Электродинамика двумерных материалов

Муравьев Вячеслав

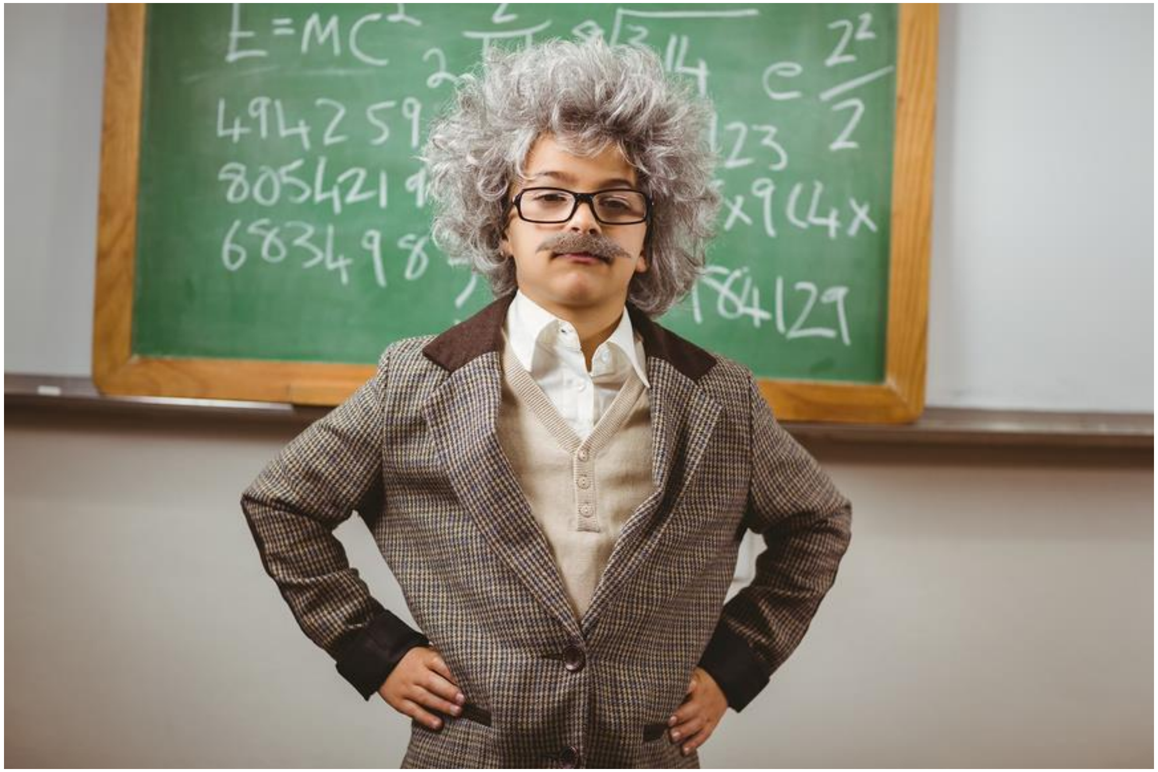
к.ф.-м.н. старший научный сотрудник ИФТТ РАН
CAO TeraSense Group Inc.

ИФТТ РАН
ISSP RAS

ПЛАН ДОКЛАДА

- Зачем заниматься наукой? Введение.
- Пару слов про ИФТТ РАН.
- Трехмерные плазменные колебания.
- Плазменные возбуждения в двумерных электронных системах.
- Новые «проксимити» плазменные возбуждения в двумерных электронных системах.
- **Ваши вопросы.**

SCIENCE



ИФТТ РАН
ISSP RAS

Зачем заниматься наукой?

Наука – это ведущий фактор, который многократно превышает по своему влиянию на жизнь среднего человека иные факторы (политика, оптимизация бизнес процессов, экономика).

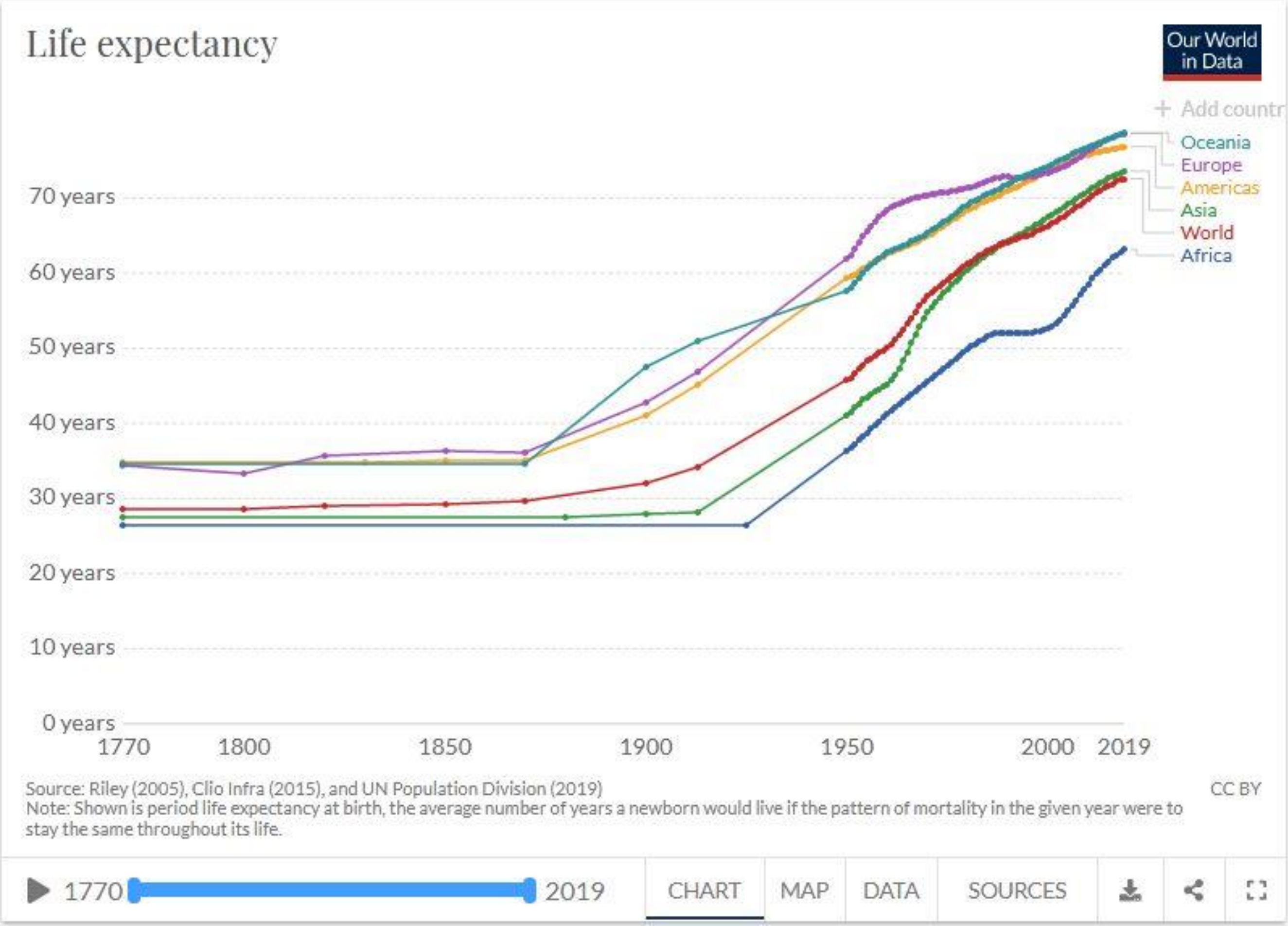
99	Azerbaijan	72.9	75.3	70.3
100	Cabo Verde	72.8	76.0	69.3
100	Solomon Islands	72.8	74.7	71.2
102	Libya	72.7	75.8	69.9
—	**World**	**72.6**	**74.9**	**70.4**
103	Grenada	72.4	74.9	70.1
103	Russia	72.4	77.6	66.9
103	Saint Vincent and the Grenadines	72.4	75.0	70.2
106	Bangladesh	72.3	74.3	70.6
107	Venezuela	72.1	76.1	68.4
108	Ukraine	72.0	76.7	67.0
—	**Arab States**	**71.9**	**73.8**	**70.2**
109	Egypt	71.8	74.2	69.6
109	Moldova	71.8	76.1	67.5
109	Syria	71.8	77.8	66.6

30	Liechtenstein	80.5		
31	Costa Rica	80.1	82.7	77.5
32	Chile	80.0	82.4	77.6
33	Czech Republic	79.2	81.8	76.6
34	Barbados	79.1	80.4	77.7
35	Lebanon	78.9	80.8	77.1
35	United States	78.9	81.4	76.3
37	Cuba	78.6	80.6	76.7
38	Poland	78.5	82.4	74.6
39	Panama	78.3	81.6	75.2
39	Croatia	78.3	81.5	75.1
41	United Arab Emirates	77.8	79.2	77.1
41	Uruguay	77.8	81.4	74.0
43	Oman	77.6	80.1	75.9

Разница в продолжительности жизни 13%

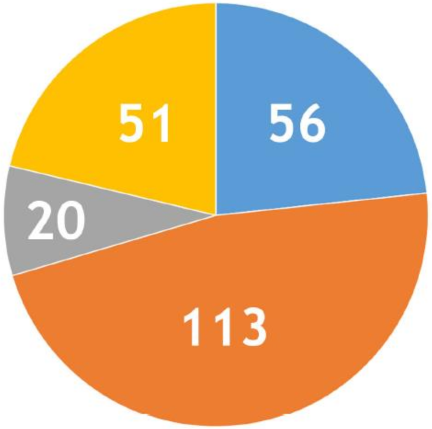
Зачем заниматься наукой?

Продолжительность жизни за последние 200 лет увеличилась в 2 раза.



ИФТТ РАН ISSP RAS

Про ИФТТ РАН



Данные за 2015 г.

440 сотрудников

240 научных сотрудников (из них 82 в возрасте до 40 лет)

- 56 докторов наук
- 113 кандидатов наук
- 20 аспирантов
- 51 ассистент

За 2015 год сотрудниками института опубликовано 320 статей в ведущих международных и отечественных научных журналах: Science, Nature, Physical Review, Scientific Reports, Applied Physics Letters, Physica, Surface Science, Physica Status Solidi, Успехи физических наук, Письма в ЖЭТФ и другие.

ОТЗЫВЫ ВЫПУСКНИКОВ КАФЕДРЫ:

Лауреат Нобелевской премии 2010 г.

Андрей Гейм

Выпускник кафедры 1982 года, Профессор Манчестерского университета (Великобритания).

«Охотно принимаю и готов принимать в будущем в свою лабораторию выпускников кафедры ФТТ, уровень подготовки которых, по-прежнему, очень высок.»

Премия общества Макса Планка 2001 г.

Игорь Кукушкин

Выпускник кафедры физики твердого тела 1984 г. Доктор физ.-мат. наук, профессор, член-корр. РАН, главный научный сотрудник ИФТТ РАН.

«Трудно перечислить всех замечательных Ученых, с которыми мне посчастливилось общаться в Черноголовке, поскольку в этом месте, наверное, самая высокая в мире плотность интеллекта на единицу площади. Кроме уникальной возможности общения с умными людьми и профессиональными учеными, в ИФТТ собраны самые современные установки, так что остается просто прийти и реализовать практически любую интересную идею. Приходите и реализуйте свой потенциал!»

Про ИФТТ РАН

Государственная премия РФ им. Зворыкина 2008 г.

Алексей Устинов

Выпускник кафедры 1984 года, Профессор Технологического института Карлсруэ (Германия).

«Великолепное место для развития своих научных талантов и идей. Рекомендую кафедру физики твердого тела всем интересующимся физикой студентам!»

ИФТТ РАН ISSP RAS

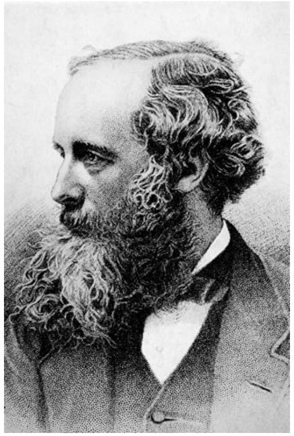
ELECTROMAGNETISM

$$\nabla \cdot \mathbf{D} = \rho$$

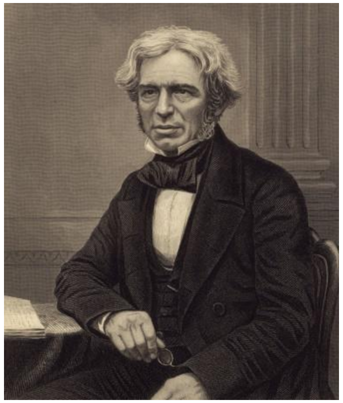
$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$



