

Детектирование ТГц излучения двумерными полупроводниками

Аспирант З г.о.:

Кадыков А.М.

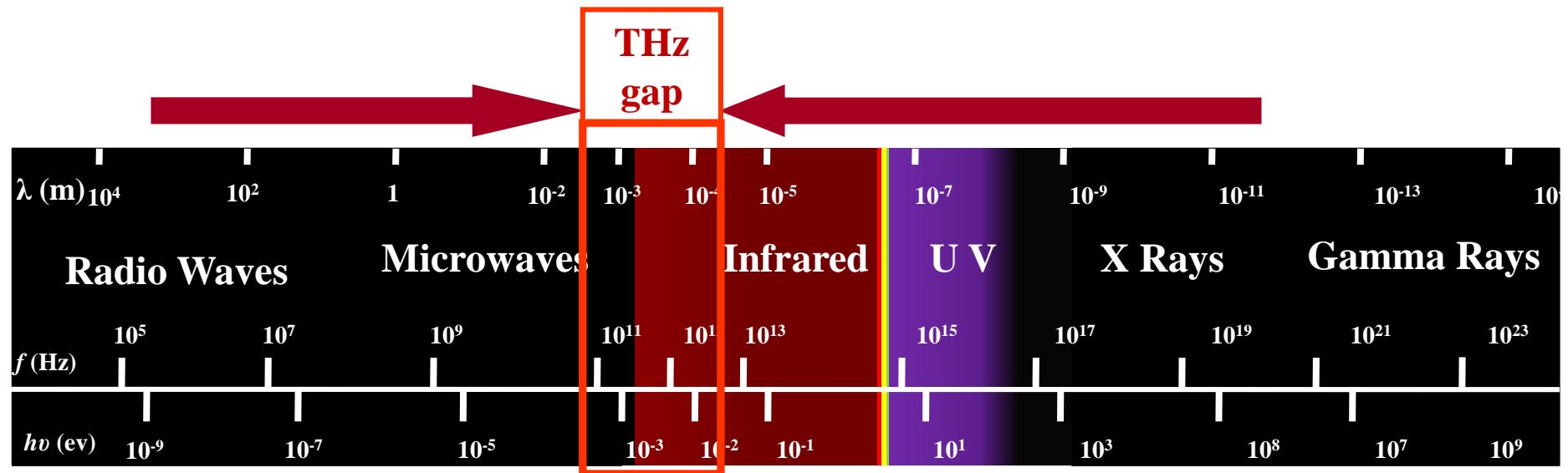
Научные руководители:

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¹Институт физики микроструктур РАН, Нижний Новгород

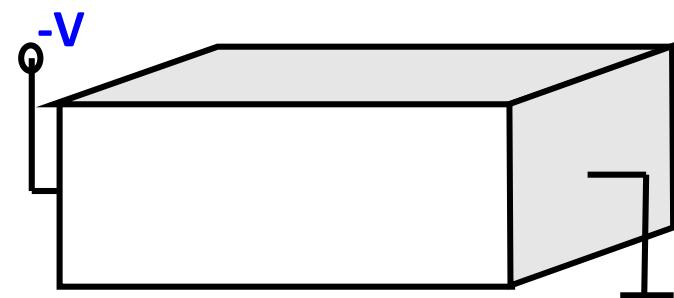
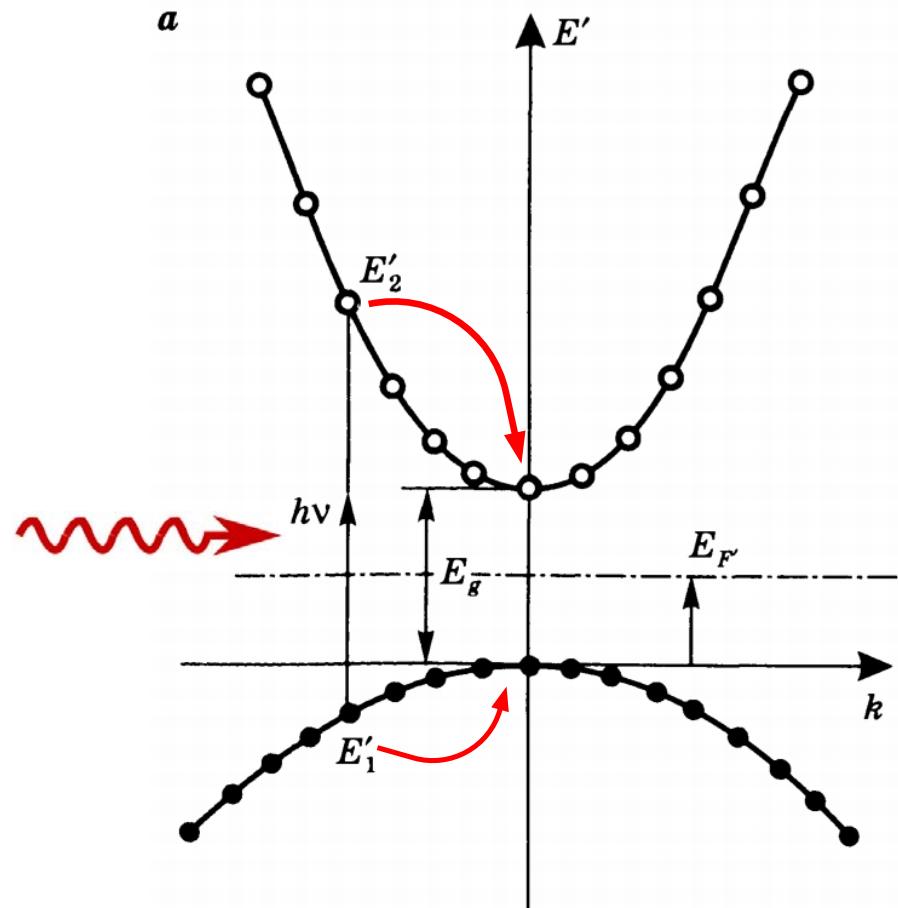
²Laboratoire Charles Coulomb, Universite Montpellier 2, France

ТГц диапазон



- Безопасное сканирование
- Высокоскоростная передача данных
- Исследование вращательных спектров молекул
- И др.

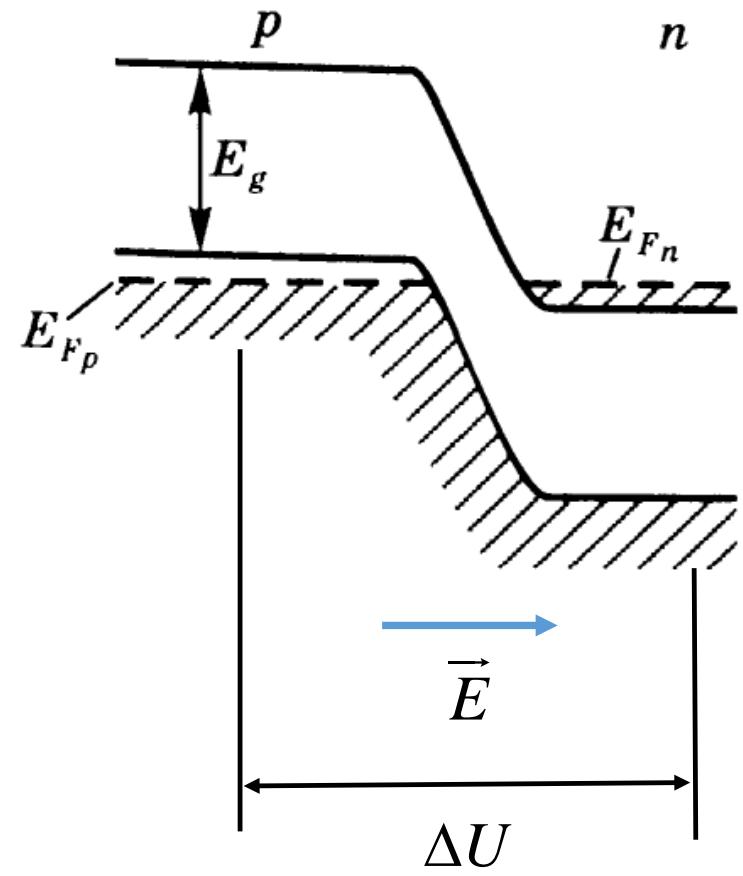
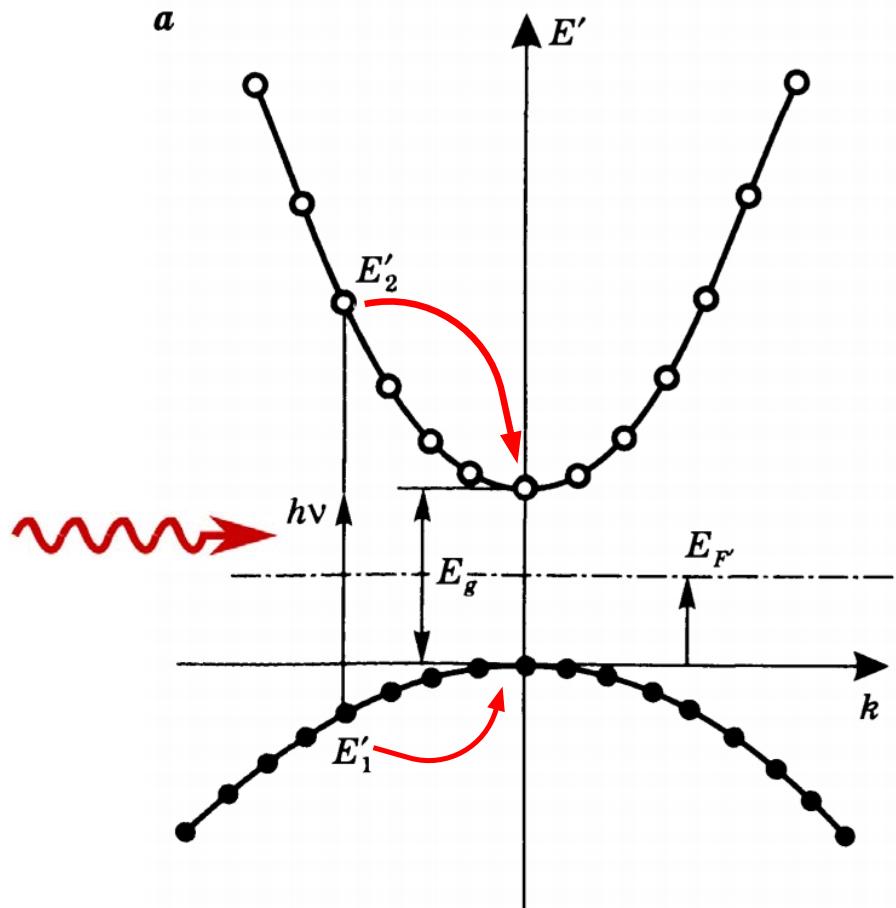
Межзонная рекомбинация



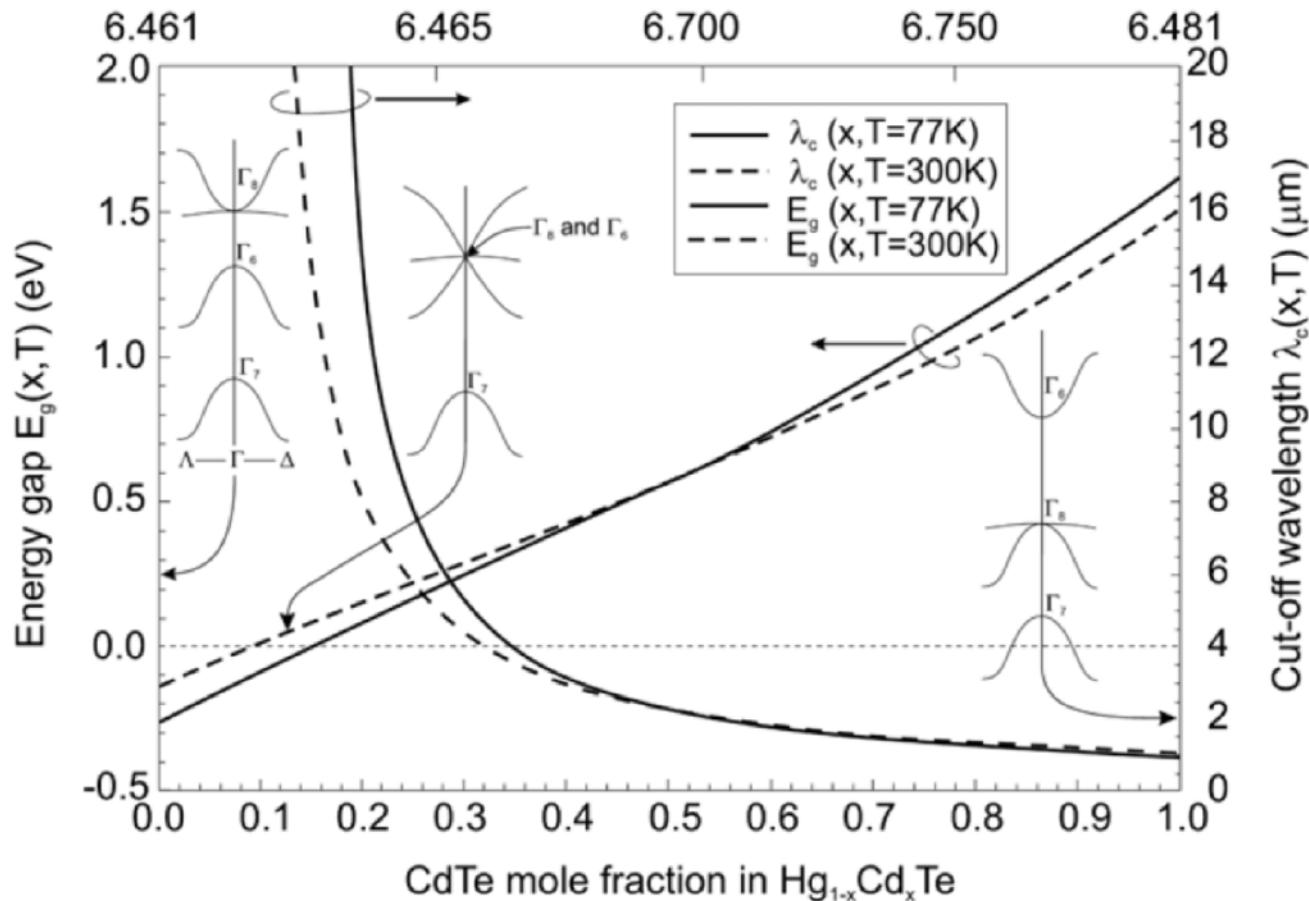
$$\vec{j} = en\vec{v}_d = en\mu\vec{E}$$

$$n \uparrow \Rightarrow \vec{j} \uparrow$$

Межзонная рекомбинация

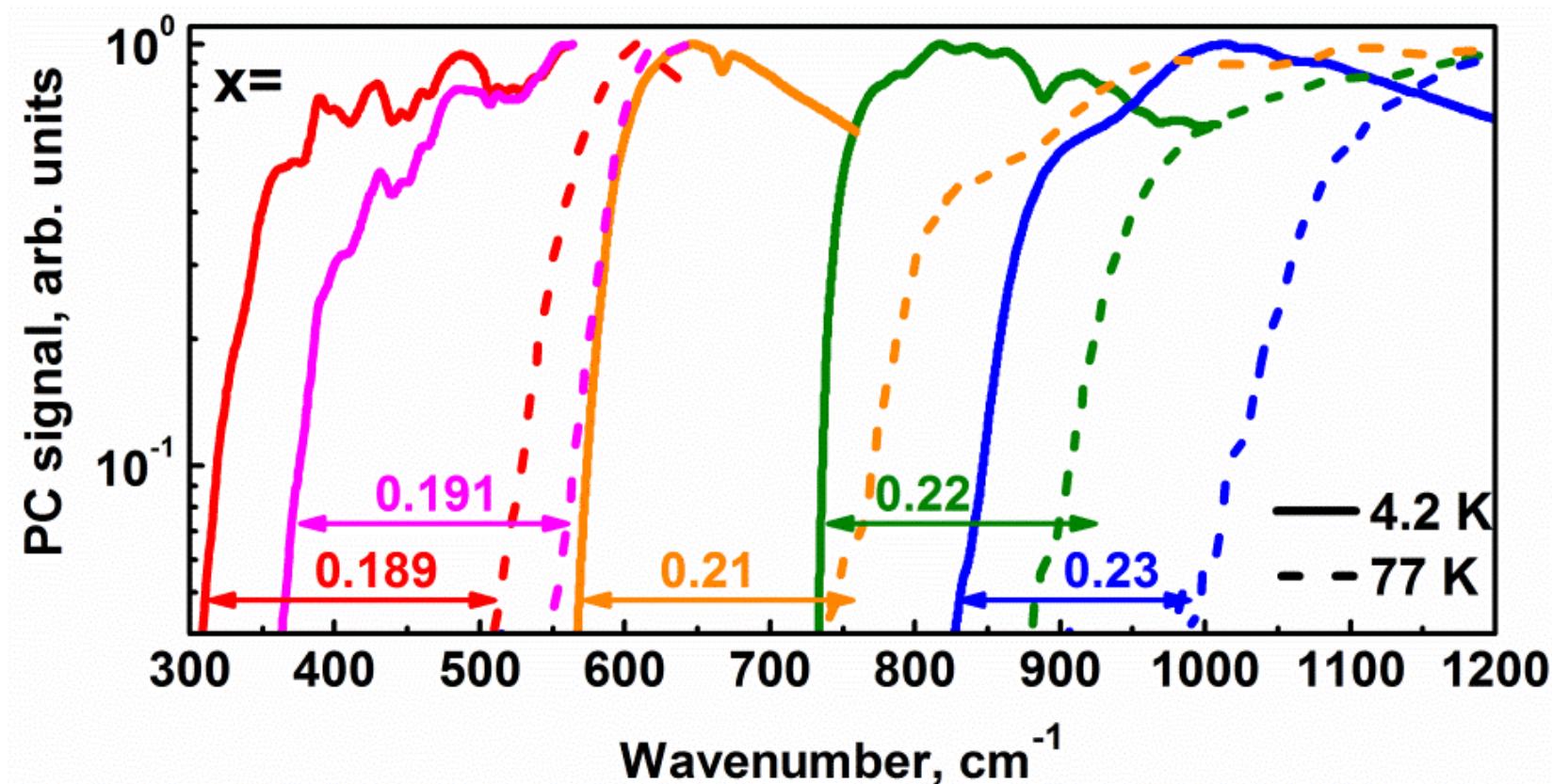


Детектирование с помощью твёрдых растворов HgCdTe

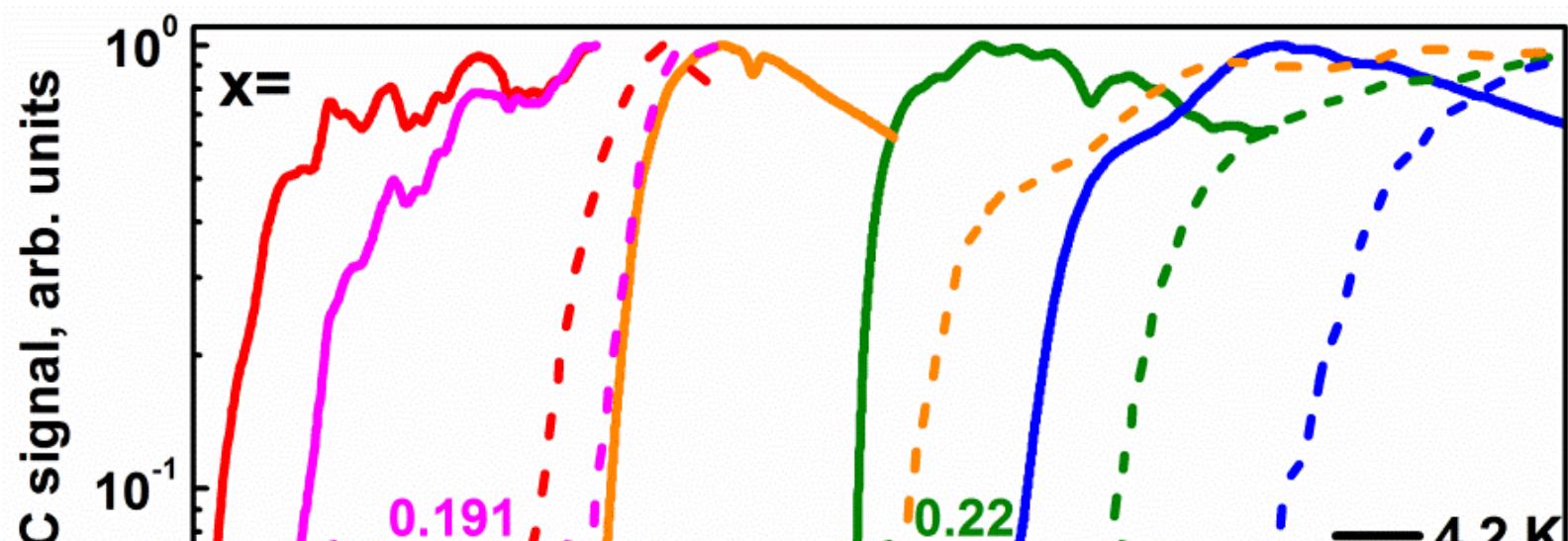


A .Rogalski, Rep. Prog. Phys. 68, 2267 (2005)

