Кафедра наноэлектроники и квантовых компьютеров

Приборы полупроводниковой микро- и наноэлектроники

В.В. Вьюрков – лектор, зам. зав. кафедрой

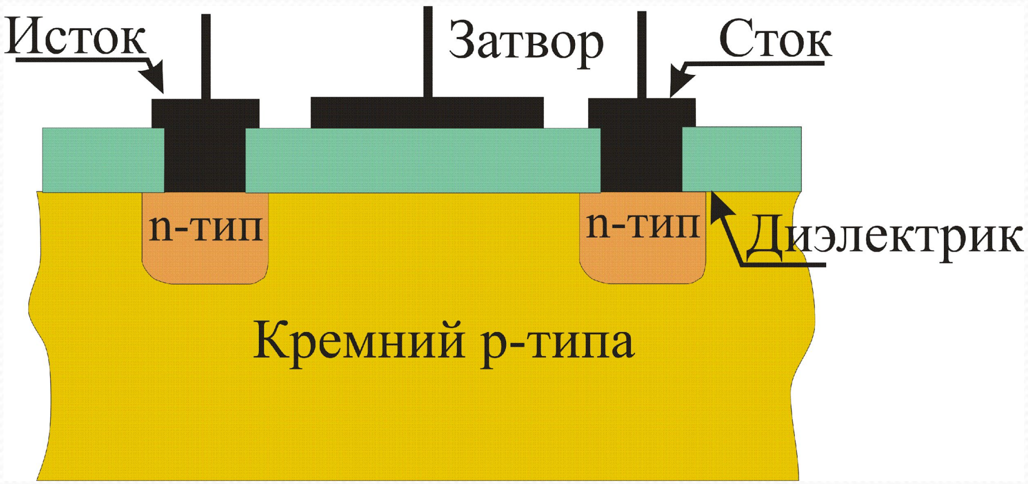
Факультет физической и квантовой электроники (ФФКЭ МФТИ)

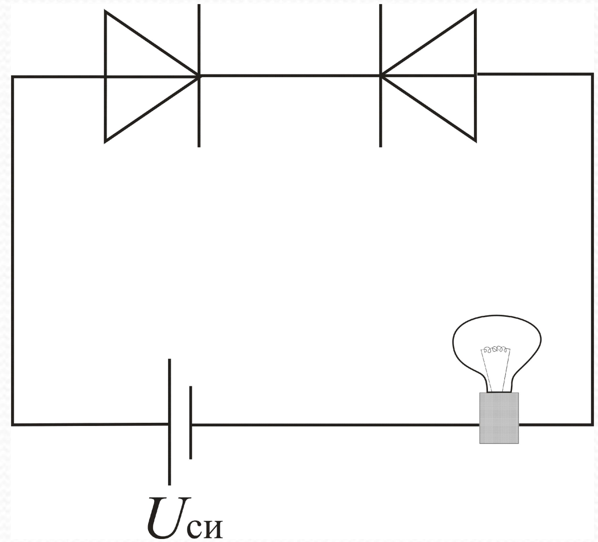
Физико-технологический институт
Российской академии наук

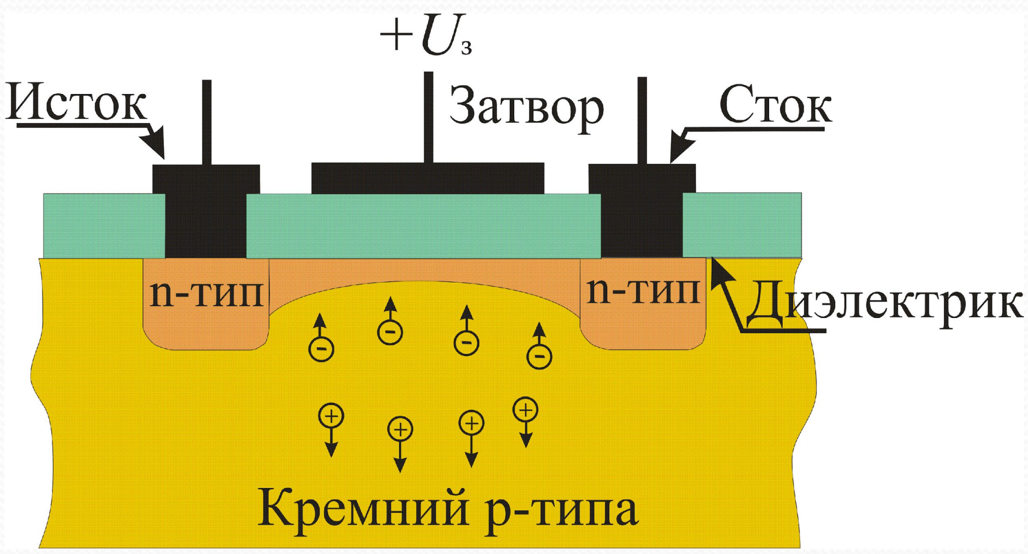
План лекций

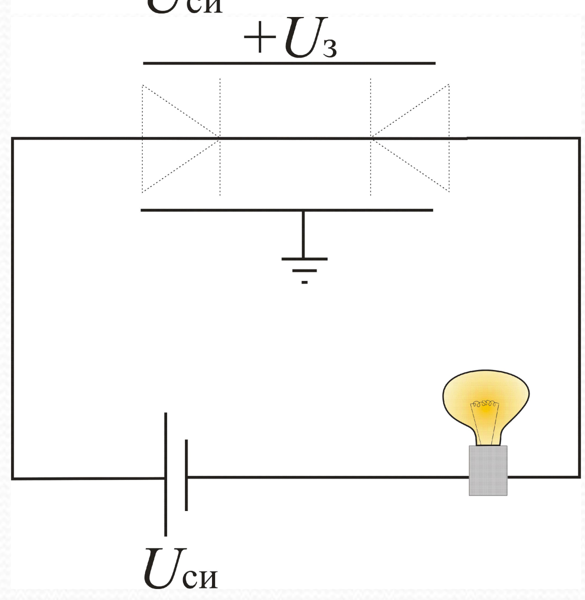
- Технология наноэлектронных приборов
- Теория наноэлектронных приборов
- Квантовые компьютеры

Полевой транзистор – прибор с варьируемым сопротивлением

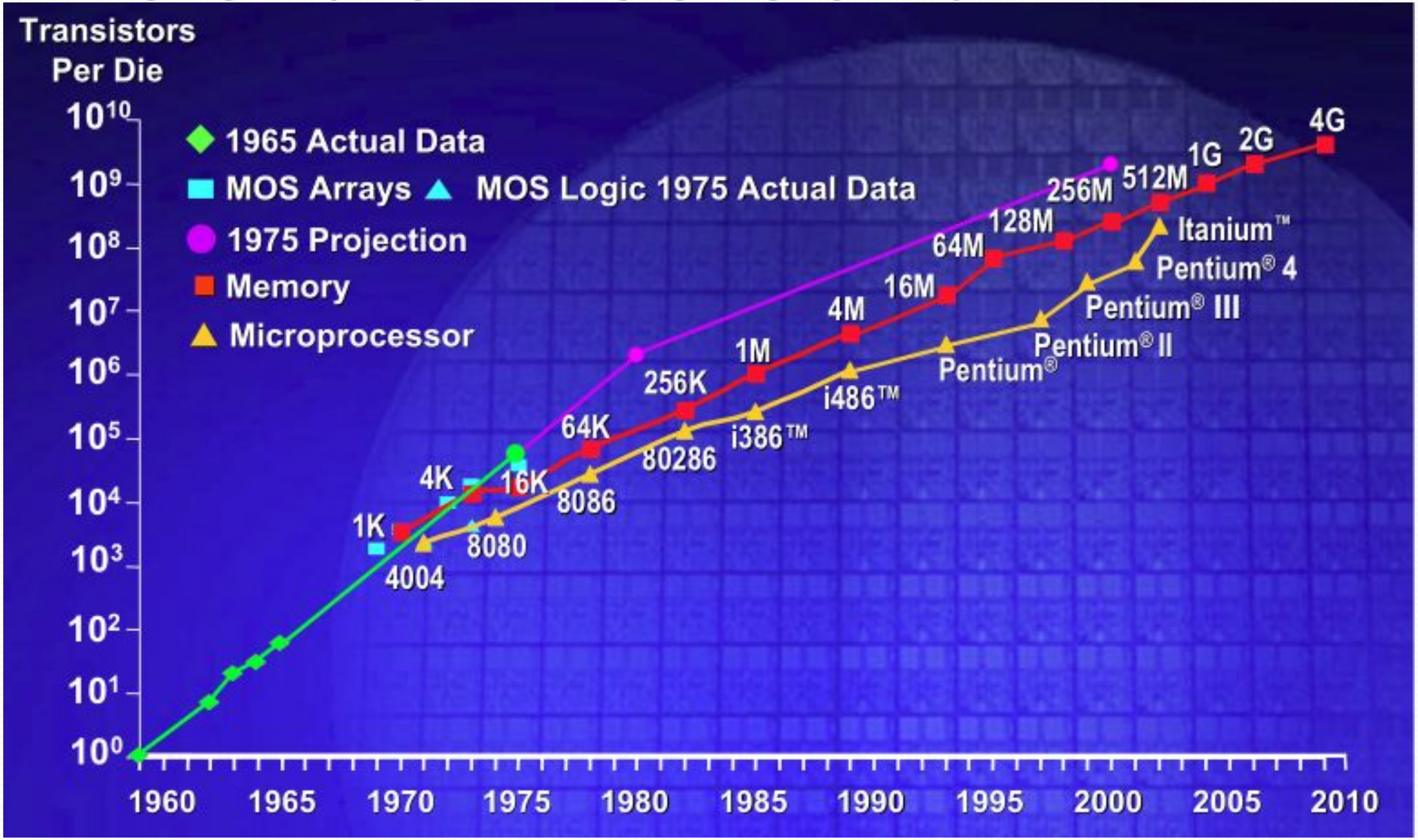






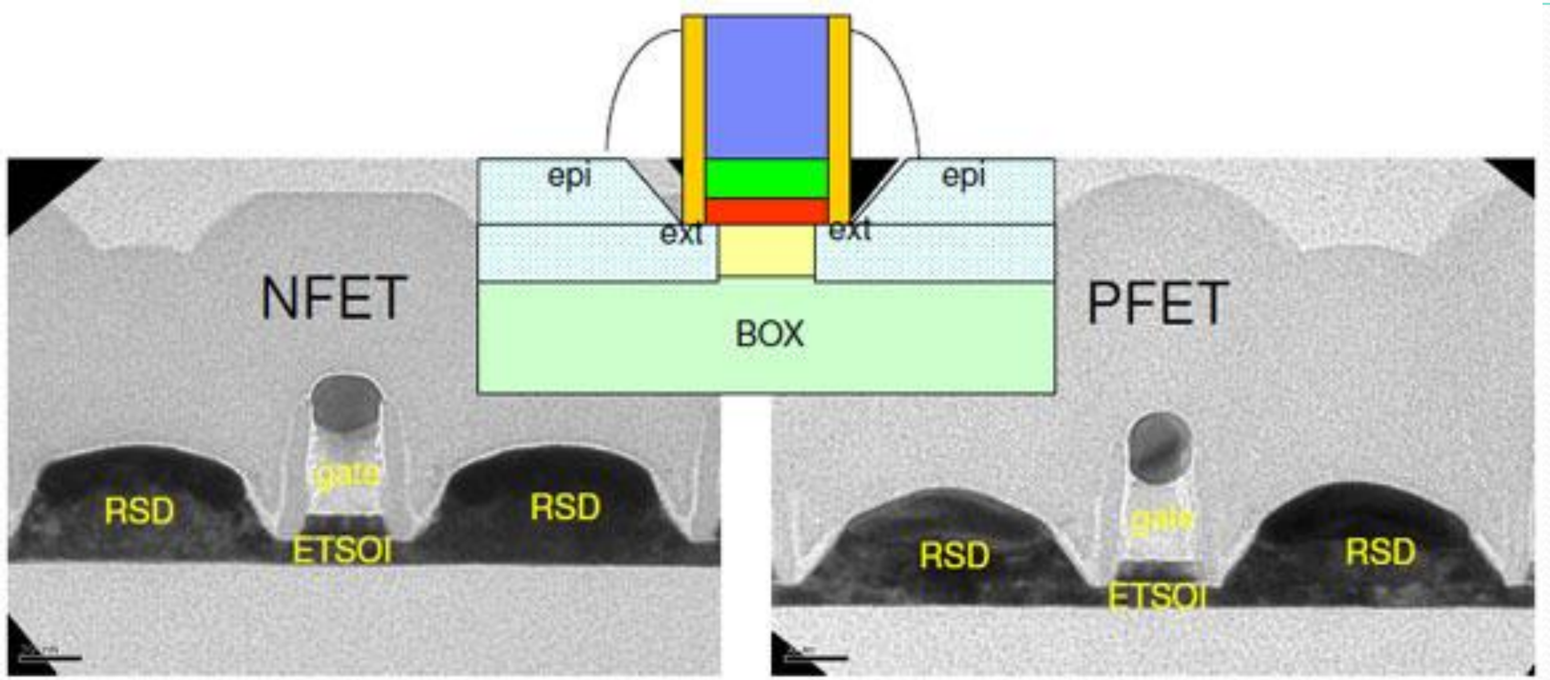


The end of Moore's 'law'?

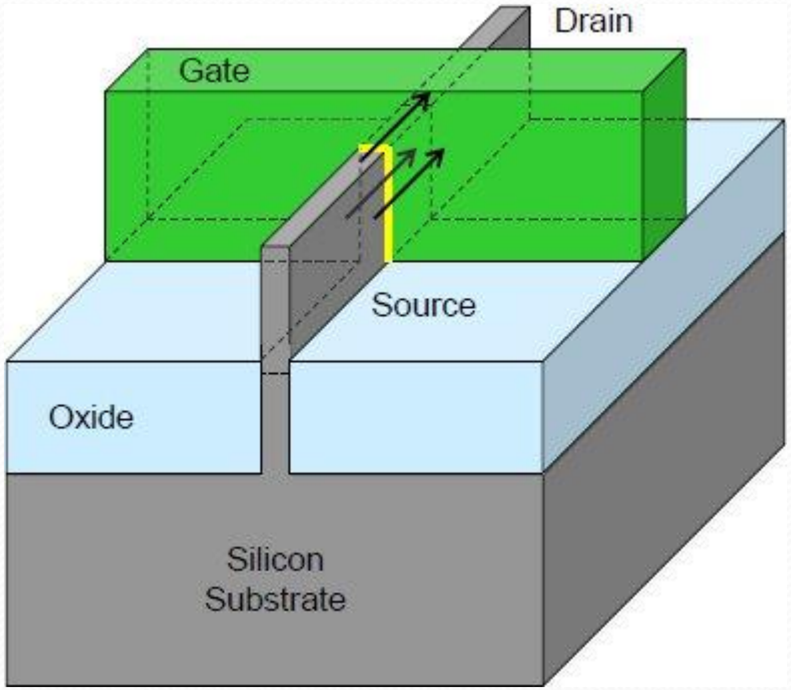


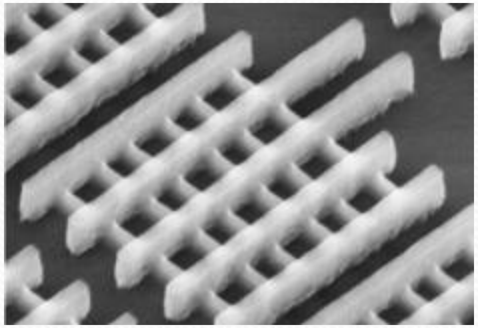
IBM Gains Confidence in 22 nm ETSOI

(IEDM Conf., Dec. 2009)

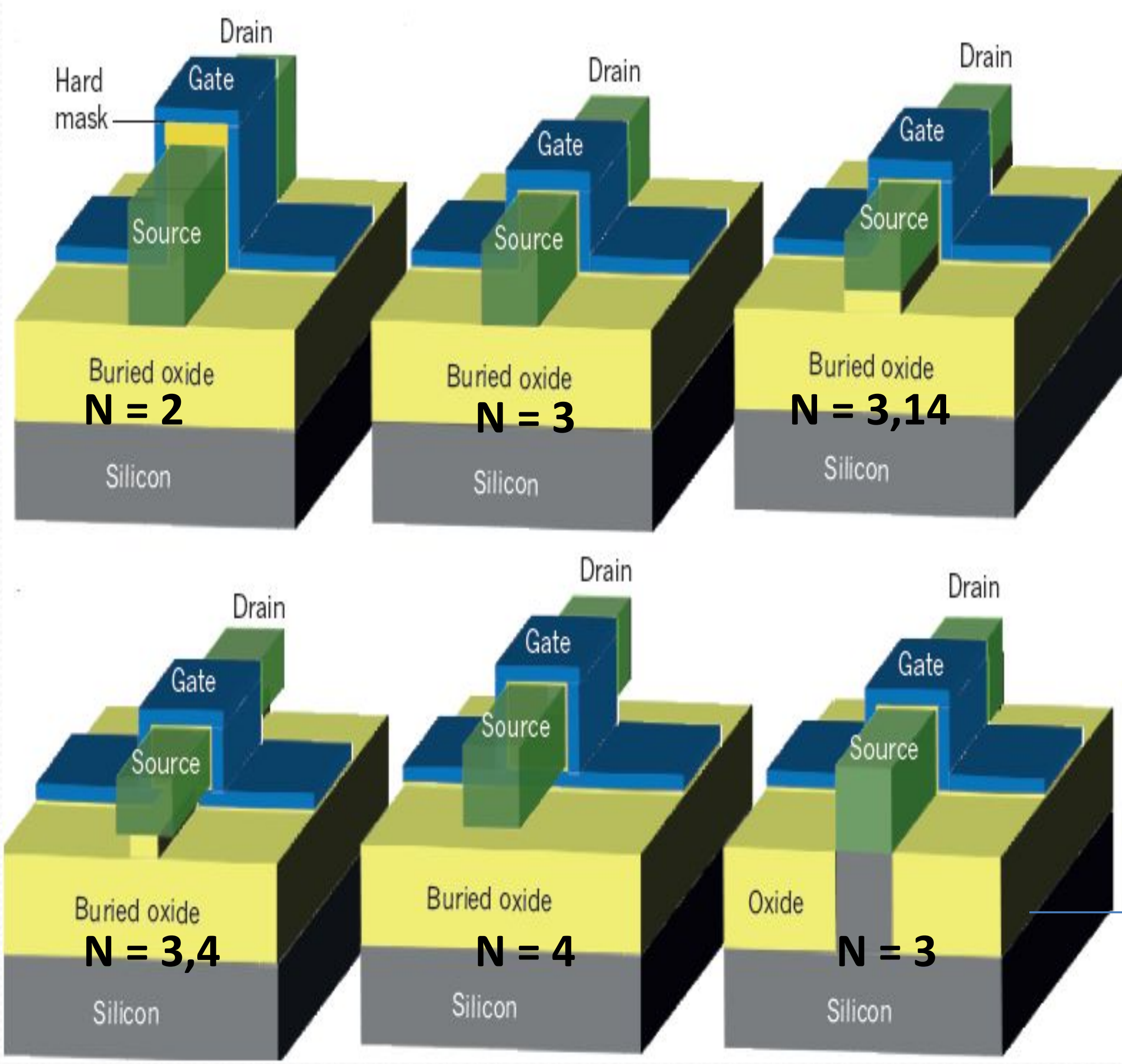


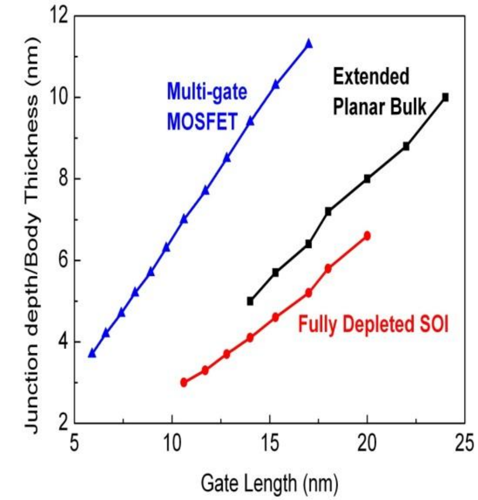
Intel Going Vertical for 22nm Transistors in 2011



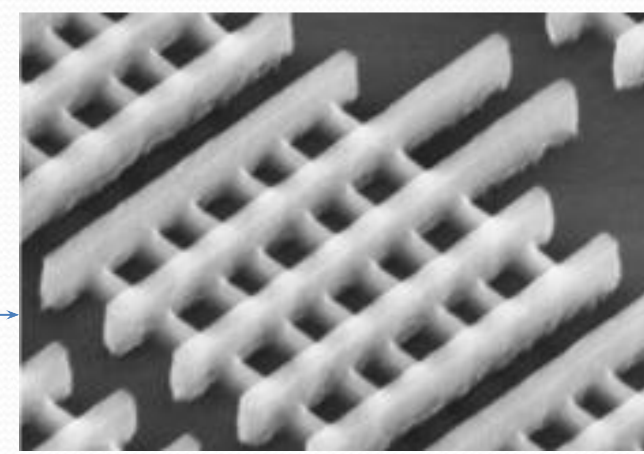


Multi-gate FETs

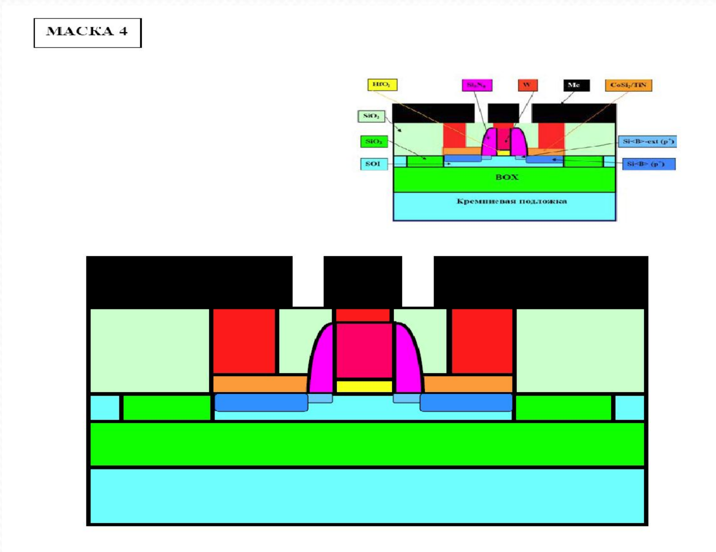


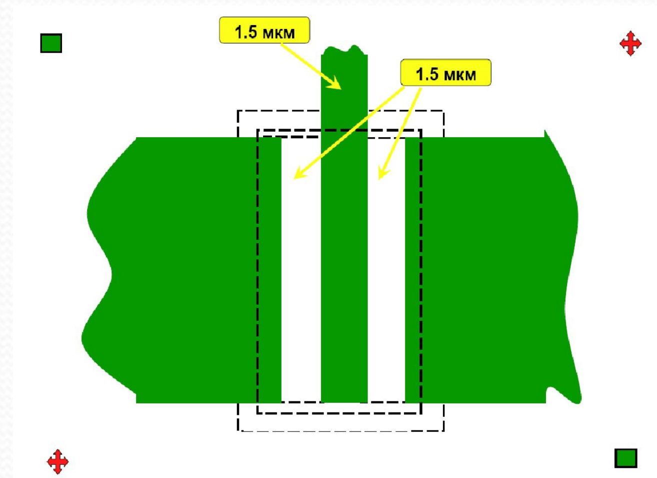


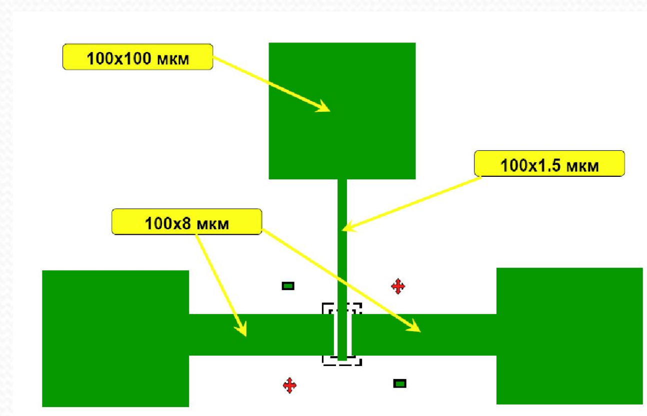
Intel Corp.



Экспериментальный технологический маршрут изготовления МДП КНИ - нанотранзистора



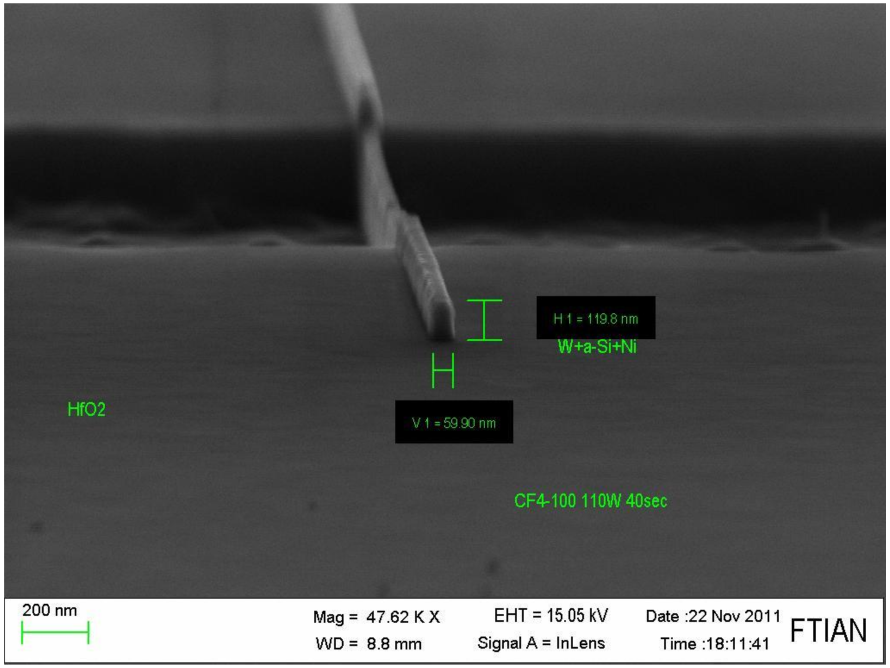


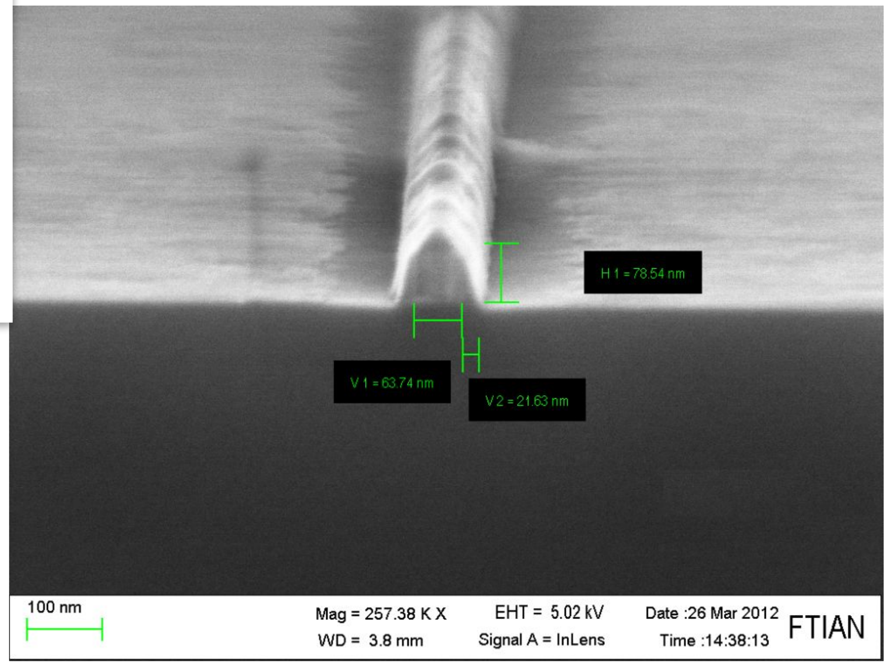


Основные этапы изготовления :

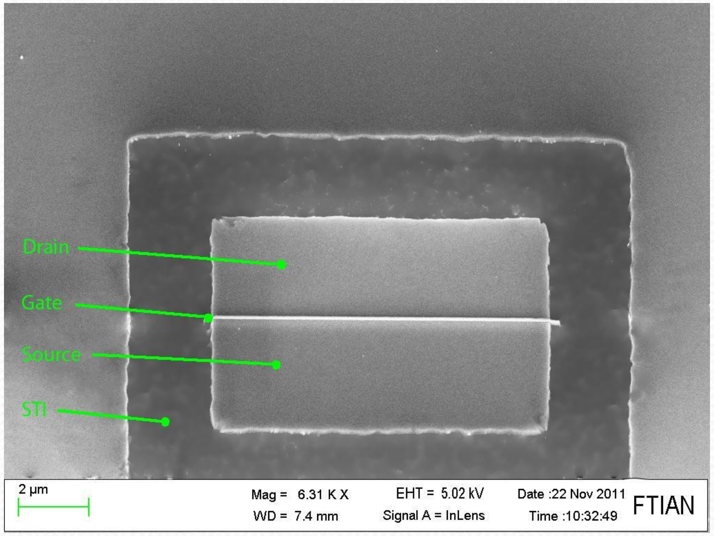
1. Формирование STI изоляции;
2. Изготовление затворного стека;
3. Изготовление спейсеров, истока/стока;
5. Изготовление контактов к стоку/ истоку;
6. Изоляция транзистора, формирование контактных окон;
7. Металлизация.