James Maxwell

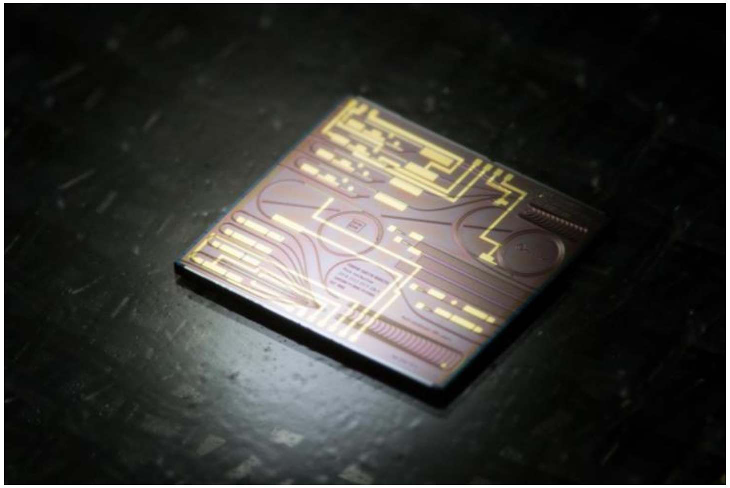


Michael Faraday

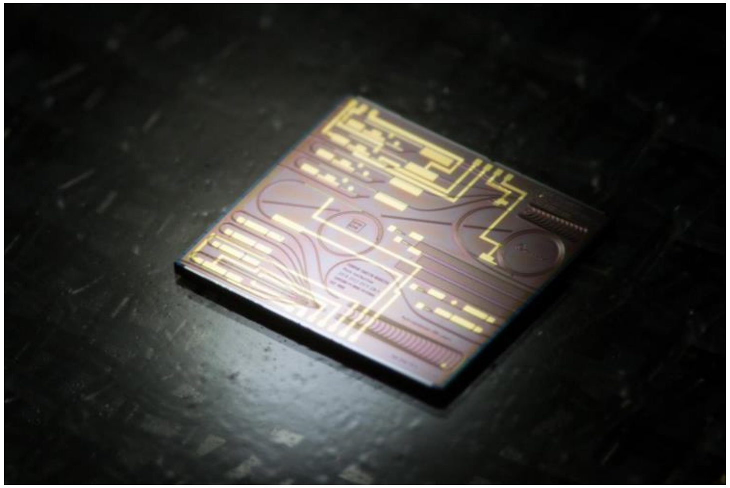
Heinrich Hertz

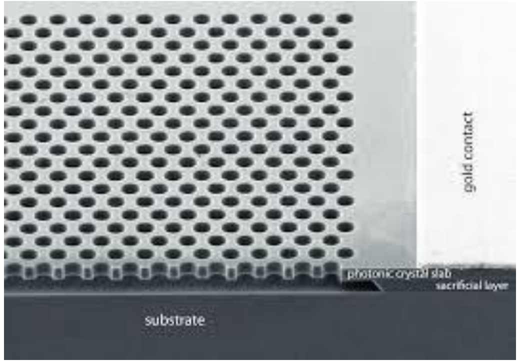
ИФТТ РАН
ISSP RAS

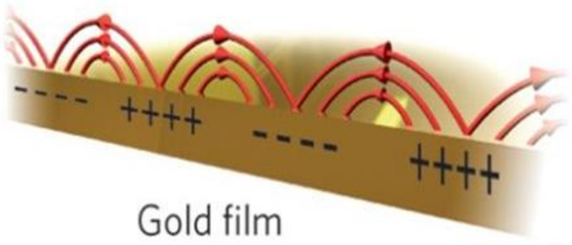
2D ELECTROMAGNETISM – PHOTONIC INTEGRATED CIRCUITS



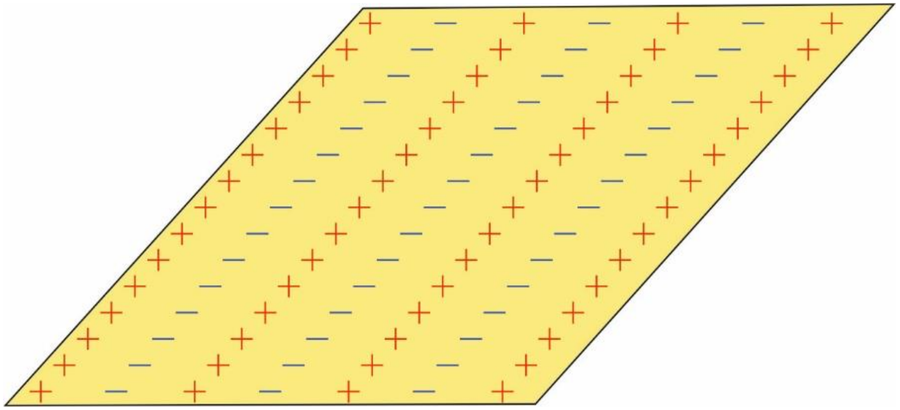
2D ELECTROMAGNETISM – PHOTONIC INTEGRATED CIRCUITS

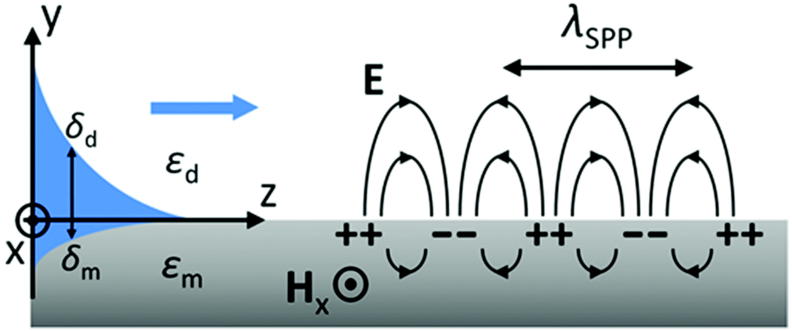




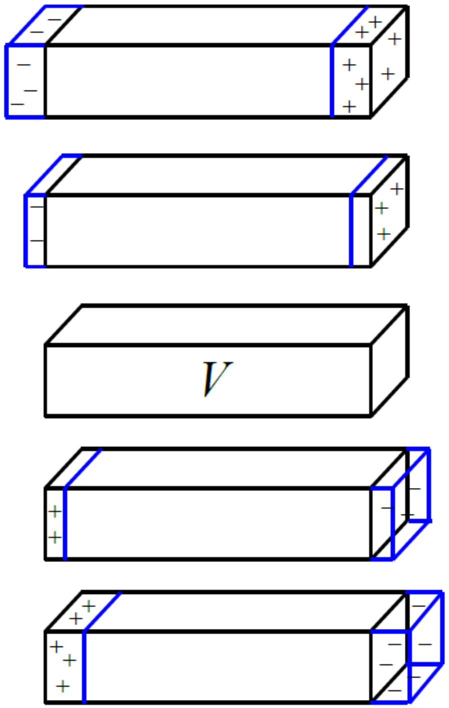


PLASMONS AS A PLAYGROUND TO STUDY
2D ELECTROMAGNETISM



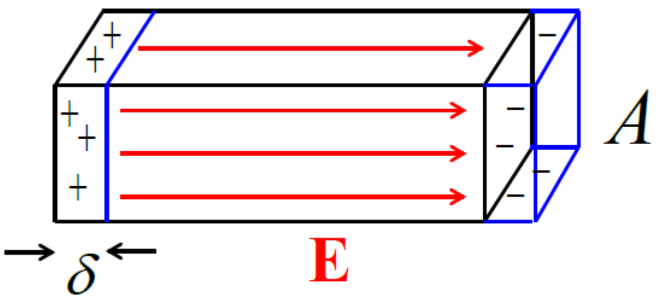


3D PLASMA OSCILLATIONS



A slab of electrons moving back and forth on top of
a slab of neutralizing positive charge: **plasma oscillations**.

3D PLASMA OSCILLATIONS



Total charge on one side:

$$enA\delta$$

Uniform electric field caused by surface charge: $E = 4\pi en\delta$

Total force on all electrons: $F = enVE = -4\pi n^2 e^2 V\delta$

Set force equal to total mass times acceleration: $F = M\ddot{\delta}$

$$-4\pi n^2 e^2 V\delta = mnV\ddot{\delta} \quad \Rightarrow \quad \ddot{\delta} = -\frac{4\pi ne^2}{m}\delta$$

Plasma frequency: $\omega_{pl}^2 = \dfrac{4\pi ne^2}{m}$

3D PLASMON

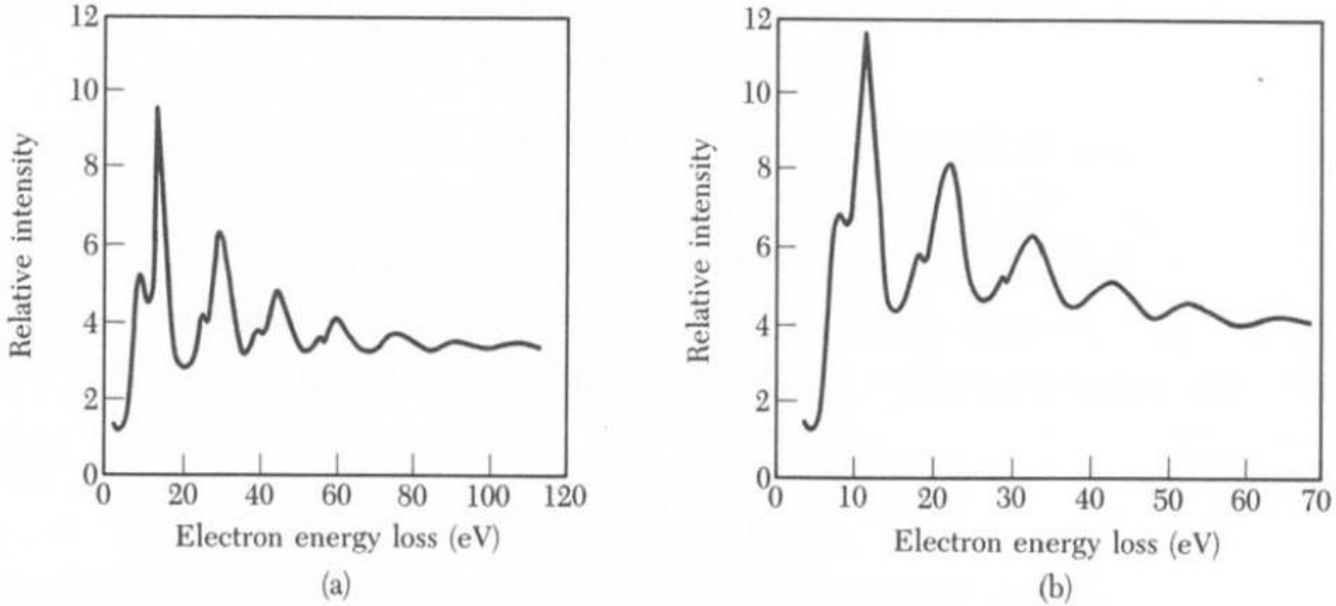
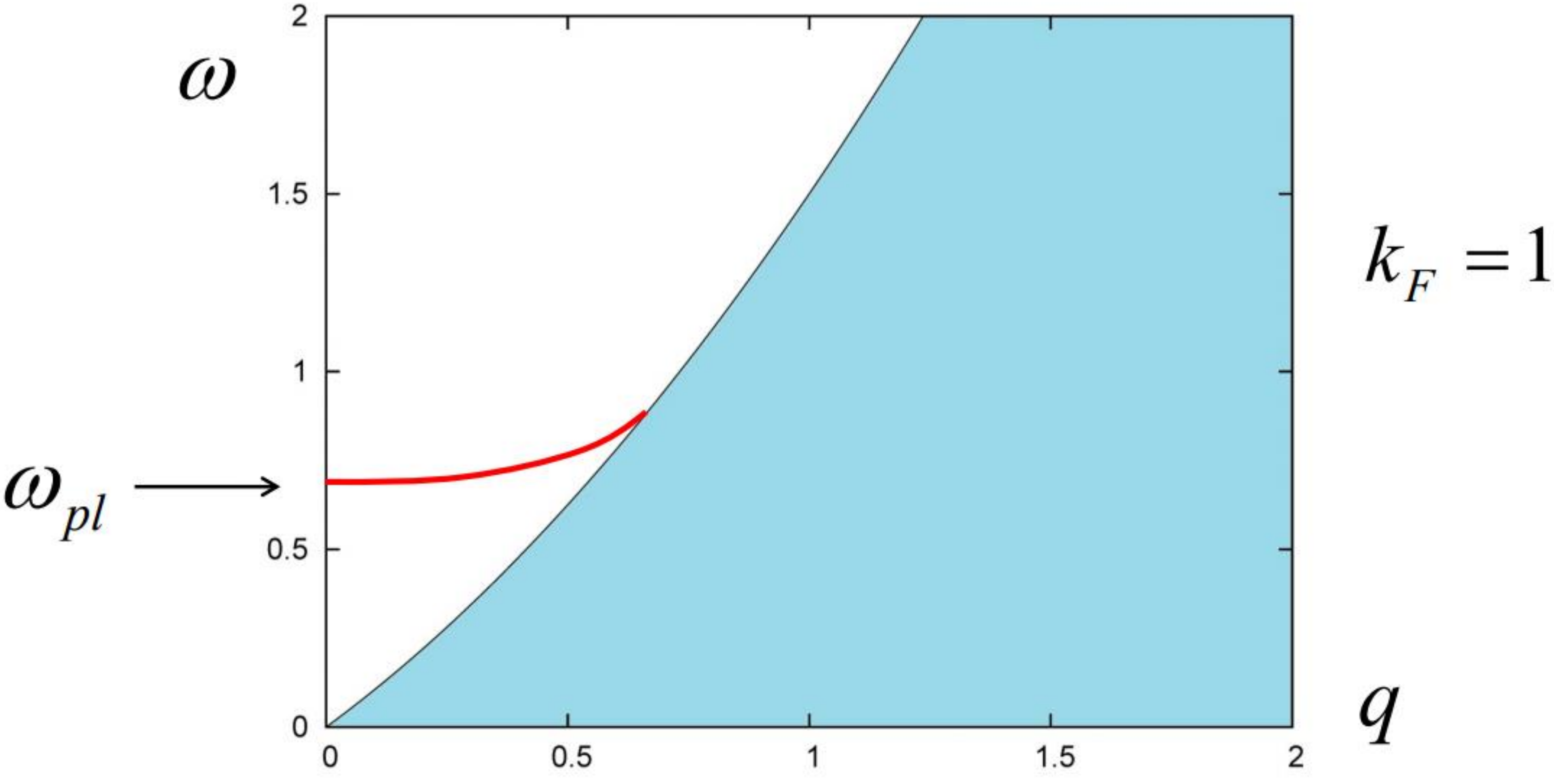


Figure 8 Energy loss spectra for electrons reflected from films of (a) aluminum and (b) magnesium, for primary electron energies of 2020 eV. The 12 loss peaks observed in Al are made up of combinations of 10.3 and 15.3 eV losses, where the 10.3 eV loss is due to surface plasmons and the 15.3 eV loss is due to volume plasmons. The ten loss peaks observed in Mg are made up of combinations of 7.1 eV surface plasmons and 10.6 eV volume plasmons. Surface plasmons are the subject of Problem 1. (After C. J. Powell and J. B. Swan.)