Детектирование с помощью твёрдых растворов HgCdTe

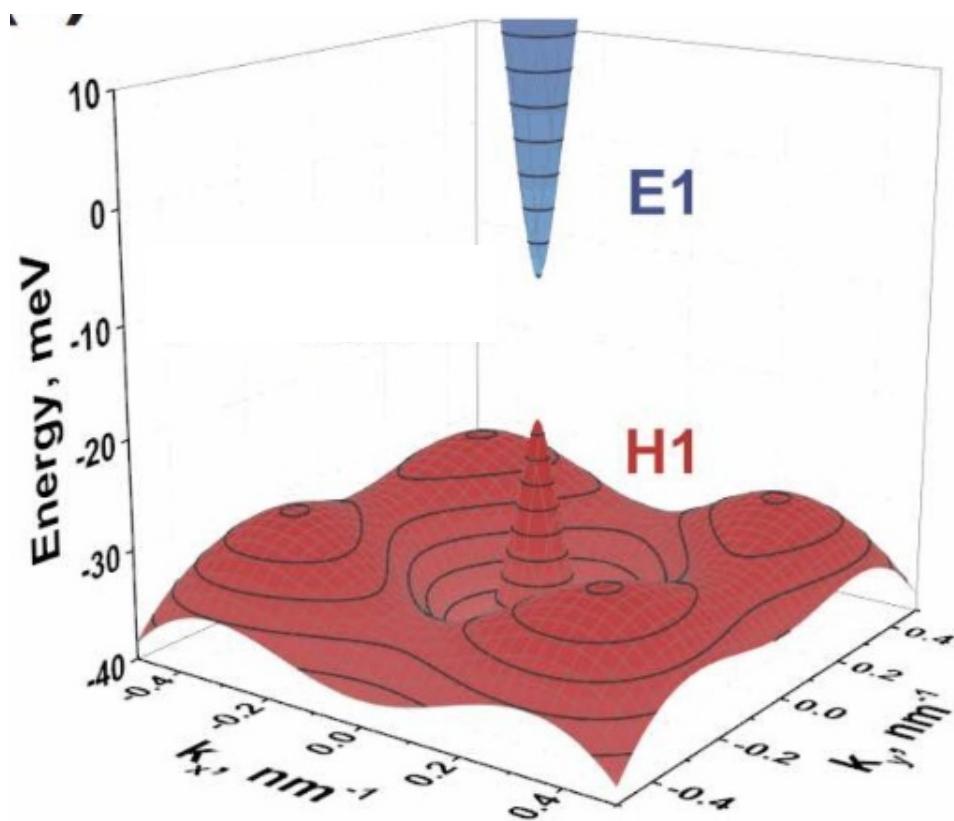
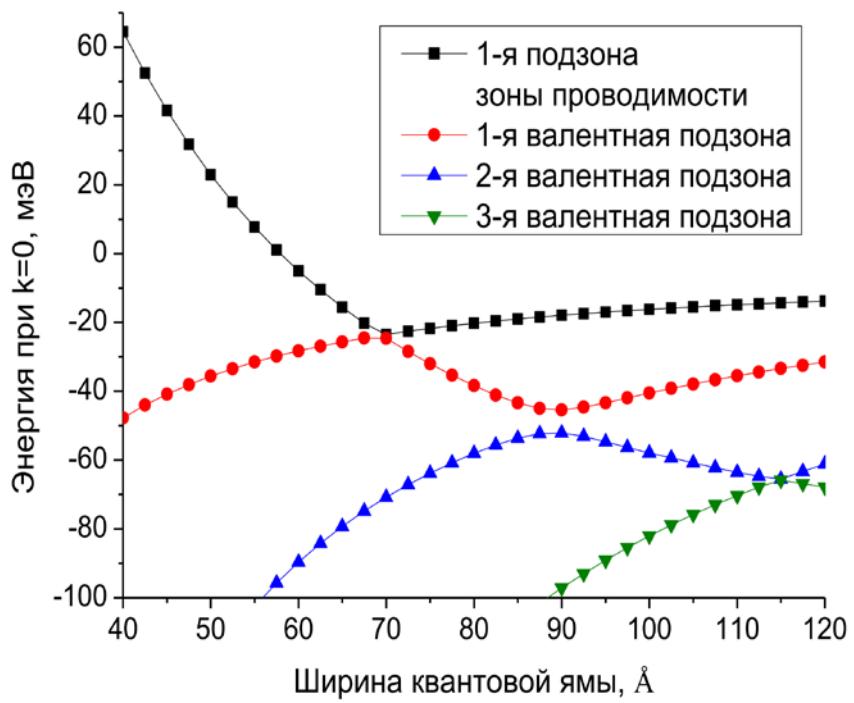


Детектирование с помощью твёрдых растворов HgCdTe



- Необходима малая E_g
- Возрастает вклад рекомбинаций Оже и Шокли-Рида-Холла

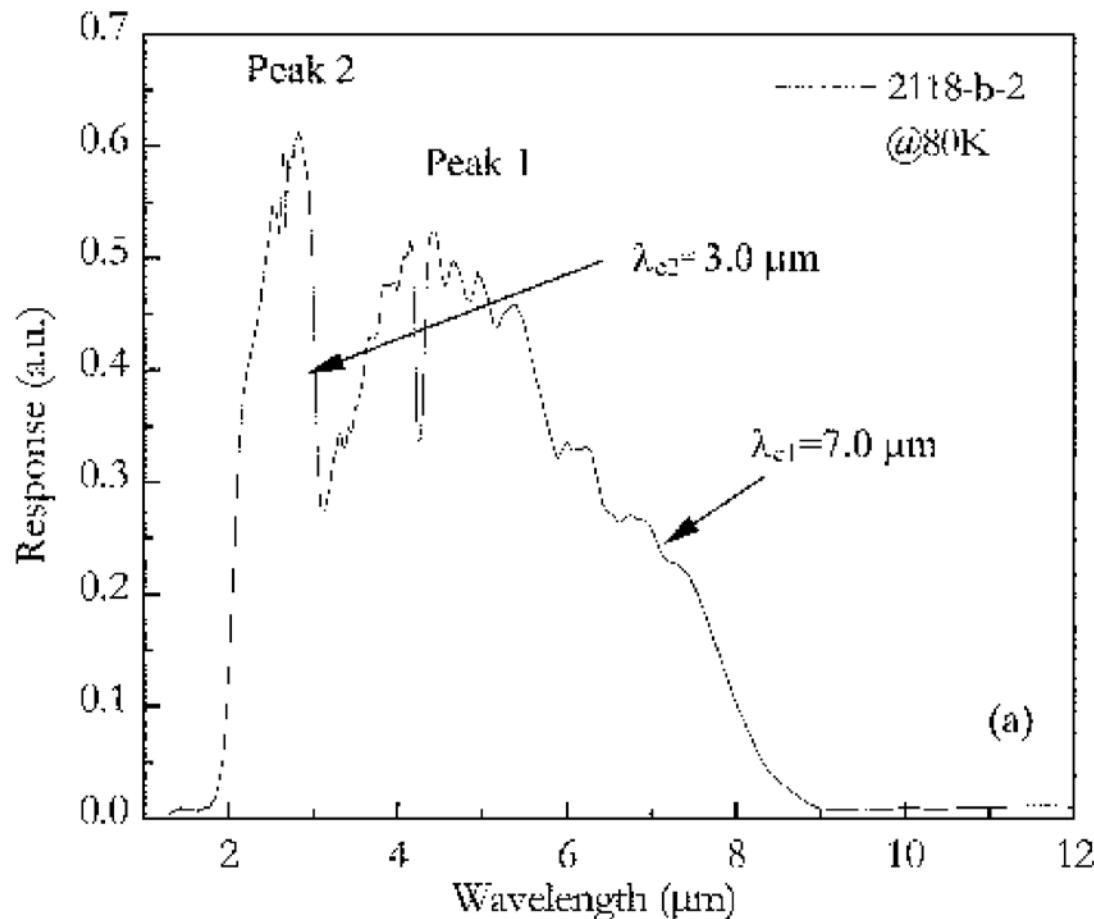
Квантовые ямы HgTe/CdHgTe



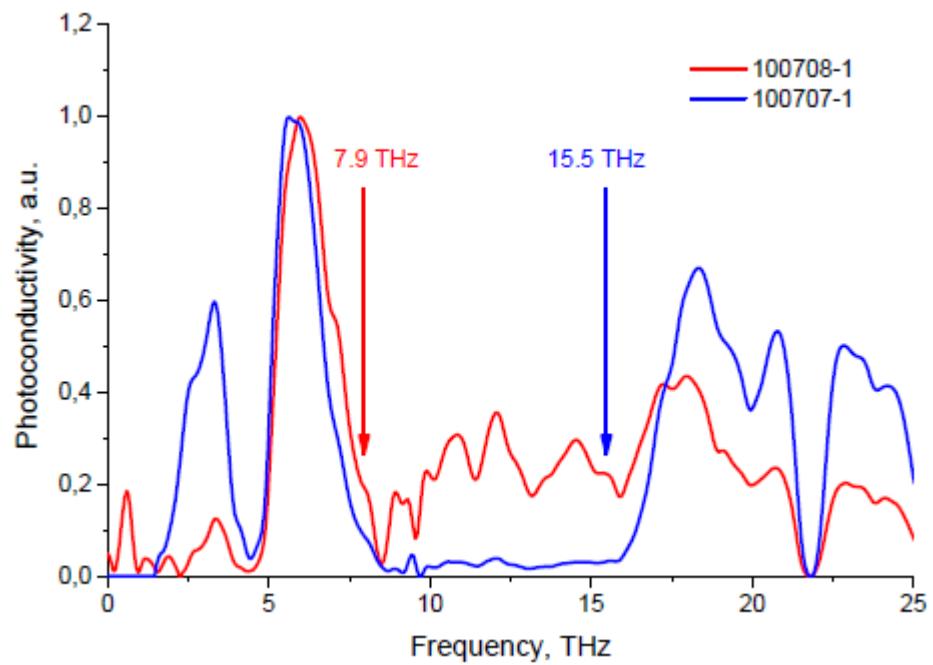
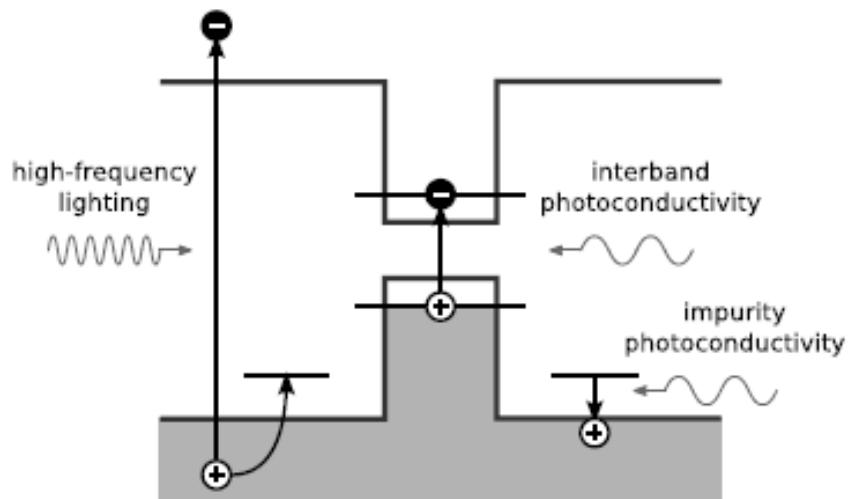
Zholudev, M. S. (2013) *Terahertz Spectroscopy of HgCdTe/CdHgTe quantum wells.*

arXiv:1702.06869

Сверхрешётки HgTe/CdHgTe



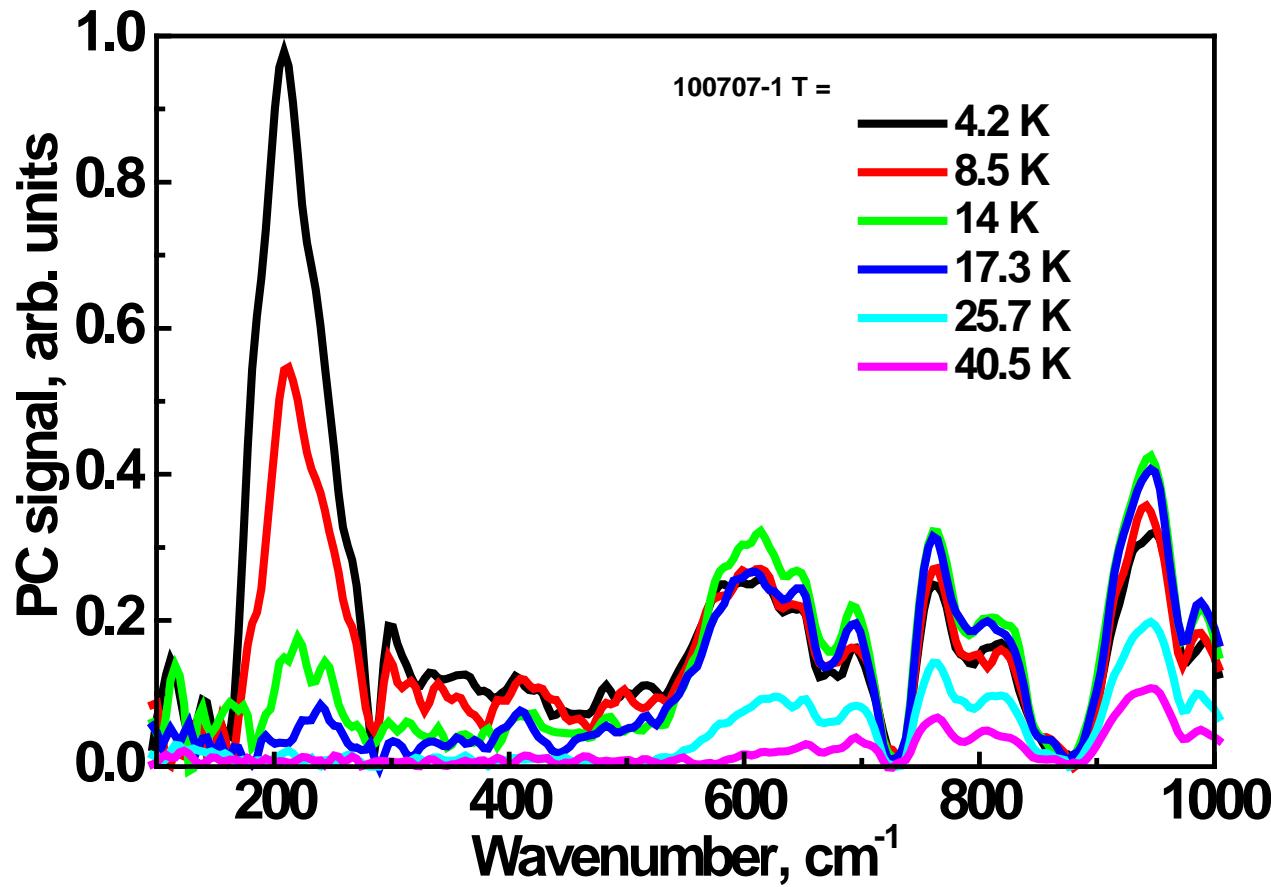
Примесное детектирование



$$\vec{j} = e n \vec{v}_d \quad n \uparrow \Rightarrow \vec{j} \uparrow$$

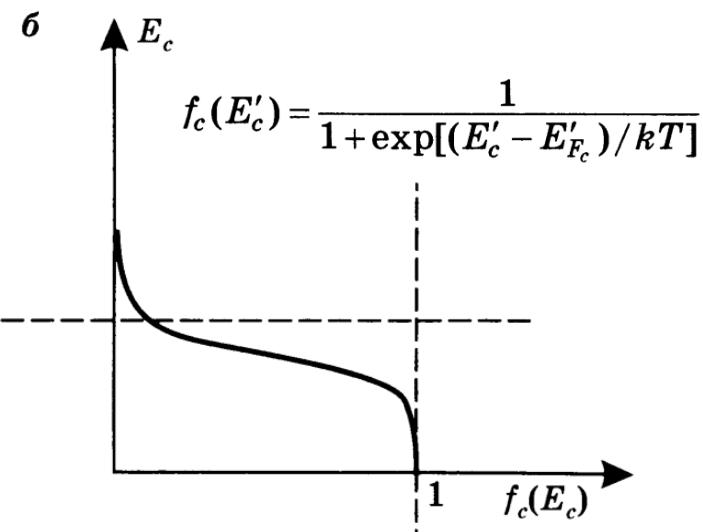
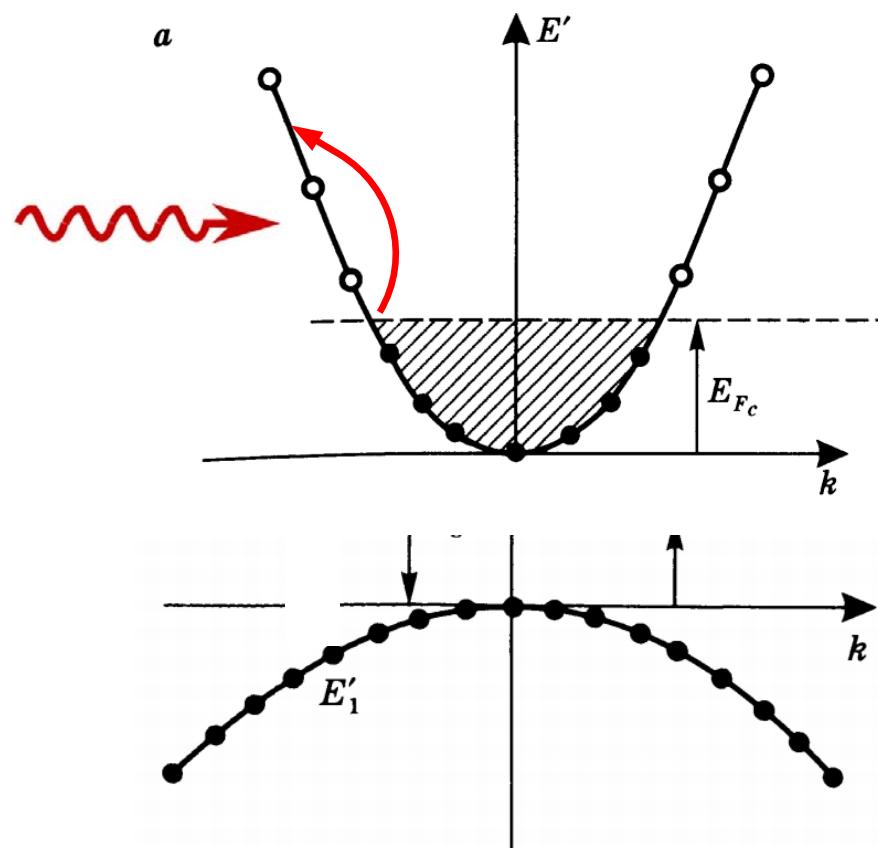
| | | | |
|----------|-------|-------|----|
| 100707-1 | 0.186 | 0.702 | 30 |
| 100708-1 | 0.176 | 0.646 | 30 |

