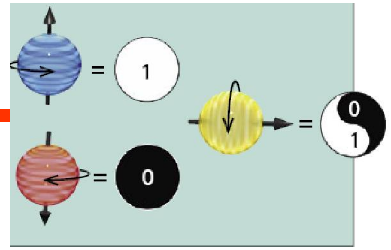



# 半导体量子芯片

郭国平

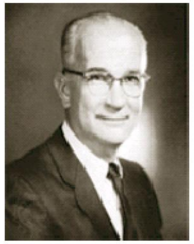
中科院量子信息重点实验室
中国科学技术大学

# 目 录

# 半导体芯片起源

20世纪50－60年代物理学家针对电子管面临的物理极限问题，研发了晶体管和集成电路，实现了信息技术从电子管到晶体管芯片的第一次跨越式变革。

1956年度诺贝尔物理奖

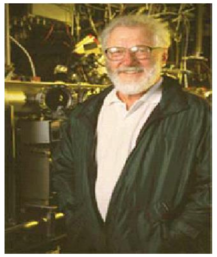

肖克利( William Shockley)

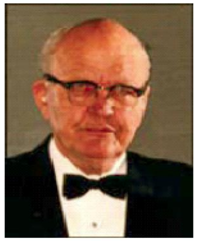

巴丁(JohnBardeen)


布拉坦(Walter Brattain)

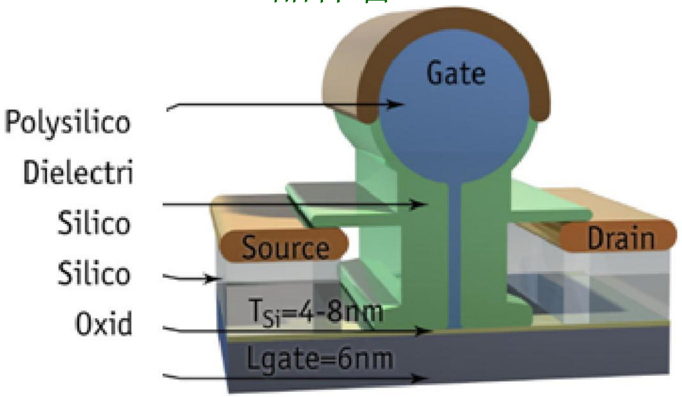
2000年度诺贝尔物理奖


若尔斯-阿尔费罗夫(ZHORES I. ALFEROV)


赫伯特-克勒默(HERBERT KROEMER)

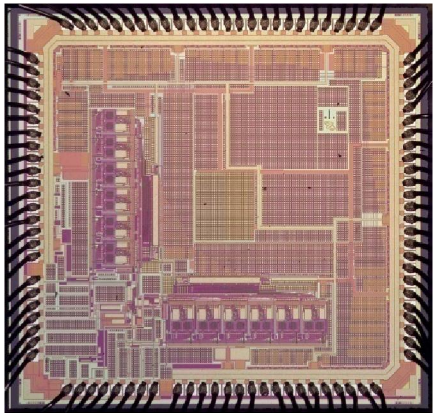

杰克-S-基尔比(JACK S. KILBY)

晶体管




集成

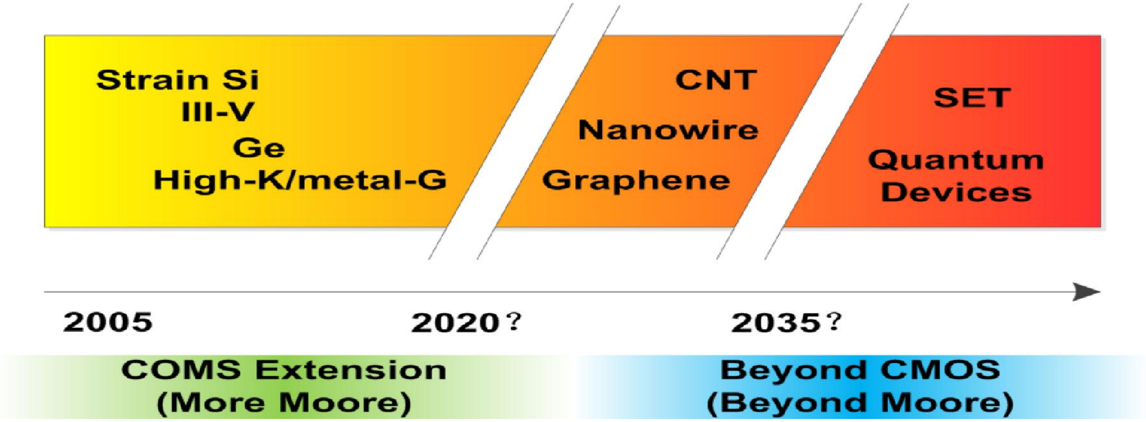
芯片(集成电路)



电流导通　1状态　比特(经典信息单元)
电流截止　0状态

# 挑战和机遇

随着摩尔定律的发展，尺寸等导致的量子效应越来越明显，发热和功耗也越来越严重。




半导体信息技术第二次

变革的浪潮即将来临!

International Technology Roadmap for Semiconductors

NATURE | NEWS FEATURE

عربي

No Moore 2016 ITRS

## The chips are down for Moore's law

The semiconductor industry will soon abandon its pursuit of Moore's law. Now things could ge a lot more interesting.

M. Mitchell Waldrop

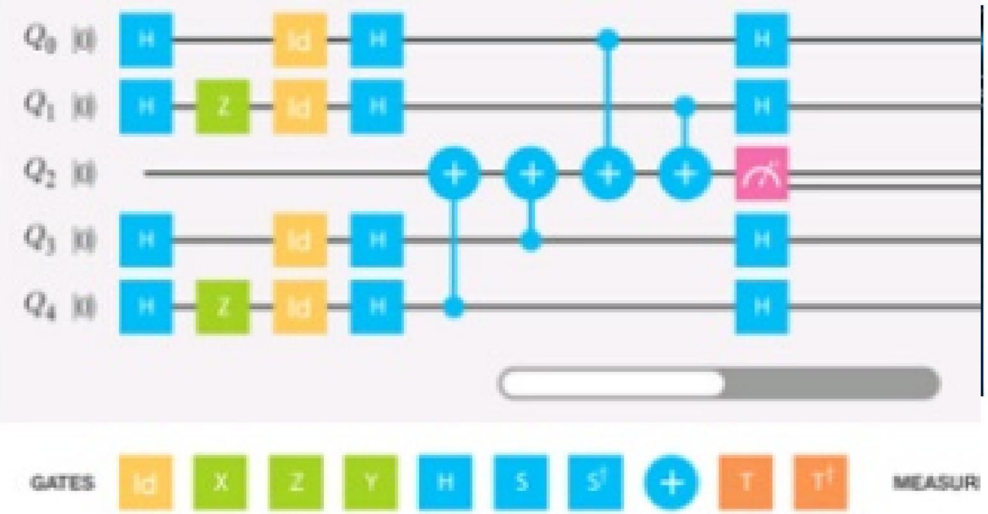
09 February 2016

# 国内外进展与趋势

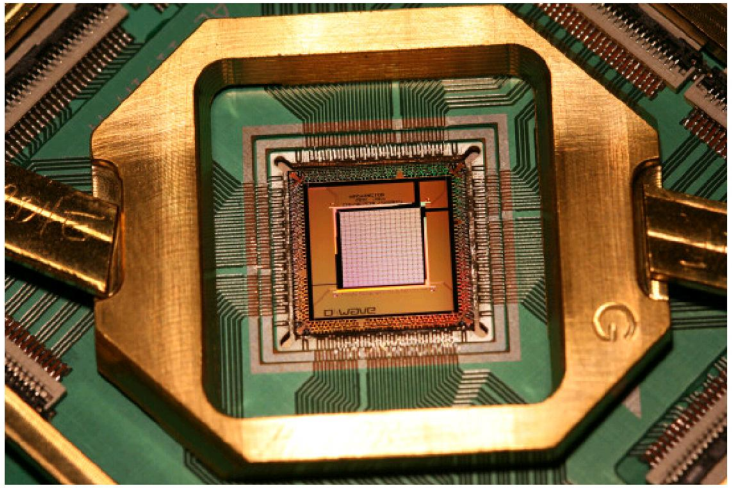
## Intel to invest $50 million in quantum computer research

By Joel Hruska on September 4, 2015 at 7:30 am | 24 Comments

0 shares




## GOOGLE'S QUANTUM COMPUTER JUST GOT A BIG UPGRADE




D-Wave's quantum chip. GOOGLE

HRL Laboratories, LLC

DARPA

## Explore the IBM Quantum Experience

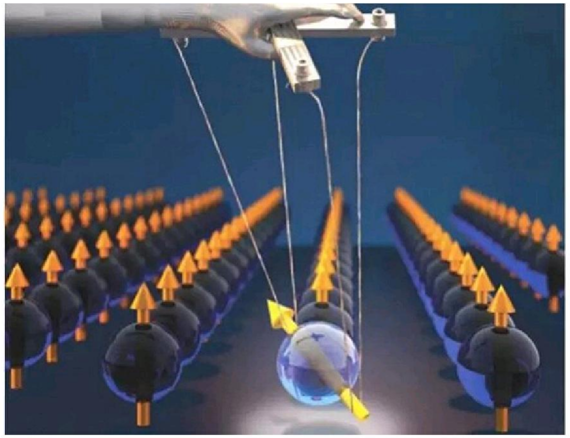
The IBM Quantum Experience is a virtual lab where you can design and run your own algorithms through the cloud on real quantum processors located in the IBM Quantum Lab at the Thomas J Watson Research Center in Yorktown Heights, NY.

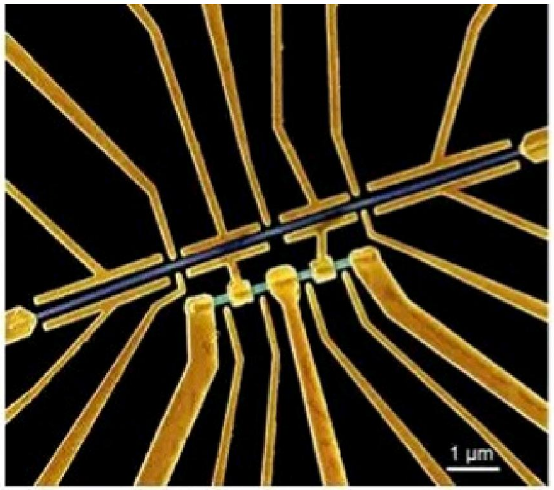
美国DARPA（HRL）、Intel、IBM和Google等多家科研单位和公司开展量子芯片研究

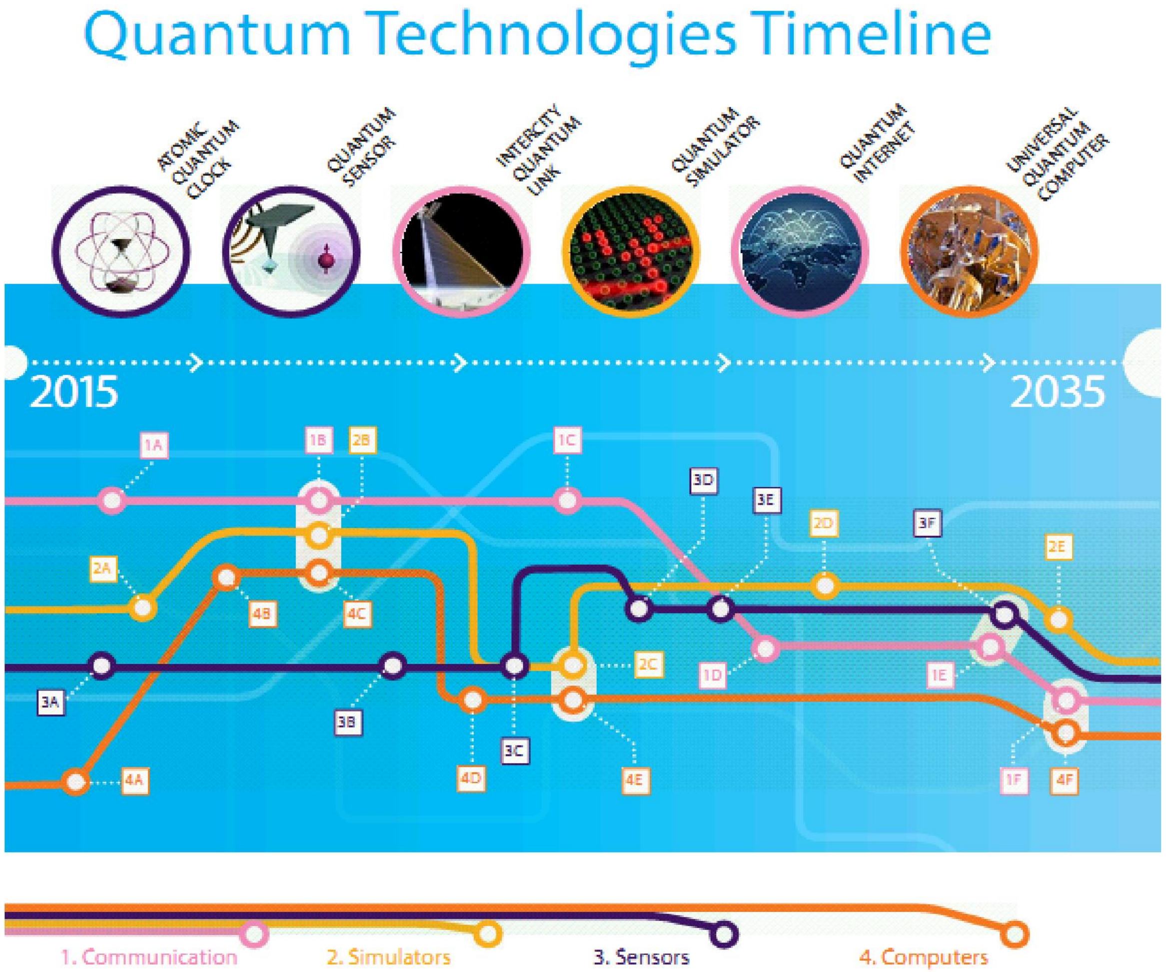
# 国内外进展与趋势


欧洲“量子宣言”

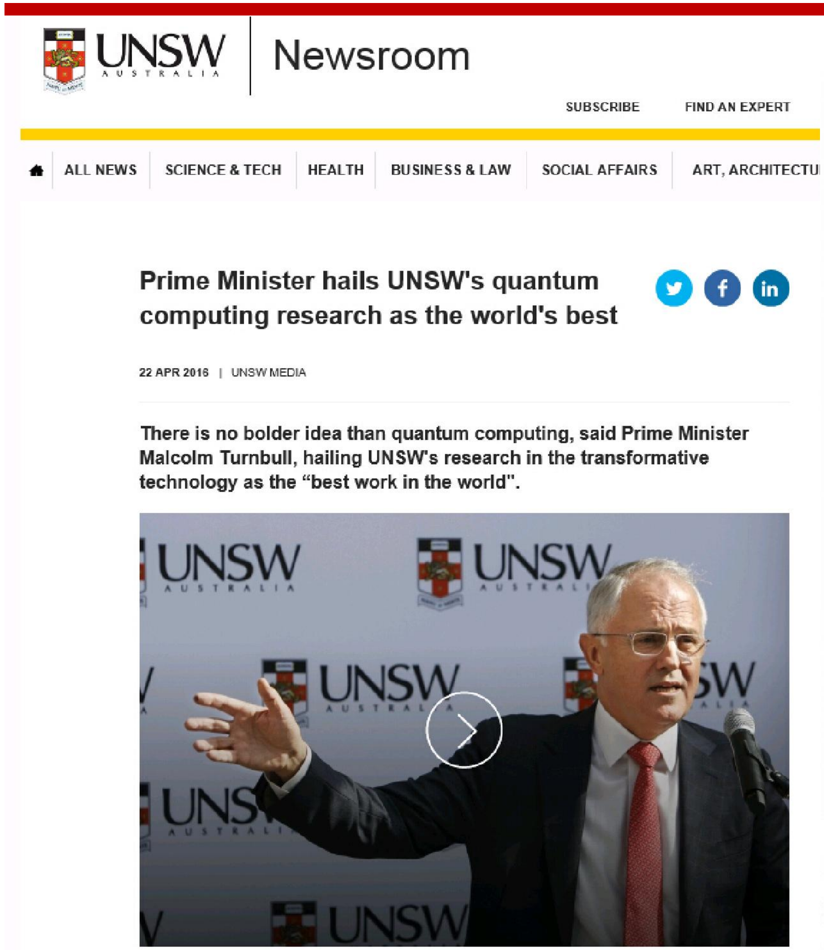
10亿欧元





# 国内外进展与趋势


UNSW AUSTRALIA | Newsroom

SUBSCRIBE FIND AN EXPERT

ALL NEWS | SCIENCE & TECH | HEALTH | BUSINESS & LAW | SOCIAL AFFAIRS | ART, ARCHITECTU

**Prime Minister hails UNSW's quantum computing research as the world's best**

22 APR 2016 | UNSW MEDIA

There is no bolder idea than quantum computing, said Prime Minister Malcolm Turnbull, hailing UNSW's research in the transformative technology as the “best work in the world".

Commonwealth Bank Chief Information Officer David Whiteing said: “Commonwealth Bank is proud to support the University of New South Wales' world-leading quantum computing research team and join the Australian Government in providing tangible support for their National Innovation and Science Agenda.

澳大利亚政府成立**硅基半导体量子芯片实验室**，抢占半导体量子芯片发展的制高点。

## 研究背景：国内外进展与趋势

国家科技重大专项

“核、高、基”专项

首 页工作动态通知公告政策文件专项介绍专题研究办事指南工作简报媒体聚焦联系方式

首页 〉专项介绍 〉核心电子器件、高端通用芯片及基础软件产品

核心电子器件、高端通用芯片及基础软件产品

错失半导体技术第一次变革缺乏核心专利！

2015年我国集成电路和部分产品的进口额比较

| | 集成电路 | 铁矿砂 | 石油（含原油、成品油） | 农产品 |
|---|---|---|---|---|
| 进口额（亿美元） | 2299.3 | 576.2 | 1344.5 | 1168.8 |
| 比值 | - | 3.99 | 1.71 | 1.97 |

半导体基础物理

材料体系 → 器件结构 → 原理机制

技术、平台和队伍等基础薄弱

- 纳米结构结构制备技术和平台
- 极低温量子输运技术和平台

## ➢ 研究背景：国内外进展与趋势

中华人民共和国科学技术部
Ministry of Science and Technology of the People's Republic of China

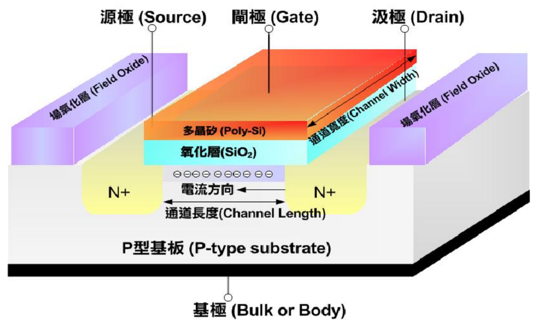
2011年“十二五”导向性重大项目（超级973）“固态量子芯片研究”要求2015年前实现比特数3的量子芯片.

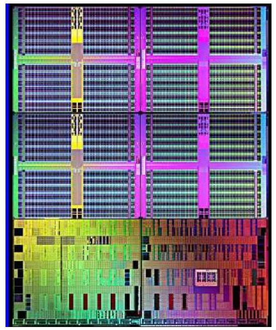
JF *** 半导体量子芯片***

2016年“十三五”重点研发计划“半导体量子芯片研究”，要求2020年前获得品质因子1000、比特数6的量子芯片.

