Terahertz sensing and imaging based on carbon nanotubes:

Frequency-selective detection and near-field imaging

Yukio Kawano

RIKEN, JST PRESTO

ykawano@riken.jp

http://www.riken.jp/lab-www/adv_device/kawano/index.html

Outline

1. THz detector :

Frequency-tunable THz detector using a carbon nanotube

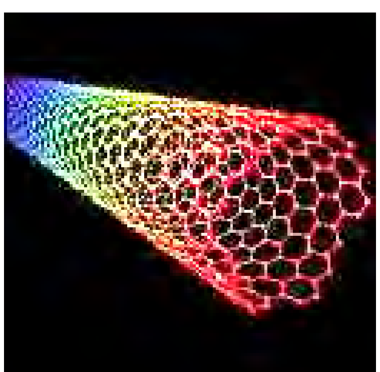
2. Near-field THz imaing :

On-chip near-field THz probe integrated with a detector

3. THz imaging application to semiconductor research

Simultaneous imaging of THz radiation and voltage

4. Summary



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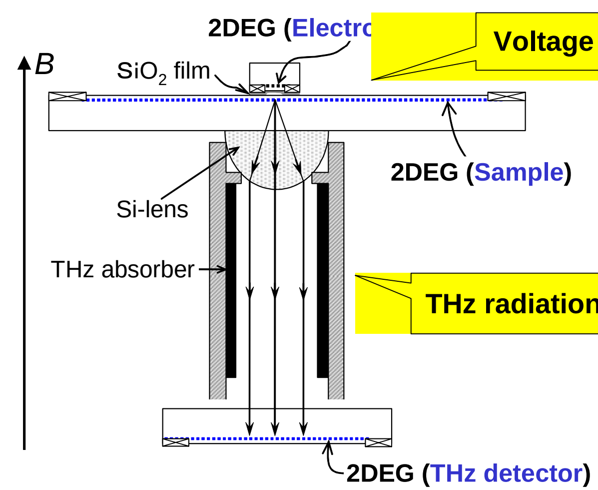
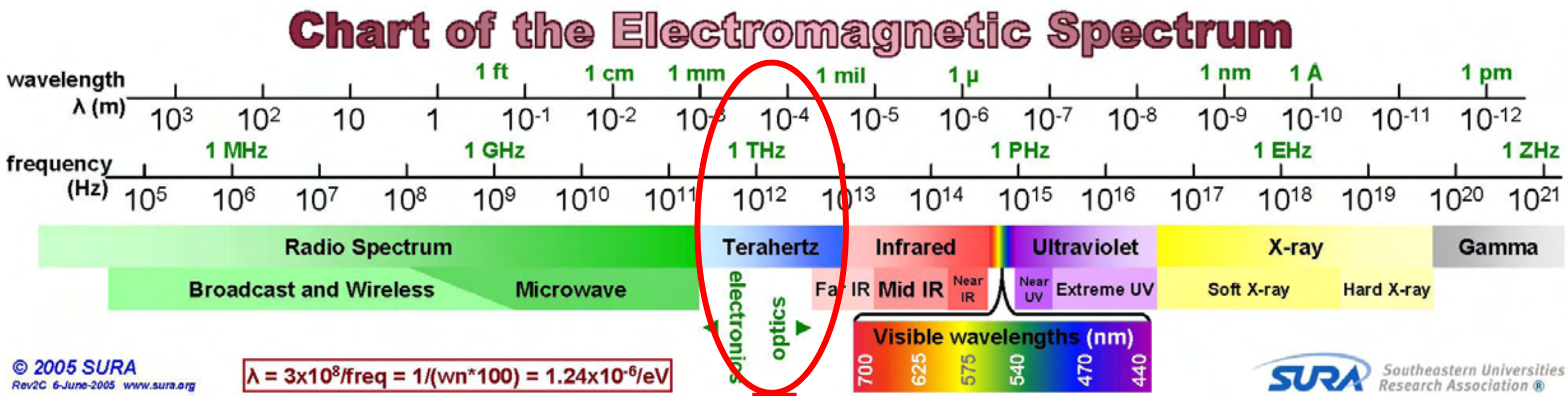


What is terahertz (THz) wave？



Wave (Electronics)

THz (10^{12}Hz) undeveloped

Light (Optics)

Related fields:

- Radio astronomy
- Biochemical spectroscopy
- Medicine
- Solid-state physics

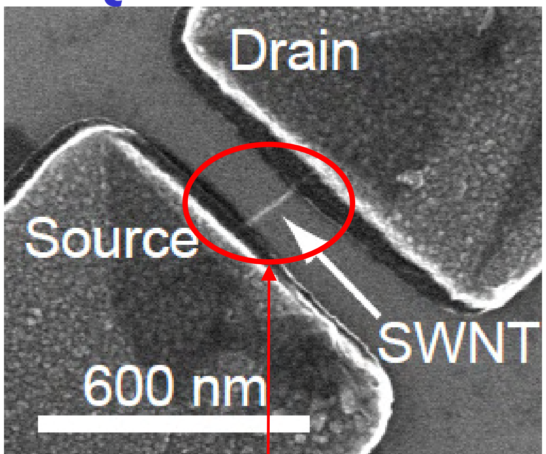
- Phonon
- Energy gap of superconductors
- Impurity level of semiconductors
- Energy spacing due to quantum confinement
- Landau level

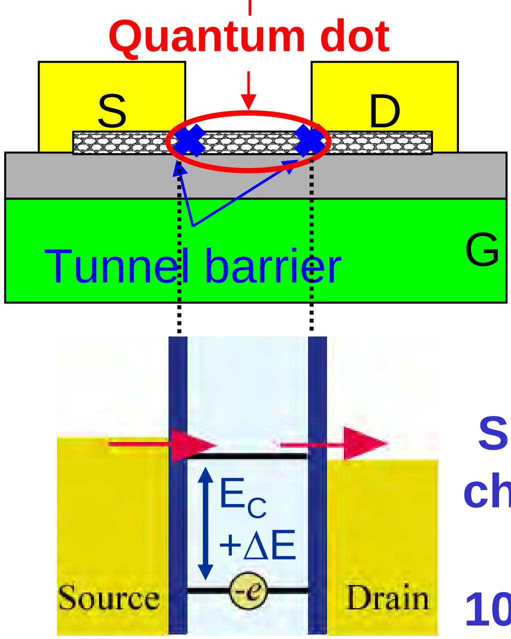
Detector, Source, Imaging, Spectroscopy….

All basic components remain undeveloped

Why can a carbon nanotube be used as a THz detector?

Carbon Nanotube Quantum Dot

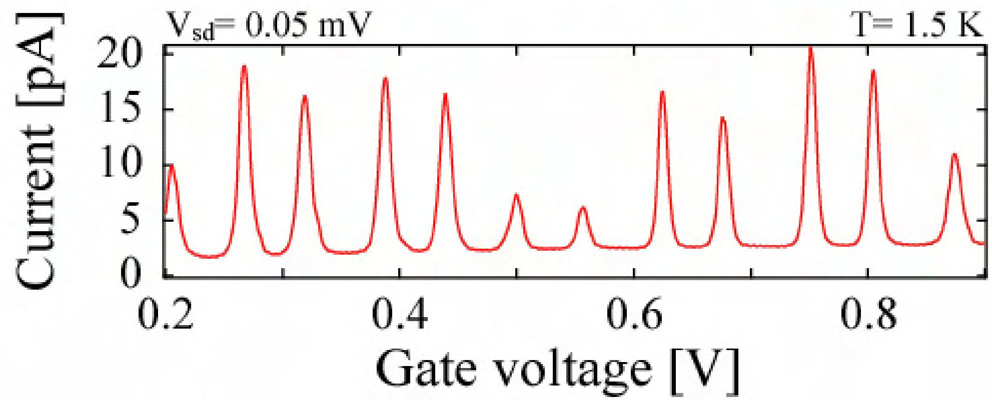




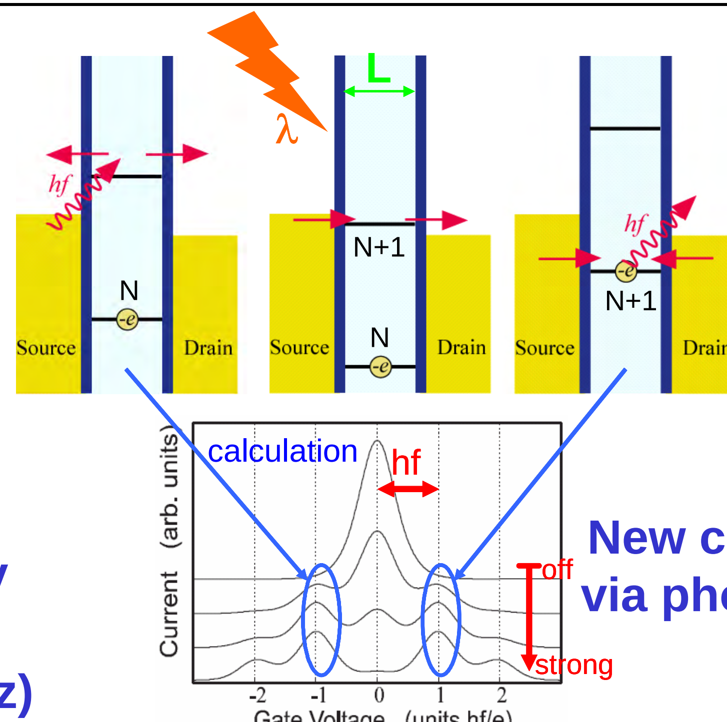
Single electron charging energy

10~50meV (=THz)