Температурное гашение примесной фотопроводимости

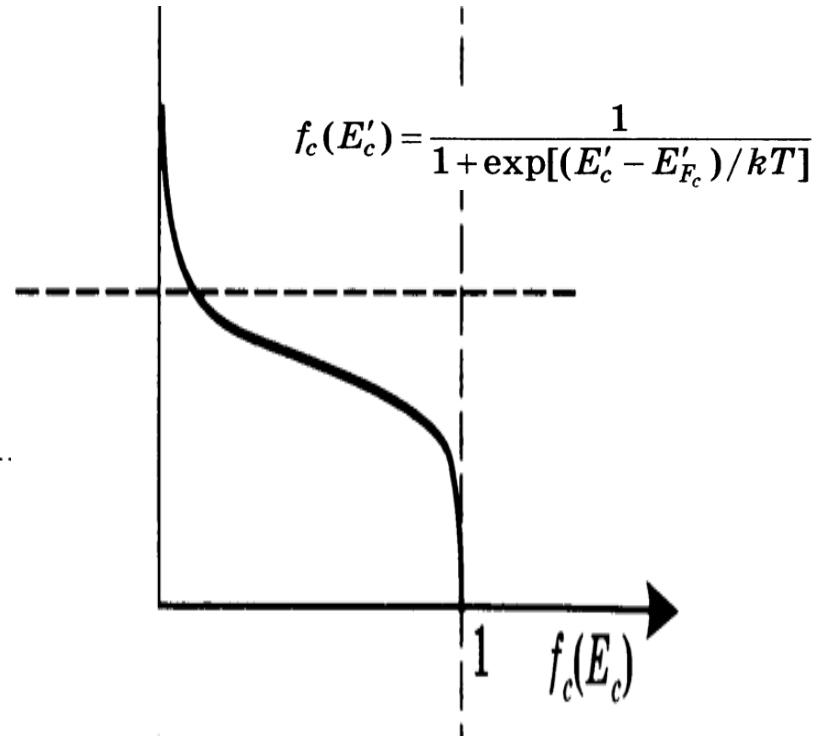
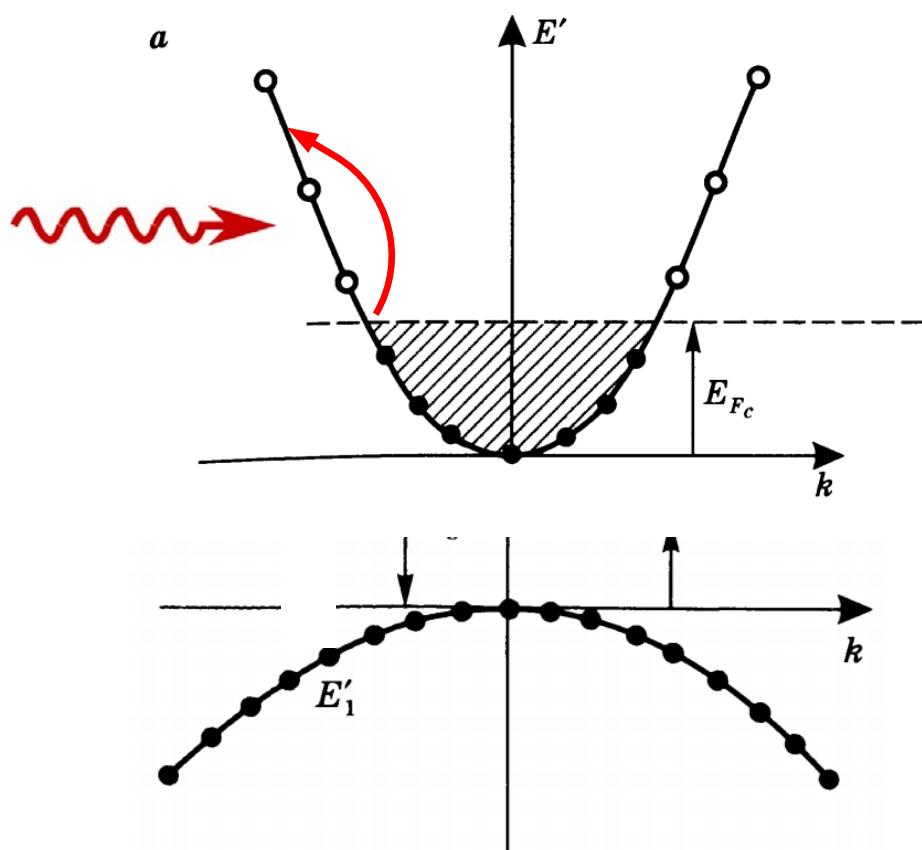


Низкая квантовая эффективность

Разогрев носителей



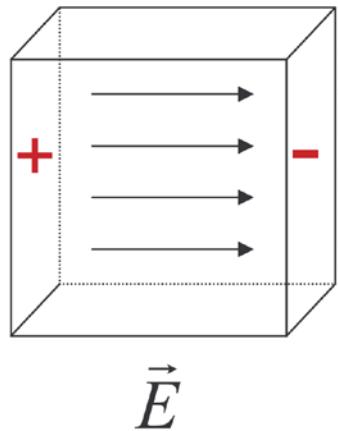
Разогрев носителей



$$\vec{j} = en\mu\vec{E}$$

$$T \uparrow \Rightarrow \Delta\mu \Rightarrow \Delta\vec{j}$$

Плазменные колебания в полупроводниках



$$\rho(\vec{r}, t) = \rho_0(\vec{r}) + \rho_1(\vec{r}, t)$$

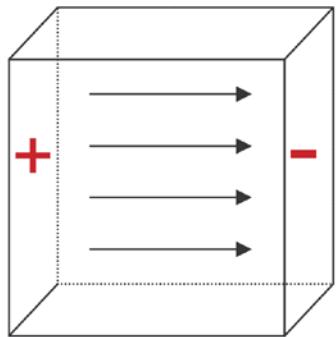
$$\vec{v}_d(\vec{r}, t) = \vec{v}_{d0}(\vec{r}) + \vec{v}_{d1}(\vec{r}, t) = \vec{v}_{d1}(\vec{r}, t)$$

$$\frac{\partial \rho}{\partial t} + \operatorname{div} \vec{j} = 0 \quad \vec{j} = \rho \vec{v}_d$$

$$\frac{\partial^2 \rho_1}{\partial t^2} + \rho_0 \operatorname{div} \frac{\partial \vec{v}_{d1}}{\partial t} = 0 \quad \frac{\partial \vec{v}_{d1}}{\partial t} = -\frac{e}{m} \vec{E}$$

$$\boxed{\frac{\partial^2 \rho_1}{\partial t^2} - \frac{e \rho_0}{m} \operatorname{div} \vec{E} = 0}$$

Плазменные колебания в объёмных полупроводниках



$$\frac{\partial^2 \rho_1}{\partial t^2} - \frac{e \rho_0}{m} \operatorname{div} \vec{E} = 0$$

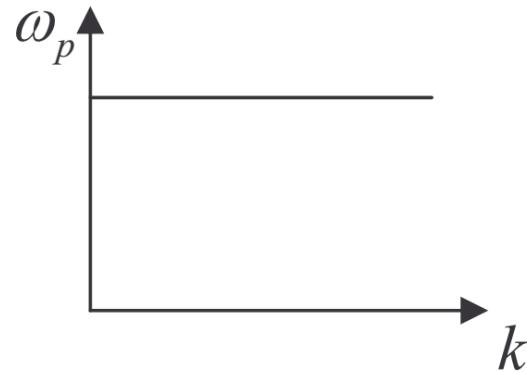
$$\text{3D: } \operatorname{div} \vec{E} = -\frac{4\pi}{\epsilon} (\rho_0 + \rho_1)$$

$$\vec{E}$$

$$\frac{\partial^2 \rho_1}{\partial t^2} + \frac{4\pi e \rho_0}{\epsilon m} \rho_1 = 0$$

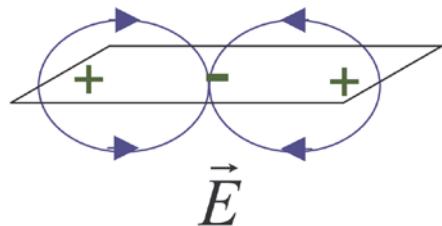
Ленгмюровские
колебания

$$\omega_p = \sqrt{\frac{4\pi n_0 e^2}{\epsilon m}}$$



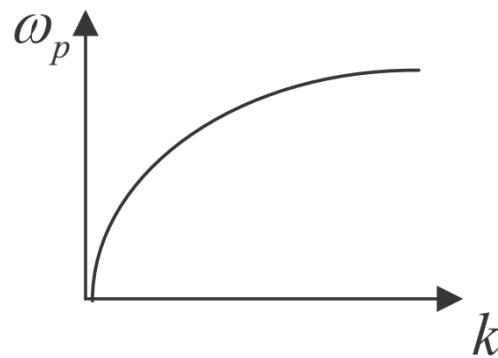
Плазменные колебания в двумерных полупроводниках

2D:



$$\frac{\partial^2 \rho_k}{\partial t^2} + \frac{2\pi n_0 e^2 k}{\varepsilon m} \rho_k = 0$$

$$\boxed{\omega(k) = \sqrt{\frac{2\pi n_0 e^2 k}{\varepsilon m}}}$$



Волны на глубокой воде:

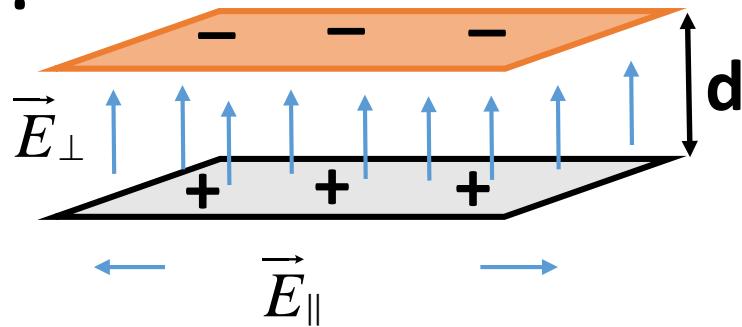
$$\omega(k) = \sqrt{gk}$$



Плазмоны в двумерных полупроводниках с затвором

Приближение плавного канала ($\lambda \gg d$)

FET:



$$\frac{\partial^2 \rho_1}{\partial t^2} - \frac{e\rho_0}{m} \operatorname{div} \vec{E} = 0$$

$$\rho = CU \quad U = V_g - V_{th}$$

$$\vec{E} = -\operatorname{grad} U = -\frac{1}{C} \operatorname{grad} \rho$$

$$\frac{\partial^2 \rho_1}{\partial t^2} - \frac{ne^2}{mC} \Delta \rho_1 = 0$$

$$\omega(k) = sk \quad s = \sqrt{\frac{ne^2}{mC}} = \sqrt{\frac{eU}{m}}$$

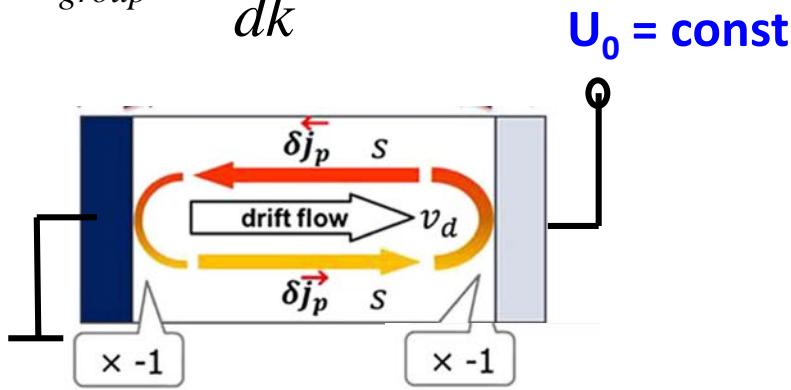
Волны на мелкой воде:

$$\omega(k) = k\sqrt{gh}$$

Неустойчивость Дьяконова-Шура

$$\omega(k) = sk$$

$$V_{group} = \frac{d\omega}{dk} = s$$



$$U_{\text{ground}} = \text{const}$$

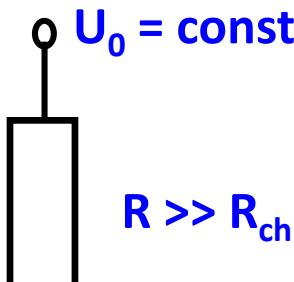
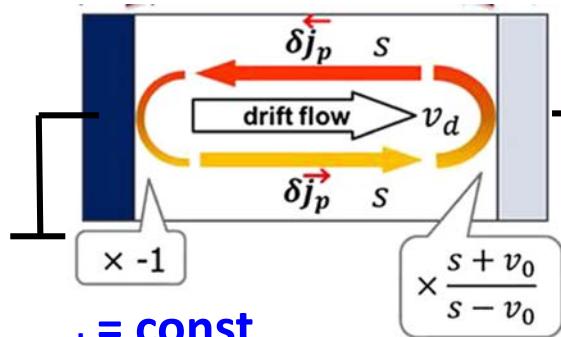
$$\text{wavy arrow} \rightarrow v = s + v_d$$

$$\text{wavy arrow} \leftarrow v = s - v_d$$

Неустойчивость Дьяконова-Шура

$$\omega(k) = sk$$

$$V_{group} = \frac{d\omega}{dk} = s$$



$v = s + v_d$

$$\Delta j' = e\Delta n'(s + v_d)$$

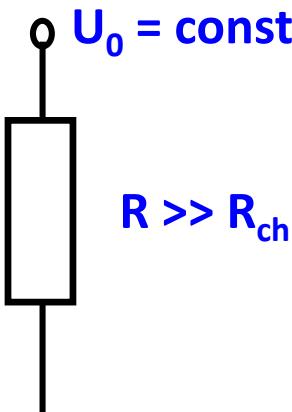
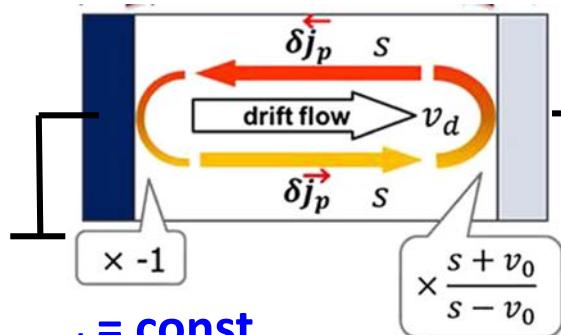
$v = s - v_d$

$$\Delta j'' = e\Delta n''(s - v_d)$$

Неустойчивость Дьяконова-Шура

$$\omega(k) = sk$$

$$V_{group} = \frac{d\omega}{dk} = s$$



↗ $v = s + v_d$

$$\Delta j' = e \Delta n' (s + v_d)$$

↖ $v = s - v_d$

$$\Delta j'' = e \Delta n'' (s - v_d)$$

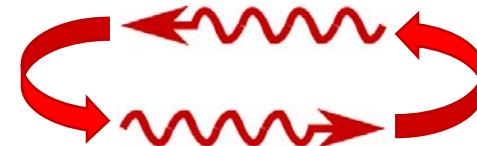
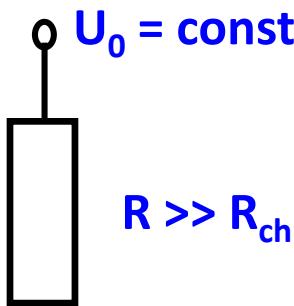
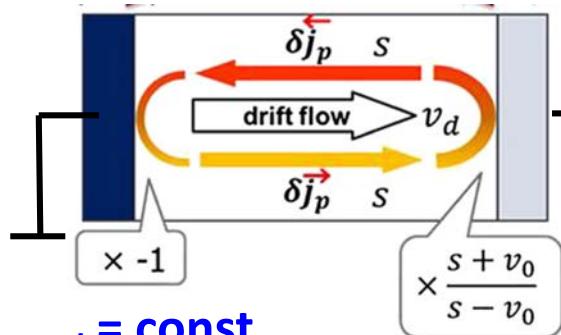
$$|\Delta j'| = |\Delta j''| \rightarrow \Delta n'' = \frac{(s + v_d)}{(s - v_d)} \Delta n'$$

$$\boxed{\frac{(s + v_d)}{(s - v_d)} > 1}$$

Неустойчивость Дьяконова-Шура

$$\omega(k) = sk$$

$$V_{group} = \frac{d\omega}{dk} = s$$



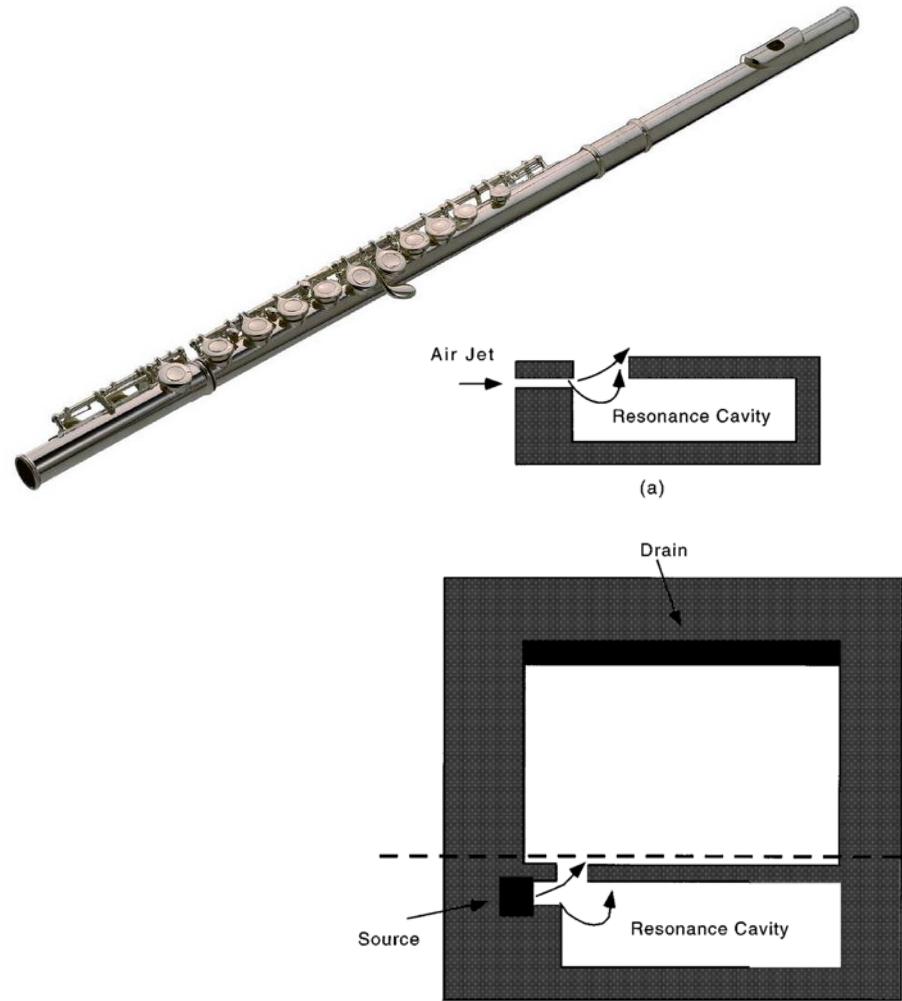
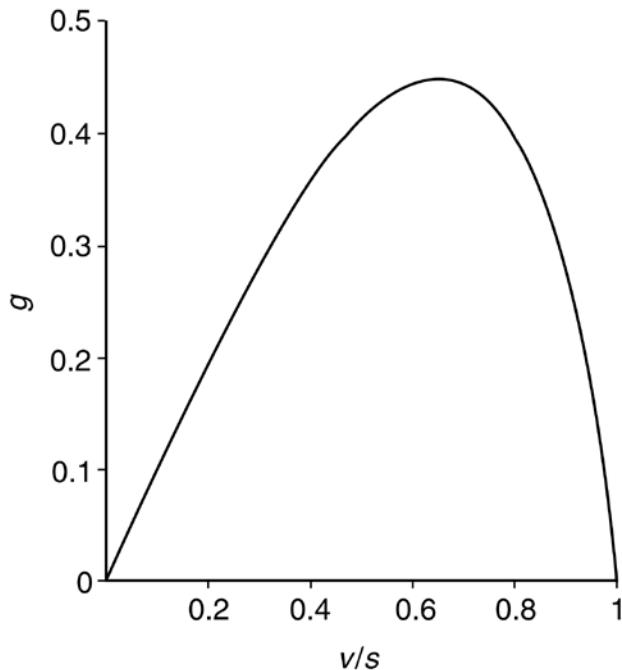
$$\tau = \frac{L}{v_0 - s} + \frac{L}{v_0 + s}$$

$$\left(\frac{v_0 + s}{v_0 - s} \right)^{\frac{t}{\tau}} = \exp(\omega'' t)$$

$$\omega'' = \frac{s}{2L} \left(1 - \frac{v_0^2}{s^2} \right) \ln \left| \frac{v_0 + s}{v_0 - s} \right|$$