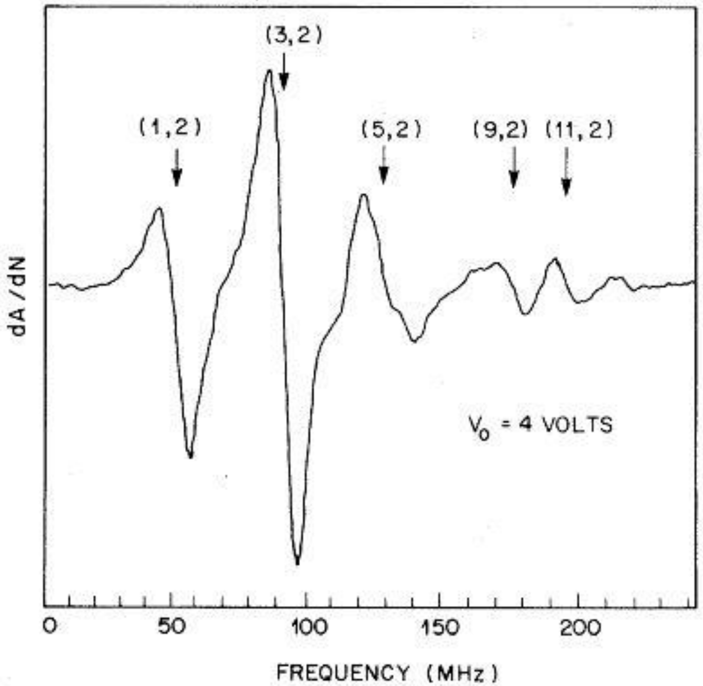
ИФТТ РАН
ISSP RAS

3D PLASMON



ИФТТ РАН
ISSP RAS

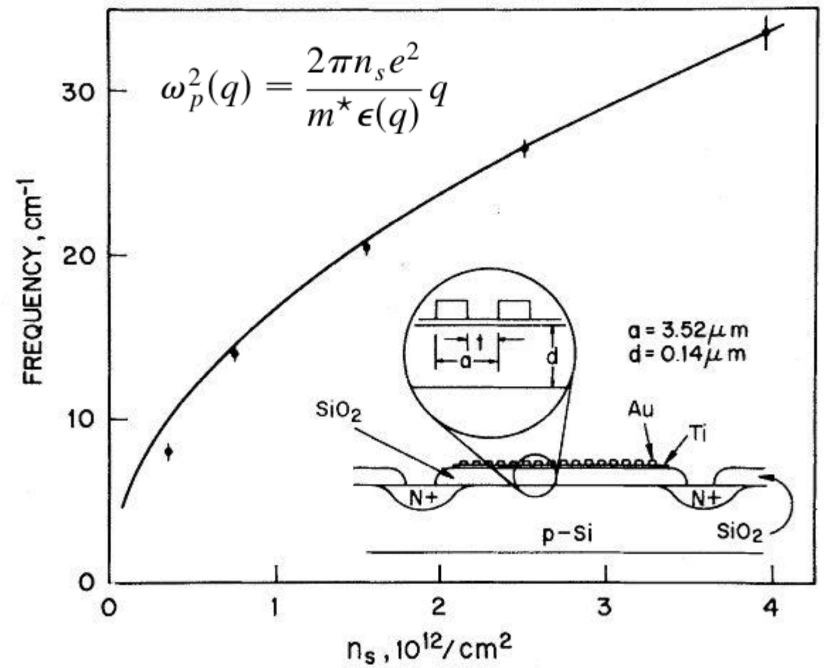
2D PLASMONS – EXPERIMENTAL DISCOVERY



VOLUME 36, NUMBER 3 PHYSICAL REVIEW LETTERS 19 JANUARY 1976

Observation of Two-Dimensional Plasmons and Electron-Ripplon Scattering in a Sheet of Electrons on Liquid Helium

C. C. Grimes and Gregory Adams
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 12 November 1975)

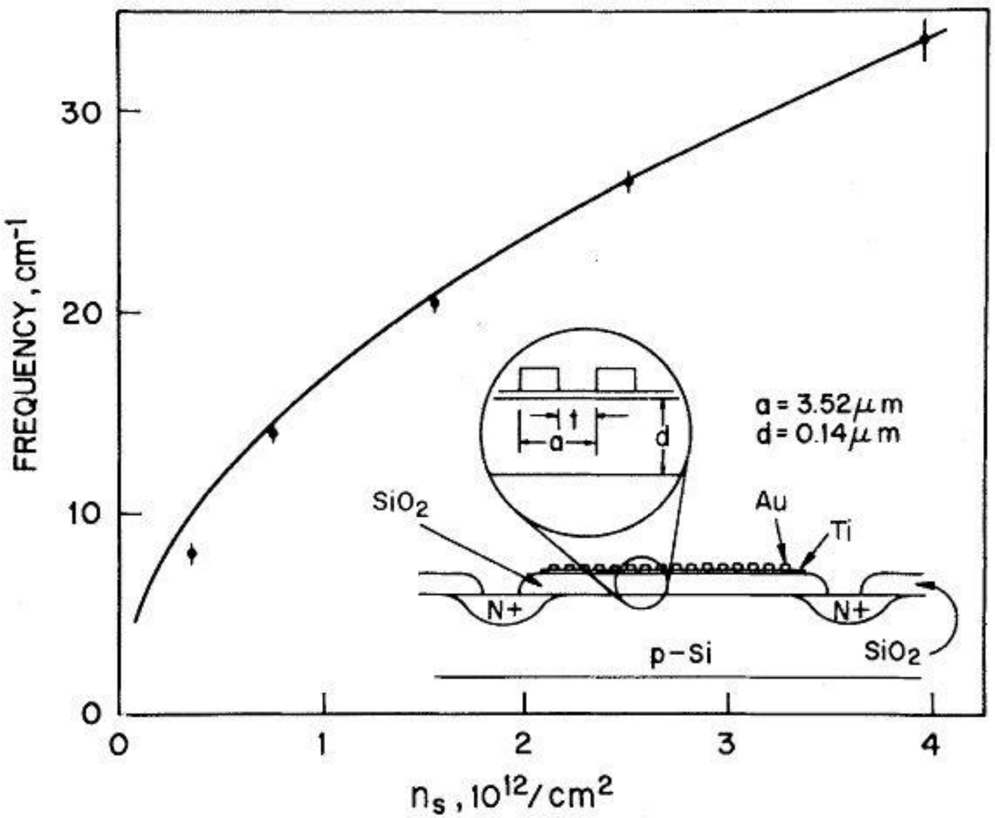


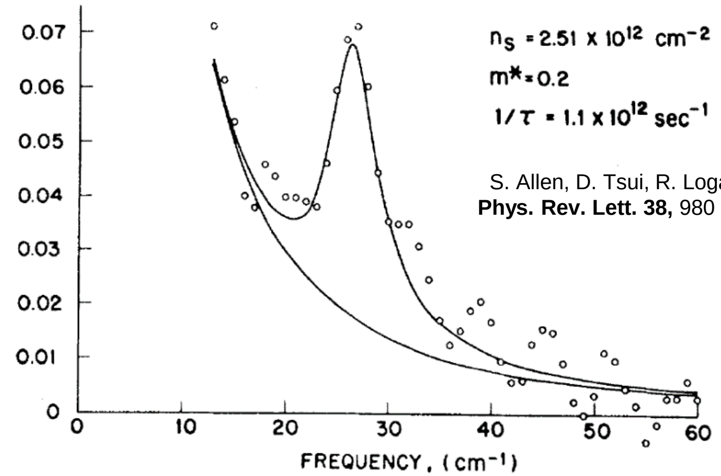
VOLUME 38, NUMBER 17 PHYSICAL REVIEW LETTERS 25 APRIL 1977

Observation of the Two-Dimensional Plasmon in Silicon Inversion Layers

S. J. Allen, Jr., D. C. Tsui, and R. A. Logan
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 18 March 1977)

2D PLASMONS SPECTRUM

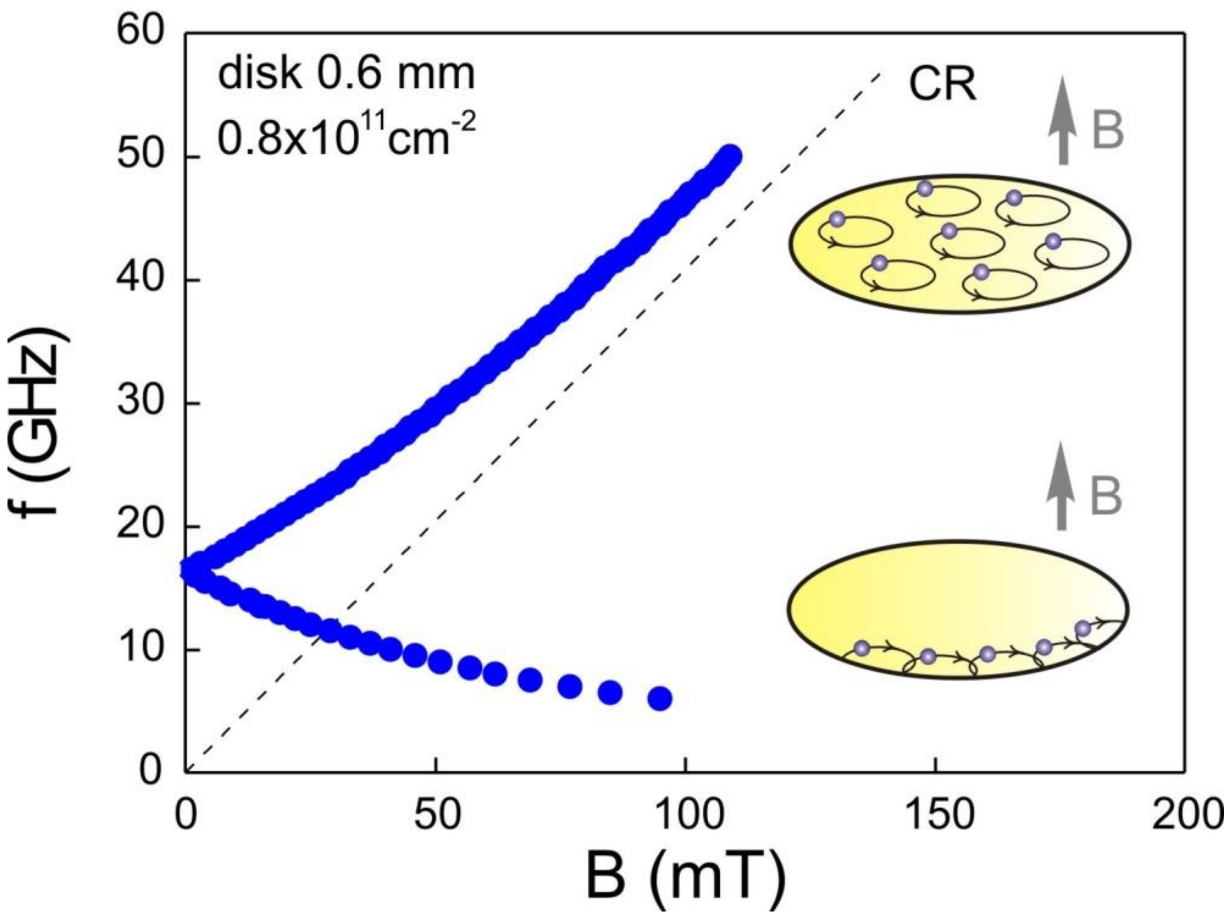




S. Allen, D. Tsui, R. Logan,
Phys. Rev. Lett. 38, 980 (1977)

$$\omega_p^2(q) = \frac{n_s e^2}{2m^\star \epsilon_0 \epsilon(q)} q.$$

ИФТТ РАН
ISSP RAS

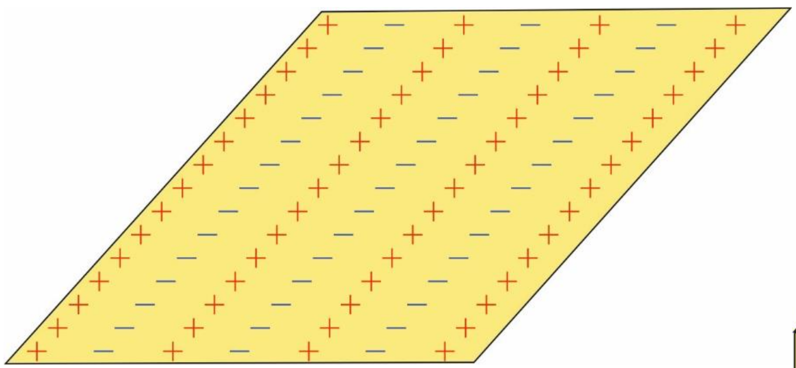


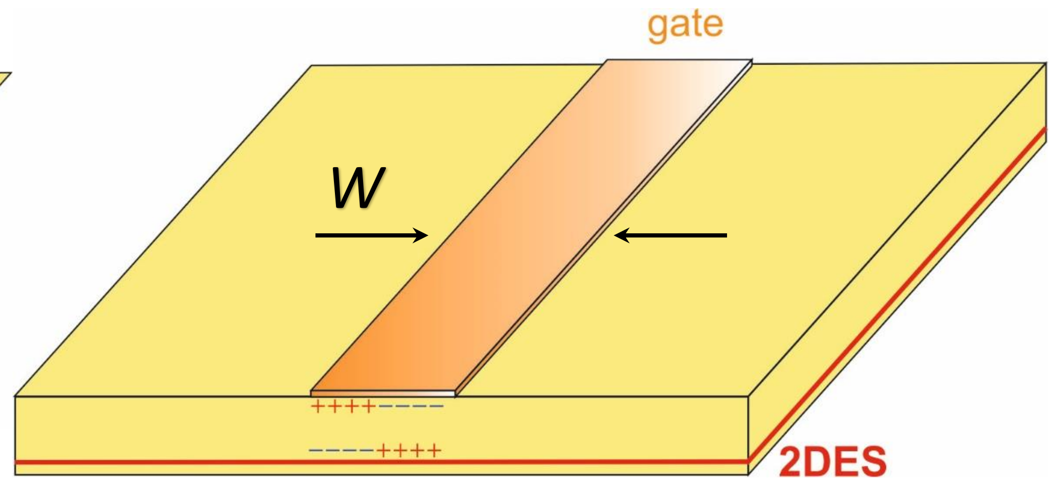
ИФТТ РАН
ISSP RAS

2D PLASMONS

$$\omega_{\mathrm{p}}(q) = \sqrt{\frac{n_s e^2}{2m^* \varepsilon \varepsilon_0} q}$$

$$\omega_g(q) = \sqrt{\frac{n_s e^2 h}{m^* \varepsilon \varepsilon_0} q} \qquad (qh \ll 1)$$