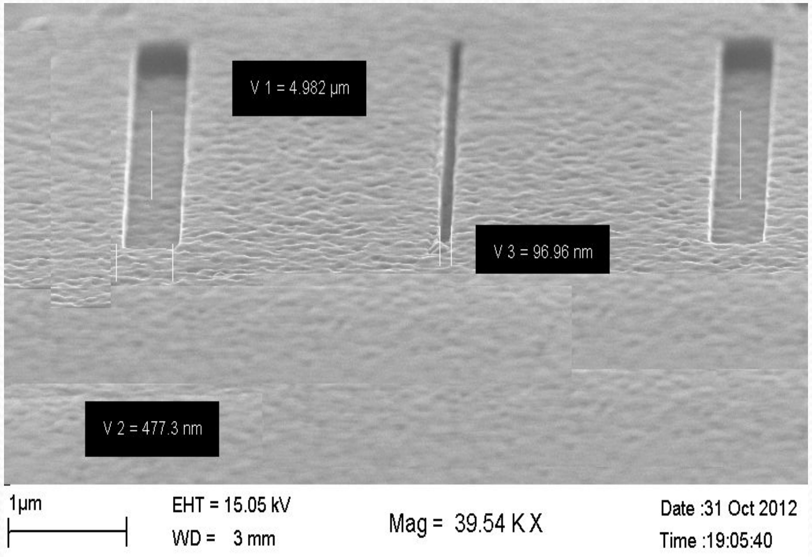
Изготовление полевого транзистора

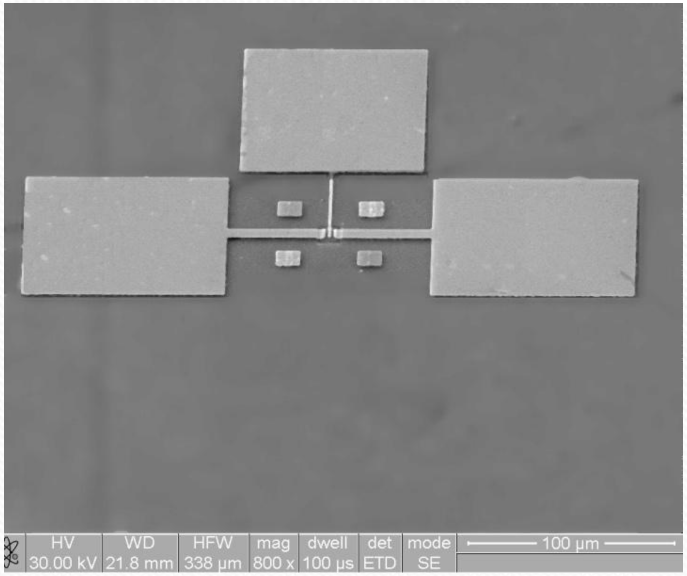




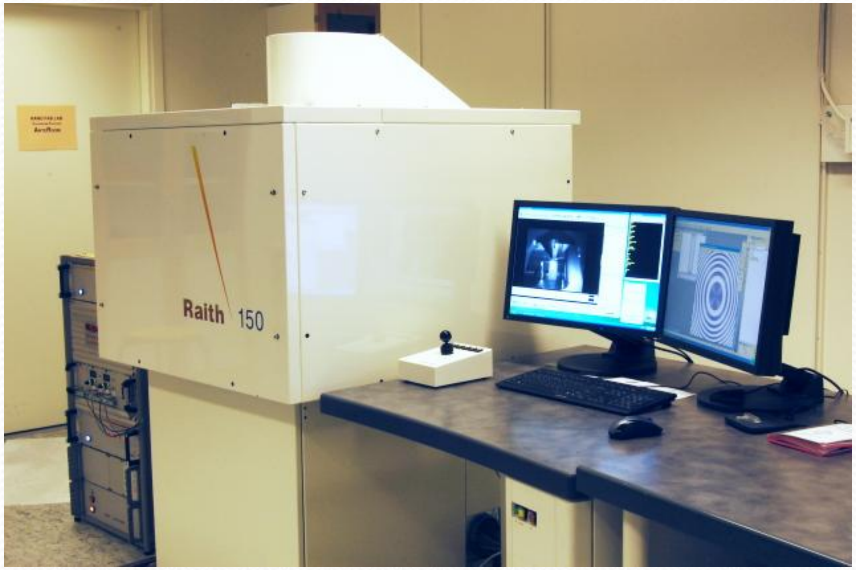
Изготовление полевого транзистора







Электронный литограф Raith-150



- 150x150mm stage for direct writing over 6” wafers
- Automatic airlock for sample loading
- Schottky thermal field-emission filament
- 200V-30kV beam acceleration
- 2pA-10nA beam current
- 2nm beam resolution at 20kV
- Laser interferometer for stage positioning with ~30nm precision

Аналитический автоэмиссионный растровый электронный микроскоп для исследования наноструктур ULTRA ZEISS

Пространственное разрешение	1.0 нм при 15 кВ 1.7 нм при 1 кВ 4.0 нм при 0.1 кВ
Диапазон увеличений	12x – 900 000x в режиме вторичных электронов 100x – 900 000x в режиме обратно рассеянных электронов
Источник электронов	Автоэмиссионный (термоэмиссионного типа).Стабильность лучше, чем 0.2% в час.
Диапазон ускоряющих напряжений	20 В – 30 000 В
Диапазон рабочих токов	4 пА – 20 нА

Установка атомно-слоевого осаждения FlexAl (Oxford Instruments Plasma Technology)

Substrates	Up to 200mm wafers handling and pieces on carrier plate
Precursosrs	Bubbled liquid and solid precursors
Max precursor source temperature	200ºC (oven and jacket)
Additional precursors	Water + ozone
Mfc controlled gas lines with rapid delivery system	1) thermal gas precursors (e.g. NH_3, O_2) 2) plasma gases (e.g. O_2, N_2, H_2)
In situ diagnostic features	Ellipsometry, OES
Swagelok 10ms rapid pulsing ALD valves	Yes
Removable inner chamber	Yes
Wafer stage temperature range	550ºC

Установки фотолитографии (Zuss) и нанесения резиста (Sawatec)

Установка плазмохимического травления Plasma Lab 100 Dual (Oxford Instruments Plasma Technology)

	ICP Etch(380)
Загрузка	шлюз
Подложки	до 200 мм
Диапазон температур	от -140°C до +400°C
Возбуждение плазмы	ВЧ
Линий газоподачи с РРГ	до 12 на каждую камеру
Плазменная очистка камеры	есть
Вакуумная система	ТМН
Система управления	PC2000
Рабочие газы	HCl, C_4H_8, CF_4, SF_6, O_2

Установка быстрого фотонного отжига Annealsys AS-100

- Pyrometer and thermocouple control
- Fast digital PID temperature controller
- Temperature range: RT to 1200°C
- Ramp rate up to 200°C/s
- Cooling rate up to 100°C/s
- RTA (Rapid Thermal Annealing)
- RTO (Rapid thermal oxidation)
- Diffusion, contact annealing
- Nitridation

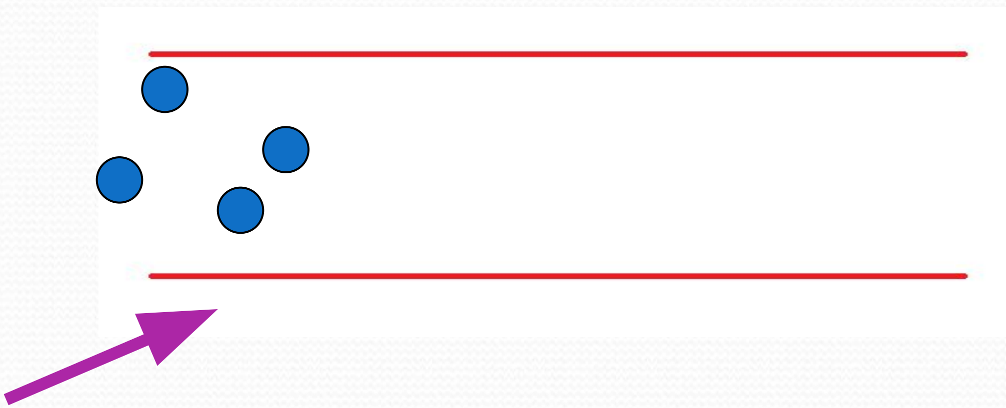
Теория наноэлектронных приборов

- Требования современной электроники: Low-power и High-performance
  - Альтернативные механизмы переноса тока: туннелирование
  - Альтернативные материалы: графен и его модификации
  - Масштабирование традиционных полевых транзисторов;

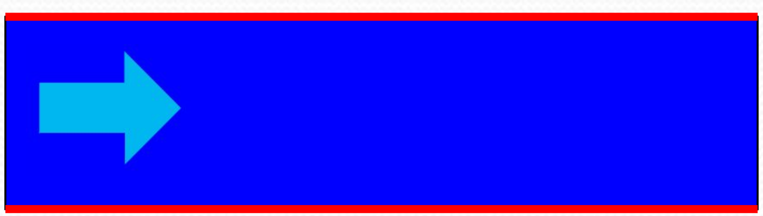
SIMULATION

Эволюция моделей электронного транспорта

Charged waves:
Schrödinger equation

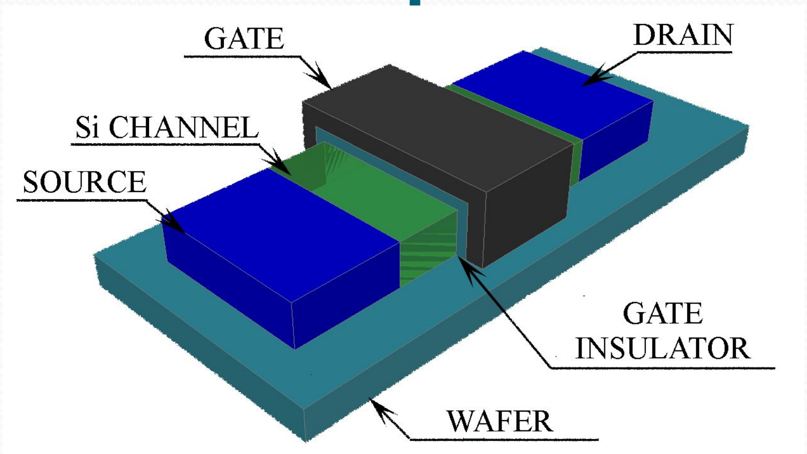


Charged particles:
Boltzmann kinetic equation

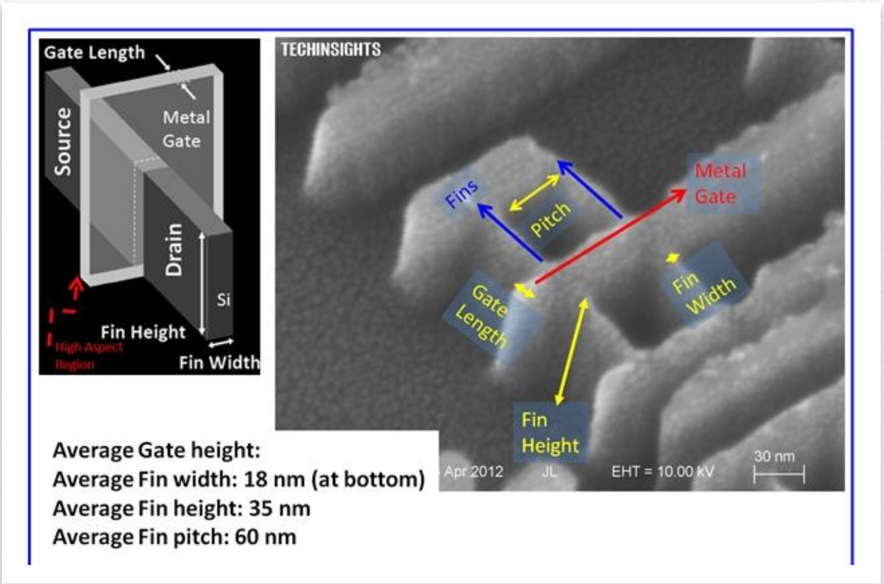


Charged fluid:
Hydrodynamic equations

Квантовые эффекты в полевых нанотранзисторах



- Поперечное квантование;
- Туннелирование и интерференция электронных волн;
- Квантовая статистика.

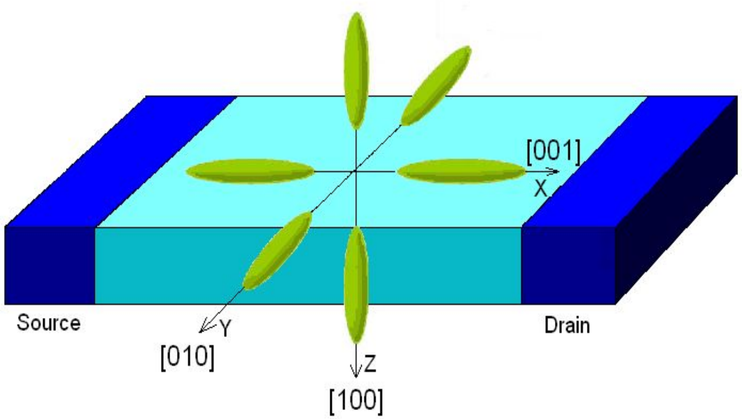


Silicon conduction band structure

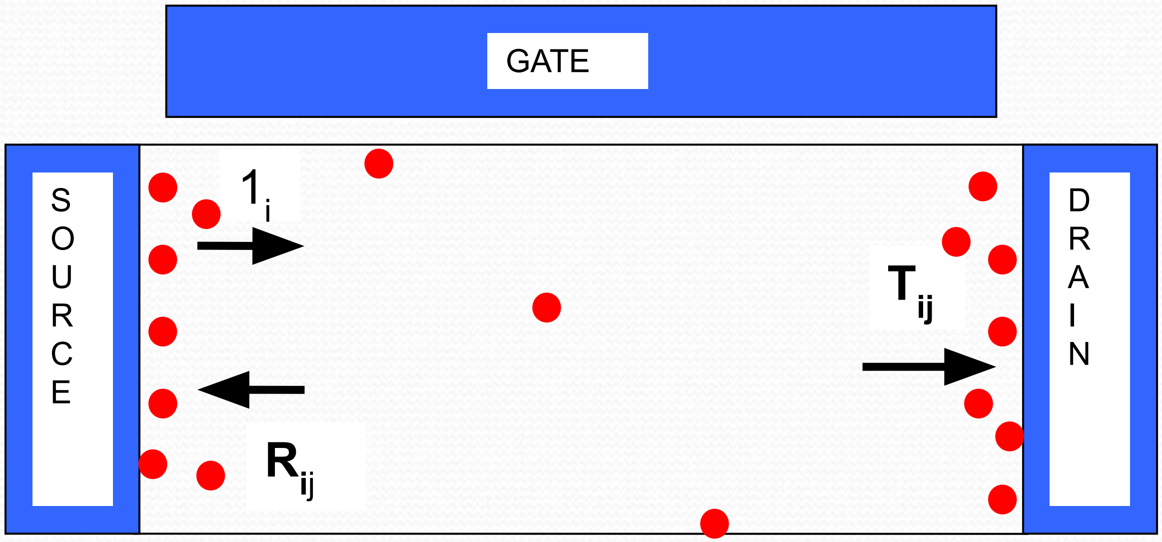
- Effective mass and transversal quantization energy

$$m_t = 0.19m_0, m_l = 0.98m_0$$

$$\varepsilon_0 = \frac{\hbar^2}{2m}\left[\frac{\pi}{d_{Si}}\right]^2$$



Landauer-Büttiker formalism



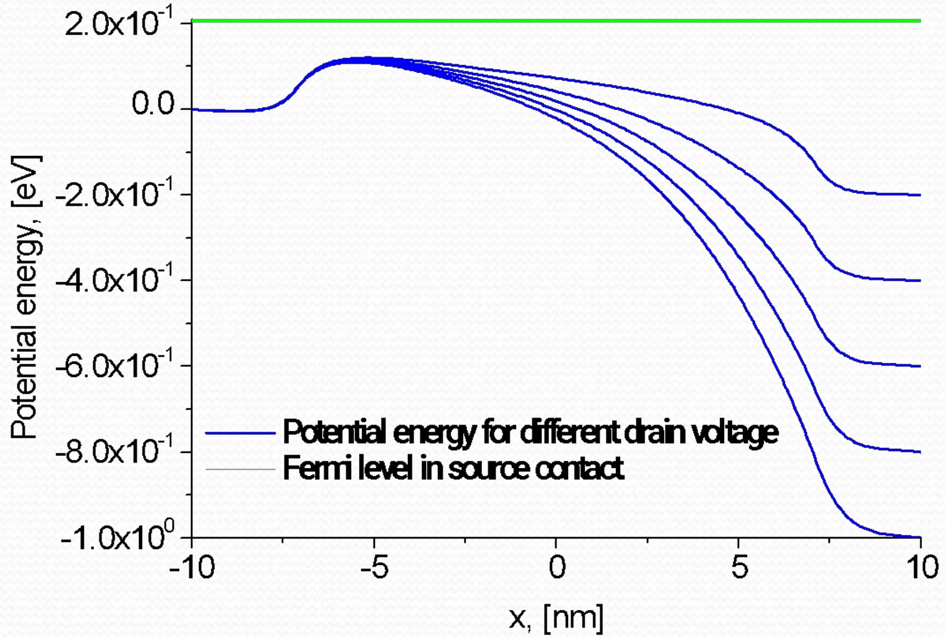
Transversal quantization ⇒ **Landauer-Buttiker formalism**

(wave-guide modes) in a channel ⇒ $I(V_D) = \frac{2e}{h} \sum_{v} \sum_{i} \sum_{j} \int dE\, T_{ij}(E) \left[f_S(E) - f_D(E) \right]$

Everlasting controversy in kinetic simulation

- Distribution function (equilibrium) is known only in contacts
- ⇔
- Strong scattering in contacts

Heavy doping – low doping junction at S/D contact



Few of incident particles surmount the barrier
=>
Equilibrium distribution for particles coming in the channel

Analytical solution obtained for modified (BGK) collision integral in τ-approximation

High self-consistent barrier at S/D contacts

Main strategy of simulation

- Self-consistent solution of

Schrödinger equation

+

Maxwell equation

(Poisson equation)

Solution of 3D Schrödinger equation

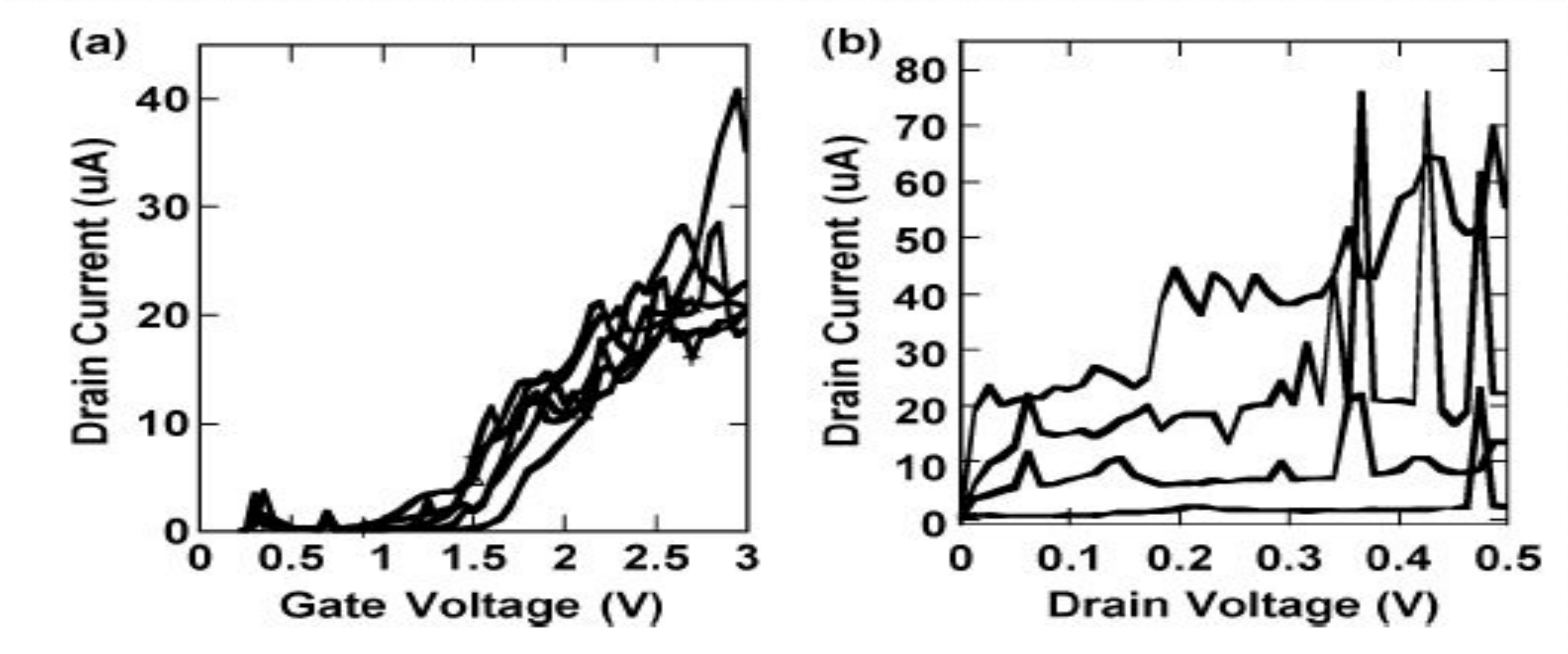
- $$-\frac{\hbar^2}{2m}\Delta\Psi(x,y,z)+V(x,y,z)\Psi(x,y,z)=\varepsilon\Psi(x,y,z)$$

  V(x,y,z) is a potential.

The direct solution of the stationary 3D Schrödinger equation via a finite difference scheme comes across a well known instability caused by **evanescent modes.**

In fact, the exponential growth of upper modes makes a **computation impossible**.

D.K.Ferry et al. (2005) (США, Arizona State University): results of simulation



Solution of Schrödinger equation:

transverse mode representation + high-precision arithmetic

- $$\Psi(x,y,z) = \sum_{i=1}^{N} a_i(x)\psi_i(y,z)$$

where ψi(y,z) is the i-th transverse mode wave function,
N is a number of involved modes.

The space evolution of coefficients $a_i(x)$ is governed by matrix elements

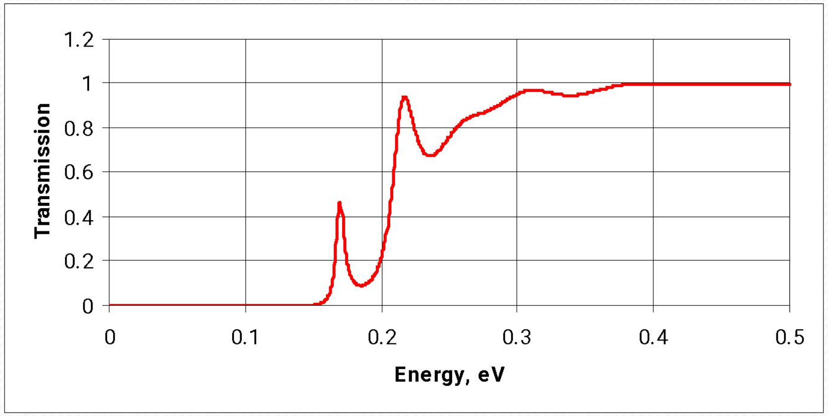
$$M_{ij}(x) = <\psi_i(y,z)\,|V(x,y,z)|\,\psi_j(y,z)>$$

The off-diagonal elements M_{ij} manage the mode conversion.

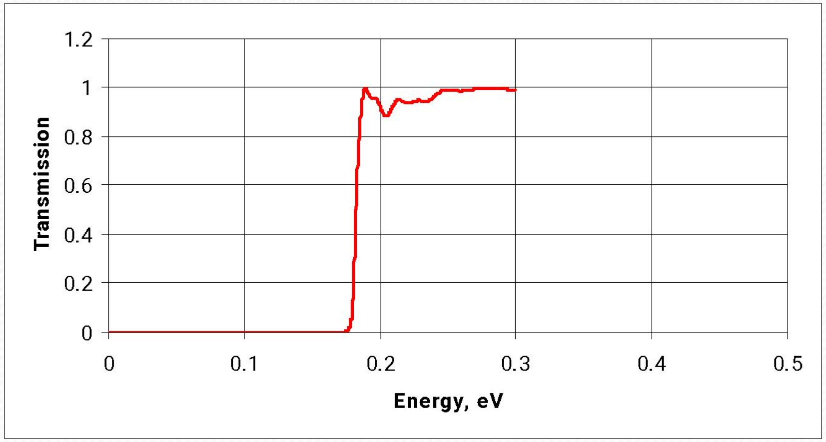
The diagonal elements M_{ii} manage the quantum reflection, interference and tunneling of the i-th mode.

Calculated transmission coefficient T(E) vs. electron energy E

(4 random impurities in a channel)



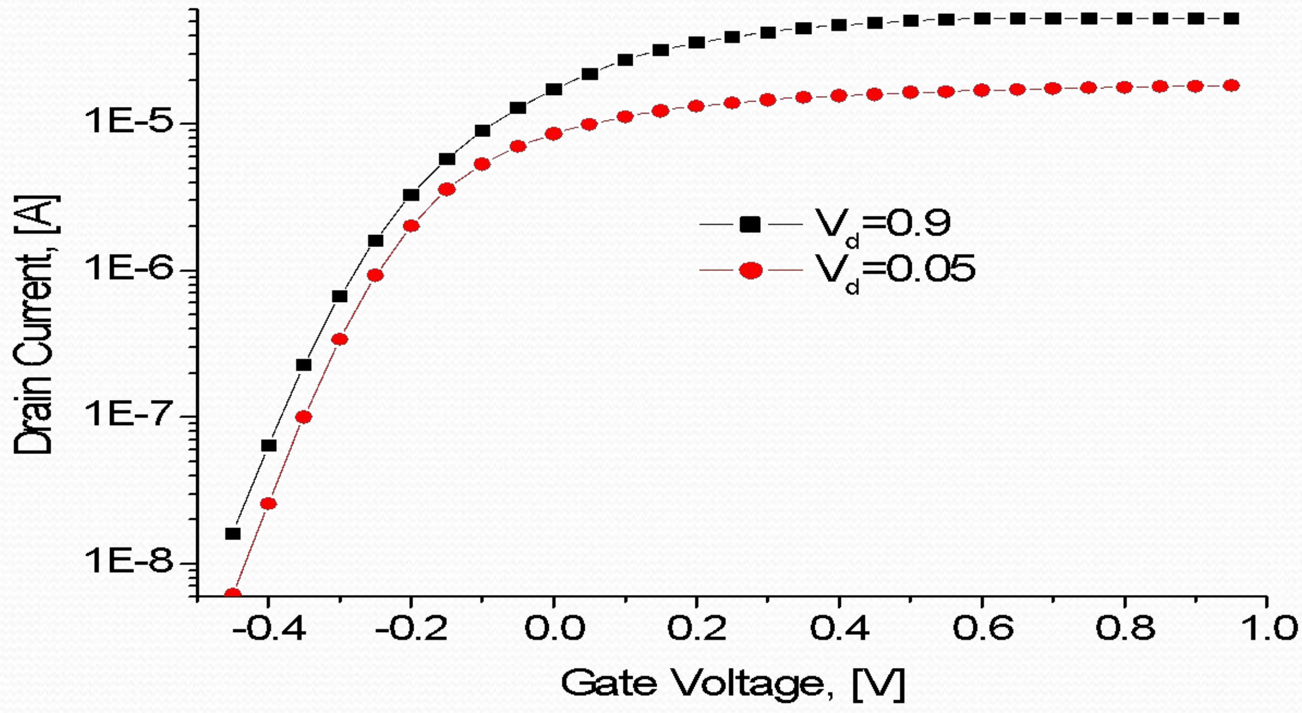
[100] and [010] valleys



[001] valleys

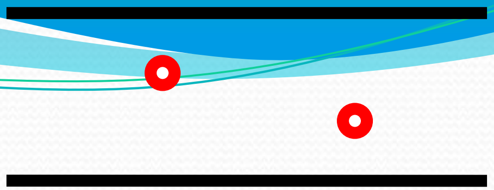
Transistor parameters are 10nm channel length and width, 5nm body thickness, 10^20 cm^-3 source/drain contact doping, 5nm contact length.

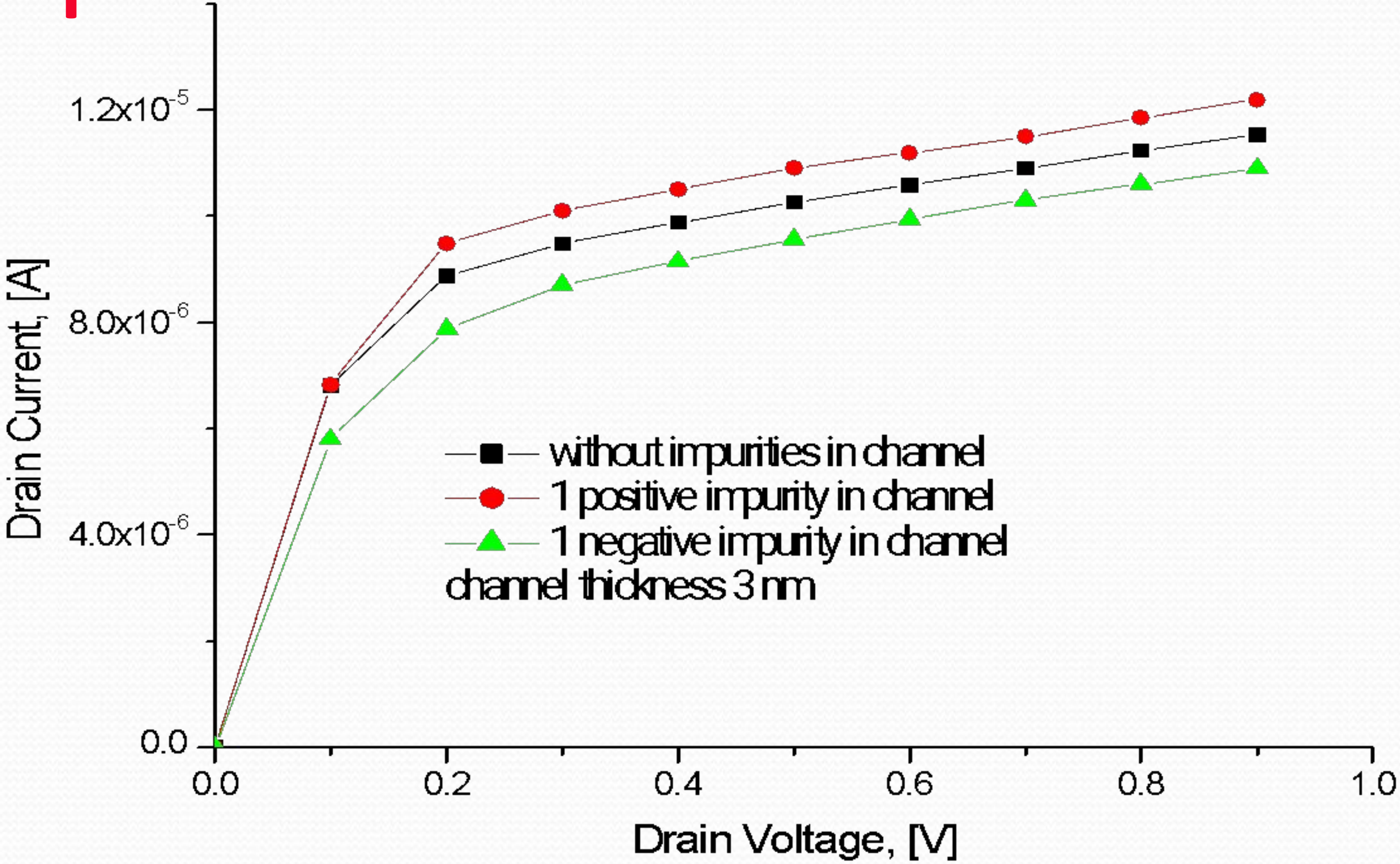
Gate voltage characteristics



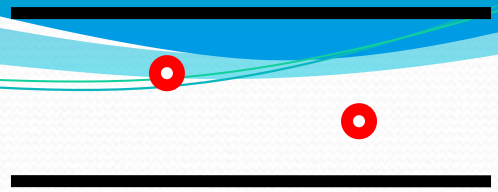
Sub-threshold swing is 71 mV per decade of current.