# 研究背景：传统芯片和量子芯片比较

半导体晶体管 → 半导体芯片（处理器-CPU） → 计算机



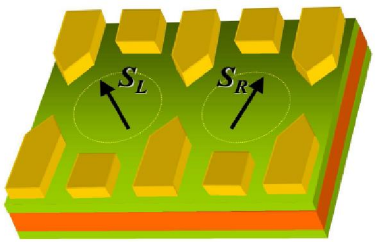
避免克服量子效应

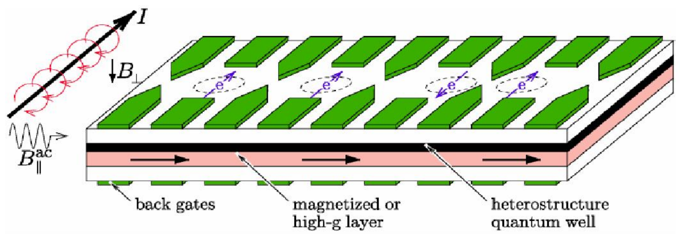
- 可逆运算**解决功耗和发热**问题
- **指数加速**的计算能力

电流导通　1状态　比特(经典信息单元)
电流截止　0状态

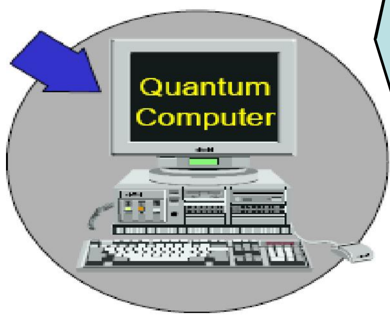
信息的量子化

单电子晶体管 → 半导体量子芯片（量子处理器-Quantum CPU） → 量子计算机



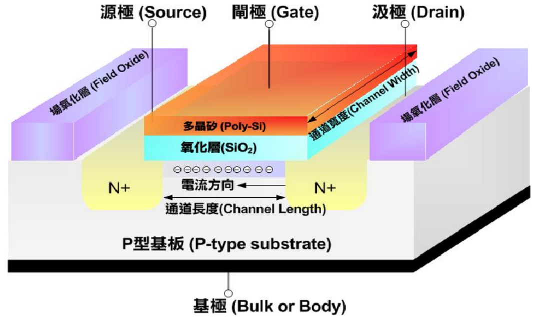

开发利用量子效应

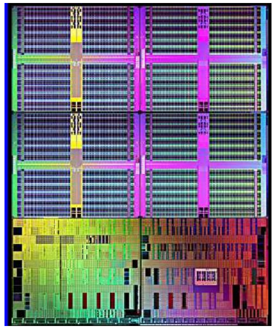



电子自旋向上　1状态　量子比特(量子信息单元)
电子自旋向下　0状态

# 传统芯片和量子芯片比较

半导体晶体管 → 半导体芯片（处理器-CPU） → 计算机



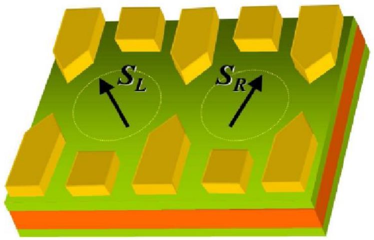
避免
克服
量子
效应

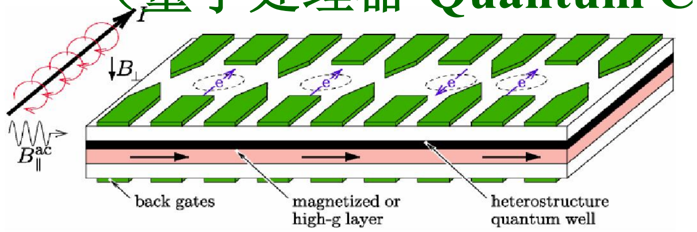
对N个量子存储器实行一次操作，相当于对经典存储器进行２的Ｎ次方个操作.

电流导通　1状态　　比特(经典信息单元)
电流截止　0状态

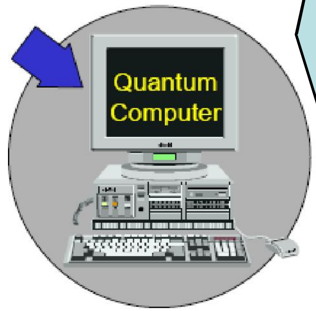
信息的
量子化

单电子晶体管 → 半导体量子芯片（量子处理器-Quantum CPU） → 量子计算机




开发
利用
量子
效应



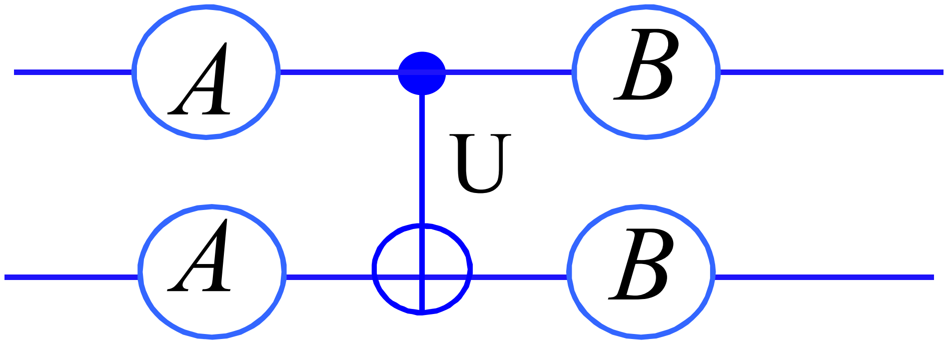

电子自旋向上　1状态　　量子比特(量子信息单元)
电子自旋向下　0状态

# 量子芯片核心任务

**普适量子计算：**

**单比特逻辑门+两比特逻辑门（CNOT）**

**A、B是两个不平行的单比特逻辑门**




**U为两比特逻辑门**

**实用化量子计算要求：比特品质因子Q>10000**

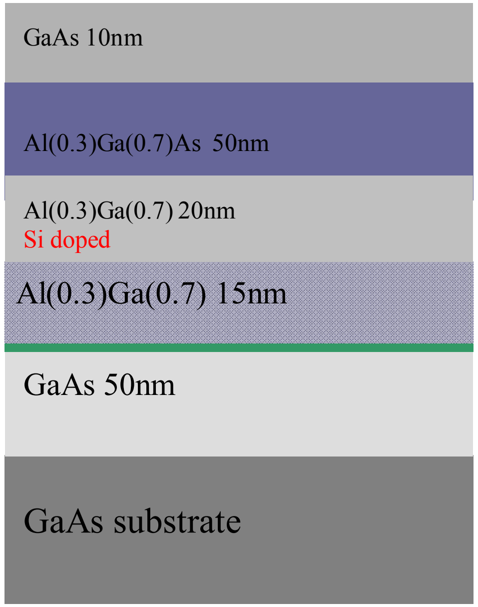
**Q =Min(相干时间)/Max（基本逻辑门时间）**

核心任务：1. **构造**高品质的量子比特；

2. **调控**量子比特实现普适逻辑门

3. **扩展**量子比特的量子数据总线架构

# 半导体基片材料的选取和设计

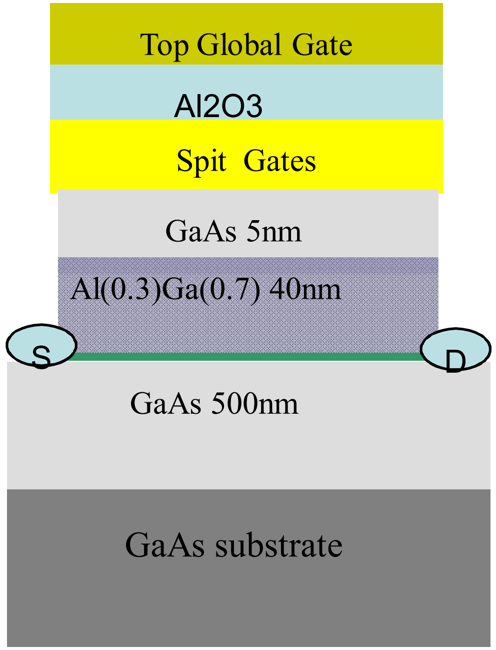



## 掺杂/非掺杂 GaAs量子点

#28 的 Si 是 1.0e18

#34 的 Si 应该是 9.0e17

掺杂越高浓度越大，量子点的制备和操控越简单，但本底噪声越大！




**Customer Part: Custom GaAs 29**

**GaAs FET Structure Specification**

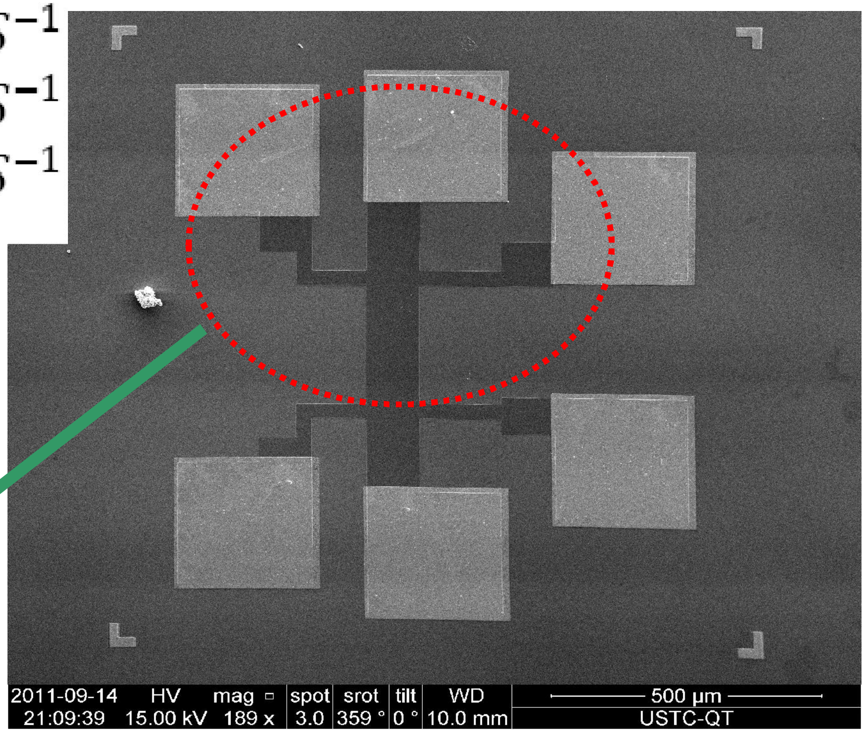
| Layer | Type | Material | Group | Repeat | Mole Fraction (x) | Mole Fraction (y) | Strain (ppm) | PL (nm) | Thickness (A) | Dopant | CV Level | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | i | GaAs | | | | | | | 100 | | | |
| 4 | i | Al(x)GaAs | | | 30.0 | | | | 500 | | | |
| 3 | N | Al(x)GaAs | | | 30.0 | | | | 200 | Si | 7.0e17 | |
| 2 | i | Al(x)GaAs | | | 30.0 | | | | 150 | | | |
| 1 | i | GaAs | | | | | | | 5000 | | | |
| SUBSTRATE | | | | | | | | | | | | |