Feature 1・・・Single electron transistor



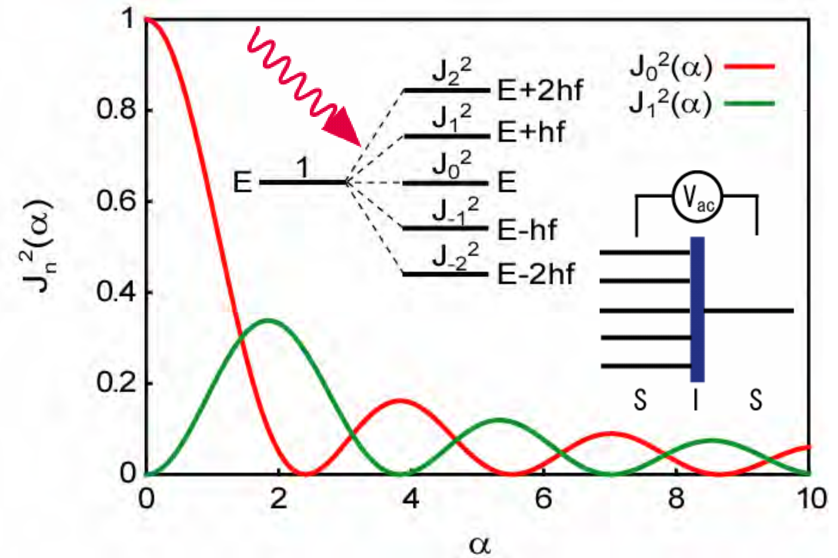
Feature 2・・・Photon-assisted tunneling



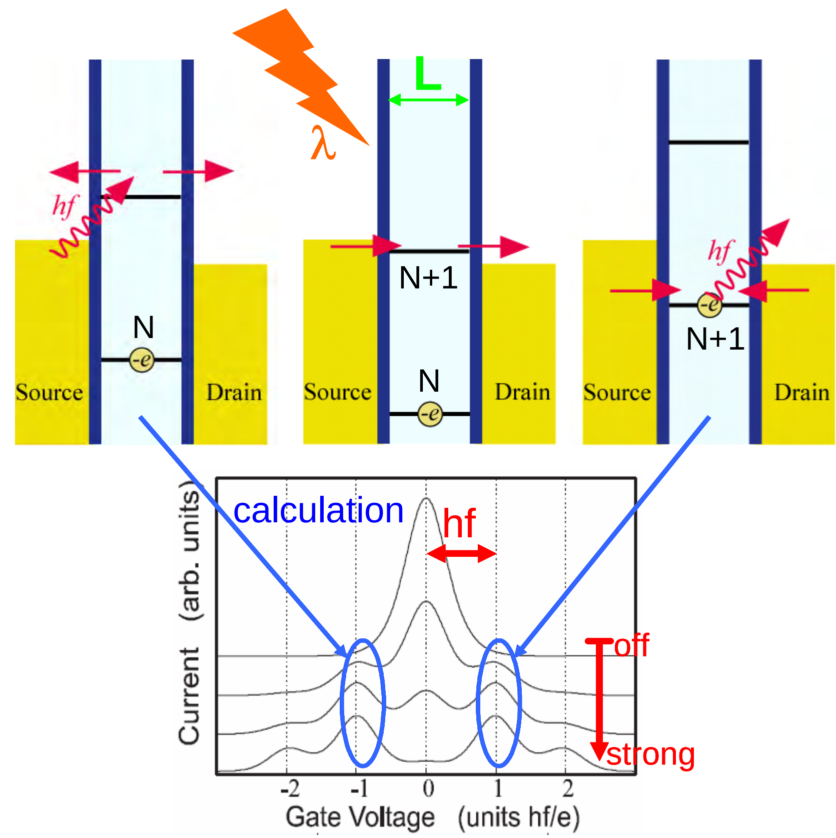
New current signals via photon detection

Photon-assisted tunneling: *Tien-Gordon model*

Photon sidebands via combination with AC electric field



Quantum dot (QD): Generation of new satellite currents



- ***New energy levels are formed at <u>intervals of nhf</u>***
- ***The current follows the <u>Bessel function</u> of the illuminated power***

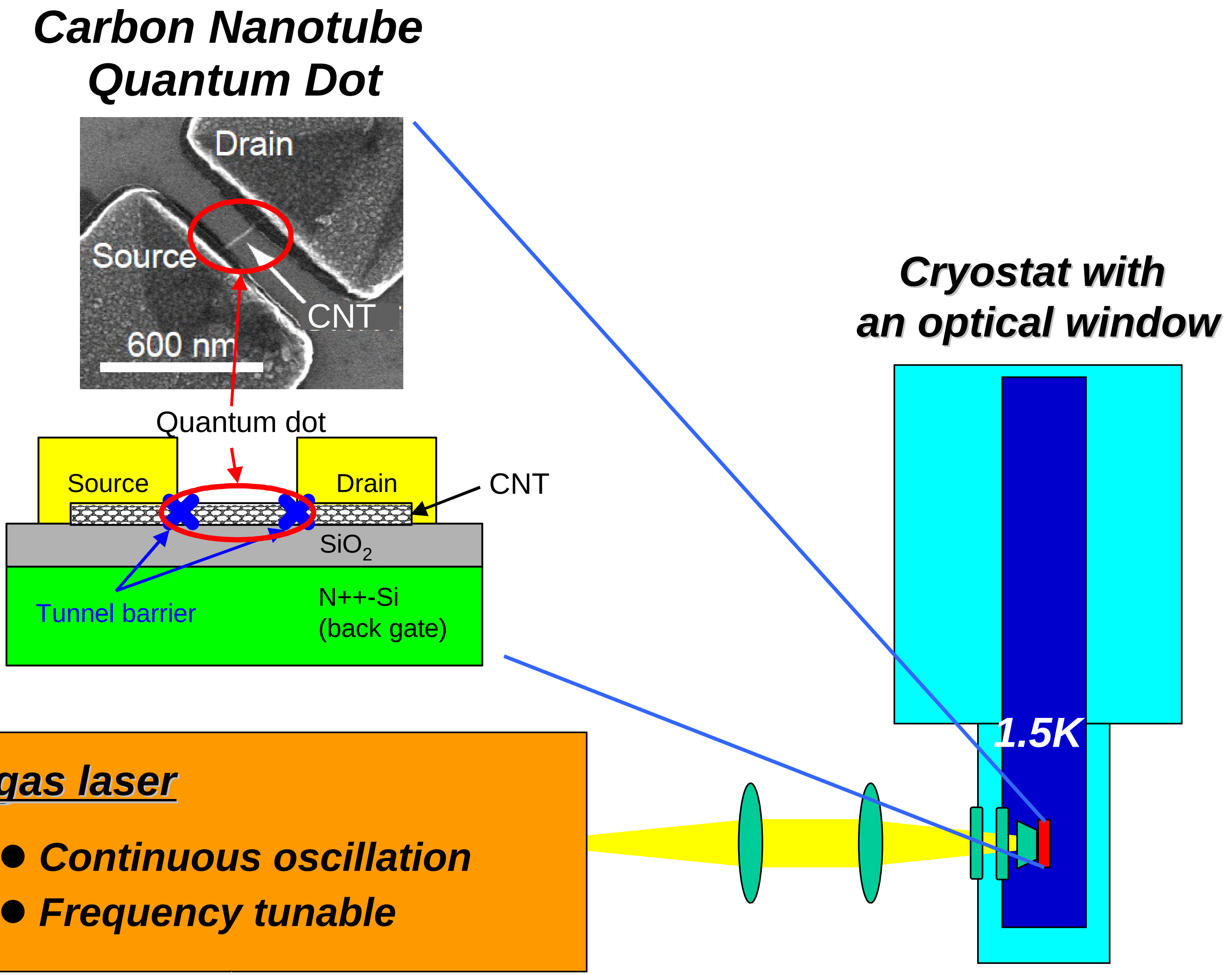
Semiconductor QD: <u>Microwave (GHz)</u> region

In our work:

Carbon nanotube QD ⇨ <u>THz</u> region

10^2-10^3 higher

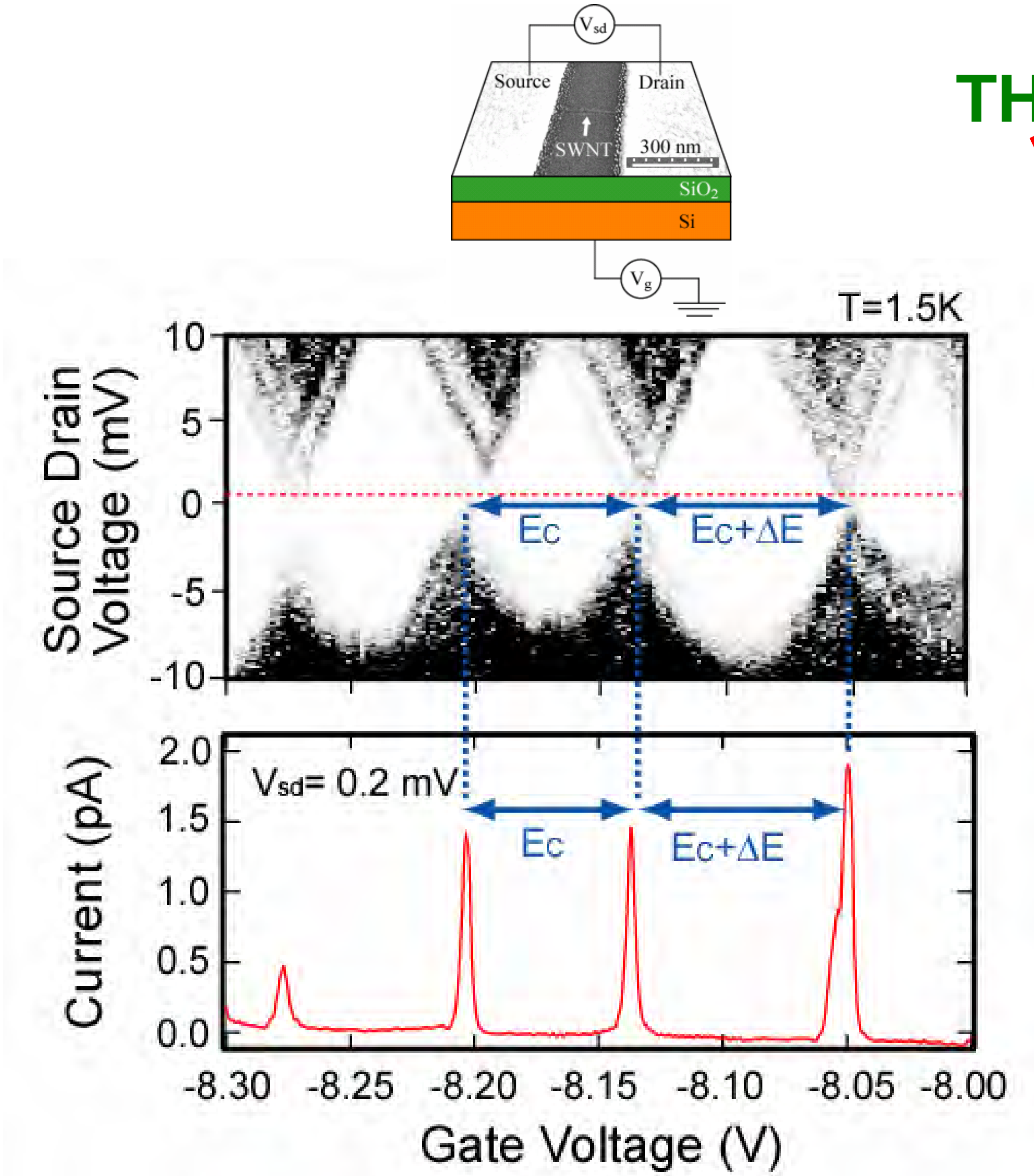
Experimental setup



THz gas laser

- *Continuous oscillation*
- *Frequency tunable*

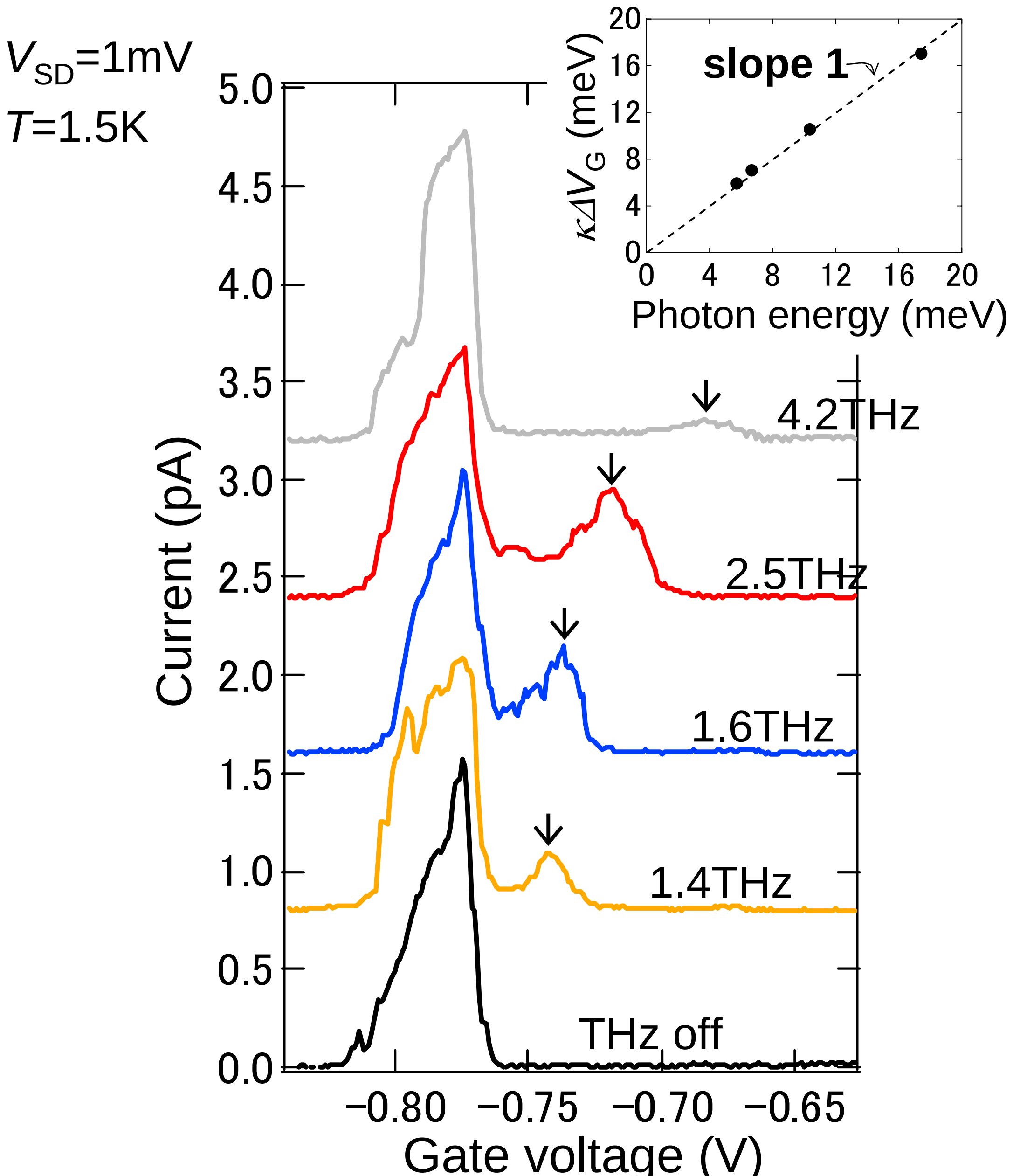
Transport properties (without THz irradiation)



THz

- thermal enregy @ 1.5 K
  : $k_BT \sim 0.15$ meV
- Charging energy
  : $E_C = 9.1$ meV
- 0-D level spacing
  : $\Delta E = 2.1$ meV
- tunnel rate
  : $\Gamma = 10$ MHz
  (for 1.6 pA)
- tunnel barrier height
  : $\phi_B \sim 5$ meV
- photon energy
  : $hf = 10.3$ meV
  (for $f = 2.5$ THz)

THz irradiation effect: THz frequency dependence

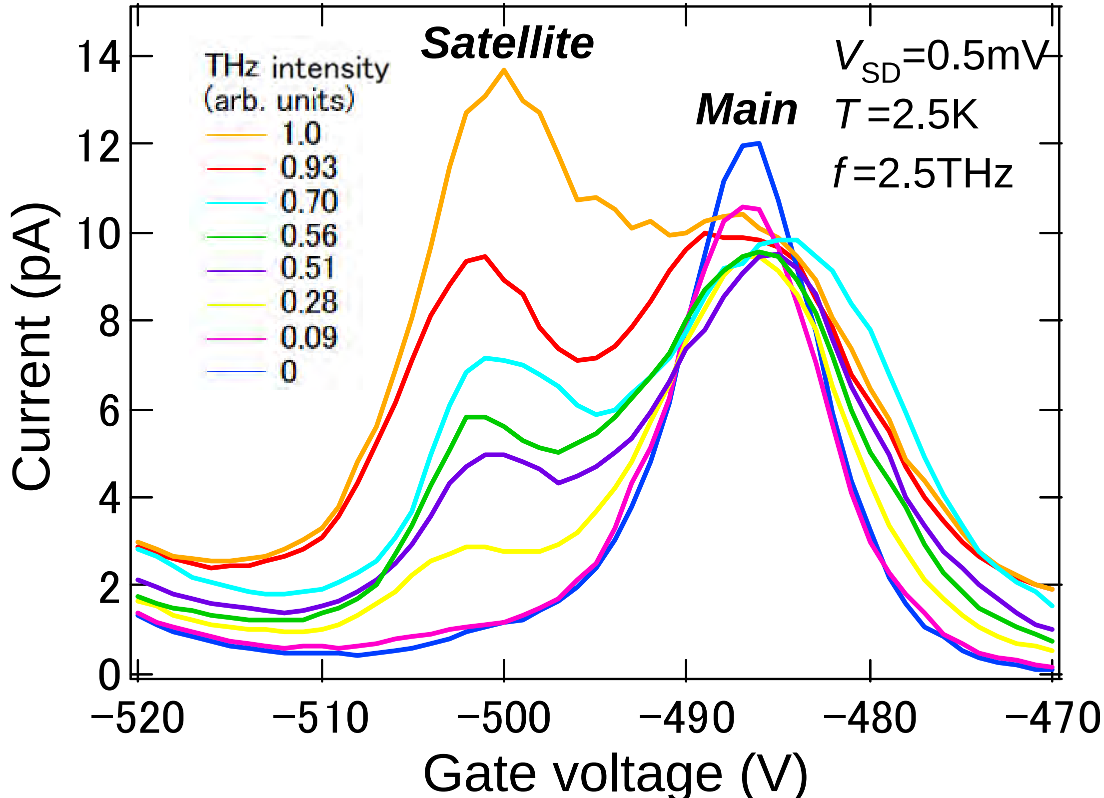


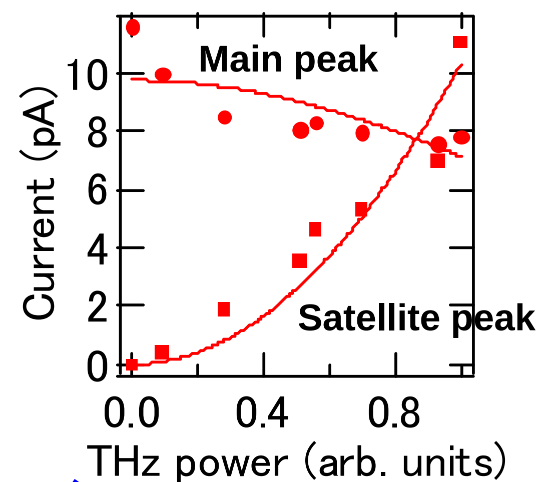
Y. Kawano et al., J. Appl. Phys., 103, 034307 (2008)

- ***Satellite currents by THz irradiation***
- ***Linear dependence on THz-photon energy***

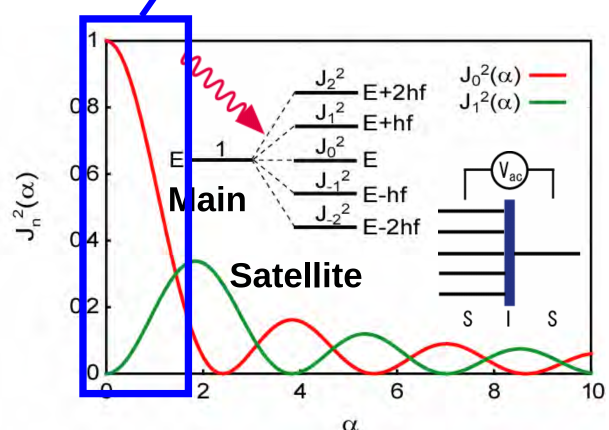
Evidence for: THz photon-assisted Tunneling (Frequency-tunable THz detection)

