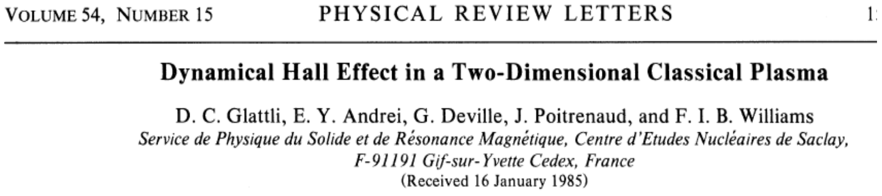
(azimuthal 1, +/- 1)



VOLUME 54, NUMBER 15 PHYSICAL REVIEW LETTERS 15 APRIL 1985

Observation of Bulk and Edge Magnetoplasmons in a Two-Dimensional Electron Fluid

D. B. Mast
Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221
and
A. J. Dahm
Department of Physics, Case Western Reserve University, Cleveland, Ohio 44106
and
A. L. Fetter
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305

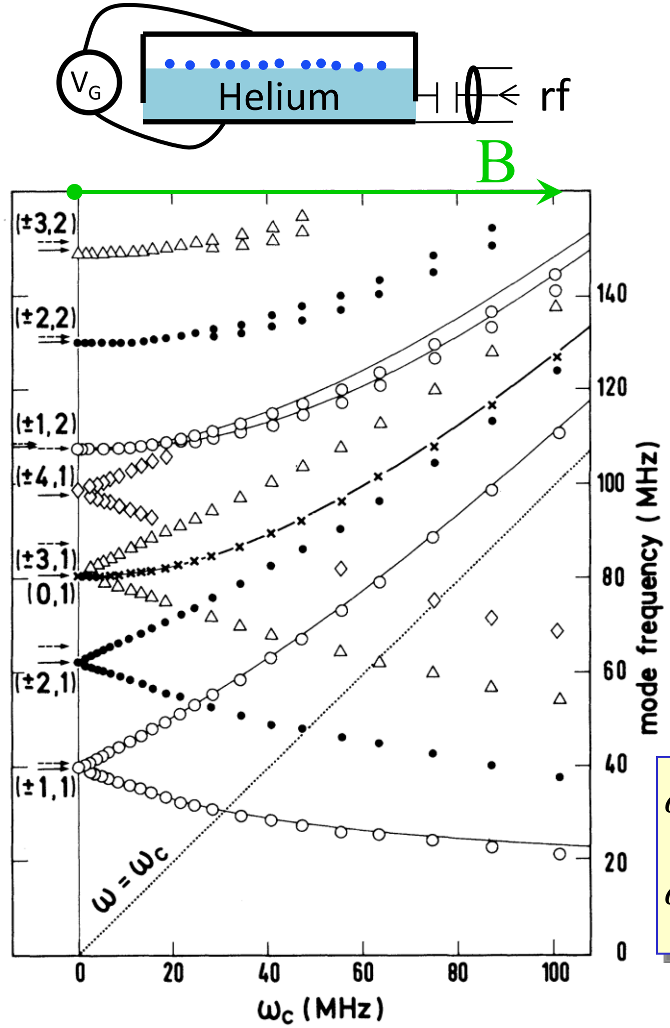


VOLUME 54, NUMBER 15 PHYSICAL REVIEW LETTERS

Dynamical Hall Effect in a Two-Dimensional Classical Plasma

D. C. Glattli, E. Y. Andrei, G. Deville, J. Poitrenaud, and F. I. B. Williams
Service de Physique du Solide et de Résonance Magnétique, Centre d'Etudes Nucléaires de Saclay, F-91191 Gif-sur-Yvette Cedex, France
(Received 16 January 1985)

Edge Magneto-Plasmons (EMP) are classical



2D electrons
on Helium liq.

$$n_s = 10^8 \text{ cm}^{-2}$$

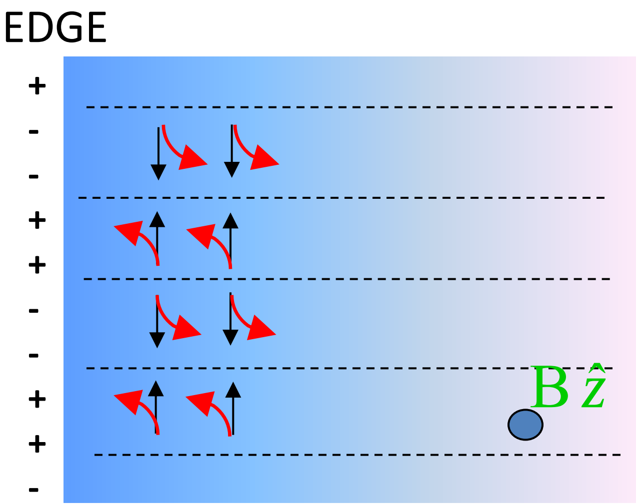
$$\mu \approx 100 \text{ x } 10^6 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$$

$$E_F \; 0.2 \text{ K} \approx kT$$

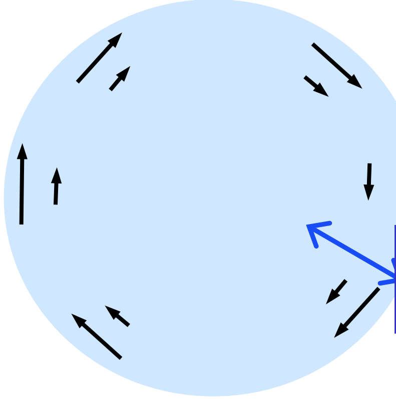
$$\omega_P(k) = \left(\frac{n_s e^2}{2 m \varepsilon \varepsilon_0} k \right)^{1/2}$$

$$\omega_{MP}{}^{bulk} = \left(\omega_P(k)^2 + \omega_c{}^2 \right)^{1/2}$$

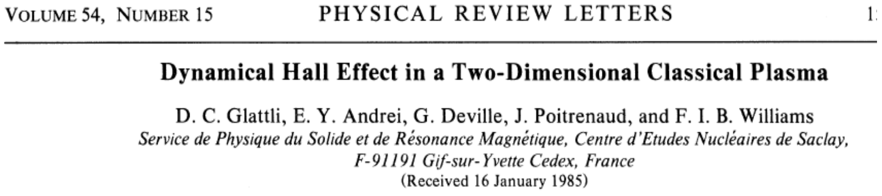
$$\omega_{EMP} \approx \frac{\omega_P(q)^2}{\omega_c} \qquad k^2 = q^2 - \kappa^2$$



the dynamical Hall current
localises charge on the edge



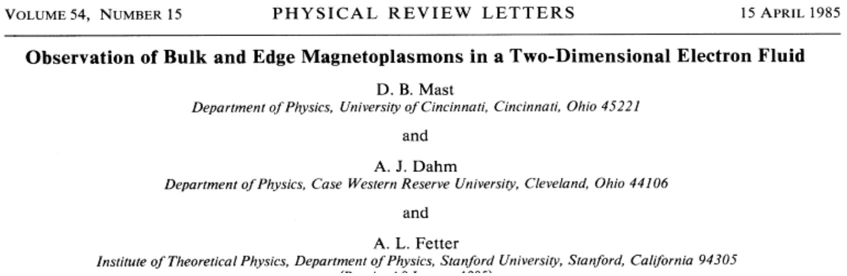
$$\frac{1}{\kappa} \approx \frac{1}{q} \frac{\omega_P(q)}{\omega_C}$$



Volume 54, Number 15 PHYSICAL REVIEW LETTERS 1

Dynamical Hall Effect in a Two-Dimensional Classical Plasma

D. C. Glattli, E. Y. Andrei, G. Deville, J. Poitrenaud, and F. I. B. Williams
Service de Physique du Solide et de Résonance Magnétique, Centre d'Etudes Nucléaires de Saclay, F-91191 Gif-sur-Yvette Cedex, France
(Received 16 January 1985)

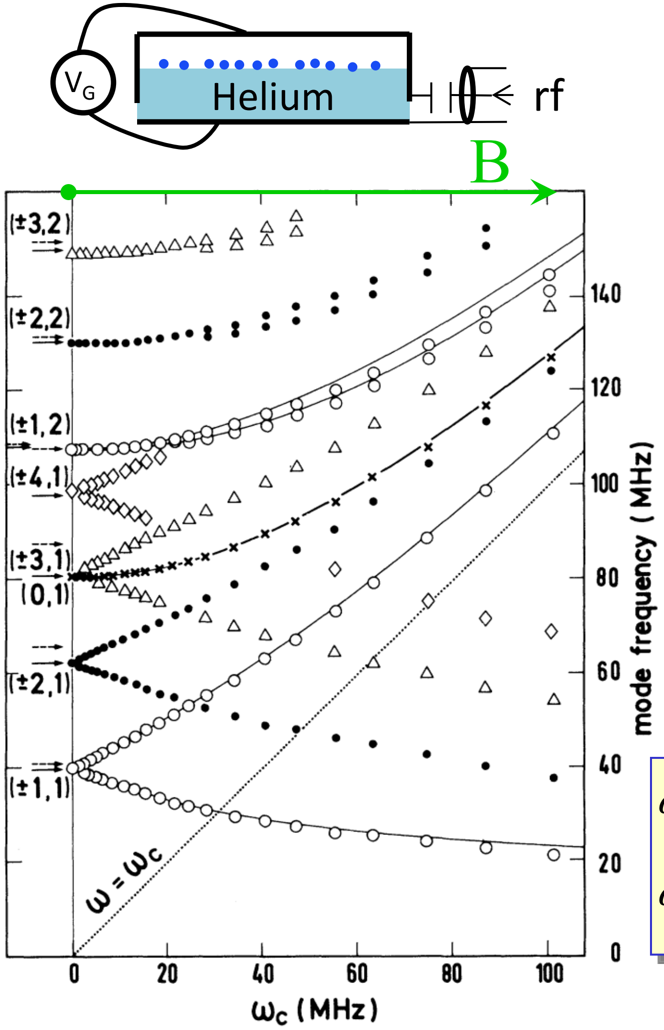


Volume 54, Number 15 PHYSICAL REVIEW LETTERS 15 April 1985

Observation of Bulk and Edge Magnetoplasmons in a Two-Dimensional Electron Fluid

D. B. Mast
Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221
and
A. J. Dahm
Department of Physics, Case Western Reserve University, Cleveland, Ohio 44106
and
A. L. Fetter
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305

Edge Magneto-Plasmons (EMP) are classical



2D electrons
on Helium liq.

$$n_s = 10^8\ \mathrm{cm}^{-2}$$

$$\mu \approx 100\,\mathrm{x}\,10^6\ \mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$$

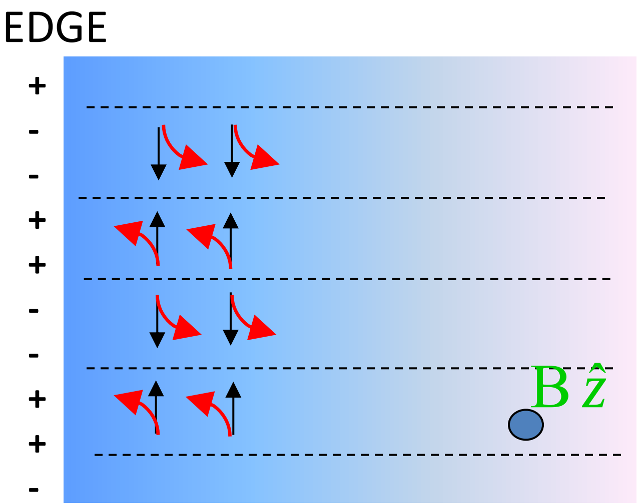
$$E_F\ 0.2\,\mathrm{K} \approx kT$$

$$\omega_P(k) = \left(\frac{n_s e^2}{2m\varepsilon\varepsilon_0}k\right)^{1/2}$$

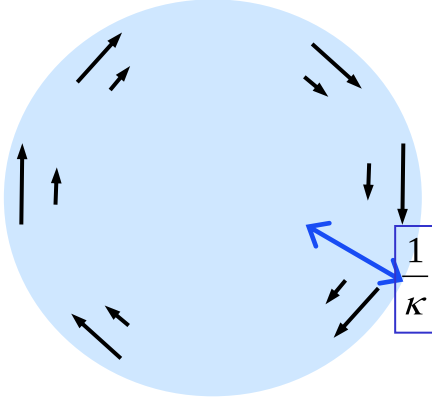
$$\omega_{EPM} \approx \frac{\sigma_{Hall}}{2\varepsilon\varepsilon_0}q$$

$$\omega_{MP}{}^{bulk} = \left(\omega_P(k)^2 + \omega_c{}^2\right)^{1/2}$$

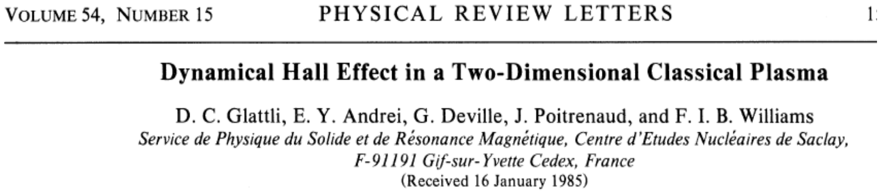
$$\omega_{EMP} \approx \frac{\omega_P(q)^2}{\omega_c} \qquad k^2 = q^2 - \kappa^2$$



the dynamical Hall current
localises charge on the edge



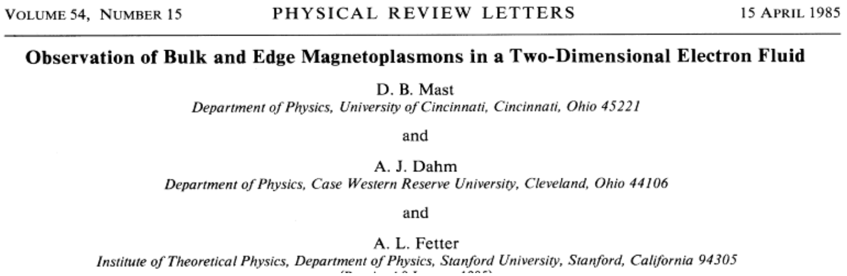
$$\frac{1}{\kappa} \approx \frac{1}{q}\frac{\omega_P(q)}{\omega_C}$$



Volume 54, Number 15 PHYSICAL REVIEW LETTERS

Dynamical Hall Effect in a Two-Dimensional Classical Plasma

D. C. Glattli, E. Y. Andrei, G. Deville, J. Poitrenaud, and F. I. B. Williams
Service de Physique du Solide et de Résonance Magnétique, Centre d'Etudes Nucléaires de Saclay, F-91191 Gif-sur-Yvette Cedex, France
(Received 16 January 1985)



Volume 54, Number 15 PHYSICAL REVIEW LETTERS 15 April 1985

Observation of Bulk and Edge Magnetoplasmons in a Two-Dimensional Electron Fluid

D. B. Mast
Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221
and
A. J. Dahm
Department of Physics, Case Western Reserve University, Cleveland, Ohio 44106
and
A. L. Fetter
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305

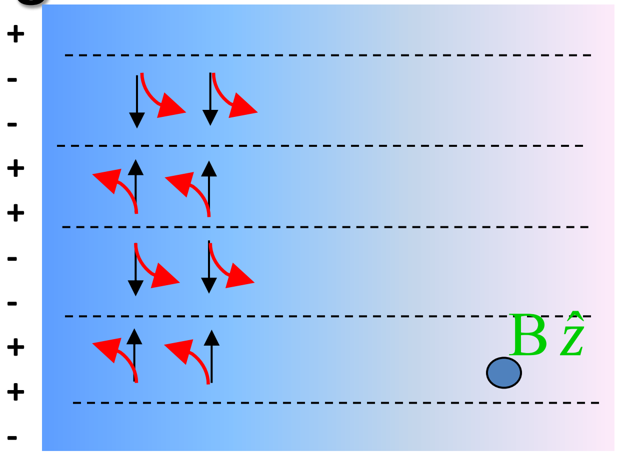
Edge Magneto-Plasmons (EMP) in the Quantum Hall Regime

$$\sigma_{Hall} = p.\frac{e^2}{h}$$

→ QH plateaus in EMP frequency ?