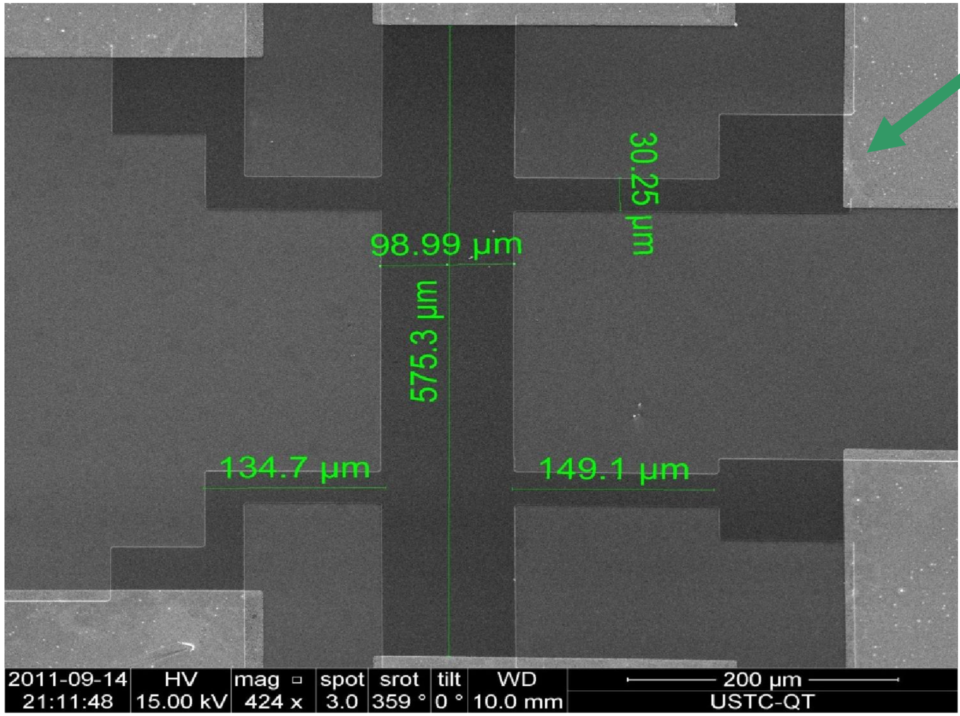
# 各种半导体基片参数的测定

#28: $n=3.2\times10^{11}cm^2$ $\mu=1.5\times10^5 cm^2V^{-1}S^{-1}$

#34: $n=2.1\times10^{11}cm^2$ $\mu=0.6\times10^5 cm^2V^{-1}S^{-1}$

#29: $n=1.3\times10^{11}cm^2$ $\mu=0.2\times10^5 cm^2V^{-1}S^{-1}$

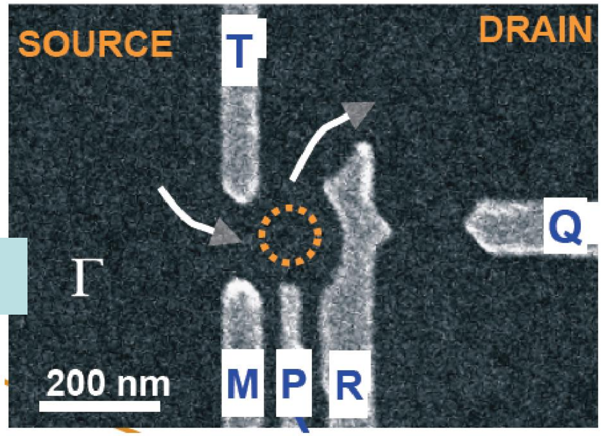


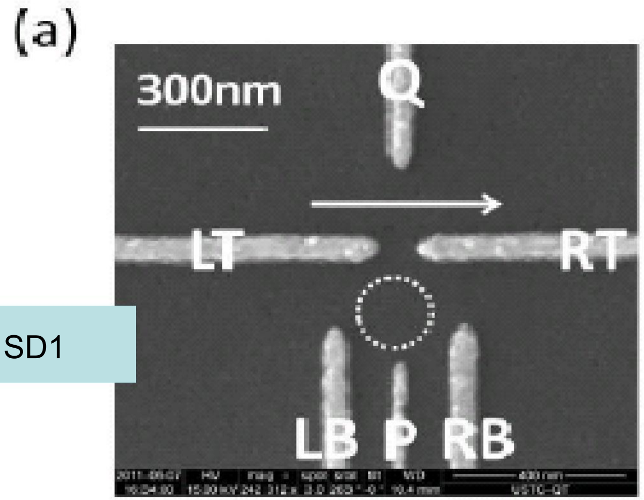

迁移率和电子气浓度对做量子点影响不大，但影响加工工艺和量子点尺寸以及欧姆接触的电导。

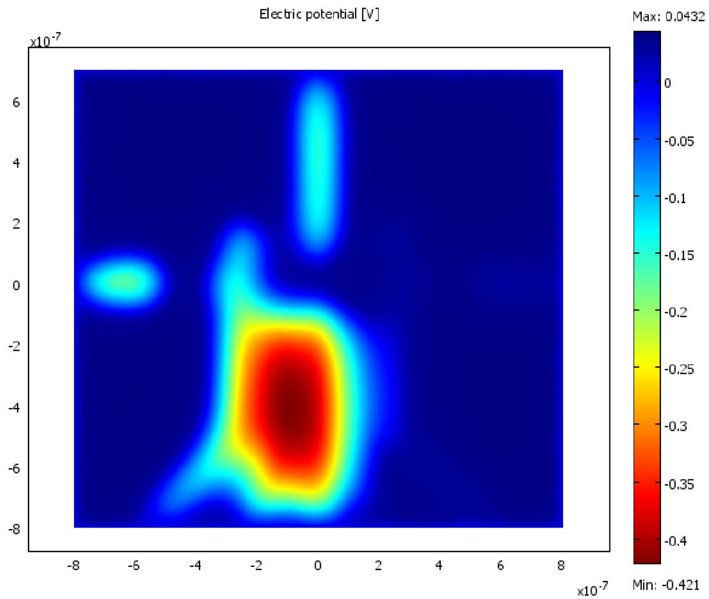
# 半导体栅型量子点的设计和制备

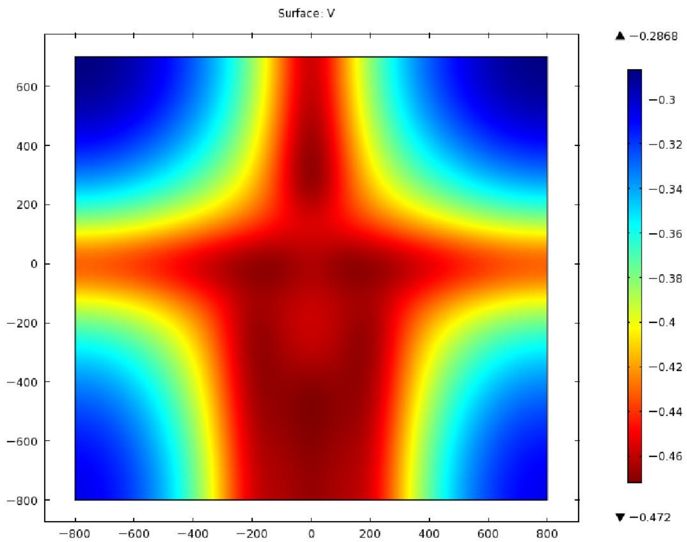
SD2



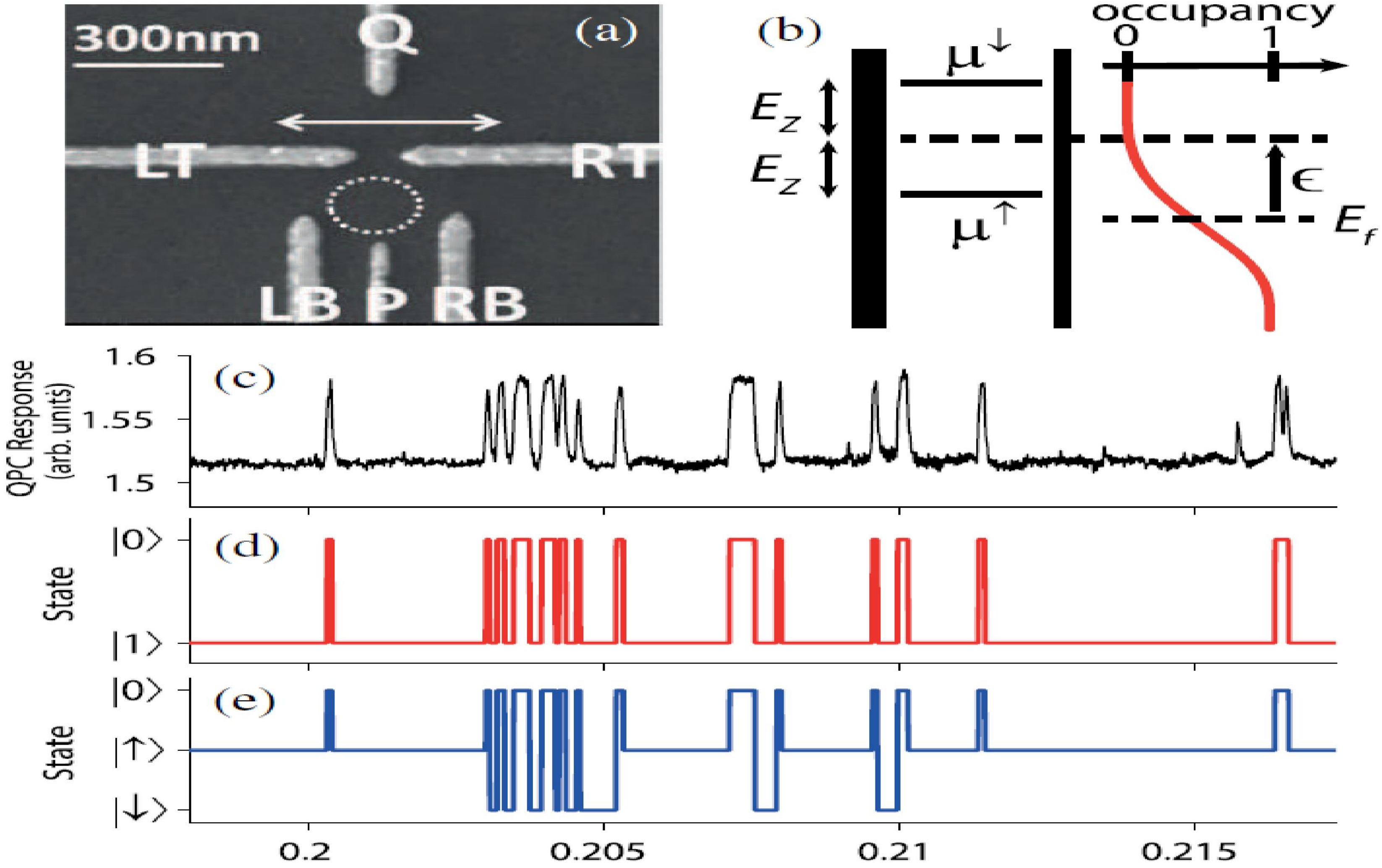

SD1



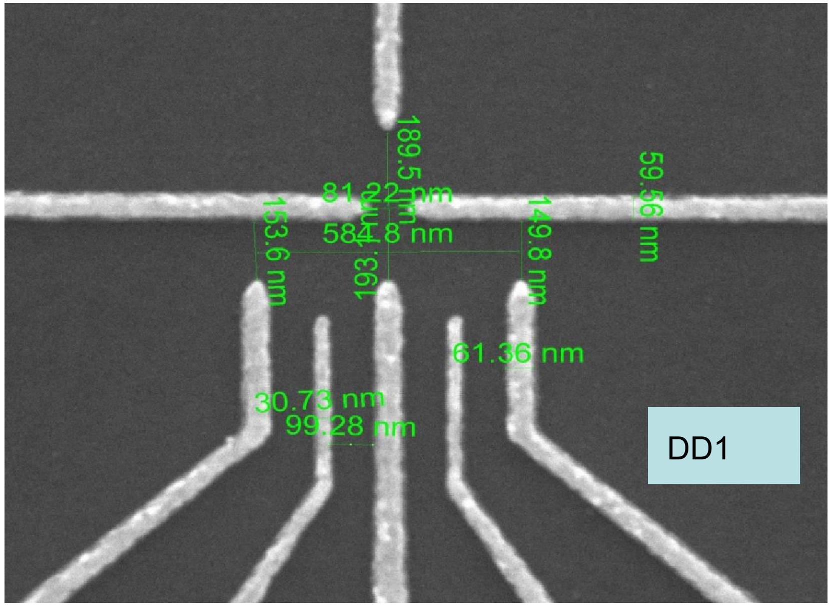
# 半导体栅型量子点的设计和制备

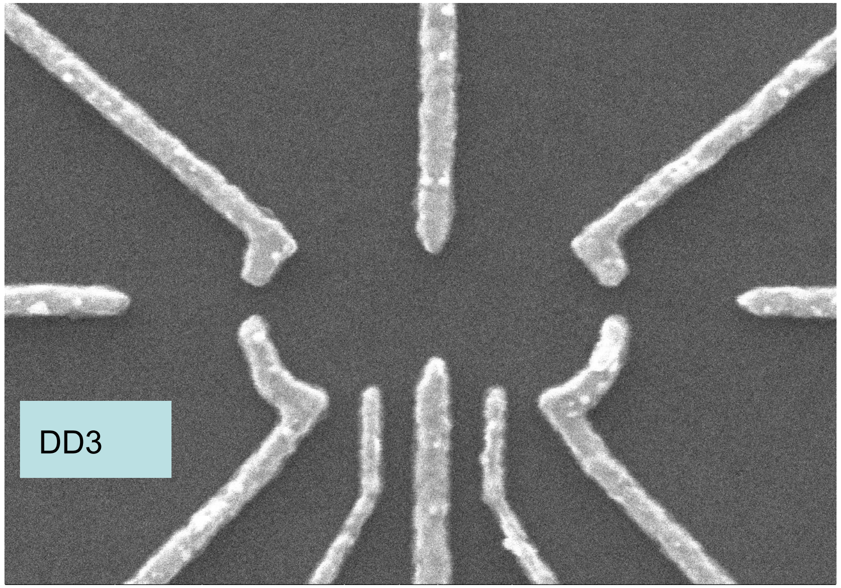


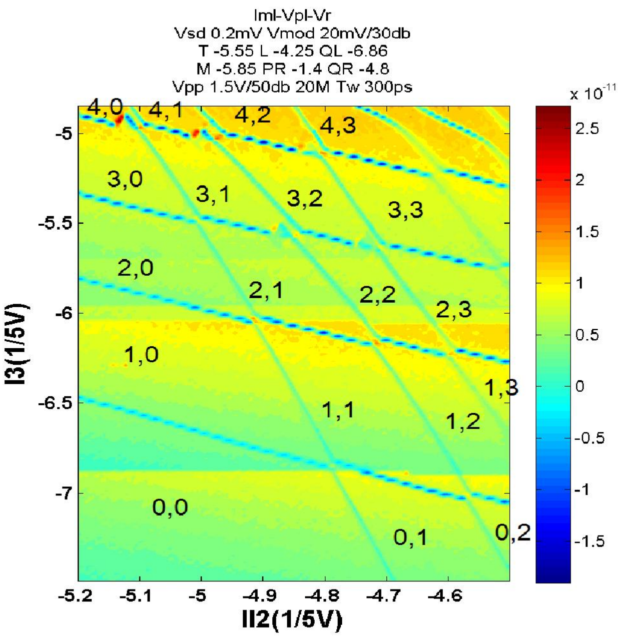

PRL **111,** 126803 (2013) PHYSICAL REVIEW LETTERS week ending 20 SEPTEMBER 2013

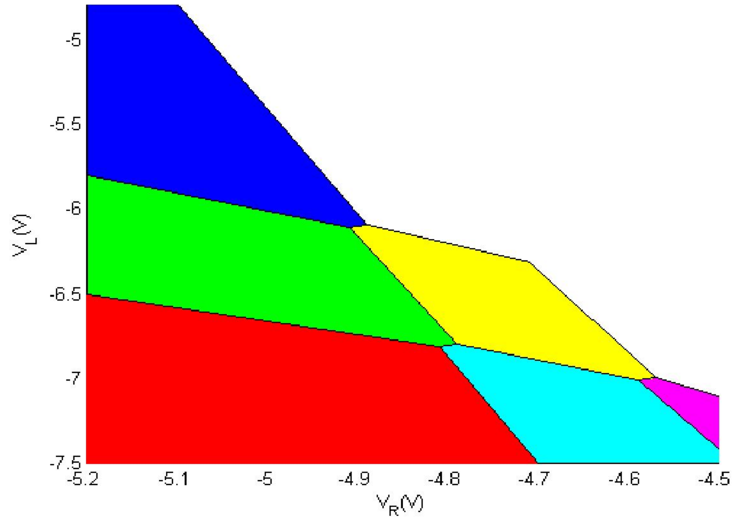
**Detection and Measurement of Spin-Dependent Dynamics in Random Telegraph Signals**

# 半导体栅型量子点的设计和制备

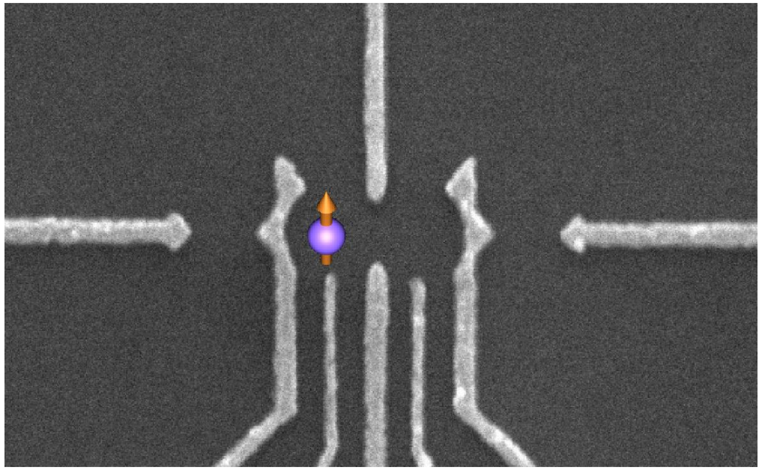


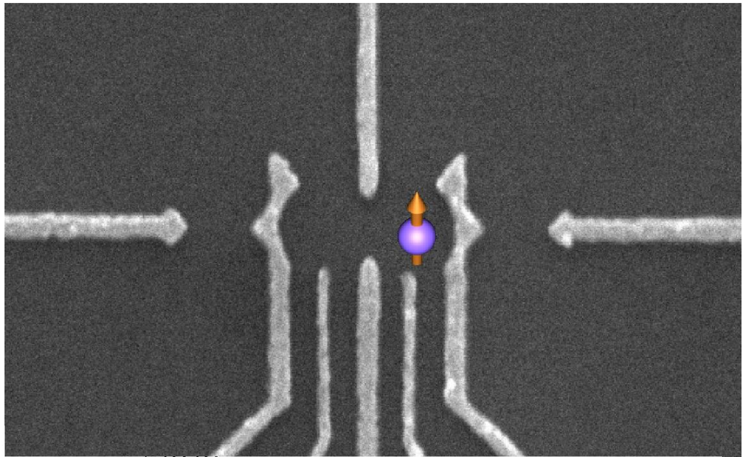



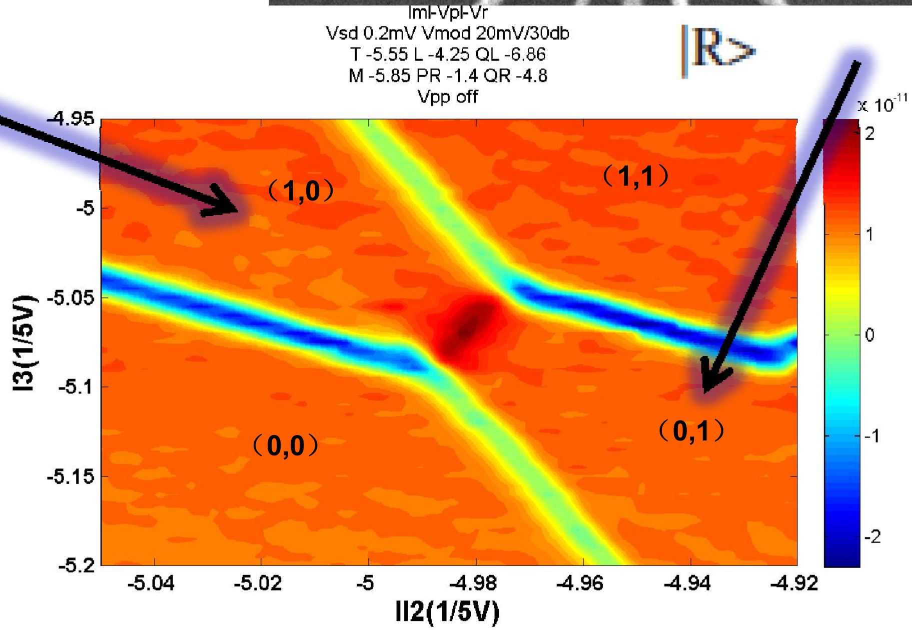
# 双量子点单电荷位置编码



$|L\rangle$



$|R\rangle$




the basis states $|L\rangle = (1, 0)$ and $|R\rangle = (0, 1)$

电荷量子比特的哈密顿量

$$H = \frac{1}{2}\epsilon\sigma_z + \Delta\sigma_x$$

# 超快单比特普适量子逻辑门

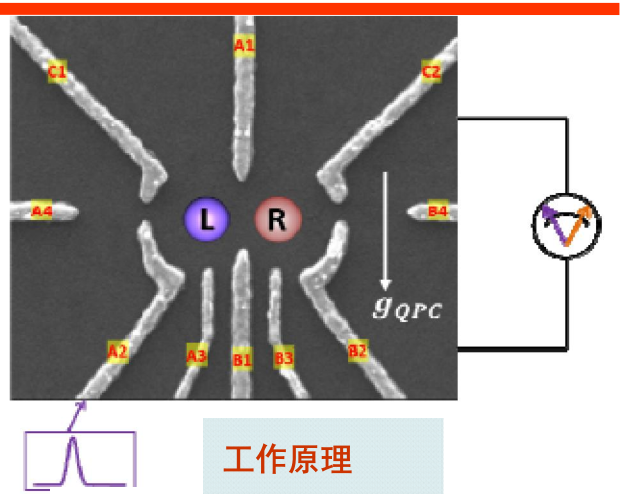
**Ultrafast Universal Quantum Control of Quantum Dot Charg**

**Qubit Using Landau-Zener-Stückerlberg Interference**

*Gang C... HaiOu Li*[1], *Tao Tu*[1], *Li Wang*[1], *Chen Zhou*[1], *Ming Xiao*[1], *HongWen*
*... Guo*[1], *GuoPing Guo*[1*]

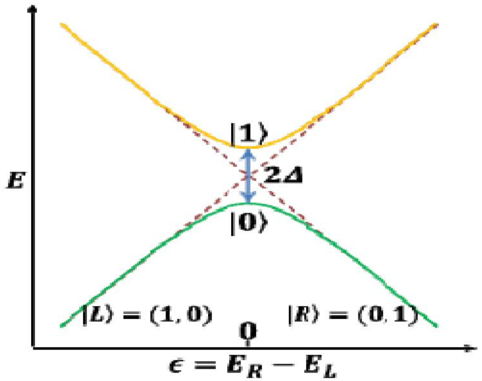
*1 Key ... inese Academy of Sciences, University of Scienc*
*and ... ple's Republic of China*
*2 Dep ... rsity of California at Los Angeles, 405 Hilgard*
*Aven...*

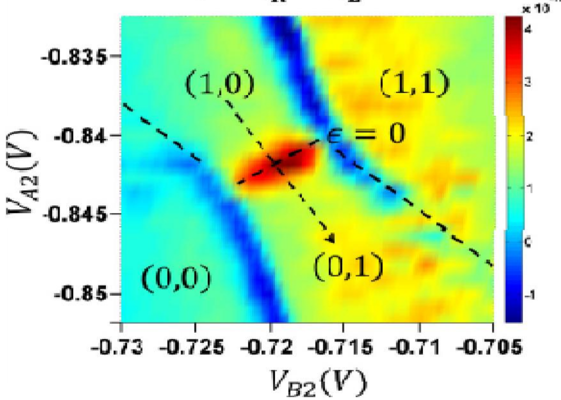
利用**LZ**干涉实现超快普适的量子逻辑门操作




工作原理

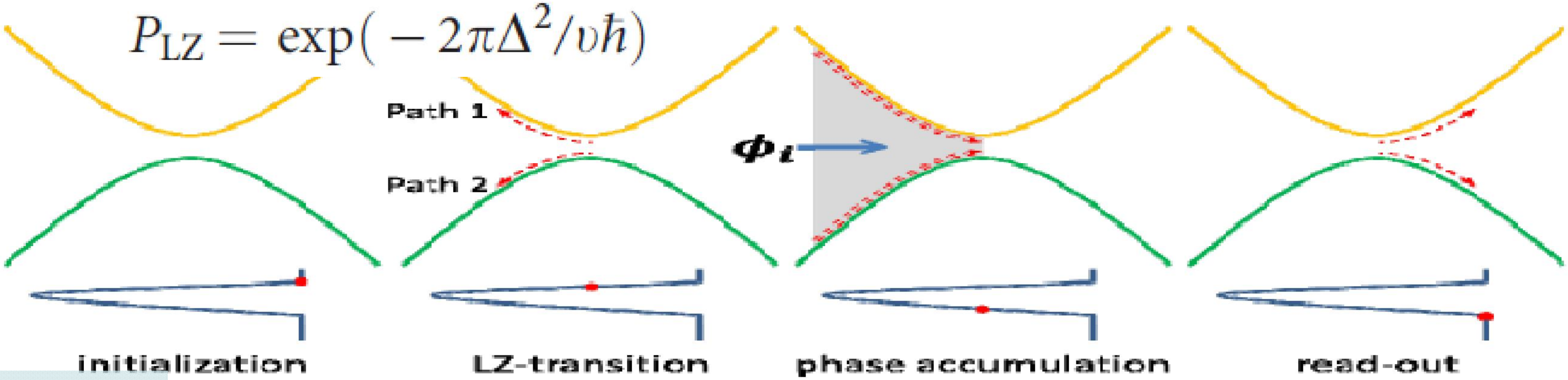
A basic requirement for quantum information processing is the ability of universal control the state of a single qubit[1-3] on timescales much shorter than the coherence time. Although ultrafast optical control of a single exciton (electron-hole pair)[4] or a single spin[5-7] in quantum dots have been achieved, scaling up such methods remains major challenging. Here we demonstrate a complete control of the quantum dot charge qubit with the time scales of picosecond, orders of magnitude faster than those previously measured in the charge[8,9] or spin based qubits[10-12] also with electric fields in quantum dots. We observed tunable qubit dynamics in charge stability diagram, in time domain, and in pulse amplitude space of the driven pulse. Our analysis indicated that the results are well described by Landau-Zener-Stückerlberg (LZS) interference[13]. These results establish the feasibility of a full set of all-electrical single qubit operations and enable potential multiple-qubit implementations[14,15]. Although our experiment is carried out in a solid-state architecture, the technique is independent of the particular physical encoding of quantum information, and has the potential for wider application.