THz irradiation effect: THz power dependence

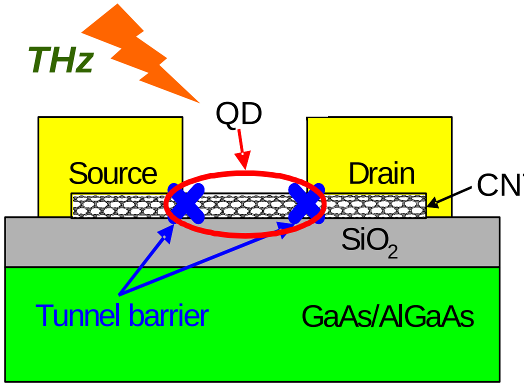


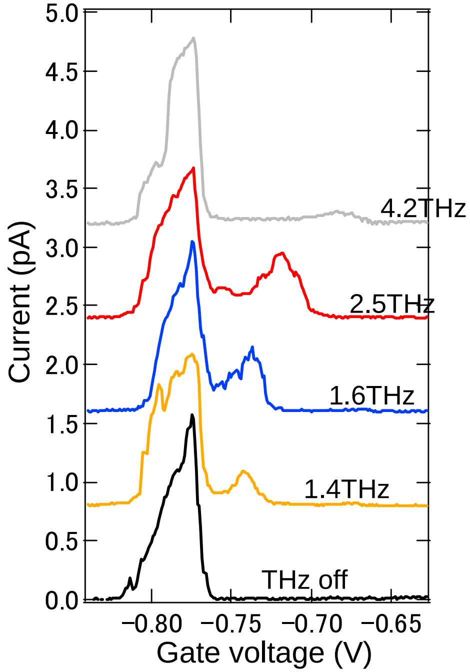


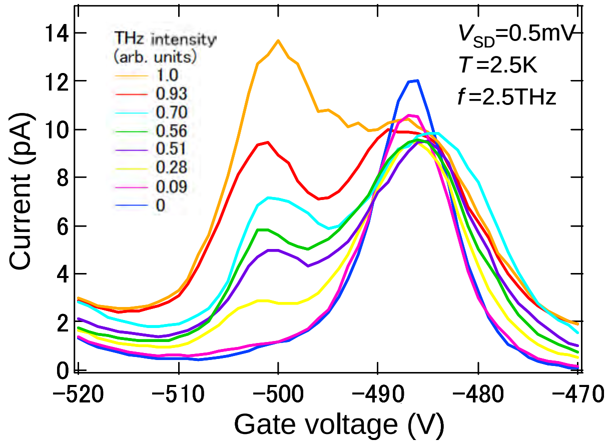
Theoretically, the current follows the Bessel function of the illuminated power



Performance as a THz detector







(1) Frequency bandwith:

Frequency tunable in 1.4-4.2THz

(2) Sensitivity:

100-1000 times larger *than a conventional Si bolometer*

(3) Operation temperature:

Carbon nanotube quantum dot: ***~4K (in principle, ~20K)***

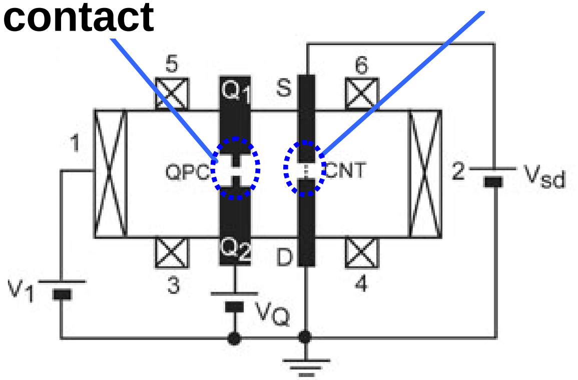
Earlier highly sensitive detector: ***＜0.3K***

Future improvement

(1) Sensitivity

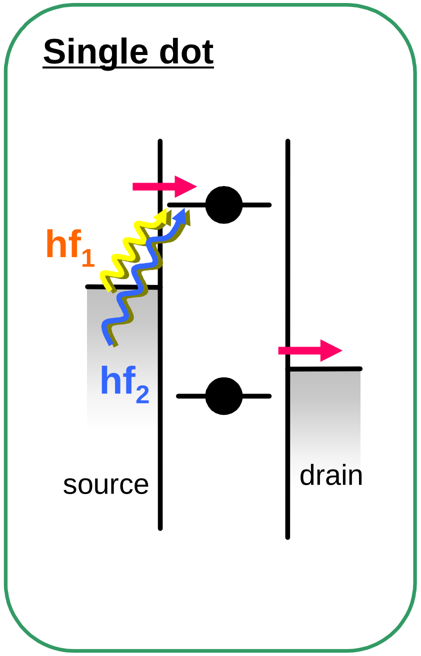
Quantum point contact

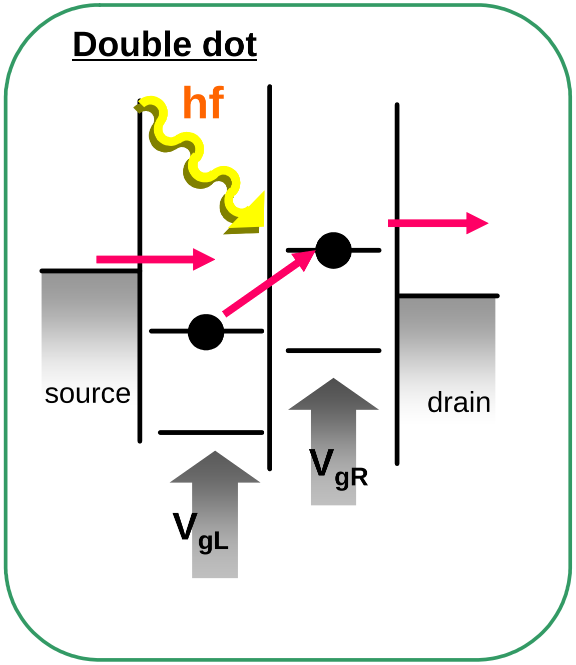
Carbon nanotube



Readout of a single THz-excited electron by quantum point contact

(2) Frequency tunability

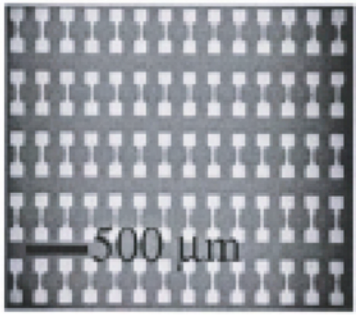




Fabrication of a double quantum dot

(3) THz camera

Two-dimensional array of many carbon natnobues



N. R. Franklin *et al*., APL **81**, 913 (2002)

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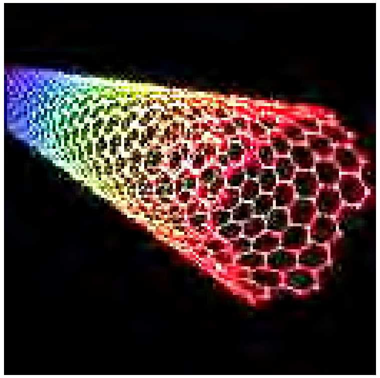

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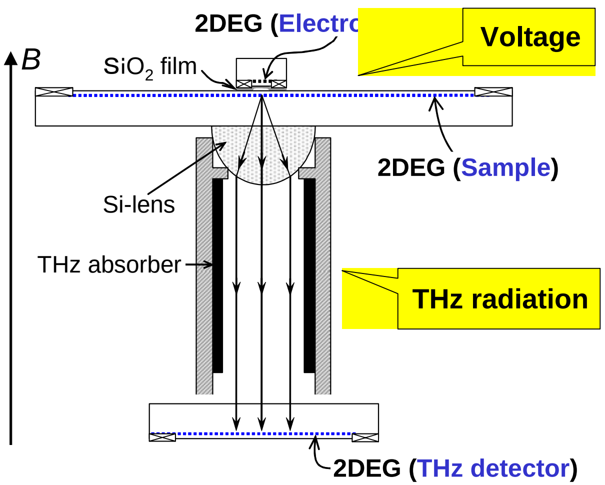


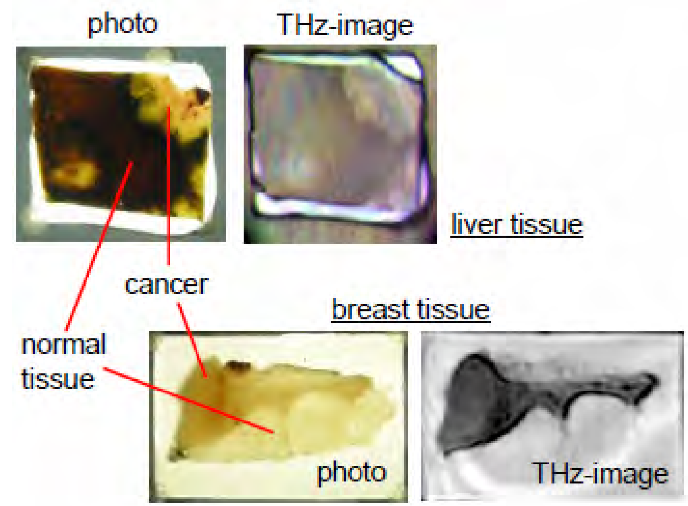
THz imaging applications

● Nondestructive Inspection

Defect inspection of space shuttles

● Medicine

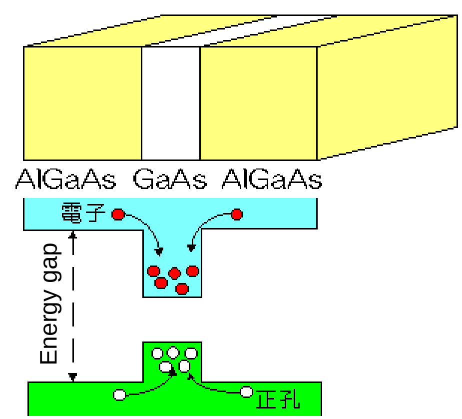
Imaging of cancer cells



● Astronomy

Far-infrared image of Magellanic clouds

● Materials Science



Semiconductor

Superconductor

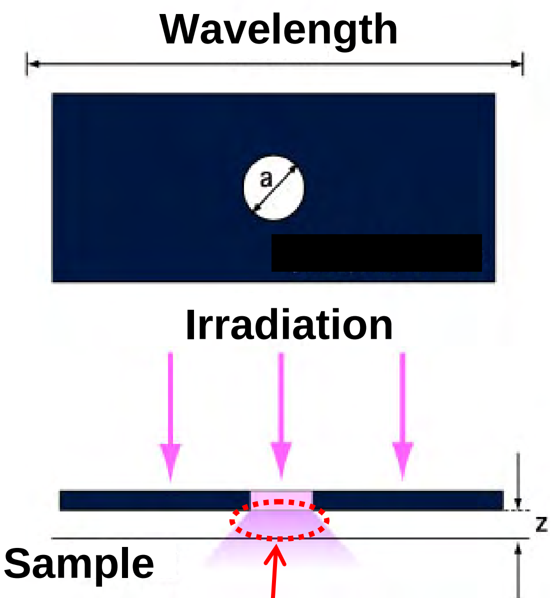
Organic conductor

Carbon nanotube

etc.