$$\omega_{EPM} \approx \frac{\sigma_{Hall}}{2\varepsilon\varepsilon_0} q$$

QHE regime ?



the dynamical Hall current localises charge on the edge

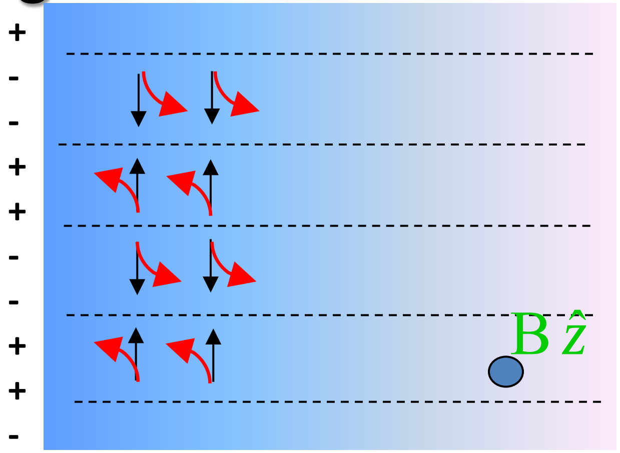
→ combines with QHE edge channels

Edge Magneto-Plasmons (EMP) in the Quantum Hall Regime

$$\sigma_{Hall} = p . \frac{e^2}{h}$$

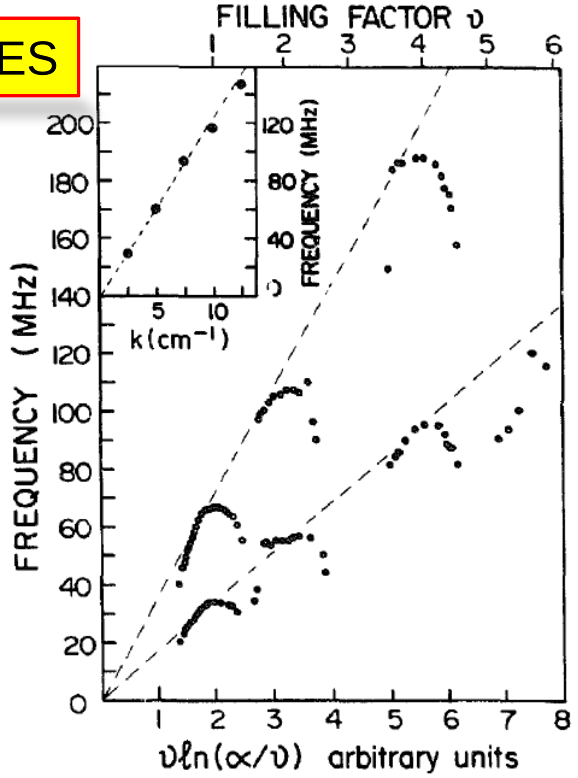
$$\omega_{EPM} \approx \frac{\sigma_{Hall}}{2\varepsilon\varepsilon_0} q$$

QHE regime ?



→ combines with QHE edge channels

YES



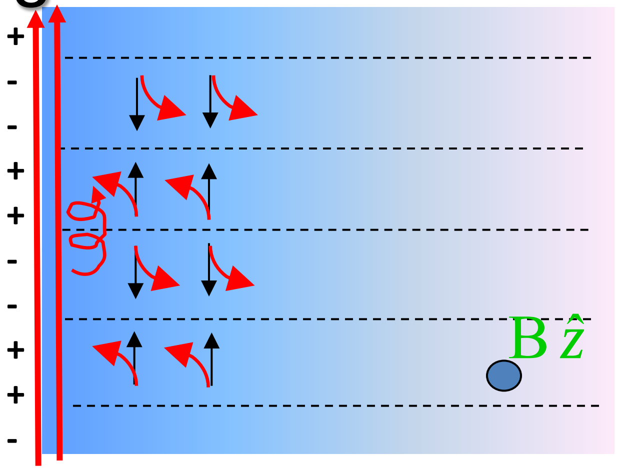
E.Y. Andrei, D.C. Glattli, F. Williams and M. Heiblum Surf. Sci. 196 501-506 (1998)

Edge Magneto-Plasmons (EMP) in the Quantum Hall Regime

$$\sigma_{Hall} = p.\frac{e^2}{h}$$

$$\omega_{EPM} \approx \frac{\sigma_{Hall}}{2\varepsilon\varepsilon_0} q$$

QHE regime



→ combines with QHE edge channels

→ adds single particle DRIFT Velocity

$$\omega_{MP}{}^{bulk} = \left(\omega_P(k)^2 + \omega_c{}^2\right)^{1/2}$$

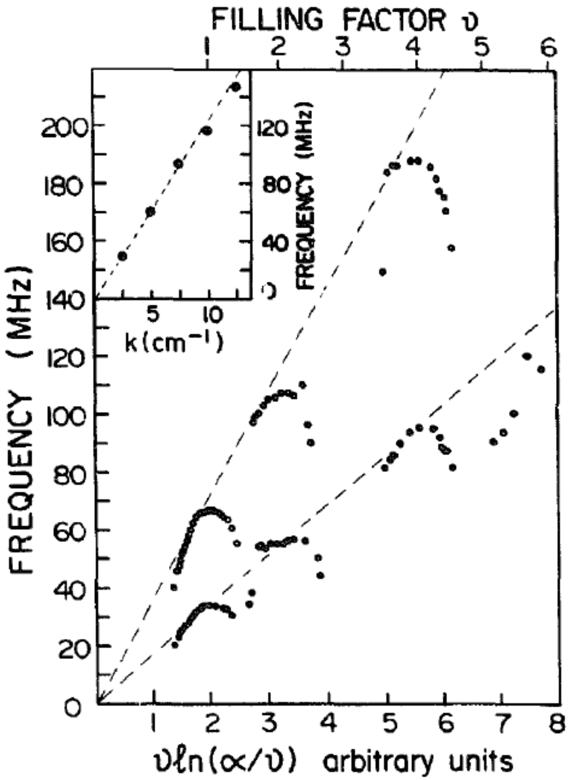
$$\omega_{EMP} \approx \frac{\omega_P(q)^2}{\omega_c} + v_{drift} q$$

$$\approx \alpha_{QED} \frac{c}{\varepsilon_{eff}} k$$

$$\approx 10^6 \text{ m/s}$$

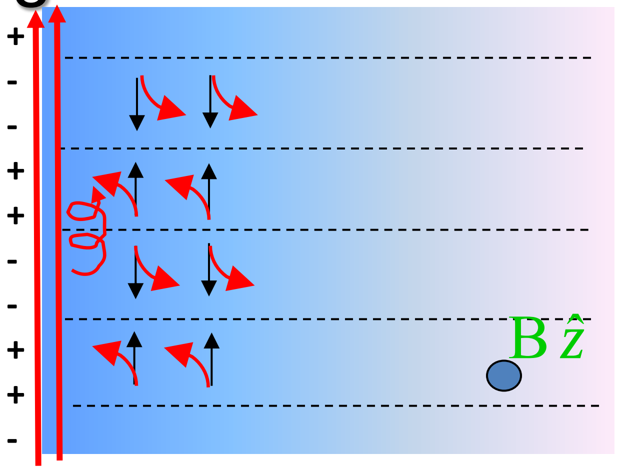
small in GaAs 2DEGs

$$\approx 10^4 \text{ to} 10^5 \text{ m/s}$$



E.Y. Andrei, D.C. Glattli, F. Williams and M. Heiblum Surf. Sci. 196 501-506 (1998)

Edge Magneto-Plasmons (EMP) in the Quantum Hall Regime



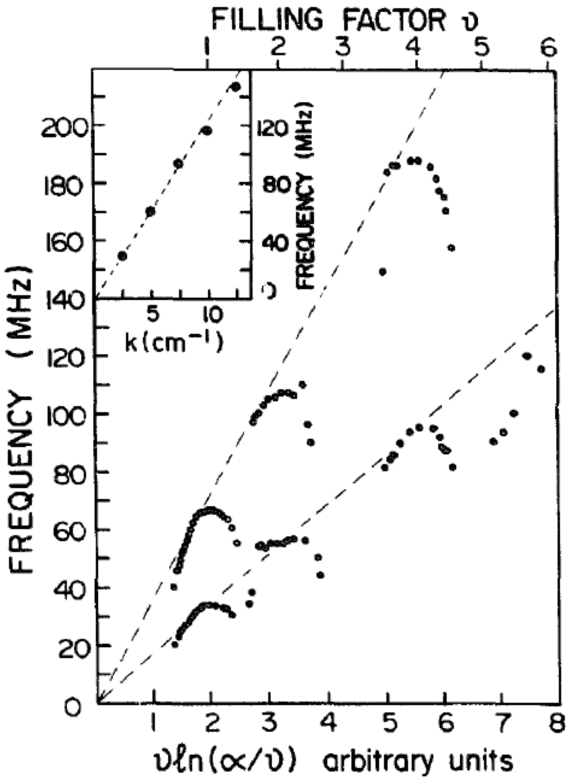
$$\sigma_{Hall} = p.\frac{e^2}{h}$$

$$\omega_{EPM} \approx \frac{\sigma_{Hall}}{2\varepsilon\varepsilon_0} q$$

QHE regime

→ combines with QHE edge channels

→ adds single particle DRIFT Velocity



$$\omega_{MP}{}^{bulk} = \left(\omega_P(k)^2 + \omega_c{}^2\right)^{1/2}$$

$$\omega_{EMP} \approx \frac{\omega_P(q)^2}{\omega_c} + v_{drift} q$$

$$\approx \alpha_{QED} \frac{c}{\varepsilon_{eff}} k$$

large in GRAPHENE 2DEGs

$$\approx 10^6 \text{ m/s}$$

in graphene : $v_{drift} \sim v_{Fermi}$

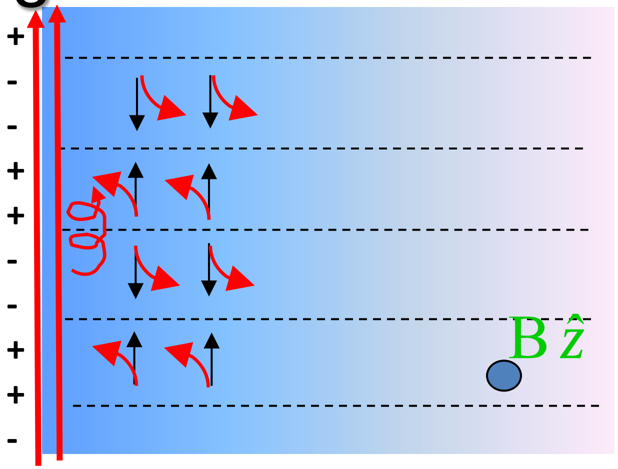
Edge Magneto-Plasmons (EMP) in the Quantum Hall Regime

complete expression :

$$\omega_{EMP} = \frac{\sigma_{Hall}}{2\pi\varepsilon_0\varepsilon_{eff}}\, q\left(\log\frac{2}{|q|w}+1\right)+v_D q$$

w : cutt-off length with respect to sharp edge

Damping extremely low compare with bulk plasmons



THEORY WORK:
Fetter, A. L., Edge magnetoplasmons in a bounded two-dimensional electron fluid.
Phys. Rev.B 32, 7676-7684 (1985).
Volkov, V. A. and Mikhailov, S. A. Theory of edge magnetoplasmons in a two-dimensionalelectron gas.
JETP Lett. 42, 556-560 (1985).
Volkov, V. A., Galchenkov, D. V., Galchenkov, L. A. , Grodnenskii, I. M., Matov, O. R. and Mikhailov, S. A. Edge magnetoplasmons under conditions of the quantum Hall effect.
JETP Lett. 44, 655-659 (1986).
Volkov, V. A. and Mikhailov, S. A. Edge magnetoplasmons: low-frequency weakly damped excitations in inhomogeneous two-dimensional electron systems.
Sov. Phys. JETP 67, 1639-1653 (1988).
also - L. Glazman
- Allan McDonald

All theory work addressed conventional 2DEG in QHE regime

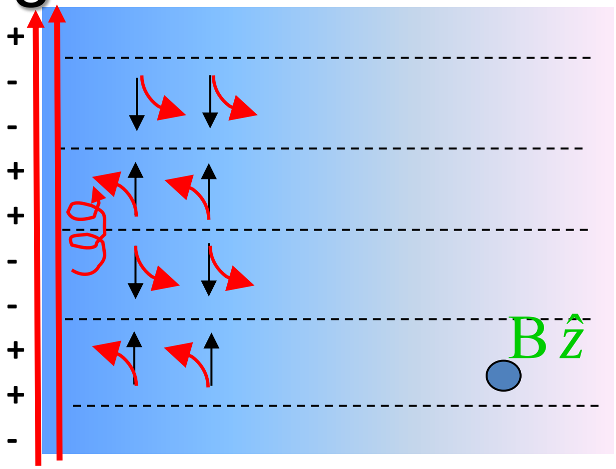
Edge Magneto-Plasmons (EMP) in the Quantum Hall Regime

complete expression :

$$\omega_{EMP} = \frac{\sigma_{Hall}}{2\pi\varepsilon_0\varepsilon_{eff}} q\left(\log\frac{2}{|q|w}+1\right)+v_D q$$

w : cutt-off length with respect to sharp edge

Damping extremely low compare with bulk plasmons



EMP EXPERIMENTAL WORKs:
Allen, S. J., Stormer, H. L. and Hwang, J. C. M.
Phys. Rev. B 28, 4875-4877 (1983).
Andrei, E. Y., Glattli, D. C., Williams, F. I. B. and Heiblum M.
Surf. Science 196, 501-506 (1988).
Ashoori, R. C., Stormer, H. L., Pfeiffer, L. N., Baldwin, K. W. and West, K..
Phys. Rev. B 45, 3894-3897 (1992).
Zhitenev, N. B., Haug, R. J., Klitzing, K. v. and Eberl, K.
Phys. Rev. Lett. 71, 2292-2295 (1993).
Ernst G., Haug, R. J., Kuhl, J., von Klitzing, K. v. and Eberl, K..
Phys. Rev. Lett. 77, 4245-4248 (1996).
Kumada, N., Kamata, H. and Fujisawa, T.
Phys. Rev. B 84, 045314 (2011)

All works on GaAs/GaAlAs 2DEG in QHE regime

Outline

- Introduction
  - what are edge magnetoplasmons (EMP)?
  - classical
  - quantum (QH regime)

→

- EMP in graphene

- Experiment I (exfoliated graphene 40um perimeter)
  - evidence for chiral propagation
  - velocity of EMP mode
  - carrier drift velocity

- Experiment II (SiC graphene 200um /1mm perimeter)
  - check EMP dispersion relation
  - measure damping of EMPs

- Conclusion and Perspectives

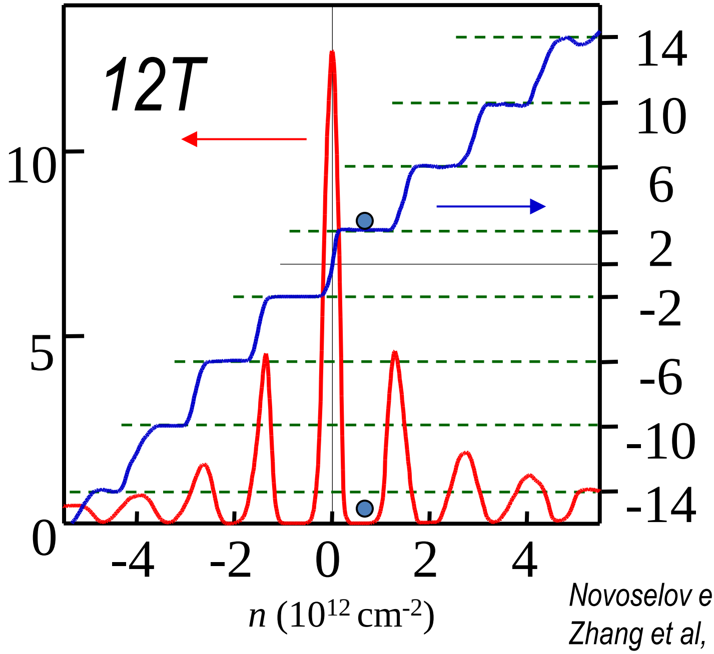
Quantum Hall Effect in Graphene

Landau Levels

$$\varepsilon_n = \pm\left(\frac{\hbar v_F}{l_c}\right)\sqrt{2n} \qquad l_c = \sqrt{\frac{\hbar}{eB}}$$