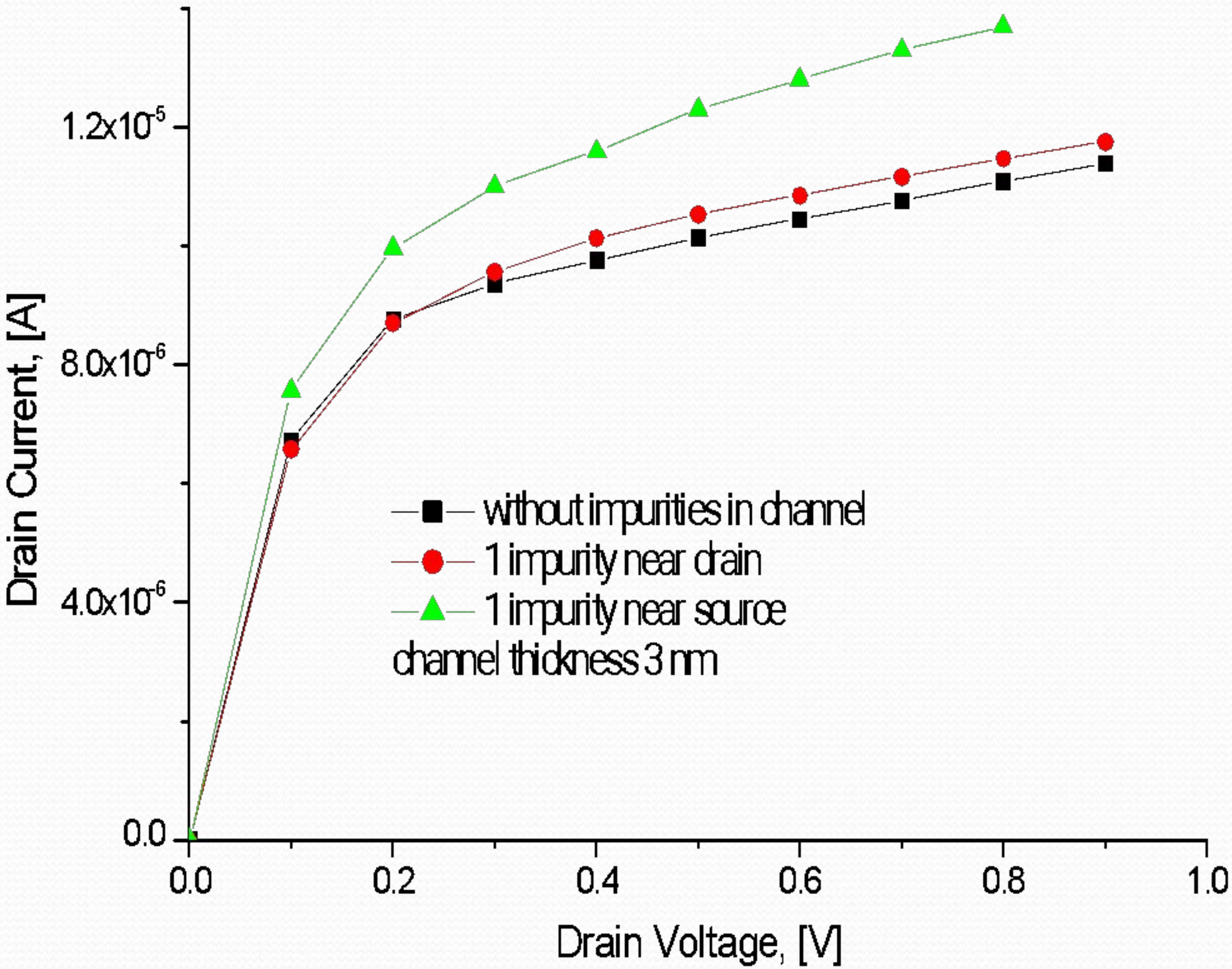
Impurities in channel:



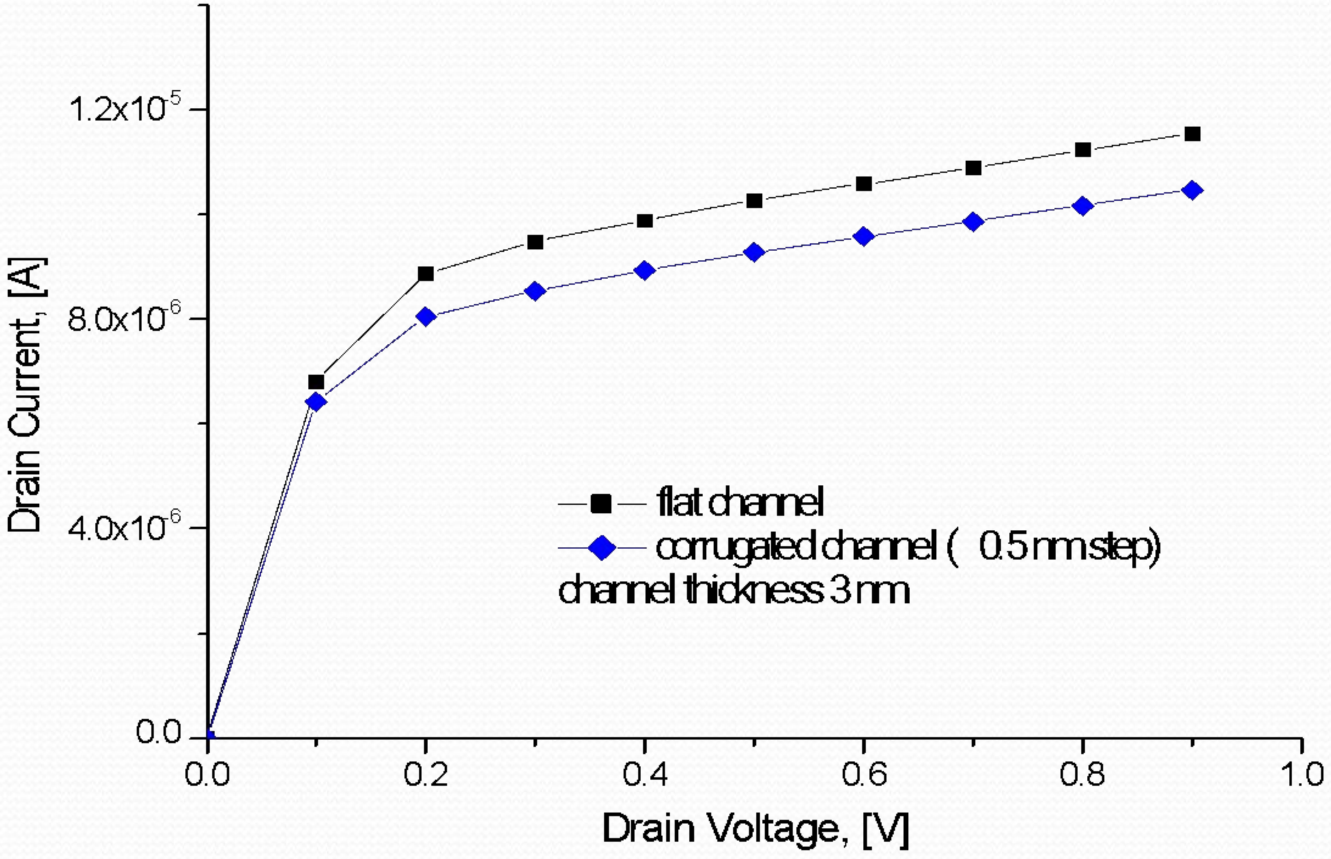


Impurities in channel:

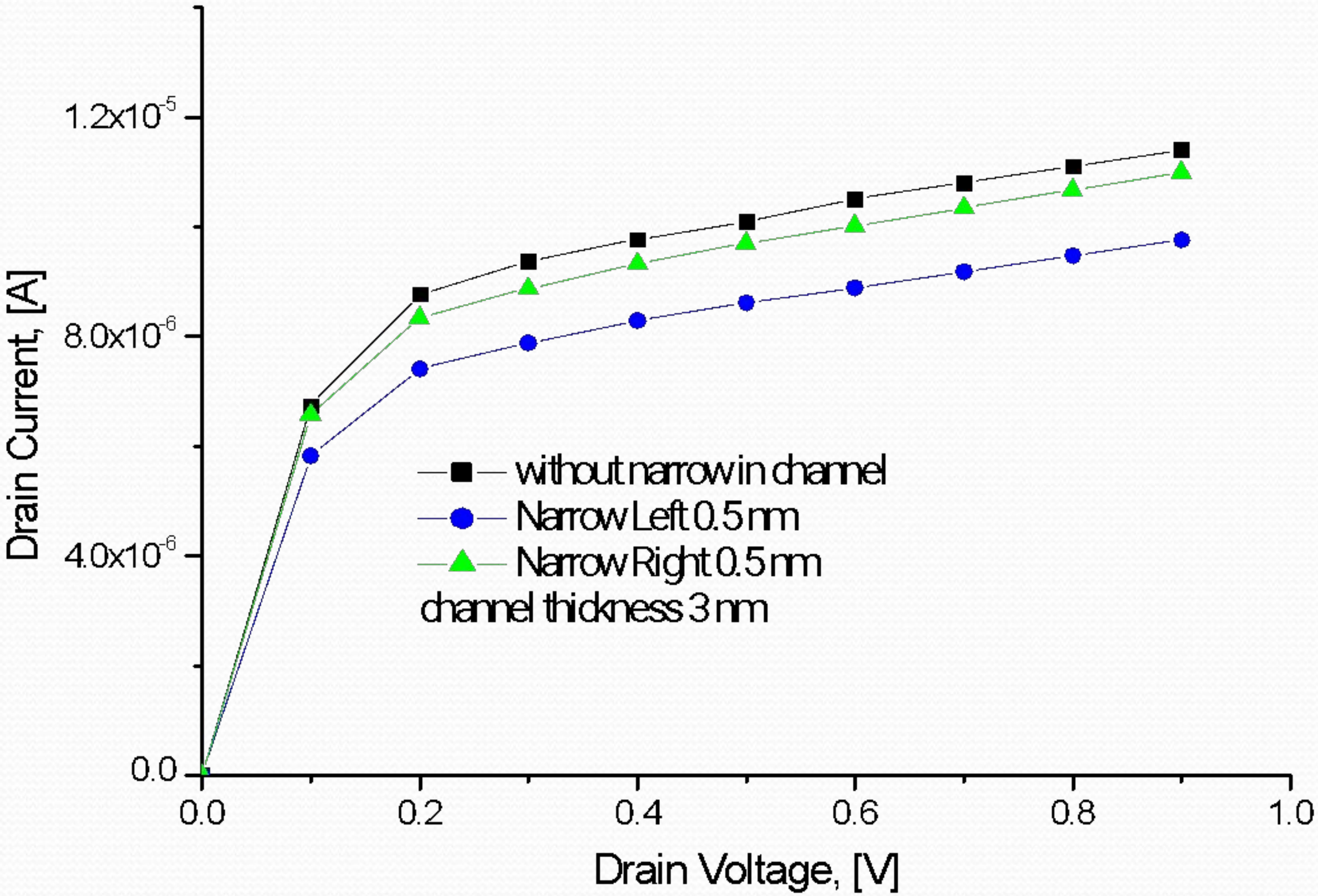




Corrugated channel:



Corrugated channel:



Dispersion of characteristics

- 5-15% in calculated I-V curves
- < 10% is an everlasting condition for large integrated circuits
- More severe demands to technology may arise.

- Требования к современной электронике

Требования к современной электронике: 1) high performance

- RC задержка инвертора
- delay time = $R_{in} * C_{out}$
- Необходима высокая проводимость канала транзисторов и малый размер транзистора

- Предельная частота:
- пролётное время

$$f_{\max} = \frac{v}{L_{ch}}$$

- Необходима малая длина канала (Intel – 22nm)
- и/или высокая подвижность (новые материалы)

Требования к современной электронике: 2) low power

- Потребляемая активная мощность

$$P_a = \frac{CV_{DD}^2}{2} f$$

- Необходимо малое напряжение питания и быстрое переключение между состояниями

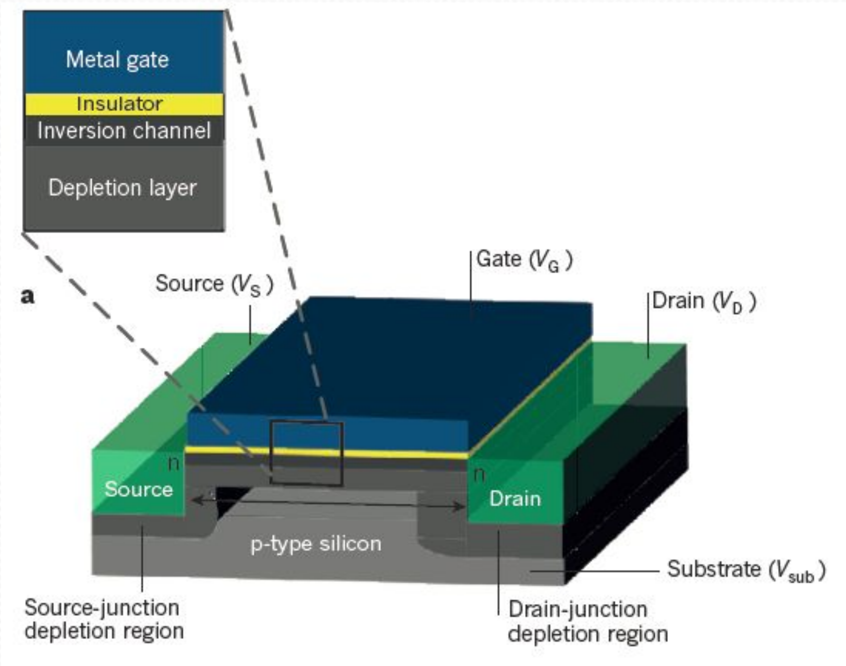
- Пассивная мощность

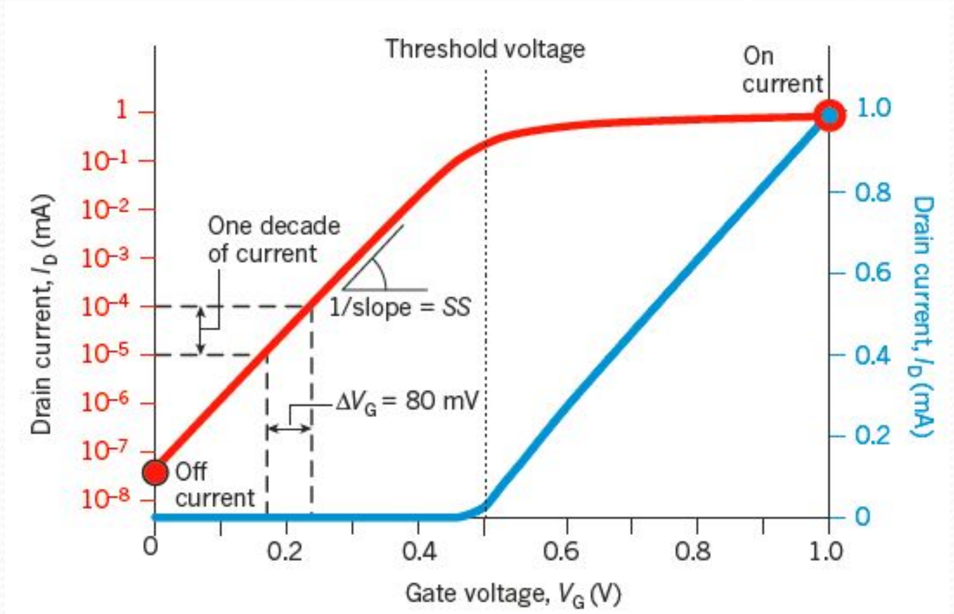
$$P_p = I_{OFF} V_{DD}$$

- Необходим малый ток в закрытом состоянии
- Большое отношение

$$I_{ON} / I_{OFF}$$

Снижение энергопотребления





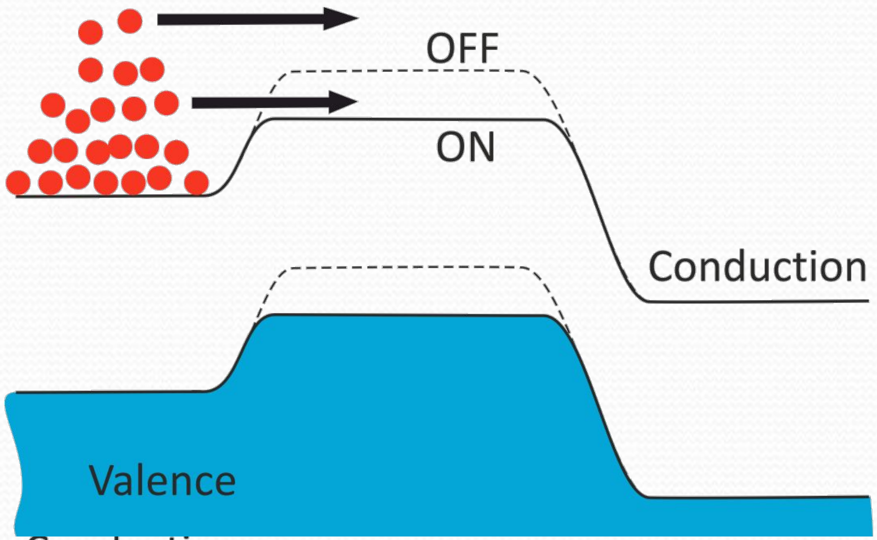
Предельная крутизна переключения: 60 мВ/дек для термоэмиссионого механизма переноса тока

Как сделать круче?

Туннельные транзисторы

позволяют достичь
подпороговой крутизны выше (60мВ/дек)-1
при комнатной температуре

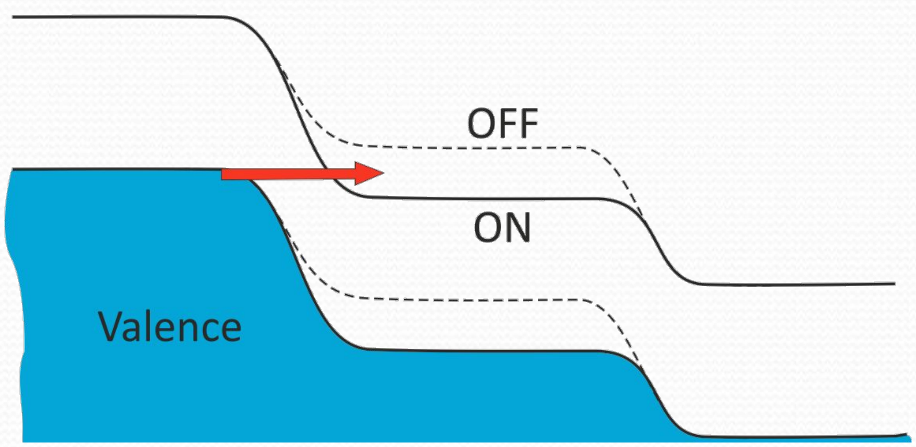
Tunnel FET vs. thermionic FET



$$I \propto \exp\left[-\frac{eV_B}{kT}\right]$$

$$\frac{d\ln I}{dV_G} \le \frac{e}{kT} = \left(60\ \mathrm{mV/dec}\right)^{-1}$$

Limits the drive voltage V_{DD}>240 mV to achieve 4 decade switching



$$I \propto \left[E_v - E_c\left(V_G\right)\right]^{\alpha} \exp\left[-\frac{F_{cr}}{F\left(V_G\right)}\right]$$

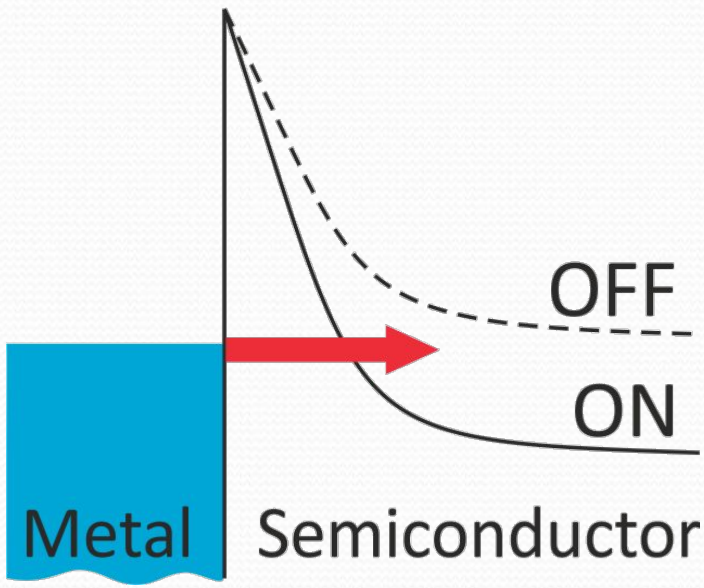
$$\left.\frac{d\ln I}{dV_G}\right|_{E_c \to E_v} \to \infty$$

Low voltage switching possible – low power operation

Tunnel transisors

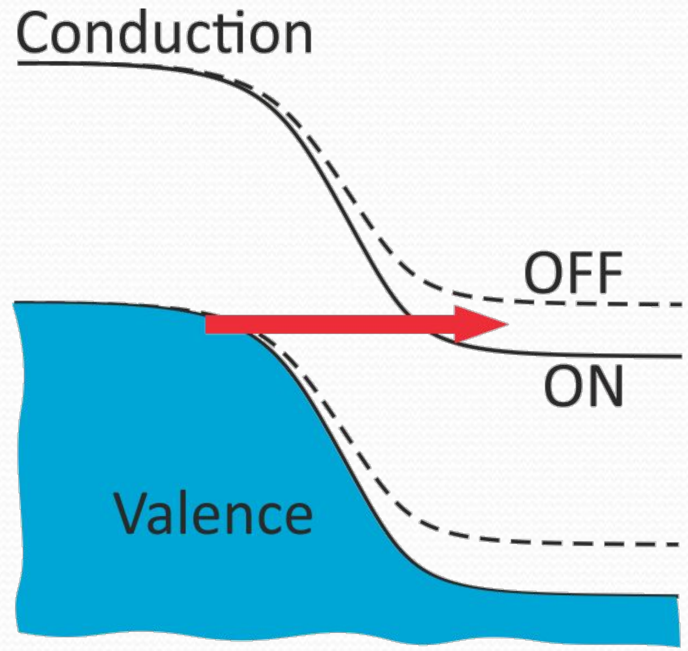
Shottky-barrier FET

- Gate-controlled reverse-biased Shottky junction
- Intraband metal-semiconductor tunneling



Interband tunnel FET

- Gate-controlled reverse-biased Esaki junction
- Valence-to-conduction band tunneling



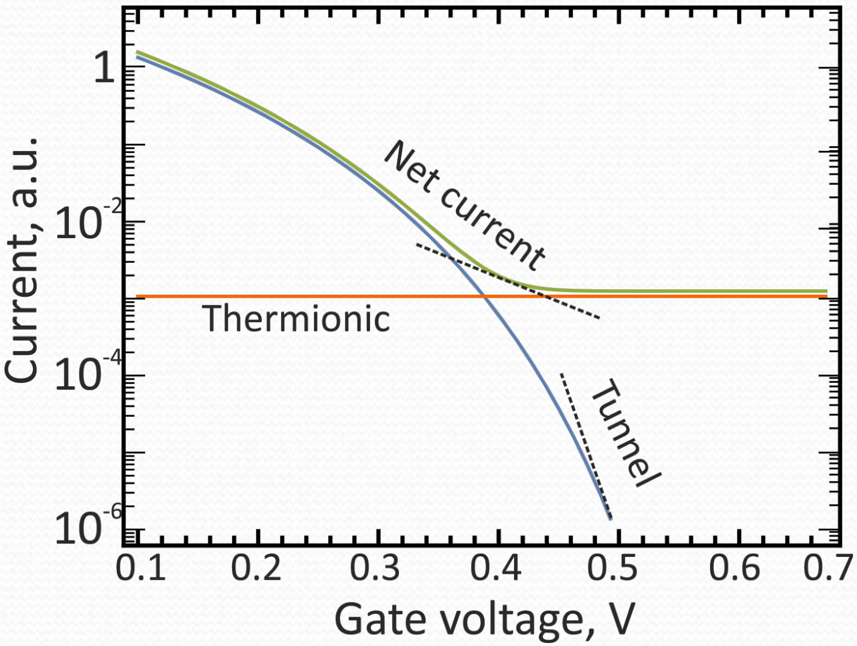
Shottky-barier TFETs: ultimate subthreshold slope

$$I = I_{tun} + I_{therm}$$

$$I_{therm} \propto \exp\left\{-\frac{\Phi_b}{kT}\right\}$$

$$I_{tun} \propto \exp\left\{-\frac{4}{3}\frac{\sqrt{2m\Phi_b^3}}{e\hbar F(V_G)}\right\}$$

The subthreshold slope of tunnel component is large only when tunnel component is small and masked by thermionic current The (60 mV/dec)-1 limit persists for SB FET despite the presence of tunneling



Schematic view of current components in SB FET vs gate voltage illustrating the impossibility to achieve subthermal steepness

D. Svintsov et.al. Semiconductors 47, p. 279 (2013)
W. G Vandenberghe. et al. Appl. Phys. Lett. 102, 013510 (2013)

TFETs subthreshold: state of the

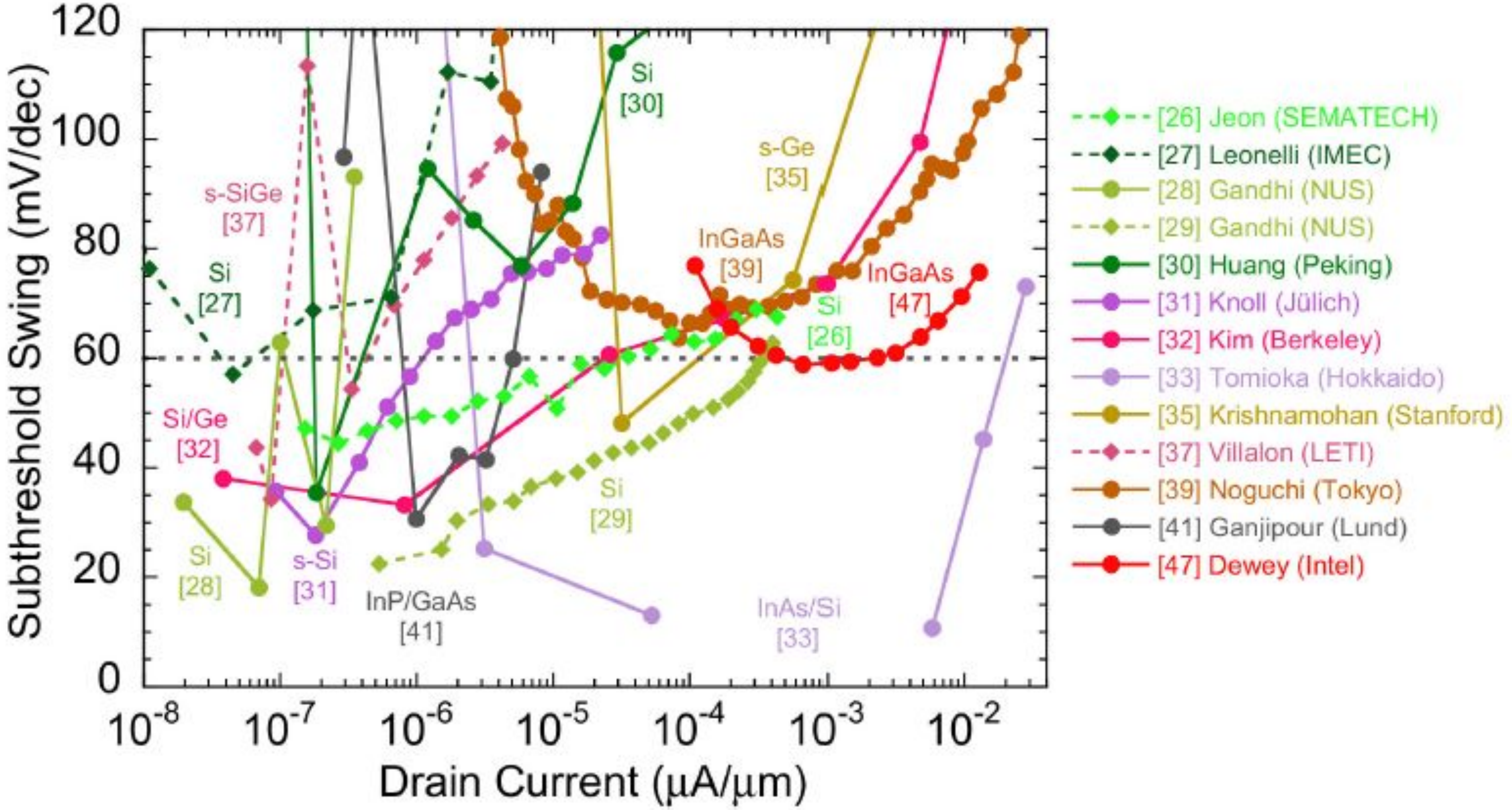
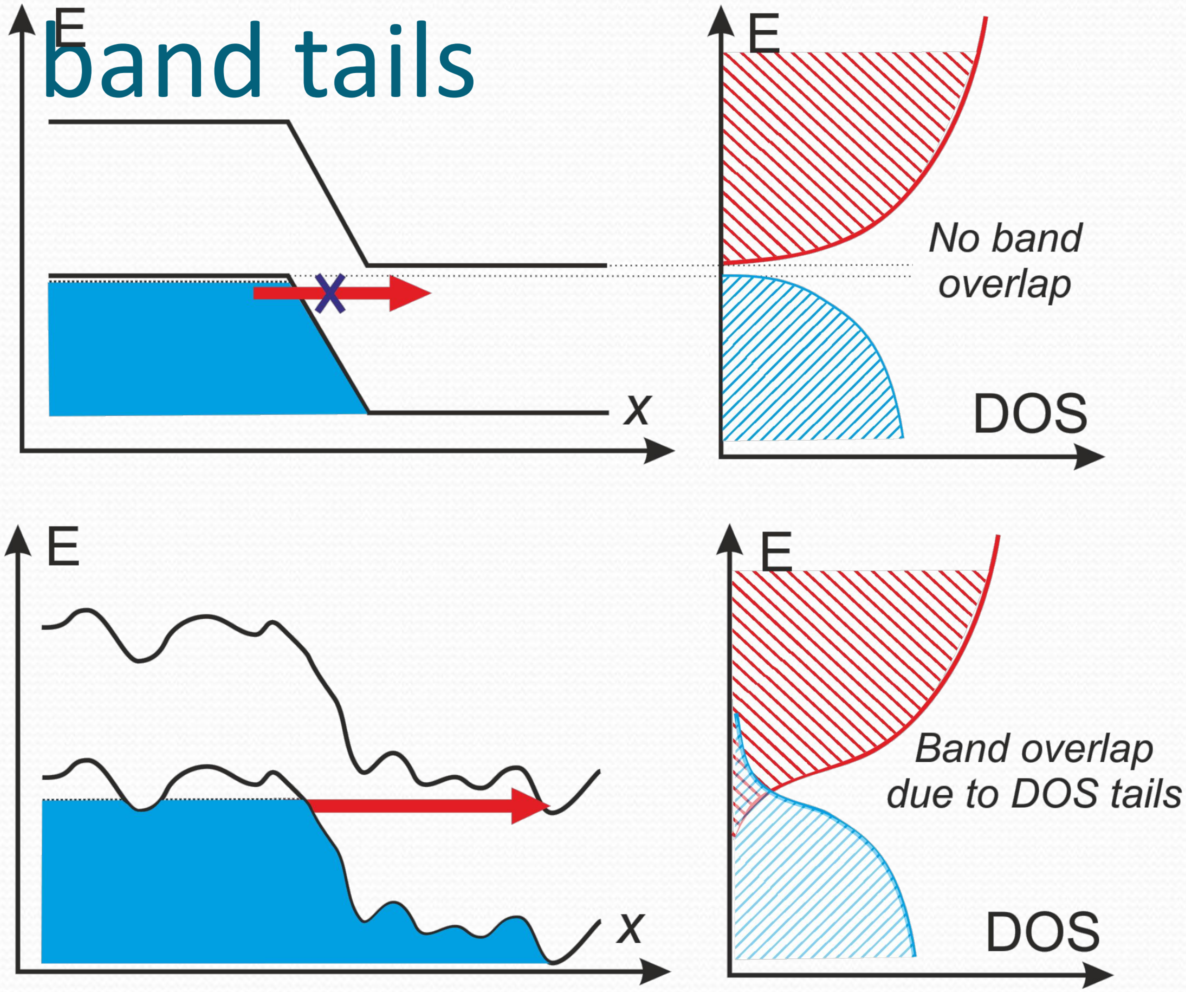


FIGURE 3. Published [26], [29], [31], [32], [37], [39], [47] and extracted [27], [28], [30], [33], [35], [41] TFET sub-threshold swing versus drain current per unit width for *n*-channel (circle with solid line) and *p*-channel (diamond symbol with dashed line) TFETs that show *SS* near or below 60 mV/decade at room temperature. With the exception of the CNT TFETs [48], [49] this is a comprehensive plot showing 12 TFETs with reported SS below 60 mV/decade.

H. Lu ans A.C. Seabaugh IEEE Journal of the Electron Devices Society ***2*** *p. 44-49 (2014)*

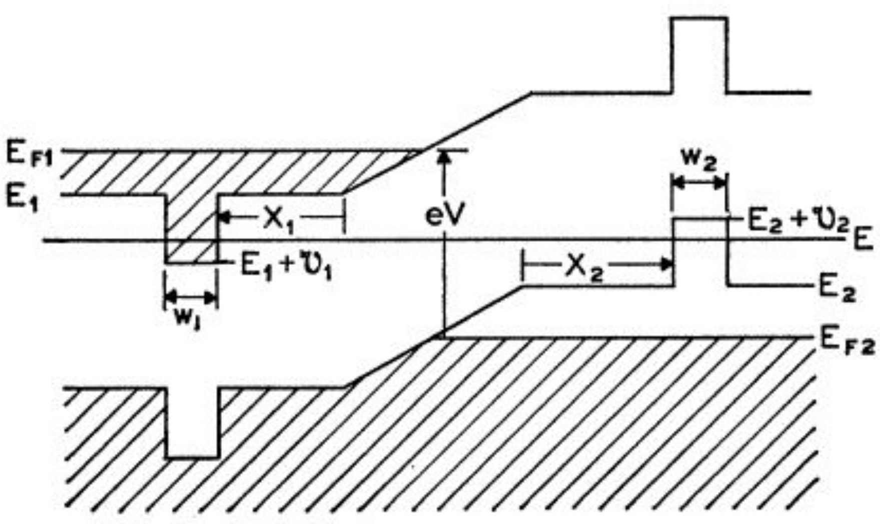
Limits of the subthreshold slope: band tails



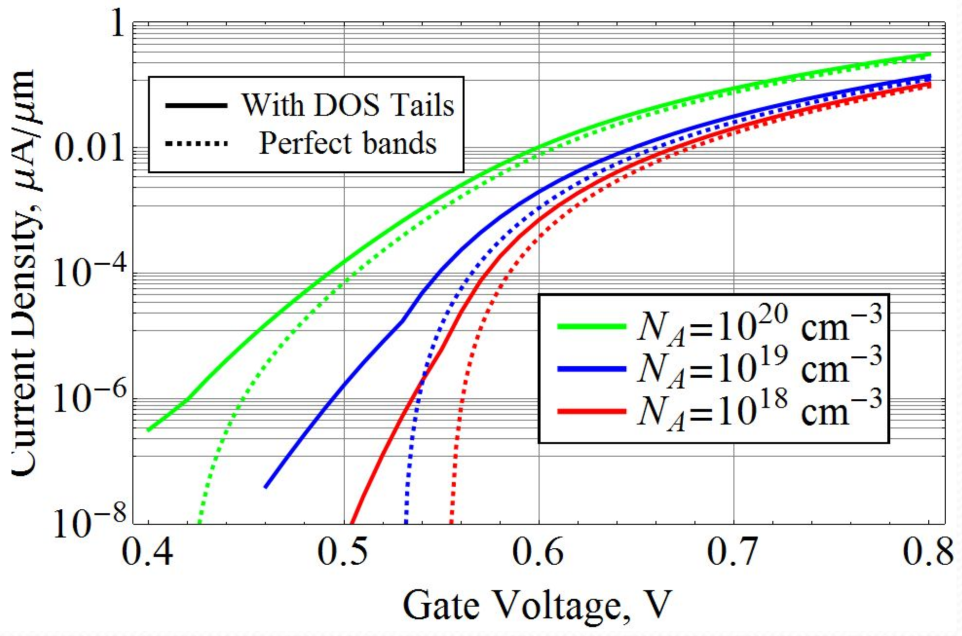
Nonzero current due to tunneling from the DOS tails!