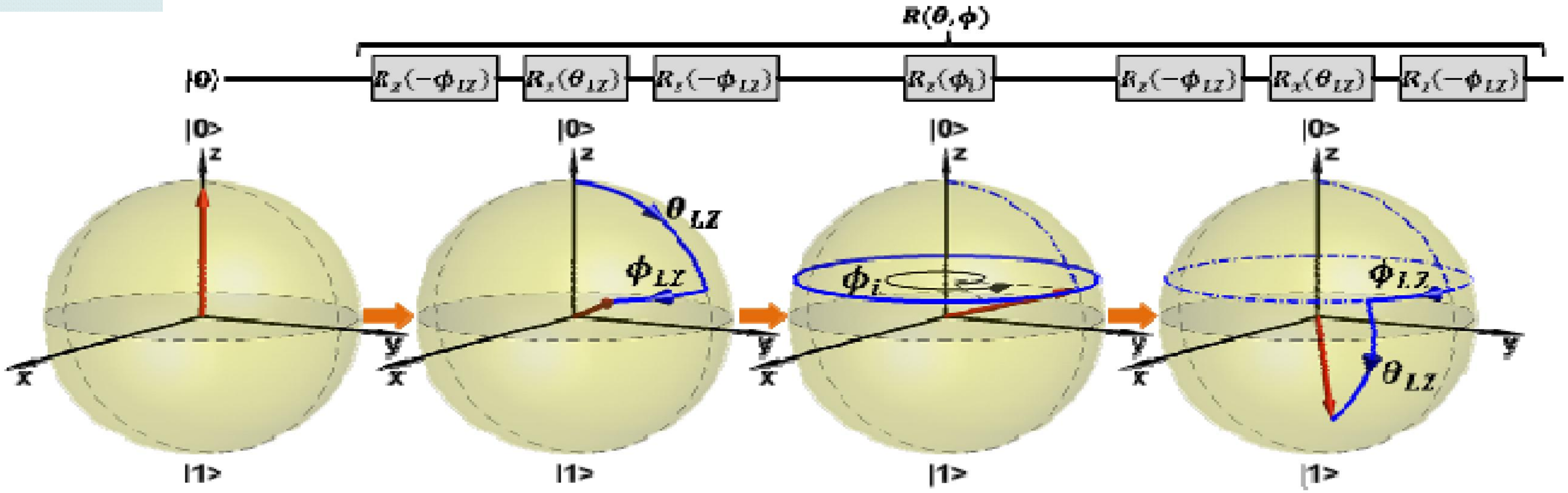




通过设计合适的高频脉冲序列，实现了电荷单量子比特超快量子逻辑门 *Nature Communications 4, 1401(2013)*

# 超快单比特普适逻辑门操控




**工作原理**

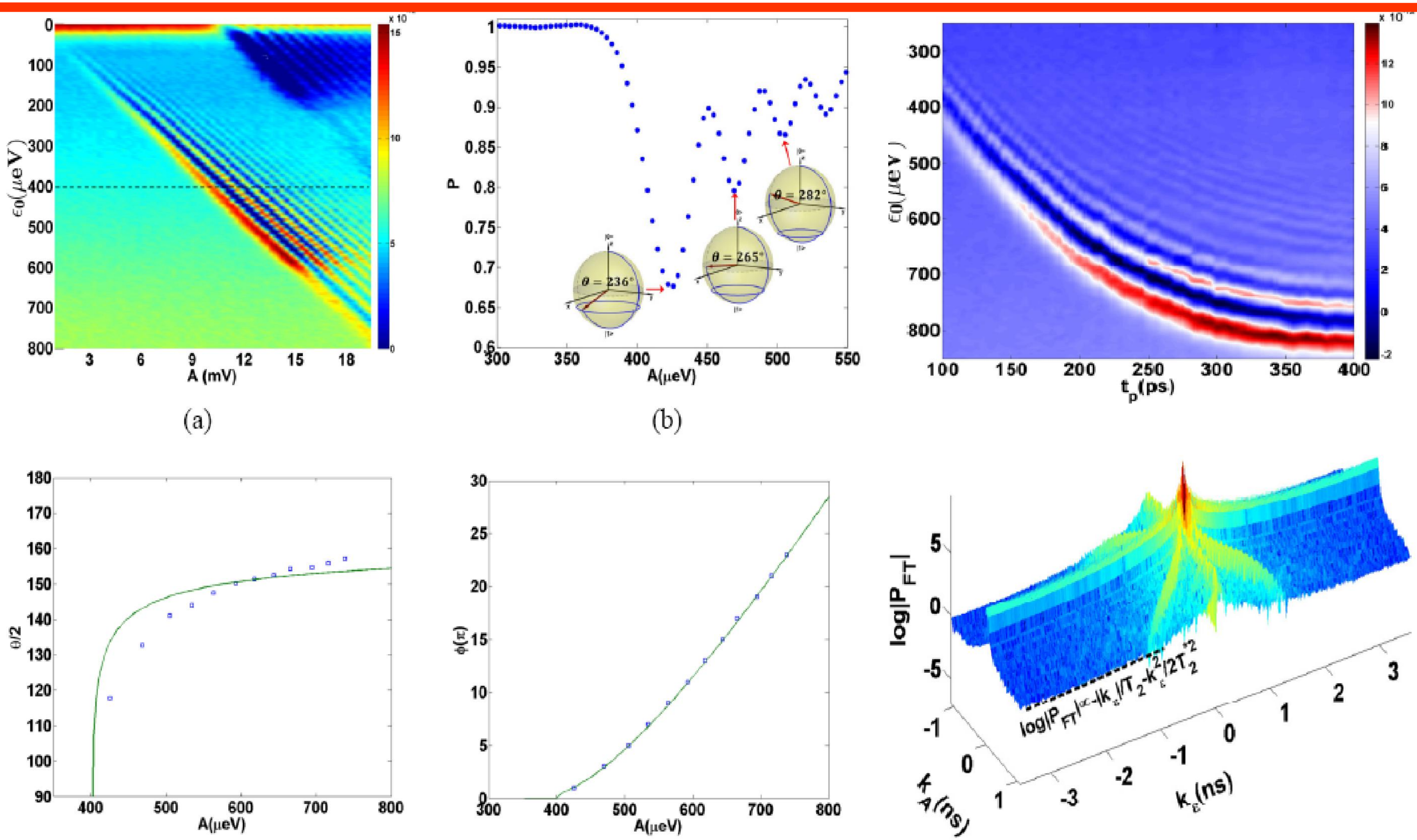



$$|\Psi_{out}\rangle = R_z(-\phi_{LZ})R_x(\theta_{LZ})R_z(-\phi_{LZ})R_z(\phi_i)R_z(-\phi_{LZ})$$

$$\times R_x(\theta_{LZ})R_z(-\phi_{LZ})|\Psi_{in}\rangle = R(\theta,\phi)|\Psi_{in}\rangle$$

◆控制脉冲高度和宽度在皮秒量级实现任意单量子比特逻辑门，比自旋量子比特快了2个量级

# 超快单比特普适逻辑门操控

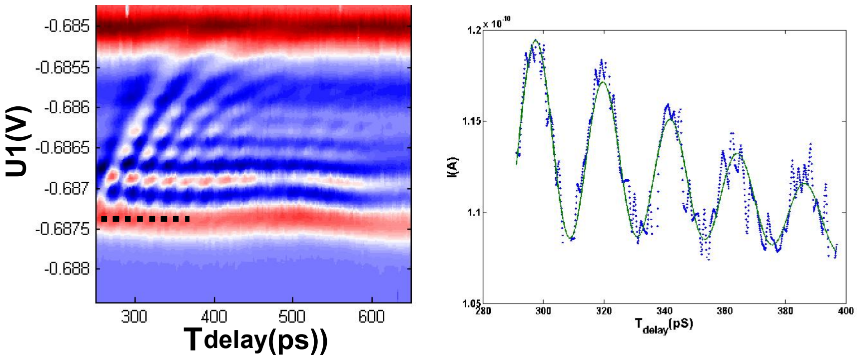


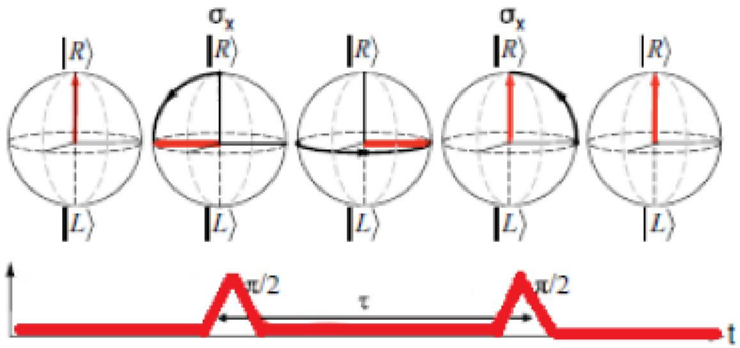

◆ 实现并观察到了单个电子的可控隧穿和路径干涉.

◆ 结合频域和时间域测量了T2* ～ 3ns

# 高速脉冲序列调控量子态

## 单量子比特操控

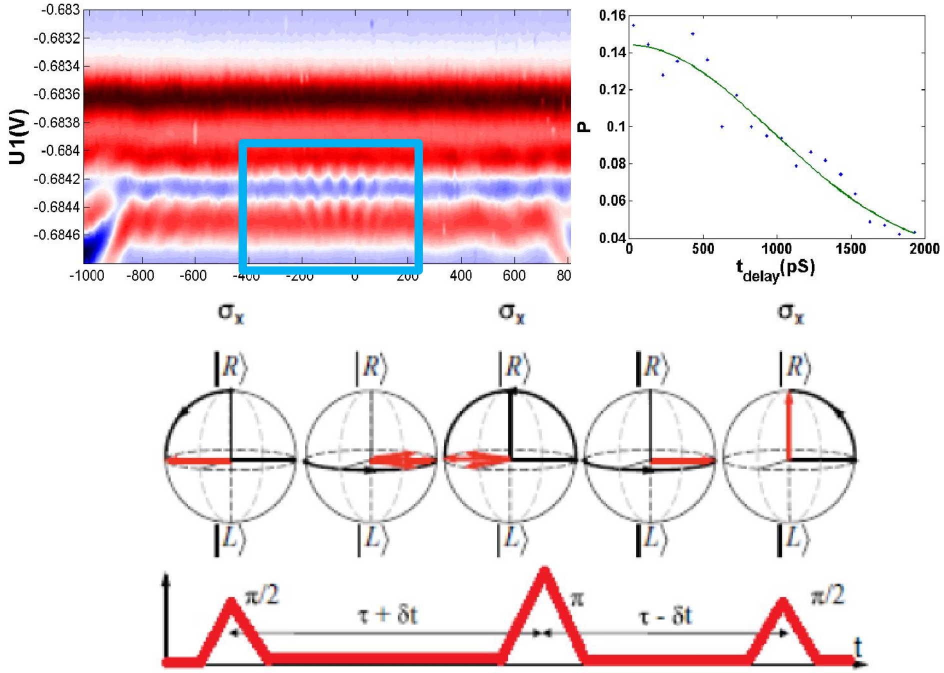



$$\Delta P_R = A_0 \times \exp\left[-\left(\frac{\tau-\tau_0}{T_2^*}\right)^2\right] \times \cos\left[2\pi f\left(\tau-\tau_0\right)\right].$$

$T_2^* \sim 230 ps$

**单量子比特Ramsey干涉**




P = $y_0 + A\exp(-(t/T_2)^2)$

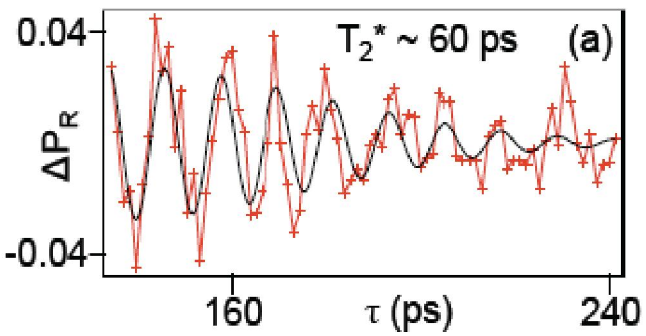
$T_2 \sim 1360 ps$

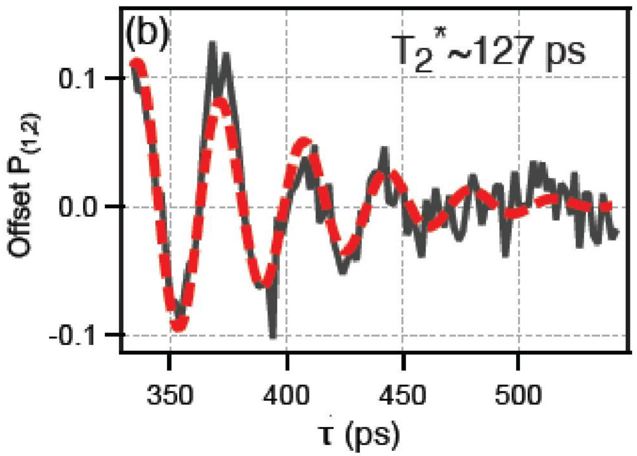
**单量子比特Echo操控**

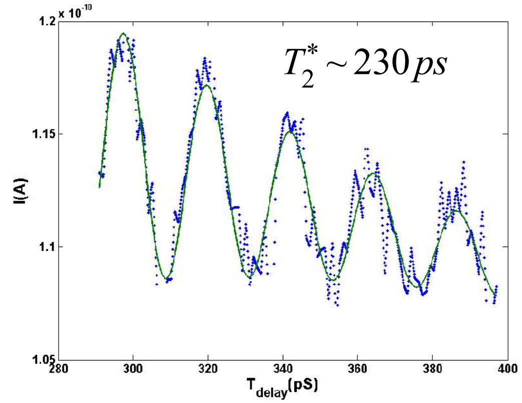
# 高速脉冲序列调控量子态

## 比较
## Ramsey

| **Princeton，Petta组** | **Wisconsin，Eriksson组** | **USTC** |
|---|---|---|
| 掺杂**GaAs** | 掺杂**GeSi** | 掺杂**GaAs** |
| $T_2^* \sim 60ps$ | $T_2^* \sim 127ps$ | $T_2^* \sim 230ps$ |



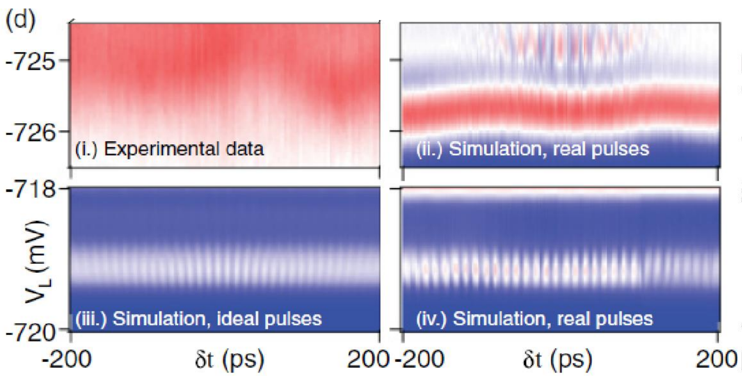



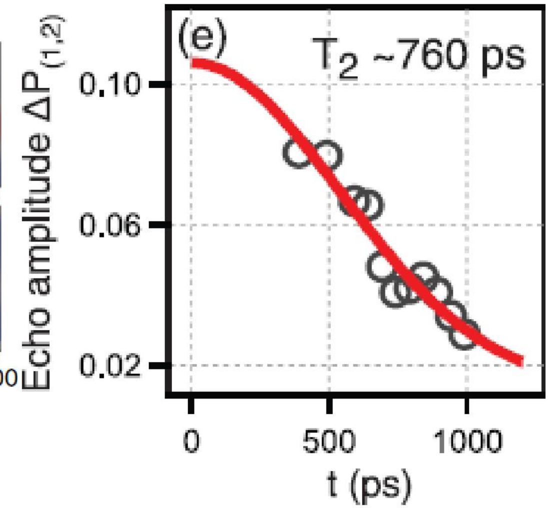
# 高速脉冲序列操控量子态

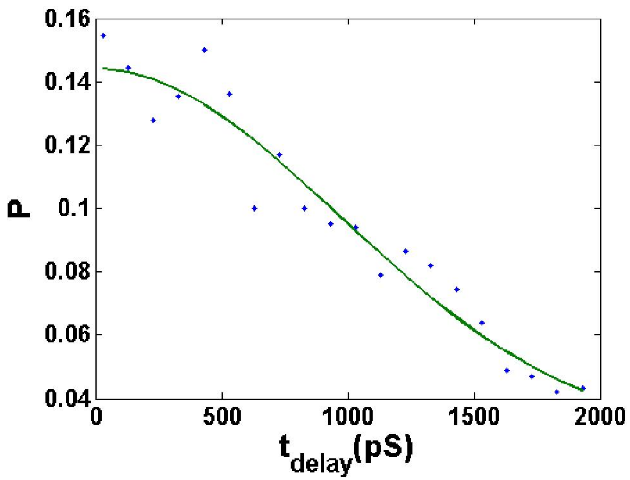
比较

**Echo**

| **Princeton，Petta组** | **Wisconsin，Eriksson组** | **USTC** |
|---|---|---|
| 掺杂**GaAs** | 掺杂**GeSi** | 掺杂**GaAs** |
| 没有成功 | $T_2 \sim 760\,ps$ | $T_2 \sim 1360\,ps$ |



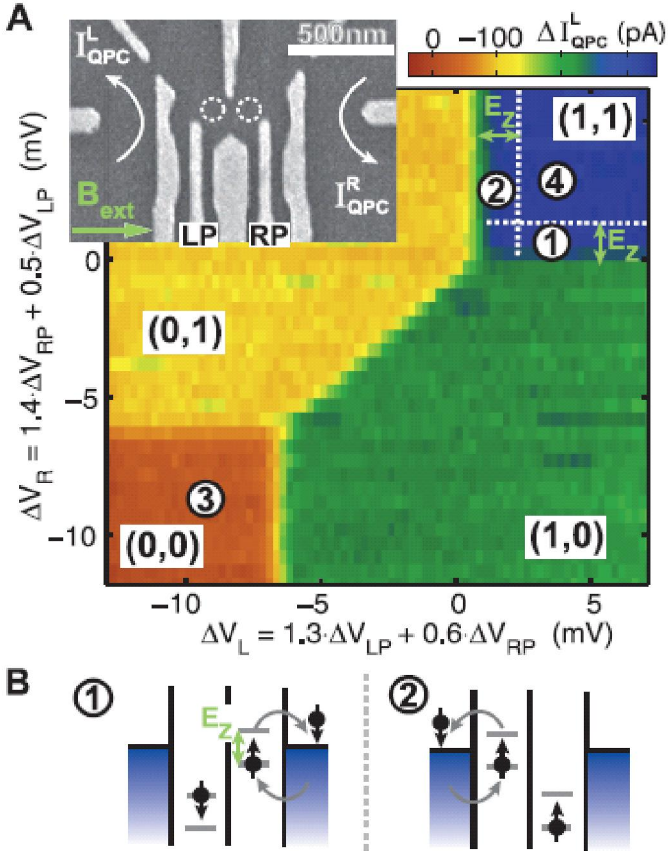
# 两比特量子控制非门

## 自旋编码双量子比特

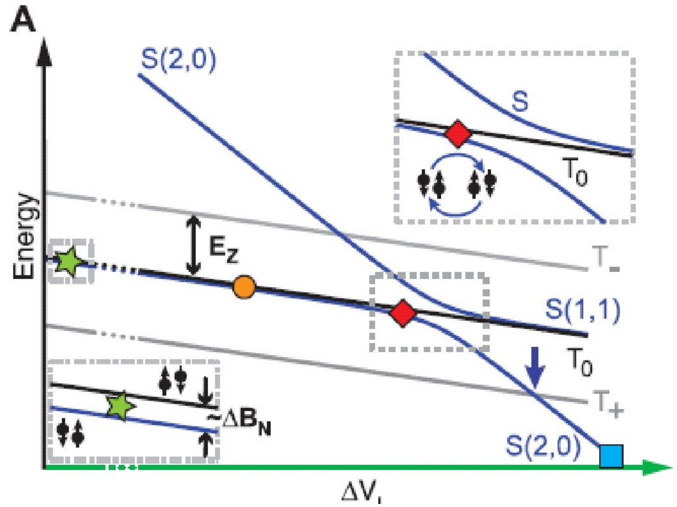
**Single-Shot Correlations and Two-Qubit Gate of Solid-State Spins**