Неустойчивость Дьяконова-Шура

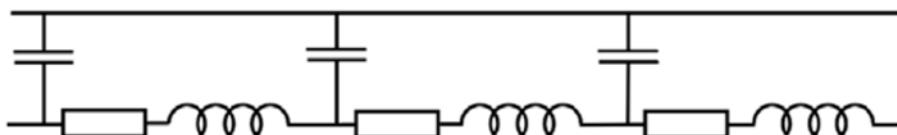
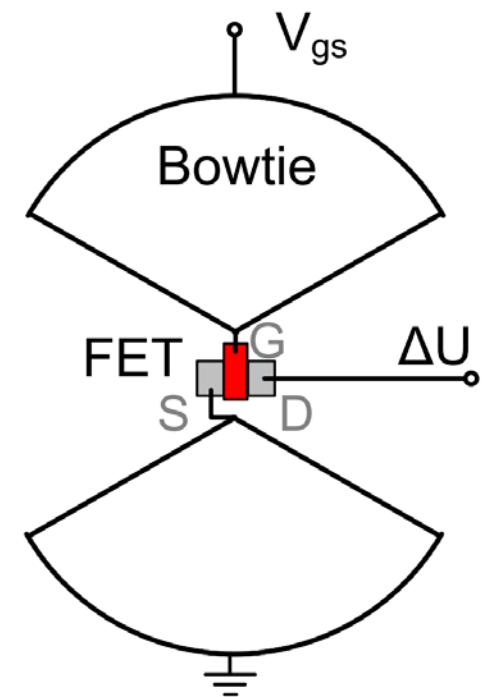
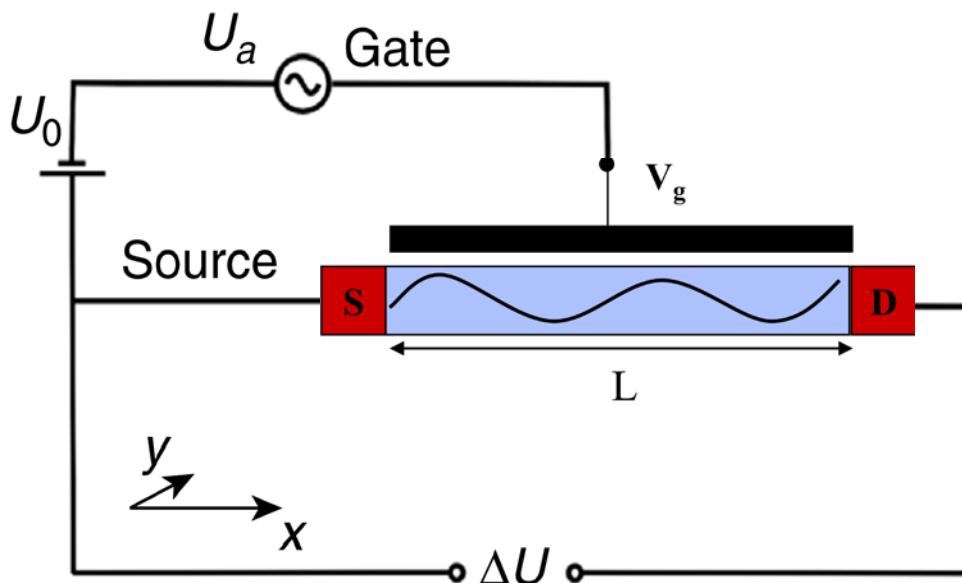
$$\omega'' = \frac{s}{2L} \left(1 - \frac{v_0^2}{s^2} \right) \ln \left| \frac{v_0 + s}{v_0 - s} \right|$$



Dyakonov, M. and Shur, M.
PRL.71(15), 2465, 1993.

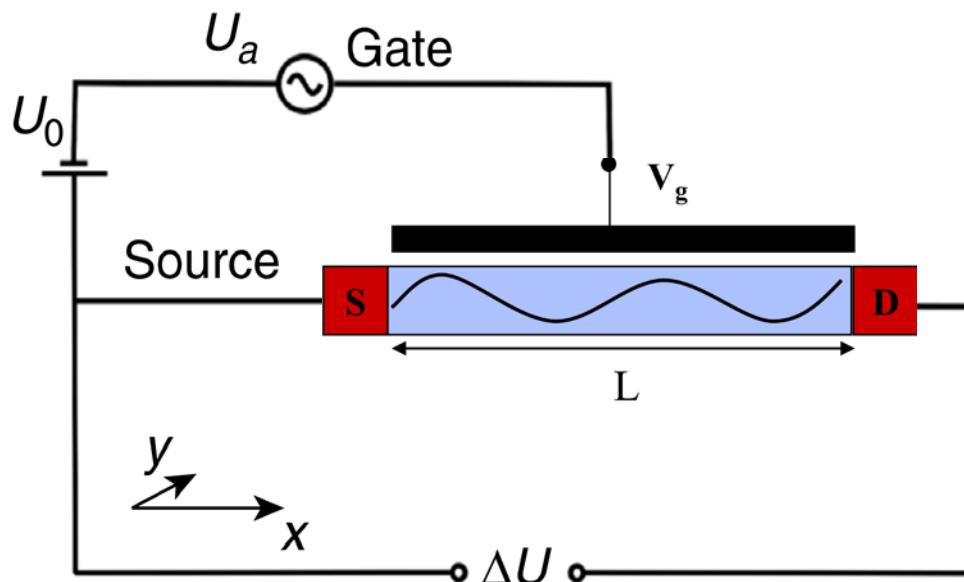
Dyakonov, M. I. and Shur, M. S.,
APL, 67(8), p. 1137, (1995)

Детектирование по механизму Дьяконова-Шура



Dyakonov, M. and Shur, M. *IEEE Transactions on Electron Devices*, 43(3), p. 380, (1996)

Детектирование по механизму Дьяконова-Шура



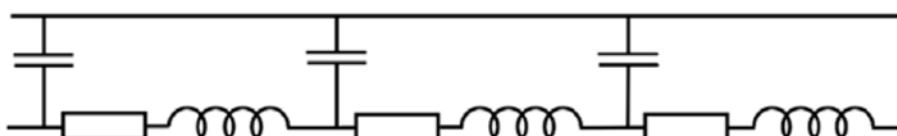
$$f_p = \frac{1}{4L} \sqrt{\frac{eU}{m}}$$

$$L = 0.1 - 1 \mu\text{m}$$

$$U = 1 \text{ V}$$

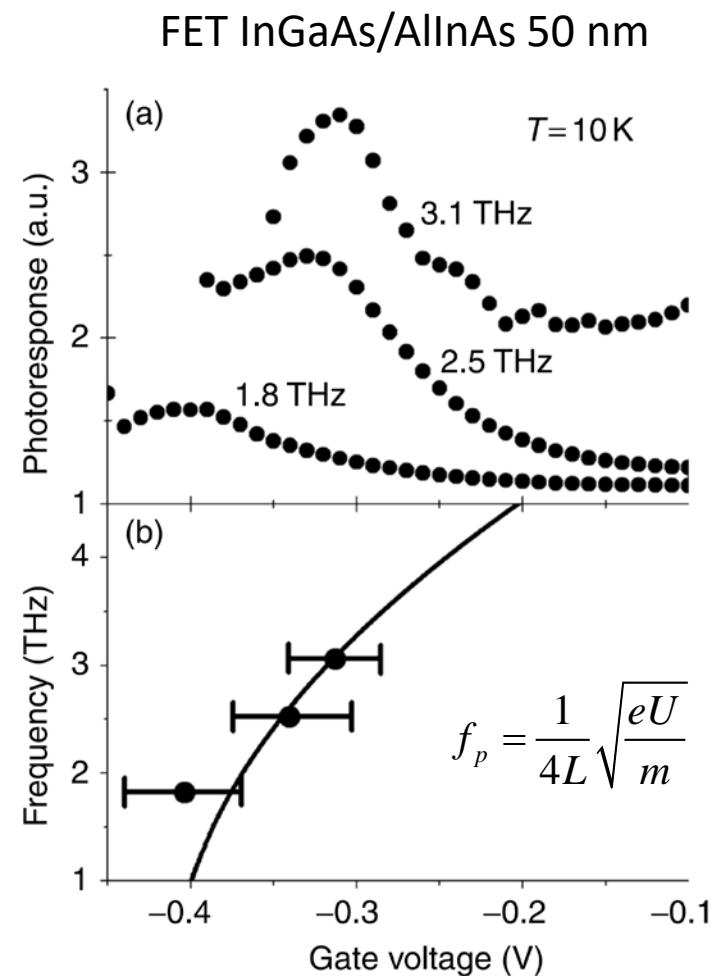
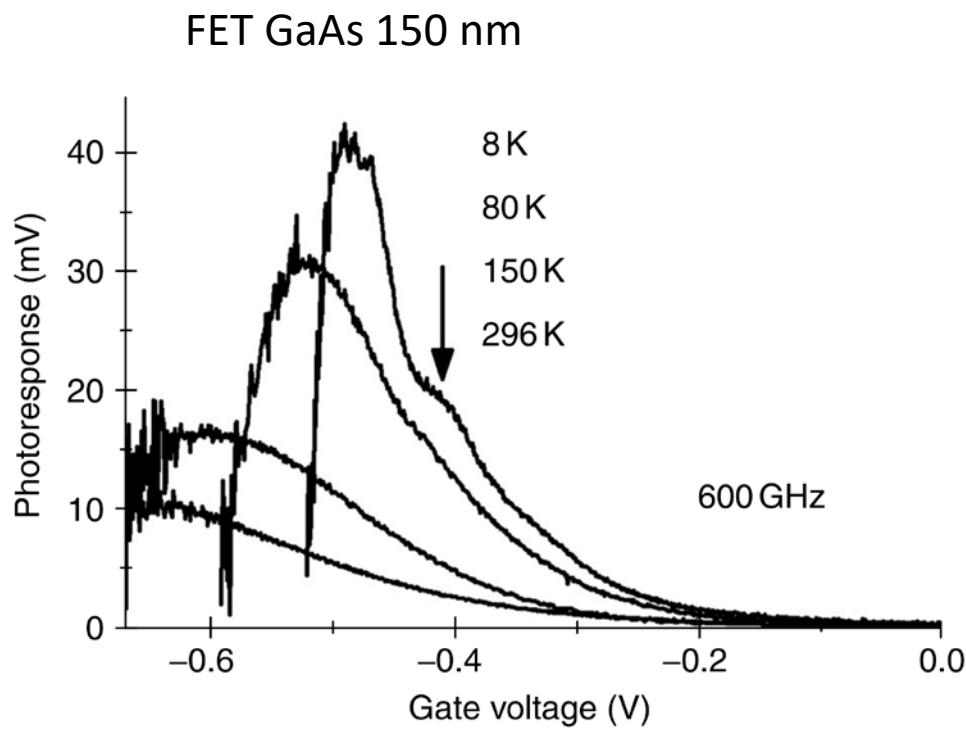
$$m = 0.06 - 0.26 m_e$$

$$\rightarrow f_p \approx 0.6 - 4 \text{ THz}$$



Dyakonov, M. and Shur, M. *IEEE Transactions on Electron Devices*, 43(3), p. 380, (1996)

Резонансное детектирование



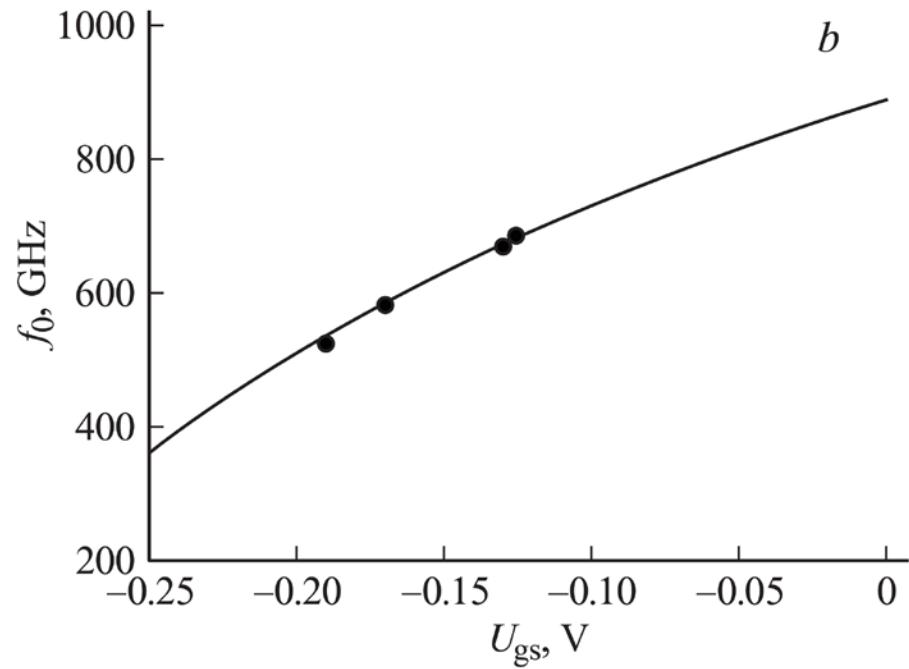
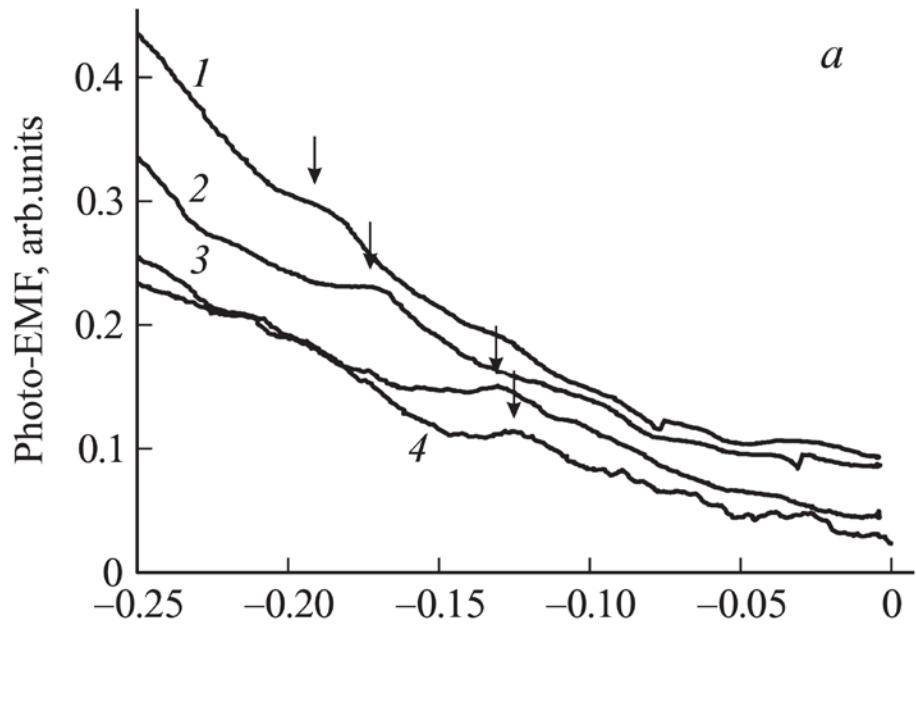
Knap, W., et al., *Journal of Applied Physics.*, 91(11), p. 9346, (2002)

El Fatimy, A. et al., *Applied Physics Letters.* 89(13), p. 131926. (2006)

Резонансное детектирование

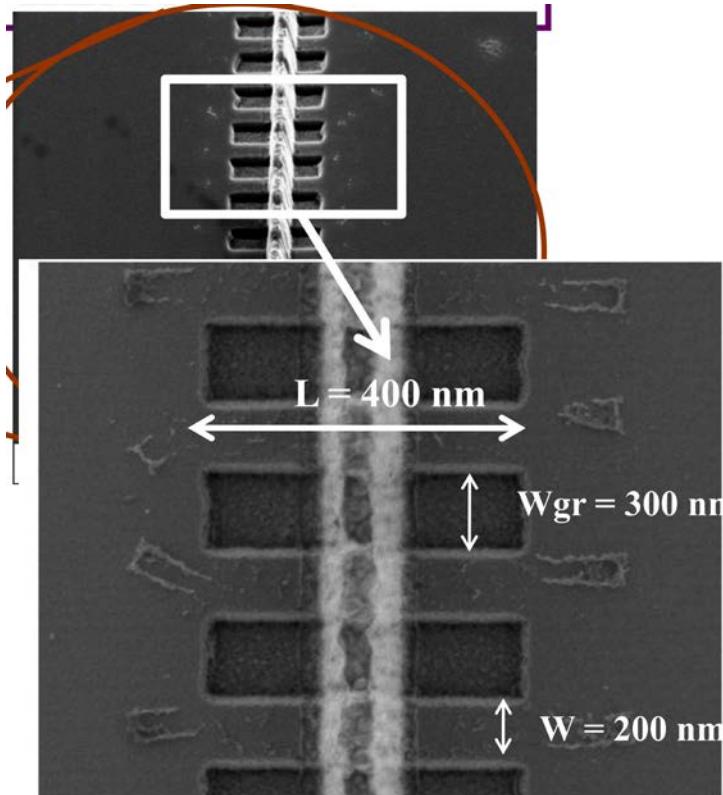
GaAs/AlGaAs при $T = 4.2\text{ K}$

$$f_0 = \frac{1}{4L} \sqrt{\frac{e}{m}} (U_{\text{gs}} - U_{\text{th}})$$

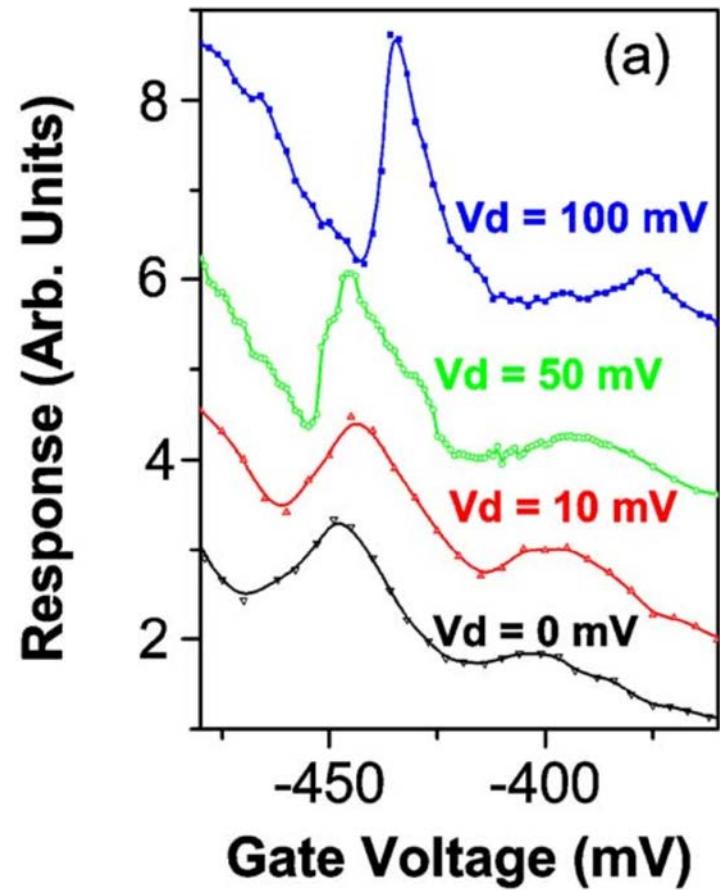


Мультиканальный FET

FET InGaAs/AlInAs 540 GHz 10 K

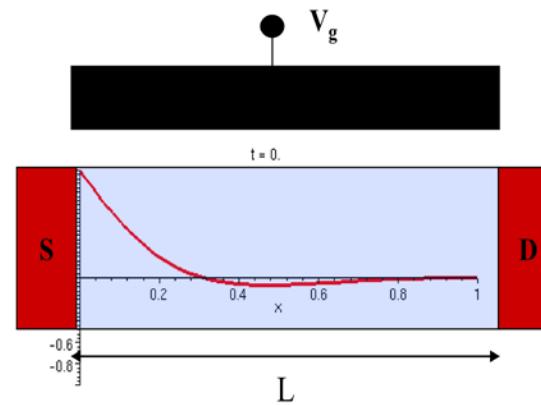
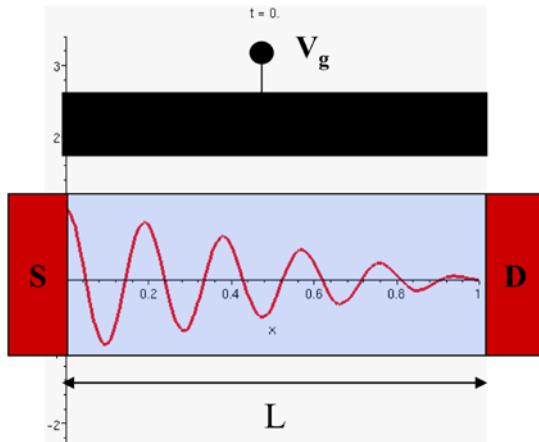