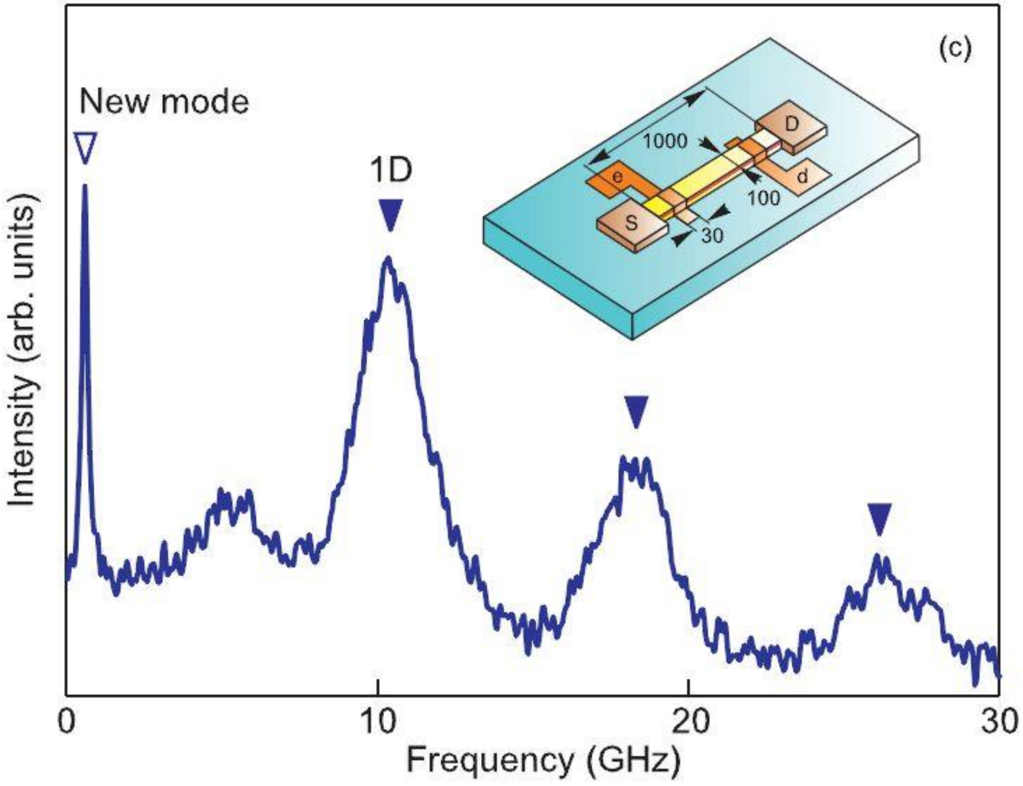




$$q_{\mathrm{tr}} = N \frac{\pi}{W} \qquad (N = 1, 2, \ldots)$$

ИФТТ РАН
ISSP RAS

NEW 2D PLASMA MODES



PRL **114,** 106805 (2015) PHYSICAL REVIEW LETTERS week ending 13 MARCH 2015

Novel Relativistic Plasma Excitations in a Gated Two-Dimensional Electron System

V. M. Muravev, P. A. Gusikhin, I. V. Andreev, and I. V. Kukushkin
Institute of Solid State Physics, RAS, Chernogolovka 142432, Russia
(Received 3 November 2014; revised manuscript received 21 January 2015; published 10 March 2015)

ИФТТ РАН
ISSP RAS

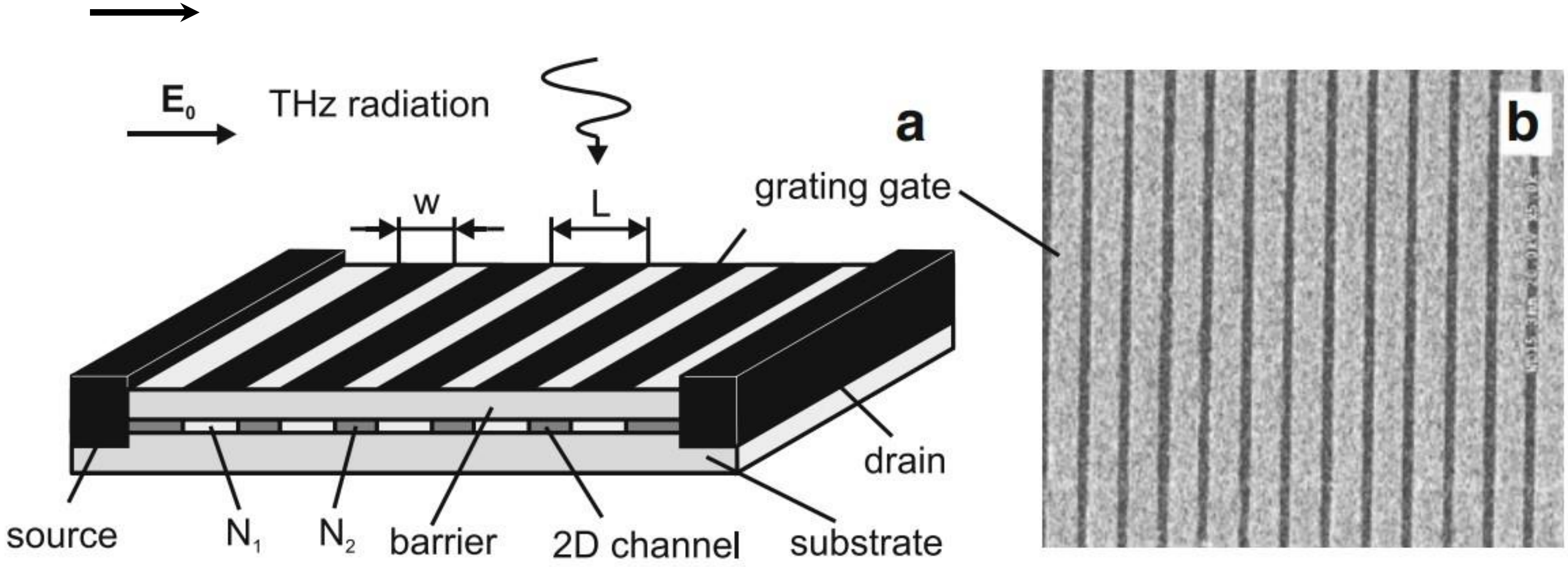
PHYSICAL NATURE

What is the physical origin of the phenomenon?

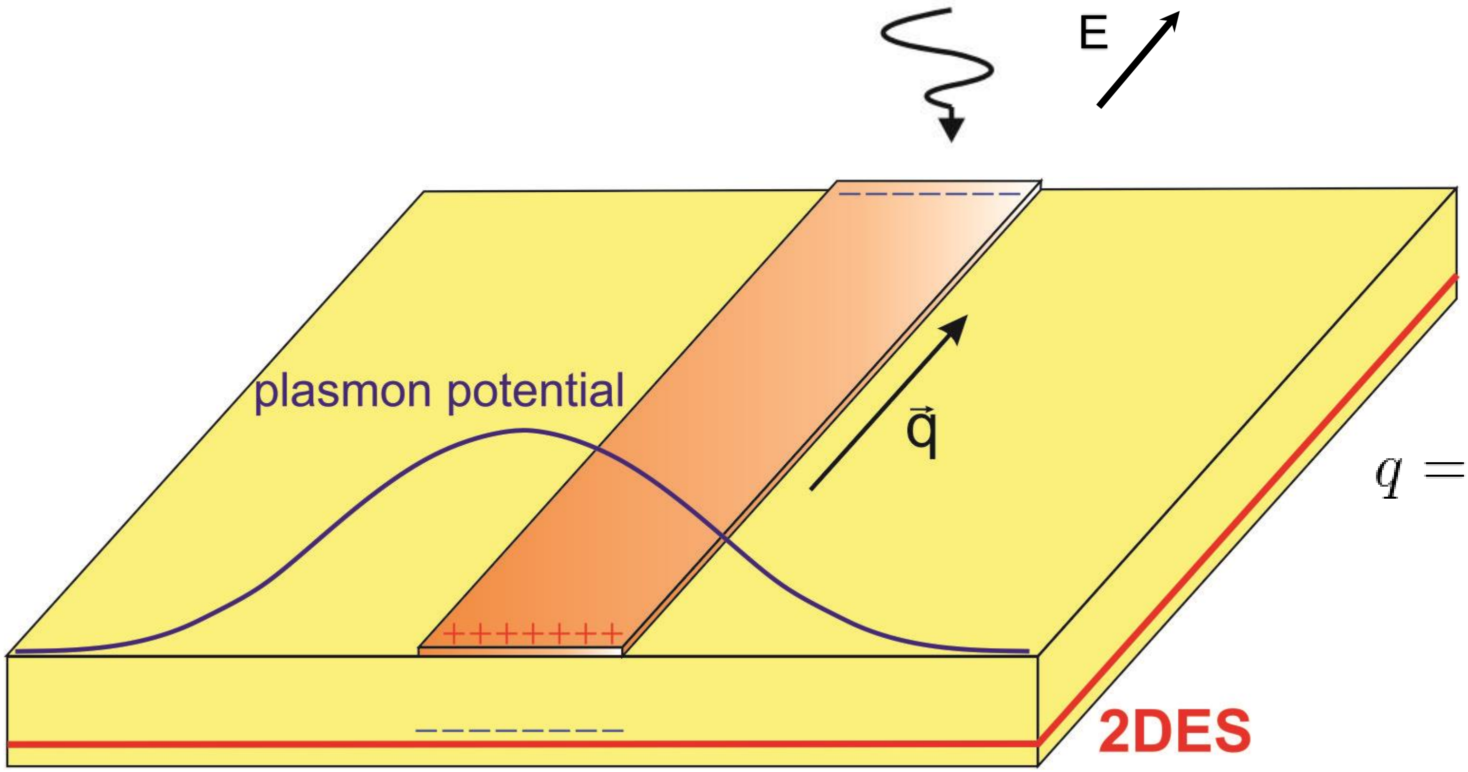
ИФТТ РАН
ISSP RAS

2D PLASMONS – EXPERIMENTAL DISCOVERY

Wave Vector (q)



LOST MODE: PROXIMITY PLASMON



$$q = \frac{\pi}{L} N$$

$$q_{\mathrm{tr}} = N \frac{\pi}{W} \; (N = 0)$$

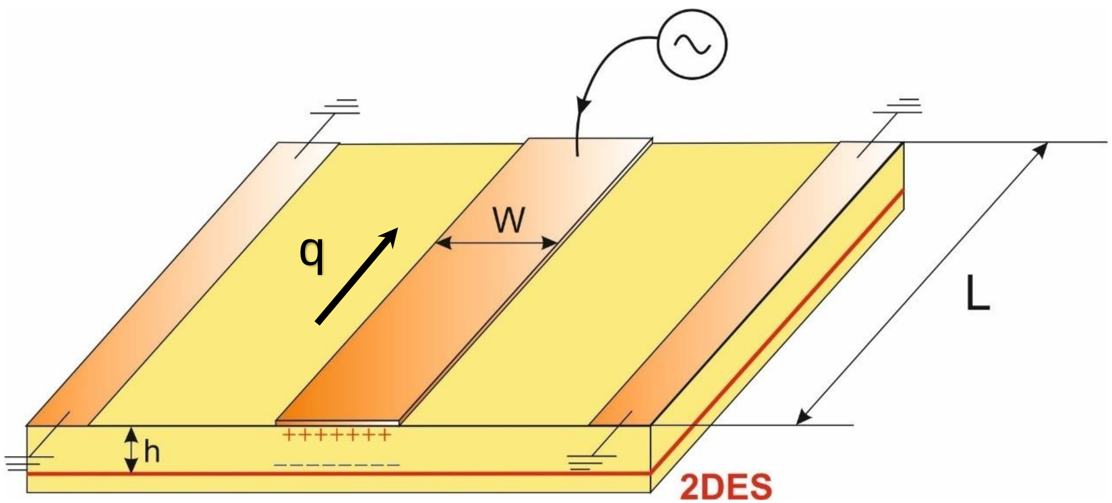
PROXIMITY PLASMON

PHYSICAL REVIEW B **99**, 165304 (2019)

Interaction of gated and ungated plasmons in two-dimensional electron systems

A. A. Zabolotnykh and V. A. Volkov*
Kotelnikov Institute of Radio-engineering and Electronics of the RAS, Mokhovaya 11-7, Moscow 125009, Russia and Moscow Institute of Physics and Technology, Institutskii per. 9, Dolgoprudny, Moscow region 141700, Russia