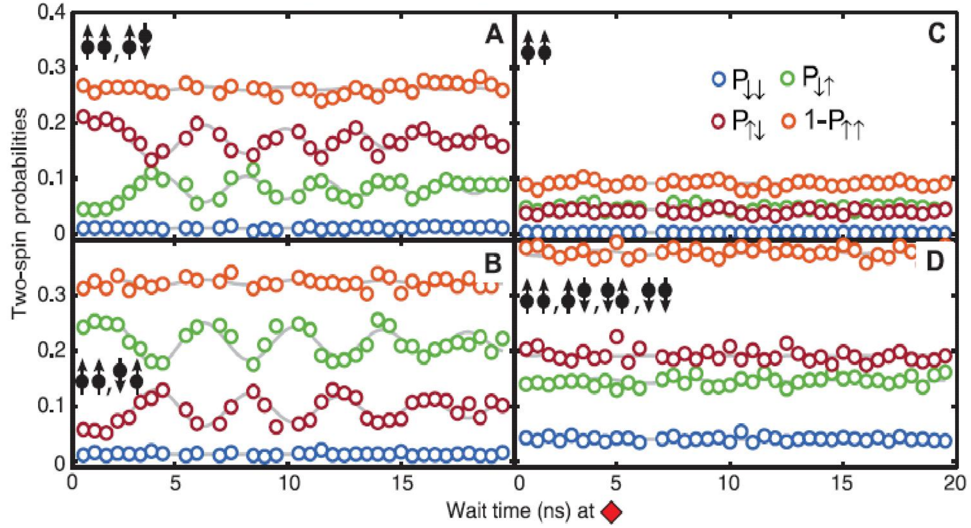
K. C. Nowack *et al.*

*Science* **333**, 1269 (2011);
DOI: 10.1126/science.1209524




单电子自旋编码



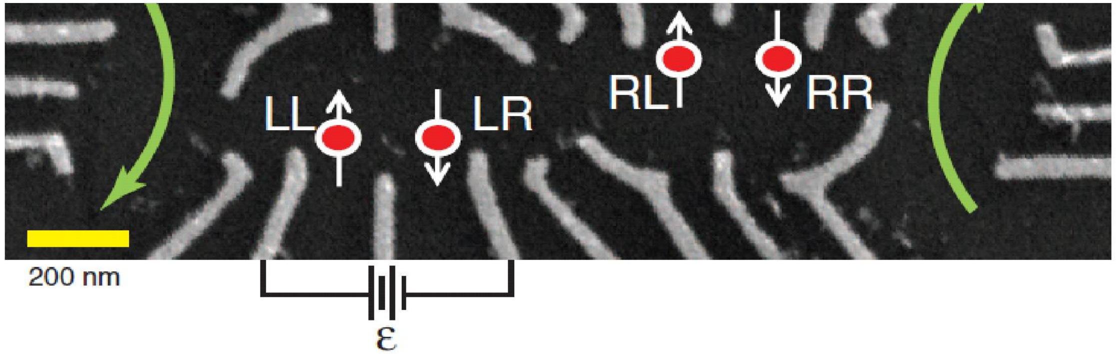



# 两比特量子控制非门

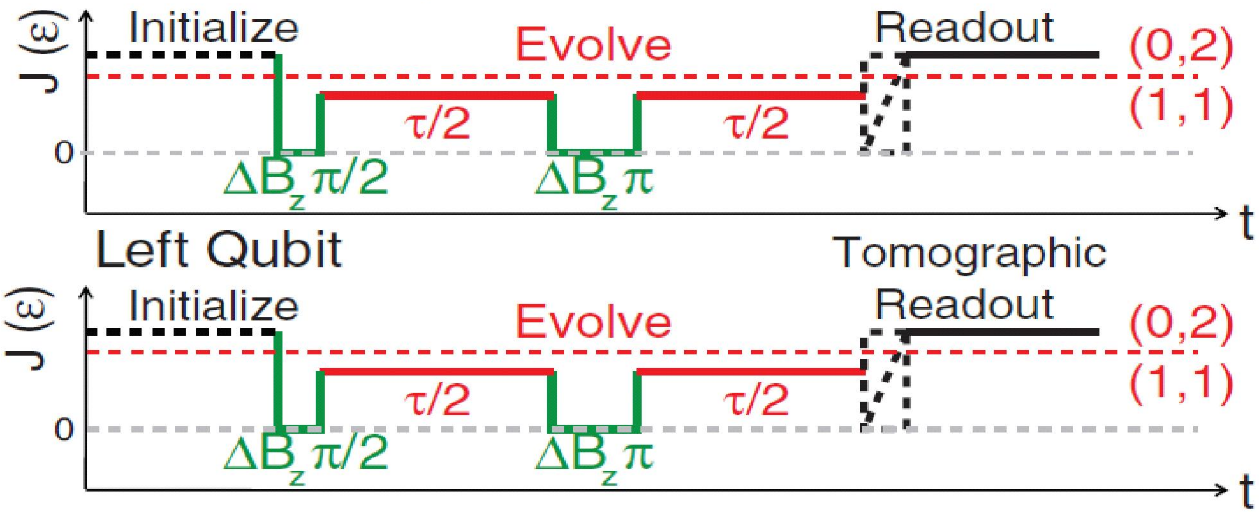
## 自旋编码双量子比特

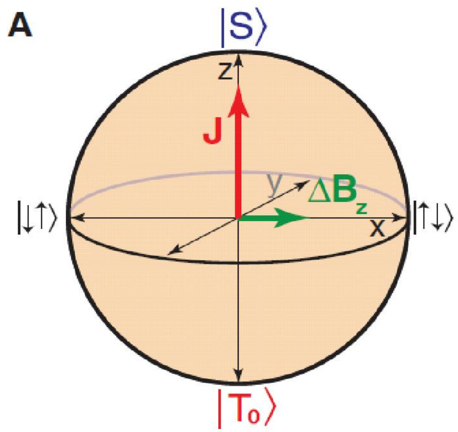
双量子点双电子
自旋单三态编码

**Demonstration of Entanglement of Electrostatically Coupled Singlet-Triplet Qubits**
M. D. Shulman *et al.*
*Science* **336**, 202 (2012);
DOI: 10.1126/science.1217692




$$H_{2-qubit} = \frac{\hbar}{2}\Big(J_1(\sigma_z \otimes I) + J_2(I \otimes \sigma_z) + \frac{J_{12}}{2}((\sigma_z - I) \otimes (\sigma_z - I)) + \Delta B_{z,1}(\sigma_x \otimes I) + \Delta B_{z,2}(I \otimes \sigma_x)\Big)$$

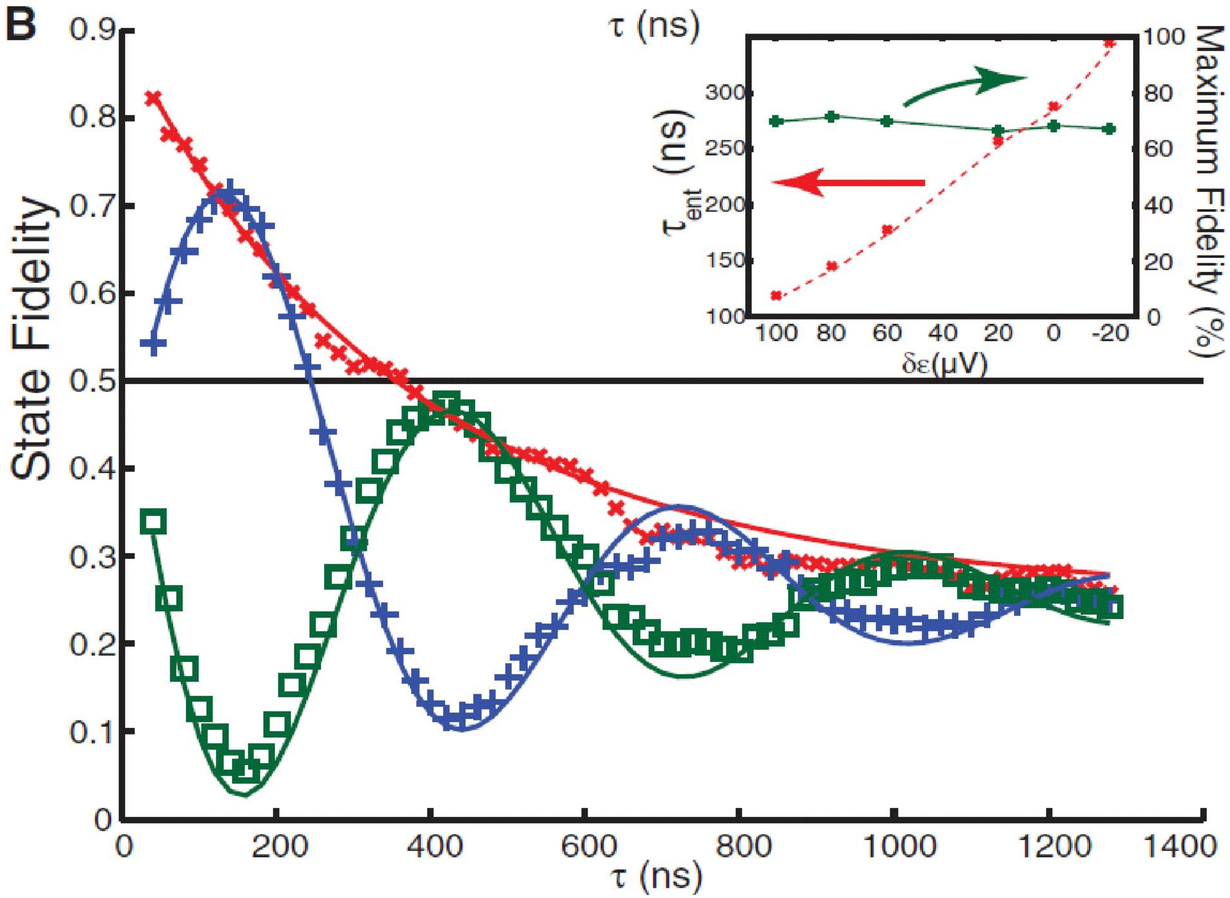


# 两比特量子控制非门

## 自旋编码双量子比特

**Demonstration of Entanglement of Electrostatically Coupled Singlet-Triplet Qubits**
M. D. Shulman *et al.*
*Science* **336**, 202 (2012);
DOI: 10.1126/science.1217692




双量子点双电子
自旋单三态编码

操控时间长

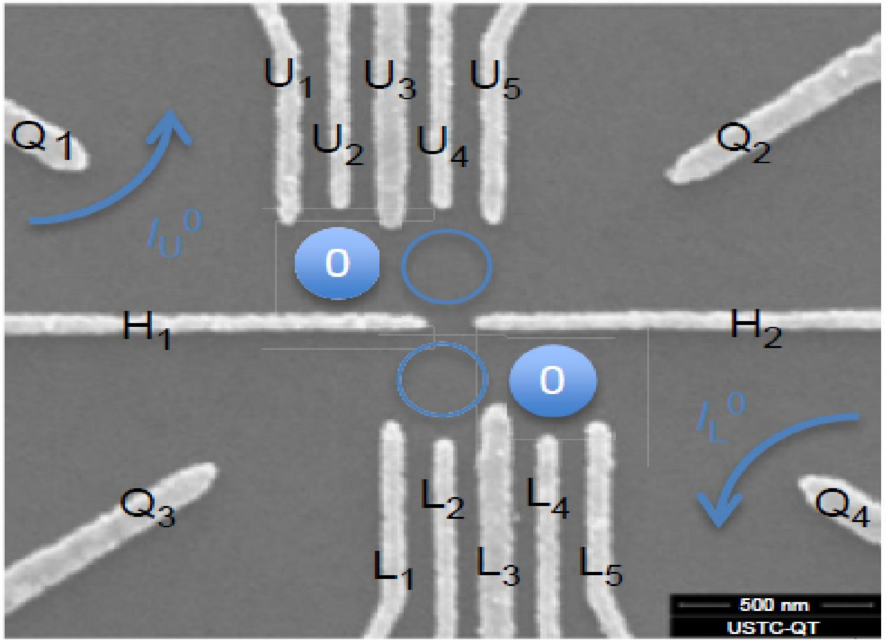
# 两比特量子控制非门

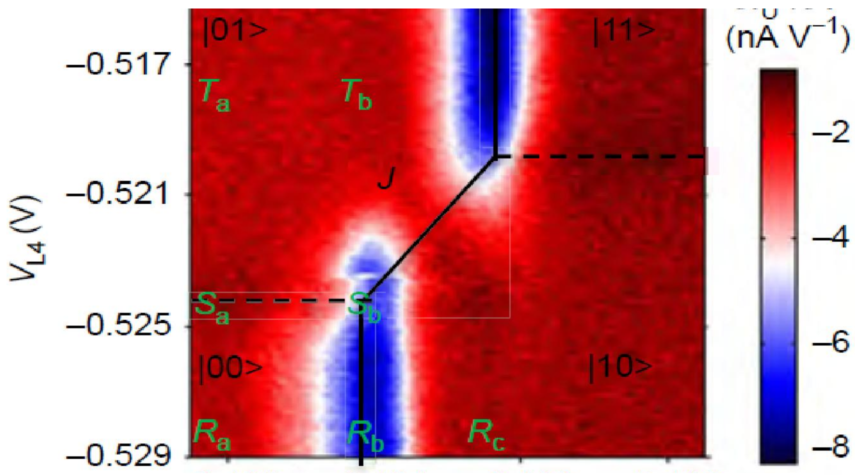
ARTICLE
Received 24 Feb 2015 | Accepted 1 Jun 2015 | Published 17 Jul 2015
DOI: 10.1038/ncomms8681
OPEN

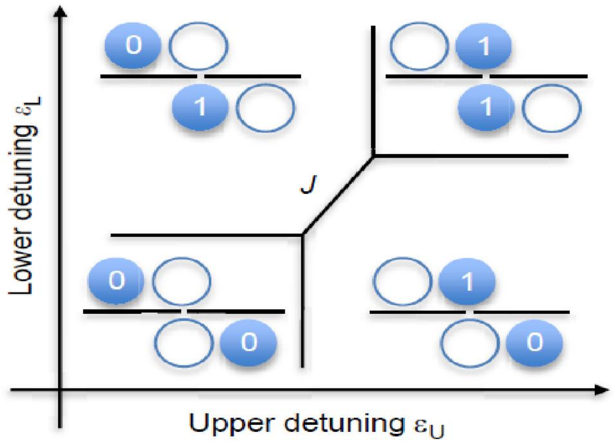
## Conditional rotation of two strongly coupled semiconductor charge qubits

Hai-Ou Li[1,2,*], Gang Cao[1,2,*], Guo-Dong Yu[2,3,*], Ming Xiao[2,3], Guang-
Hong-Wen Jiang[4] & Guo-Ping Guo[1,2]

双量子点单电子状态编码

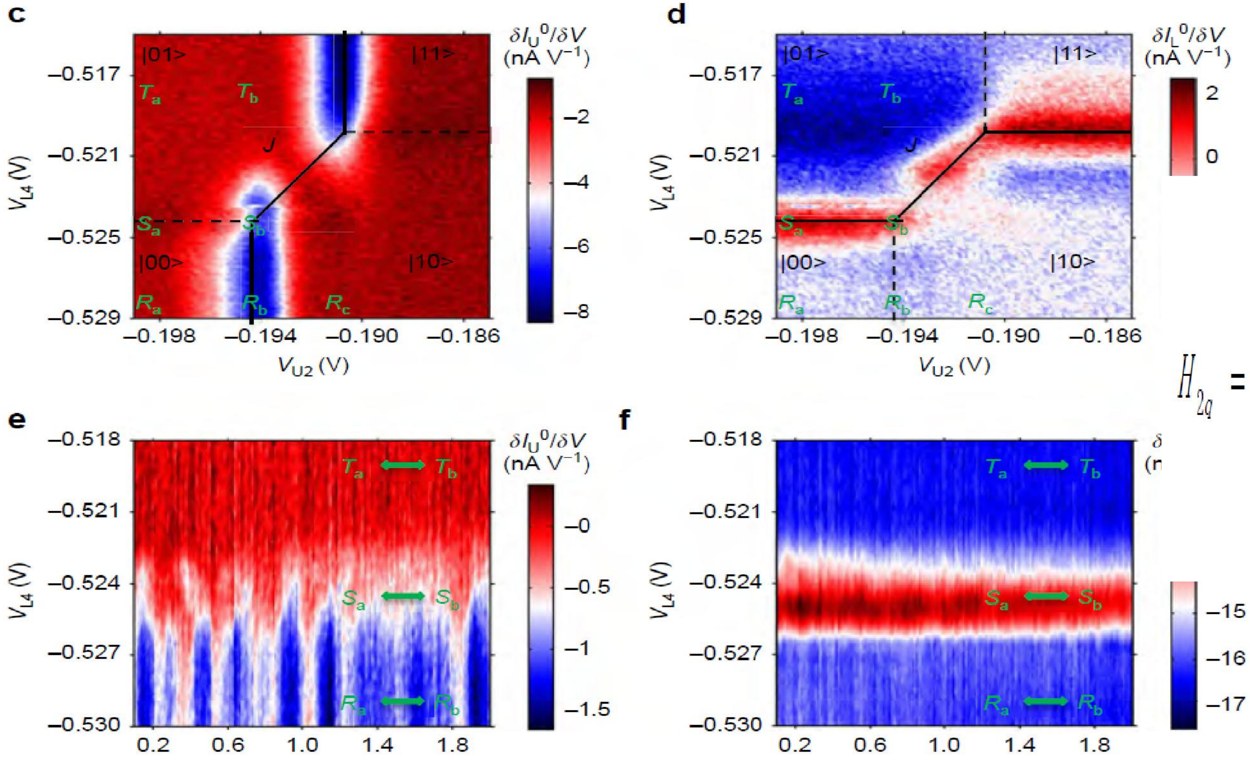


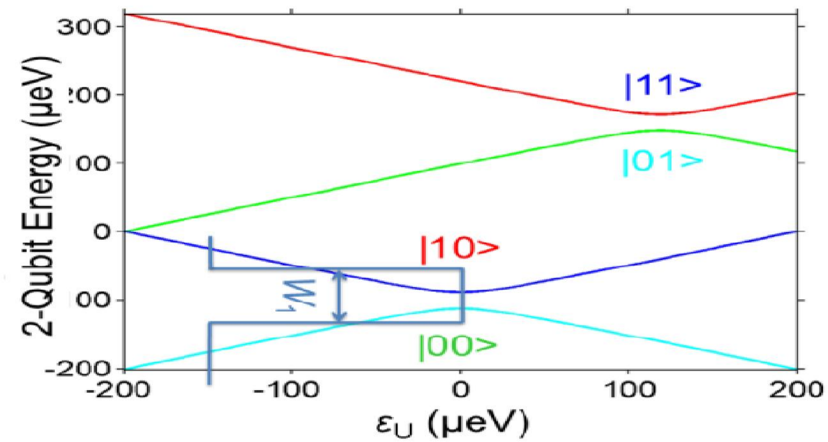



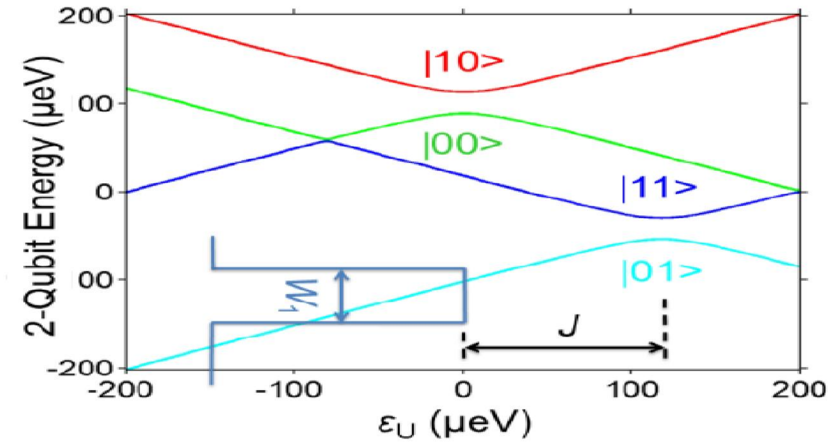

$$H_{2q} = \frac{1}{2}\sum_{i=1}^{2}(\varepsilon_i \sigma_z^{(i)} + \Delta_i \sigma_x^{(i)}) + \frac{J}{4}(I - \sigma_z^{(1)}) \otimes (I - \sigma_z^{(2)})$$