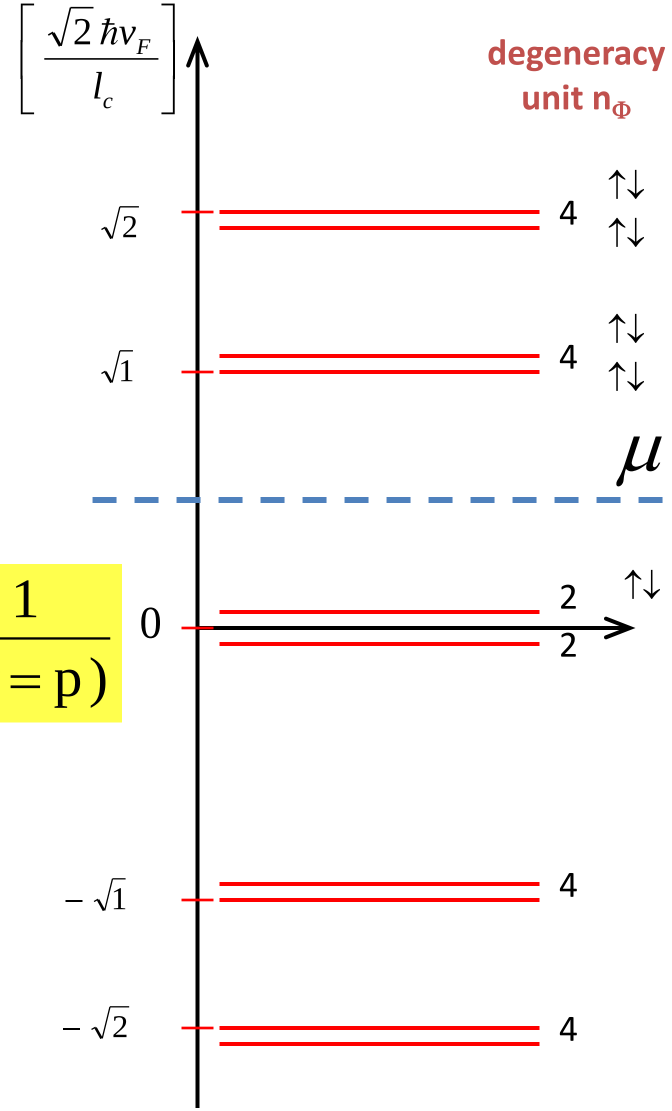
gap for : $n_s = p.n_\Phi = p.eB/h$

$$\boxed{p = \pm 2,\ \pm 6,\ \pm 10,\ \pm 14,\ \ldots}$$



$$R_{\text{Hall}} = \frac{h}{e^2}\cdot\frac{1}{(\nu = \mathrm{p})}$$

Novoselov et al, Nature 2005
Zhang et al, Nature 2005

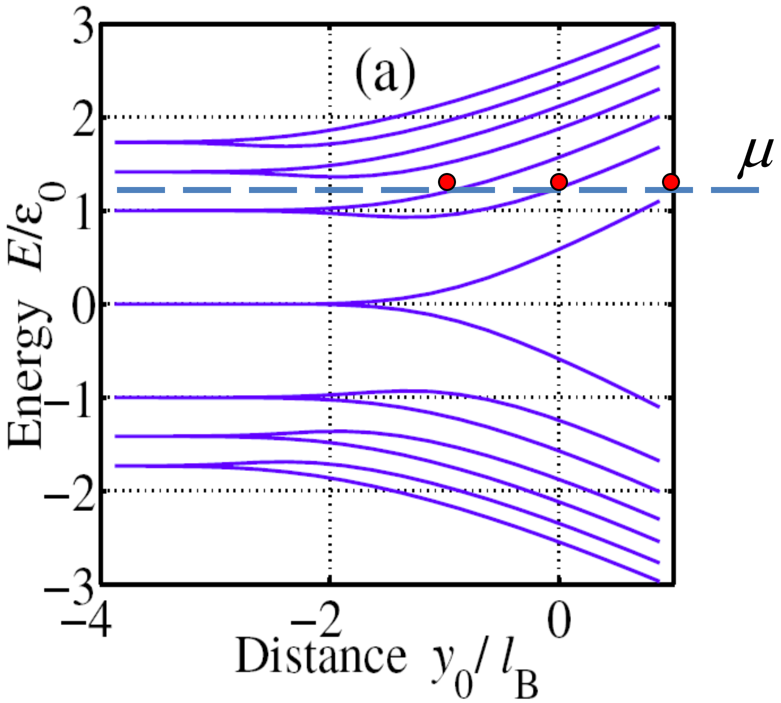


QHE Edge States in Graphene

- edges state drift velocity :

$$v_{drift} = \frac{E}{B} \approx \frac{\hbar v_F / l_c^2}{e B}$$

$$v_{drift} \approx v_F = 10^6 \text{ m.s}^{-1}$$



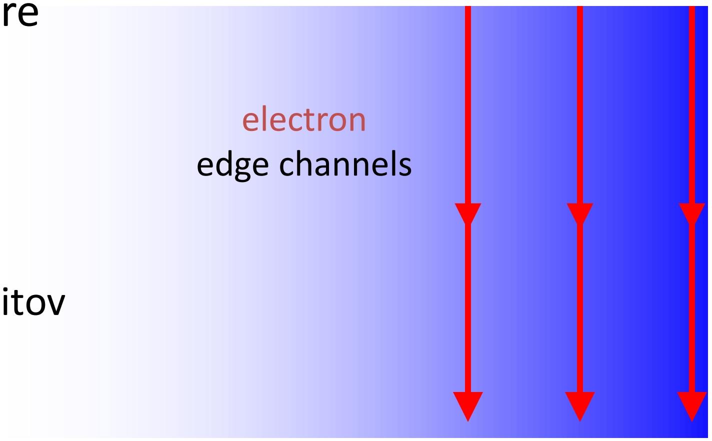
example : ν = 6 in the bulk

$$G_{Landauer} = 3 \times \frac{2e^2}{h} = \sigma_{Hall}$$

- Hall conductance agrees with Landauer picture

- valley degeneracy may be lifted at the edge

Brey, L. and Fertig, H. A..
Phys. Rev. B 73, 195408 (2006).
Dmitry A. Abanin, Patrick A. Lee, and Leonid S. Levitov
Phys. Rev. Lett. 96, 176803 (2006)
Delplace P. and Montambaux, G.
Phys. Rev. B 82, 205412 (2010).



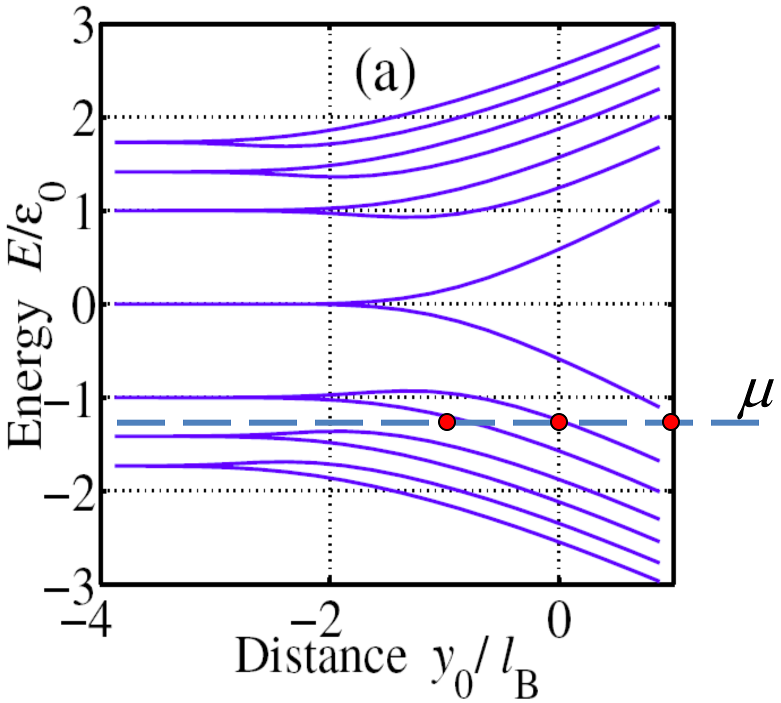
electron
edge channels

QHE Edge States in Graphene

- edges state drift velocity :

$$v_{drift} = \frac{E}{B} \approx \frac{\hbar v_F / l_c^{\,2}}{e\,B}$$

$$v_{drift} \approx v_F = 10^6 \text{ m.s}^{-1}$$



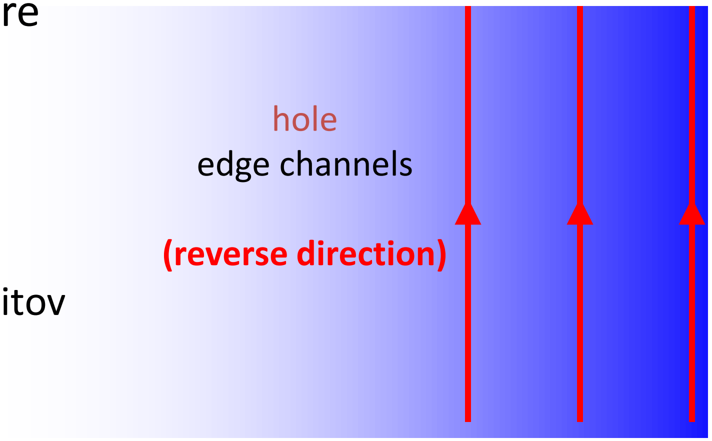
example : ν = 6 in the bulk

$$G_{Landauer} = 3 \times \frac{2e^2}{h} = \sigma_{Hall}$$

- Hall conductance agrees with Landauer picture

- valley degeneracy may be lifted at the edge

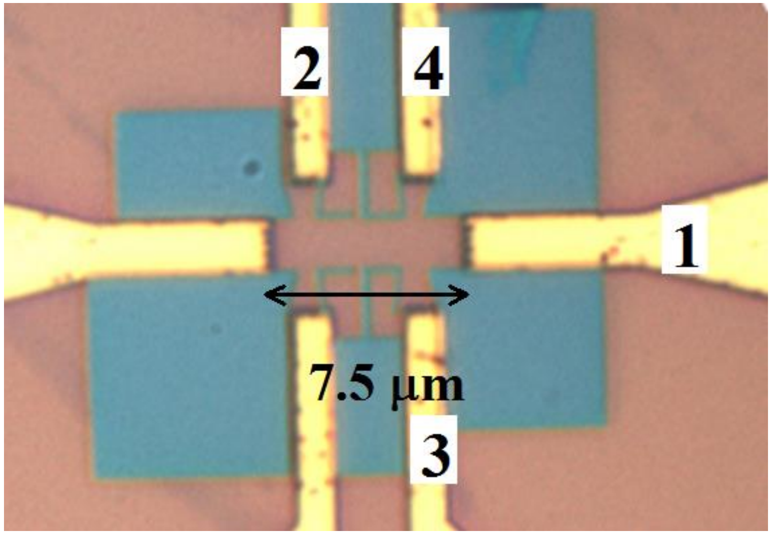
Brey, L. and Fertig, H. A..
Phys. Rev. B 73, 195408 (2006).
Dmitry A. Abanin, Patrick A. Lee, and Leonid S. Levitov
Phys. Rev. Lett. 96, 176803 (2006)
Delplace P. and Montambaux, G.
Phys. Rev. B 82, 205412 (2010).



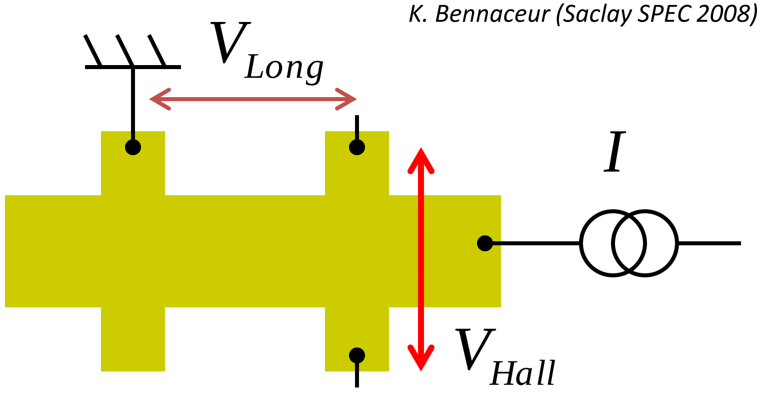
hole
edge channels

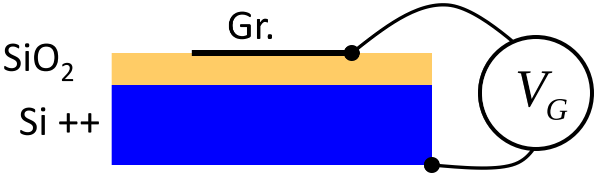
(reverse direction)