Towards improvement in spatial resolution: *Near-field technique*

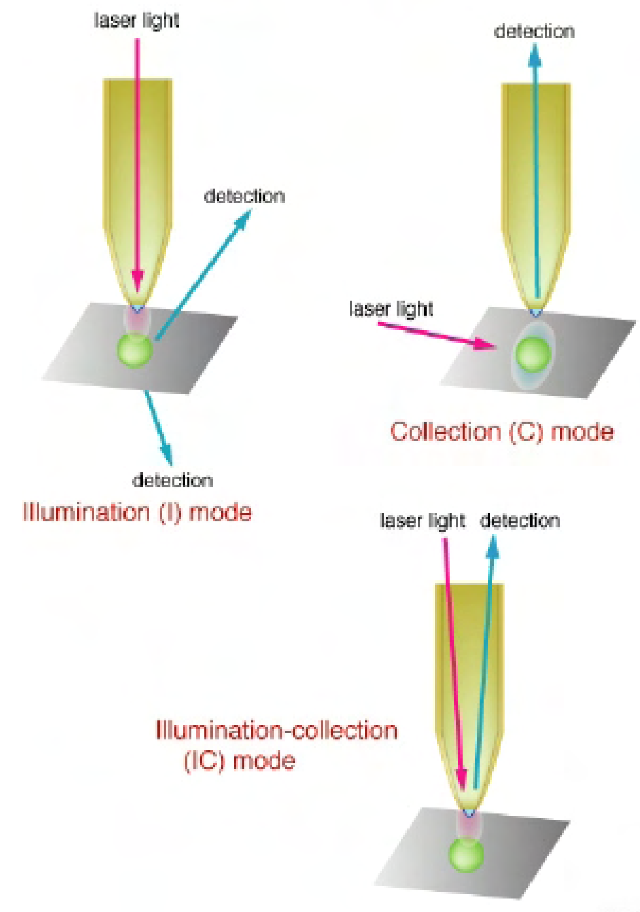
For obtaining optical images beyond the diffraction limit



Localized electromagnetic field (Evanescent field)

Resolution: determined by the tip size

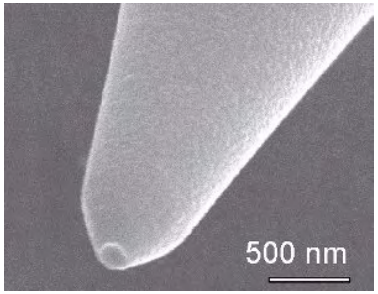
Near-field probe

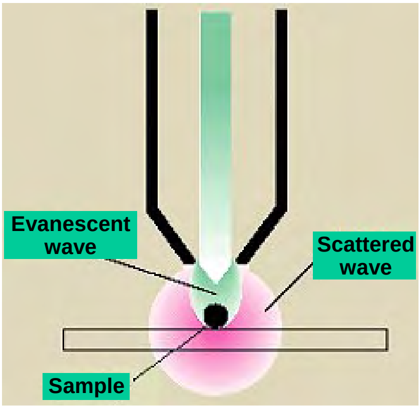


1) Aperture type: Small aperture (tapered optical fiber or wave guide)
2) Apertureless type：Small scatterer（STM/AFM probe）

Why is the development of near-field THz imaging difficult?

Visible and near-infrared regions

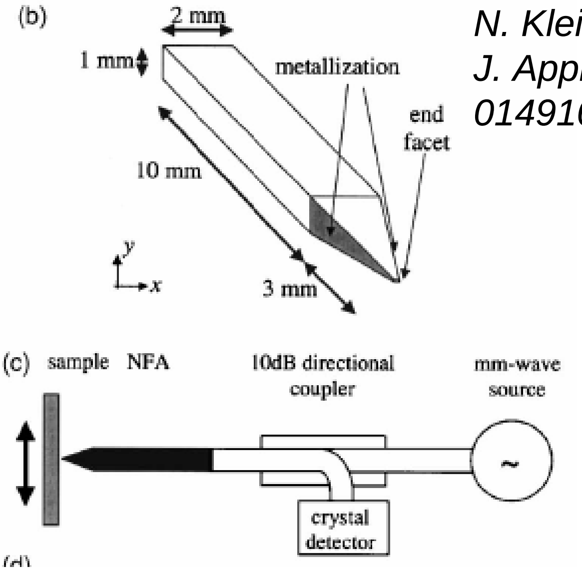




Resolution: Several tens of nm（～λ/100）

Optical fiber

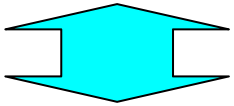
Microwave region



N. Klein et al., J. Appl. Phys. ***98****, 014910 (2005)*

Resolution: 20μm（λ/200）

Waveguide, Coaxial cable



THz region:

- **Lack of high transmission wave line**
- **Low sensitivity of commonly used detectors**

Several pages have been deleted because they contain unpublished data.

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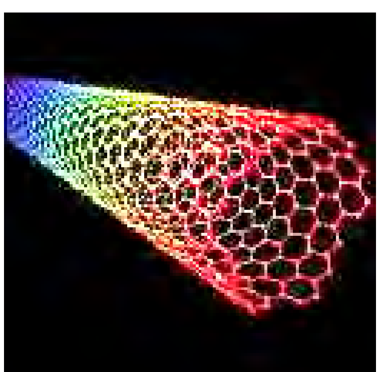

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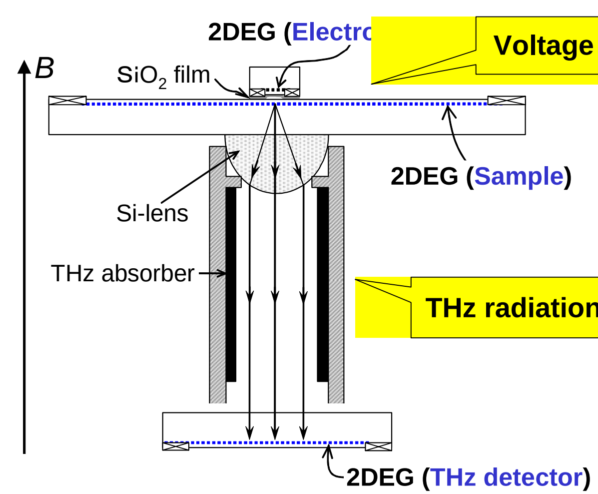


THz imaging application to materials science

Photon energy corresponding to 1THz(wavelength: 300μm): ～4meV

Direct probing of spatial properties of excited states in the meV spectrum

Materials:

- Semiconductor
- Superconductor
- Organic conductor
- Carbon nanotube

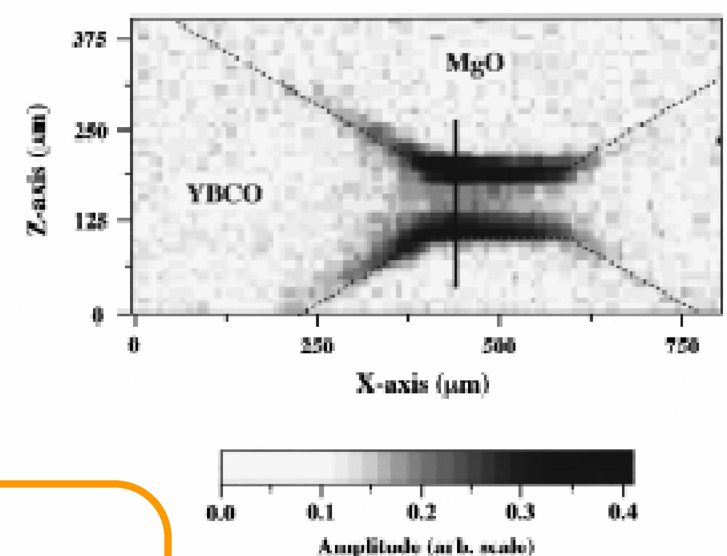
etc.

Physical properties:

- Phonon
- Energy gap of superconductor
- Impurity state of semiconductor
- Landau level
- Charge density wave

etc.

For example;
Supercurrent mapping by THz irradiation



*S. Shikii et al., APL **74**, 1317 (1999)*

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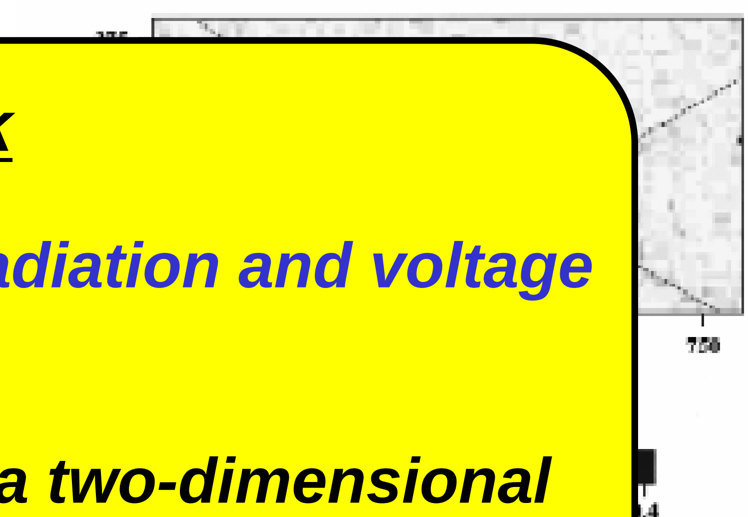


<u>*In our work*</u>

Simultaneous imaging of THz radiation and voltage

Study of spatial properties of a two-dimensional electron system on a semiconductor

<u>Mate</u>

- Se
- Superconductor
- Organic conductor
- Carbon nanotube

etc.