# 两比特量子控制非门

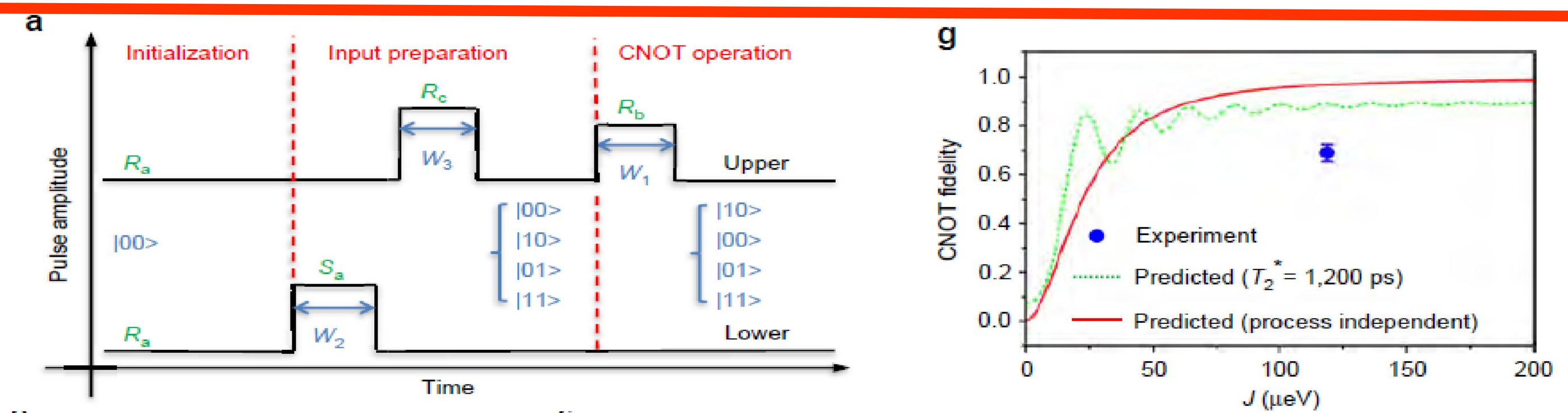


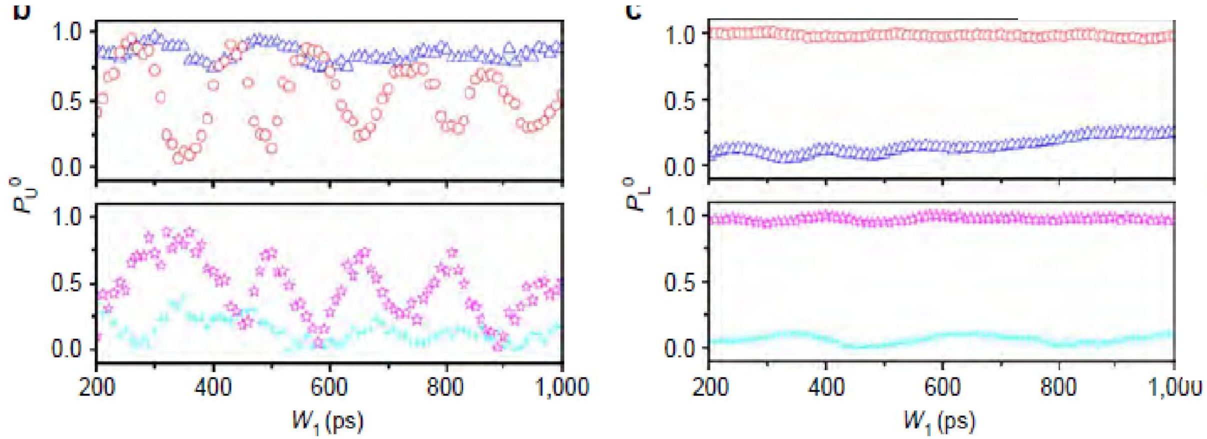

$$H_{2q} = \frac{1}{2}\begin{vmatrix} \varepsilon_U + \varepsilon_L & \Delta_U & \Delta_L & 0 \\ \Delta_U & -\varepsilon_U + \varepsilon_L & 0 & \Delta_L \\ \Delta_L & 0 & \varepsilon_U - \varepsilon_L & \Delta_U \\ 0 & \Delta_L & \Delta_U & -\varepsilon_U - \varepsilon_L + 2J \end{vmatrix}$$



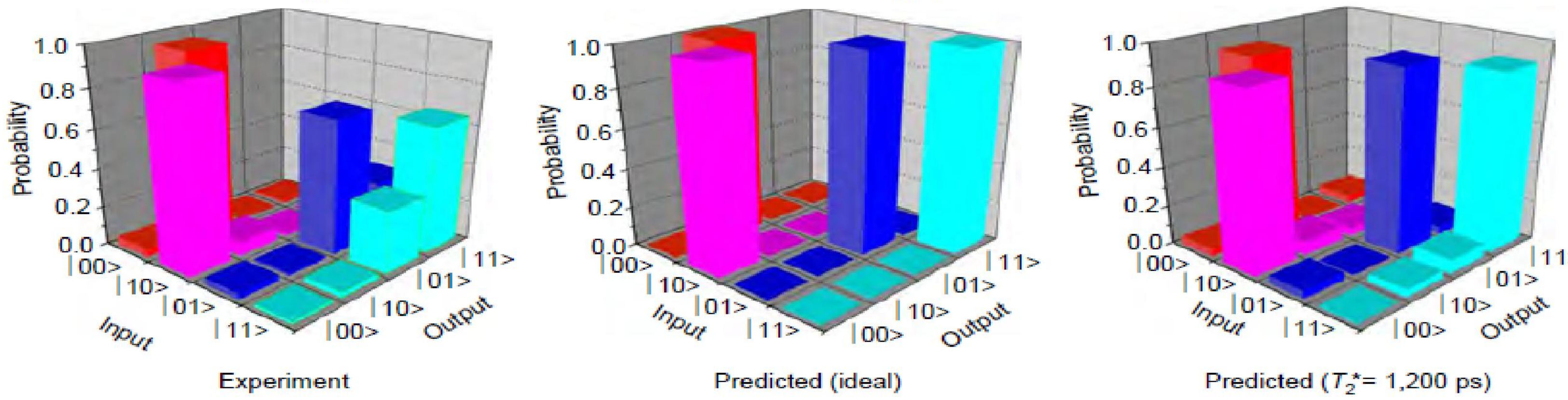



# 两比特量子控制非门

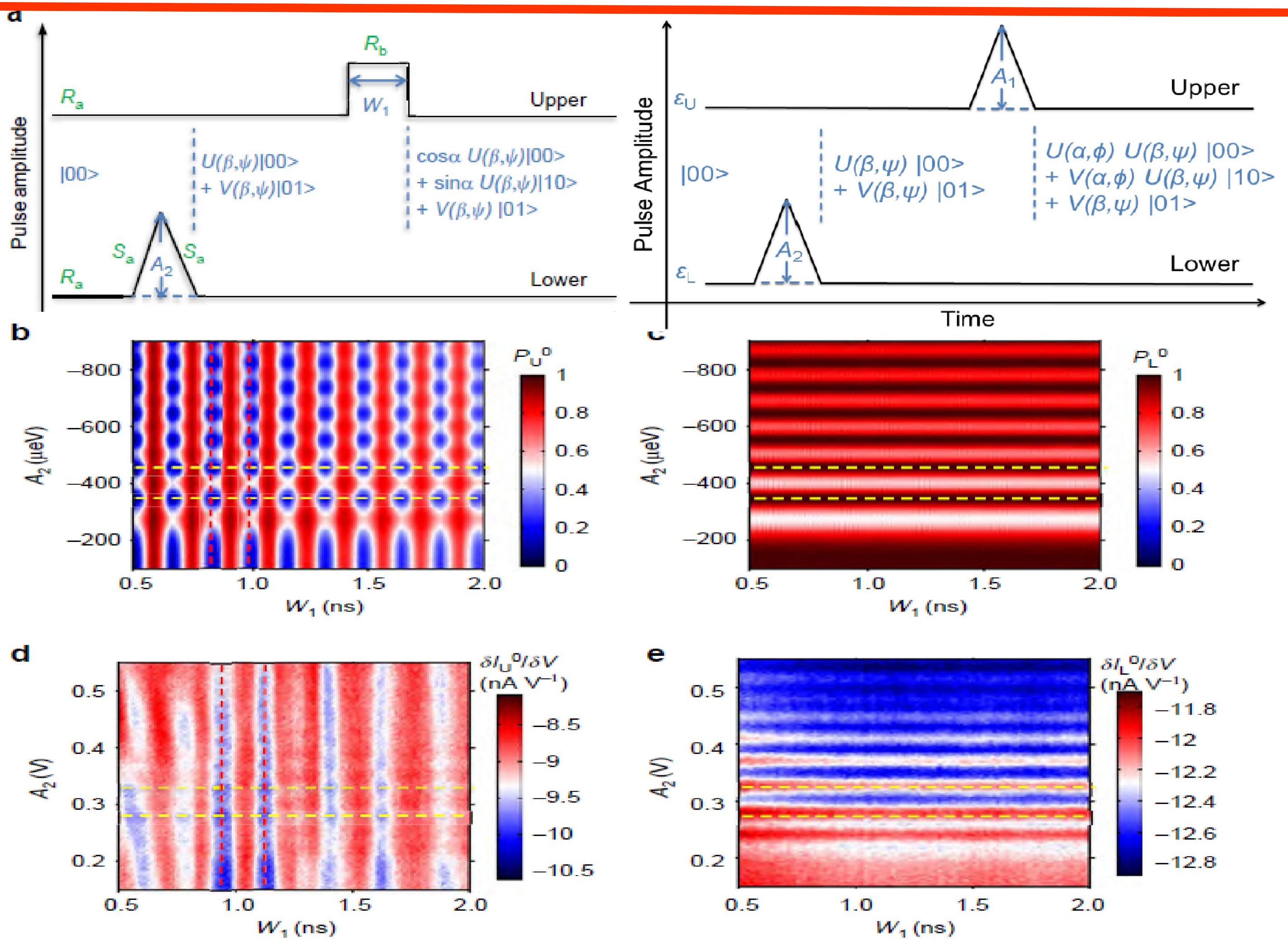



$$T_{\text{measured}} = \begin{pmatrix} 0.09 & 0.89 & 0.002 & 0.02 \\ 0.87 & 0.12 & 0.01 & 0.002 \\ 0.06 & 0.02 & 0.74 & 0.18 \\ 0.02 & 0.07 & 0.23 & 0.68 \end{pmatrix}$$



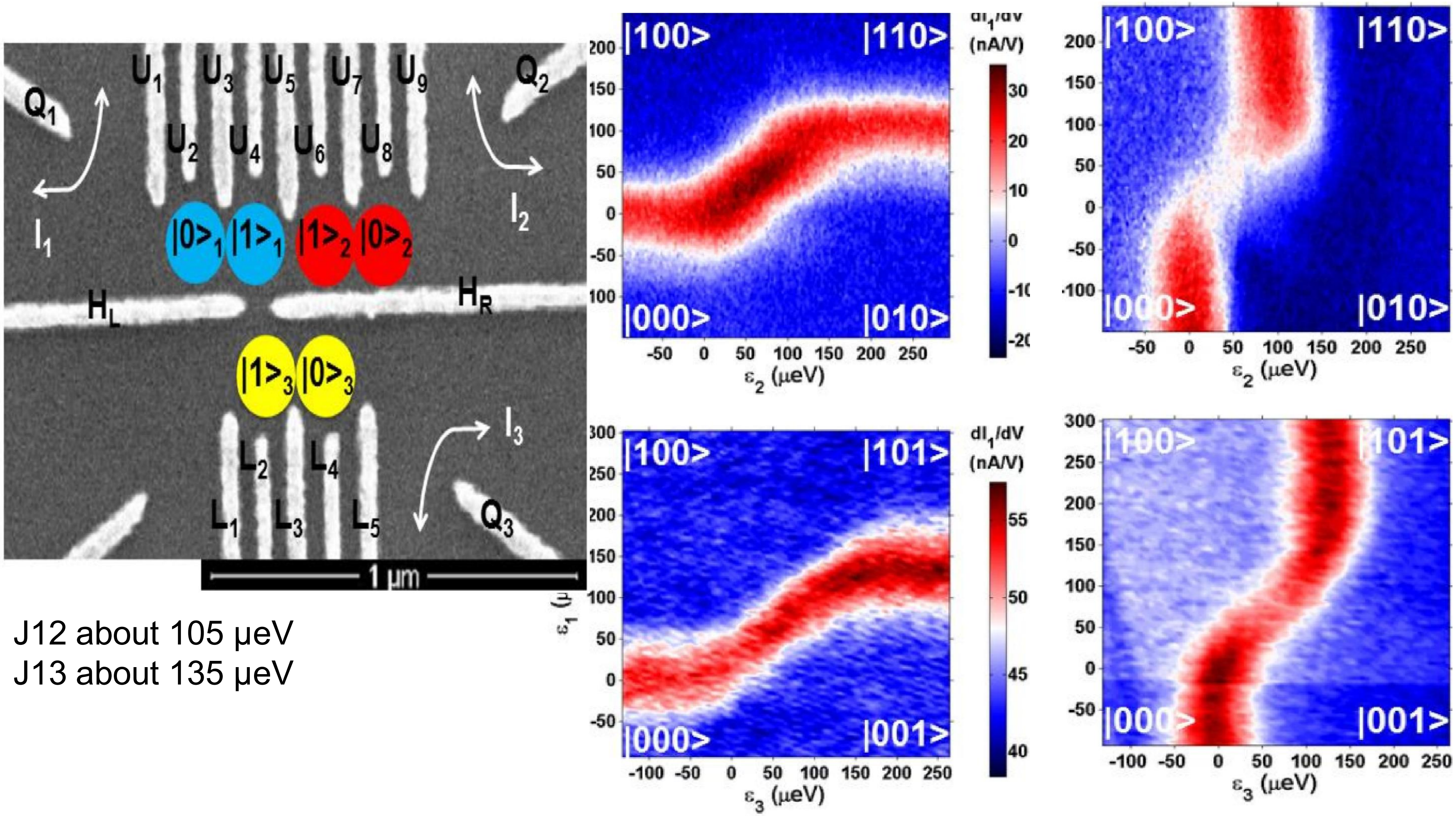
# 两比特量子控制非门


a
Pulse amplitude
$R_a$
$R_b$
$W_1$
Upper
|00>
U(β,ψ)|00>
+ V(β,ψ)|01>
cosα U(β,ψ)|00>
+ sinα U(β,ψ)|10>
+ V(β,ψ) |01>
$S_a$
$A_2$
Lower
Pulse Amplitude
$\varepsilon_U$
$A_1$
U(β,ψ) |00>
+ V(β,ψ) |01>
U(α,ϕ) U(β,ψ) |00>
+ V(α,ϕ) U(β,ψ) |10>
+ V(β,ψ) |01>
$\varepsilon_L$
Time
b
c
$A_2$ (μeV)
$W_1$ (ns)
$P_U^0$
$P_L^0$
d
e
$A_2$ (V)
$\delta I_U^0/\delta V$ (nA V$^{-1}$)
$\delta I_L^0/\delta V$ (nA V$^{-1}$)