E.O. Kane Phys. Rev. ***131****, (1963)*
S. Mookerjea et. al. IEEE EDL ***31*** *(2010)*
C.D. Bessire et. al. Nano Lett. ***11*** *(2011)*

Limits of the subthreshold slope:
band tails

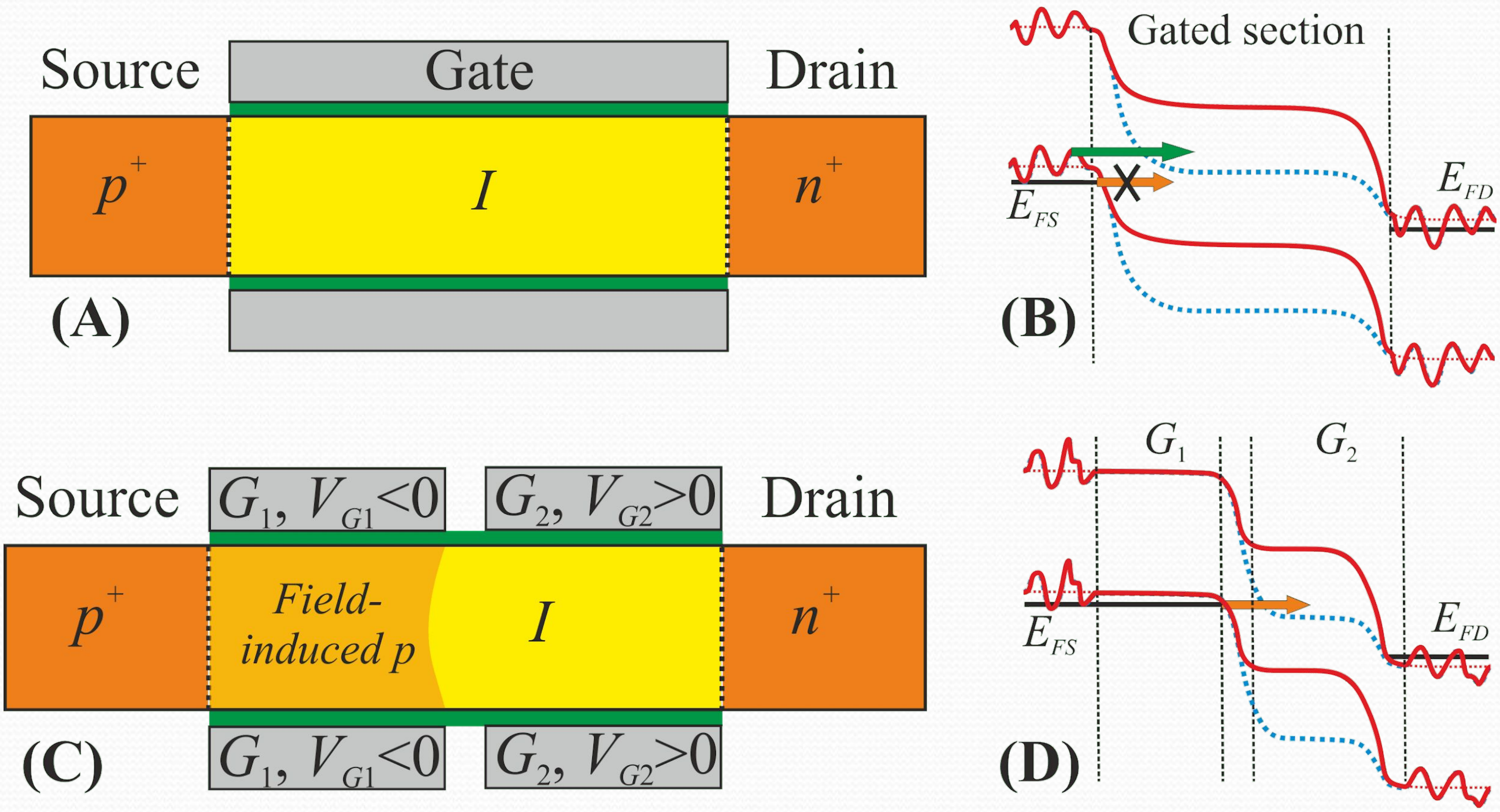


E.O. Kane 1963 *Phys. Rev* ***131*** *p. 79*

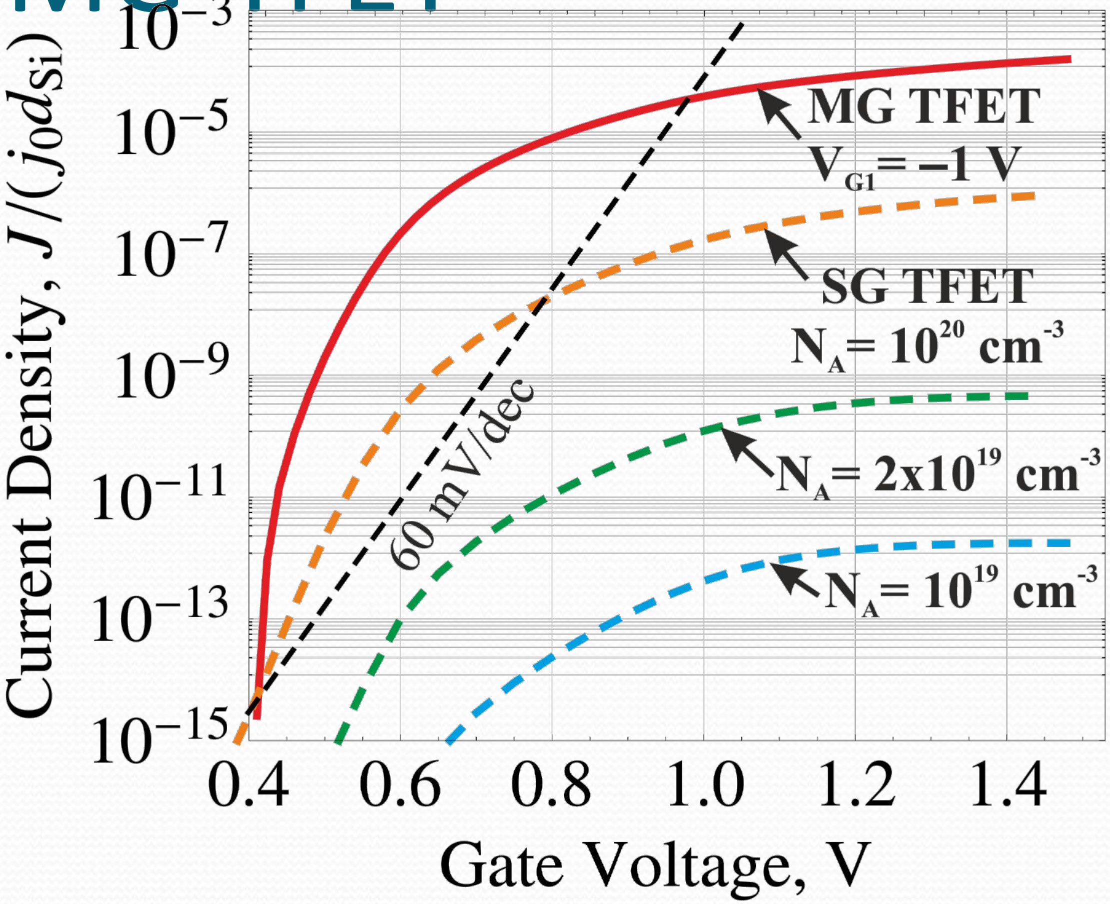


Comparison of TFET modeling with perfectly flat bands (dashed) and taking into account the band tails (solid)

Multigate TFET with electrically induced p-n junction



Simulated characteristics of MG-TFET

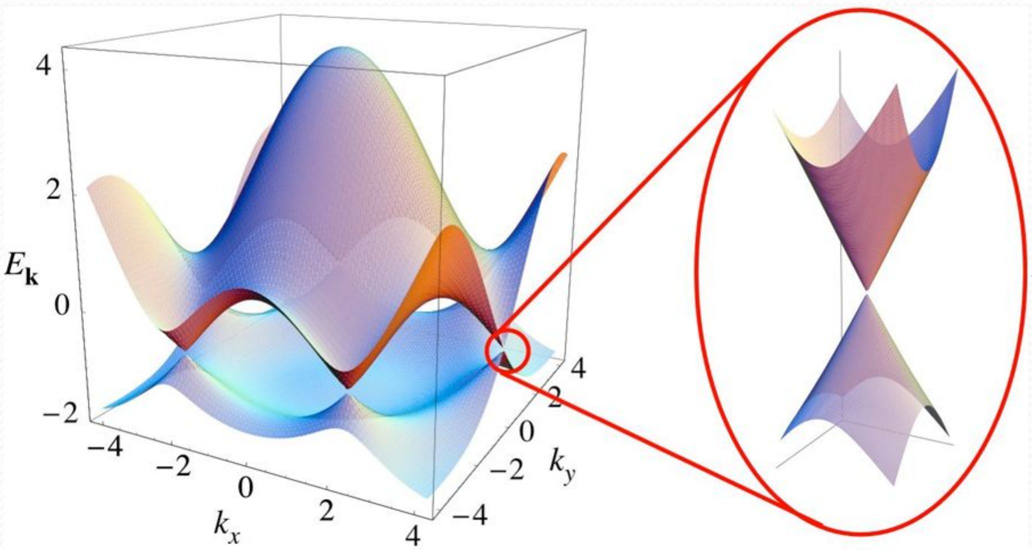


Simulated $I(V_G)$-curve for multigate FET with electrically induced junctions (MG TFET, solid) and common FETs with doped source and drain

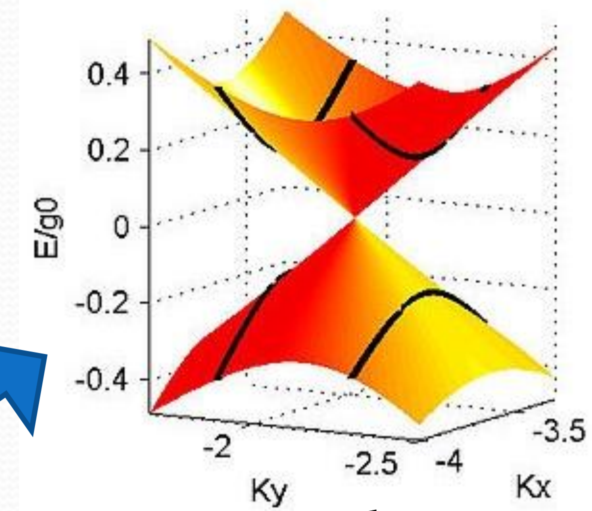
- Gate dielectric 2 nm, κ=25 (e.g. HfO_2);
- Distance between gates ("doping" and "control" gates) is 2 nm;
- 10 nm SOI thickness;
- Better subthreshold due to tunneling in undoped region (no band tails);
- Higher current due to abrupt screening of potential below the "doping" gate.

Graphene FETs

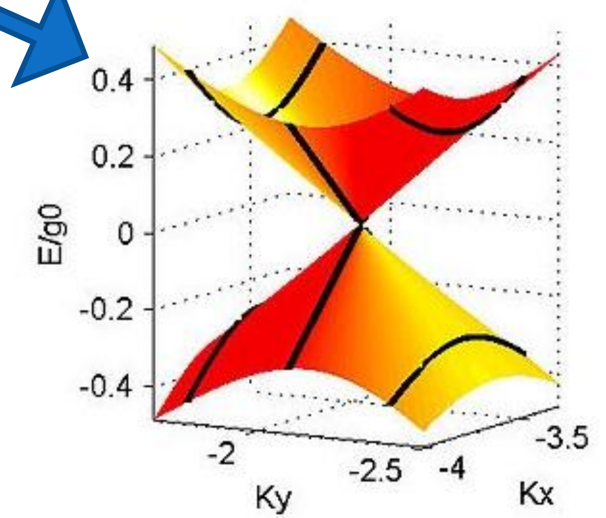
Graphene and nanotubes: electronic properties



Graphene electronic spectrum

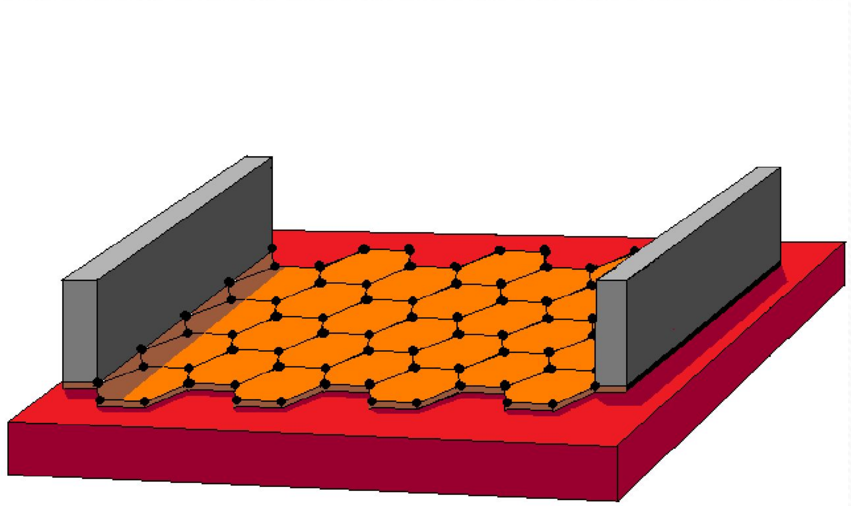


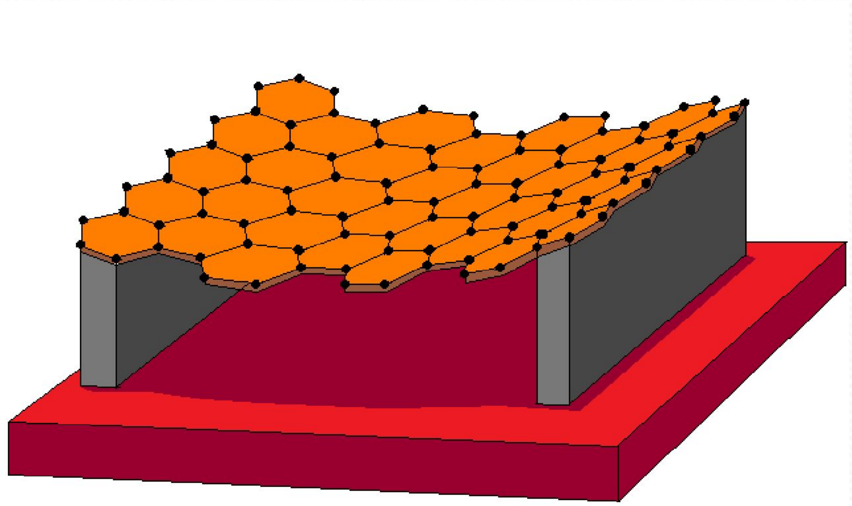
Semiconductor NT



Metallic NT

Graphene structures





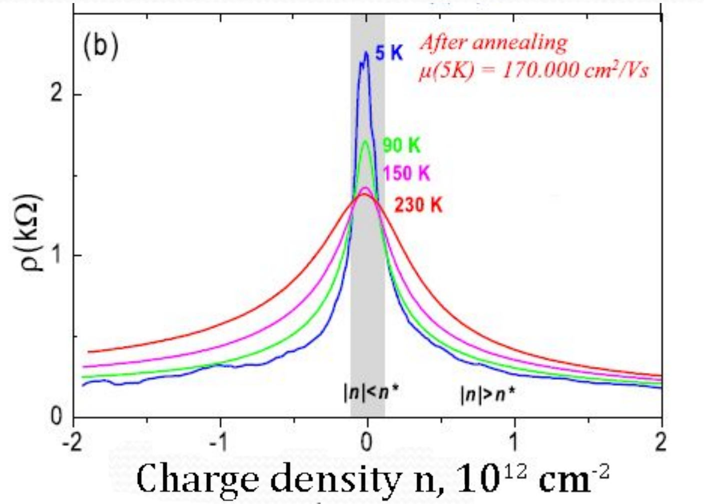
Deposited or **epitaxial** (on **SiC or hBN**) graphene: mobility 5000-10000 cm^2/V s due to interface defects and bulk phonons

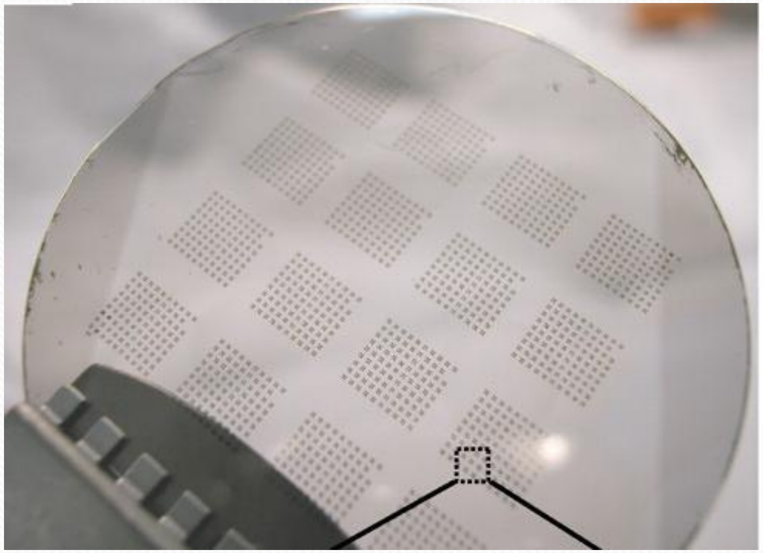
Suspended graphene or twisted graphene stack: mobility 100000-200000 cm^2/V s

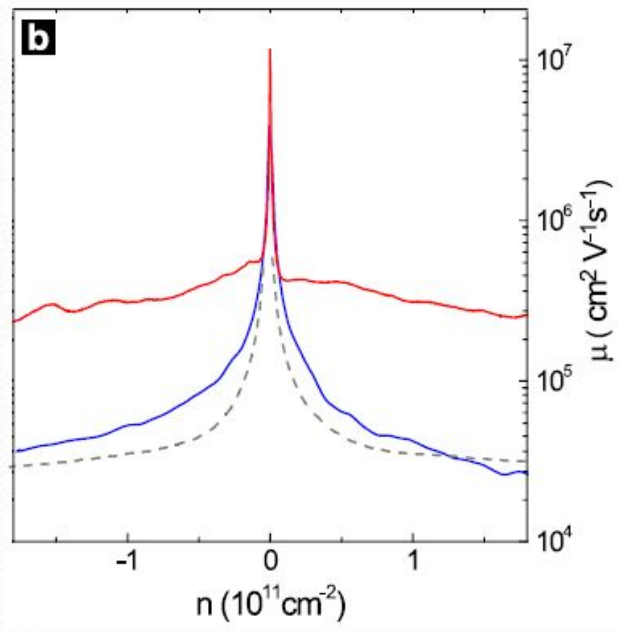
no

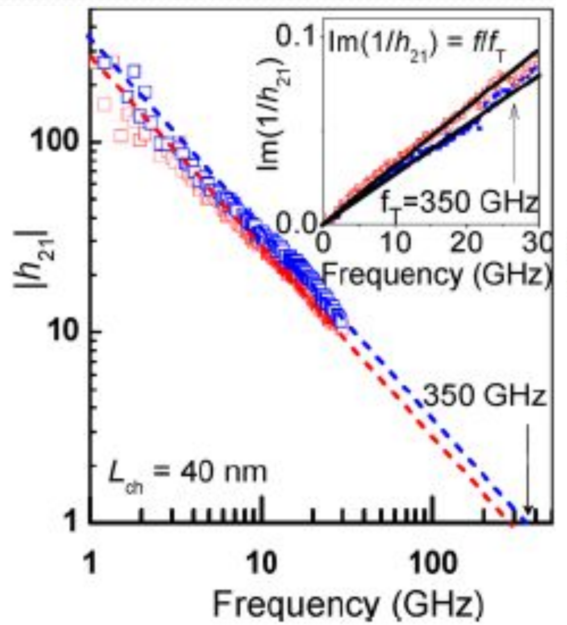
interface defects and bulk phonons

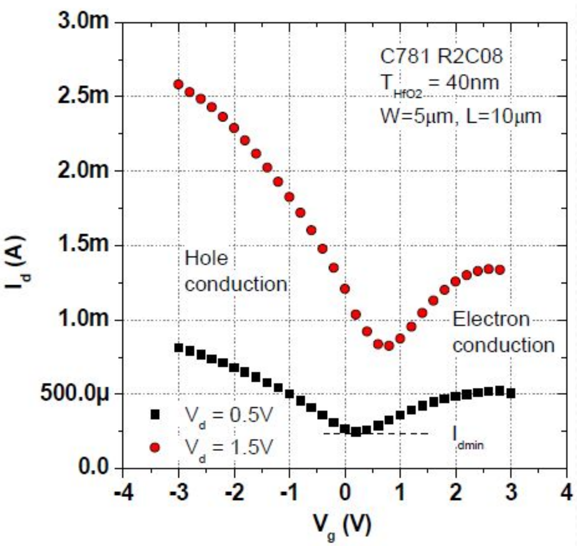
Электронные свойства графена



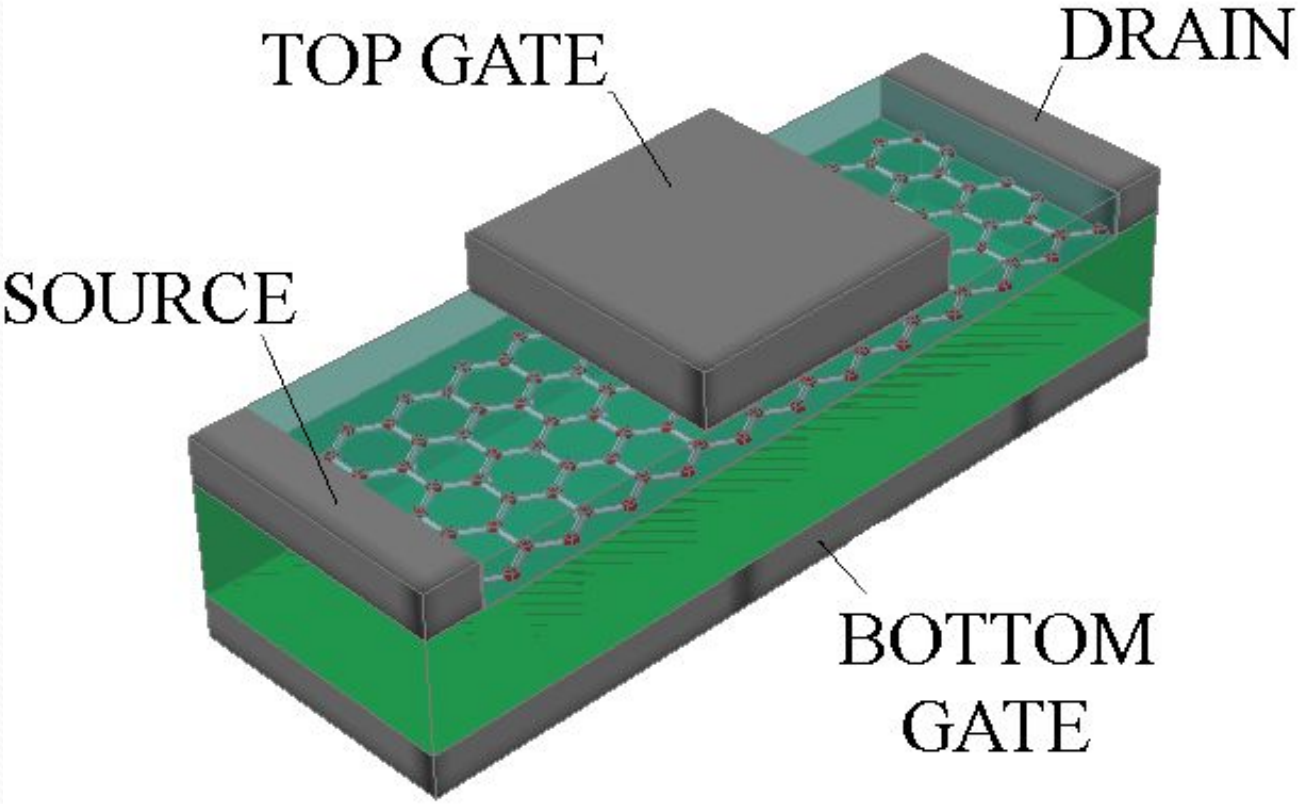








FET structure



Модель транспорта электронов в графене

- Высокая частота межэлектронных столкновений позволяет описывать транспорт в гидродинамической модели

$$\frac{\partial(\rho_e u_e)}{\partial t}+\frac{\partial}{\partial x}\left(\frac{\varepsilon_e}{2}\left[1+2\left(\frac{u_e}{v_F}\right)^2\right]\right)-en_e\frac{\partial\varphi}{\partial x_i}=-\beta_{e-i}u_e-\beta_{eh}(u_e-u_h),$$

$$\frac{\partial(\rho_h u_h)}{\partial t}+\frac{\partial}{\partial x}\left(\frac{\varepsilon_h}{2}\left[1+2\left(\frac{u_h}{v_F}\right)^2\right]\right)+en_h\frac{\partial\varphi}{\partial x_i}=-\beta_{h-i}u_h-\beta_{eh}(u_h-u_e).$$

n_e, n_h – electron and hole concentrations

ρ_e, ρ_h – electron and hole mass densities $\rho \neq nm_0$

u_e, u_h – drift velocities

β_{e-i}, β_{h-i} – friction coefficients

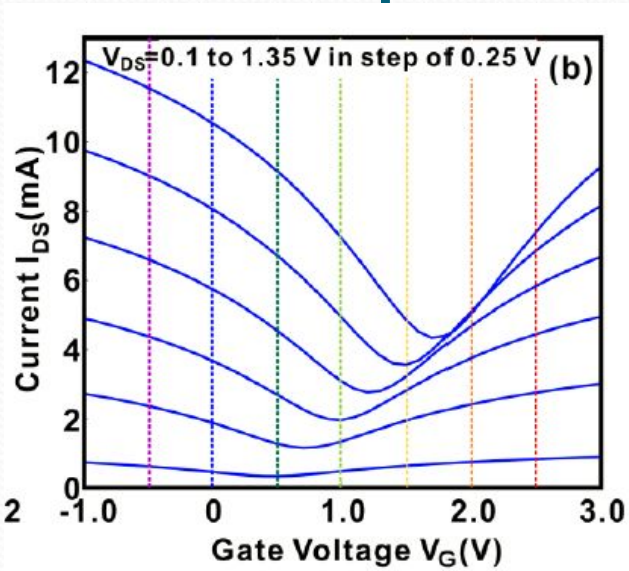
$$n=\frac{n_0}{\left[1-(u/v_F)^2\right]^{3/2}},\ \rho=\frac{\rho_0}{\left[1-(u/v_F)^2\right]^{5/2}}$$

D. Svintsov, V. Vyurkov, S. Yurchenko, V. Ryzhii, T. Otsuji *"Hydrodynamic model for electron-hole plasma in graphene"*, Journal of Applied Physics, Vol. 111, p. 083715 (2012)

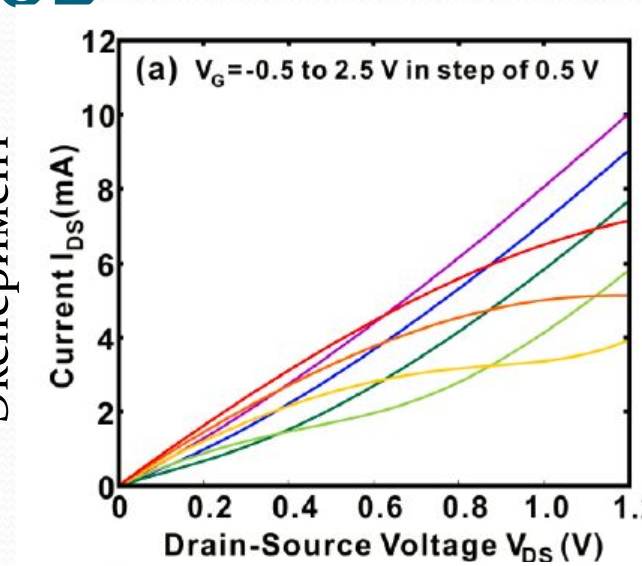
D. Svintsov, V. Vyurkov, V. Ryzhii, T. Otsuji *"Hydrodynamic electron transport and nonlinear waves in graphene"*, Physical Review B, Vol. **88**, p. 245444 (2013)

Моделирование характеристик полевых транзисторов

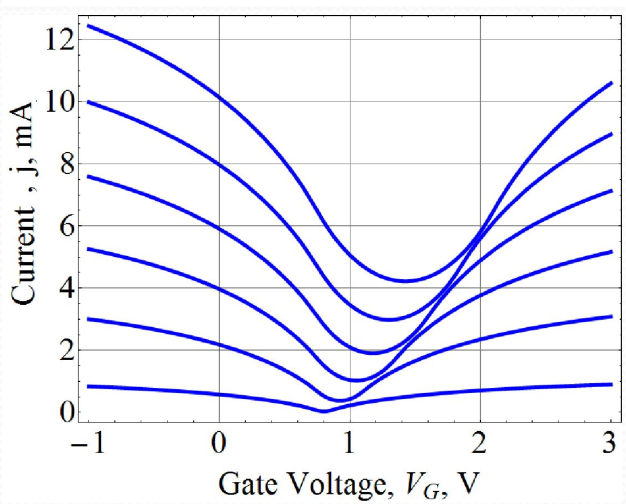
Эксперимент



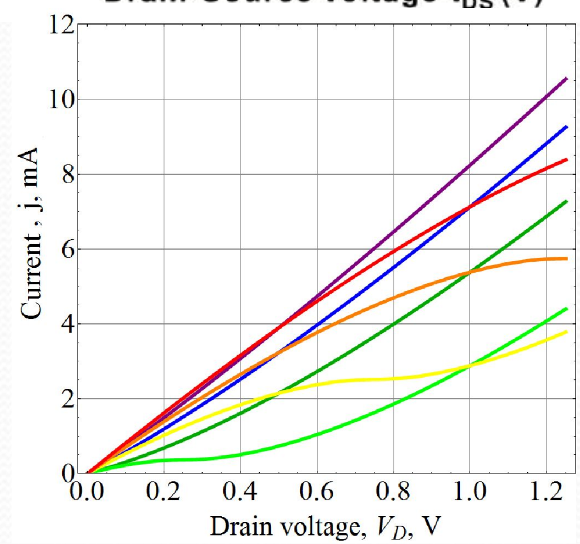
Эксперимент



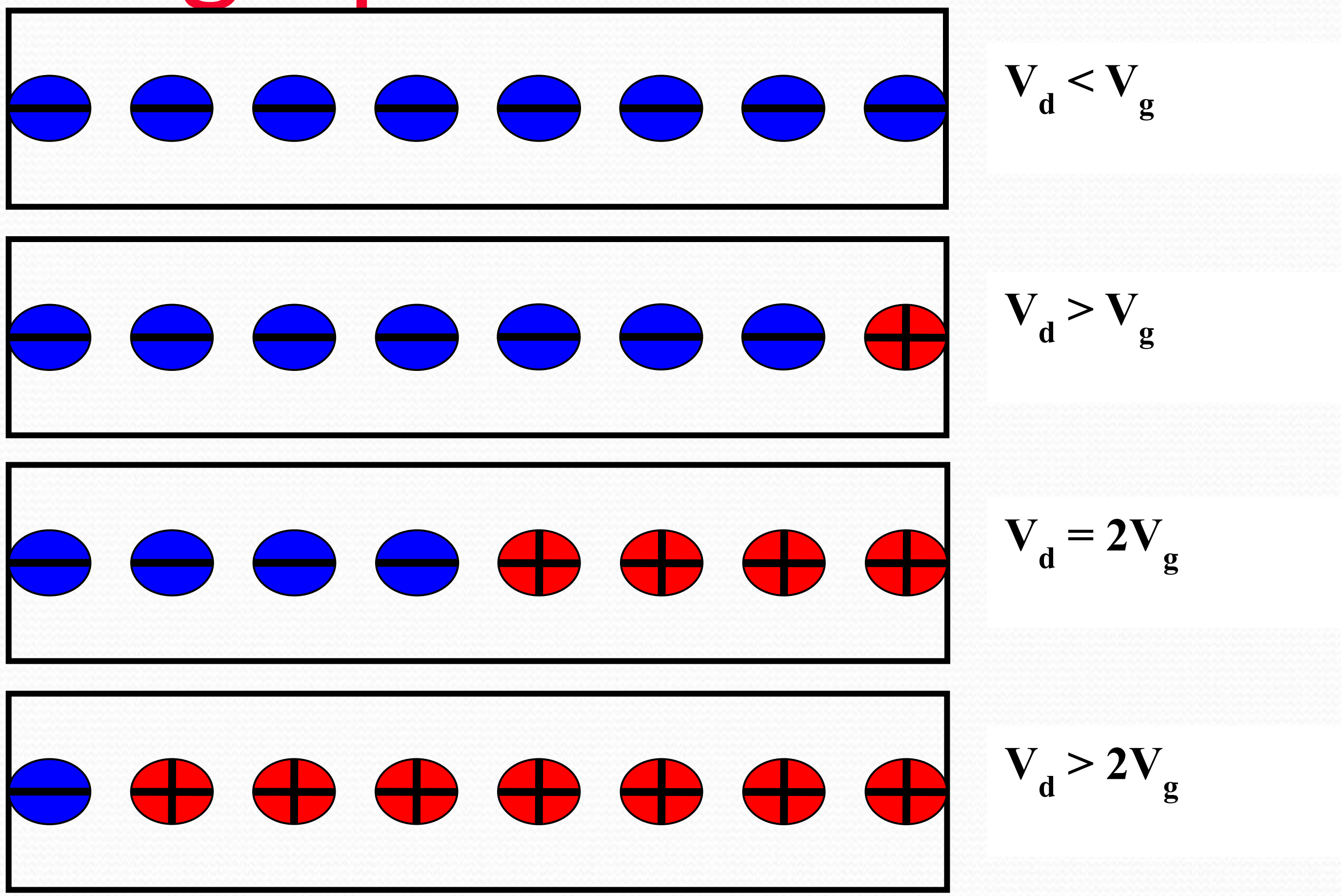
Теория



Теория



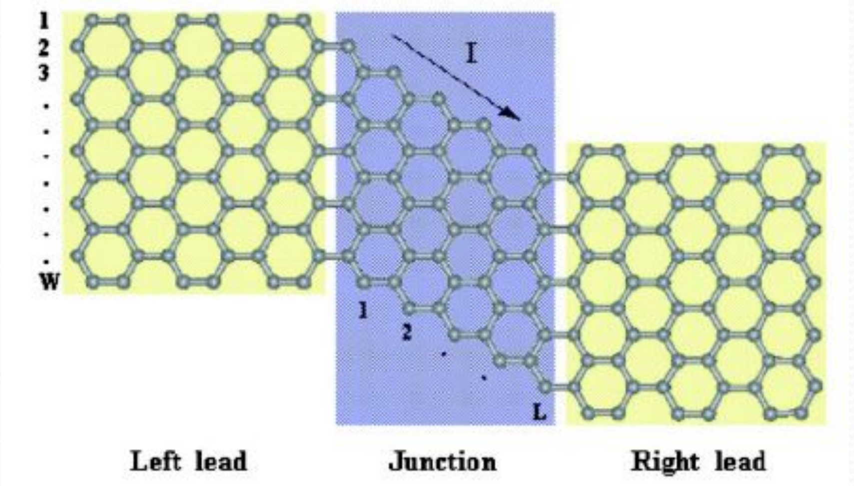
Bipolar graphene FET channel



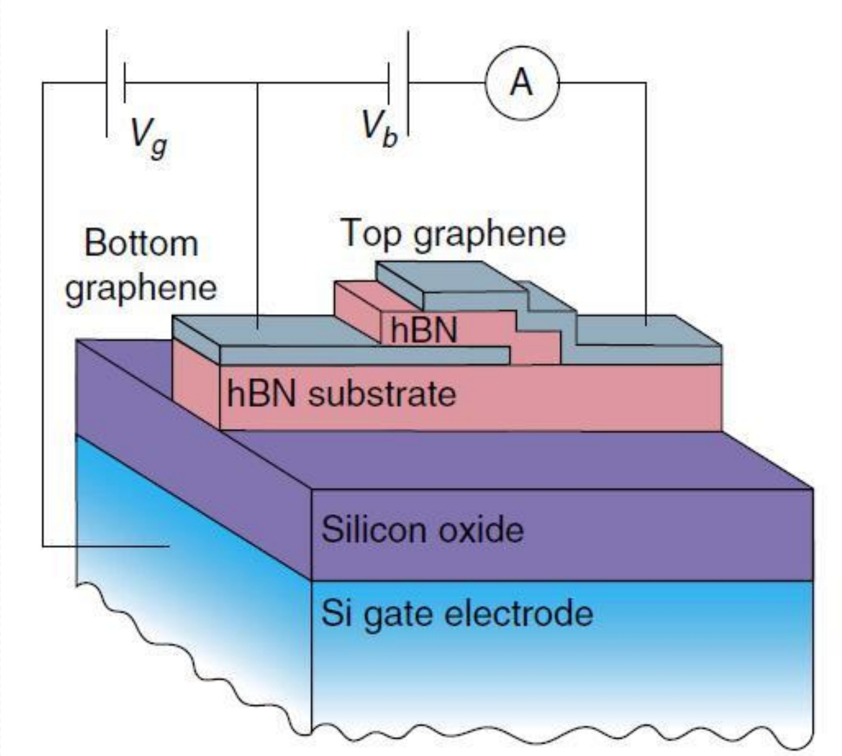
Possible applications: Logic circuits?