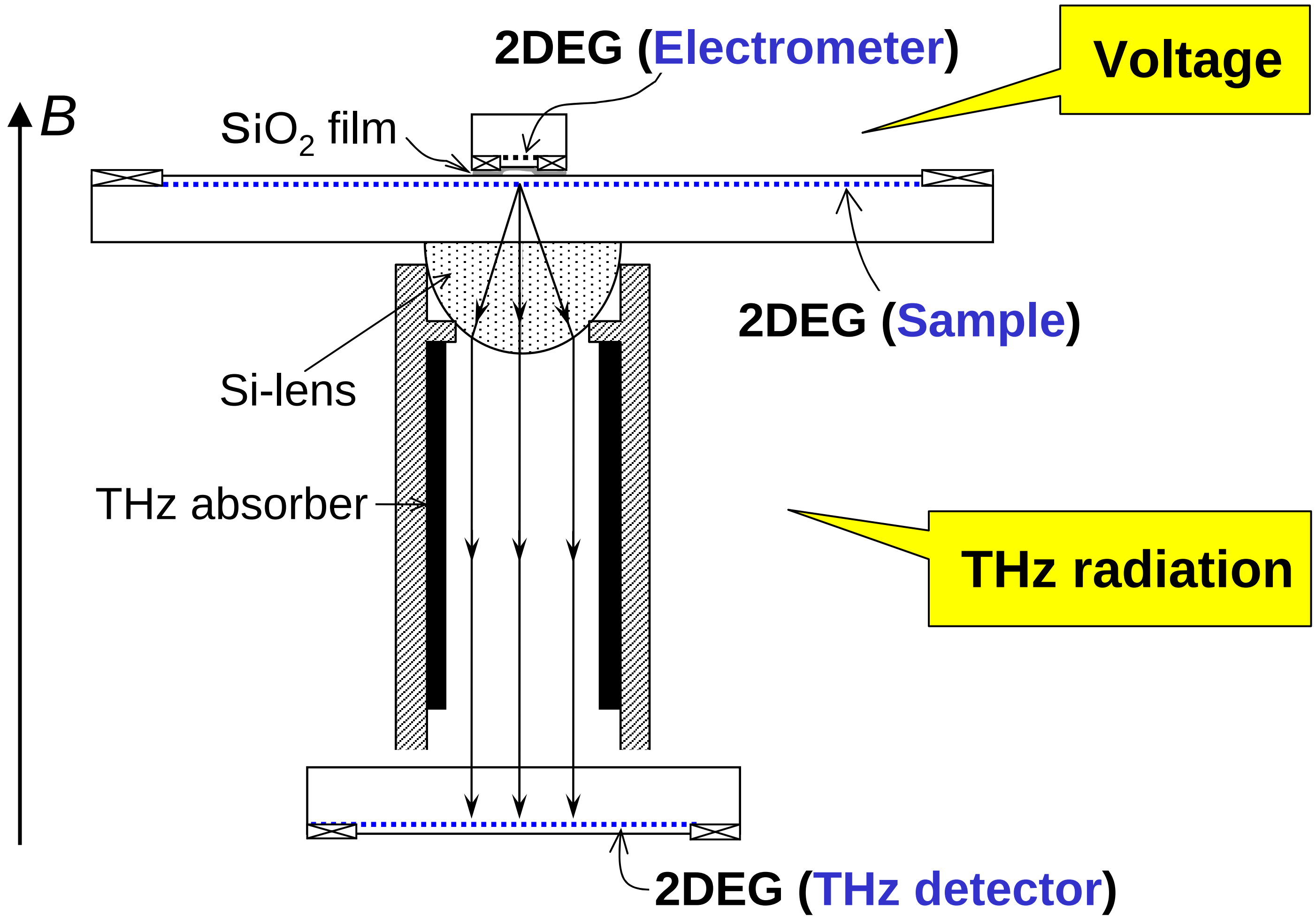
- Energy gap of superconductor
- Impurity state of semiconductor
- Landau level
- Charge density wave

etc.

APL ***74****, 1317 (1999)*

Combined system of a THz microscope and an electrometer

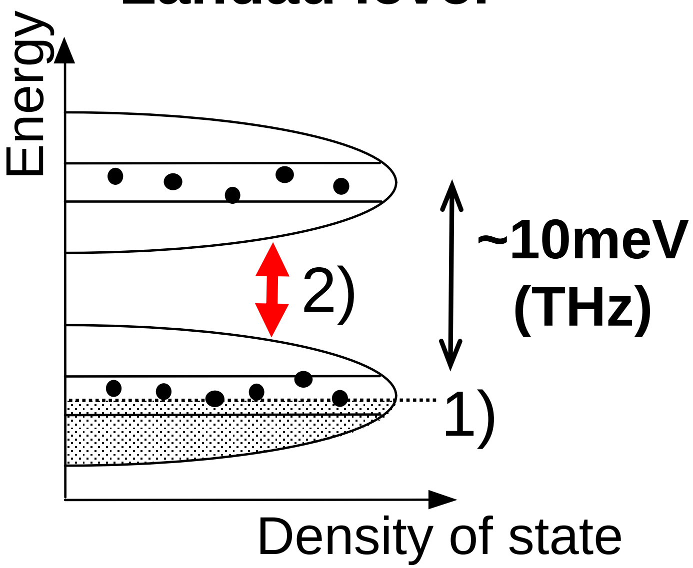
Y. Kawano et al., Phys. Rev. B 70, 081308(R) (2004).



Electrometer, Sample, THz detector:
fabricated from GaAs/AlGaAs heterostructure wafers

Motivation:
Electron density mapping for *each Landau level*

Landau level



1) Ground state (Intra-level scattering)

2) Excited state (Inter-level scattering)

How are the two states distributed ?

No method for separate imaging

Our technique:

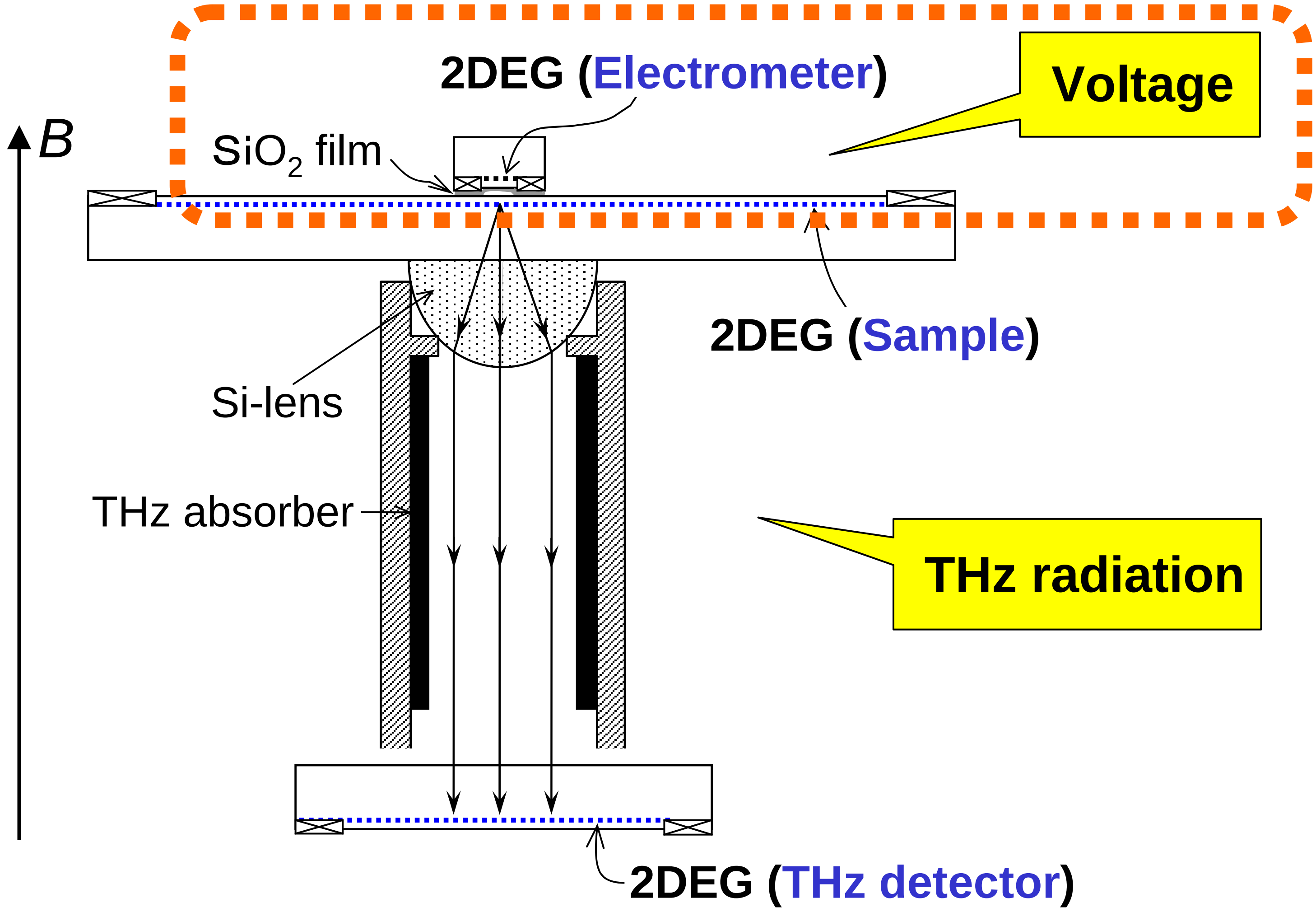
Combination between THz microscope and electrometer