# Basic Quantum gates of charge qubit

**Controlled Quantum operations of a Semiconductor Three-Qubit System**

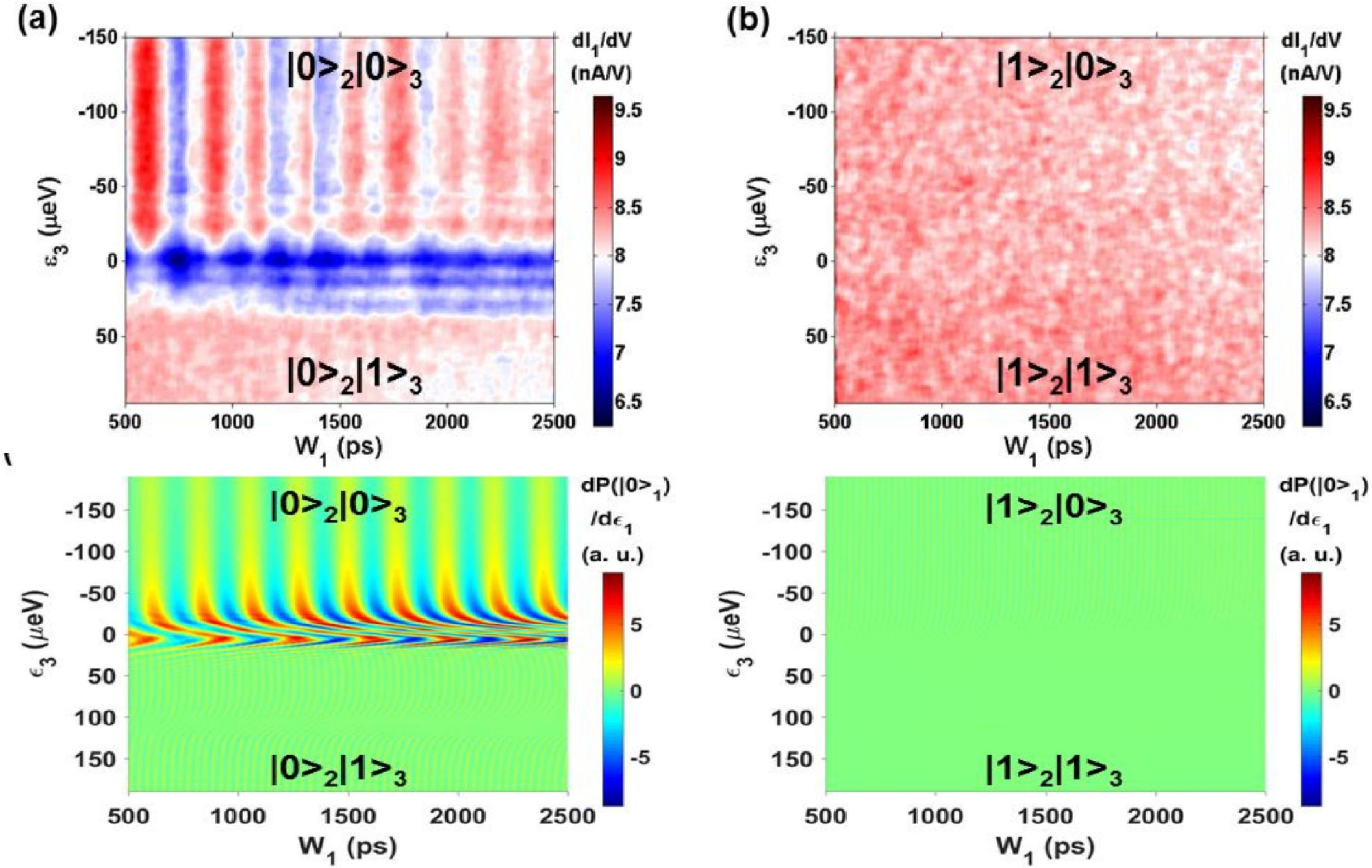
arXiv 1610.06704




J12 about 105 μeV
J13 about 135 μeV

# Basic Quantum gates of charge qubit

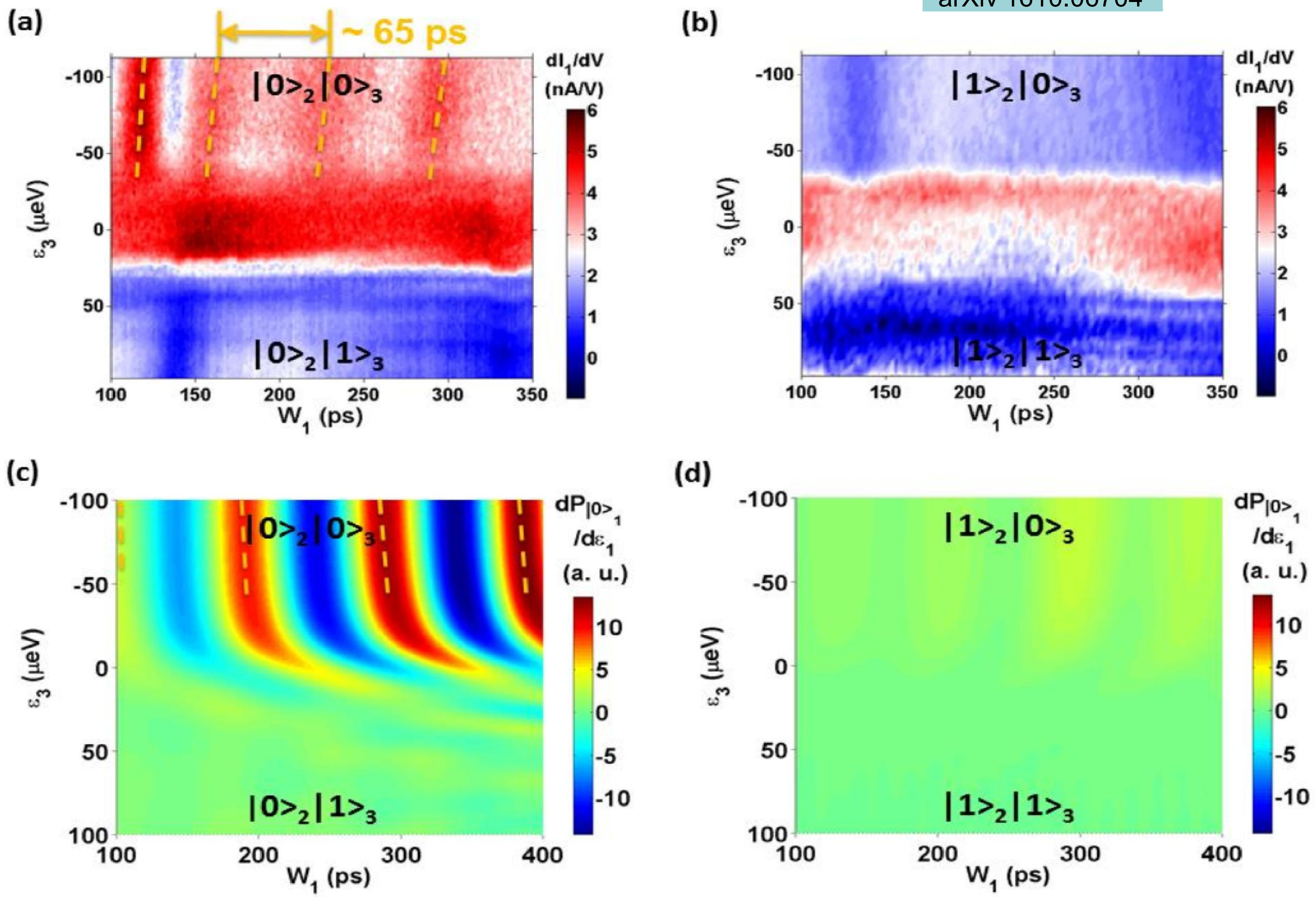
**Controlled Quantum operations of a Semiconductor Three-Qubit System**



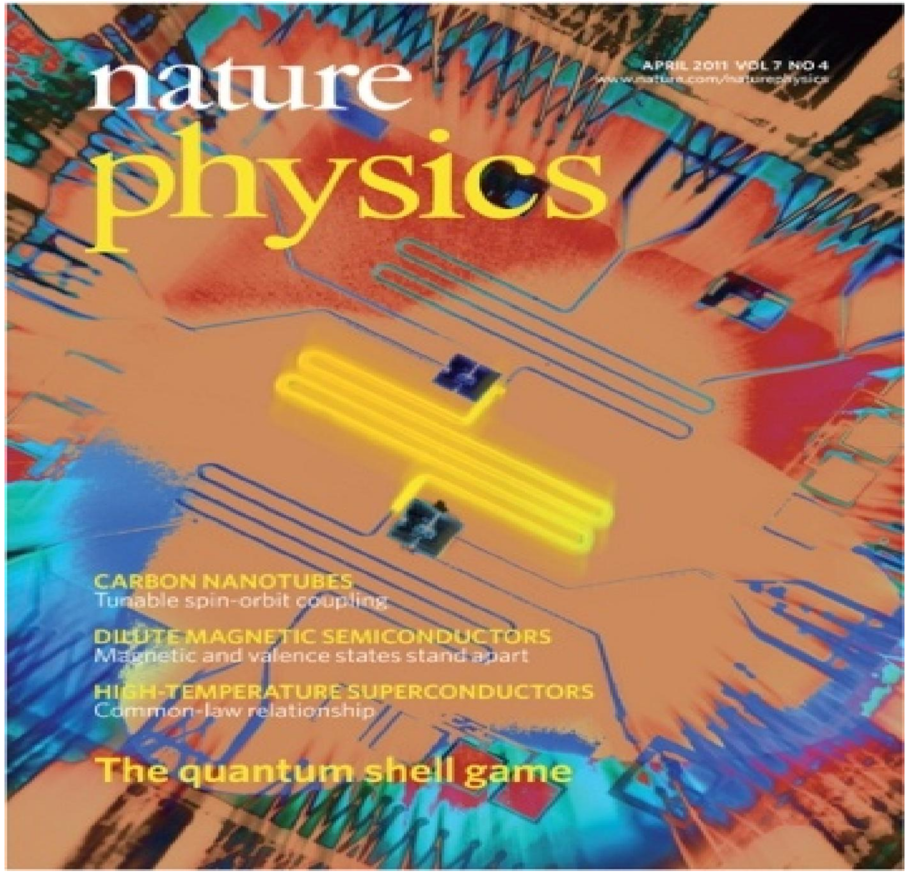
# Basic Quantum gates of charge qubit

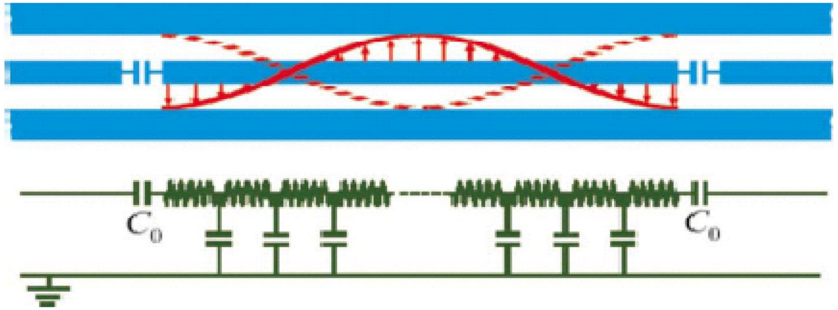
**Controlled Quantum operations of a Semiconductor Three-Qubit System**

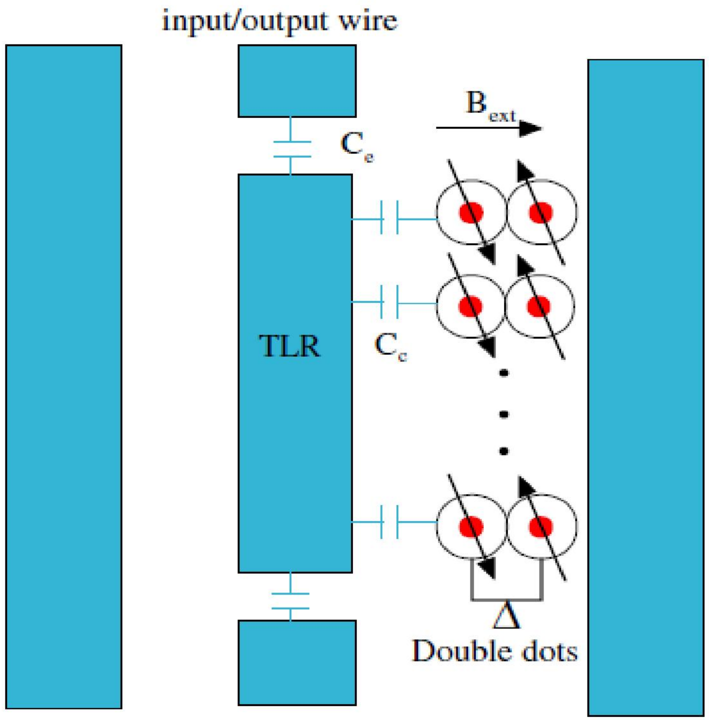
arXiv 1610.06704



# 量子数据线和量子比特的长程耦合



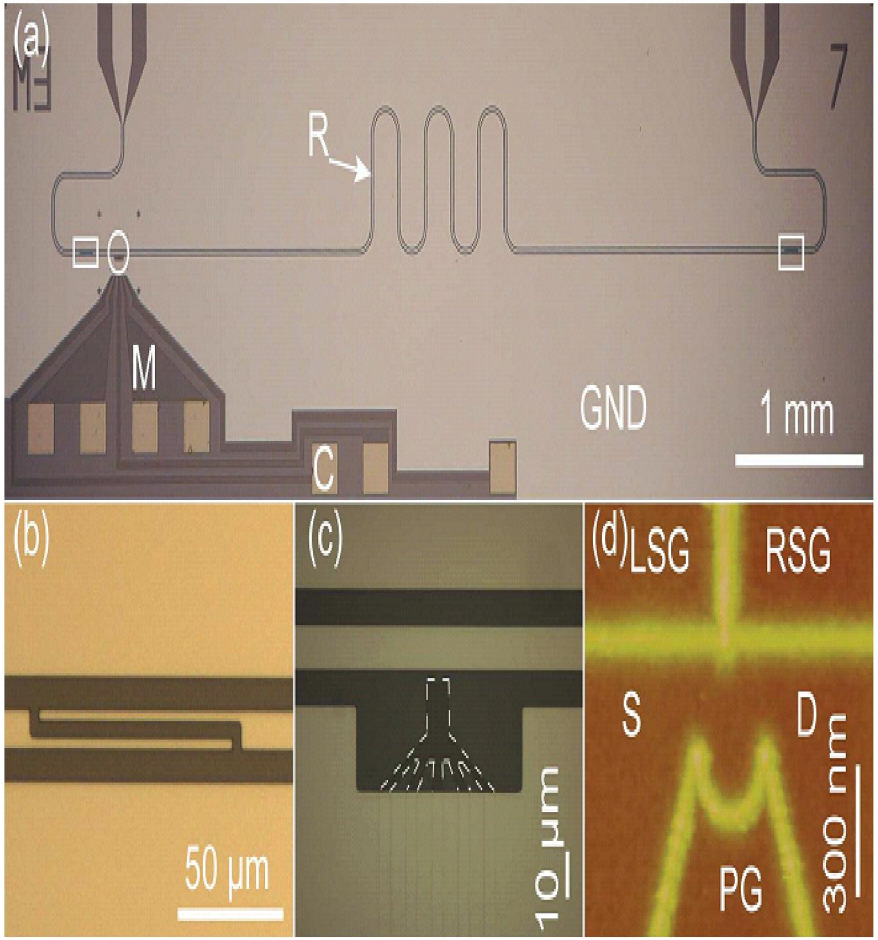

J-C Model:

$$H = \hbar\omega_r(a^+a + 1/2) + \hbar\frac{\omega_a}{2}\sigma_z + \hbar g(a^+\sigma^- + a\sigma^+)$$

**Phys. Rev. Lett. 101, 230501 (2008).**
**Phys. Rev. A 78 , 020302(R) (2008).**

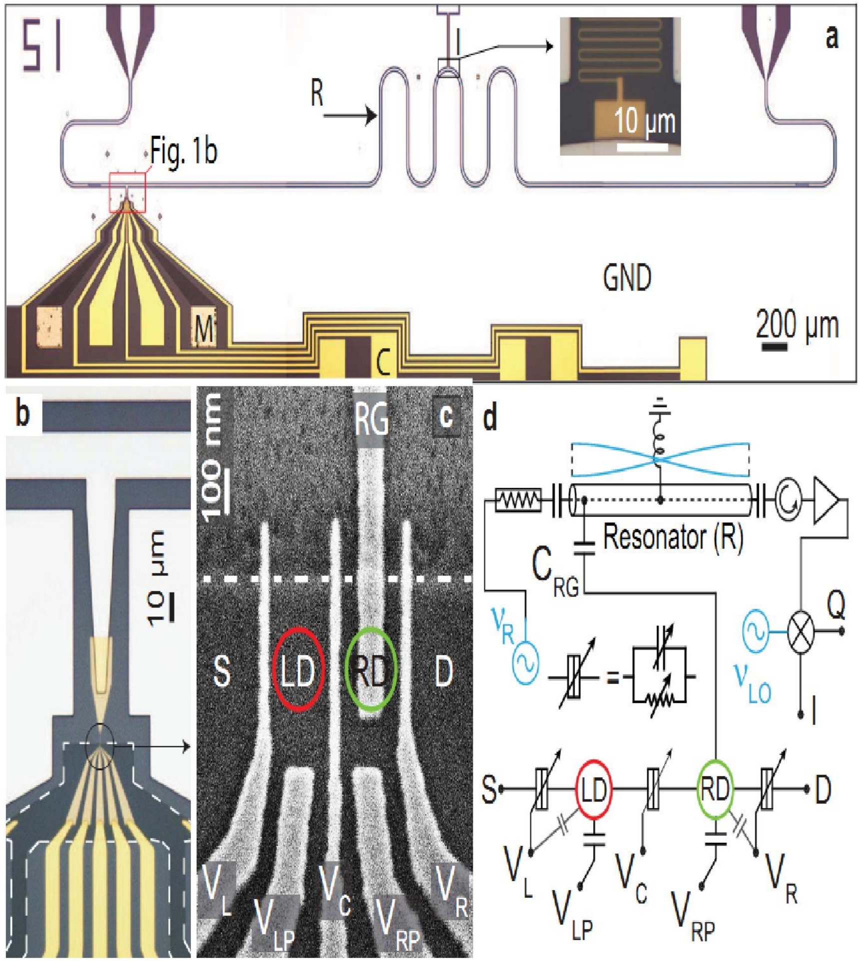
# 量子数据线和量子比特的长程耦合

**Characterization of a microwave frequency resonator via a nearby quantum dot**




Appl. Phys. Lett. 262105 98 (2011)

**Dipole-coupling of a double quantum dot to a microwave resonator**




Phys. Rev. Lett. 108, 046807 2012

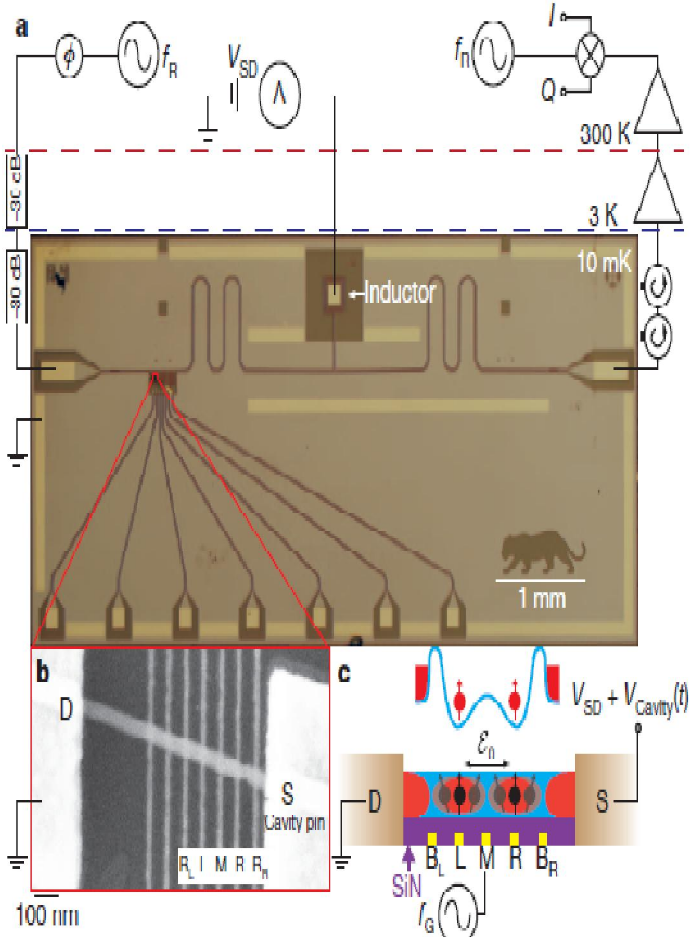
# 量子数据线和量子比特的长程耦合

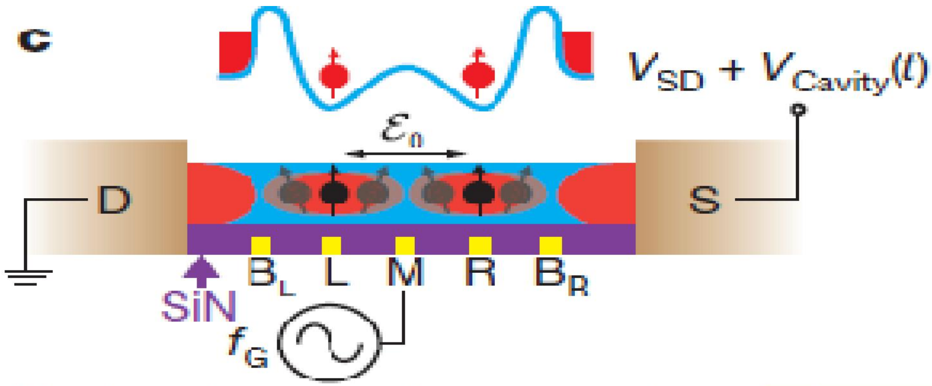
## LETTER

doi:10.1038/nature11559

### Circuit quantum electrodynamics with a spin qubit

K. D. Petersson[1], L. W. McFaul[1], M. D. Schroer[1], M. Jung[1], J. M. Taylor[2], A. A. Houck[3] & J. R. Petta[1,4]



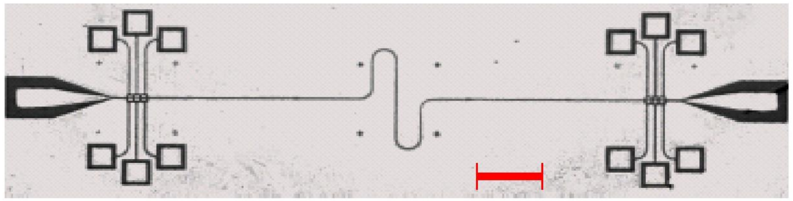




cavity[8,9]. The architecture allows us to achieve a charge–cavity coupling rate of about 30 megahertz, consistent with coupling rates obtained in gallium arsenide quantum dots[10]. Furthermore, the strong spin–orbit interaction of indium arsenide allows us to drive spin rotations electrically with a local gate electrode, and the charge–cavity interaction provides a measurement of the resulting spin dynamics. Our results demonstrate how the cQED architecture can be used as a sensitive probe of single-spin physics and that a spin–cavity coupling rate of about one megahertz is feasible, presenting the possibility of long-range spin coupling via superconducting microwave cavities.