56 узких каналов



Boubanga-Tombet, S., et al., *APL*, 92(21),
p. 212101. (2008)

Резонансное и нерезонансное детектирование



$$\omega\tau \gg 1$$

$$\omega\tau \ll 1$$

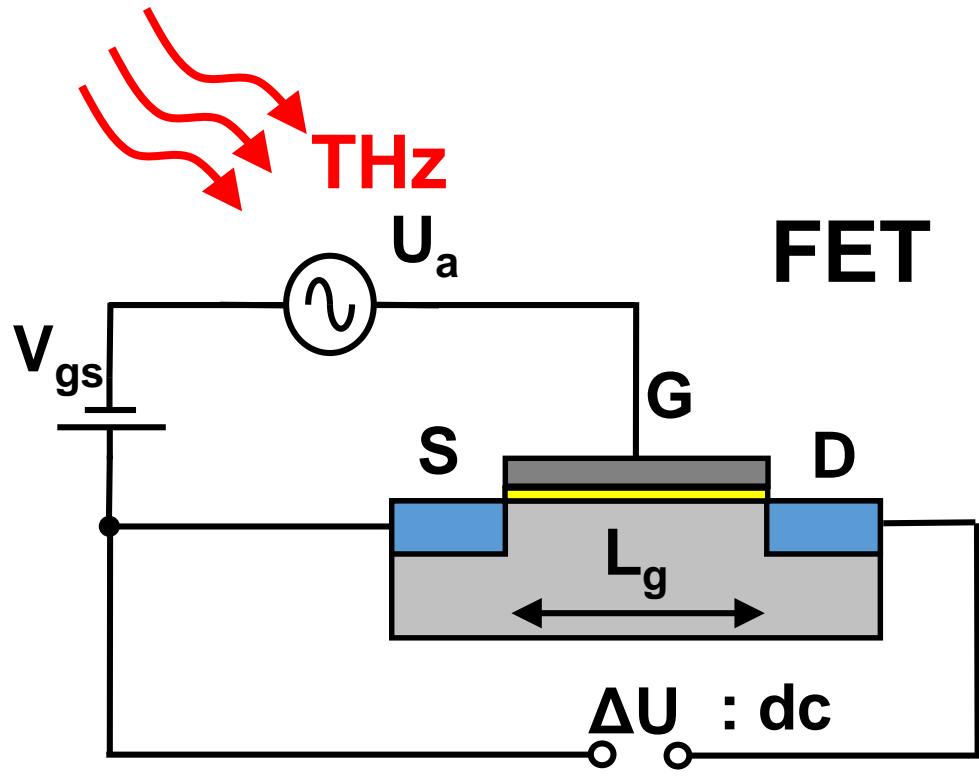
$$L \ll s\tau$$

$$l = s\sqrt{\frac{\tau}{\omega}}$$

Гелиевая температура

Комнатная температура

Нелинейность в нерезонансном случае



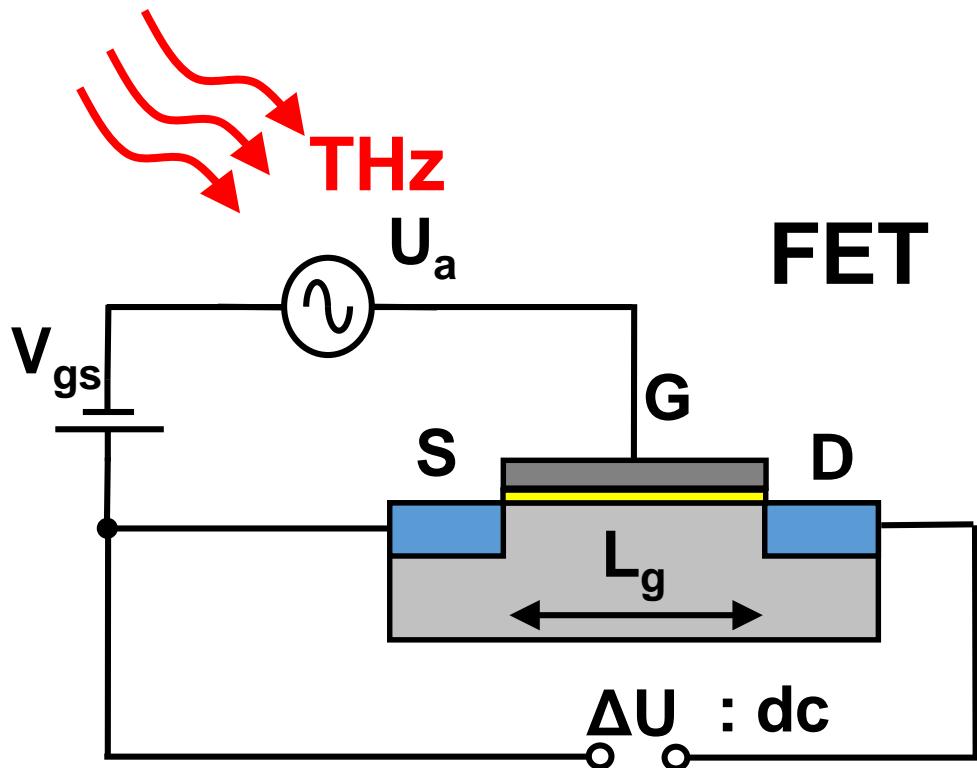
$$j = nev_d$$

$$v_d(t) = v_{d0} \cos(\omega t)$$

$$n(t) = n_0 \cos(\omega t)$$

$$\begin{aligned} j &= e \langle n(t) v_d(t) \rangle = \\ &= en_0 v_{d0} \langle \cos^2(\omega t) \rangle \end{aligned}$$

Детектирование в нерезонансном случае



$$C \frac{\partial U}{\partial t} - \frac{\partial}{\partial x} \sigma \frac{\partial U}{\partial x} = 0$$

$$U|_{x=0} = U_0 + U_a \cos(\omega t)$$

$$U|_{x \rightarrow \infty} = \text{const}$$

$$U(x, t) = U_0 + U_1(x, t) + U_2(x)$$

$$C \frac{\partial U_1}{\partial t} - \sigma_0 \frac{\partial^2 U_1}{\partial x^2} = 0$$

$$U_1(x, t) = U_a \exp(-kx) \cos(\omega t - kx)$$

$$k = \frac{\omega C}{2\sigma_0}$$

Детектирование в нерезонансном случае

$$C \frac{\partial U}{\partial t} - \frac{\partial}{\partial x} \sigma \frac{\partial U}{\partial x} = 0$$

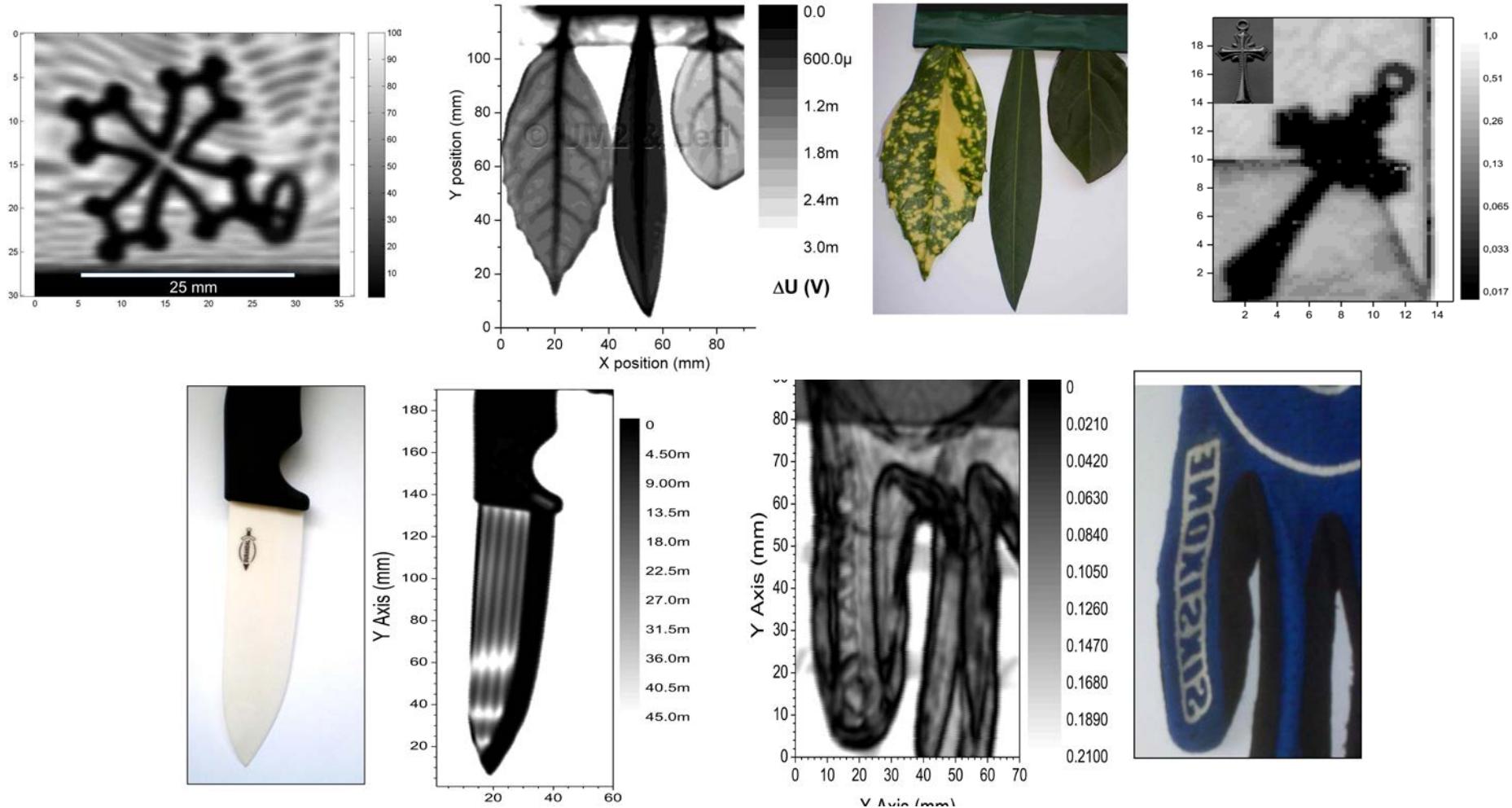
$$\begin{aligned}U(x, t) &= U_0 + U_1(x, t) + U_2(x) \\U_1(x, t) &= U_a \exp(-kx) \cos(\omega t - kx)\end{aligned}$$

$$\frac{d}{dx} \left[\sigma_0 \frac{dU_2}{dx} + \frac{\partial \sigma}{\partial U} \Bigg|_{U=U_0} \left\langle U_1 \frac{\partial U_1}{\partial x} \right\rangle \right] = 0$$

$$U_2(x) = \frac{U_a^2}{4} \frac{1}{\sigma_0} \frac{d\sigma}{dU} \Bigg|_{U=U_0} (1 - \exp(-2kx))$$

$$U(x) = \frac{U_a^2}{4} \frac{1}{\sigma_0} \frac{d\sigma}{dU} \Bigg|_{U=U_0}$$

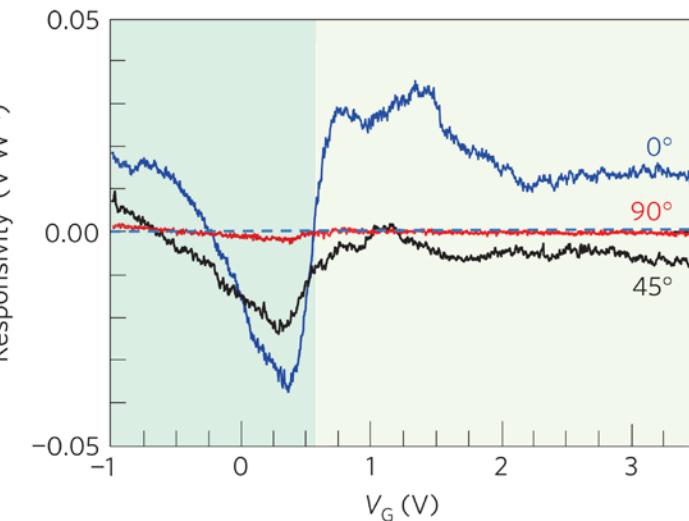
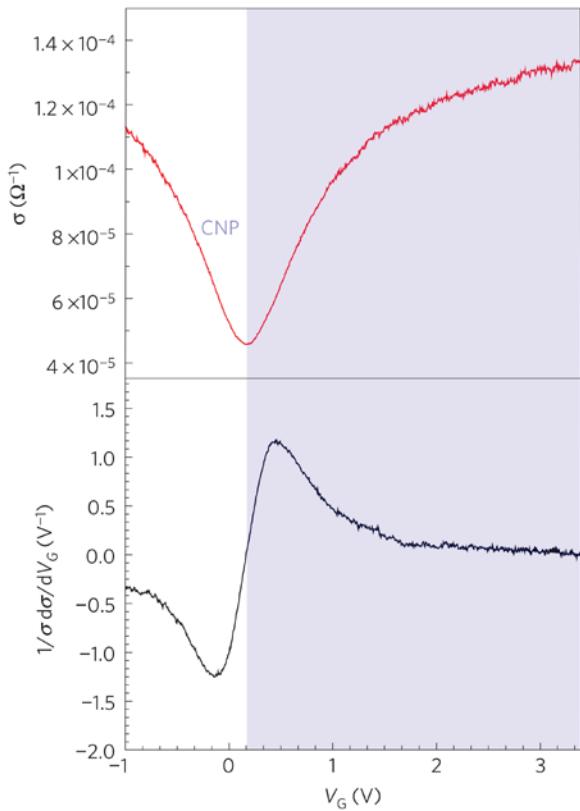
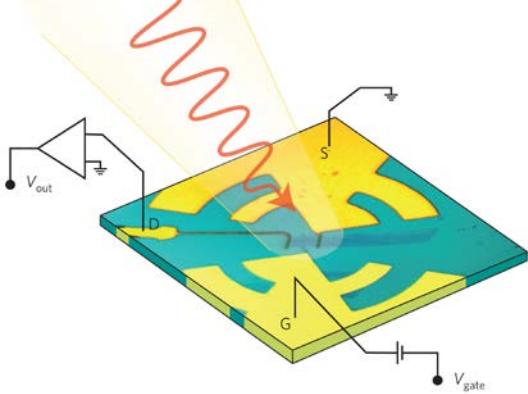
ТГц детектирование при комнатной температуре



A. Lisauskas, W. von Spiegel, S. Boubanga, A. El Fatimy, D. Coquillat, F. Teppe, N. Dyakonova, W. Knap, and H. G. Roskos, Electr. Lett. **44**, 408 (2008).

ТГц детектирование при комнатной температуре

FET graphene on SiO_2

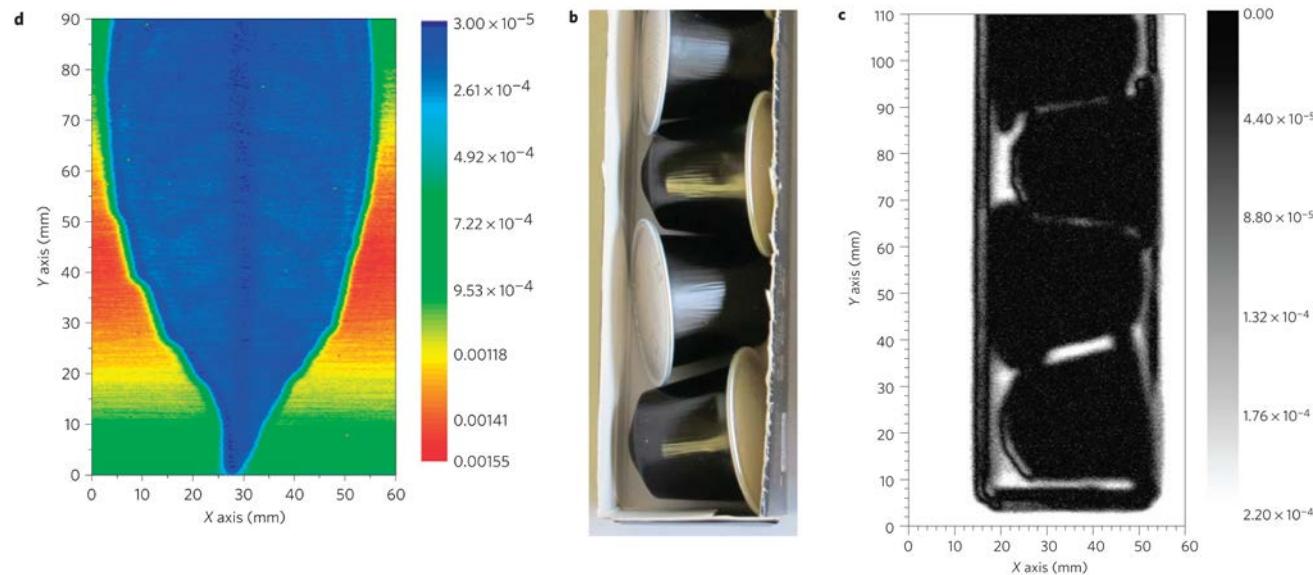
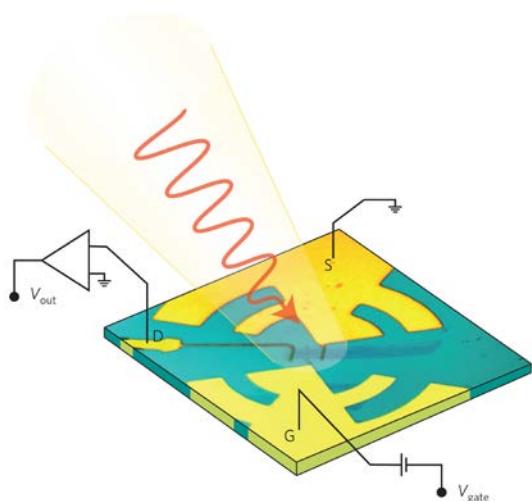


$$U(x) = \frac{U_a^2}{4} \frac{1}{\sigma_0} \frac{d\sigma}{dU} \Big|_{U=U_0}$$

Vicarelli, L., et al., *Nature Materials*, 11(10), p. 865. (2012)