- **Graphene**
- => **good** Ohmic source
- and drain contact
- **Gap=0**
- => **big** OFF-state current

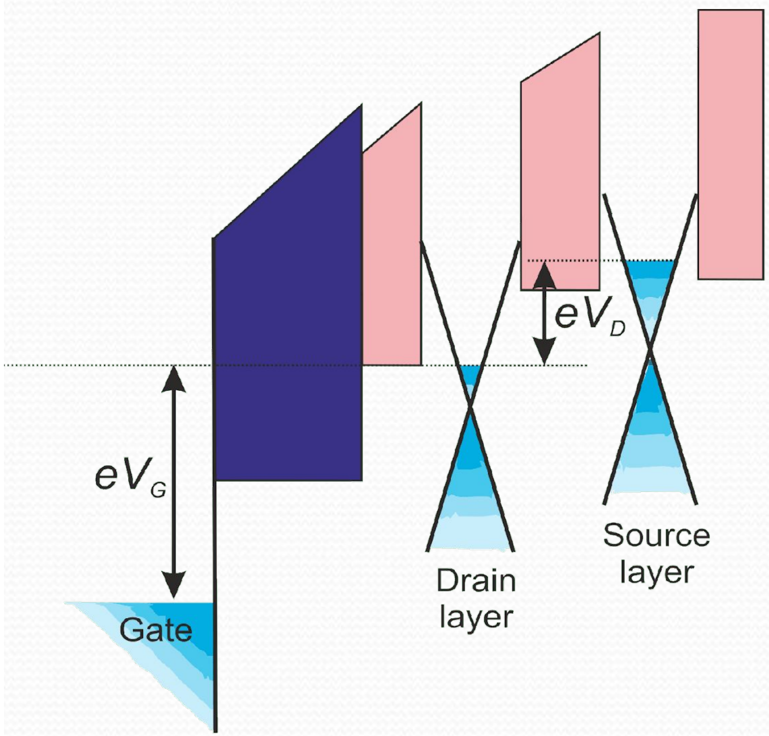
- **Bilayers, nanoribons or graphane**
- => **bad** Ohmic source and
- drain contact
- **Gap≠0**
- => **low** OFF-state current



Graphene vertical tunnel FETs



Layout of vertical graphene tunnel FET. Tunneling occurs between two graphene layers separated by 3-10 monolayers of boron nitride

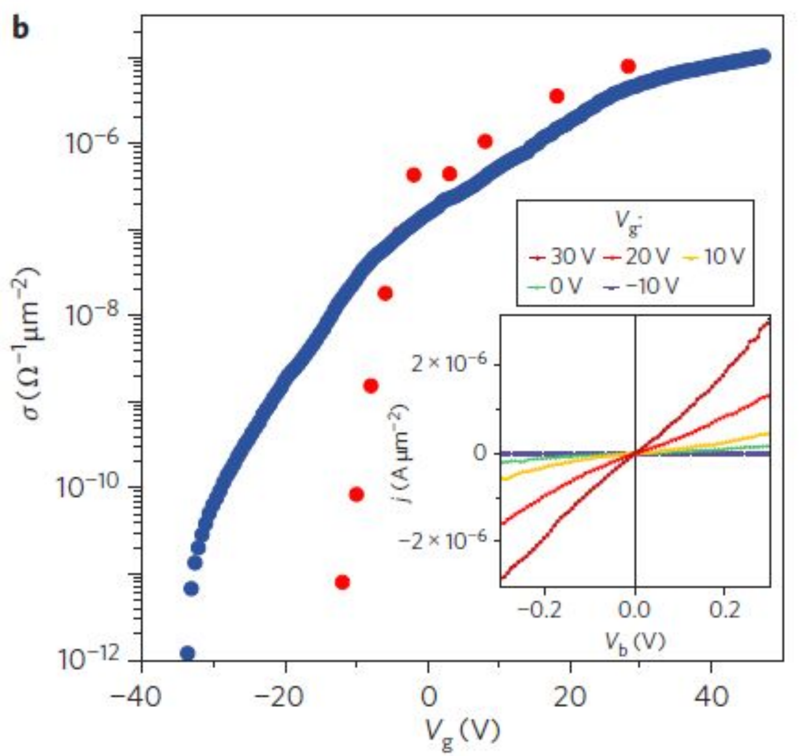


Band diagram of graphene lateral TFET. The gate voltage controls the tunnel density of states, but not the barrier height

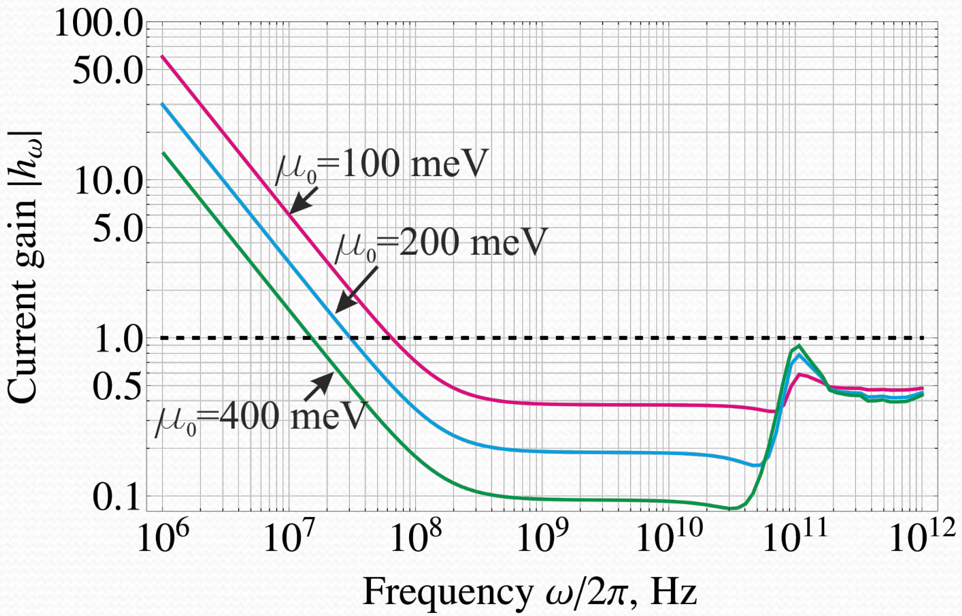
L. Britnell et al ,Science vol. ***335 p. 947*** *(2012)*

L. Britnell et. al., Nature Communications vol. ***4*** *art. no. 1794 (2013)*

Graphene vertical tunnel FETs



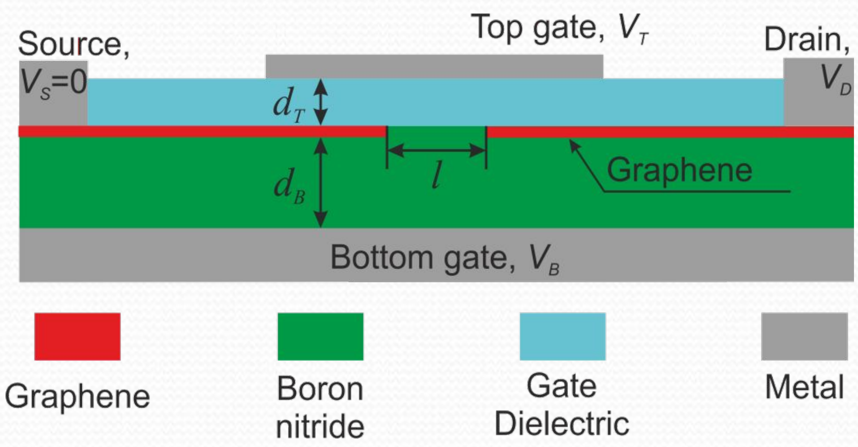
Measured tunnel conductivity of vertical graphene TFET vs. gate voltage



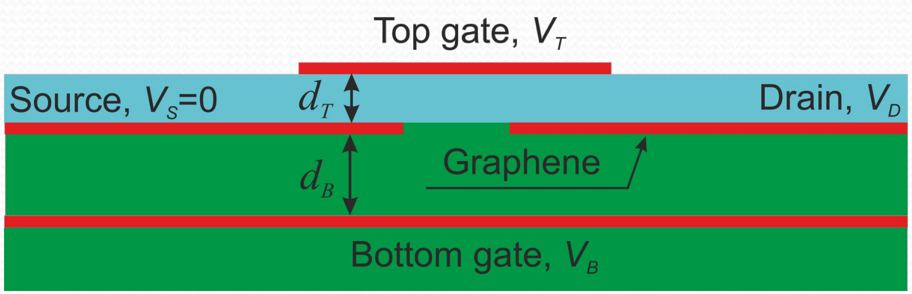
Calculated current gain of vertical graphene TFET vs. frequency at different electron Fermi energies in source layer. Cutoff frequency ~10MHz expected due to small tunneling probability

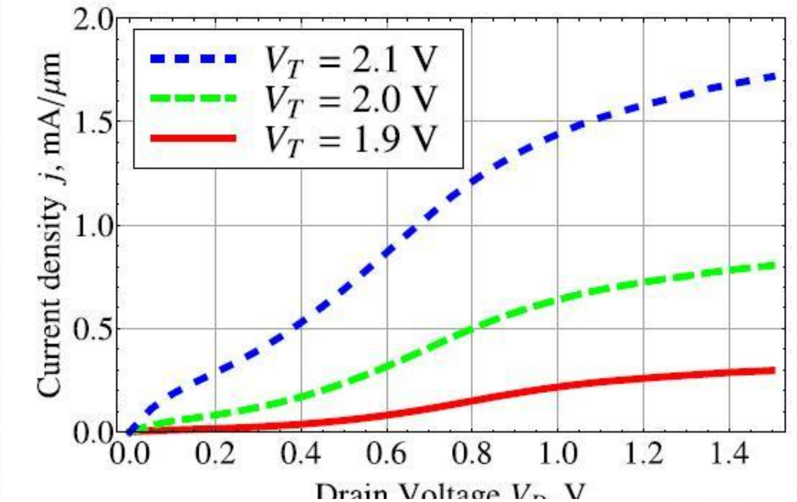
*L. Britnell et. al., Science **335** p. 947 (2012)*
*T. Georgiou et. al. Nature Nanotechnology **8** p. 100 (2013)*
*A. Mishchenko et. al. Nature Nanotechnology **9** p. 808 (2014)*

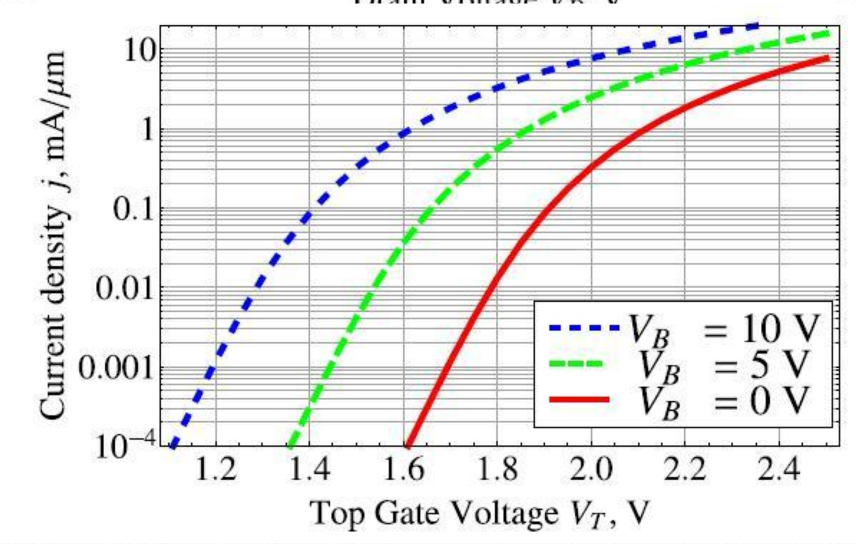
Латеральный туннельный транзистор на основе графена



Структуры предлагаемых транзисторов



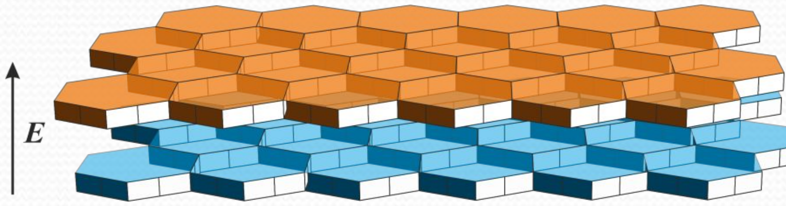


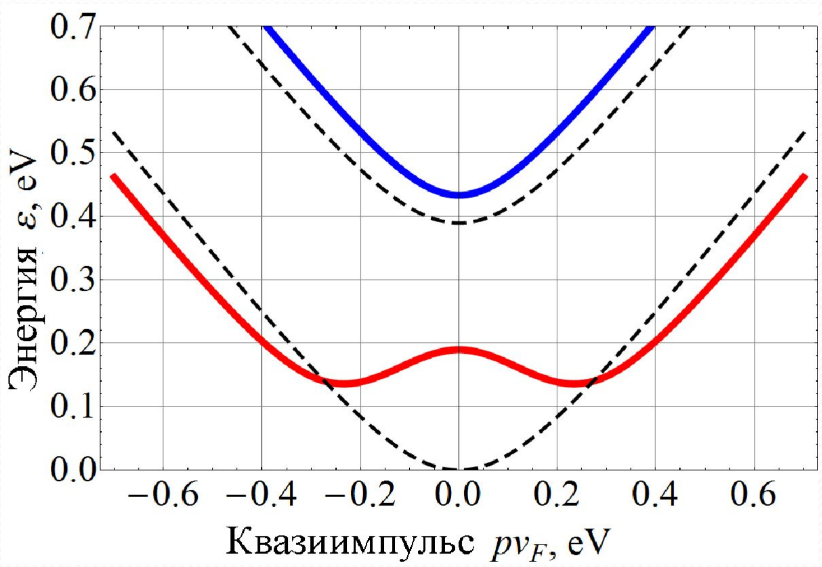


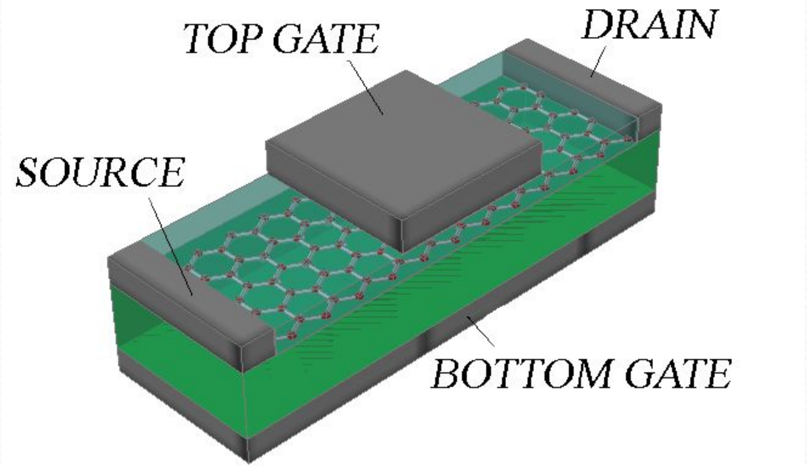
Рассчитанные характеристики, демонстрирующие насыщение тока и высокое (>10^4) отношение токов открытого и закрытого состояний

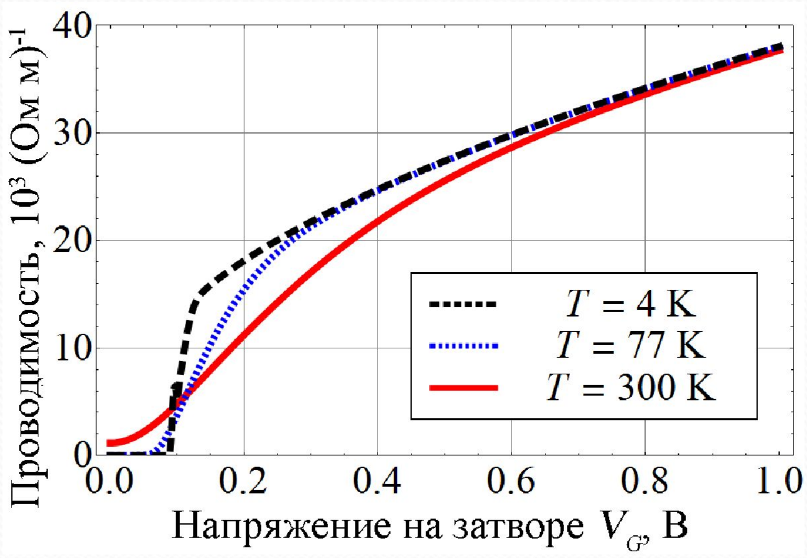
D. Svintsov *et. al.*, Semiconductors vol. **47**, p. 279-284 (2013)
D. Svintsov *et. al.*, J. Phys. D: Appl. Phys. Special issue "Graphene devices" (2014)

Транзисторы на основе двухслойного графена





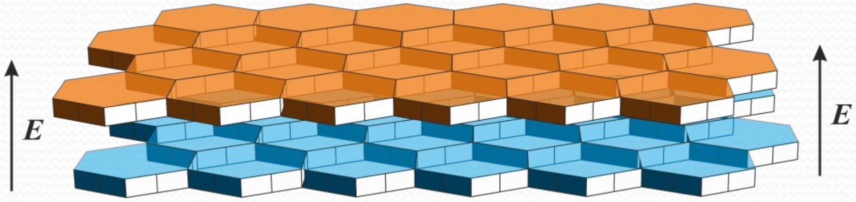


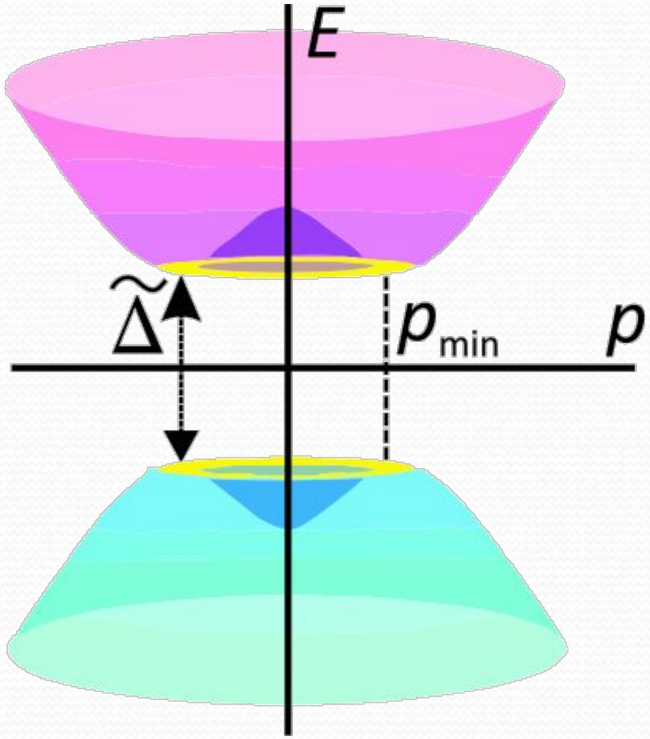


$$\varepsilon^2(p) = \frac{\gamma_1^2}{2} + \frac{\Delta^2}{4} + p^2 v_F^2 \pm \sqrt{\frac{\gamma_1^4}{4} + p^2 v_F^2 \left(\gamma_1^2 + \Delta^2\right)}$$

D. Svintsov, V. Vyurkov, V. Ryzhii, T. Otsuji *"Effect of "Mexican Hat" on Graphene Bilayer Field-Effect Transistor Characteristics"*, Japanese Journal of Applied Physics, Vol. 50, Iss. 7, p. 070112 (2011)

Graphene bilayer

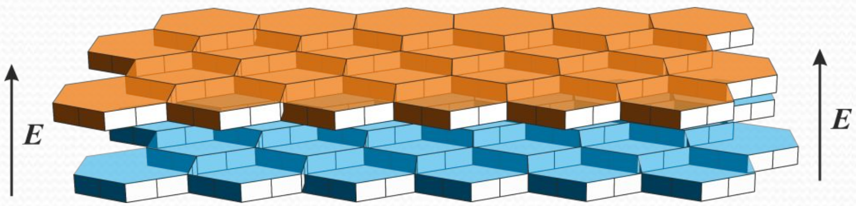




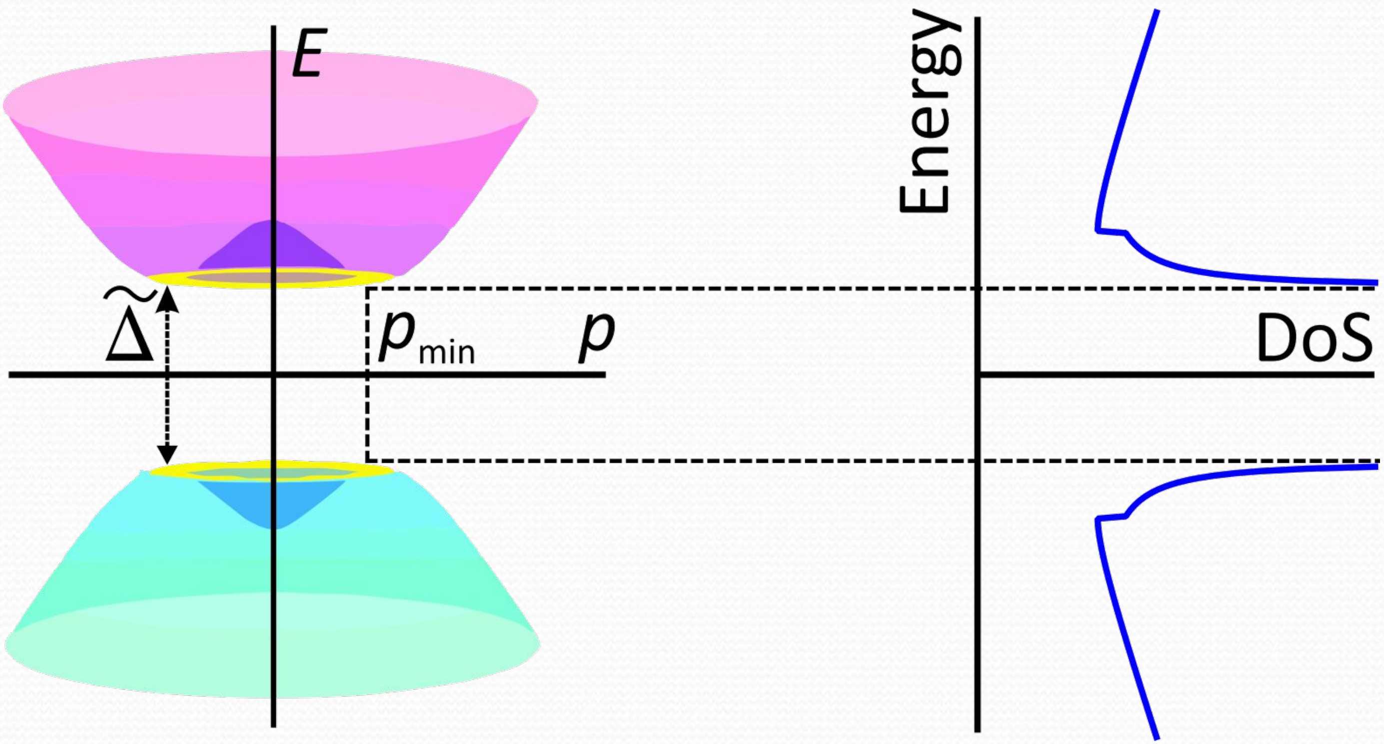
Conduction and valence band electron dispersions in graphene under applied transverse electric field

- Gap opening up to ~0.4 eV by transverse electric field;
- Symmetric "Mexican-hat" band dispersion

Graphene bilayer



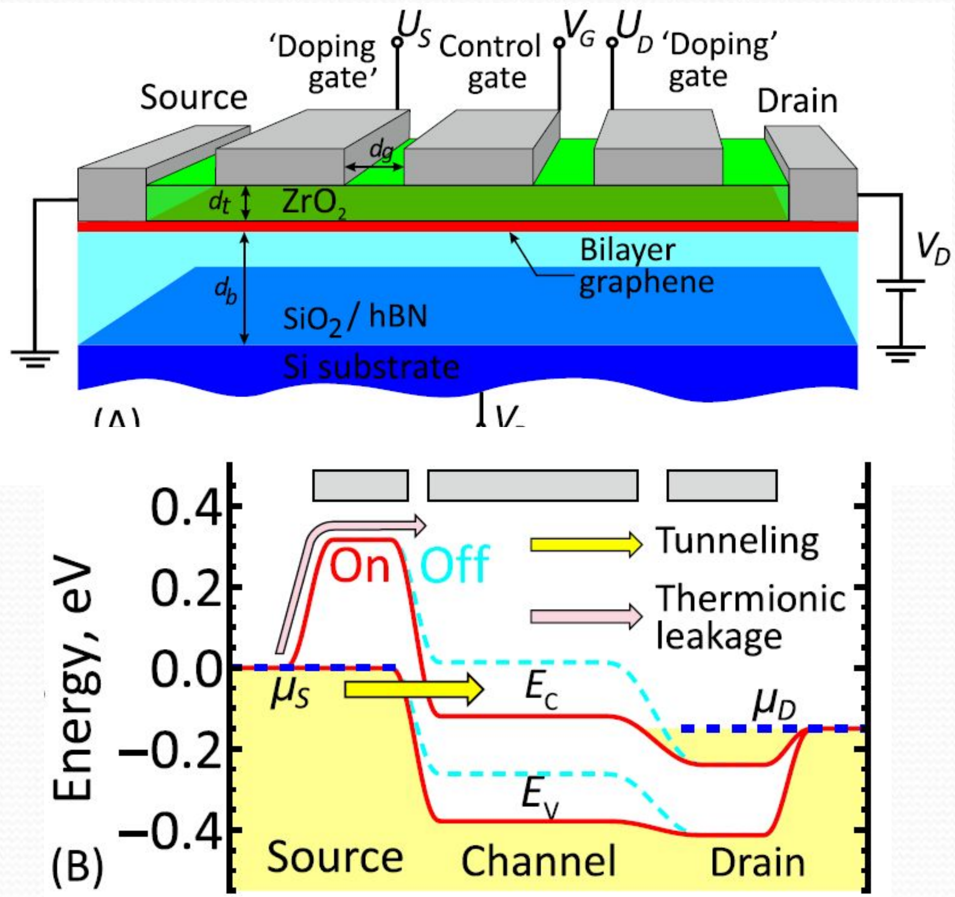
- Gap opening up to ~0.4 eV by transverse electric field;
- Symmetric "Mexican-hat" band dispersion



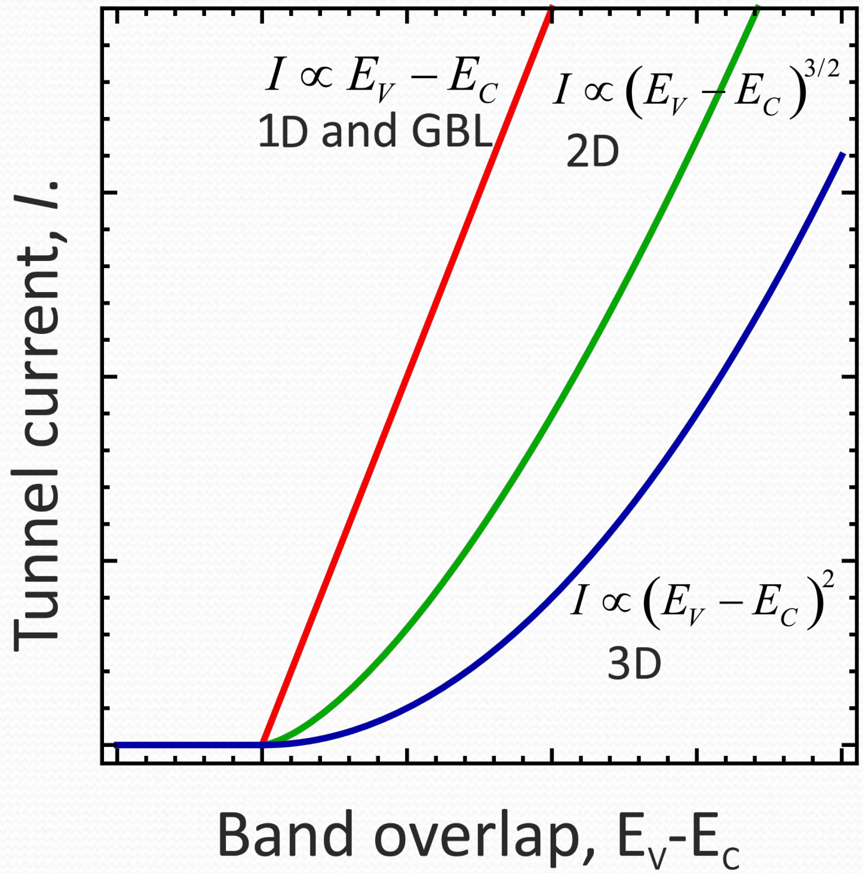
Conduction and valence band electron dispersions in graphene under applied transverse electric field

Density of states in gapped graphene bilayer demonstrating a van Hove singularity

Exploiting the van Hove singularity in tunneling

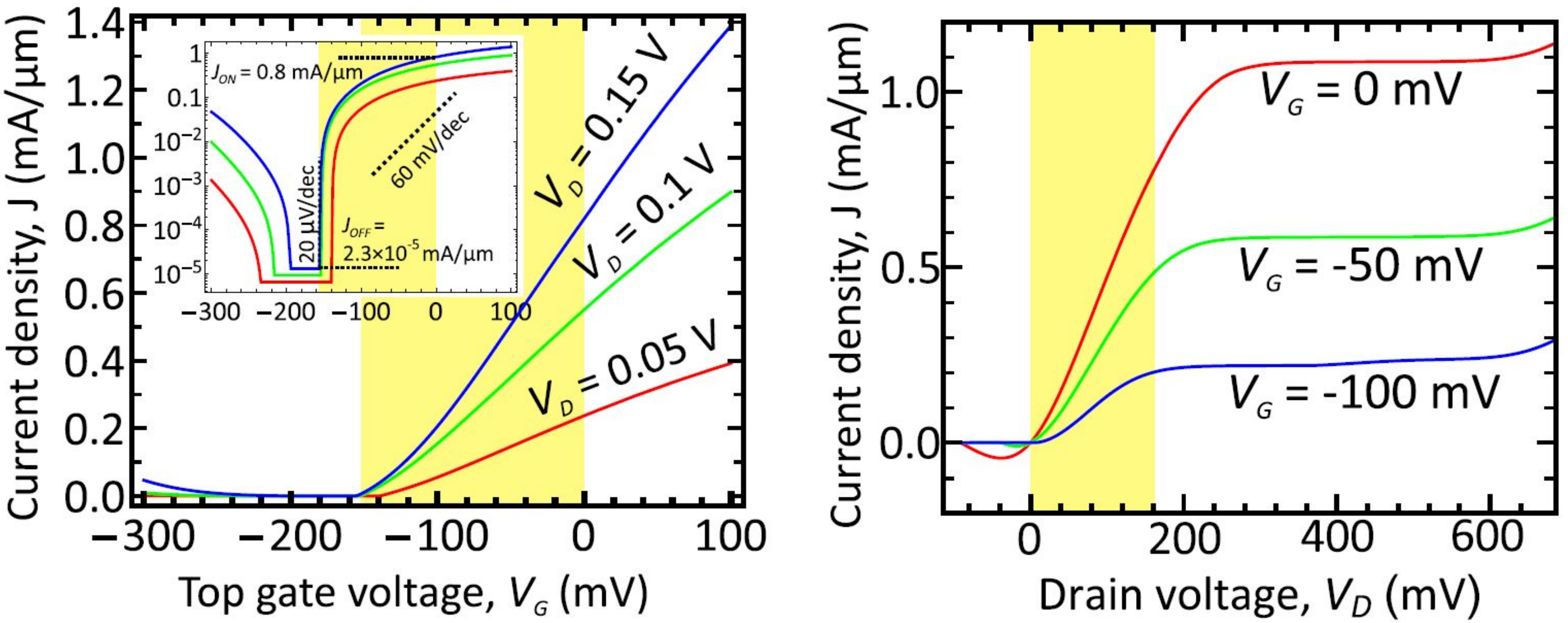


(A) Layout of the proposed graphene bilayer TFET with electrically defined source and drain regions (B) Band diagram of graphene bilayer TFET for the optimal biasing conditions: $V_B > 0$, $U_S < 0$, $U_D > 0$. At zero top gate bias, $V_G = 0$, the TFET is switched on, while at $V_G < 0$ it is switched off.