(Received 25 December 2018; published 8 April 2019)



$$\omega_{\mathrm{pr}}(q) = \sqrt{\frac{2n_s e^2 h}{m^* \varepsilon \varepsilon_0} \frac{q}{W}}$$

$$(qW \ll 1) \qquad q_{\mathrm{tr}} = 0$$

$$q = \frac{\pi}{L} N \quad (N = 1, 2, \ldots)$$

ИФТТ РАН
ISSP RAS

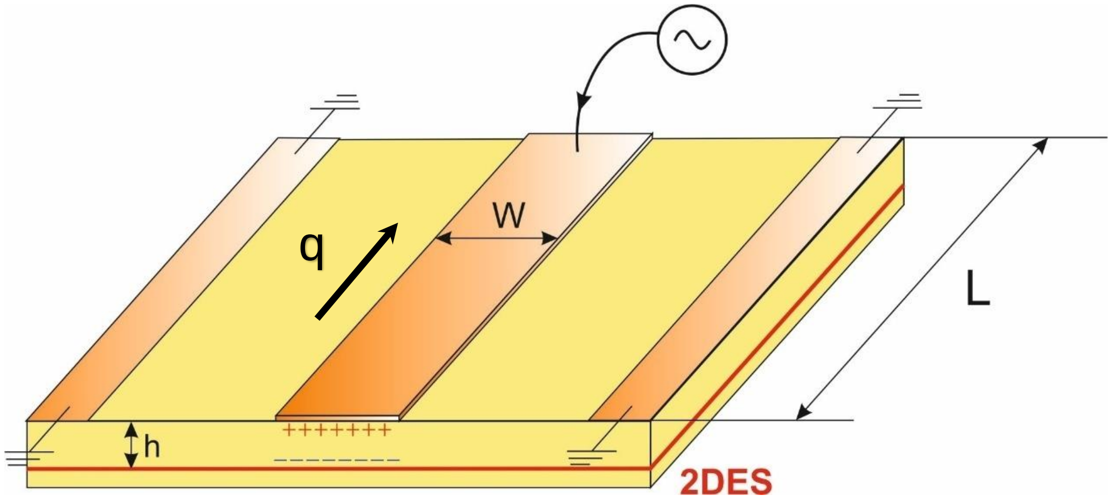
PROXIMITY PLASMON

PHYSICAL REVIEW B **99**, 165304 (2019)

Interaction of gated and ungated plasmons in two-dimensional electron systems

A. A. Zabolotnykh and V. A. Volkov*
Kotelnikov Institute of Radio-engineering and Electronics of the RAS, Mokhovaya 11-7, Moscow 125009, Russia
and Moscow Institute of Physics and Technology, Institutskii per. 9, Dolgoprudny, Moscow region 141700, Russia

(Received 25 December 2018; published 8 April 2019)



$$\omega_{\rm pr}(q) = \sqrt{\frac{2n_s e^2 h}{m^* \varepsilon \varepsilon_0}\frac{q}{W}}$$

$$\omega_p \propto \sqrt{q}$$

UNGATED PLASMON

ИФТТ РАН
ISSP RAS

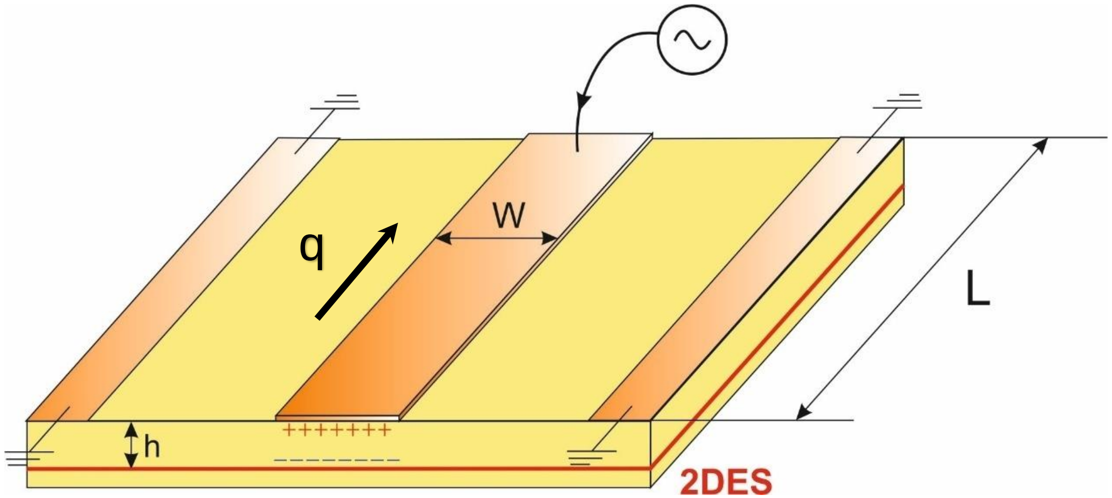
PROXIMITY PLASMON

PHYSICAL REVIEW B **99**, 165304 (2019)

Interaction of gated and ungated plasmons in two-dimensional electron systems

A. A. Zabolotnykh and V. A. Volkov*
Kotelnikov Institute of Radio-engineering and Electronics of the RAS, Mokhovaya 11-7, Moscow 125009, Russia and Moscow Institute of Physics and Technology, Institutskii per. 9, Dolgoprudny, Moscow region 141700, Russia

(Received 25 December 2018; published 8 April 2019)



$$\omega_{\mathrm{pr}}(q) = \sqrt{\frac{2n_s e^2 h}{m^* \varepsilon \varepsilon_0} \frac{q}{W}}$$

$$\omega_p \propto \sqrt{q}$$

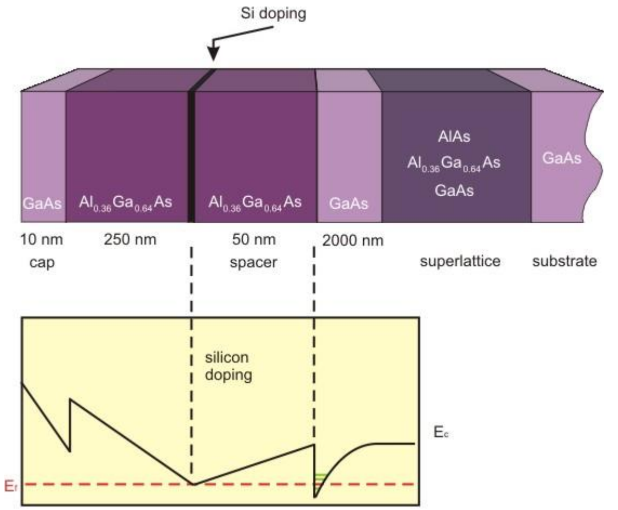
UNGATED PLASMON

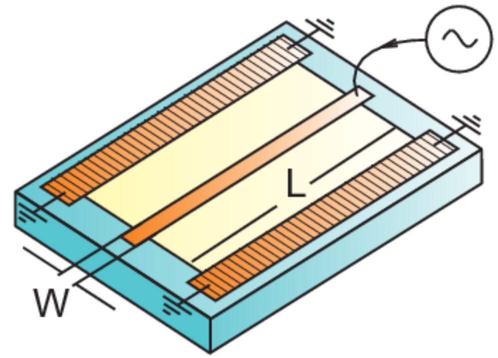
$$\omega_g \propto \sqrt{h}$$

GATED PLASMON

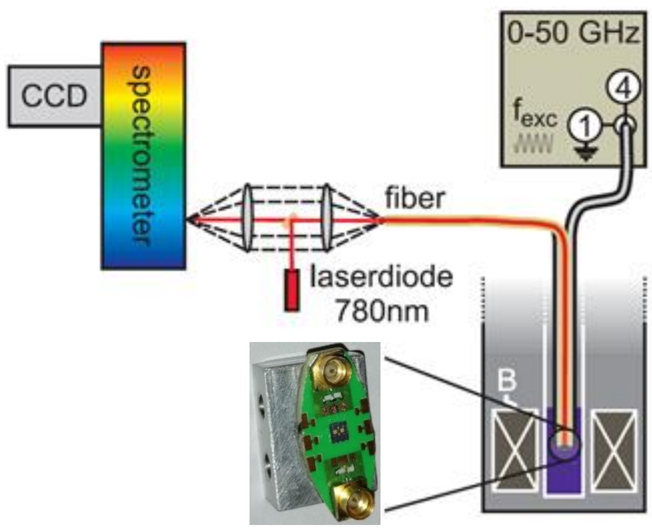
ИФТТ РАН ISSP RAS

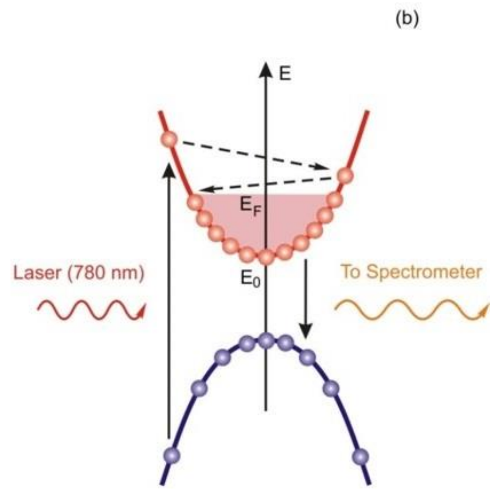
SAMPLES and METHODS

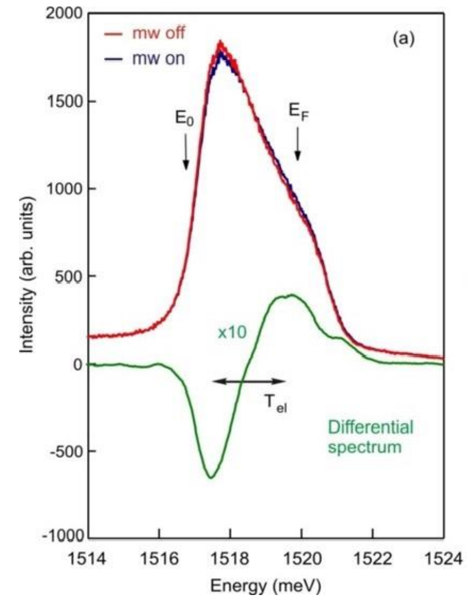




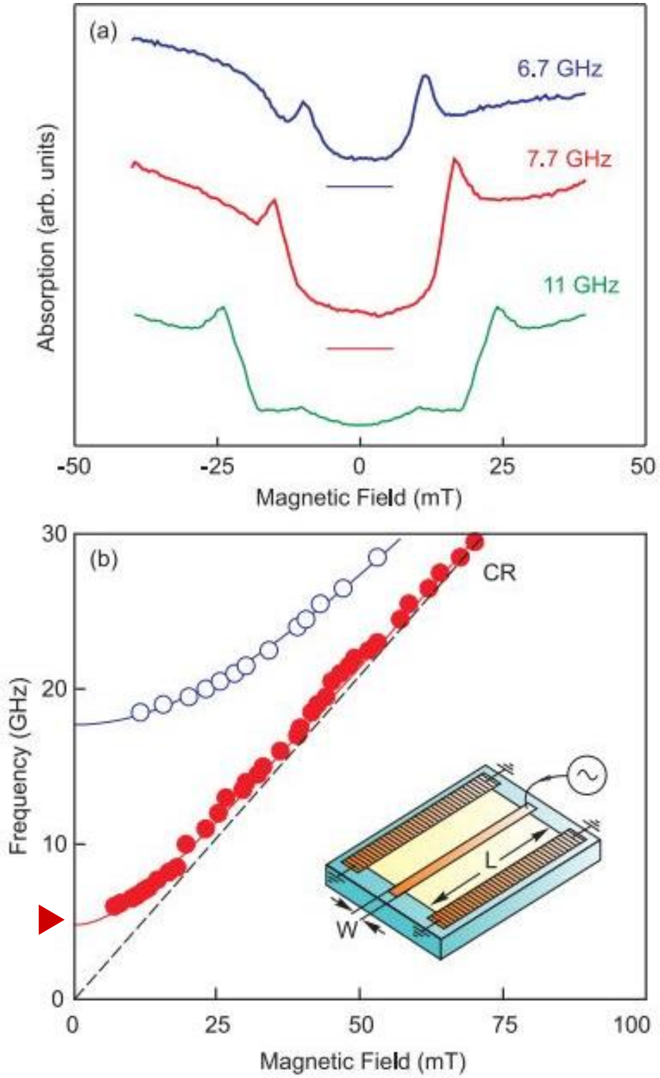
$$L = 0.5,\ 1.0,\ 1.7\ \mathrm{mm}$$
$$W = 20,\ 50,\ 100\ \mu\mathrm{m}$$







EXPERIMENTAL RESULTS

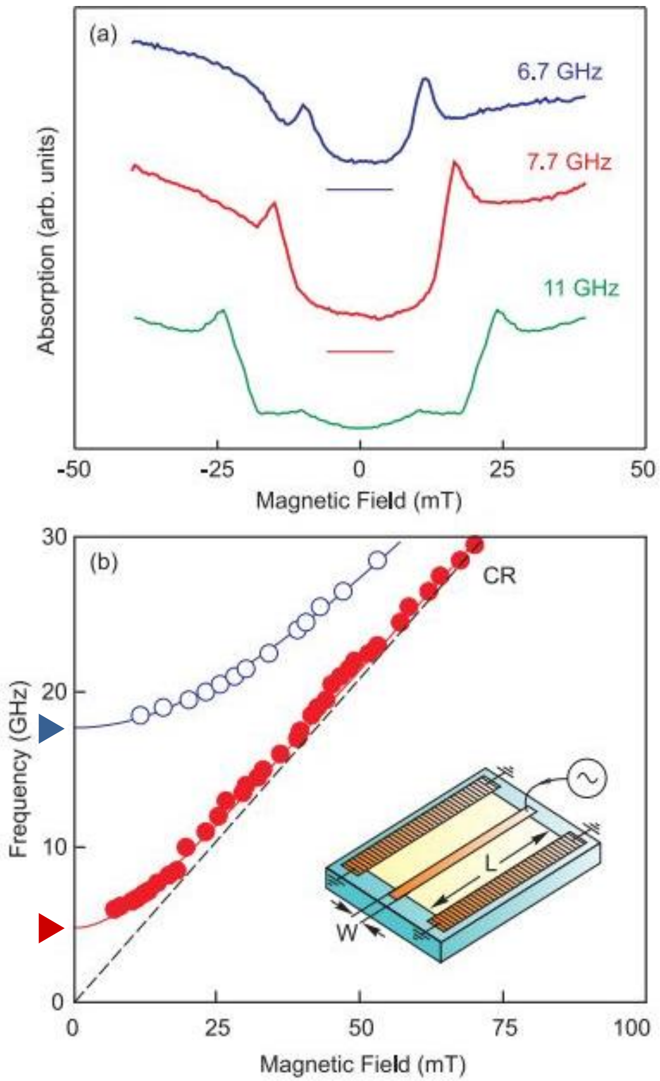


Fundamental mode (N=0)

$$\omega_{\text{pr}}(q) = \sqrt{\frac{2n_s e^2 h}{m^* \varepsilon \varepsilon_0} \frac{q}{W}} \qquad (qW \ll 1)$$