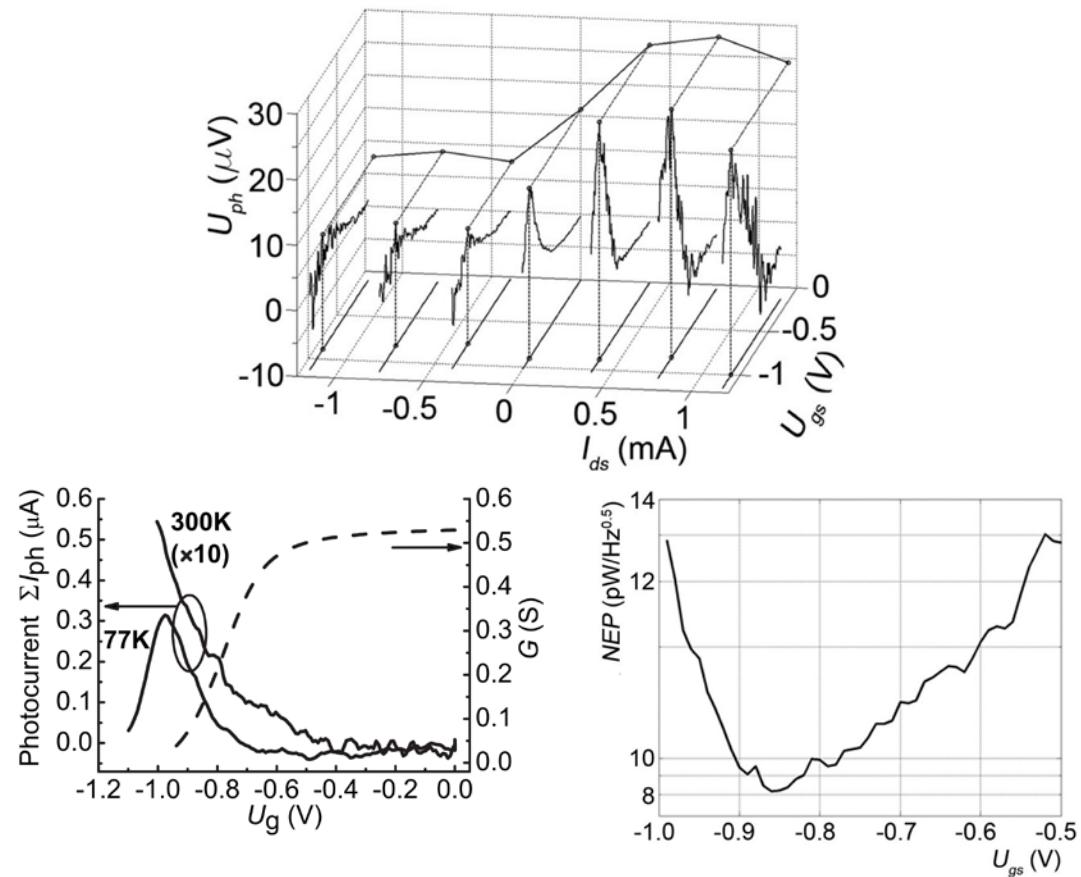
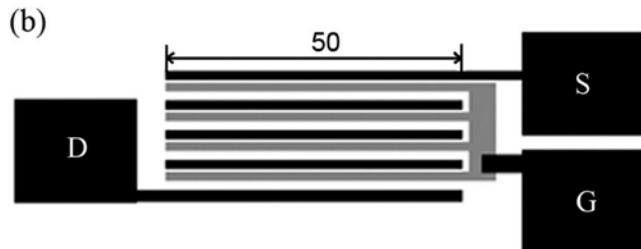
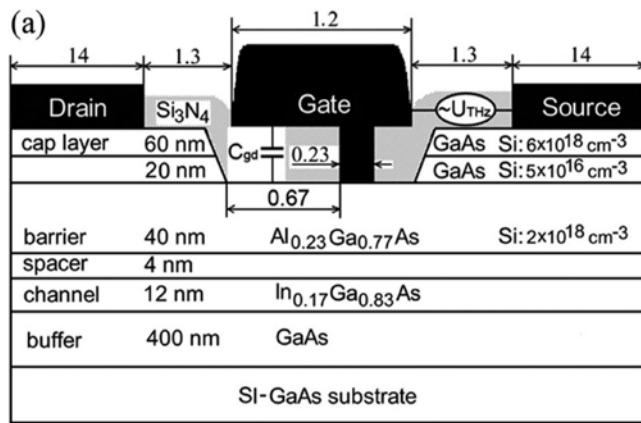
ТГц детектирование при комнатной температуре

Graphene FET



Vicarelli, L., et al., *Nature Materials*, 11(10), p. 865. (2012)

ТГц детектирование при комнатной температуре

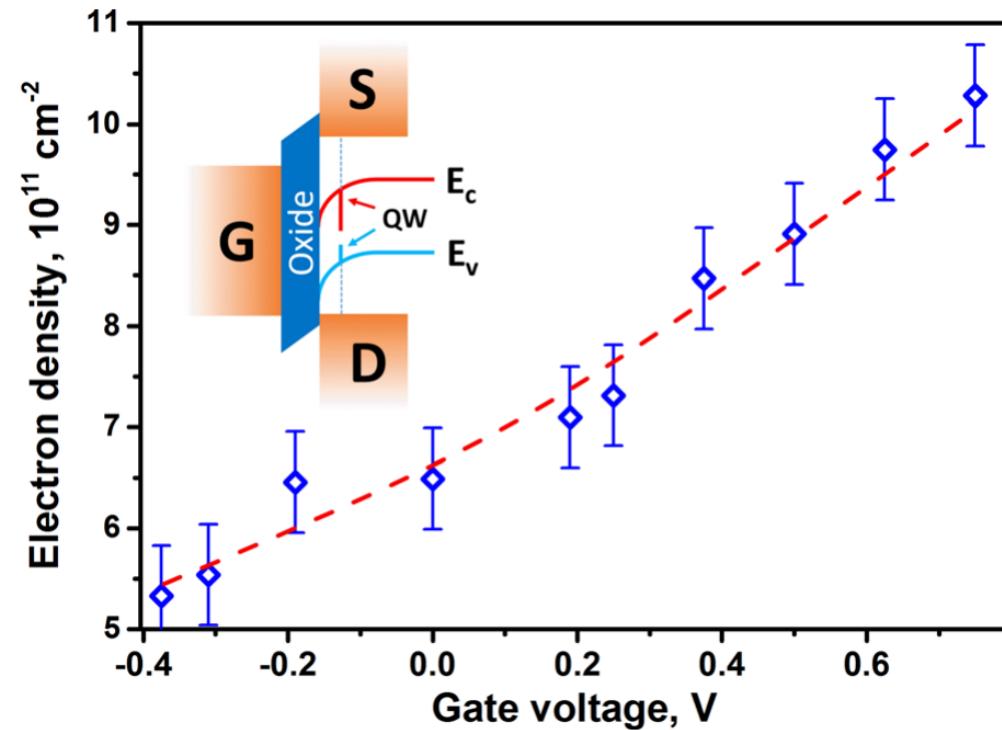
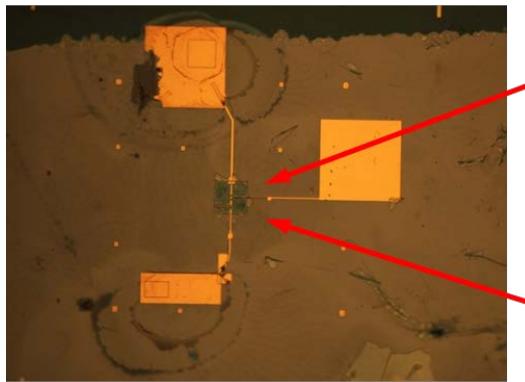
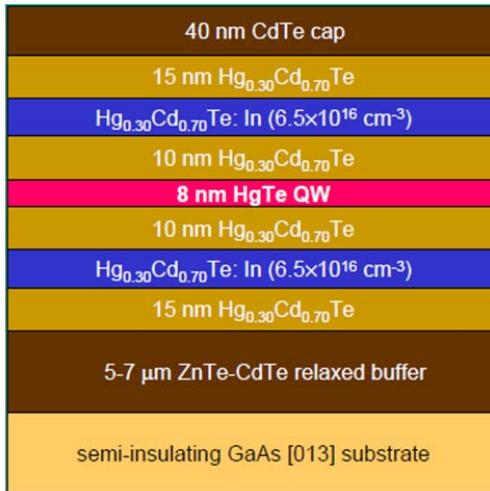


Popov, V. V., et al., *APL*, 104(16), p. 163508. (2014)

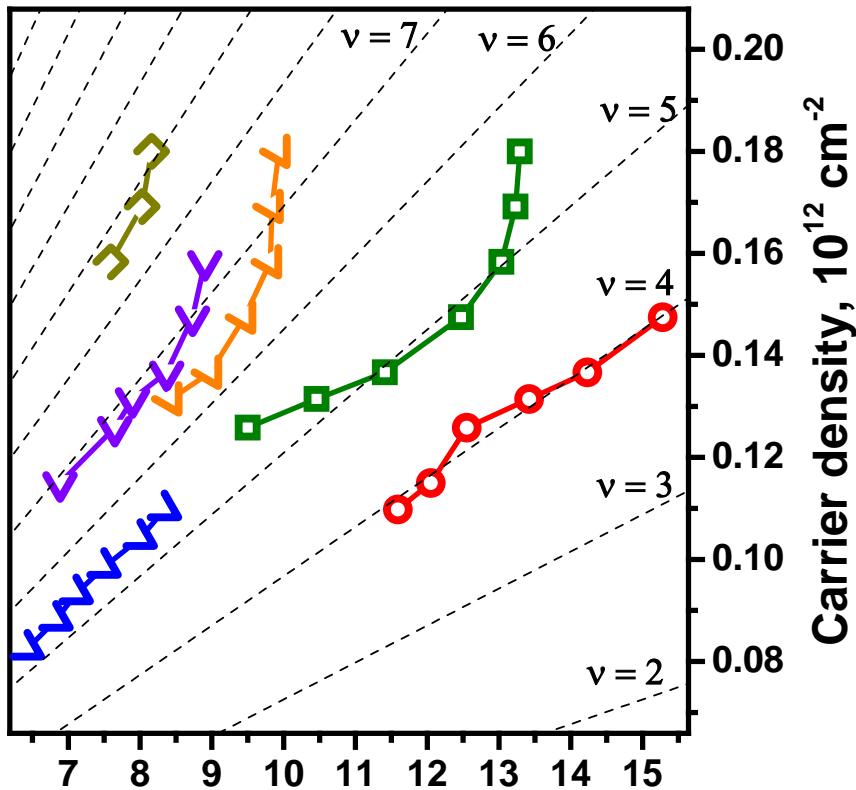
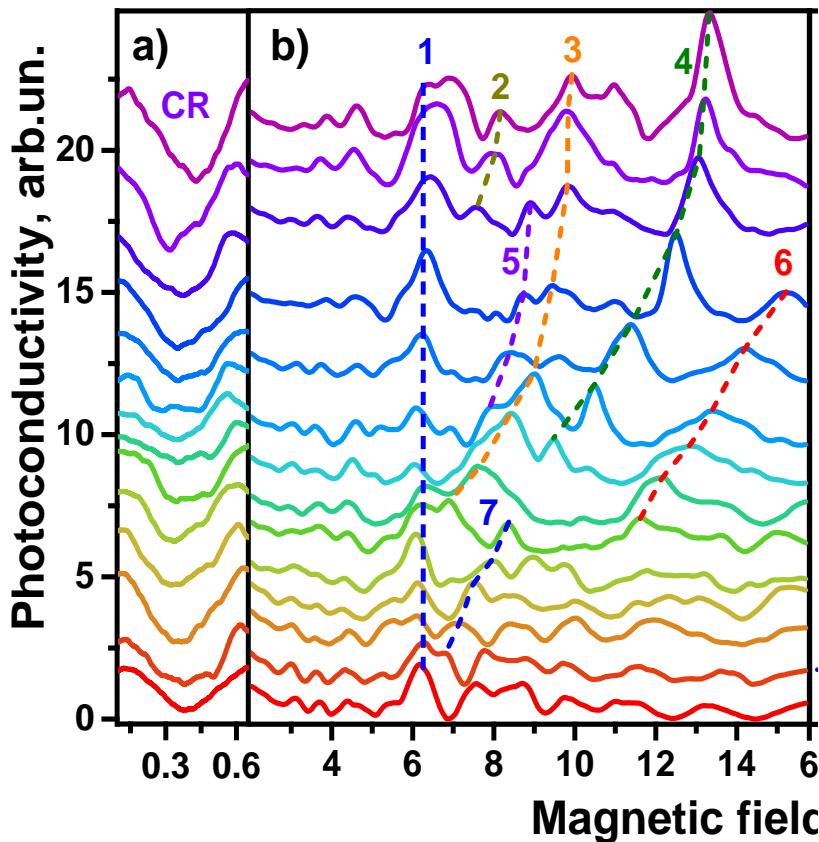
Popov, V. V., et al., *APL*, 98(15), p. 153504. (2011)

Исследование полевых транзисторов на основе гетероструктур HgTe/CdHgTe

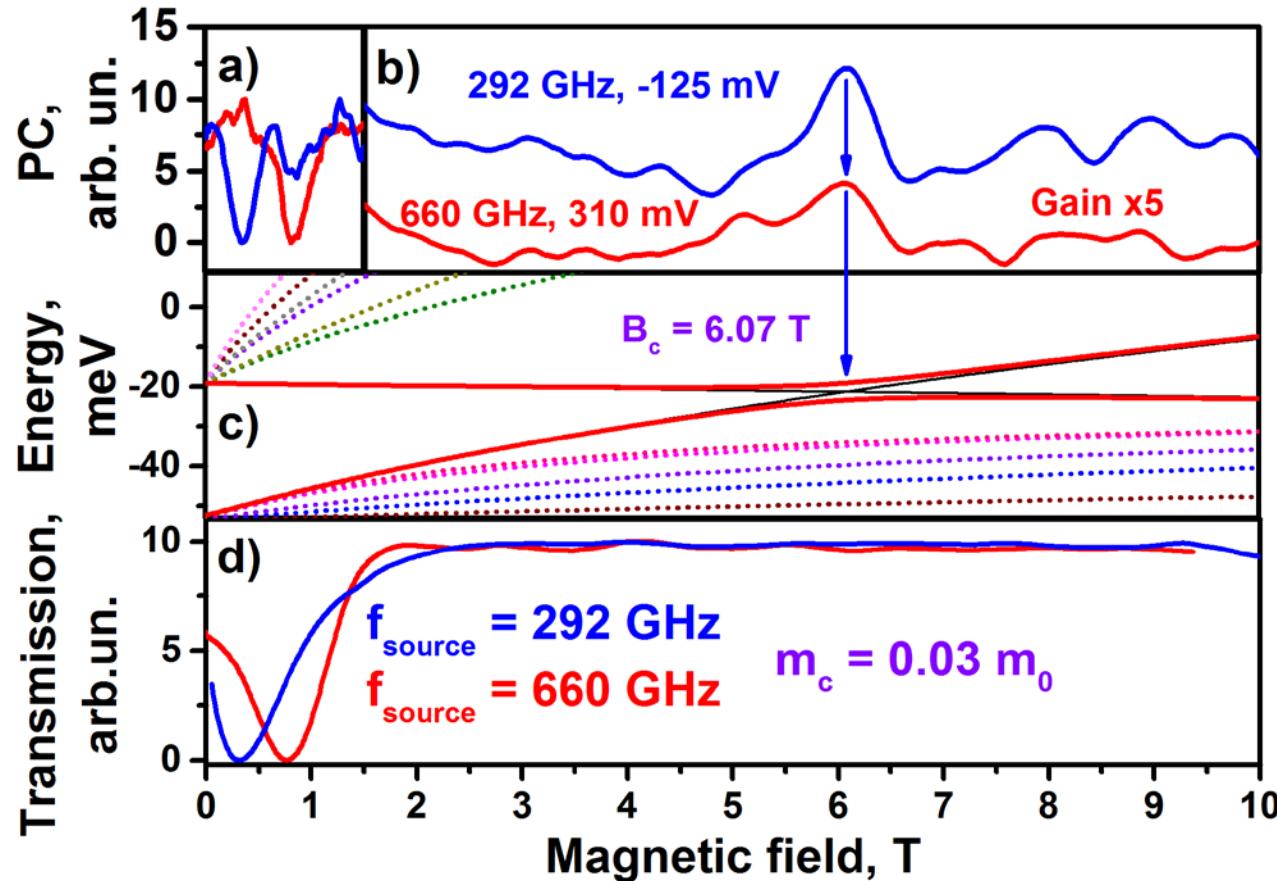
Инвертированная КЯ HgCdTe



ФОТООТКЛИК В МАГНИТНОМ ПОЛЕ ПОЛЕВЫХ ТРАНЗИСТОРОВ НА ОСНОВЕ ГЕТЕРОСТРУКТУР HgTe/CdHgTe

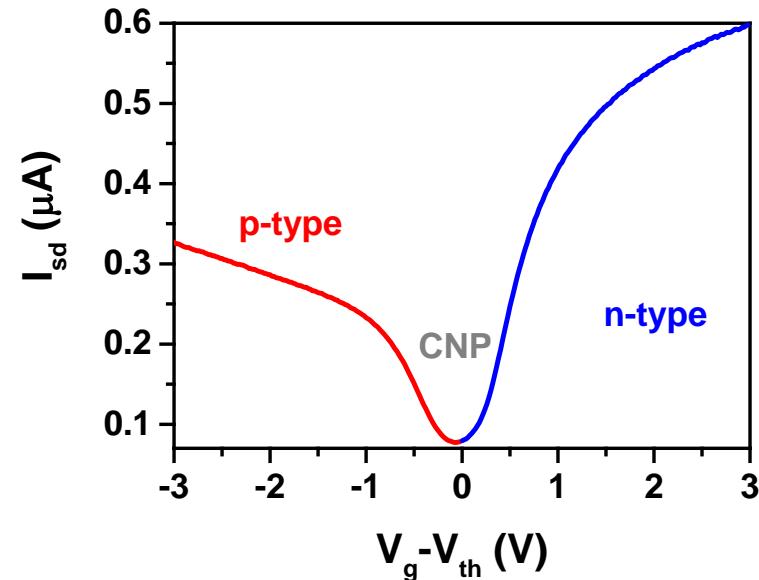
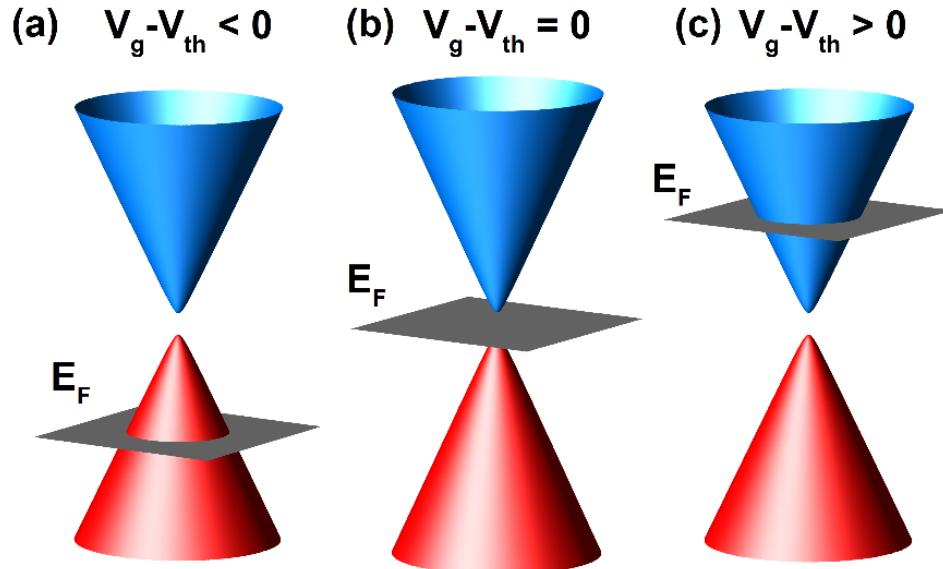
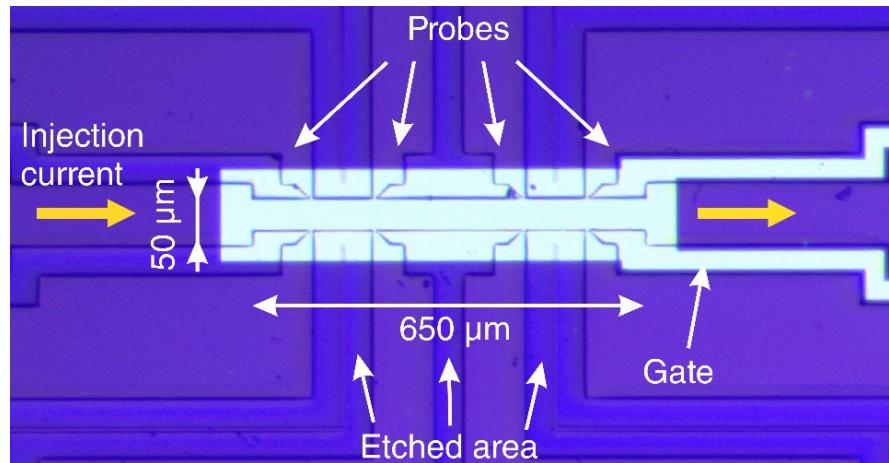