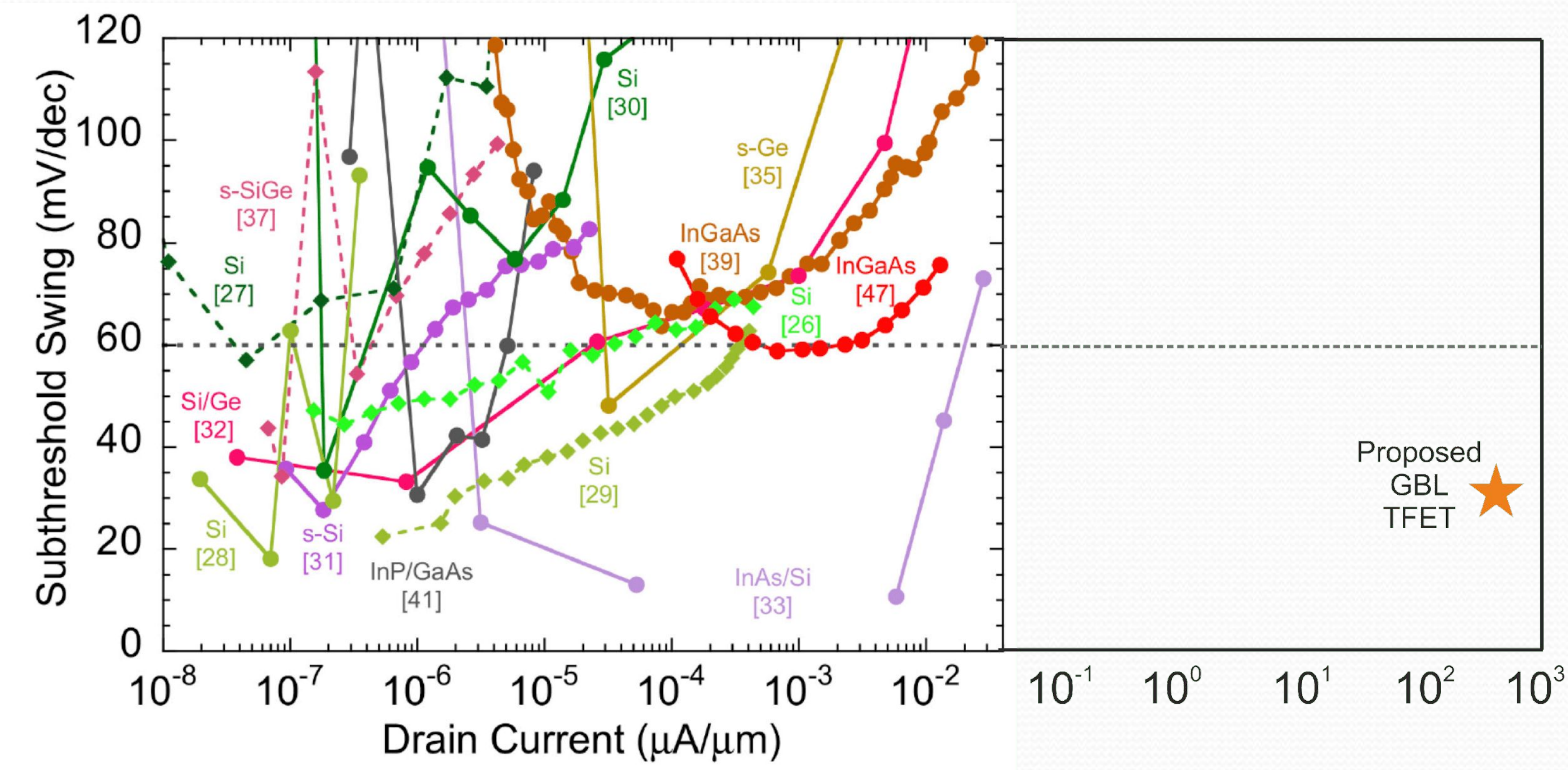
Schematic dependence of direct interband tunneling current on the band overlap in parabolic band semiconductors of different dimensionality (3D, 2D, 1D) and graphene bilayer.

Graphene bilayer TFET characteristics

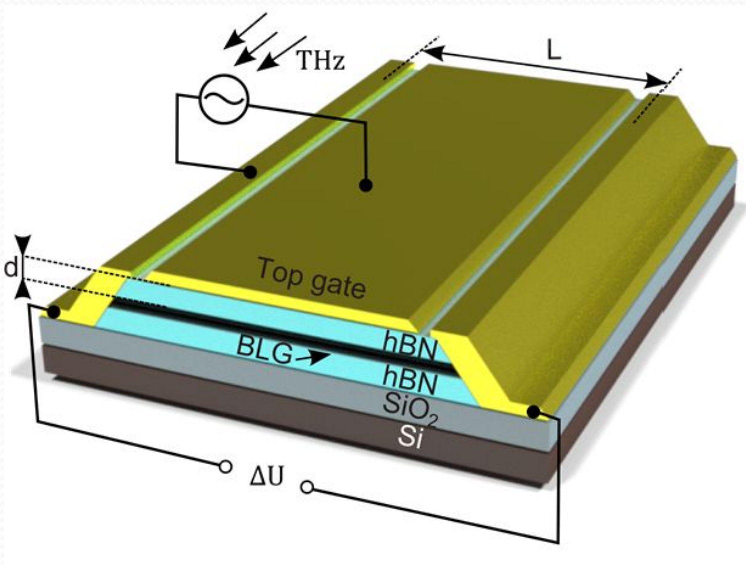


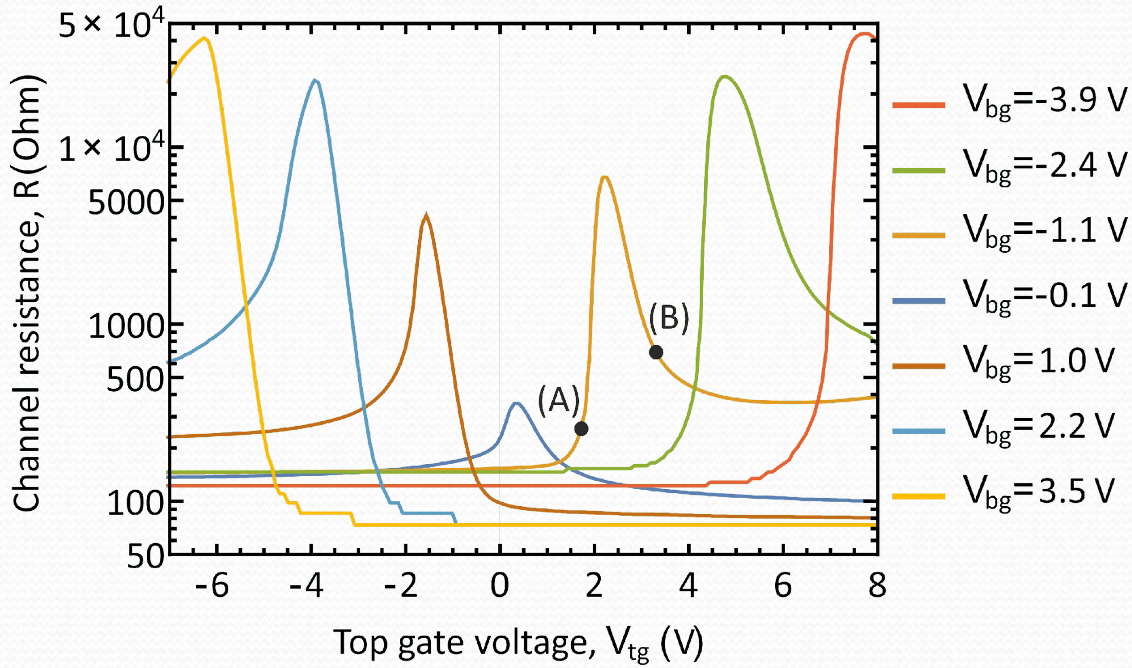
Calculated room-temperature gate transfer (left) and current-voltage (right) characteristics of graphene bilayer TFET at fixed bias voltages at auxiliary gates: V_B = 3.3 V, U_S = −0.6 V, U_D = 0.25 V. Top gate dielectric is 2 nm ZrO_2, κ = 25, back gate dielectric is 10 nm SiO2, spacing between the source doping and control gates d_g = 5 nm, spacing between drain doping and control gates is 10 nm. The regions highlighted in yellow correspond to the drive voltage swing of 150 mV, in which sufficient ON/OFF ratio and high ON-state current are achieved. Inset: gate transfer characteristic in the log scale.

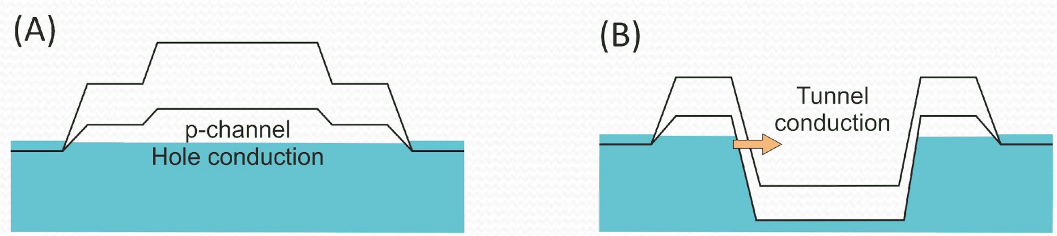
Proposed FET positioning



Observation of interband tunneling in GBL







D. A. Bandurin, D. Svintsov, I. Gayduchenko, S. G. Xu, A. Principi, M. Moskotin, I. Tretyakov, D. Yagodkin, S. Zhukov, T. Taniguchi, K. Watanabe, I. V. Grigorieva, M. Polini, G. Goltsman,A. K. Geim, G. Fedorov “*Resonant Terahertz Detection Using Graphene Plasmons*” **arXiv:1807.04703**

QUANTUM COMPUTERS

History

- Soviet mathematician **Yu. Manin** (1980) and

  R. Feynman (1982) proposed to use a quantum system (quantum computer) for simulation of quantum systems.
- ***Shor's algorithm*** (1994): for integer factorization (to undermine the modern secret communication):
- N is a number of digits
- Classical factoring algorithm ~ $2^{\sqrt{N}}$
- Shor's quantum factoring algorithm ~ N^3
- ***Grover's algorithm*** (1996): search in unsorted data base of N elements
- quantum ~ $\sqrt{N}$, classical ~ N

Bit vs. Qubit

- ***Bit***

  Discrete |0> or |1>

Qubit

Analog |0> and |1>

Qubit superpositional state

$$|\psi>=\alpha|0>+\beta|1|>$$

$$|\alpha|^2+|\beta|^2=1$$

Classical register vs. Quantum register

Bits

Classical register

|1>|0>|1>|1>|0>…

N bits of information

Sequential computation

Qubits

Quantum register

Entangled states

2^N -dimensional Hilbert space:

huge information capacity

2^{300} > number of atoms in Universe

Quantum parallelism of computation

Great acceleration of several algorithms!

Entangled states in quantum computer: quantum parallelism

Realism and locality in quantum mechanics

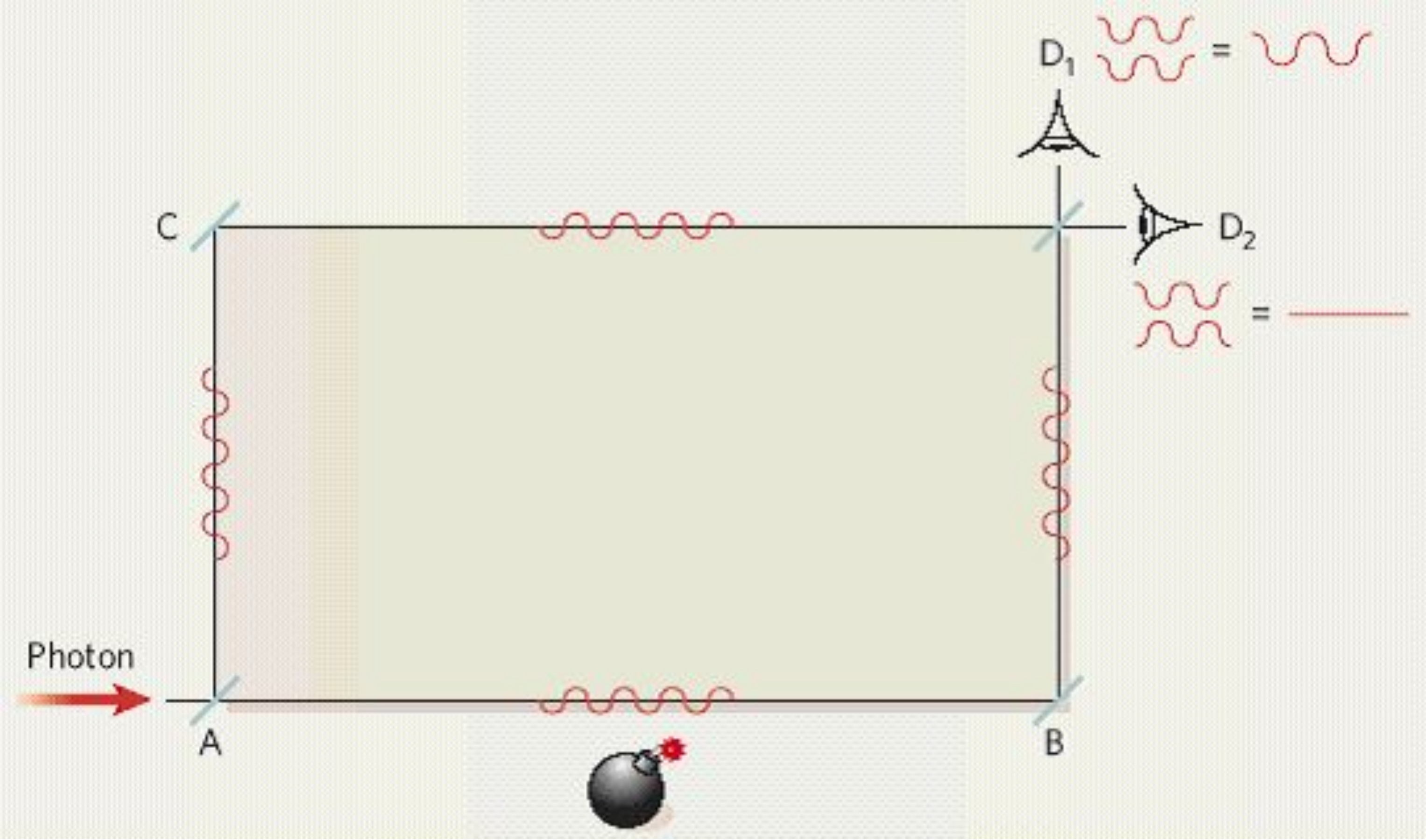
EPR pair (EPR paradox => non-locality)

$$\psi = \frac{1}{\sqrt{2}}\left(|\leftrightarrow>|\square > + |\square >|\leftrightarrow>\right)$$

- EPR pair of photons is produced in non-linear crystal via down-conversion.
- One photon is in Alice disposal, the next one is in Bob’s disposal.
- Wave function of Bob’s photon is collapsed after Alice’s measurement. Is information instantly transmitted form Alice to Bob and the relativity principle broken? No.
- The name “Eve” originates from the word “eavesdropping” – подслушивание.

Bomb paradox (Elitzur и Vaidman)

=> no realism



No cloning theorem

Proof

The **linearity** of time evolution operator U(Δ*t*) implies

$$U(\Delta t)|\psi = U(\Delta t)(a|0\rangle_A + b|1\rangle_A)|e\rangle_B$$
$$= a|0\rangle_A|0\rangle_B + b|1\rangle_A|1\rangle_B$$

$$\neq a^2|0\rangle_A|0\rangle_B + ab|0\rangle_A|1\rangle_B + ba|1\rangle_A|0\rangle_B + b^2|1\rangle_A|1\rangle_B$$

Consequences:

'--' quantum computing – error correction much complicated

'++' quantum communication – secrecy is possible

Quantum communication:

Alice – Bob – Eve (eavesdropping)

I. **EPR pairs**   Alice ---------------- Bob
↑   EPR pair ↑

II. **Single photons**   Alice --□---------- Bob

Realizations of quantum computers

- Dopant atoms in silicon
- Quantum dots
- Ions in traps
- Cold atoms in optic traps
- NV-centers in diamond
- Superconducting structures: charge, phase and transmon
- 2D electron gas with Quantum Hall Effect
- 2D electron gas on Helium,
- and so on

Classical vs. Quantum

- ***Bits***

  Discrete |0> or |1>

Qubits

Analog Qubit superpositional state |0> and |1>

$$|\psi >= \alpha\,|0> + \beta\,|1|>$$

Accuracy 10-4

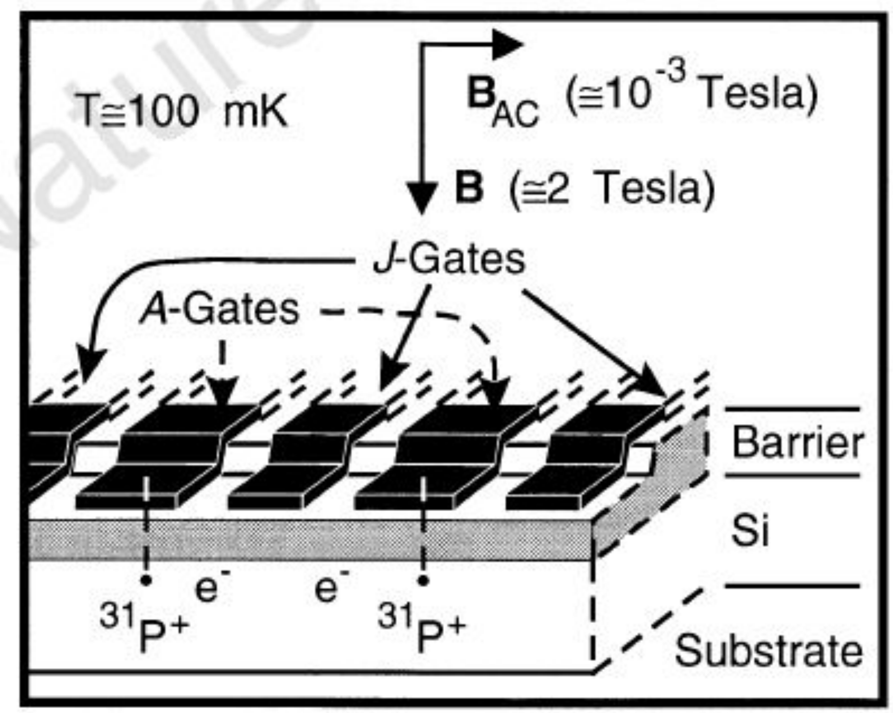
Noise (decoherence) and technological variability!!!

Error correction???

Classical vs. quantum

Прототип 1 - квантовый компьютер на ядерных спинах атомов фосфора в моноизотопном кремнии (Кейн, 1998)

Главная технологическая операция –
помещение одиночных примесных атомов фосфора в узлы кристаллической решетки моноизотопного кремния в определенных местах структуры – до сих пор не разработана.

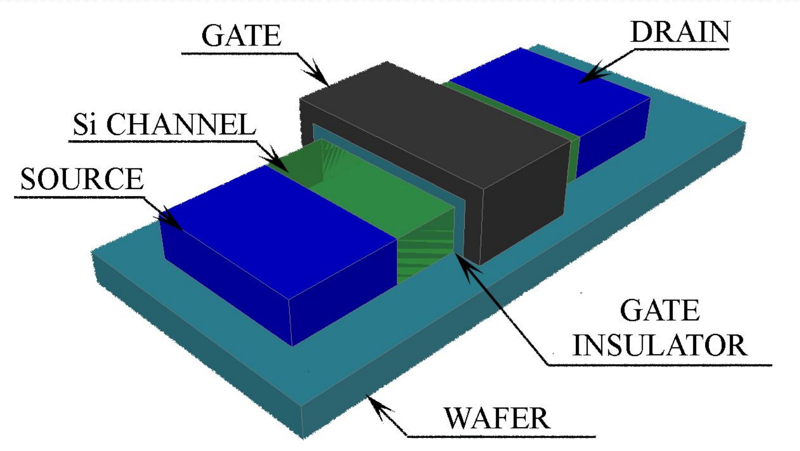


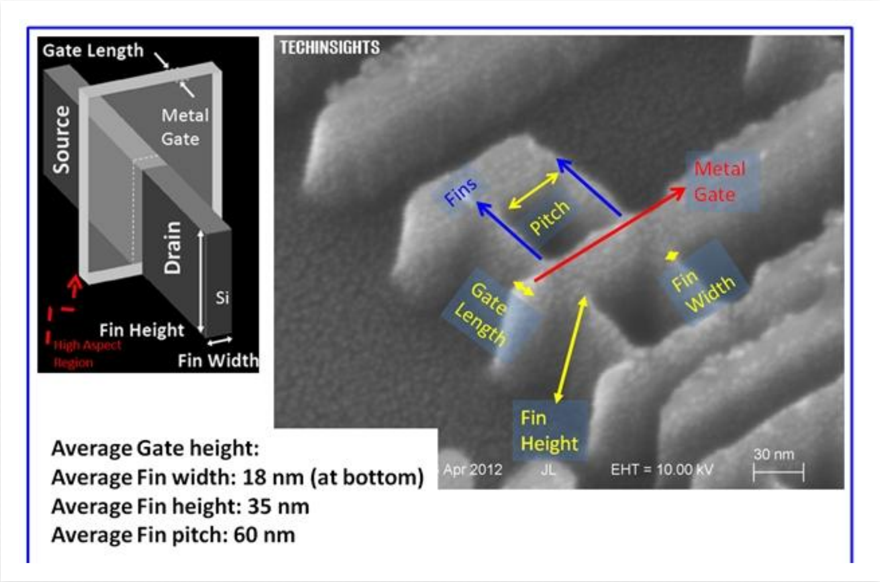
Предыстория

- Квантовый компьютер на основе двойных квантовых точках
- . *Fedichkin*, M. *Yanchenko*, K.A. *Valiev*, Nanotechnology 11, 387 (2000) 141, 146 39.
- Квантовый компьютер без перемещения заряда (борьба с декогерентизацией)
- V. Vyurkov, S. Filippov, L. Gorelik. Quantum computing based on space states without charge transfer. Physics Letters A 374, 3285–3291 (2010)
- Измерение состояния квантового регистра в канале транзистора в режиме кулоновской блокады тока
- M. Rudenko, V. Vyurkov, S. Filippov, A. Orlikovsky. Quantum register in a field-effect transistor channel. Int. Conf. “Micro- and nanoelectronics – 2014”, Moscow, Russia, October 6-10, 2014, Book of Abstracts, p. q1-05

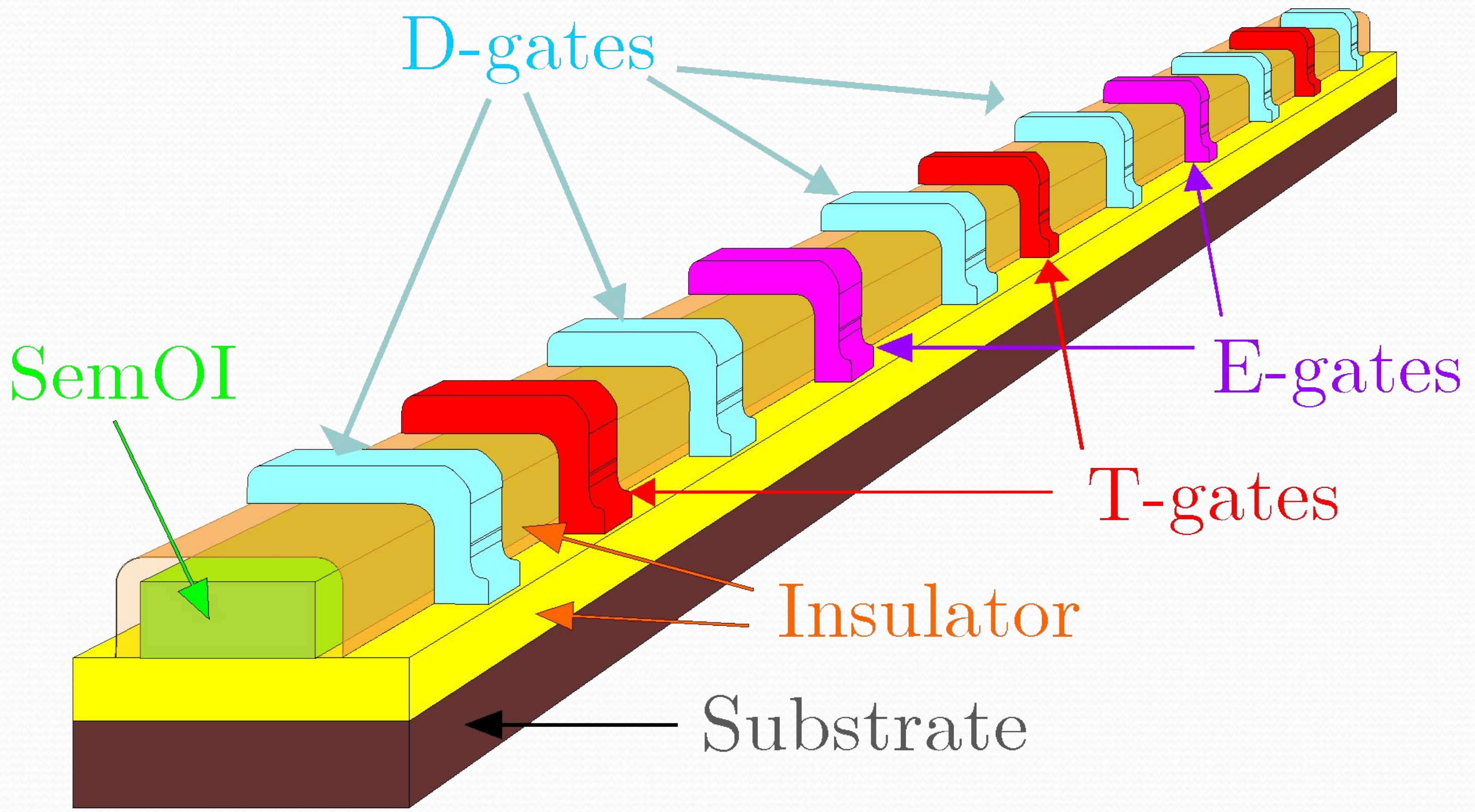
From quantum transistor to quantum computer

- Quantum confinement;
- Tunneling and interference of electron waves;
- Quantum statistics.