THz imaging --- Spectroscopic information

Voltage imaging --- Transport information

Combined system of a THz microscope and an electrometer

Y. Kawano et al., Phys. Rev. B 70, 081308(R) (2004).



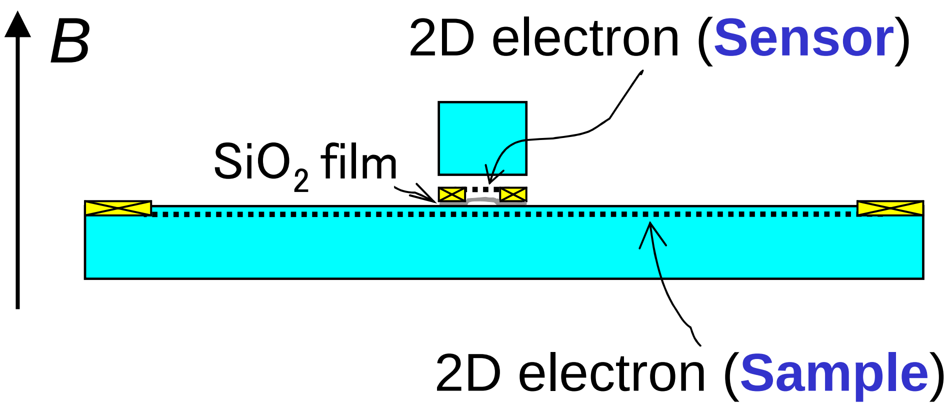
Electrometer, Sample, THz detector:
fabricated from GaAs/AlGaAs heterostructure wafers

Scanning electrometer

Imaging of voltage distributions

Y. Kawano et al., Appl. Phys. Lett. 84, 1111 (2004).
Y. Kawano et al., Appl. Phys. Lett. 87, 252108 (2005).

Setup



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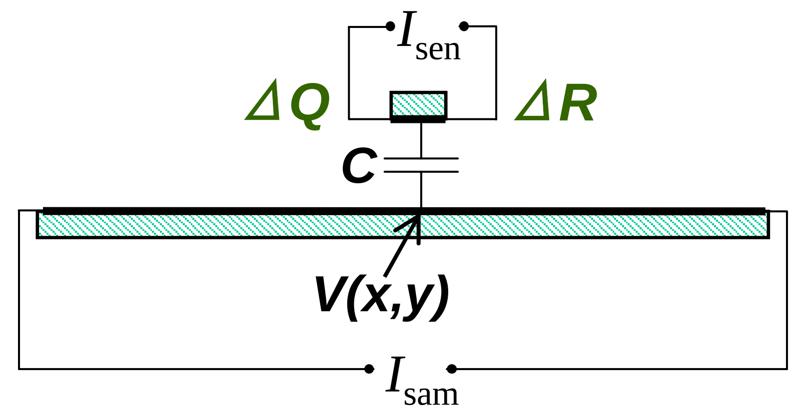
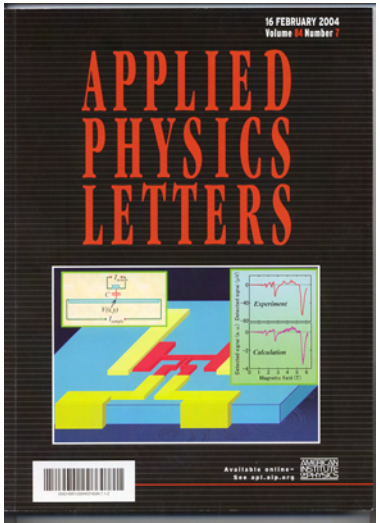
Equivalent circuit



$$CV(x,y) = \Delta Q \longrightarrow \Delta R$$

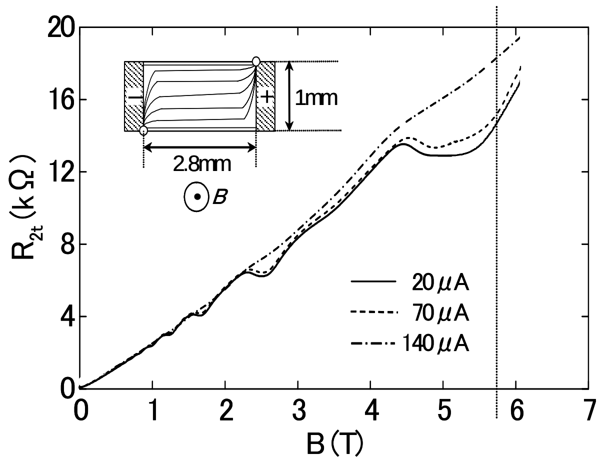


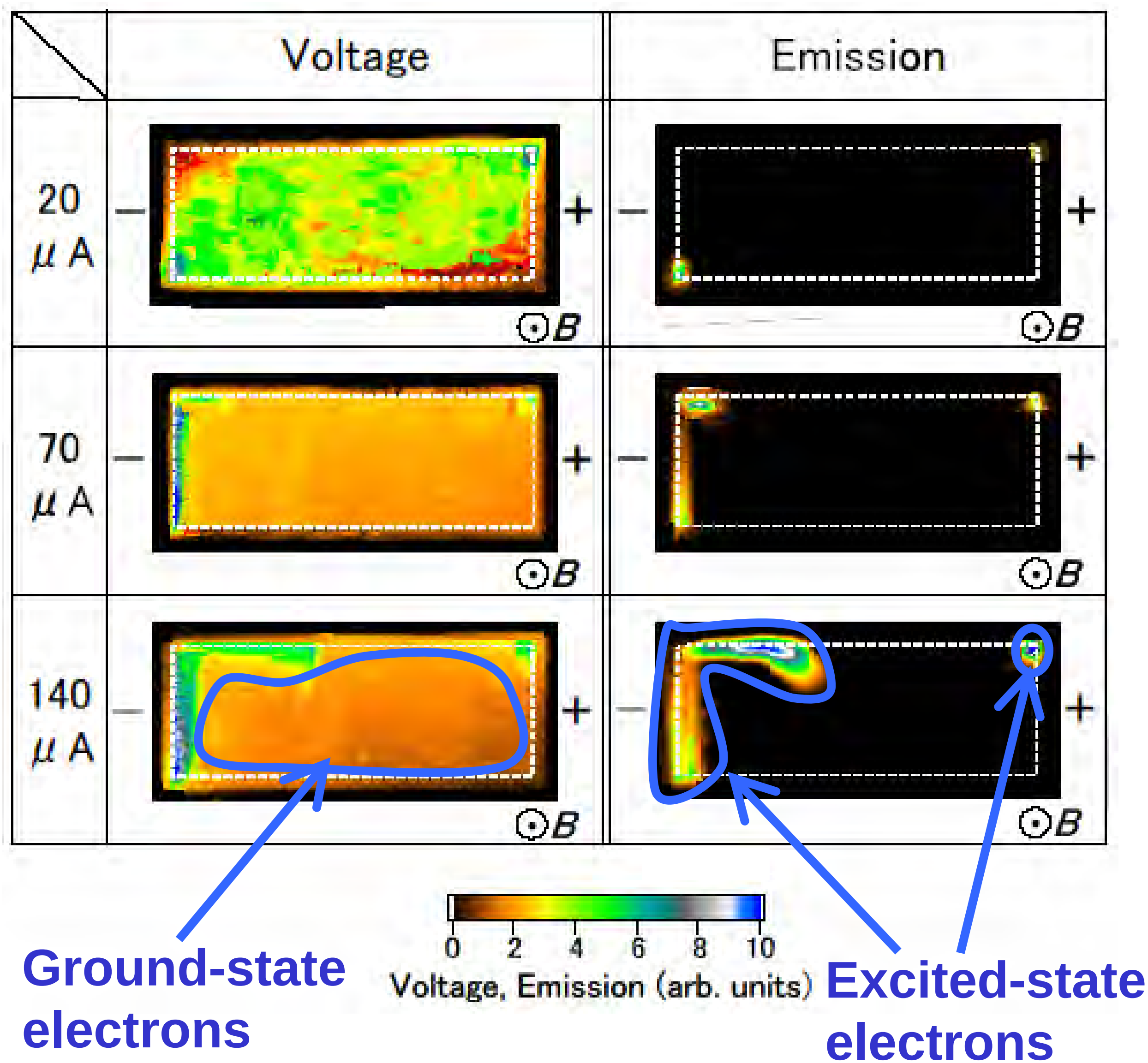
Selected as a cover page of Applied Physics Letters

- **Capacitive coupling between two 2DEGs**
- **Large magnetoresistance oscillation**
  → Highly sensitive detection
- **Low impedance → High speed detection**

Mapping of voltage & THz cyclotron emission

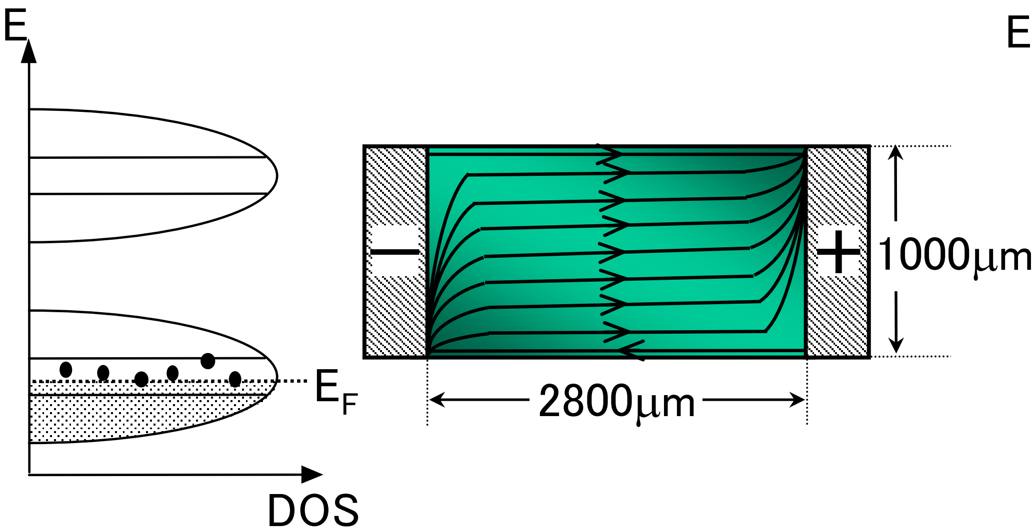
Y. Kawano et al., Phys. Rev. B 70, 081308(R) (2004).