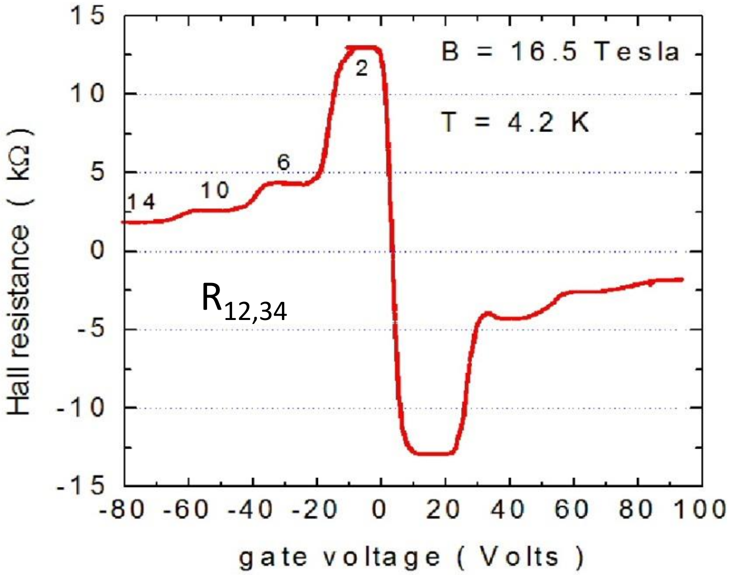
CHIRAL QHE Edge States in Graphene

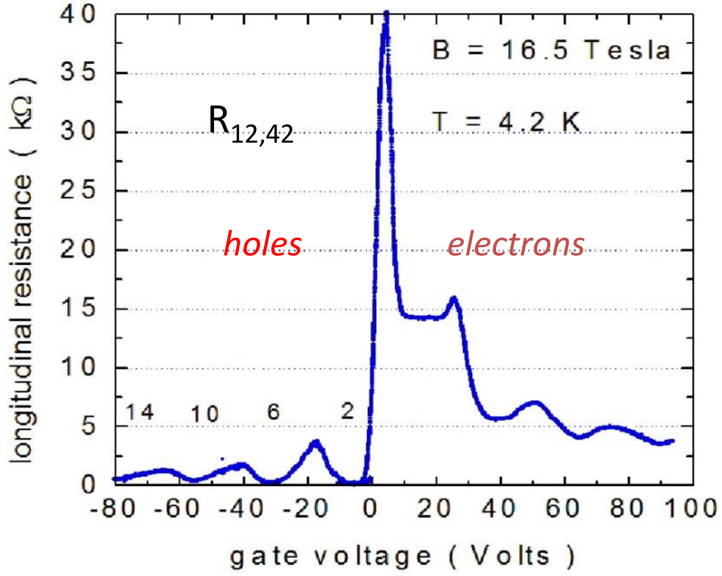


K. Bennaceur (Saclay SPEC 2008)



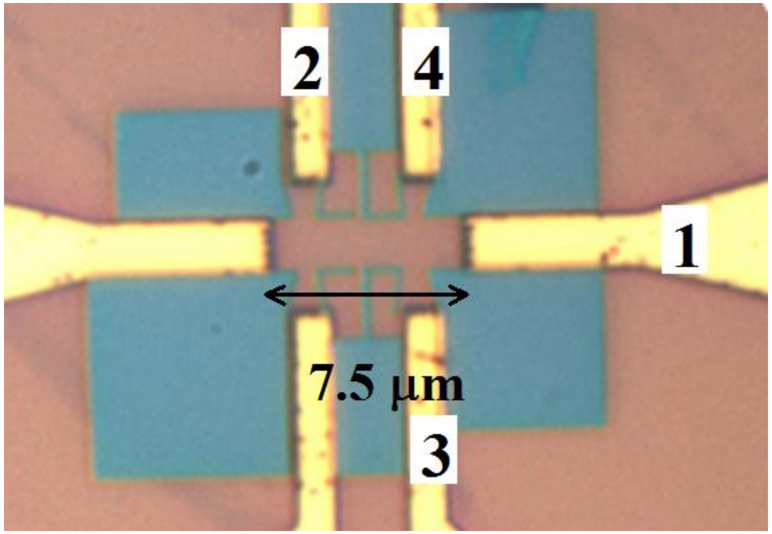




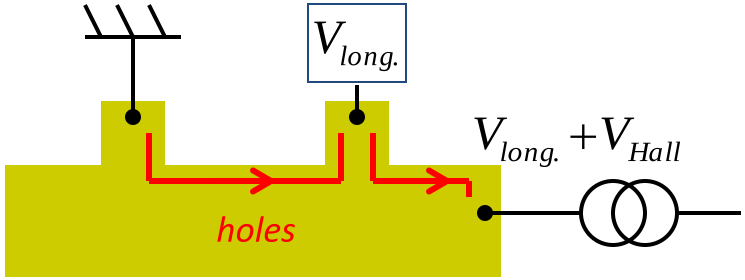


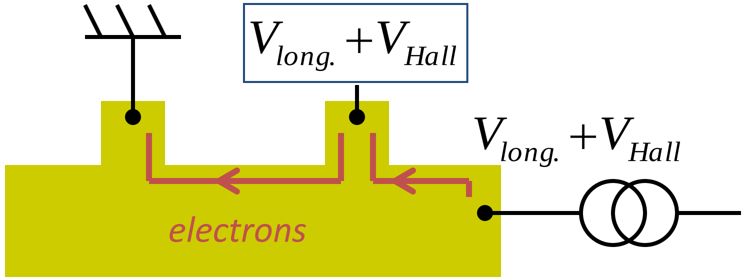
K. Bennaceur, D. C. G. (2007) SPEC, CEA Saclay

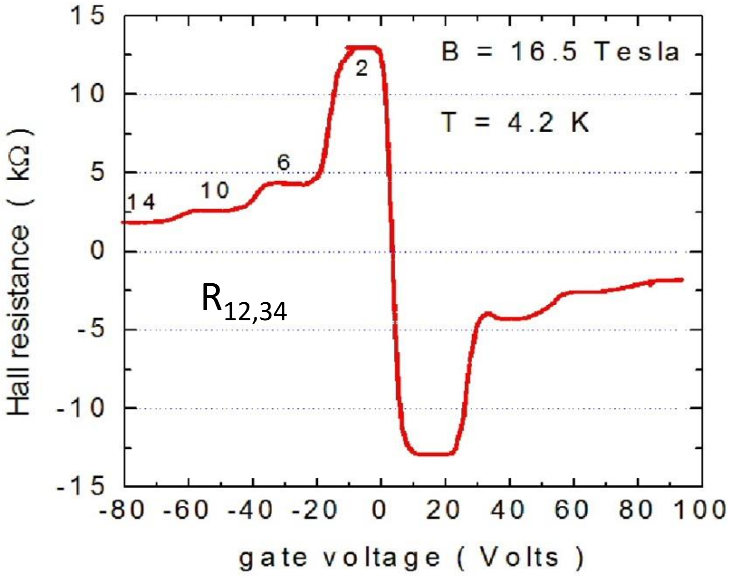
CHIRAL QHE Edge States in Graphene

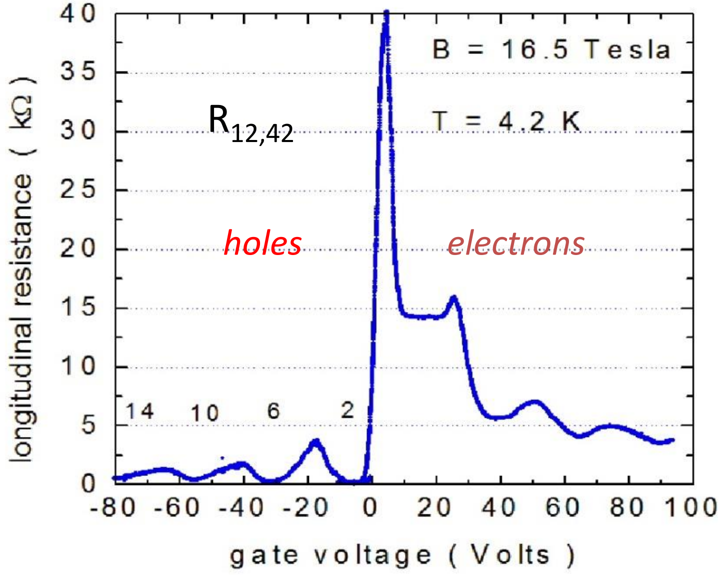


K. Bennaceur (Saclay SPEC 2008)





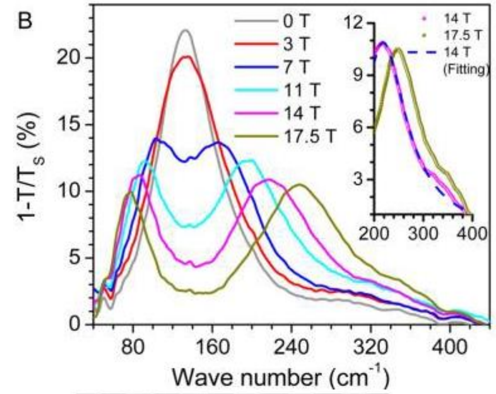


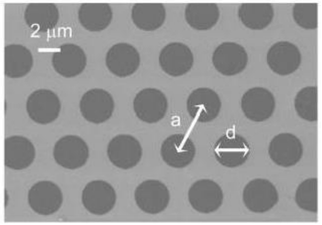


K. Bennaceur, D. C. G. (2007) SPEC, CEA Saclay

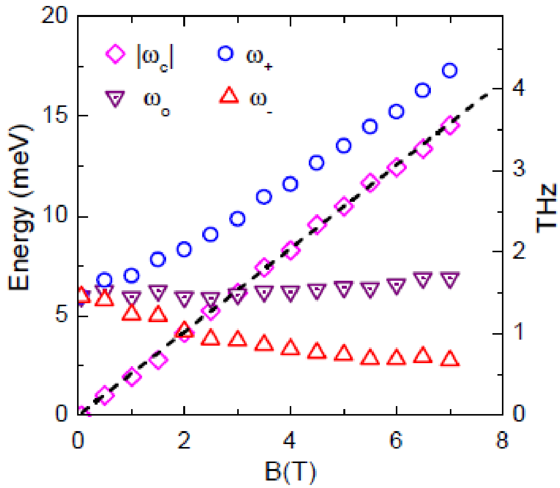
CHIRAL EDGE MAGNETO-PLASMONS in GRAPHENE ???

preliminary good sign of edge magneto-plasmons from optical I.R –THz absorption





CVD Graph. transf. on SiO2



confinement due to terraces on SIC grown Graphene

Crassee, I., Orlita, M., Potemski, M., Walter, A. L., Ostler, M., Seyller, Th., Gaponenko, I., Chen, J. and Kuzmenko, A. B. “Intrinsic Terahertz Plasmons and Magnetoplasmons in Large Scale Monolayer Graphene, “Nano Letters 12, 2470 (2012).

Yan, H., Li, Z., Li, X., Zhu, W., Avouris, P. and Xia, F. “Infrared Spectroscopy of Tunable Dirac Terahertz Magneto-Plasmons in Graphene” Nano Lett. 2012, 12, 3766−3771

NO QUANTUM HALL REGIME
CHIRALITY remained to be SHOWN
DRIFT VELOCITY not MEASURED

Outline

- Introduction
  - what are edge magnetoplasmons (EMP)?
  - classical
  - quantum (QH regime)

- EMP in graphene

- Experiment I (exfoliated graphene 40um perimeter)
  - evidence for chiral propagation
  - velocity of EMP mode
  - carrier drift velocity

- Experiment II (SiC graphene 200um /1mm perimeter)
  - check EMP dispersion relation
  - measure damping of EMPs

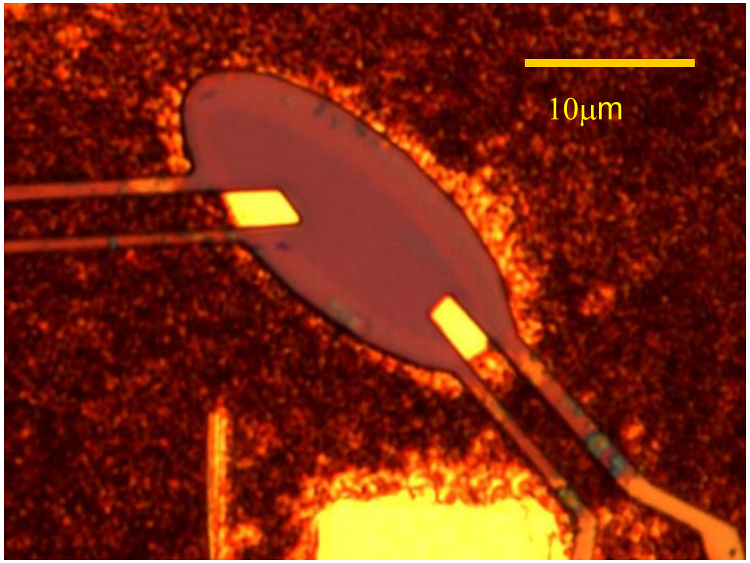
- Conclusion and Perspectives

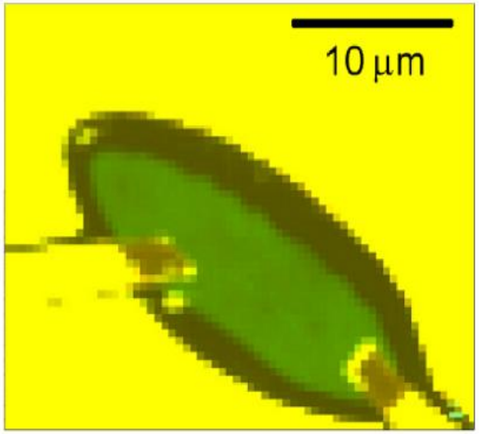
Sample Fabrication

Exfoliated Graphene (natural graphite)

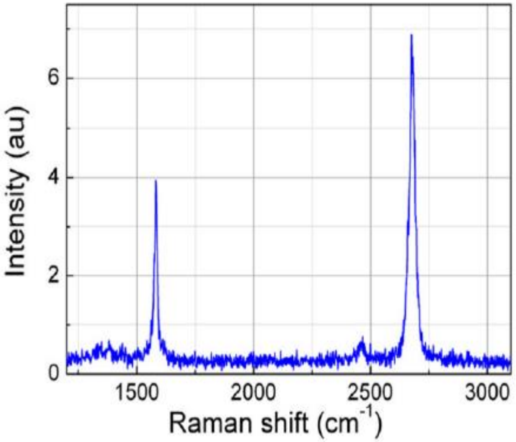
30X30 um^2 flake pattern as ellipsoidal shape by nanolithography