ИФТТ РАН
ISSP RAS

EXPERIMENTAL RESULTS



Fundamental mode (N=0)

- $$\omega_{pr}(q) = \sqrt{\frac{2n_s e^2 h}{m^* \varepsilon \varepsilon_0} \frac{q}{W}} \qquad (qW \ll 1)$$

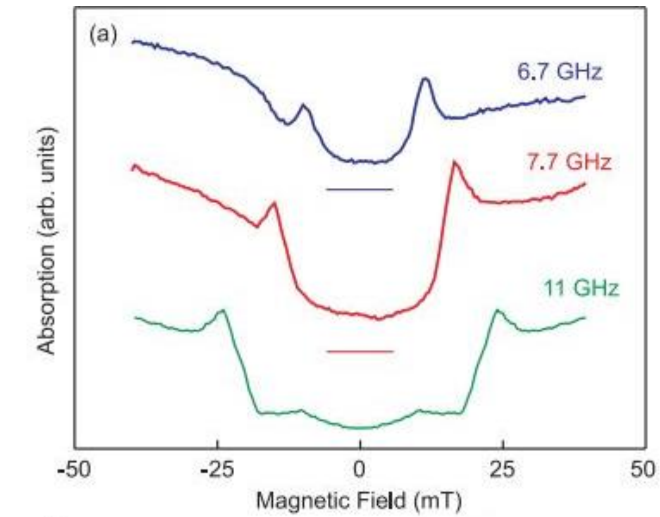
Mode with N=2

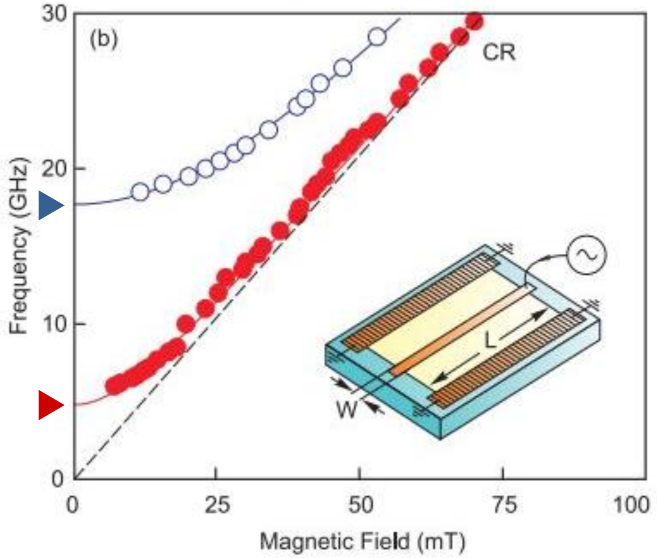
- $$\omega^2 = \omega_g(q_{tr})^2 + \omega_{pr}(q)^2 = \frac{n_s e^2 h}{m^* \varepsilon \varepsilon_0} \left(q_{tr}^2 + \frac{4}{W} q \right)$$

$$q_{tr} = N \frac{\pi}{W} \qquad N = 2$$

ИФТТ РАН
ISSP RAS

EXPERIMENTAL RESULTS





Fundamental mode (N=0)

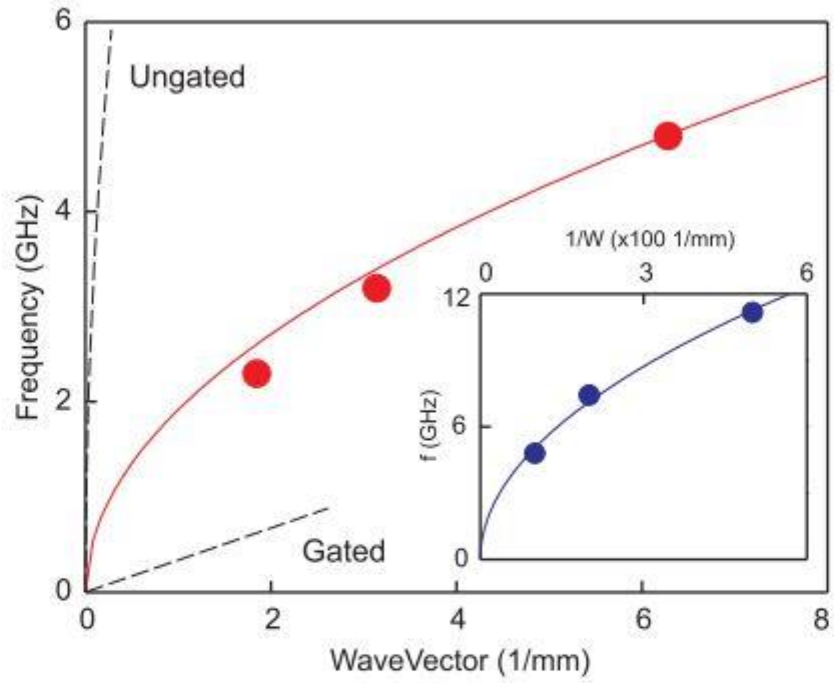
- $$\omega_{\text{pr}}(q) = \sqrt{\frac{2n_s e^2 h}{m^* \varepsilon\varepsilon_0} \frac{q}{W}} \qquad (qW \ll 1)$$

Mode with N=2

- $$\omega^2 = \omega_g(q_{\text{tr}})^2 + \omega_{\text{pr}}(q)^2 = \frac{n_s e^2 h}{m^* \varepsilon\varepsilon_0}\left(q_{\text{tr}}^2 + \frac{4}{W} q\right)$$

$$q_{\text{tr}} = N\frac{\pi}{W} \qquad N = 2$$

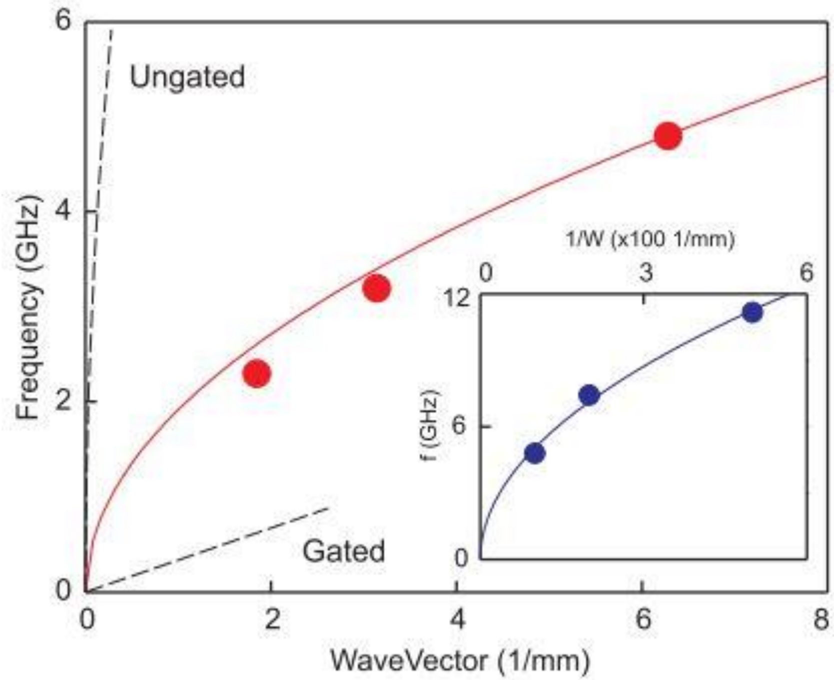
SPECTRUM OF PROXIMITY PLASMON



- Gated plasmon
- 1D plasmon

$$\omega_{pr} = \sqrt{\frac{2n_s e^2 h}{m^* \epsilon \epsilon_0} \frac{q}{W}}$$

SPECTRUM OF PROXIMITY PLASMON



- Gated plasmon
- 1D plasmon

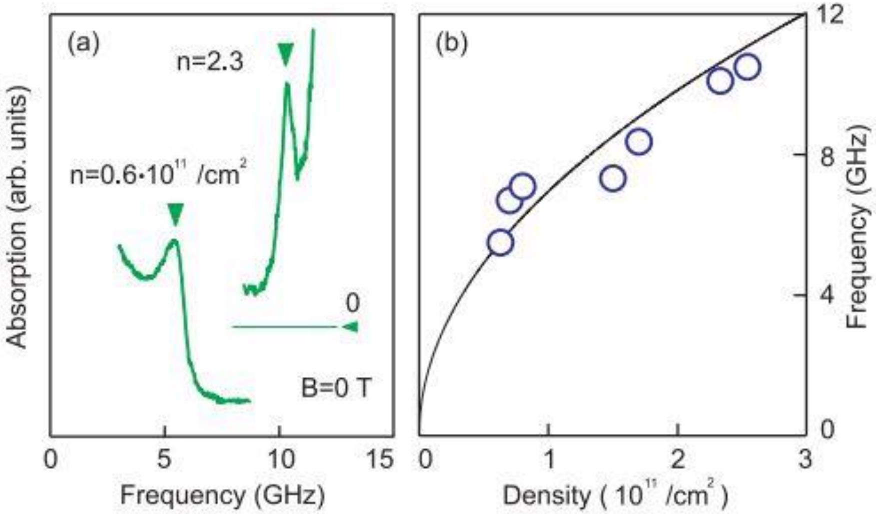
BUT: square-root dispersion

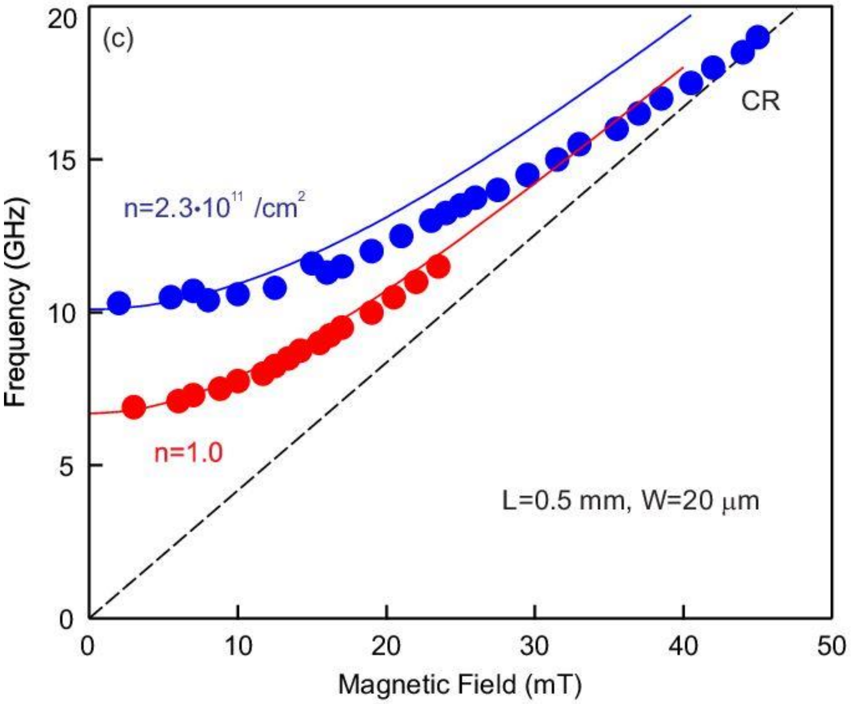
$$\omega_{pr} \propto \sqrt{q}$$

$$\omega_{pr} = \sqrt{\frac{2n_s e^2 h}{m^* \epsilon \epsilon_0} \frac{q}{W}}$$

ИФТТ РАН
ISSP RAS

ANOMALOUSLY STRONG INTERACTION WITH LIGHT





ИФТТ РАН
ISSP RAS

Публикации по теме за последний год по теме

PHYSICAL REVIEW B **102**, 081301(R) (2020)

Rapid Communications

Physical origin of relativistic plasmons in a two-dimensional electron system

V. M. Muravev,[1] P. A. Gusikhin,[1] A. M. Zarezin,[1,2] A. A. Zabolotnykh,[3] V. A. Volkov,[3] and I. V. Kukushkin[1]

[1]*Institute of Solid State Physics, RAS, Chernogolovka, 142432 Russia*

[2]*Moscow Institute of Physics and Technology, Dolgoprudny, 141700 Russia*

[3]*Kotelnikov Institute of Radio-engineering and Electronics of the RAS, Mokhovaya 11-7, Moscow 125009, Russia*

PHYSICAL REVIEW B **99**, 241406(R) (2019)

Rapid Communications

Two-dimensional plasmon induced by metal proximity

V. M. Muravev, P. A. Gusikhin, A. M. Zarezin, I. V. Andreev, S. I. Gubarev, and I. V. Kukushkin

Institute of Solid State Physics, RAS, Chernogolovka, 142432 Russia

(Received 8 May 2019; published 26 June 2019)

PHYSICAL REVIEW B **100**, 205405 (2019)

Proximity plasma excitations in disk and ring geometries

V. M. Muravev,[1] A. M. Zarezin,[1,2] P. A. Gusikhin,[1] A. V. Shupletsov,[3] and I. V. Kukushkin[1]

[1]*Institute of Solid State Physics, RAS, Chernogolovka, 142432 Russia*

[2]*Moscow Institute of Physics and Technology, Dolgoprudny, 141700 Russia*

[3]*P. N. Lebedev Physics Institute, 119991 Moscow, Russia*

(Received 30 August 2019; published 5 November 2019)