ФОТООТКЛИК В МАГНИТНОМ ПОЛЕ ПОЛЕВЫХ ТРАНЗИСТОРОВ НА ОСНОВЕ ГЕТЕРОСТРУКТУР HgTe/CdHgTe

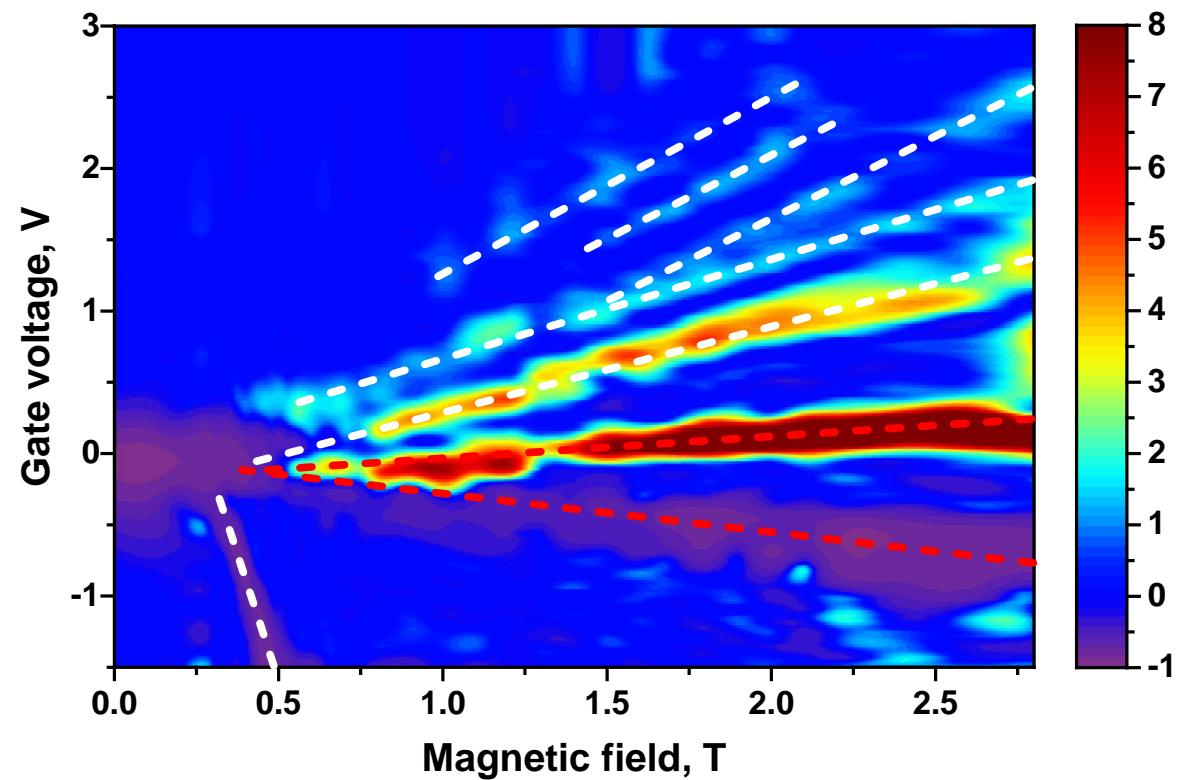
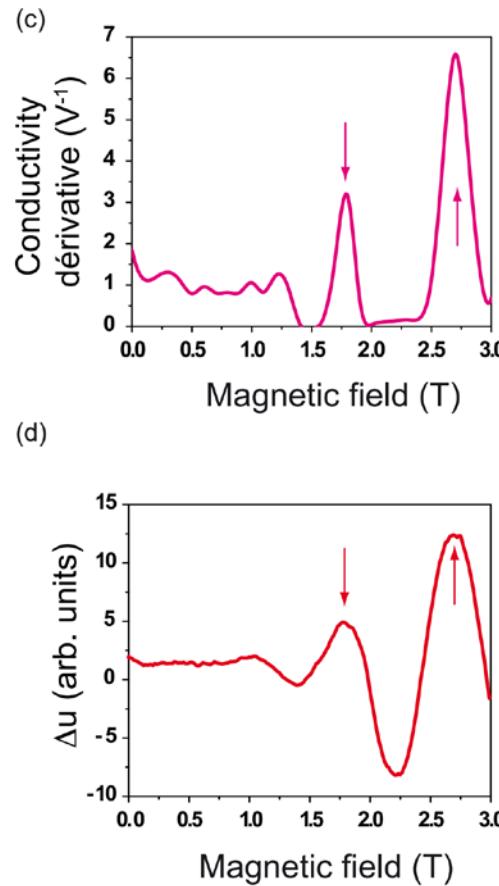


Холловский мостик с затвором

$$d_{\text{QW}} = 6.6 \text{ nm} \\ > d_c \approx 6.3 \text{ nm}$$

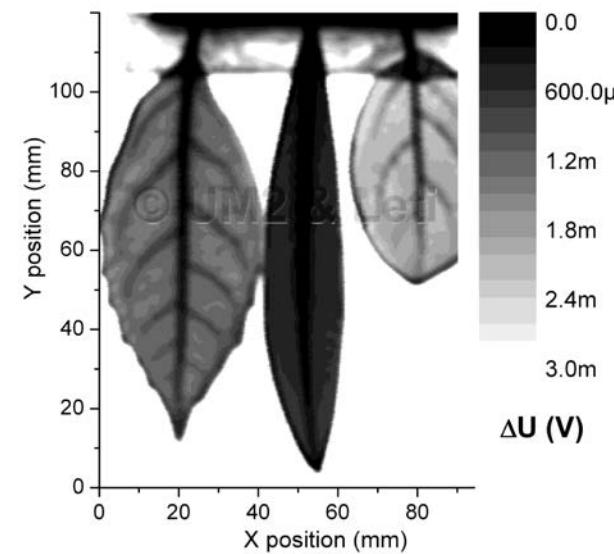
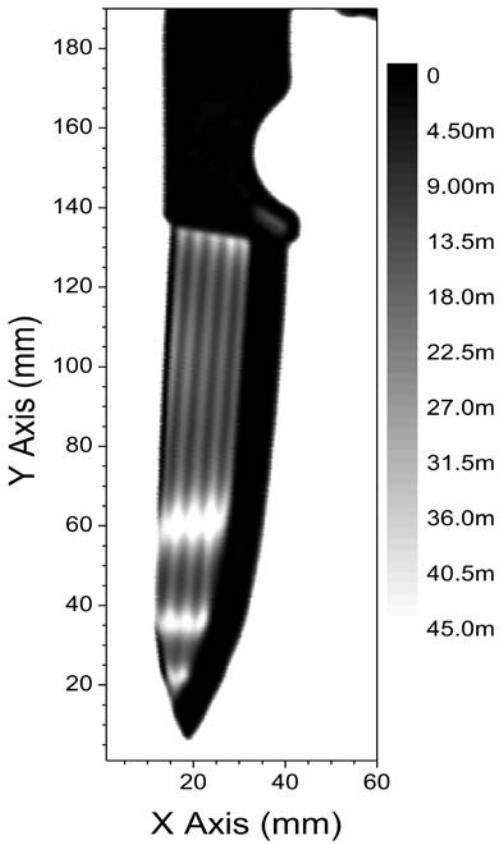


Фотоотклик на монохроматичное ТГц излучение



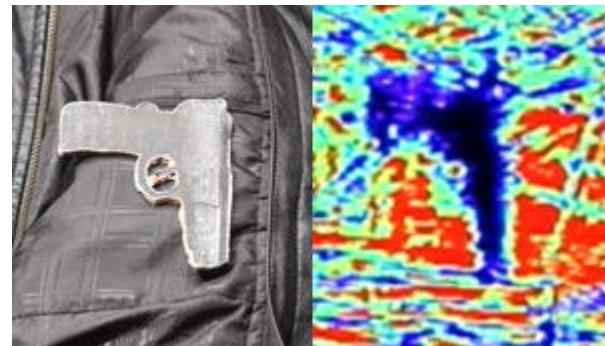
$$\Delta U = \frac{U_a^2}{4} \left[\frac{1}{\sigma} \frac{d\sigma}{dU} \right]_{U=V_g} = \frac{U_a^2}{4} \frac{d(\ln \sigma)}{dV_g}$$

Спасибо за внимание



Практические разработки

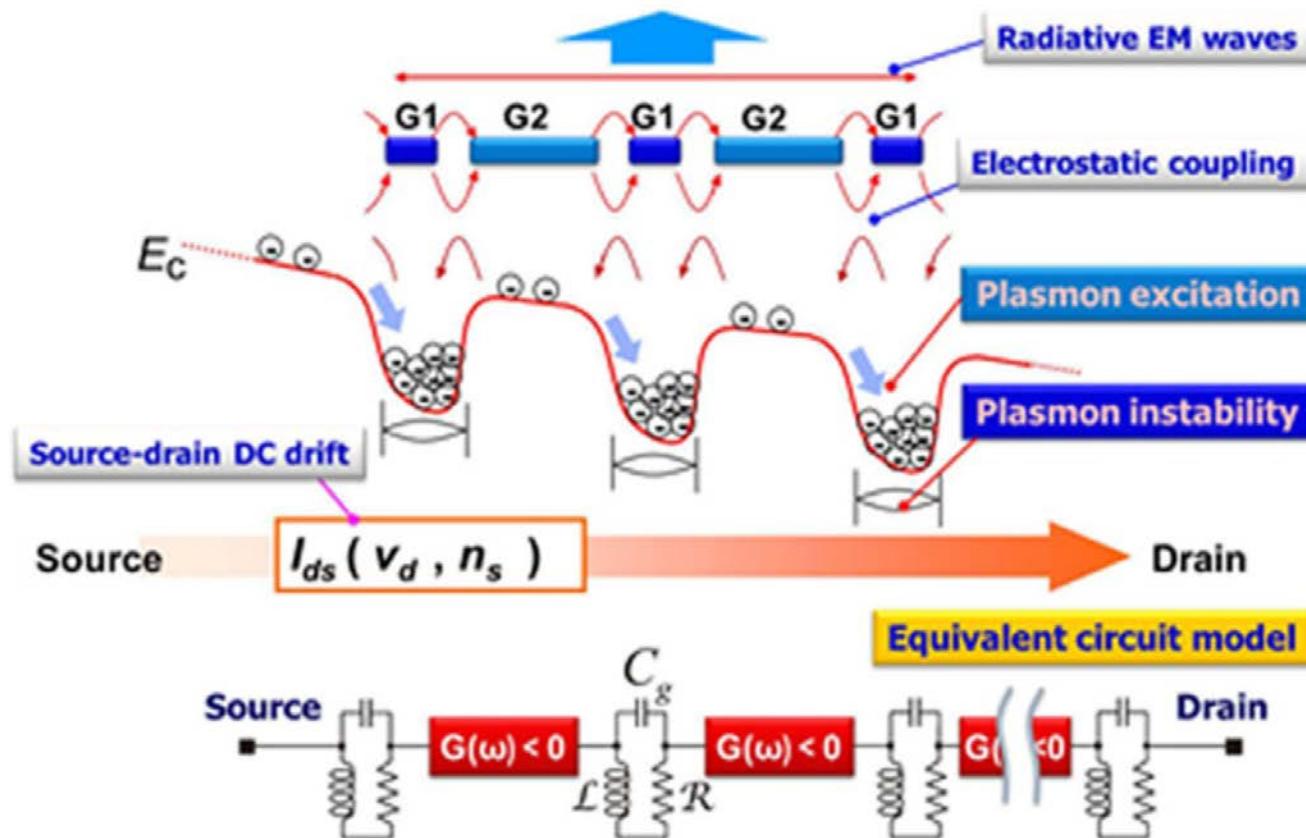
Tera~~S~~ense



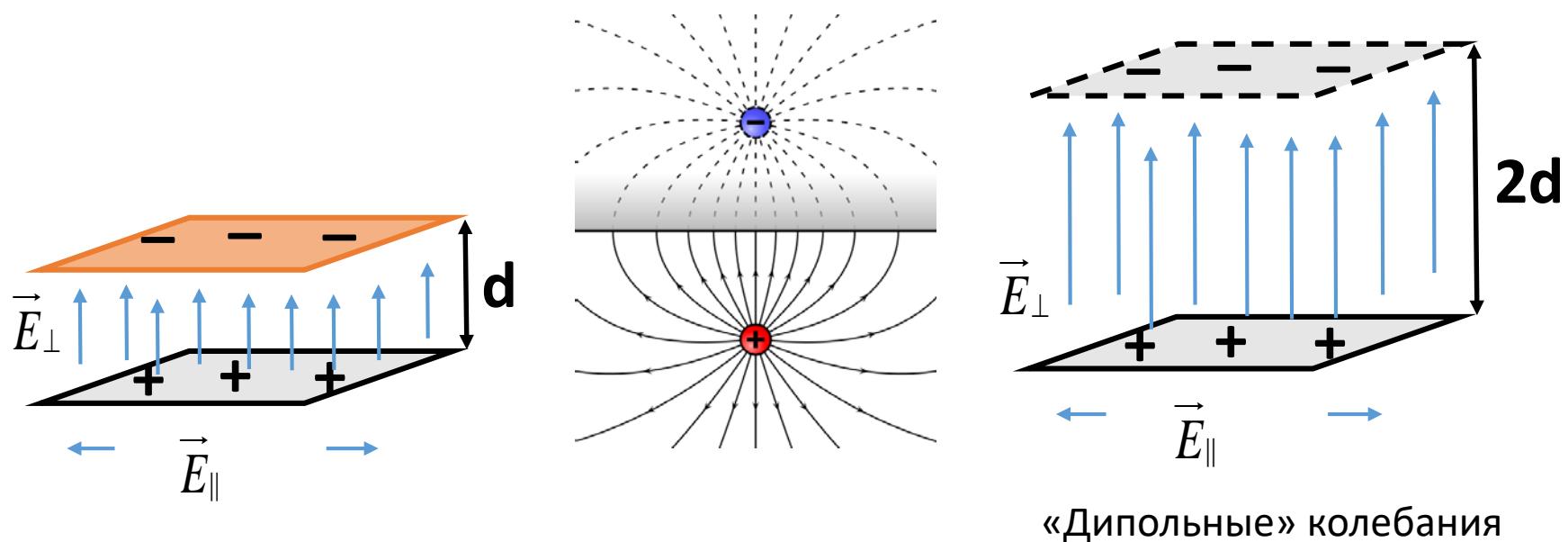
Ultrafast Terahertz Detectors

| | Ultrafast | Fast |
|------------------------|--------------------------|--------------------------|
| Response time | 150 ps | 1 μ s |
| Spectral range | 50 GHz - 0.7 THz | 50 GHz - 0.7 THz |
| Impedance | 50 Ω | 10 k Ω |
| Responsivity | 0.5 V/W | 10 V/W |
| Noise equivalent power | 2 nW/ $\sqrt{\text{Hz}}$ | 1 nW/ $\sqrt{\text{Hz}}$ |
| No power supply | ✓ | ✓ |

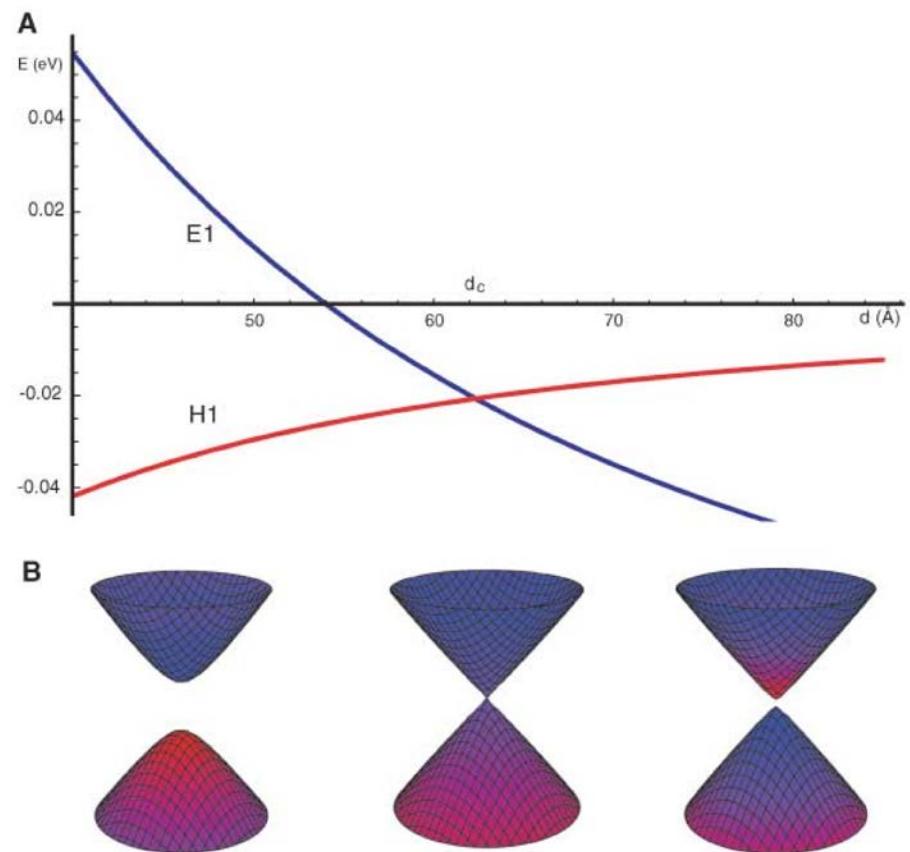
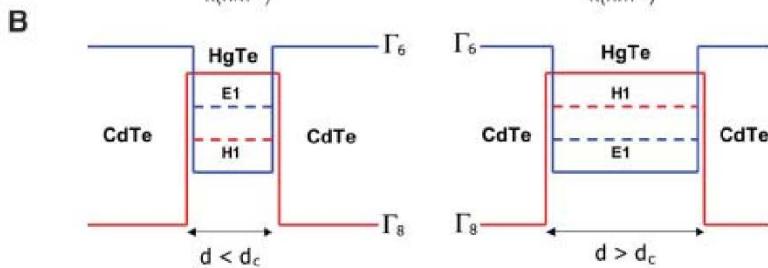
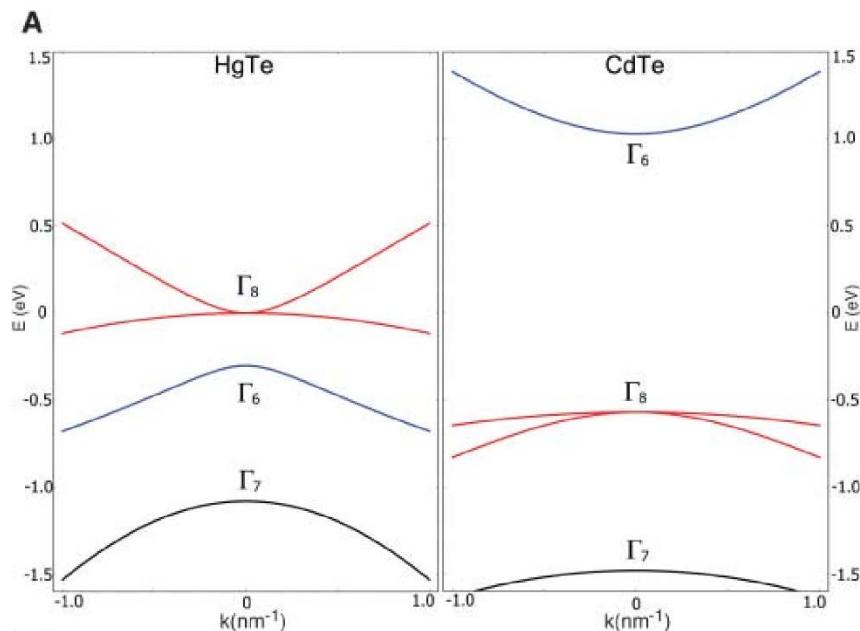
Затворы в виде двойной решётки