sample photo



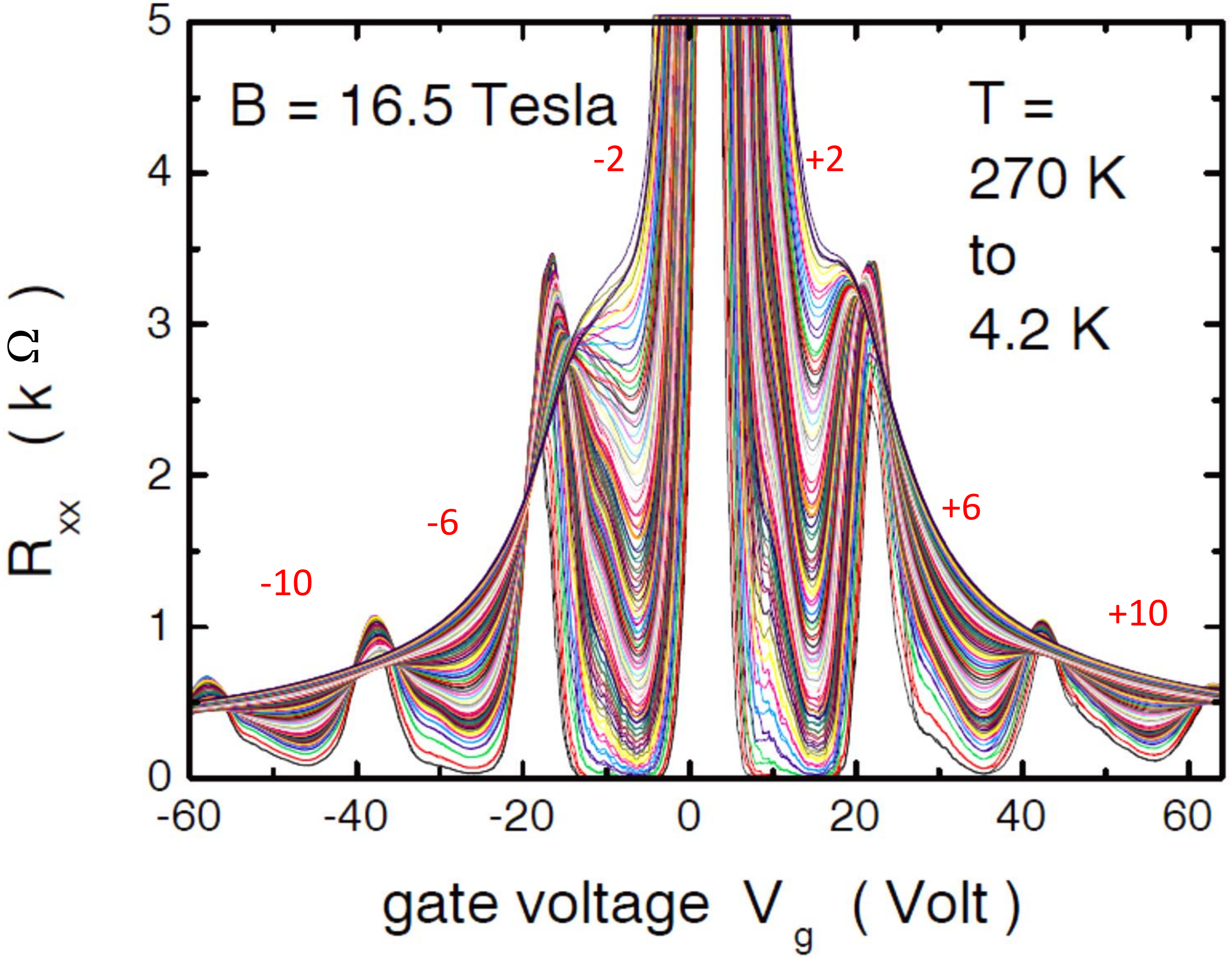


Raman map



One Raman spectrum

SIMILARLY PREPARED SAMPLE SHOWED GOOD QHE in TRANSPORT

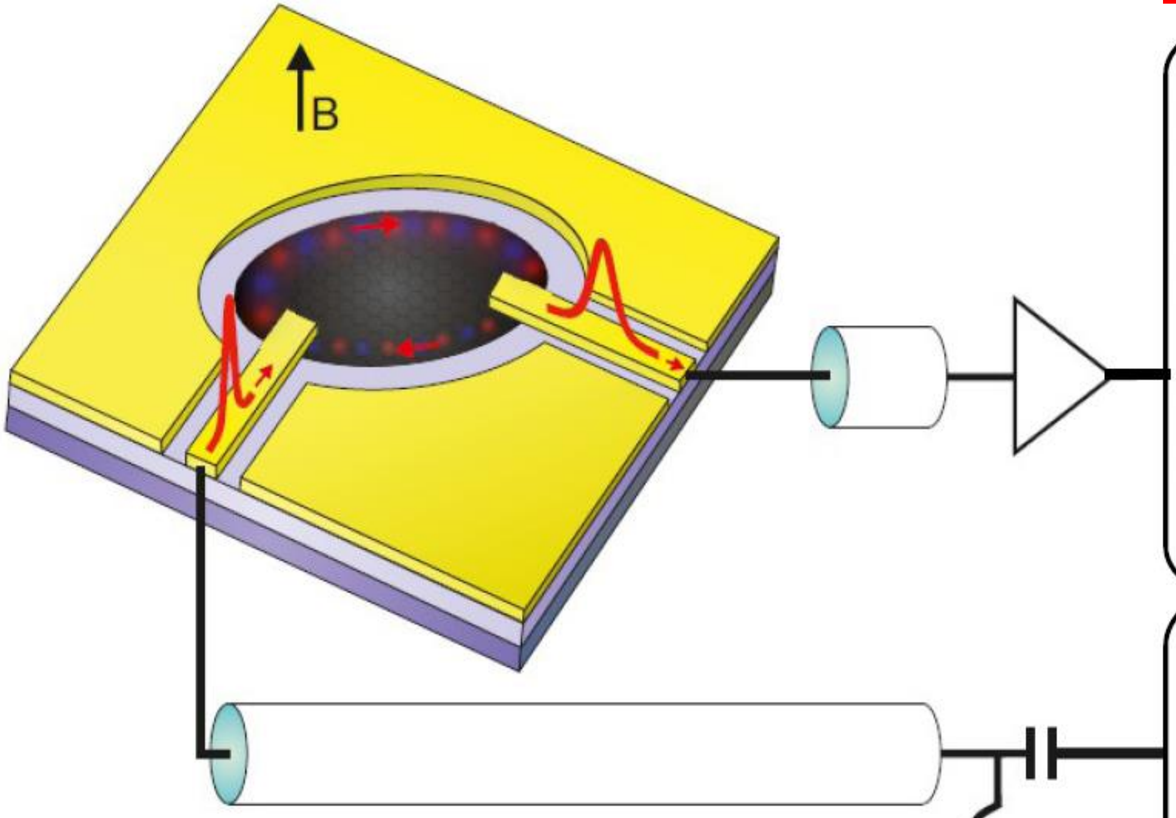


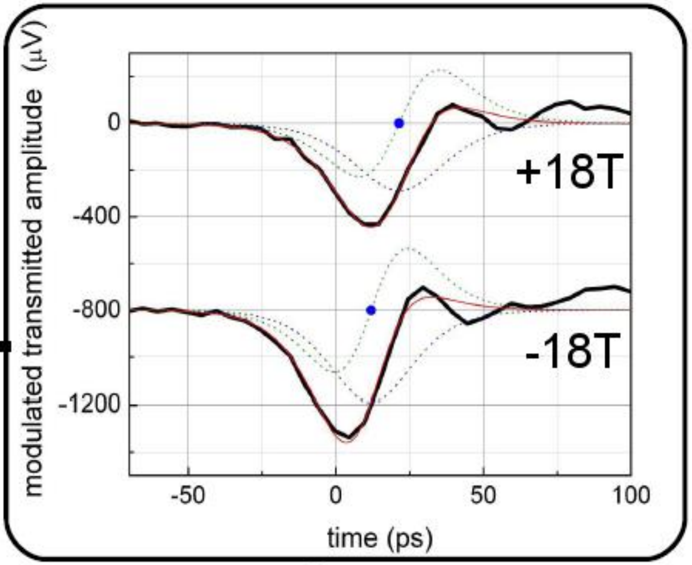
QHE still persists at near ambient temperature

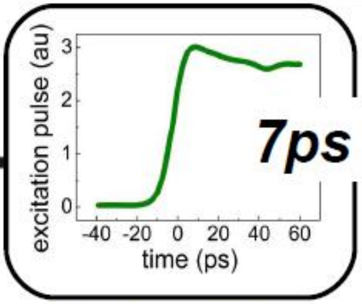
Experimental setup

$l \sim 40\mu m, v \sim 1*10^{6} ms^{-1}, f \sim 25GHz$

50GHz 19T 2.2K







~100mV

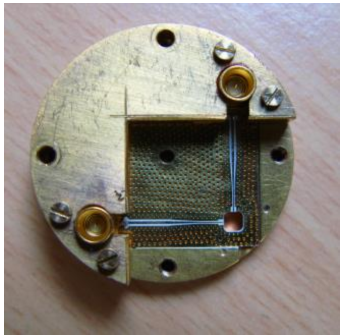
7ps rise time

+30V

-30V

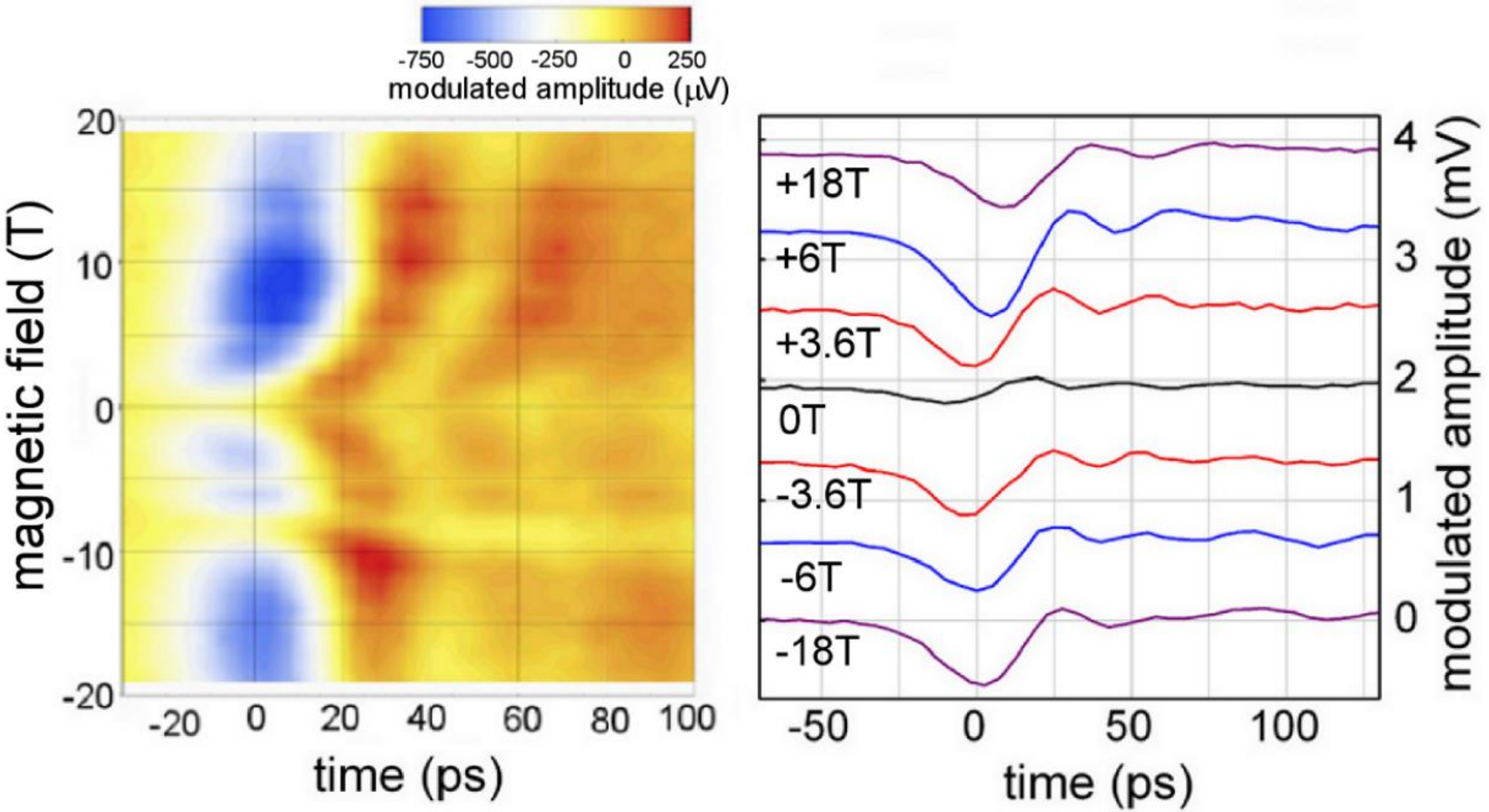
~1Hz

(also sidegate)



coplanar waveguide designed with CST microwave studio

Modulated transmission as function of field

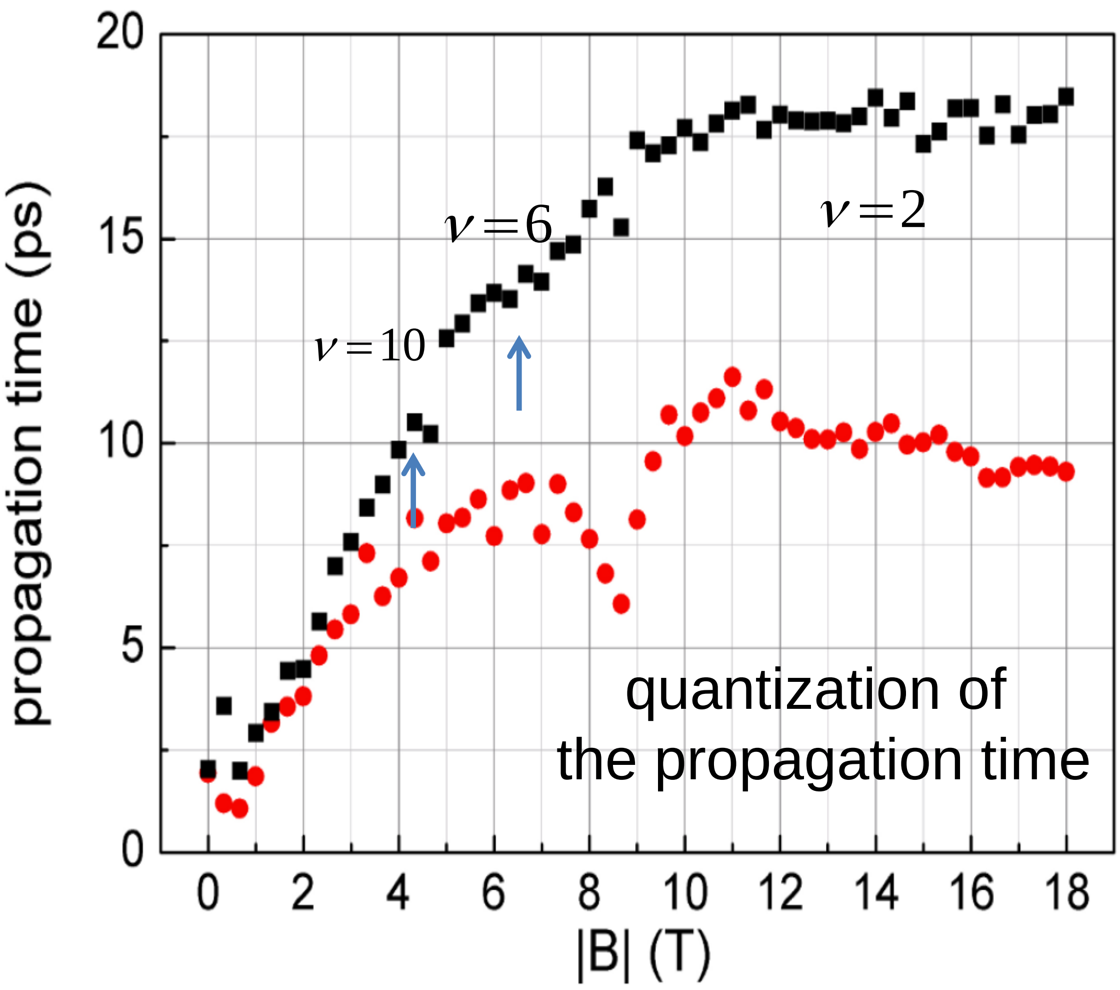


Different arrival times for +B and -B: chirality

Arrival time increases with field, signature of EMP

Petkovic, F. I. B. Williams, K. Bennaceur, F. Portier, P. Roche, and D. C. Glattli, Phys. Rev. Lett 110, 016801 (2013)

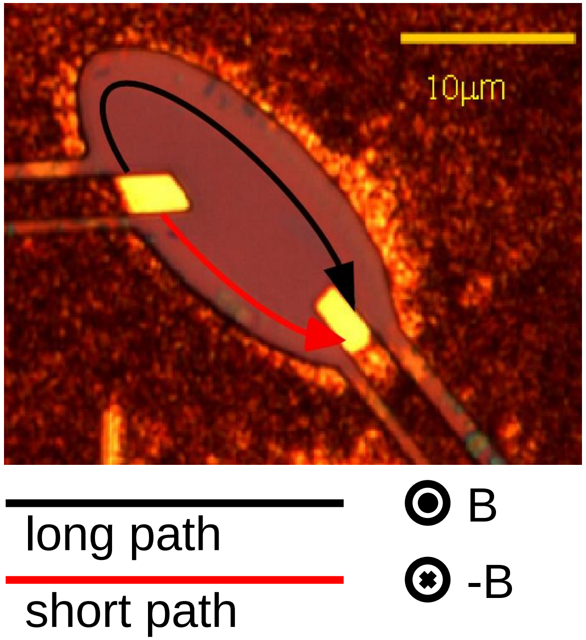
Propagation time *vs* field



quantization of
the propagation time

$$v_D=(0.7\pm0.3)*10^8\,cms^{-1}$$

Petkovic, F. I. B. Williams, K. Bennaceur, F. Portier, P. Roche,
and D. C. Glattli, Phys. Rev. Lett 110, 016801 (2013)