Separate distributions of ground-state and excited-state electrons

- ***Ground-state electrons***

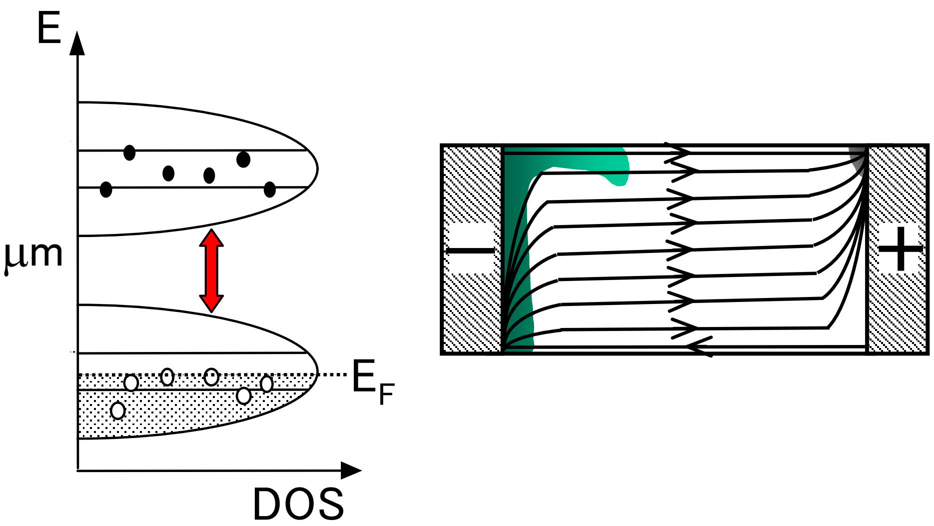


Ionized impurity scattering

Period: <u>0.05～0.2μm</u>

Local behavior

- ***Excited-state electrons***



Acoustic phonon scattering

Drift velocity *E/B* × Scattering time τ

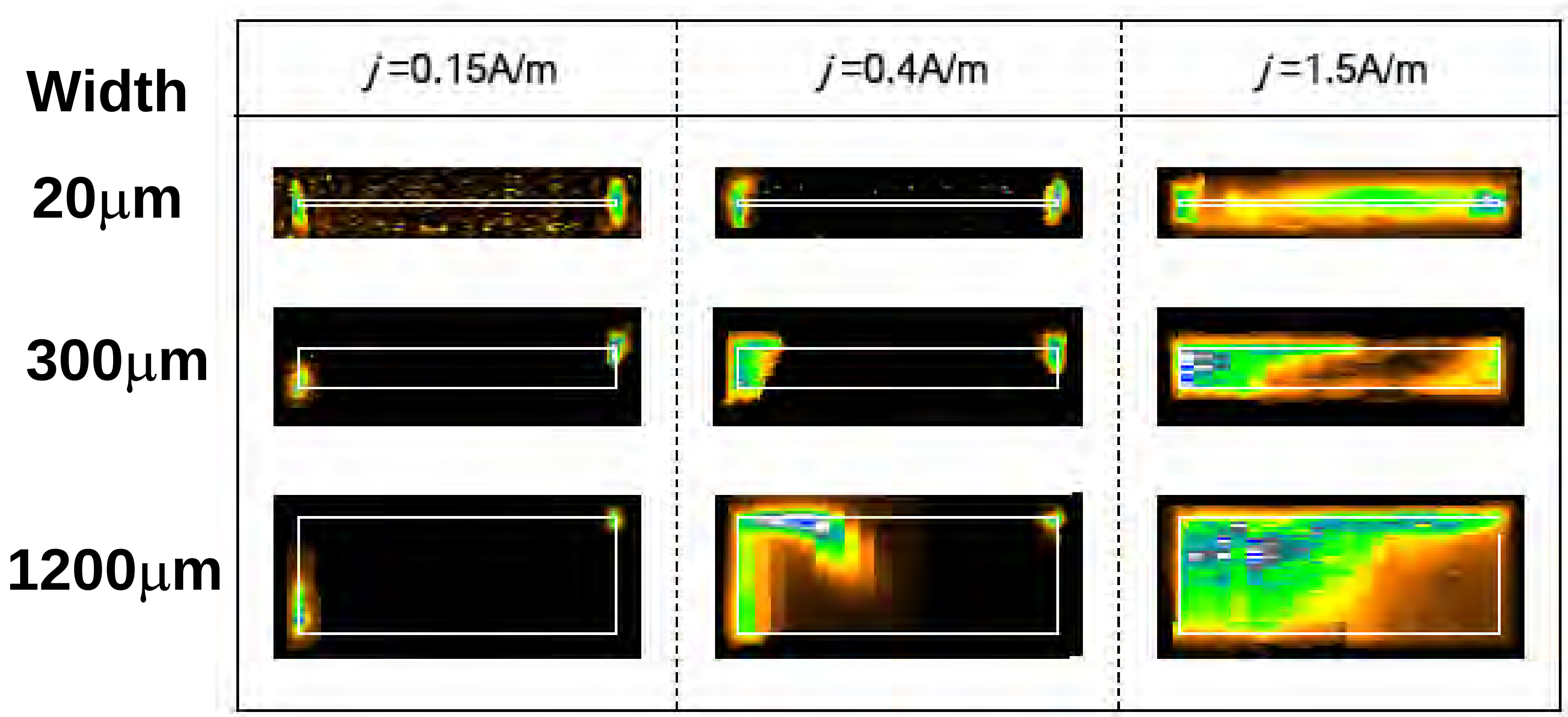
＝3 × 10^3 (m/s) × 10～100 (ns)

＝**<u>30～300μm</u>**

Non-local behavior

Macroscopic size effect of THz emission images

Y. Kawano et al., Phys. Rev. Lett. 95, 166801 (2005).



(Length: 4mm)

Size effect arising from a long equilibrium length of excited electrons

Future perspective：
Research on Graphen with Near-field THz Imaging

2D electron on Graphen

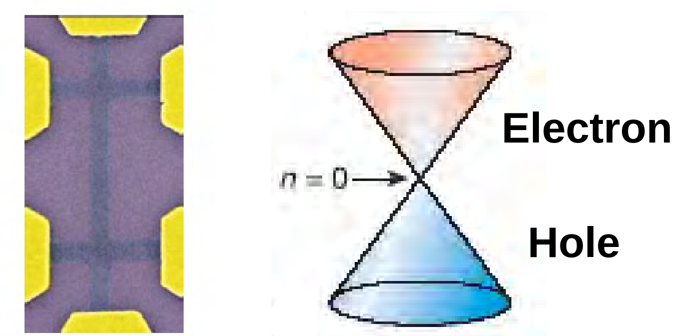
Surface 2D electrons:
compatible with near-field techniques

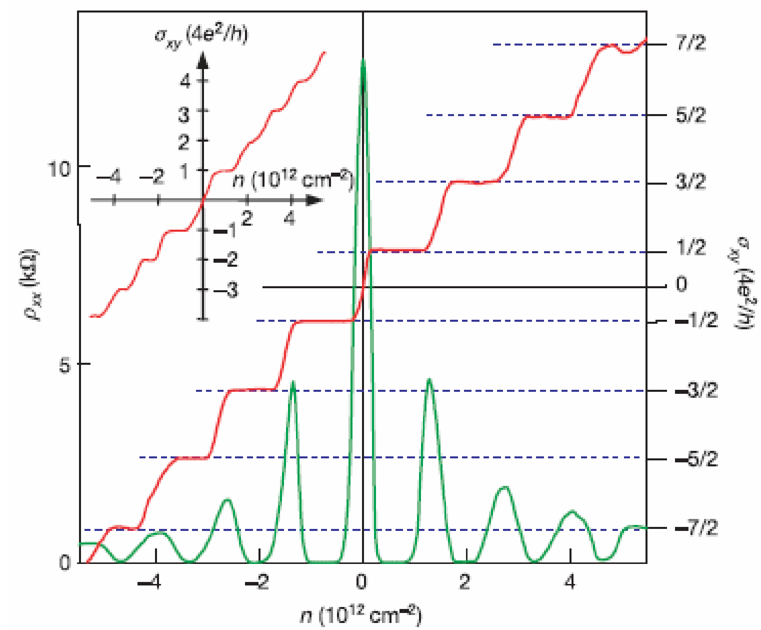
Wide-band energy spectrum
(several to several tens THz)

Dirac particle

Electron-hole symmetry

Direct probing of electron transport and energy dissipation

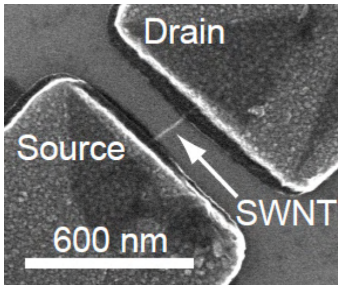


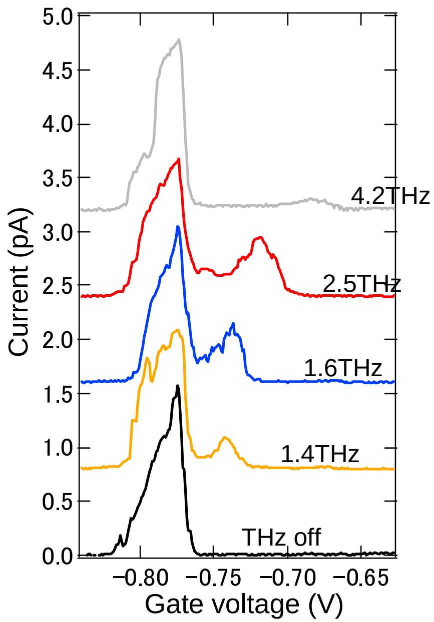


K. S. Novoselov et al., Nature ***438****, 7065 (2005)*

Summary

(1) Carbon nanotube THz detector





(2) On-chip near-field THz probe

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(3) Simultaneous imaging of THz radiation and voltage