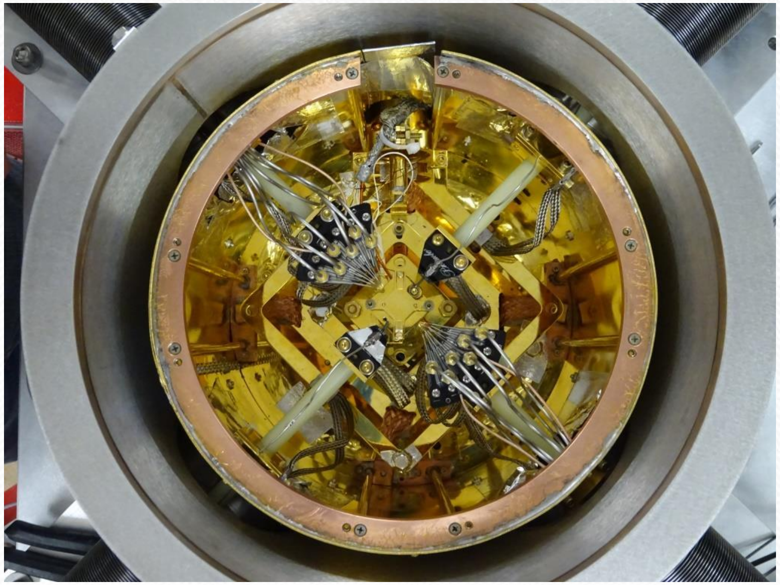


Quantum computer in transistor channel

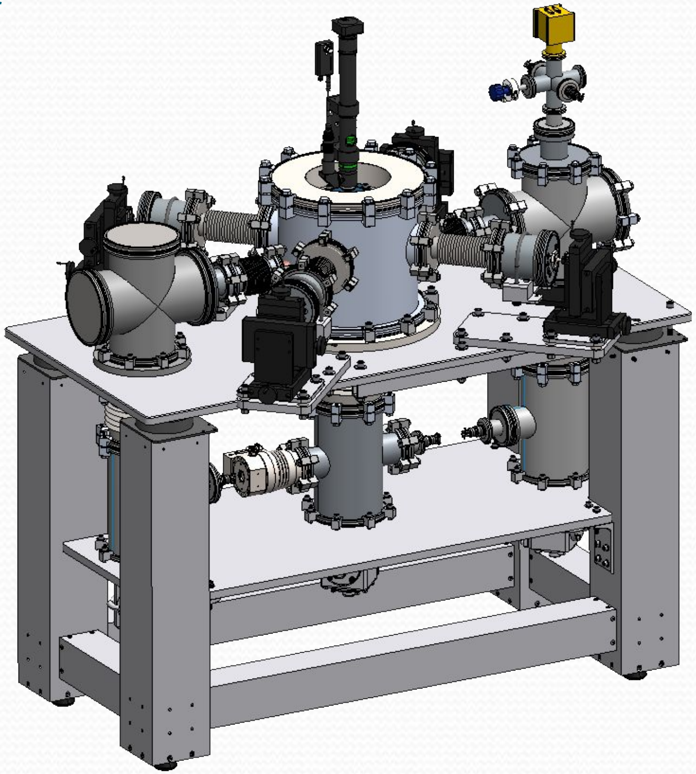


ФТИАН

1а. Технический облик - лабораторный



Микросхема регистра с контактами

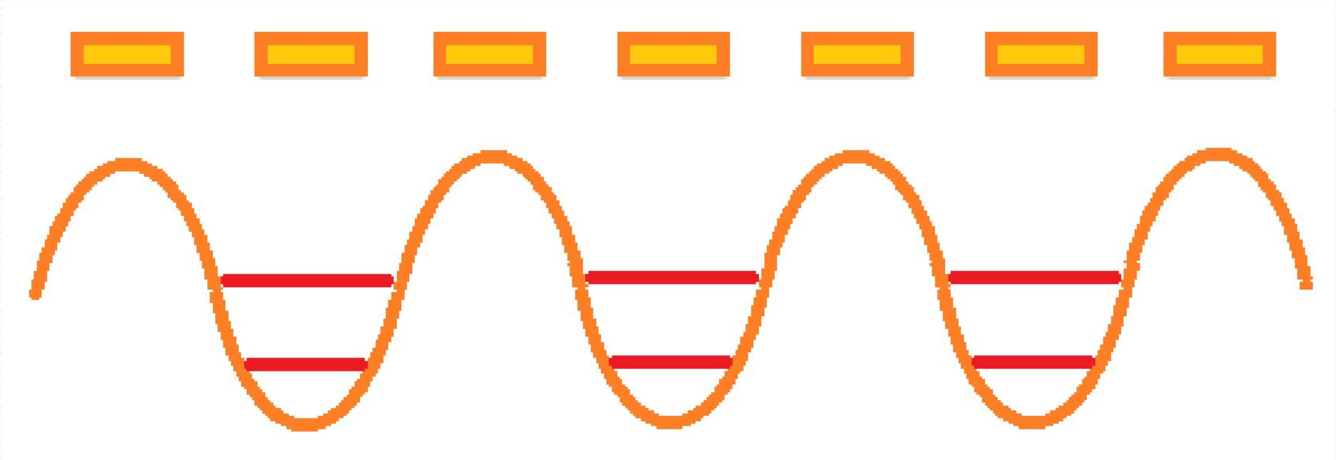


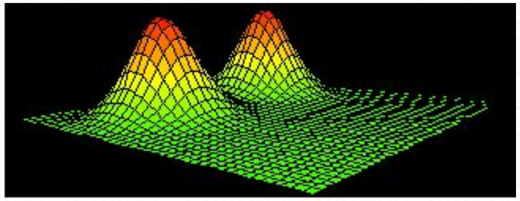
Измерительная установка

1б. Технический облик - коммерческий

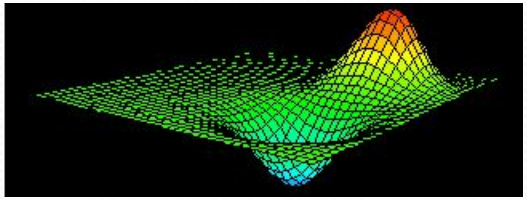
Интегральная схема регистра с управляющей и измерительной системой

Field-defined quantum dots





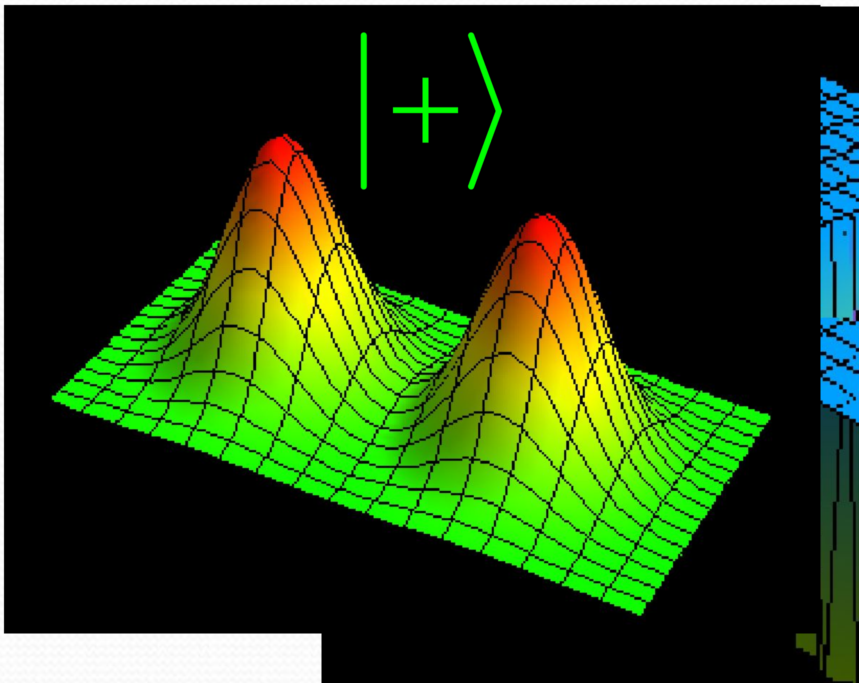
Symmetric state in DQD

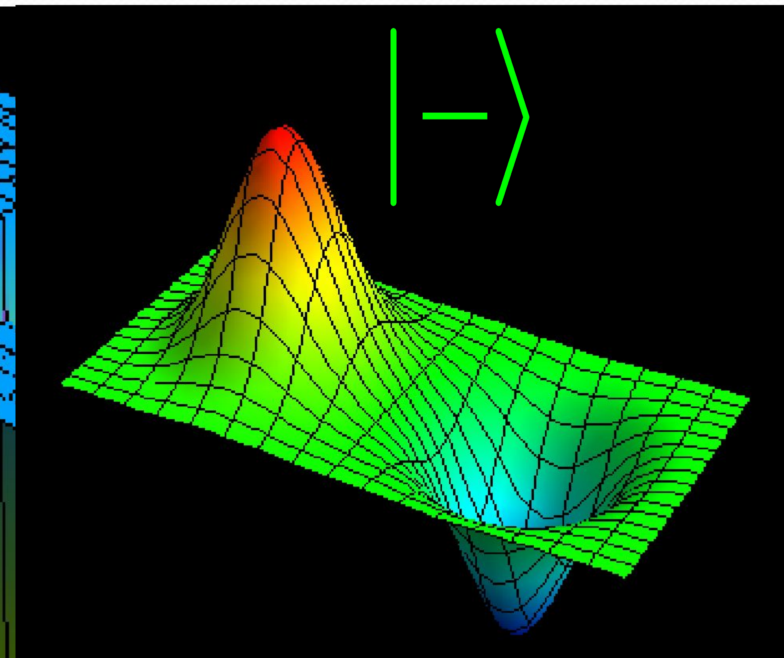


Asymmetric state in DQD

Basic states in a DQD

Electron wave-function in a DQD

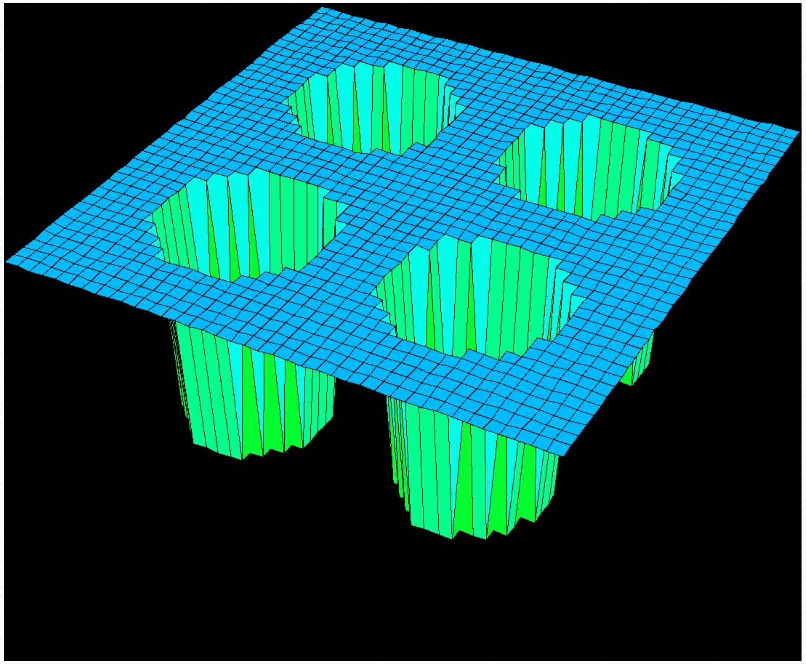




S[redacted]

Antisymmetric

Basic states of two DQDs
(without charge transfer !)



Potential in two DQDs

$$|++\rangle$$

$$|+-\rangle$$

$$|-+\rangle$$

$$|--\rangle$$

basis* (the middle two states, $|+-\rangle$ and $|-+\rangle$, are boxed)

Wave-function of two electrons in two DQDs

Basic states of a qubit

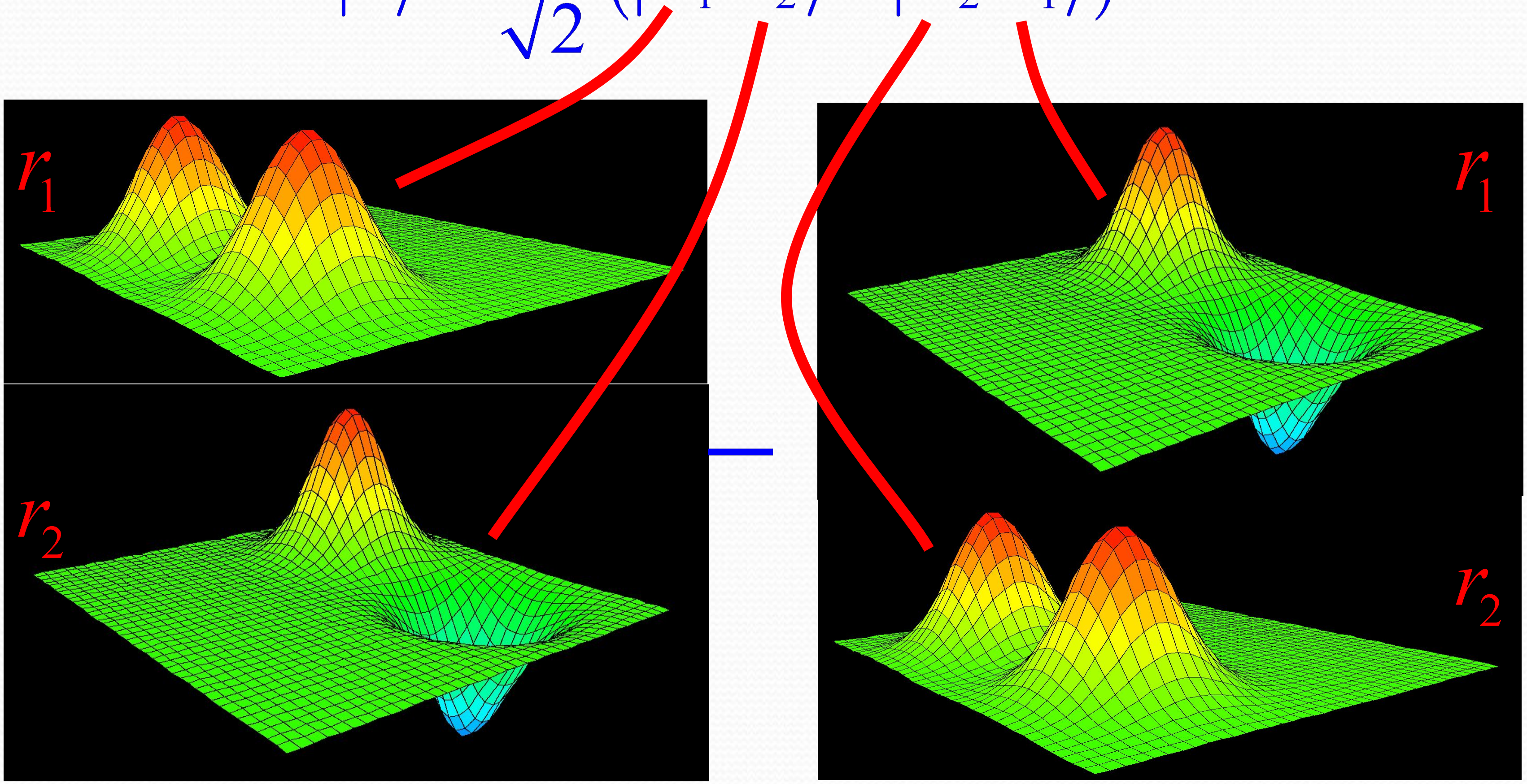
Spin-polarized electrons:

$$|0\rangle = \frac{1}{\sqrt{2}}\left(|+_1 -_2\rangle - |+_2 -_1\rangle\right)$$

$$|1\rangle = \frac{1}{\sqrt{2}}\left(|-_1 +_2\rangle - |-_2 +_1\rangle\right)$$

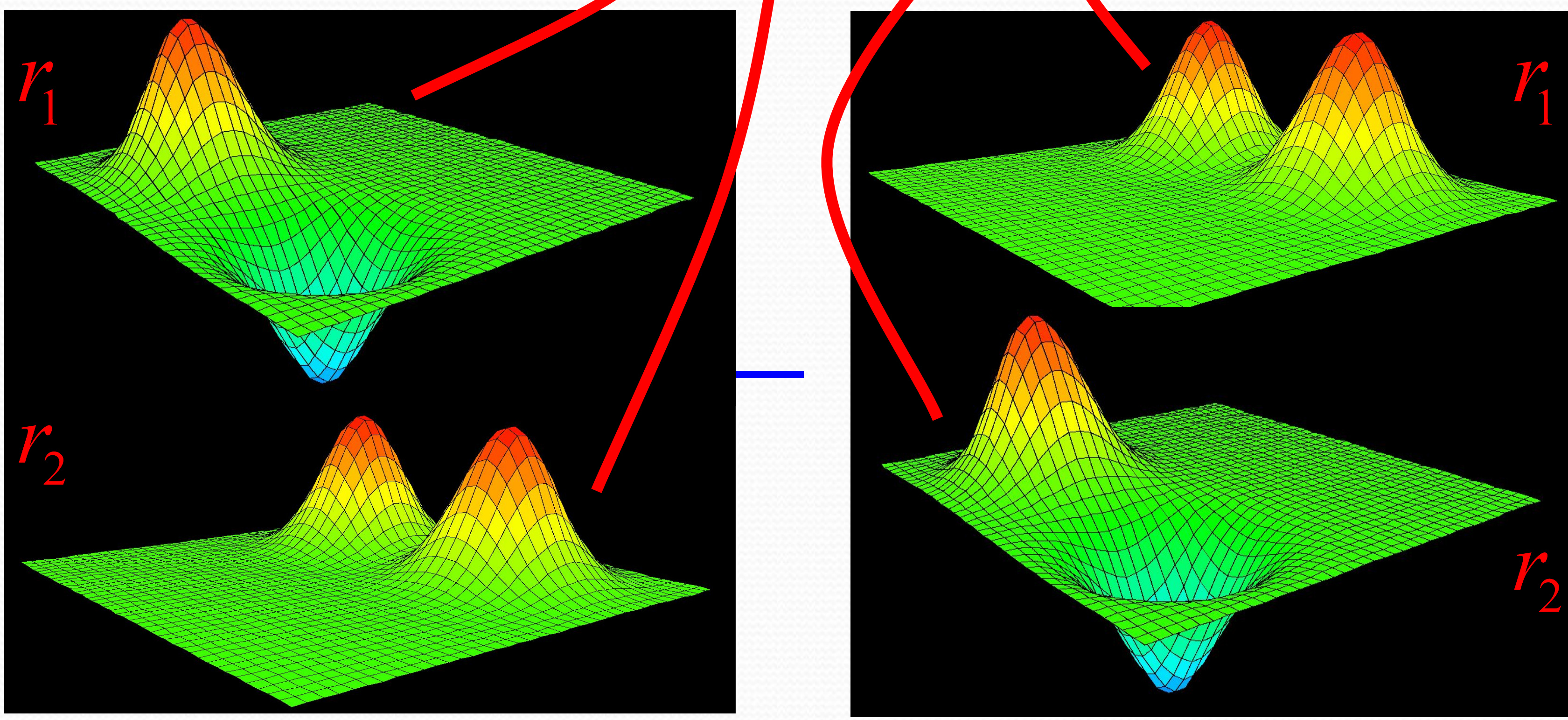
Qubit states

$$|0\rangle = \frac{1}{\sqrt{2}}\left(|+_1 -_2\rangle - |+_2 -_1\rangle\right)$$

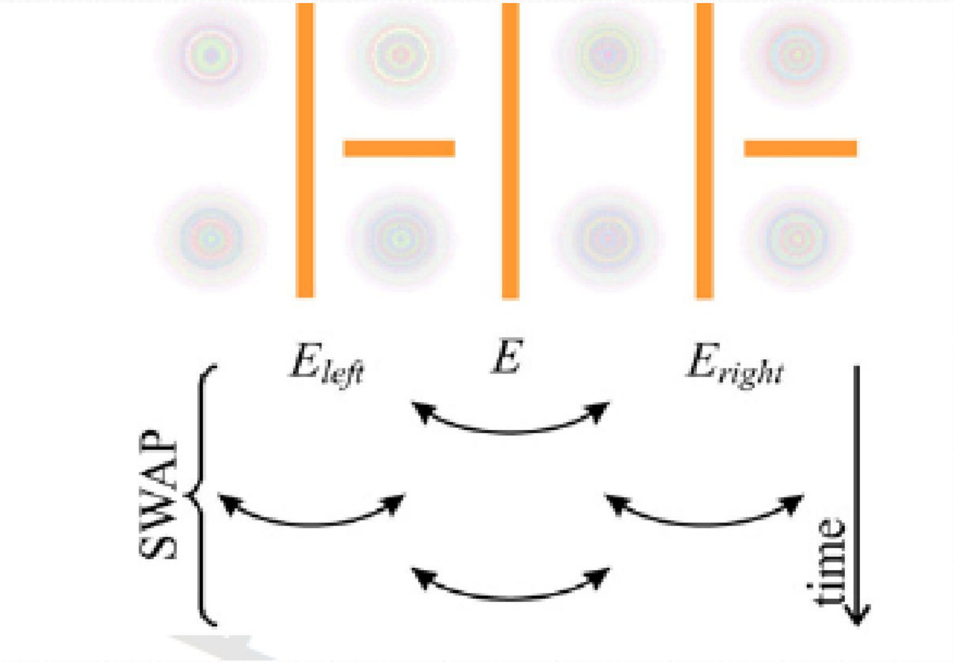


Qubit states

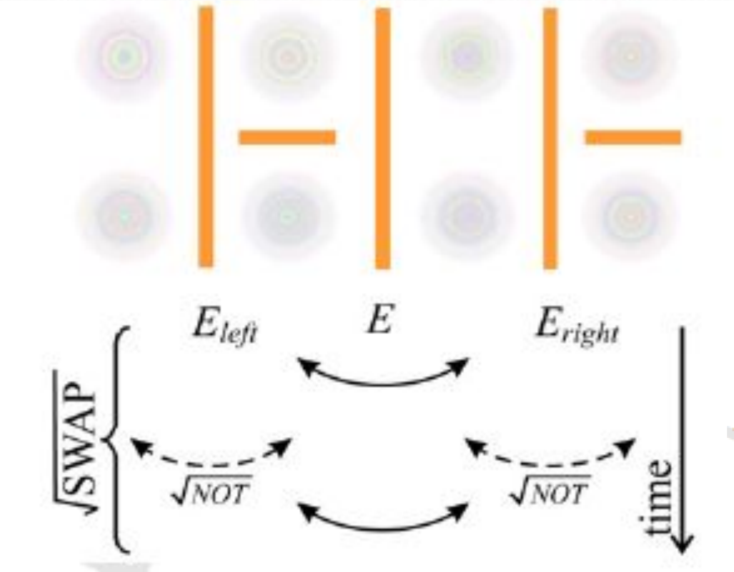
$$|1\rangle = \frac{1}{\sqrt{2}}\left(|-_1 +_2\rangle - |-_2 +_1\rangle\right)$$



Realization of SWAP-gate



Realization of sqrt-SWAP



$\sqrt{SWAP}$

$$\sqrt{SWAP} = \hat{E} \cdot \sqrt{NOT_1}\sqrt{NOT_2} \cdot \hat{E} = \frac{1}{2i}\begin{pmatrix} 2i & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & i & i & -1 & 0 \\ 0 & i & 1 & -1 & i & 0 \\ 0 & i & -1 & 1 & i & 0 \\ 0 & -1 & i & i & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2i \end{pmatrix}.$$

Realization of CNOT-gate

As far as matrices 4×4 are concerned, a controlled phase shift gate is given by the formula [2]

$$(\hat{Z}_1(\pi/2) \otimes \hat{Z}_2(-\pi/2)) \cdot \sqrt{SWAP}(\hat{Z}_1(\pi) \otimes \hat{1}_2) \cdot \sqrt{SWAP}, \qquad (23)$$

where $\hat{Z}$ is the phase shift gate. In a similar way, direct calculation shows that in our case

$$\hat{\Pi} = \left[(\hat{Z}_1(\pi/2) \otimes \hat{Z}_2(-\pi/2)) \cdot \sqrt{SWAP}\right]^2 \times (\hat{Z}_1(\pi) \otimes \hat{1}_2) \cdot \sqrt{SWAP}. \qquad (24)$$

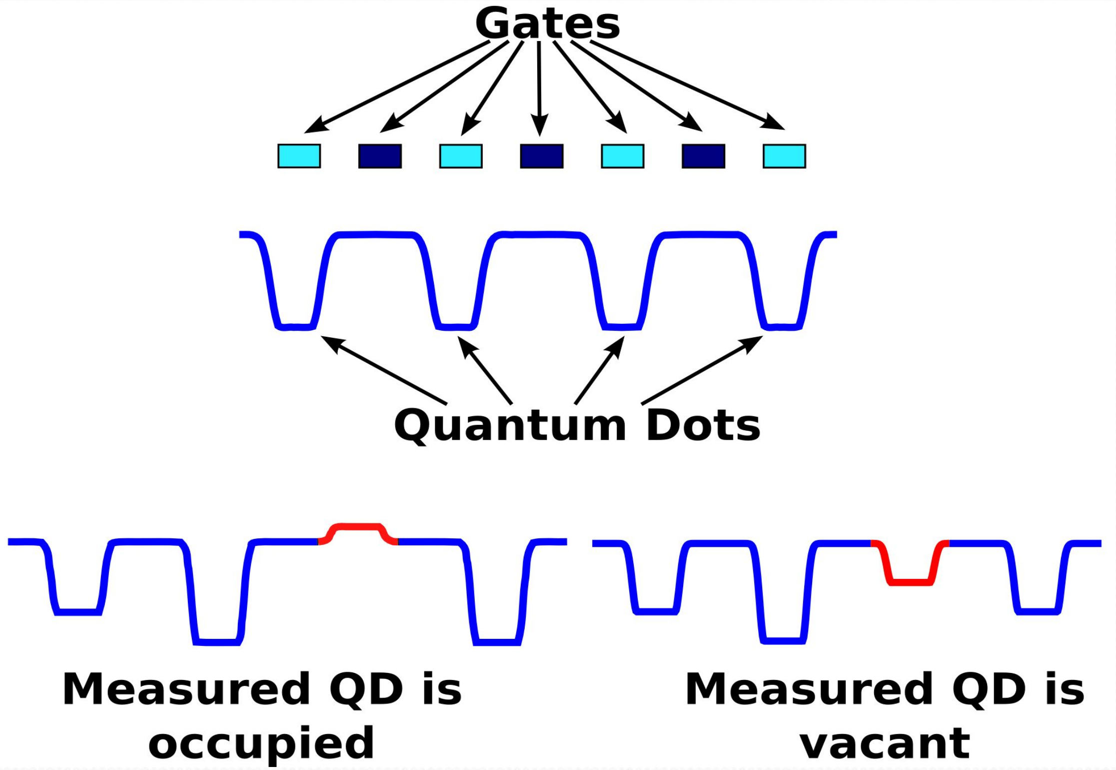
Eventually, the CNOT operation looks like

$$CNOT = (\hat{1}_1 \otimes \hat{H}_2) \cdot \hat{\Pi} \cdot (\hat{1}_1 \otimes \hat{H}_2), \qquad (25)$$

where $\hat{H}$ is Hadamard's transformation:

$$\hat{1}_1 \otimes \hat{H}_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & \sqrt{2} & 0 & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & \sqrt{2} & 0 \\ 0 & 0 & 0 & 1 & 0 & -1 \end{pmatrix}. \qquad (26)$$

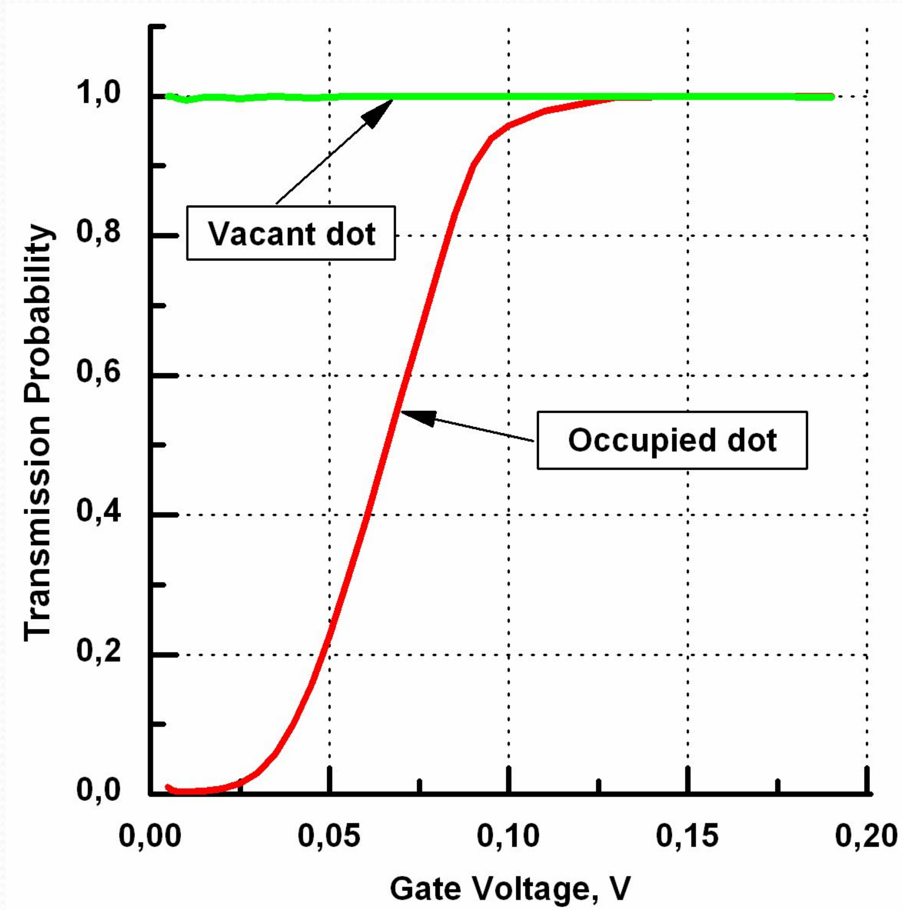
Coulomb blockade of current for measurement



Dot occupied => potential barrier   Dot vacant => potential well

Rough condition of Coulomb blockade: dot size D > Bohr radius

Calculated transmission coefficients

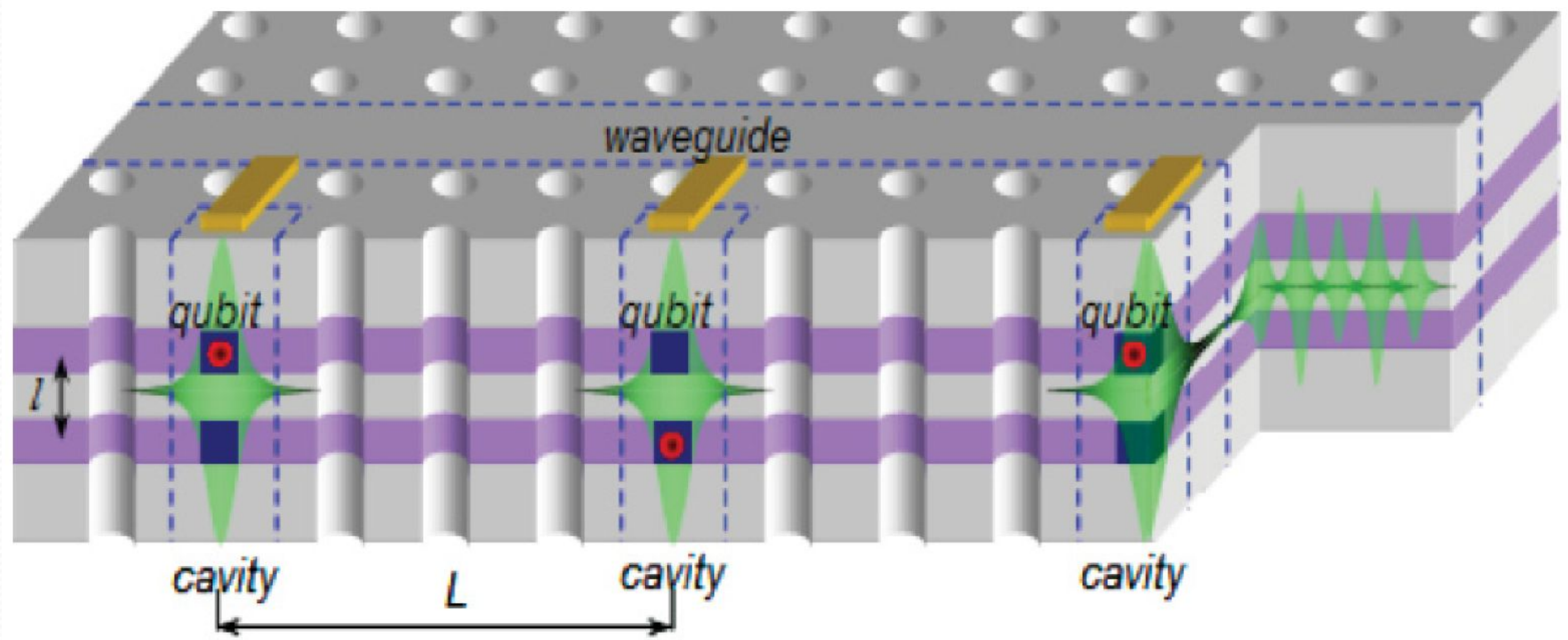


For fairly smooth potential profile the transmission through the well tends to 1

whereas the transmission through the barrier tends to 0

Альтернативные проекты QC во ФТИАН

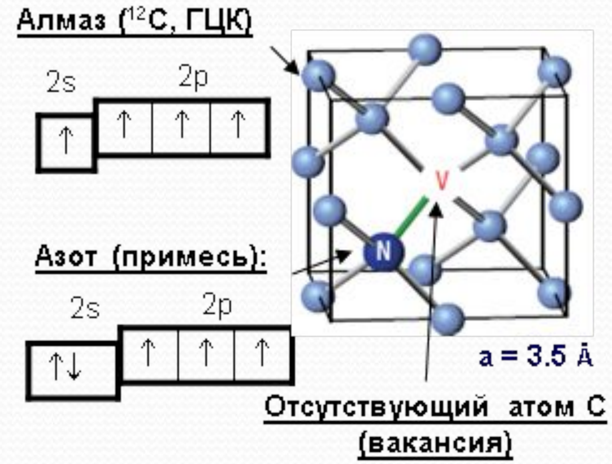
Квантовый регистр на основе двойных квантовых точек в оптическом резонаторе

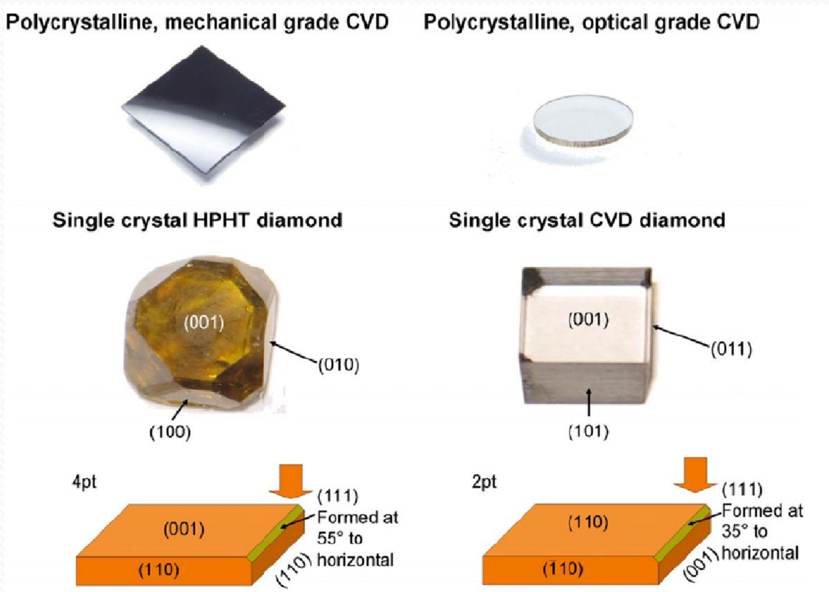


Квантовые компьютеры на NV-центрах в алмазе

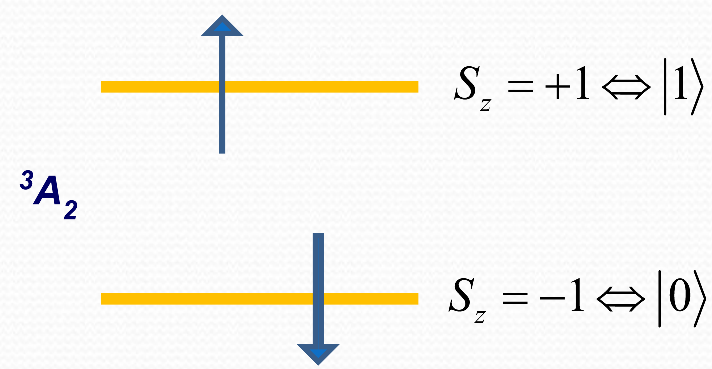
Искусственные алмазы:

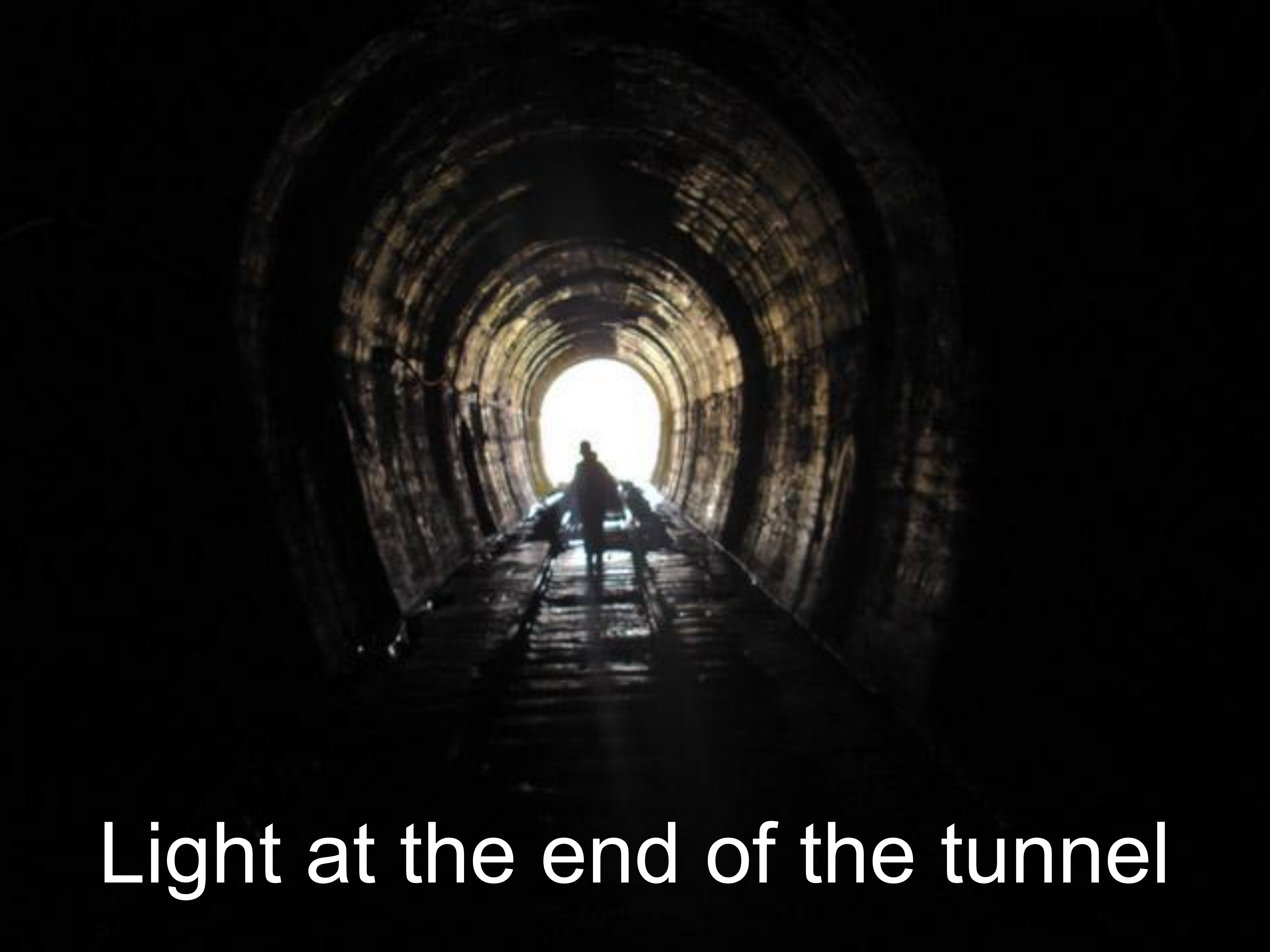
теплопроводность	*к > 2000 Вт/м·К*
скорость звука	*c = 17300 м/с*
плотность	*ρ = 3515 кг/м³*
модуль Юнга	*E ~ 1000 ГПа*





Спиновый кубит на электронных уровнях NV-центра




Light at the end of the tunnel

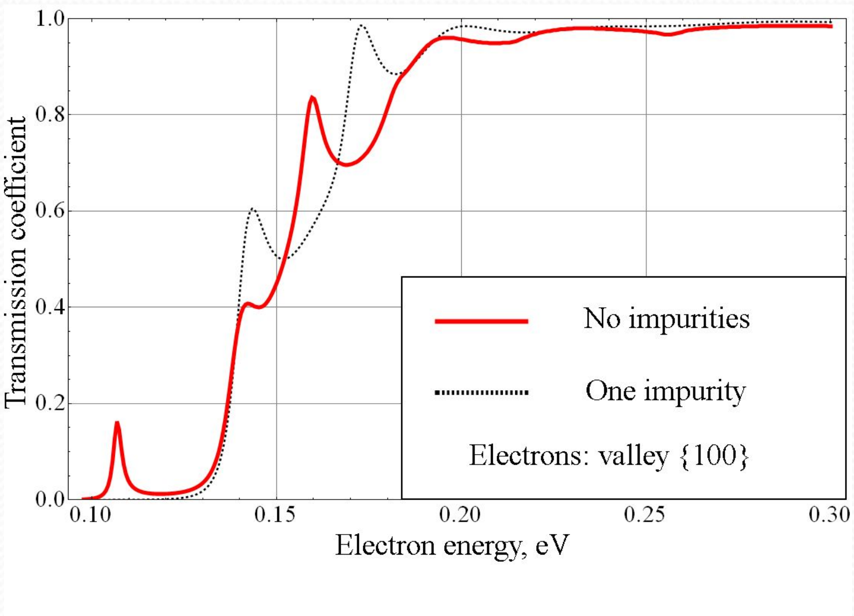
Collaboration

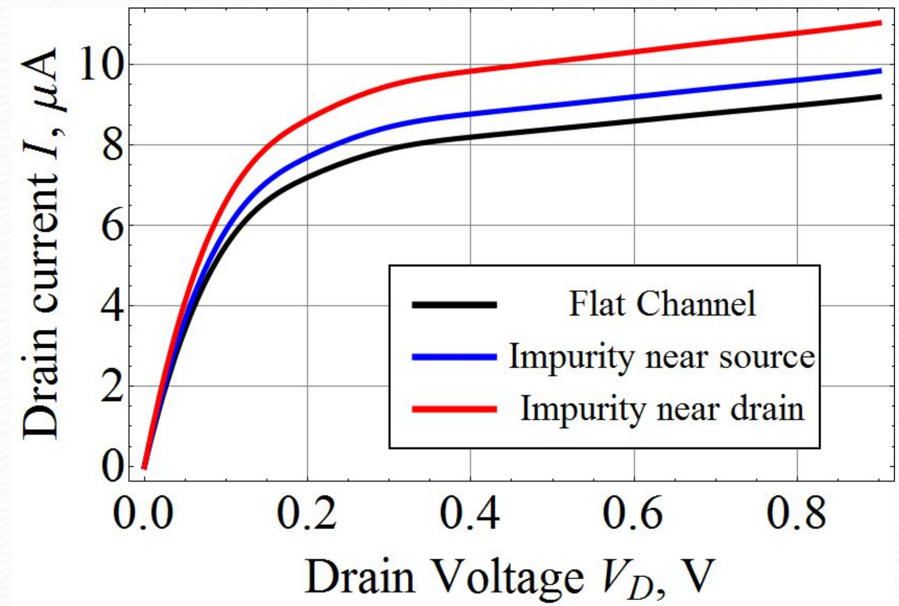
- **Наноэлектронные технологии**
- **АО Микрон и НИИМЭ**
- **ИФП СО РАН**
- **Фраунгоферовский институт (Германия)**
- **Графен**
- **Лаборатория двумерных систем МФТИ (Д. Свинцов)**
- **Университет Тохоку (Япония)**
- **ИПТМ РАН**
- **ТГц**
- **МГУ им. М.В. Ломоносова**
- **ИСВЧПЭ РАН**
- **Квантовые компьютеры**
- **Лаборатория квантовой информатики МФТИ (С. Филиппов)**
- **МГУ им. М.В. Ломоносова**
- **ИФП СО РАН**

СПАСИБО за ВНИМАНИЕ!!!

THANK YOU !!!

Квантовые эффекты в полевых нанотранзисторах



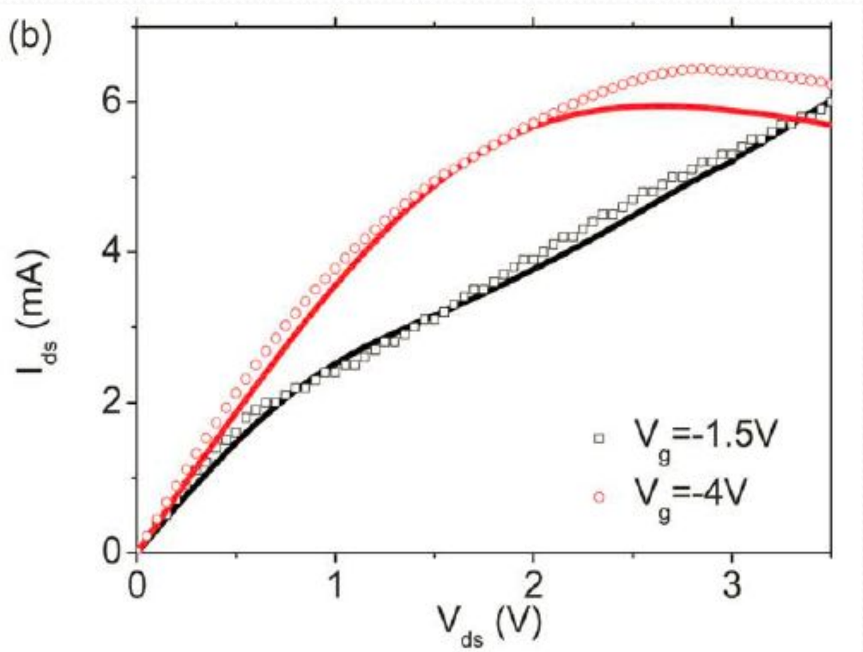


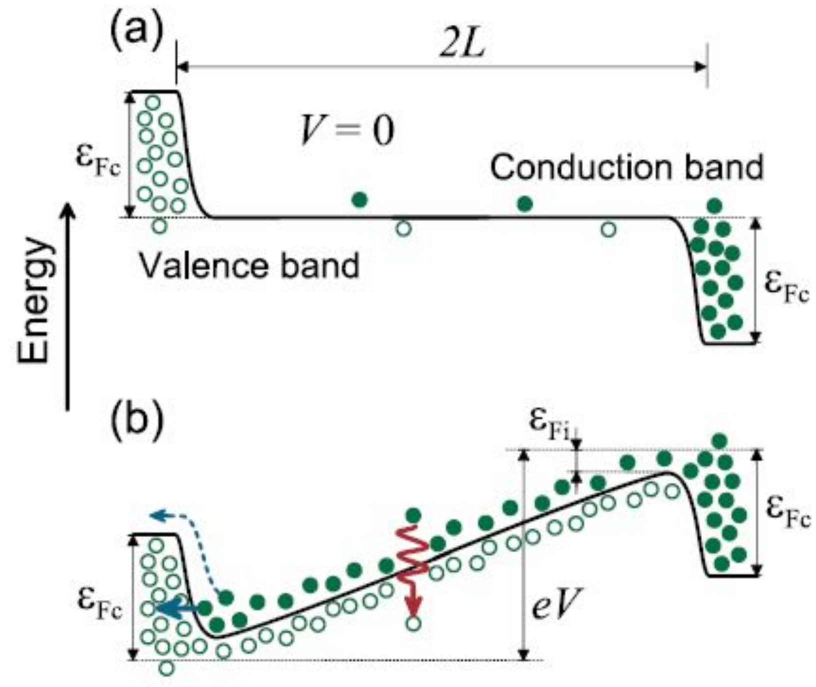
- Уравнение Шредингера: $$-\frac{\hbar^2}{2m}\Delta\Psi(x,y,z)+V(x,y,z)\Psi(x,y,z)=\varepsilon\Psi(x,y,z)$$
- Уравнение Пуассона: $$\Delta\varphi=-\frac{4\pi}{\varepsilon}en$$
- Формула Ландауэра: $$I=\frac{2e}{h}\sum_{i=0}^{\infty}\int dE\,T_i(E)\left[f_s(E)-f_d(E)\right]$$

Теория наноэлектронных приборов

- Цели современной наноэлектроники: Low-power и High-performance
  - Альтернативные механизмы переноса тока: туннелирование
  - Альтернативные материалы: графен и его модификации (в сотрудничестве с университетом Тохоку, Япония)
  - **Масштабирование традиционных полевых транзисторов.**

Транзисторы на основе графена: новые вопросы



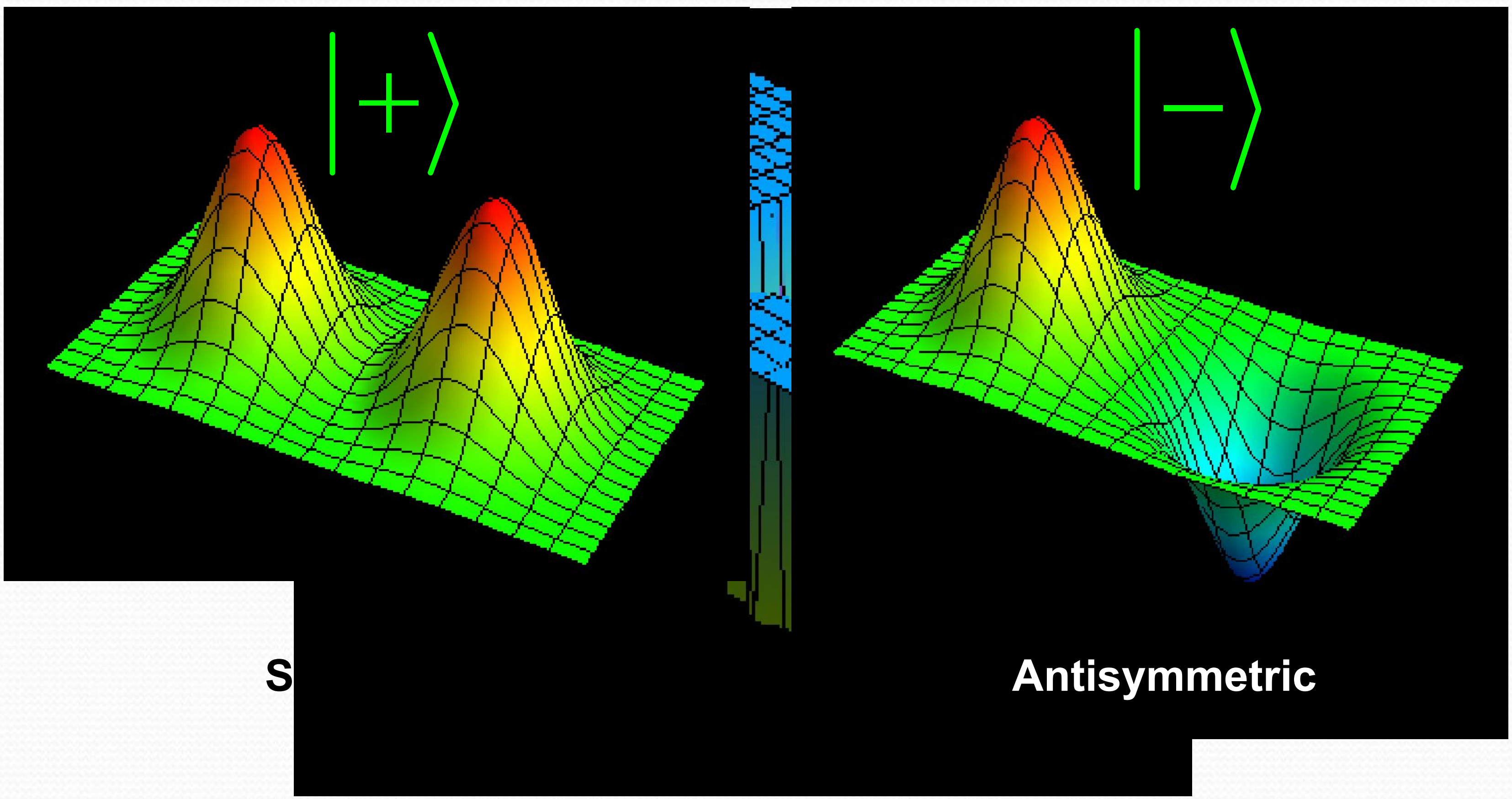


- **Объяснение отрицательной дифференциальной проводимости;**
- **Амбиполярные эффекты в полевых транзисторах – одновременное наличие электронов и дырок;**
- **Создание инжекционных лазеров на основе графена.**

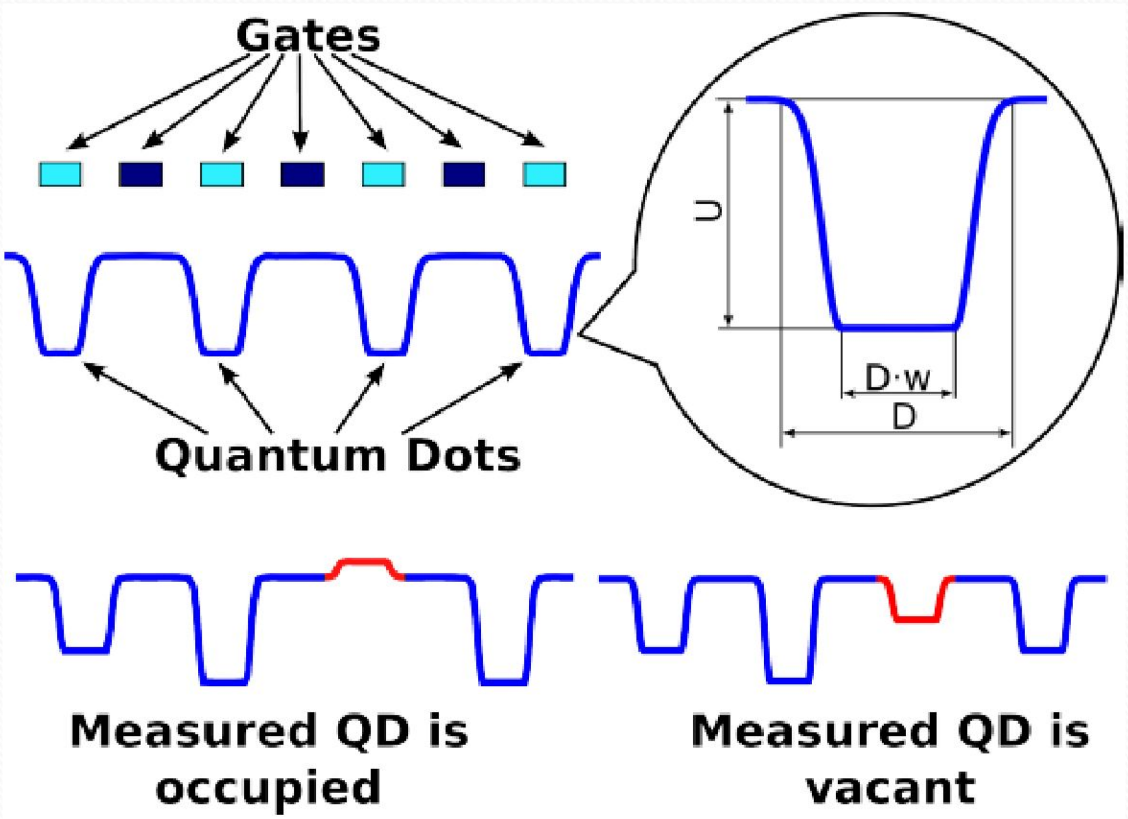
V. Ryzhii, I. Semenikhin, M. Ryzhii, D. Svintsov, V. Vyurkov, A. Satou, and T. Otsuji *"Double injection in graphene p-i-n structures"*, Journal of Applied Physics, Vol. 113, p. 244505 (2013)

Basic states in a DQD

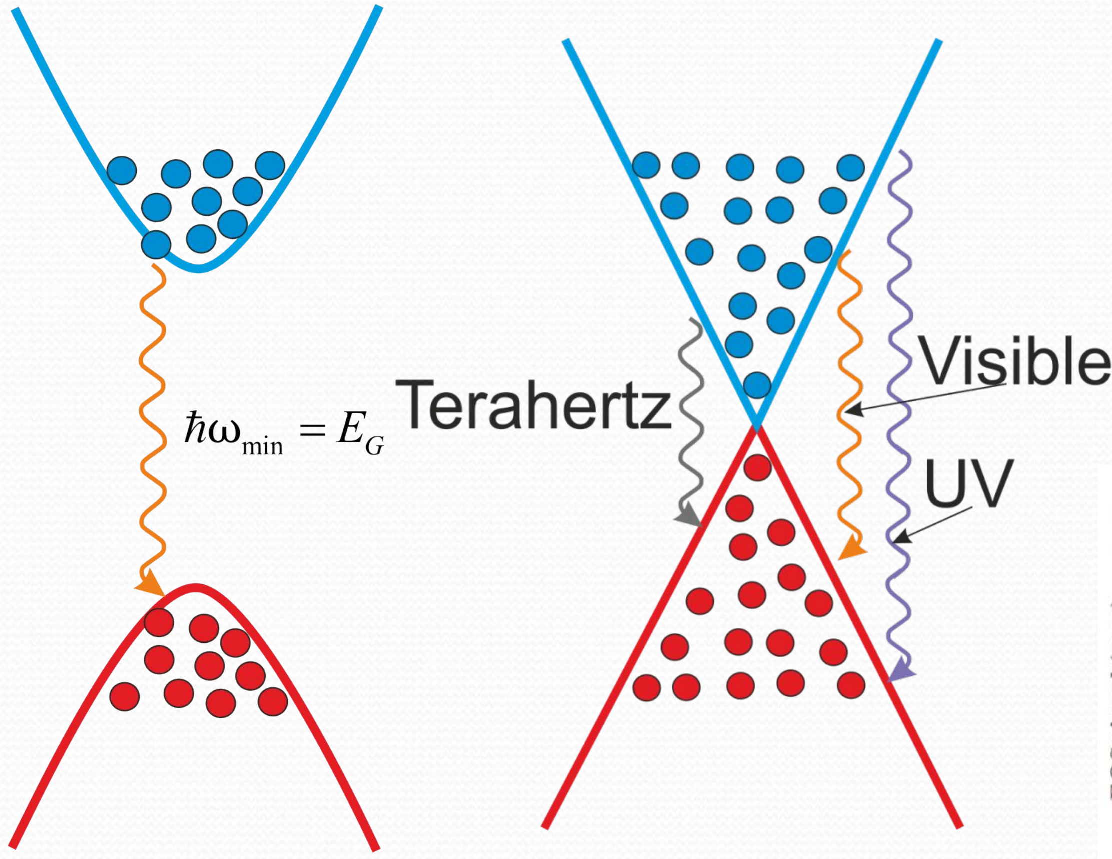
Electron wave-function in a DQD

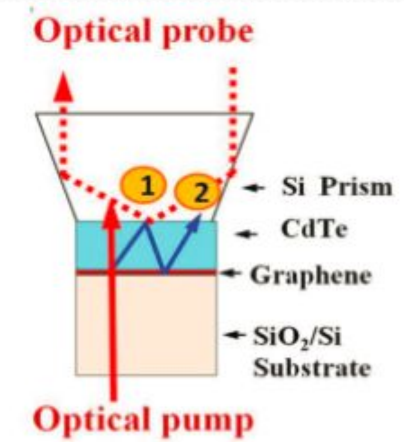


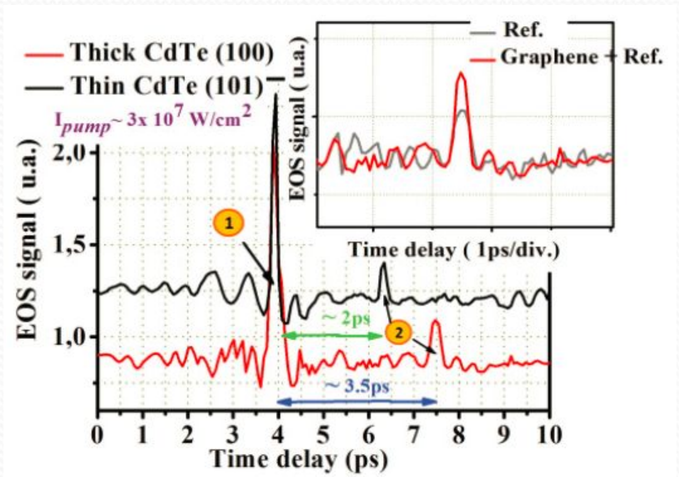
Coulomb blockade for measurement



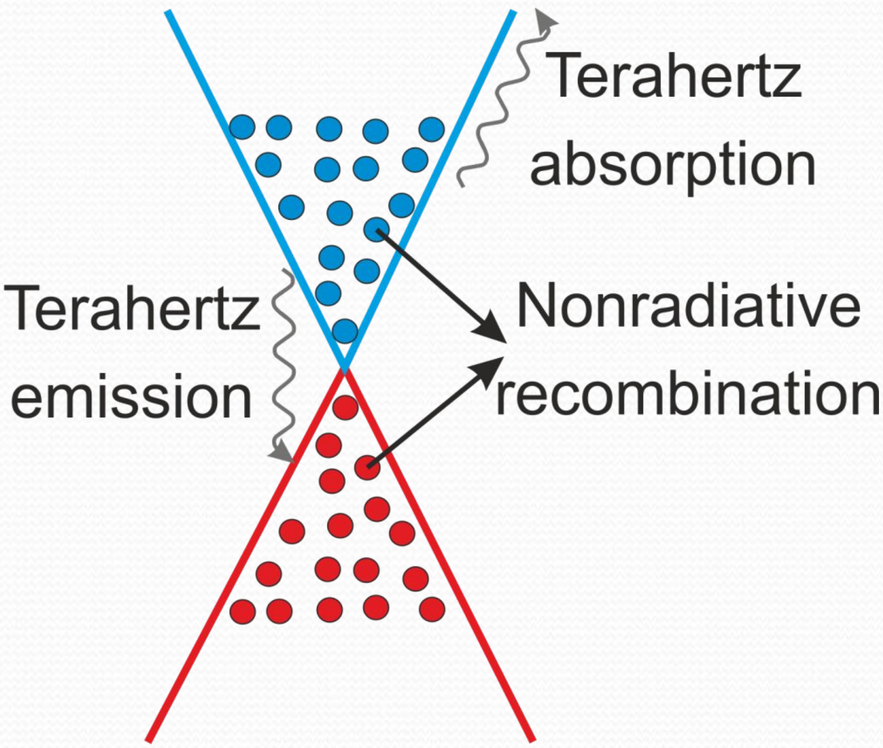
Терагерцовые лазеры на основе графена

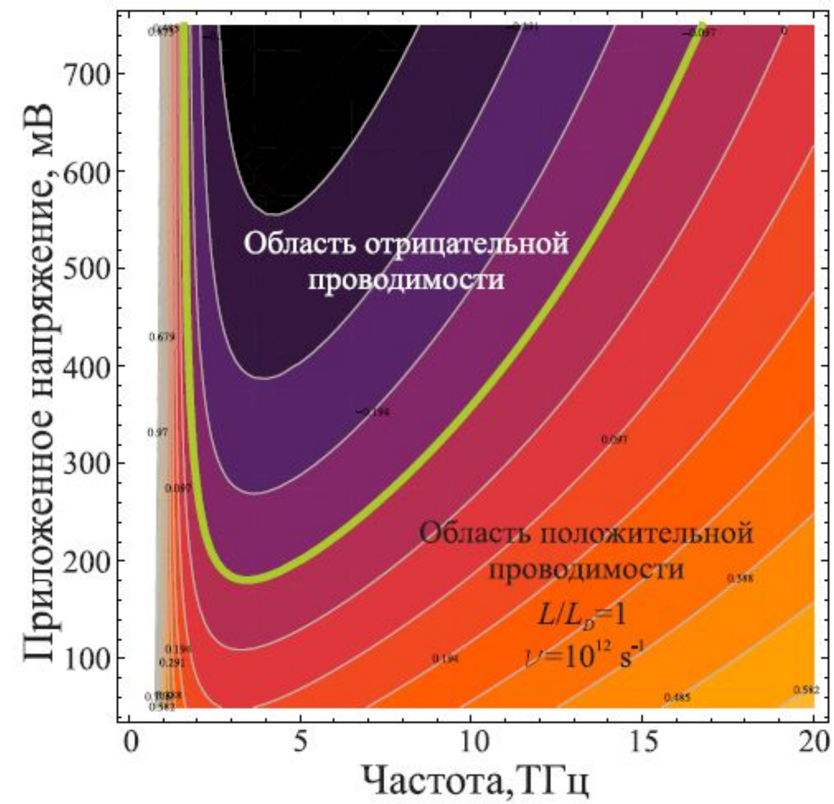






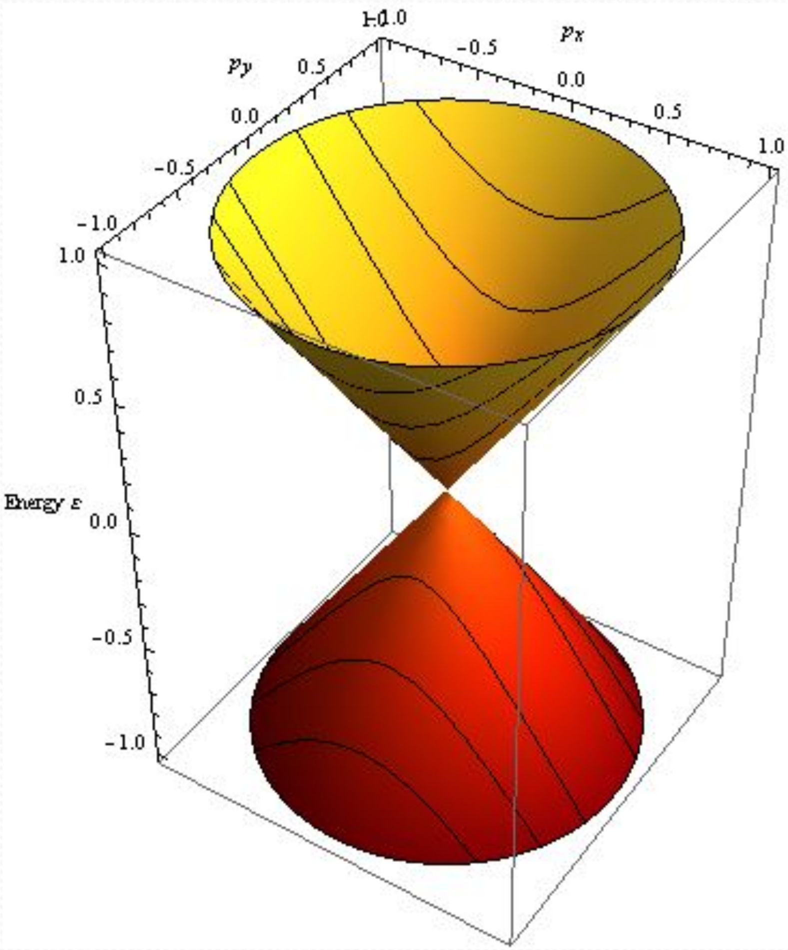
Терагерцовые лазеры на основе графена





Создание квантовой теории оптического поглощения в графене с неравновесными носителями;
Расчет рекомбинационных процессов, обусловленных взаимодействием квазичастиц.

Электронные свойства графена



- Бесщелевой полупроводник;
- Линейный закон дисперсии

$$\hat{H} = v_F \begin{pmatrix} 0 & \hat{p}_x - i\hat{p}_y \\ \hat{p}_x + i\hat{p}_y & 0 \end{pmatrix}$$

$$\varepsilon(p) = \pm p v_F$$

- Отсутствие обратного рассеяния

$$\langle \mathbf{p} | V(\mathbf{r}-\mathbf{r}') | \mathbf{p}' \rangle = \frac{V_{\mathbf{q}}}{2}\left(1+\cos\theta_{\mathbf{pp}'}\right)$$