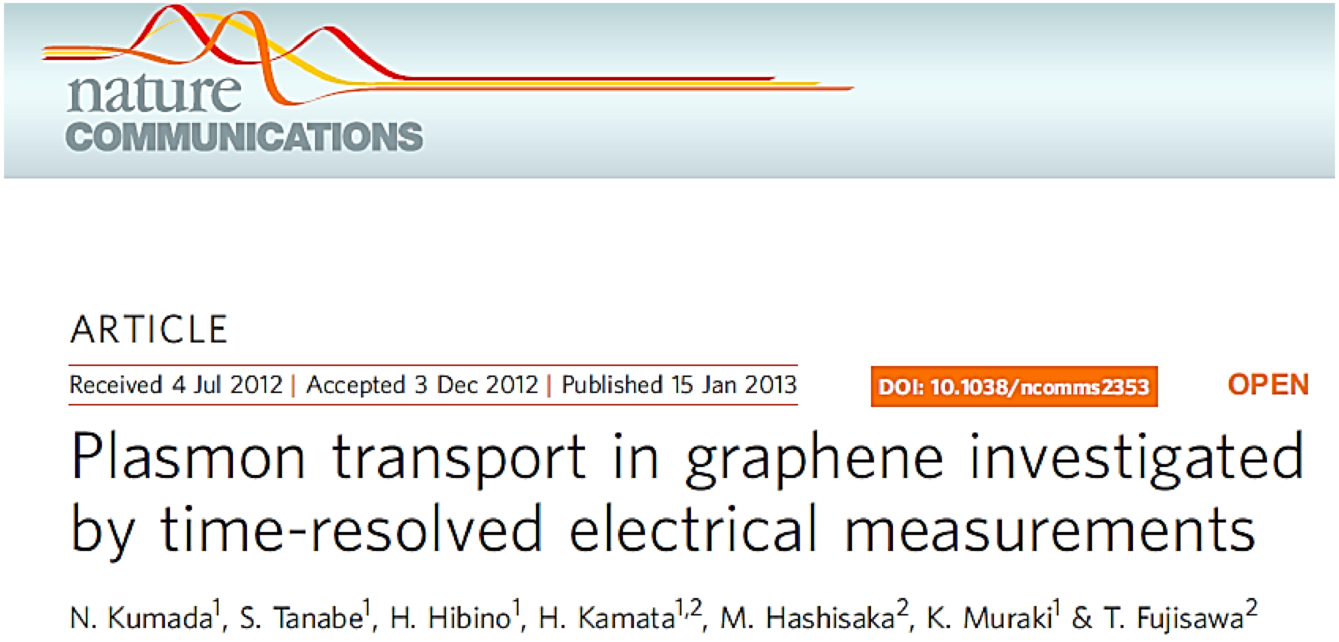


$$v_g=\frac{\partial\,\omega_{EMP}}{\partial\,q}=\frac{\sigma_{Hall}}{2\pi\varepsilon_0\varepsilon_{eff}}\left(\log\frac{2}{|q|w}\right)+v_{Drift}$$

$$\propto\sqrt{N+1}-\sqrt{N}$$

$$\nu=4N+2=\frac{h\,n_s}{eB}$$

N – Landau level index



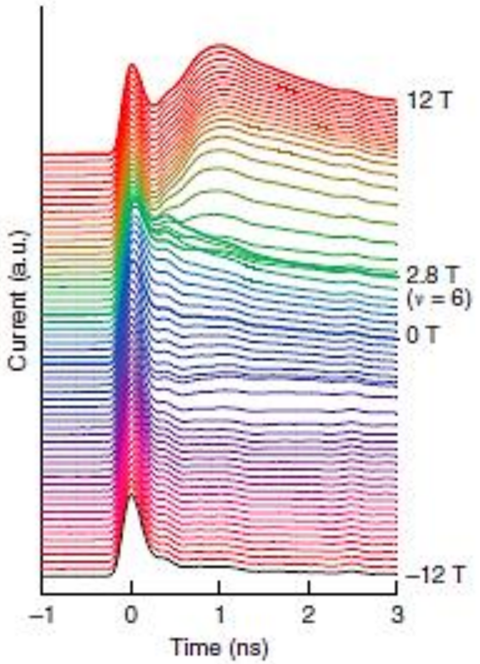
nature COMMUNICATIONS

ARTICLE

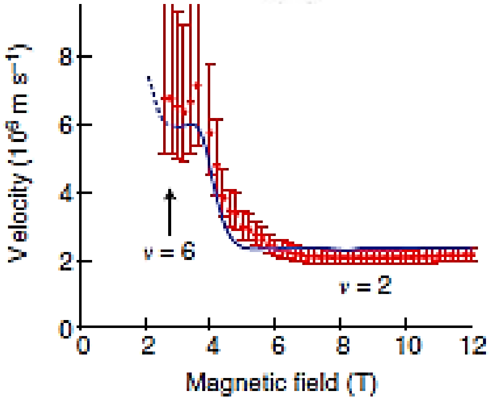
Received 4 Jul 2012 | Accepted 3 Dec 2012 | Published 15 Jan 2013 DOI: 10.1038/ncomms2353 OPEN

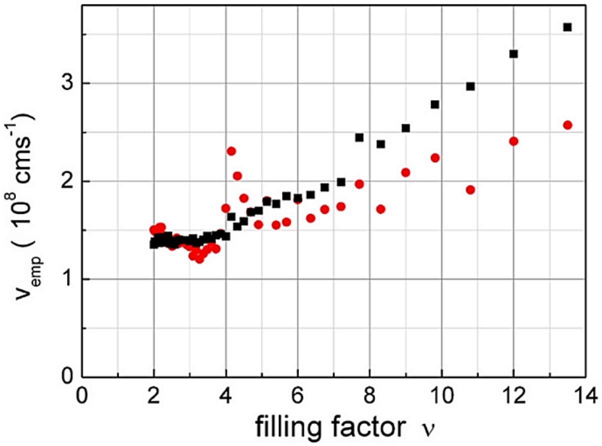
Plasmon transport in graphene investigated by time-resolved electrical measurements

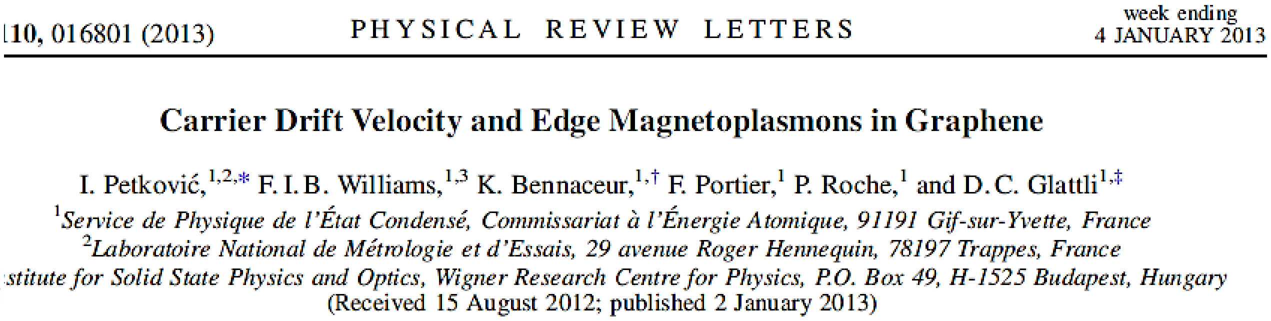
N. Kumada[1], S. Tanabe[1], H. Hibino[1], H. Kamata[1,2], M. Hashisaka[2], K. Muraki[1] & T. Fujisawa[2]



epitaxial graphene on 0001 SiC







110, 016801 (2013) PHYSICAL REVIEW LETTERS week ending 4 JANUARY 2013

Carrier Drift Velocity and Edge Magnetoplasmons in Graphene

I. Petković,[1,2,*] F. I. B. Williams,[1,3] K. Bennaceur,[1,†] F. Portier,[1] P. Roche,[1] and D. C. Glattli[1,‡]
[1]Service de Physique de l'État Condensé, Commissariat à l'Énergie Atomique, 91191 Gif-sur-Yvette, France
[2]Laboratoire National de Métrologie et d'Essais, 29 avenue Roger Hennequin, 78197 Trappes, France
stitute for Solid State Physics and Optics, Wigner Research Centre for Physics, P.O. Box 49, H-1525 Budapest, Hungary

(Received 15 August 2012; published 2 January 2013)

Outline

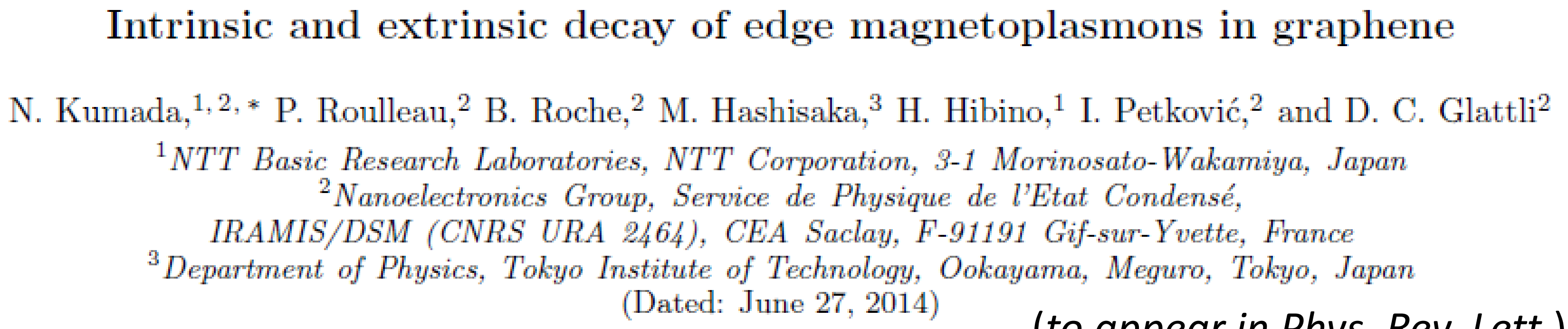
- Introduction
  what are edge magnetoplasmons (EMP)?
  classical
  quantum (QH regime)

- EMP in graphene

- Experiment I (exfoliated graphene 40um perimeter)
  evidence for chiral propagation
  velocity of EMP mode
  carrier drift velocity

→ - Experiment II (SiC graphene 200um /1mm perimeter)
  check EMP dispersion relation
  measure damping of EMPs

- Conclusion and Perspectives



Intrinsic and extrinsic decay of edge magnetoplasmons in graphene

N. Kumada,[1,2,*] P. Roulleau,[2] B. Roche,[2] M. Hashisaka,[3] H. Hibino,[1] I. Petković,[2] and D. C. Glattli[2]

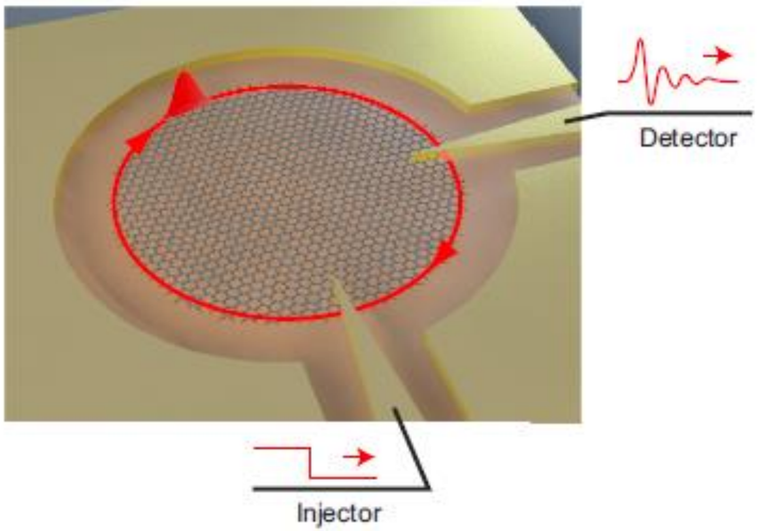
[1] *NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Japan*
[2] *Nanoelectronics Group, Service de Physique de l'Etat Condensé,*
IRAMIS/DSM (CNRS URA 2464), CEA Saclay, F-91191 Gif-sur-Yvette, France
[3] *Department of Physics, Tokyo Institute of Technology, Ookayama, Meguro, Tokyo, Japan*
(Dated: June 27, 2014)

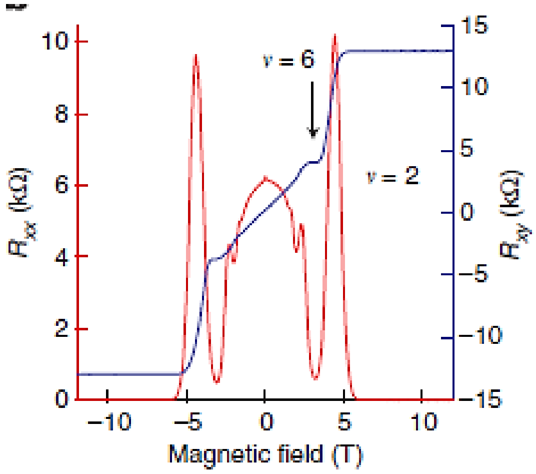
(*to appear in Phys. Rev. Lett.*)

Graphene on SiC (from NTT Atsugi Jpn)

larger size : 1mm and 200μm perimeter

dc- 50GHz CEA Saclay microwave set-up

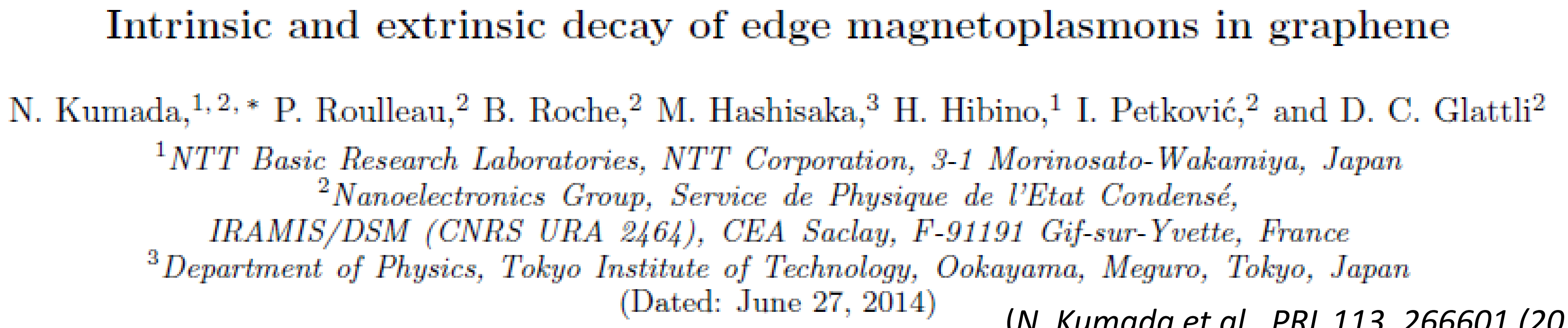




mobility ~ 10 000 $cm^2 V^{-1}s^{-1}$
density ~ 6 10^{11} cm^{-2}

capacitive coupling
(input and output)

swept frequency
or
time domain measurents



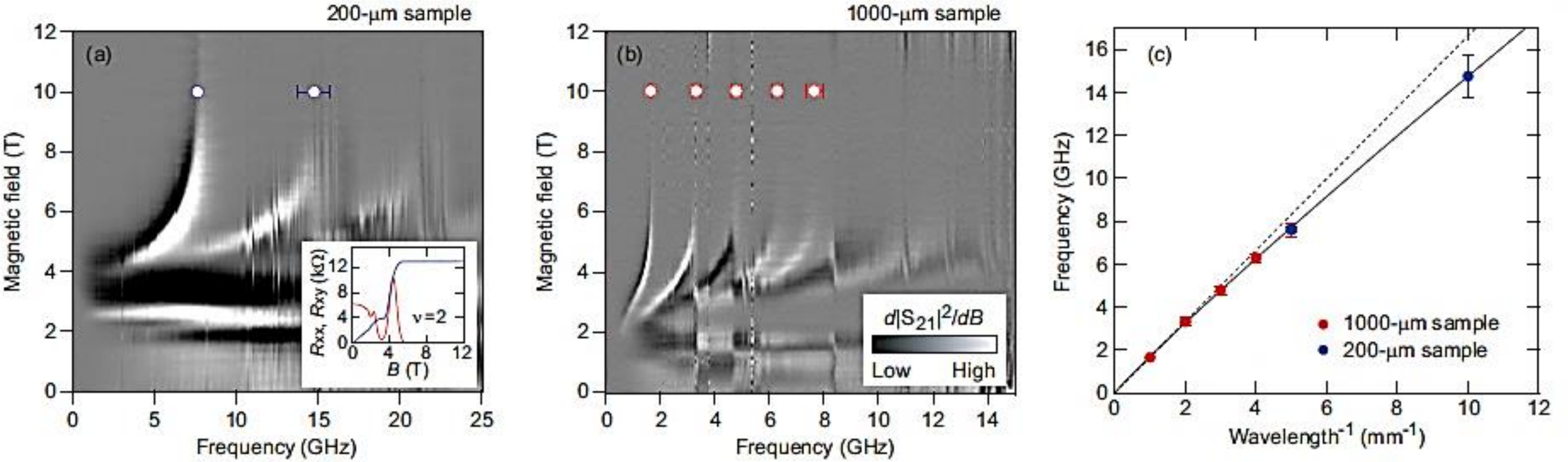
Intrinsic and extrinsic decay of edge magnetoplasmons in graphene