ИФТТ РАН
ISSP RAS

INNOVATION

PROXIMITY PLASMON

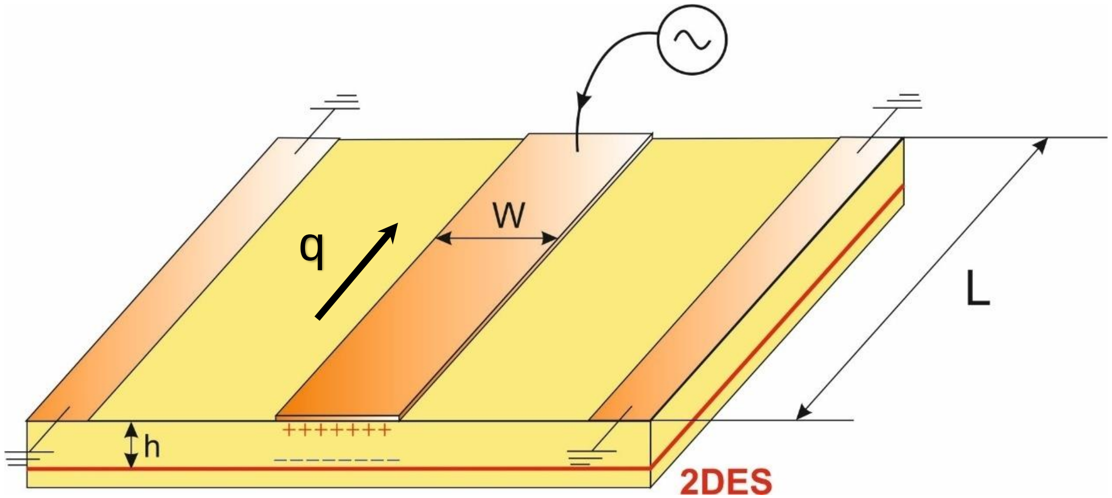
PHYSICAL REVIEW B **99**, 165304 (2019)

Interaction of gated and ungated plasmons in two-dimensional electron systems

A. A. Zabolotnykh and V. A. Volkov*

Kotelnikov Institute of Radio-engineering and Electronics of the RAS, Mokhovaya 11-7, Moscow 125009, Russia and Moscow Institute of Physics and Technology, Institutskii per. 9, Dolgoprudny, Moscow region 141700, Russia

(Received 25 December 2018; published 8 April 2019)



$$\omega_{\rm pr}(q) = \sqrt{\frac{2n_s e^2 h}{m^* \varepsilon \varepsilon_0} \frac{q}{W}}$$

$$(qW \ll 1) \qquad q_{\rm tr} = 0$$

$$q = \frac{\pi}{L} N \quad (N = 1, 2, \dots)$$

ИФТТ РАН
ISSP RAS

PRACTICAL APPLICATION

WIKIPEDIA
The Free Encyclopedia

Main page
Contents
Featured content
Current events
Random article
Donate to Wikipedia
Wikipedia store

Interaction

Help

Not logged in Talk Contributions Create account Log i

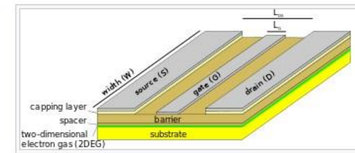
Article Talk Read Edit View history Search Wikipedia

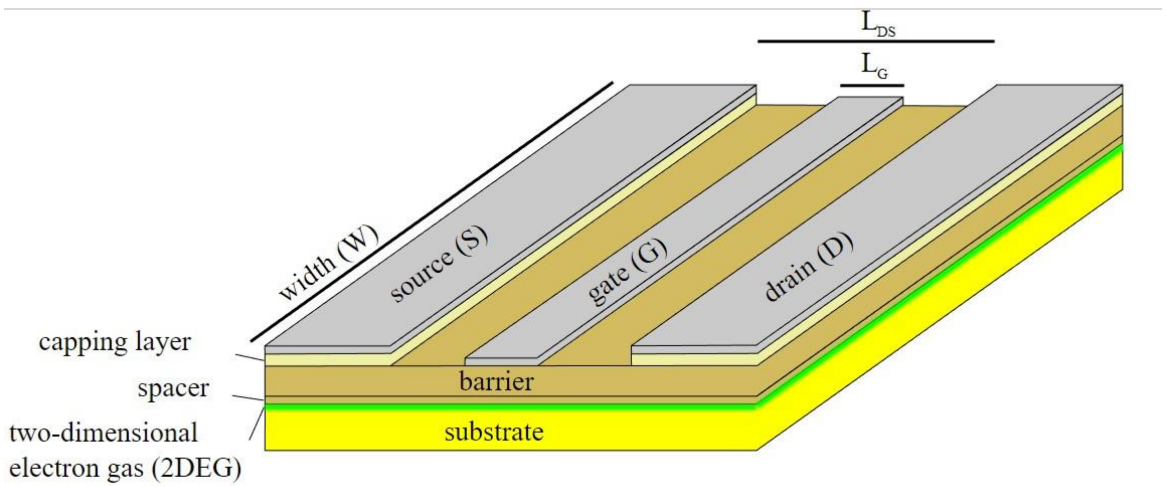
High-electron-mobility transistor

From Wikipedia, the free encyclopedia

"HEMT" redirects here. For the military truck, see Heavy Expanded Mobility Tactical Truck.

A **High-electron-mobility transistor** (**HEMT**), also known as **heterostructure FET** (**HFET**) or **modulation-doped FET** (**MODFET**), is a field-effect transistor incorporating a junction between two materials with different band gaps (i.e. a heterojunction) as the channel instead of a doped region (as is generally the case for MOSFET). A commonly used material combination is GaAs with AlGaAs, though there is wide variation, dependent on the application of the device. Devices incorporating more indium generally show better high-frequency performance, while in recent years, gallium nitride HEMTs have attracted attention due to their high-power performance. Like other FETs, HEMTs are used in integrated circuits as digital on-off switches. FETs can also be used as amplifiers for large amounts of current using a small voltage as a control signal. Both of these uses are made possible by the FET's unique current-voltage characteristics. HEMT transistors are able to operate at higher frequencies than ordinary transistors, up to millimeter wave frequencies, and are used in high-frequency products such as cell phones, satellite television receivers, voltage converters, and radar equipment. They are widely used in satellite receivers, in low power amplifiers and in the defense industry.





PRACTICAL APPLICATION

FUJITSU

W = 150 nm
L = 1 μm

f = 2.5 ТГц

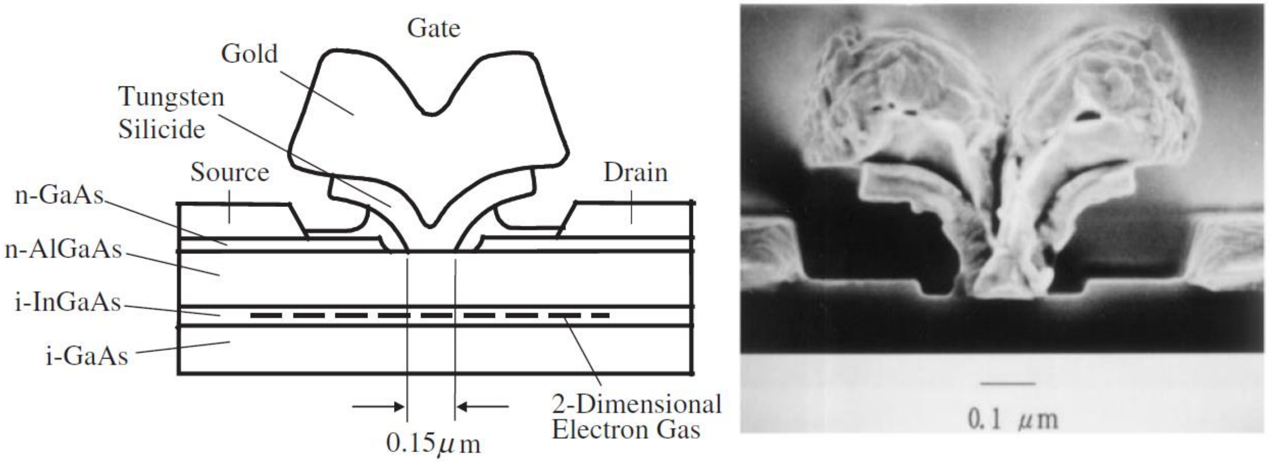
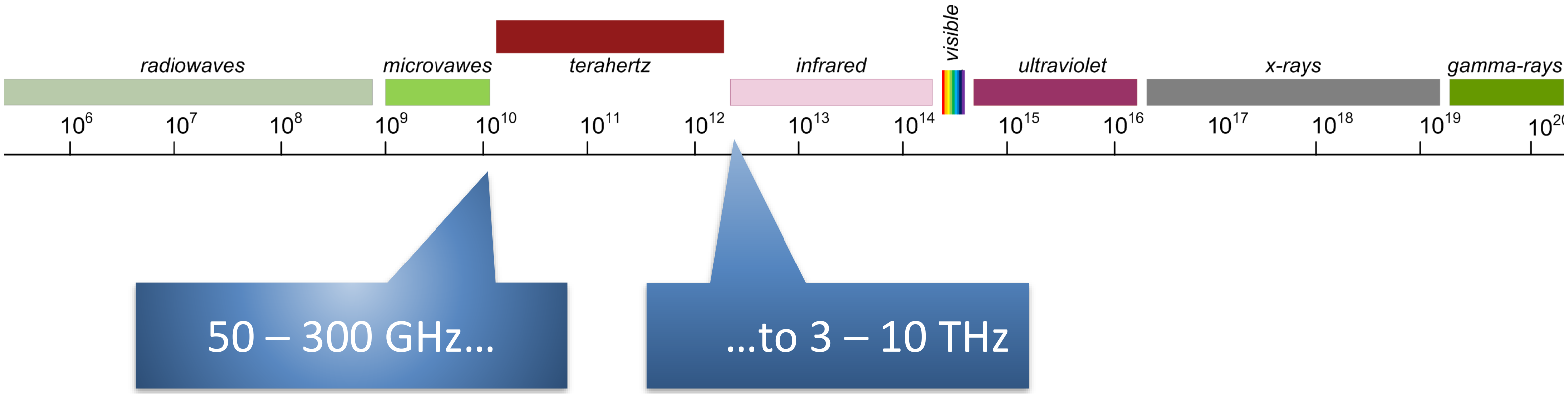


Fig. 8. SEM photograph and schematic diagram of recessed-gate pseudomorphic low-noise HEMT.

What is TERAHERTZ?



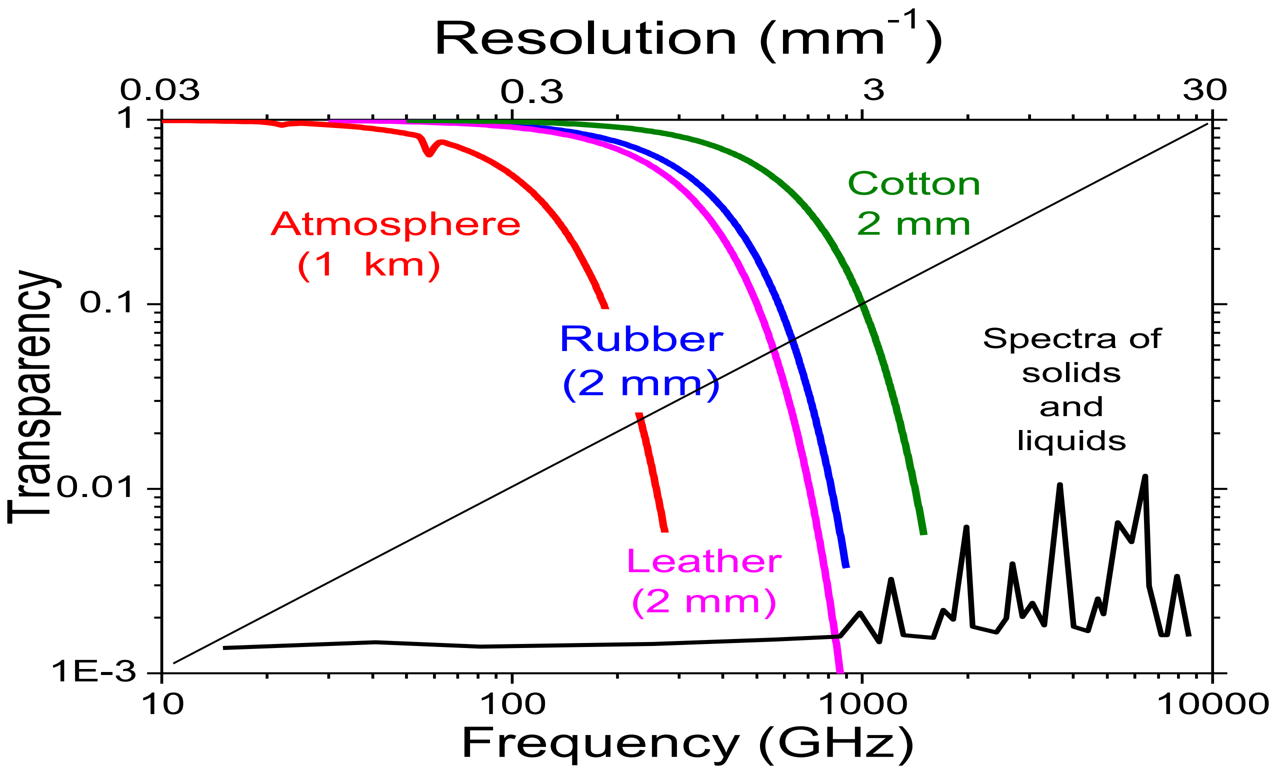
The last not occupied diapason in the Electromagnetic spectrum.

“Terahertz gap”

TeraSEnse
sensing another vision

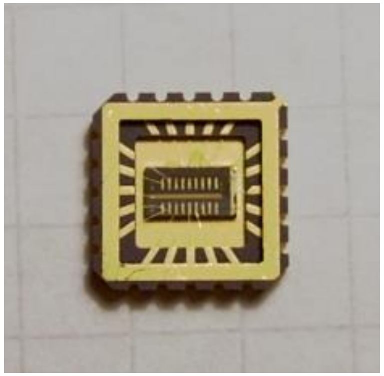
WHY T-RAYS?