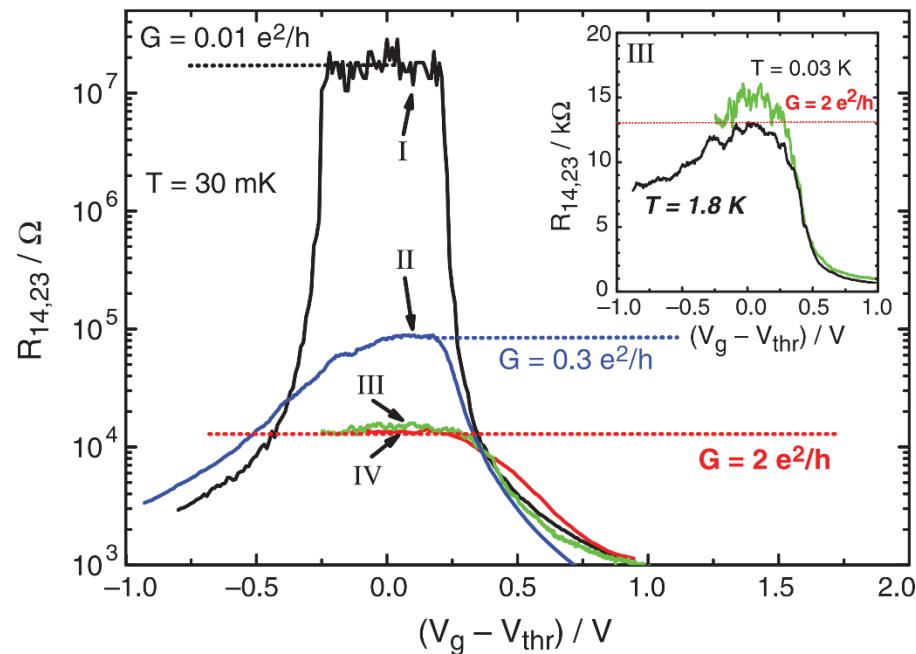
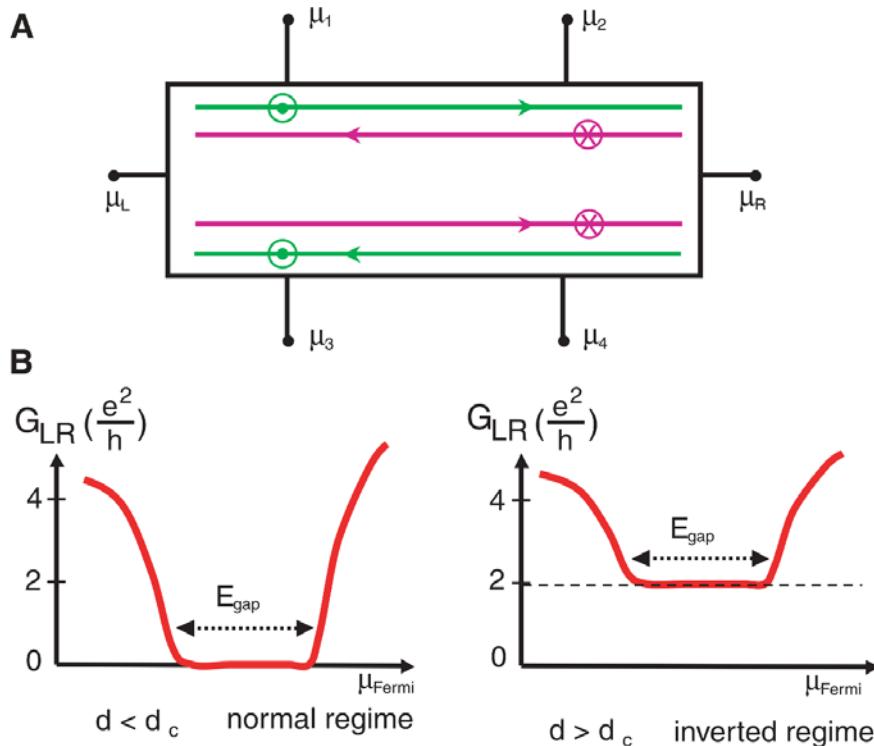
Плазмоны в двумерных полупроводниках с затвором



Зонная структура КЯ HgTe/CdHgTe



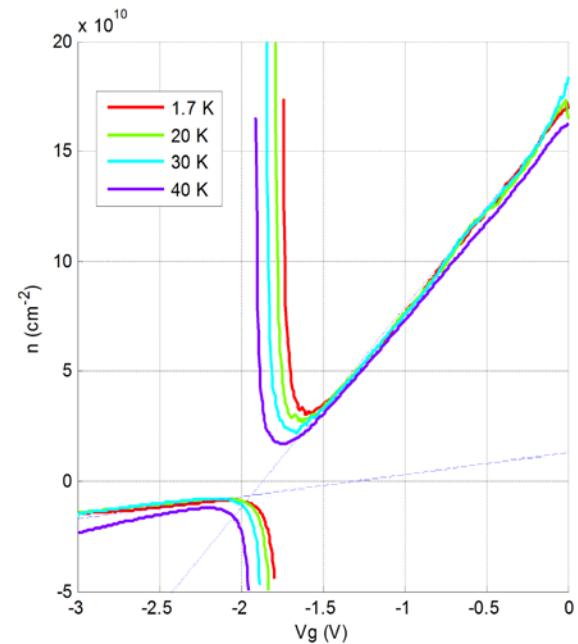
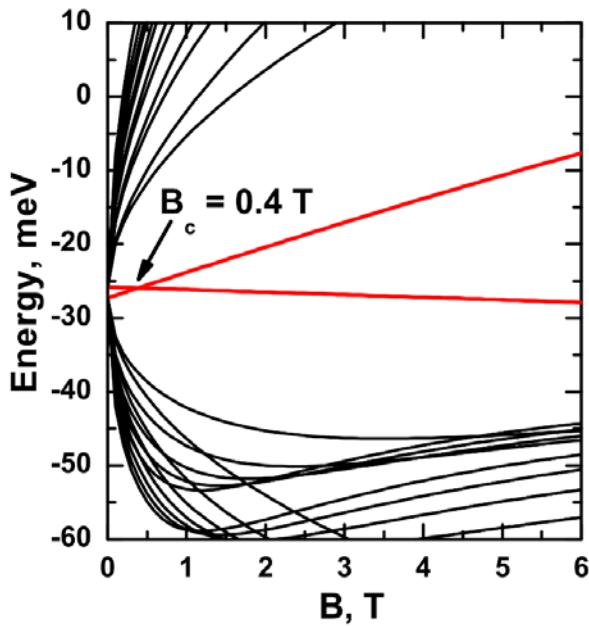
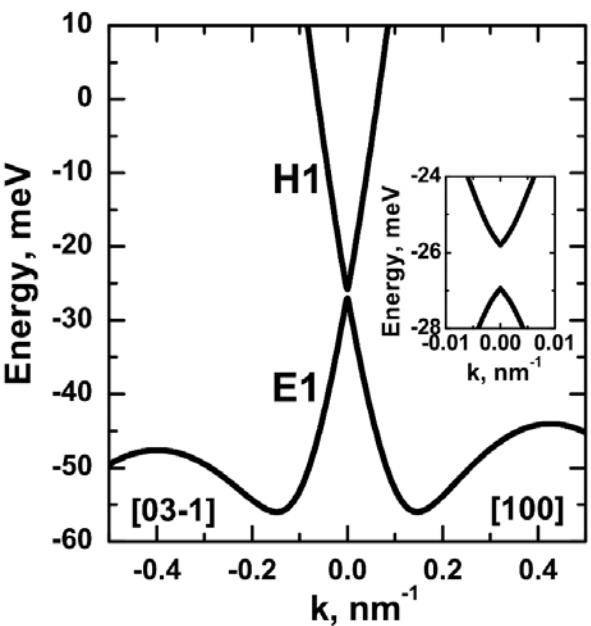
Квантовый спиновый эффект Холла



Bernevig, B. A., Hughes, T. L. and Zhang,
S.-C. (2006), *Science*, 314(5806), pp.
1757–1761.

Konig, M., et. al., *Science*, 318(5851), pp. 766–770.

Связь E_F с затворным напряжением

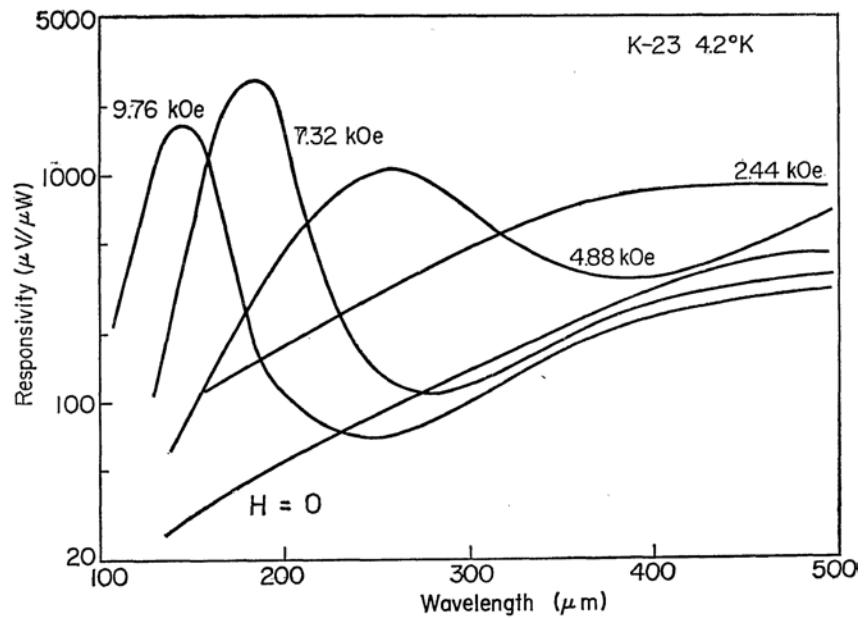


$$n \sim V_g$$

$$n \sim \int_{E_F} D(E) dE$$

Циклотронный резонанс между уровнями Ландау

n-type InSb
4.2 K



Циклотронный резонанс и плазменные колебания

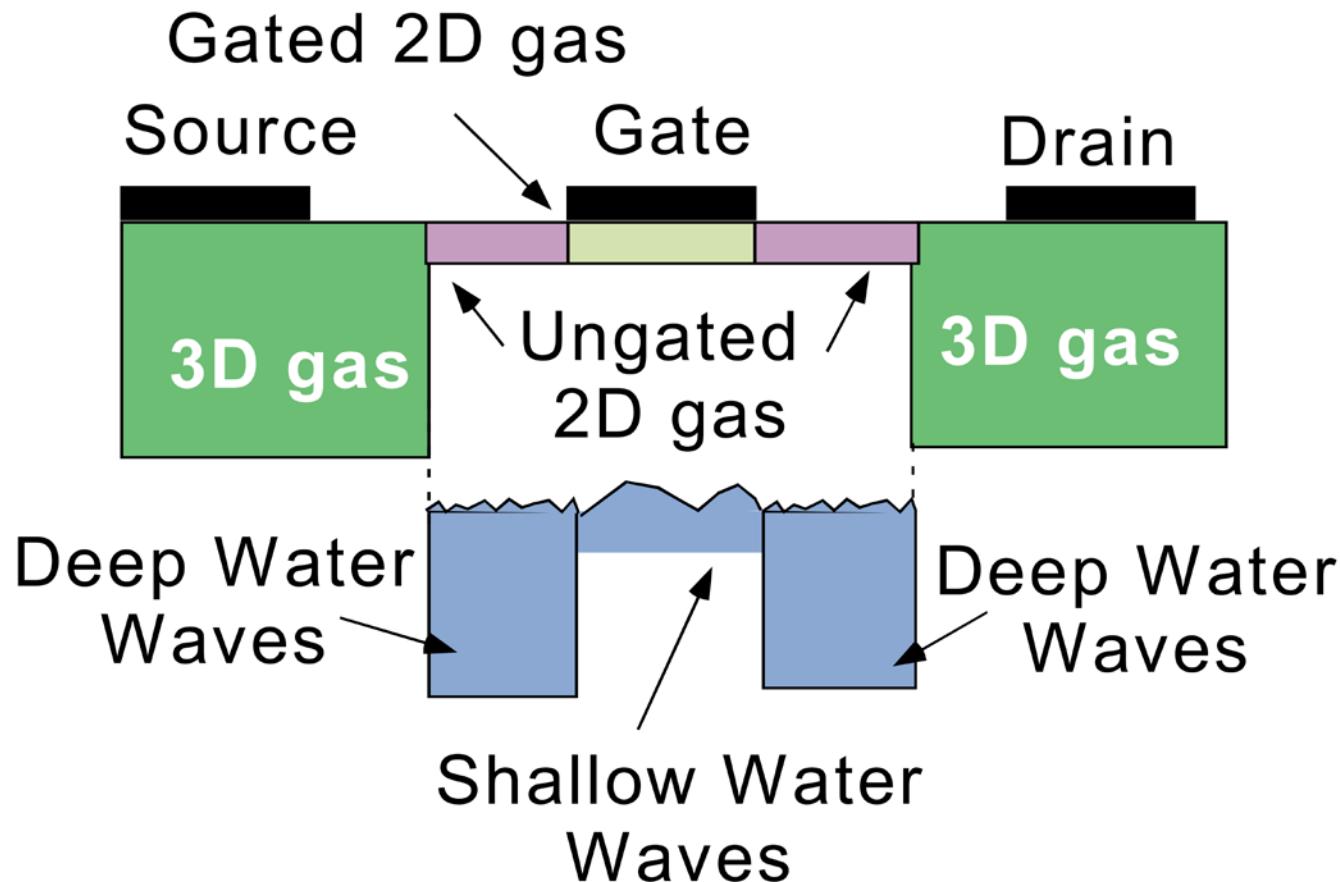
$$\omega = sk$$

$$\omega = \sqrt{\omega_c^2 + (sk)^2}$$

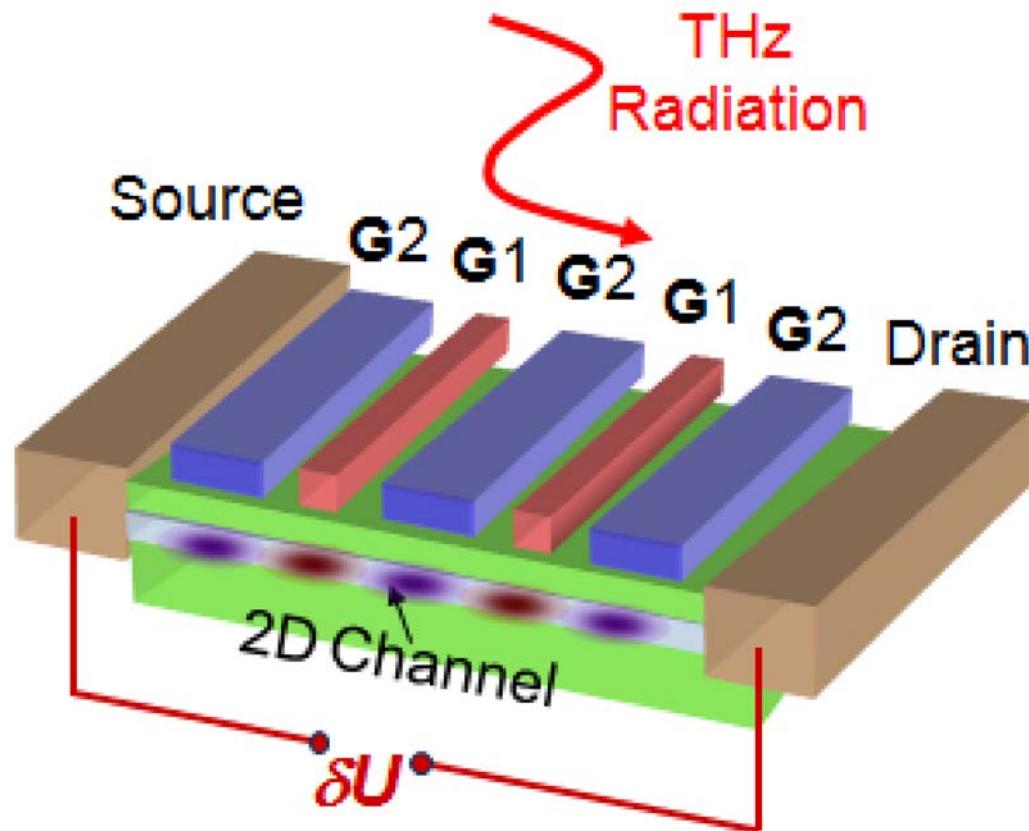
$$k = \frac{\omega}{s} \sqrt{1 - \frac{\omega^2}{\omega_c^2}}$$

При $\omega < \omega_c$ плазменные возбуждения не распространяются

Утечка плазменных возбуждений из подзатворной области



FET с двойным решётчатым затвором



Параметры ТГц детекторов комнатной температуры

| | Sampling frequency (MAX) | NEP (pW/Hz^{0.5}) |
|-----------------|--------------------------|------------------------------------|
| Golay Cell | ~20Hz | 100 |
| Pyroelectric | <10KHz | 1000 |
| Schottky Diodes | < 20GHz | 10 |
| Microbolometers | <1MHz | 10 |
| Si transistors | 30GHz or higher | 10 |

Разогрев электронного газа

$$j = nev_d$$

$$v_d = \mu E$$

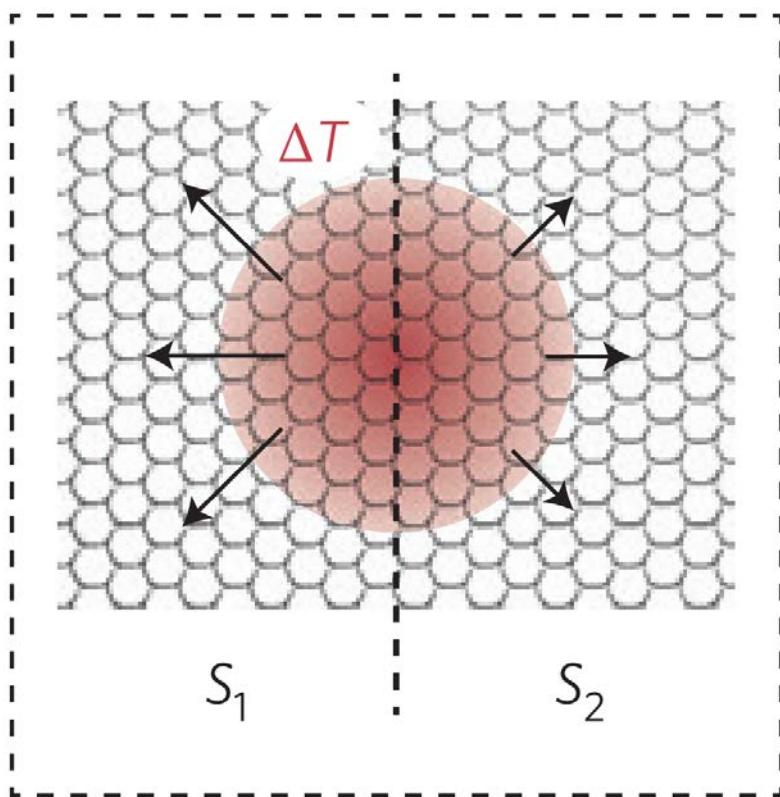
$$\frac{1}{\mu} = aT^{-3/2} + bT^{3/2}$$


Changes by 2DEG THz heating

PC \sim injection current

Фототермоэлектрический эффект

Photo-thermoelectric



$$V_{\text{PTE}} = (S_1 - S_2) \Delta T_e$$

$$\bar{V}_{\text{PTE}} = \int \mathbf{S} \cdot \nabla T_e \, dx$$

$$S = - \frac{\pi^2 k_B^2 T_e}{3q} \frac{1}{\sigma} \frac{\partial \sigma}{\partial \varepsilon}$$