N. Kumada,[1, 2, *] P. Roulleau,[2] B. Roche,[2] M. Hashisaka,[3] H. Hibino,[1] I. Petković,[2] and D. C. Glattli[2]

[1]*NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Japan*
[2]*Nanoelectronics Group, Service de Physique de l'Etat Condensé,*
IRAMIS/DSM (CNRS URA 2464), CEA Saclay, F-91191 Gif-sur-Yvette, France
[3]*Department of Physics, Tokyo Institute of Technology, Ookayama, Meguro, Tokyo, Japan*
(Dated: June 27, 2014)

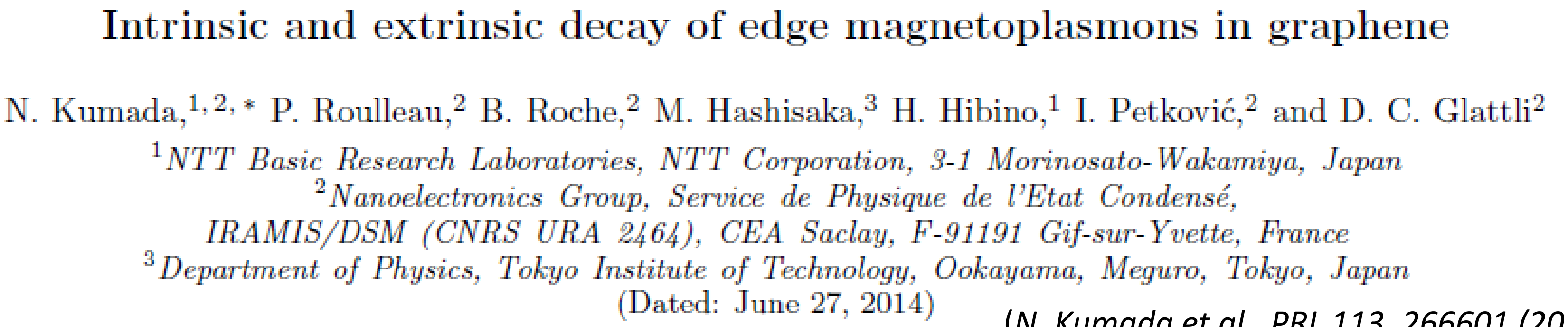
(*N. Kumada et al., PRL 113, 266601 (2014)*)

frequency domain measurements :



complete quantitative test
of the EMP frequency formula

$$\omega = v_{\varphi} q = \left[\frac{2\sigma_{xy}}{\varepsilon_{\text{eff}}} \left(\ln \frac{2}{|q|w} + C \right) + v_D \right] q,$$

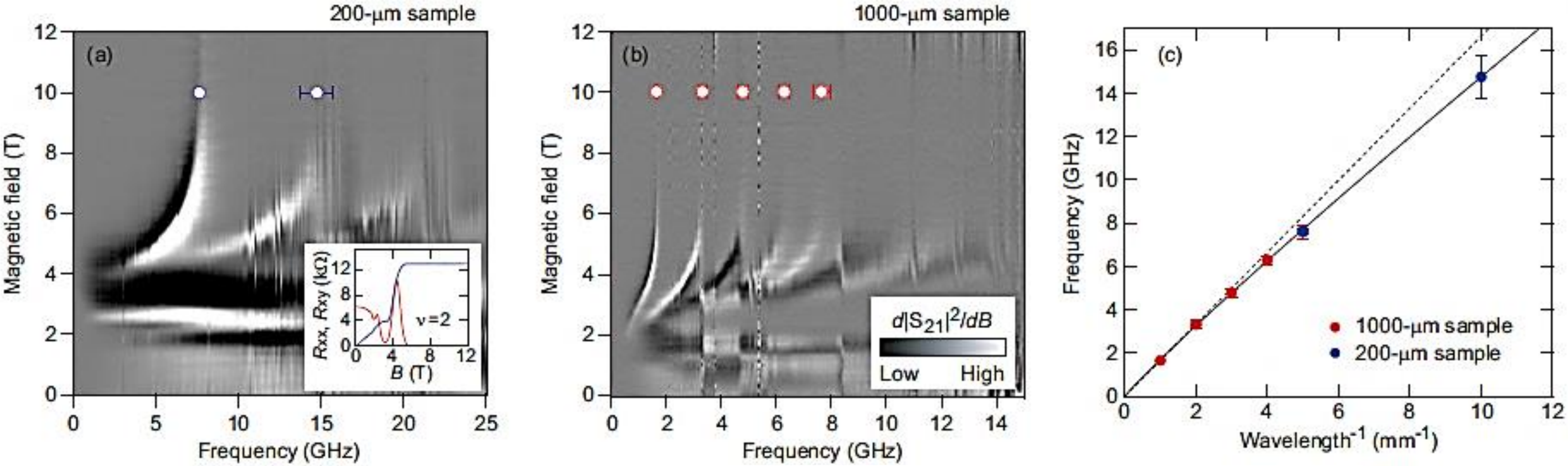


Intrinsic and extrinsic decay of edge magnetoplasmons in graphene

N. Kumada,[1, 2, *] P. Roulleau,[2] B. Roche,[2] M. Hashisaka,[3] H. Hibino,[1] I. Petković,[2] and D. C. Glattli[2]
[1] *NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Japan*
[2] *Nanoelectronics Group, Service de Physique de l'Etat Condensé, IRAMIS/DSM (CNRS URA 2464), CEA Saclay, F-91191 Gif-sur-Yvette, France*
[3] *Department of Physics, Tokyo Institute of Technology, Ookayama, Meguro, Tokyo, Japan*
(Dated: June 27, 2014)

(N. Kumada et al., PRL 113, 266601 (2014)

frequency domain measurements :



complete quantitative test
of the EMP frequency formula

$$\omega = v_\varphi q = \left[\frac{2\sigma_{xy}}{\varepsilon_{\text{eff}}}\left(\ln\frac{2}{|q|w} + C\right) + v_D\right]q,$$

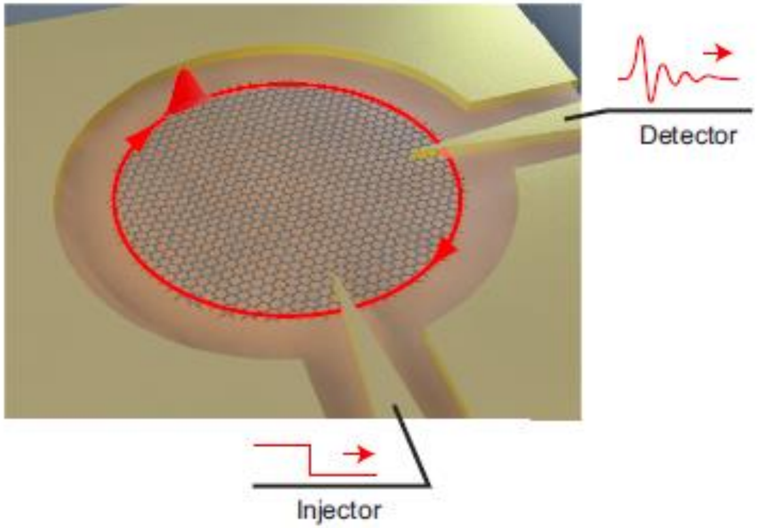
V_D = 0.5 ±0.1 10^8 cm/s (consistent with 0.7±0.1 10^8 found by I. Petkovic PRL 2013)

w ≈ 4 nm (much smaller than in GaAs/GaAlAs ≈ 500 nm)

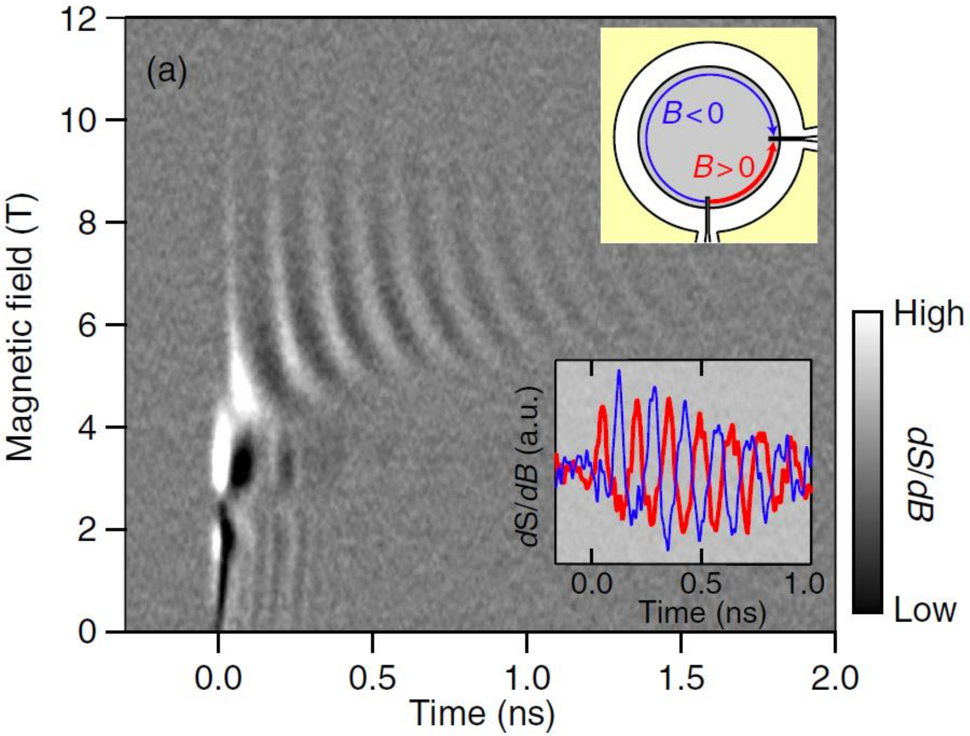
Decay time of the Graphene Edge MagnetoPlasmons

time domain measurements :

(N. Kumada et al., PRL 113, 266601 (2014))



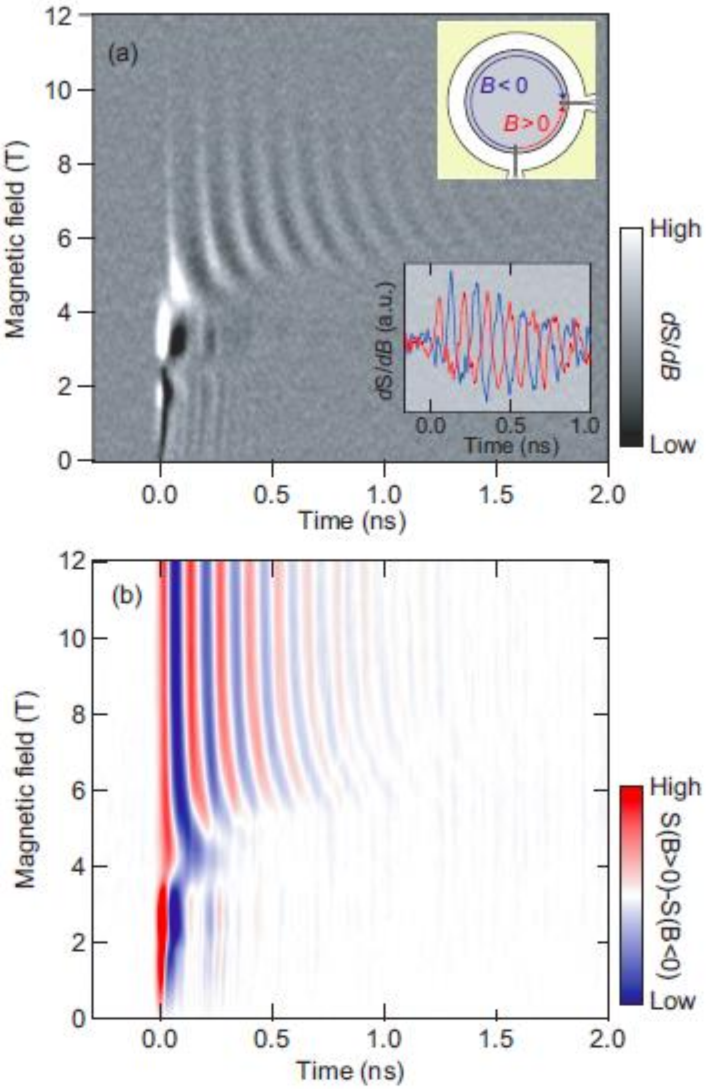
pulse rise time: 70 ps

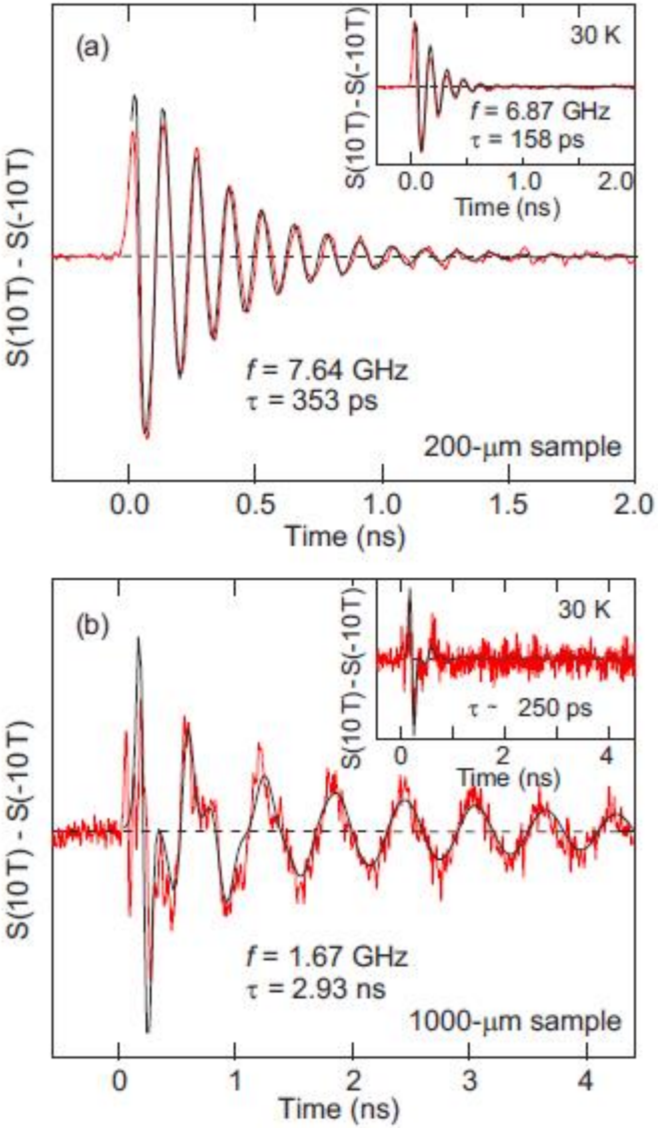


Decay time of the Graphene Edge MagnetoPlasmons

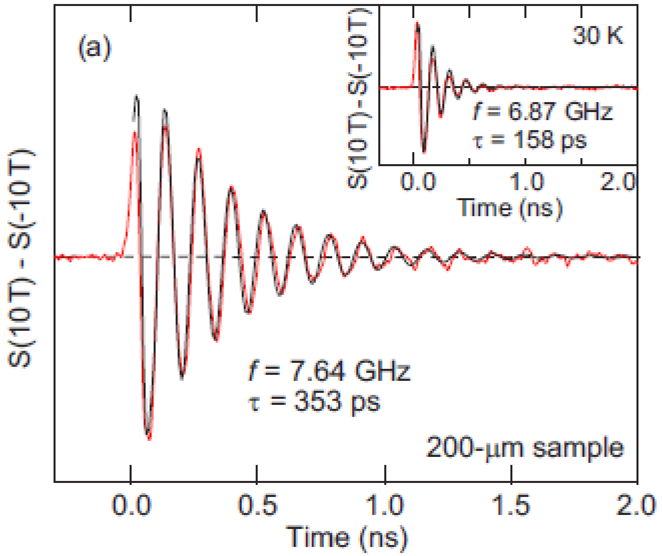
time domain measurements :