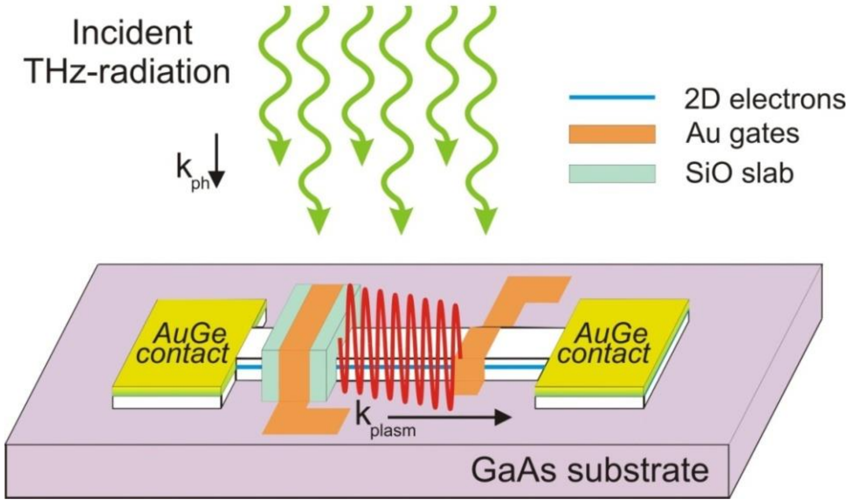
Security | **Test Control** | **Communications**



TeraSEnse
sensing another vision

PLASMONS FOR TERAHERTZ DETECTION





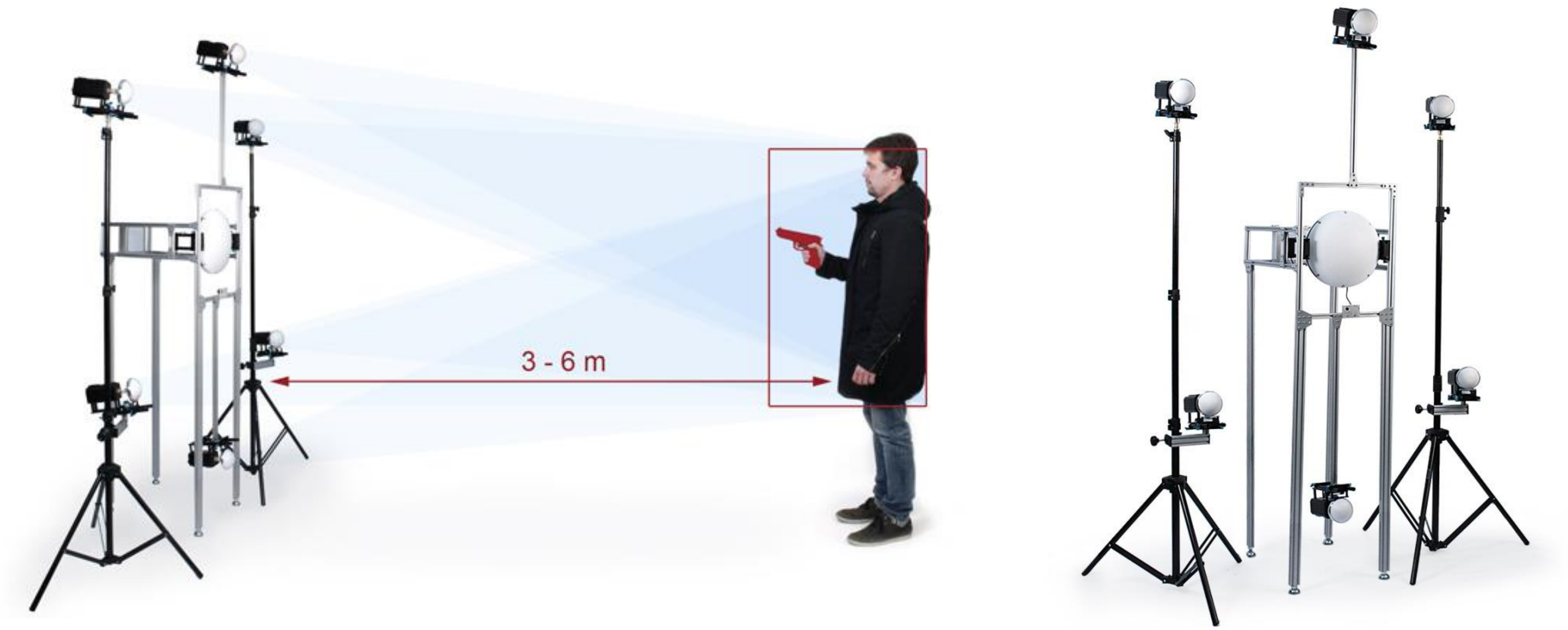
- on-chip detector with no bias of 0.05 - 1 THz radiation
- broadband frequency sensitivity
- manufacture cycle involves only optical lithography steps
- fully compatible with existing manufacturing lines

US Patent WO 2001020346 A3 (filed 07.10.2008) “Apparatus and Method of Detecting Electromagnetic Radiation”

US Patent CA 2811905 A1 (filed 10.12.2009) “Tera- and Gigahertz Solid State Miniature Spectrometer”

TeraSEnse
sensing another vision

Terahertz Security Scanner (100 GHz)



Терагерцовый досмотровый сканер (100 ГГц)

Terahertz Security Scanner (100 GHz)

TeraSEnse
sensing another vision

Terahertz Linear Scanner

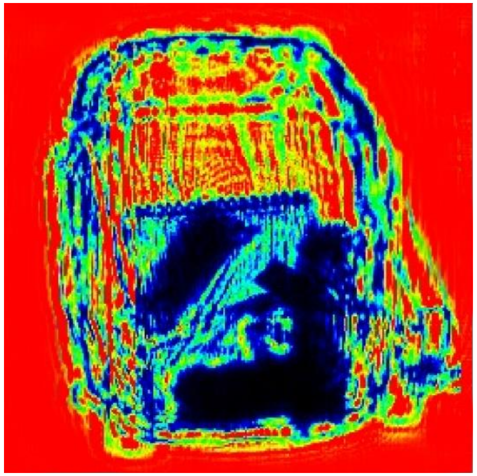
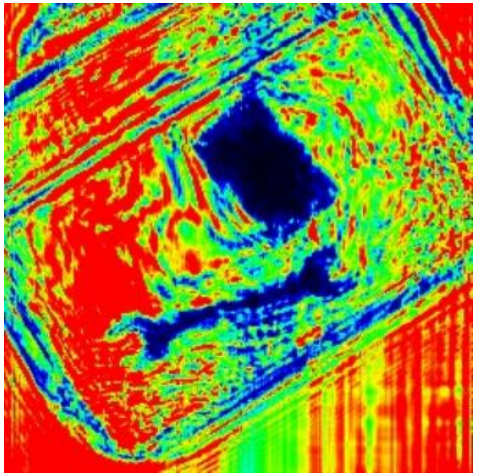
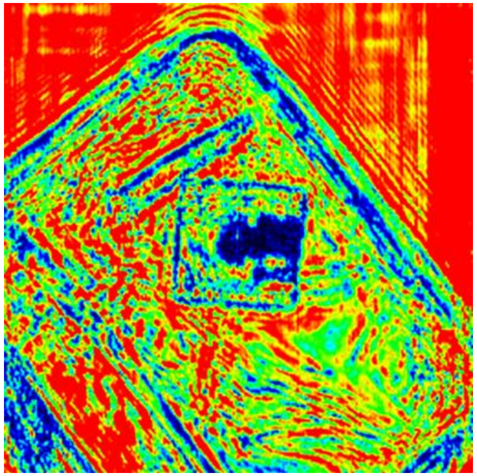
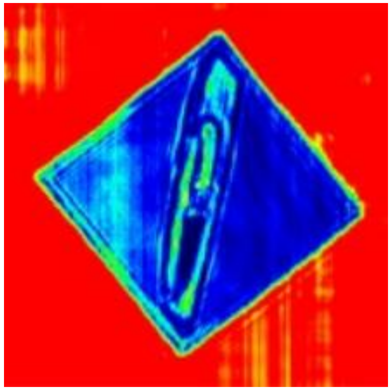
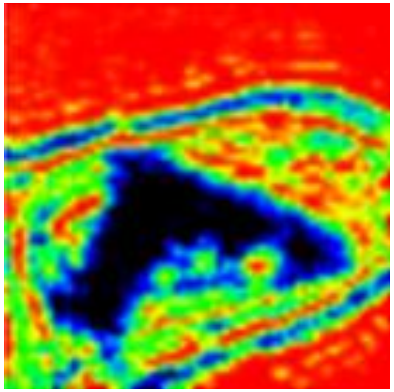
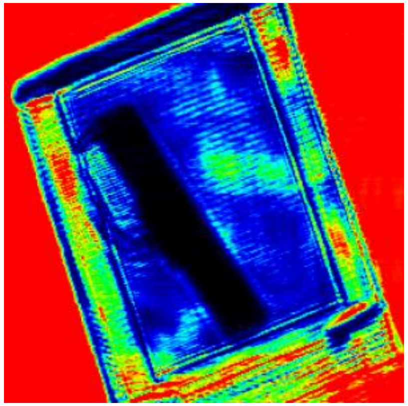
100 ГГц и 300 ГГц

Number of pixels:	256 (256 x 1)
Pixel size:	1.5 x 3 mm^2
Imaging area:	384 x 3 mm^2
Dimensions of device:	450 x 160 x 44 mm^3
Sync out:	TTL (+5 V)
Interface:	mini-USB

Image acquisition rate:	5000 fps (5 KHz)
Responsivity:	8000 V/W
Min detectable power/pixel:	100 nW (at 5000 fps) 45 nW (at 1000 fps) 14 nW (at 100 fps)

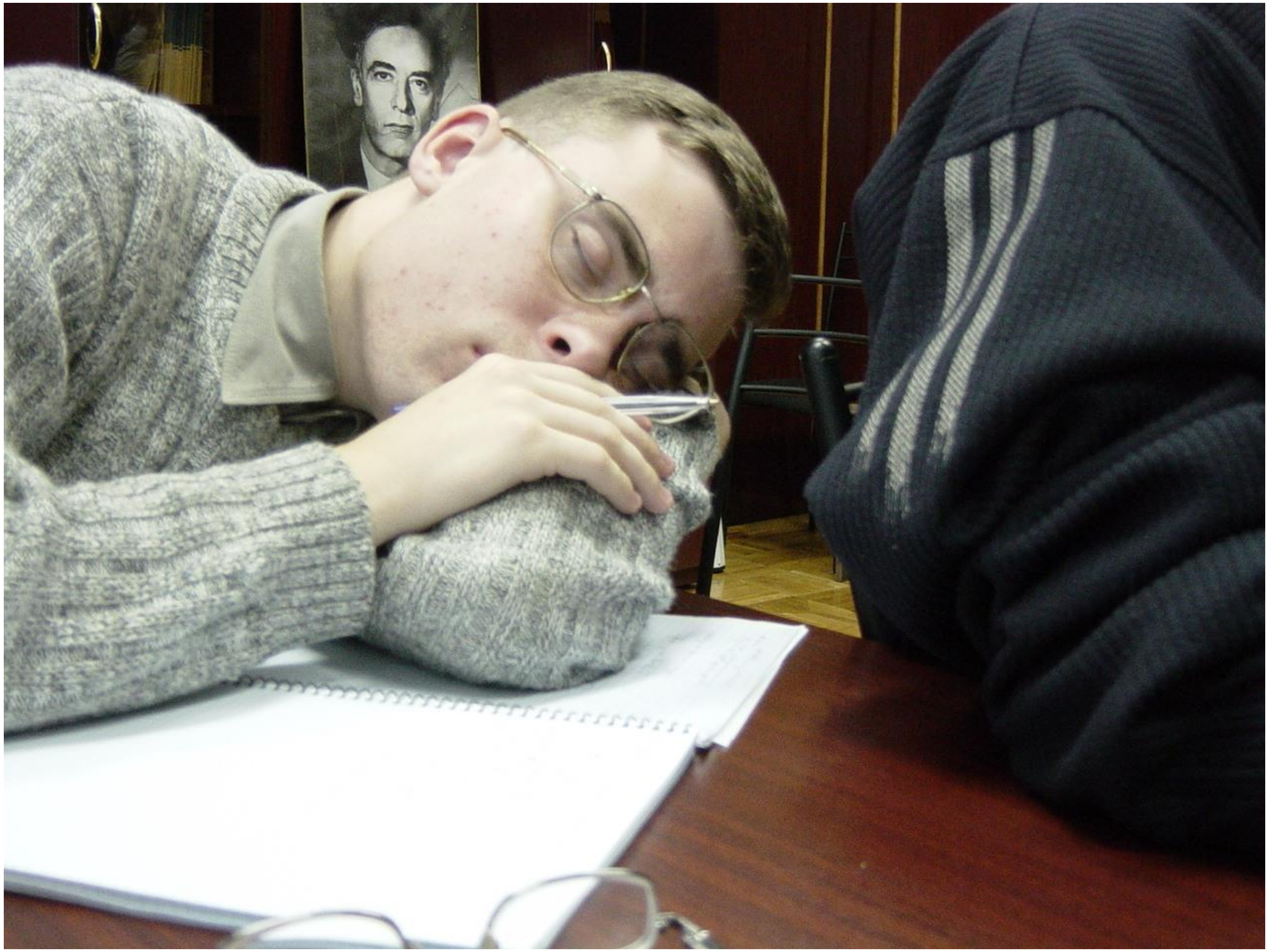
TeraSEnse
sensing another vision

Terahertz Linear Scanner

TeraSEnse
sensing another vision

ВОПРОСЫ - ДИСКУССИЯ



ИФТТ РАН
ISSP RAS

Электродинамика двумерных материалов

Муравьев Вячеслав

к.ф.-м.н. старший научный сотрудник ИФТТ РАН
CAO TeraSense Group Inc.

ИФТТ РАН
ISSP RAS