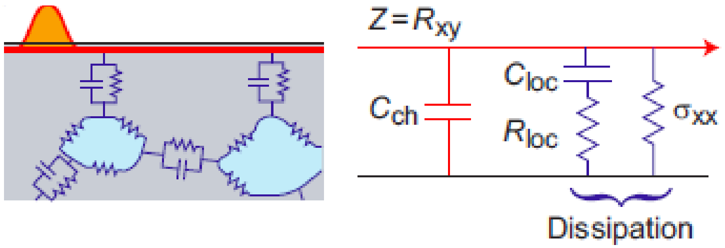
(*N. Kumada et al., PRL 113, 266601 (2014)*)





Decay time of the Graphene Edge MagnetoPlasmons

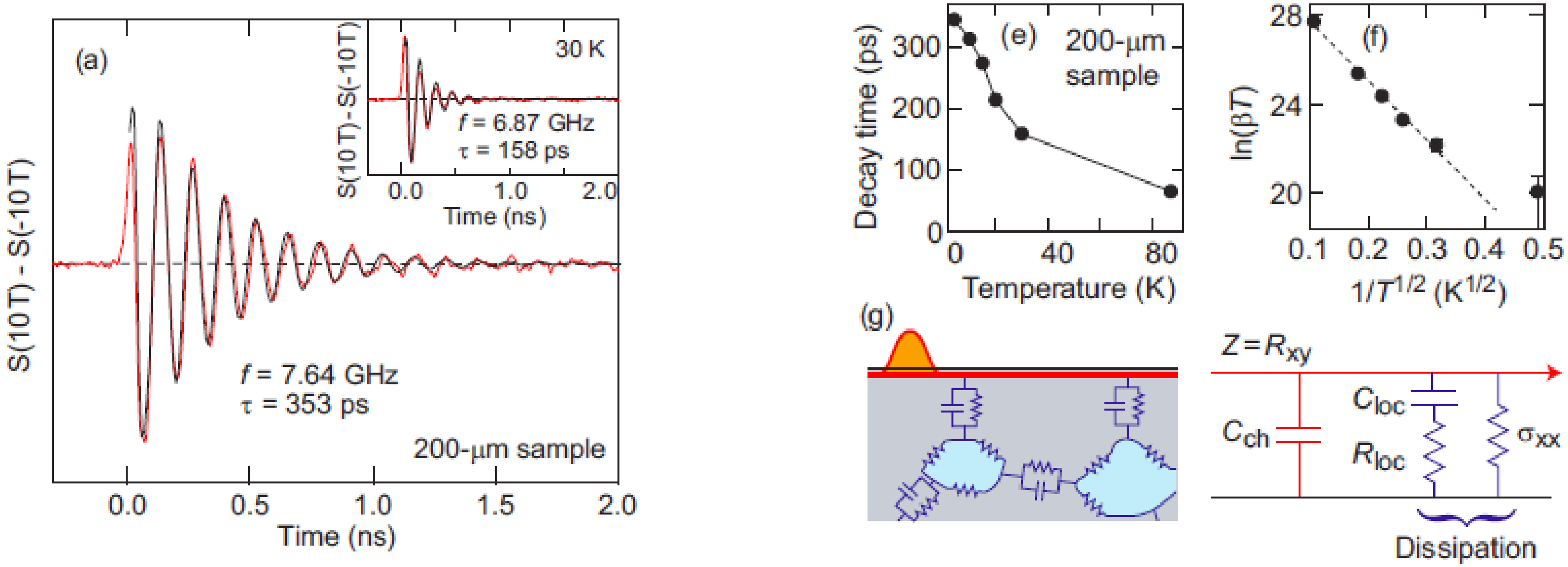




EMP damping arises from
- capacitive coupling to localized edge states in the bulk (low temperature)
- finite longitudinal resistance (high >20K temperature)

$$\frac{1}{\tau} = \alpha\, f^{2} + \beta(T)$$

Decay time of the Graphene Edge MagnetoPlasmons



EMP damping arises from

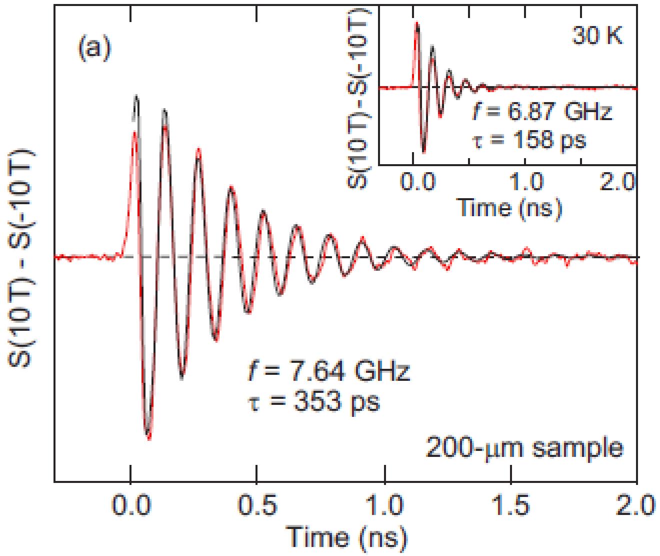
- capacitive coupling to localized edge states in the bulk (low temperature)
- finite longitudinal resistance (high >20K temperature)

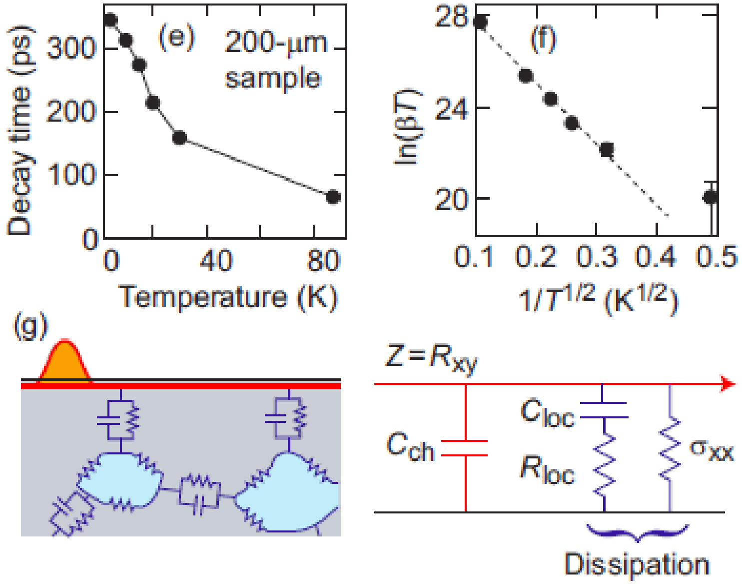
$$\frac{1}{\tau} = \alpha\, f^2 + \beta(T)$$

analysis of data give α constant and : $\beta(T) \propto \exp\left(-(T_0/T)^{1/2}\right)$

consistent with Efros-Shklovskii Var. Range Hopping with $T_0 \sim 730K$
also consistent with tranport measurements of To ~ 900 K in graphene
see *K. Bennaceur et al. Phys. Rev. B 86, 085433 (2012).*

Decay time of the Graphene Edge MagnetoPlasmons





EMP damping arises from

- capacitive coupling to localized edge states in the bulk (low temperature)
- finite longitudinal resistance (high >20K temperature)

Typical EMP resonance quality factor:

Q= 15 @ 1.7 GHz and Q=8.5 @ 7.6 GHz (at T=4.2°K)

Conclusion & Perspectives

- existence of EMP in graphene in QH regime
- chiral propagation
- provide first exp. estimation of drift velocity ~(0.7 +/-0.2) 10^6m/s
- full check of EMP dispersion relation
- EMP lifetime measurement and identification of damping mechanism
- very high Q at GHz frequency

Edge *vs* bulk plasmons

BULK	EDGE
$\omega \sim n^{1/4} \sim V_G^{1/4}$	$\omega \sim n \sim V_G$
non chiral	chiral
weak gate dependence	reversible with gate or field
damped < inverse relaxation time (~THz) THz to Infrared domain	weakly damped on Hall plateaus GHz to THz domain

possibility of chiral plasmonics
(gated rf-isolators, circulators,…)

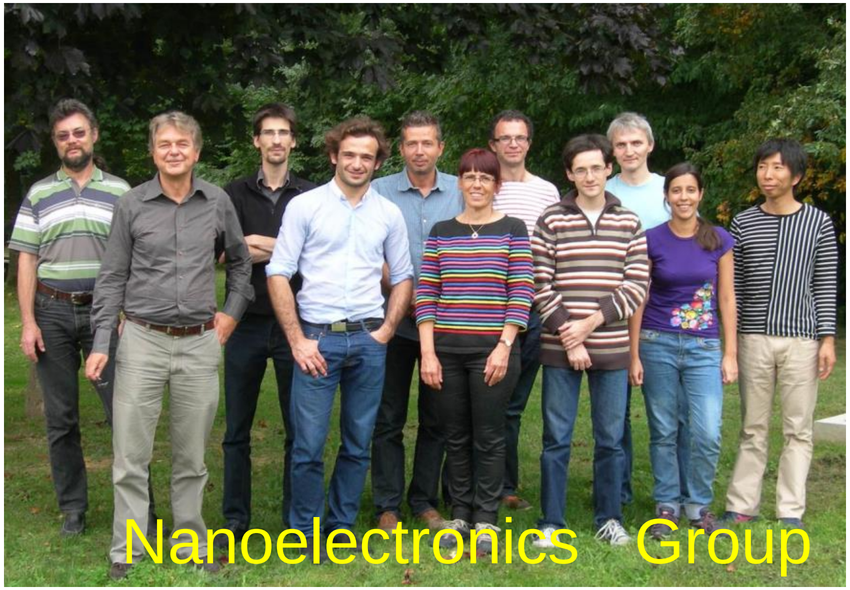
ERC Advanced Grant MeQuaNo

Chiral Plasmonics in Graphene

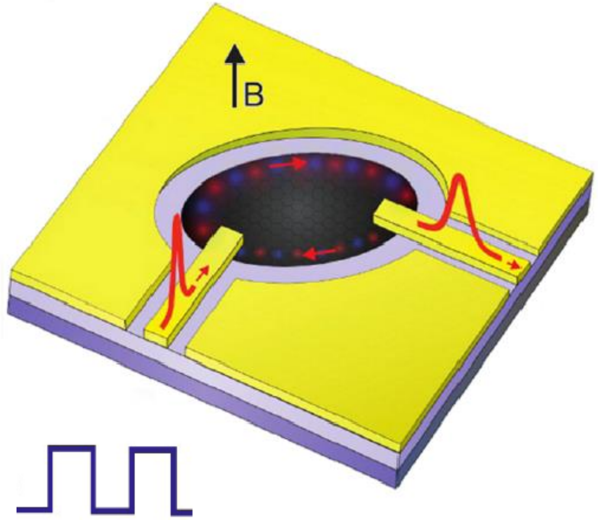
THANKS TO :

N. Kumada (Visitor NTT Atsugi Jpn)
H. Hibino (NTT Atsugi, Jpn)
M. Hashisaka (Tokyo Inst. Techn. Jpn)
I. Petkovic (post-doc, now at Yale)
F.I.B. Williams (visitor Un.Budapest)
L. Serkovic (Post-doc, now in Mexico)
Keyan Bennaceur (PhD now @ McGill Un.)
Preden Roulleau (CEA Saclay)
P. Roche (CEA Saclay)
F. Portier (CEA Saclay)
D. C. Glattli (CEA Saclay)

CEA Saclay ,France



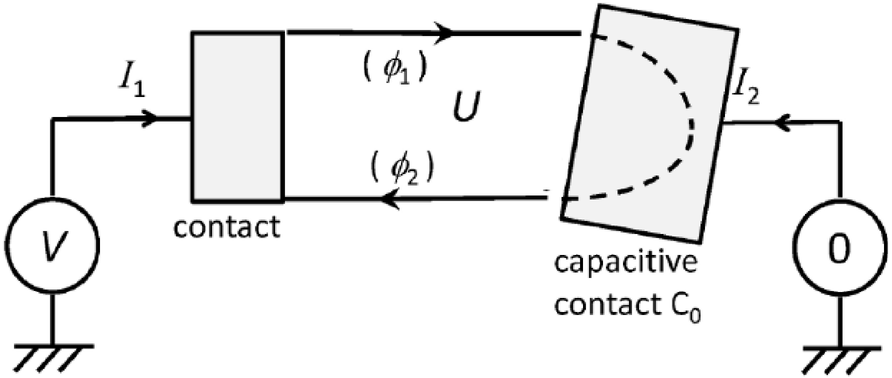
Why there is no echo



reciprocity

modulation much more efficient on one side -
one ohmic and one capacitive contact

model:



no echo is expected

(D. C. Glattli et al., supplementary material, arXiv:1206.2940 (2012))

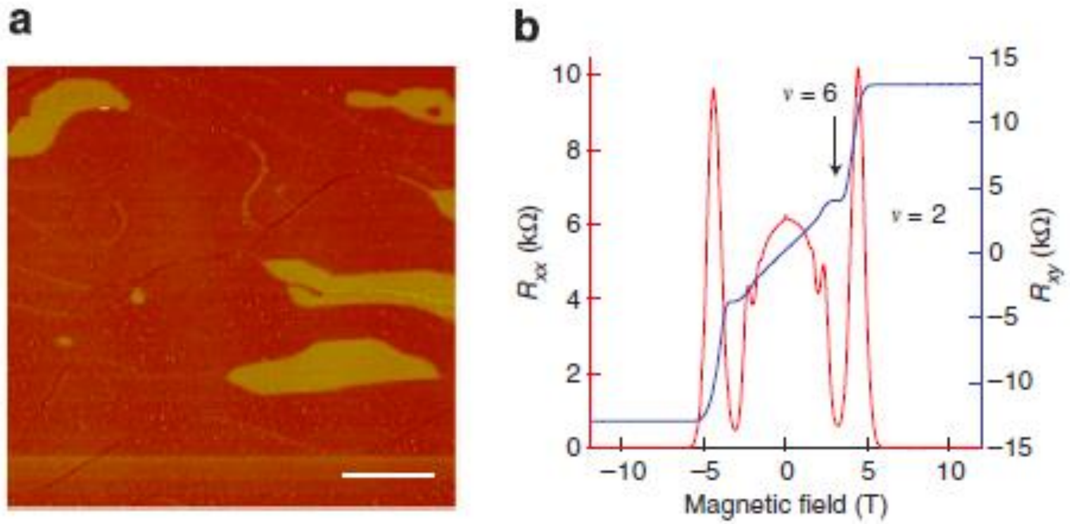


Figure 1 | Graphene on SiC and the experimental techniques. (**a**) Atomic force microscopy phase image of graphene on SiC (ref. 27). Scale bar, 1 µm. Single-layer graphene (brown colour in majority regions) covers the substrate, while two or more graphene layers (yellow colour in minority regions) are formed along the terrace edge. As few-layer graphene regions are fragmented, the single-layer graphene dominates carrier transport. (**b**) R_{xx} and R_{xy} at 1.5 K of a Hall bar device with the channel width and length of 0.2 and 1.1 mm, respectively. The mobility is 12,000 cm^2 V^{-1} s^{-1}. (**c**) Schematic illustration (not to scale) of the sample structure and the experimental setup for the time-resolved transport measurement.