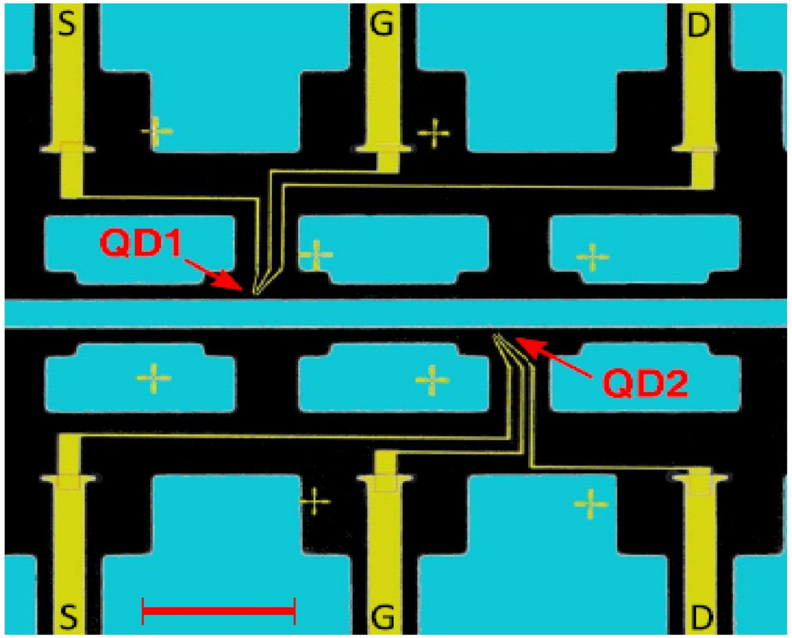
# 量子数据线和量子比特的长程耦合

**Photon mediated interaction between distant quantum dot circuits**

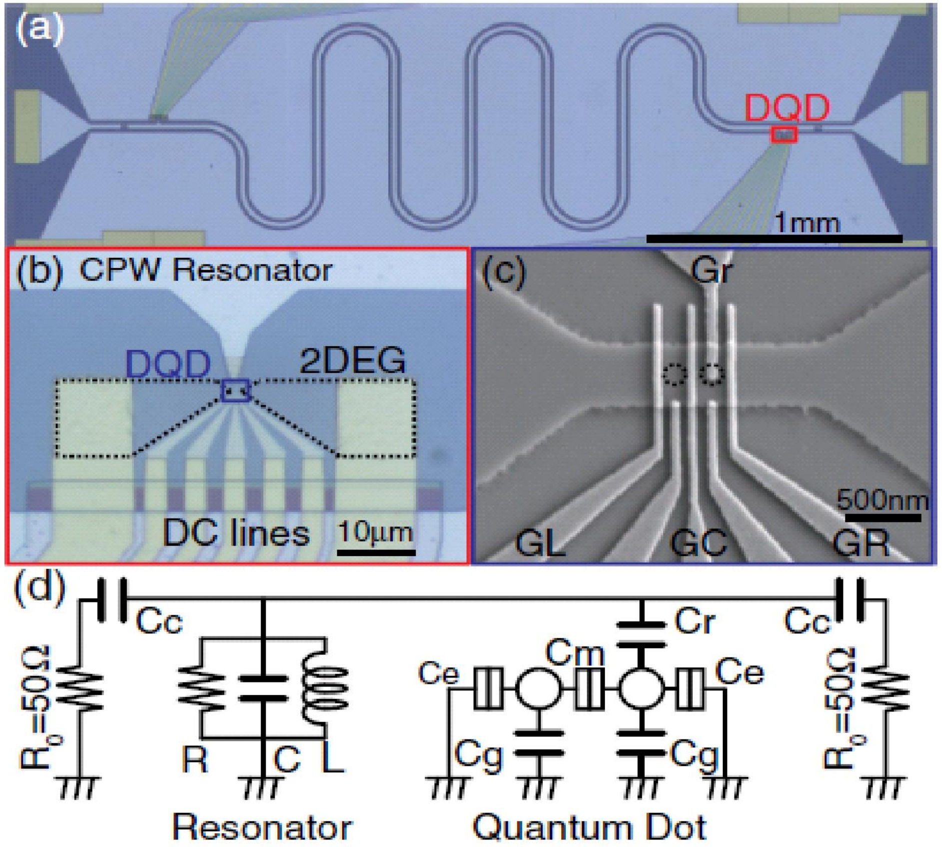
a



c Nature Communications 4, 1400 (2013)




**Vacuum Rabi Splitting in a Semiconductor Circuit QED System ???**




**PRL 110, 066802 (2013) and its comment on arXiv 1304.3697**

# 量子数据线和量子比特的长程耦合

J-C Model: $H = \hbar\omega_r(a^+a + 1/2) + \hbar\frac{\omega_a}{2}\sigma_z + \hbar g(a^+\sigma^- + a\sigma^+)$

**Strong coupling:** $2g \geq (\kappa + \gamma_{\text{dot}})/2$

$g_C/2\pi = 30$ MHz    $\kappa/(2\pi) = 8$ MHz    $(\gamma_1, \gamma_\phi, \gamma)/(2\pi) = (200, 200, 300)$ MHz

- Increasing coherence time of QD and the coupling strength is the Key to get strong coupling region.

***How about New material: Graphene and TMDs QD ?***

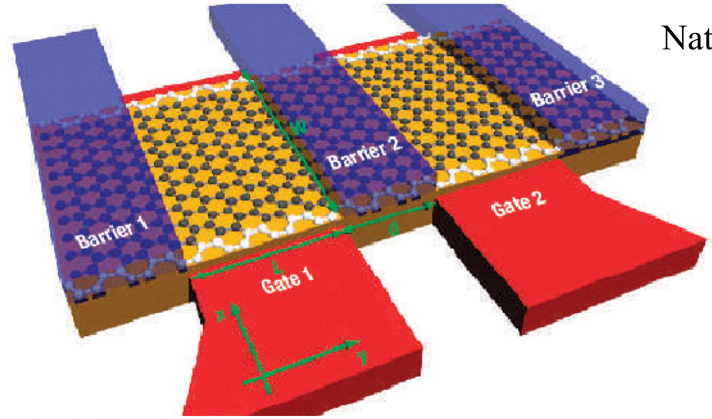
1. **Fabrication of graphene QD and its manipulation ?**
2. **Design of superconductor resonator for graphene ?**
3. **Coherence time for graphene QD qubits ?**

# Theory for graphene quantum qubit

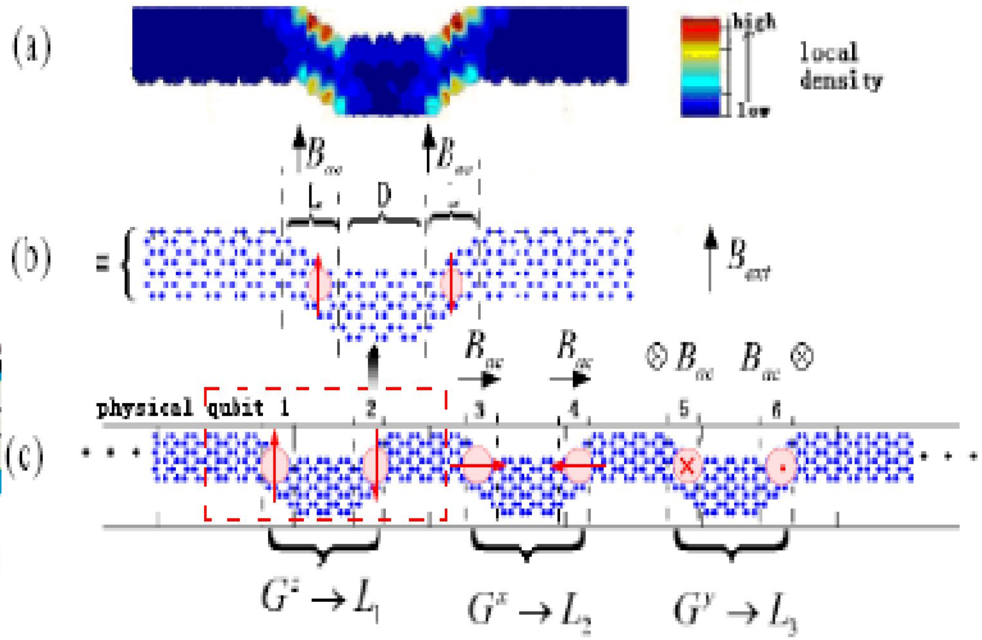
**ARTICLES**

## Spin qubits in graphene quantum dots

BJÖRN TRAUZETTEL, DENIS V. BULAEV, DANIEL LOSS AND GUIDO BURKARD*
**Department of Physics and Astronomy, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland**
***e-mail: Guido.Burkard@unibas.ch**




Nature physics 3 192(2007)




IOP A community website from IOP Publishing

nanotechweb.org

SCIENCE • APPLICATIONS • INDUSTRY

Home | Newsdesk | From the journal | Events | Buyer's guide | Jobs | Links | Blog | Contact us

LATEST NEWS ARTICLES

- Nano-lens goes cup-shaped
- Ripple control improves graphene electronics
- Flexible fabric that 'takes pictures'
- Quantum-dot arrays produced in nanotubes
- Photonic circuits move on

TECHNOLOGY UPDATE

Oct 24, 2008

**Z-shaped result for quantum computing**

Graphene nanoribbon could be used to make qubits for next-generation quantum computers. So say researchers at the Key Laboratory of Quantum Information in Hefei, China, who have shown that z-shaped ribbons can store electrons or holes in the corners of their Zs, where they can be then be written or read to.

*G. P. Guo, et.al, arXiv:0808.1618*
*New J. Phys. 11 123005 (2009)*

# Quantum coherence time T1 and T2 for graphene QD

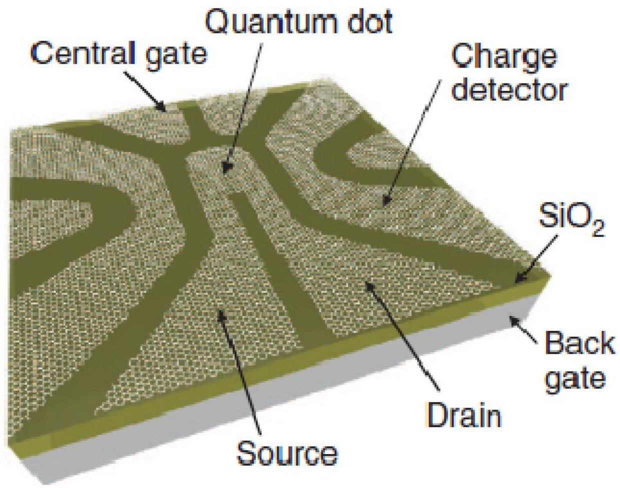
ARTICLE

Received 18 Oct 2012 | Accepted 14 Mar 2013 | Published 23 Apr 2013 DOI: 10.1038/ncomms2738 OPEN

## Probing relaxation times in graphene quantum dots

Christian Volk[1,2,*], Christoph Neumann[1,2,*], Sebastian Kazarski[1], Stefan Fringes[1], Stephan Engels[1,2], Federica Haupt[3], André Müller[1,2] & Christoph Stampfer[1,2]

A lower bound for charge excited state relaxation times on the order of 60–100 ns.




What is T2 for charge state ?

How about spin state ?

How to coupling distance graphene qubits ?

# A graphene quantum dot with a single electron transistor as an integrated charge sensor

nature asia-pacific

npg asia materials in association with TOKYO INSTITUTE OF TECHNOLOGY

home | current issue | highlights | archive | about | editorial committee | advisory b

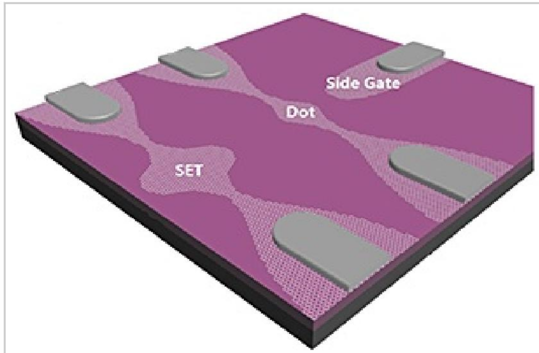
home » research highlight » Nanoelectronics: Quantum dots in charge

*NPG Asia Materials* research highlight | doi:10.1038/asiamat.2011.34
Published online 28 February 2011

## Nanoelectronics: Quantum dots in charge

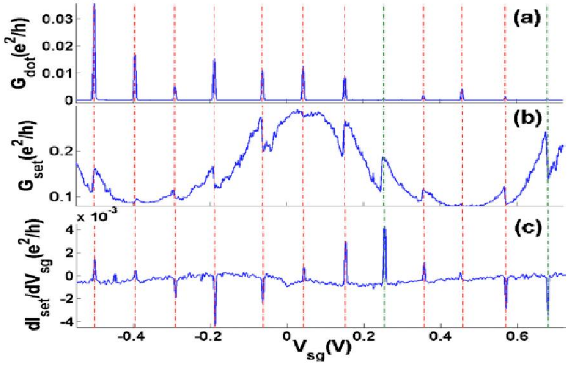
**Paired graphene quantum dots could form the basis for an electron-counting information storage system.**

Quantum dots could one day be used as solid-state quantum bits for quantum information processing. The information in a quantum dot would be encoded in the charge, spin or degree of freedom of electrons, and be read using ultrasensitive charge and spin detectors. A collaborative study between the University of Science and Technology of China and the University of California, Los Angeles, USA, has now demonstrated an integrated charge sensor system based on twin graphene dots[1], raising the hope that graphene's advantageous electronic and structural properties could serve for the future development of quantum information processing technologies.

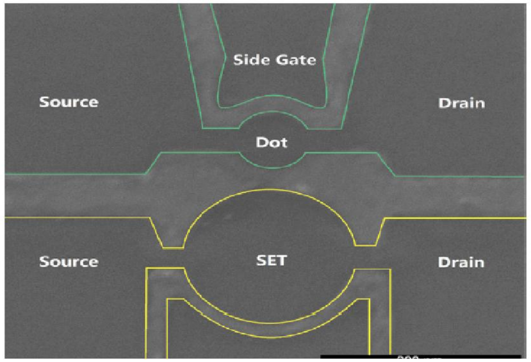


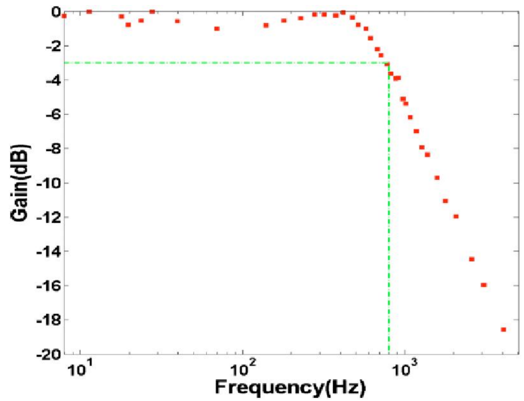

Schematic illustration of an integrated charge-sensing system based on a pair of quantum dots






(a)



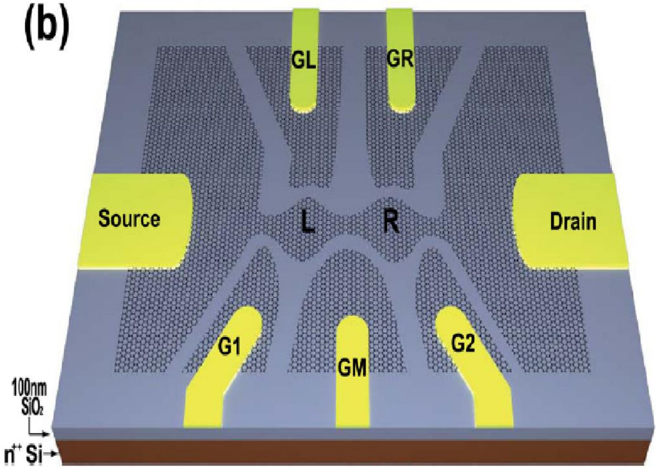

*L. J. Wang, et.al. Appl. Phys. Lett. 97, 262113 (2010).*

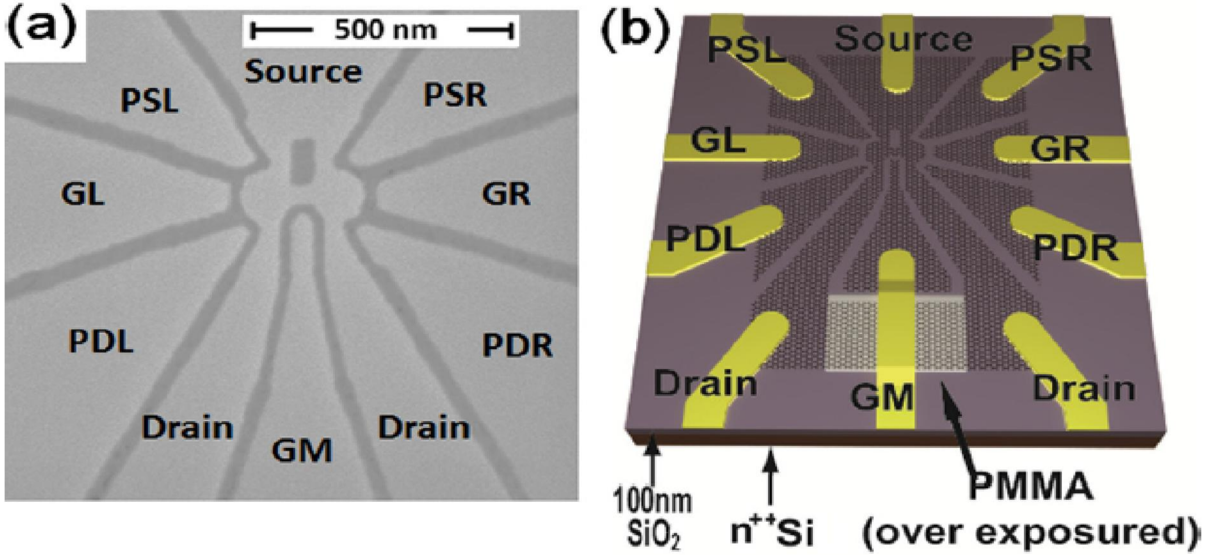
# Graphene double quantum dot in series and in parallel

APPLIED PHYSICS LETTERS **99**, 112117 (2011)

## Gates controlled parallel-coupled double quantum dot on both single layer and bilayer graphene

Lin-Jun Wang,[1] Guo-Ping Guo,[1,a)] Da Wei,[1] Gang Cao,[1] Tao Tu,[1,b)] Ming Xiao,[1]
Guang-Can Guo,[1] and A. M. Chang[2]
[1]*Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, People's Republic of China*
[2]*Department of Physics, Duke University, Durham, North Carolina 27708, USA*



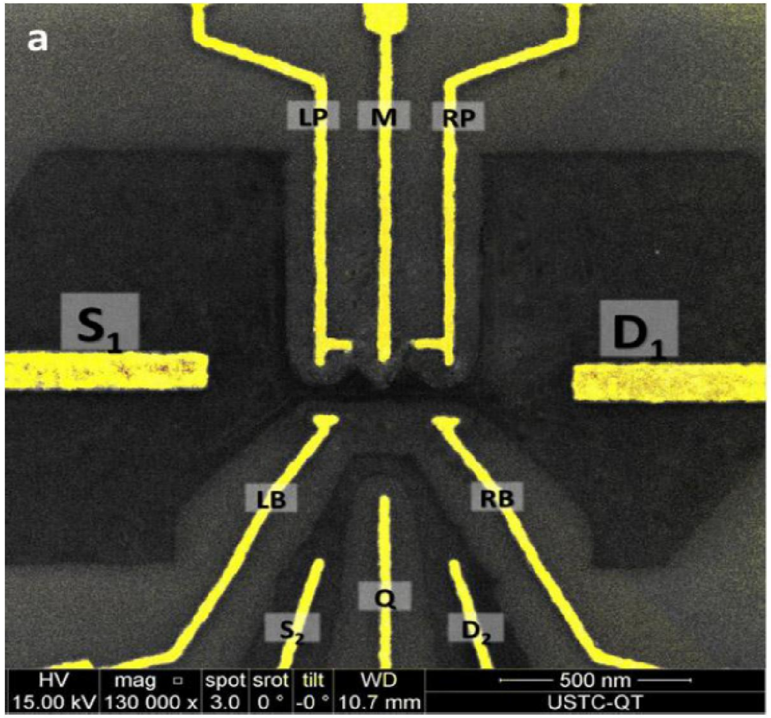



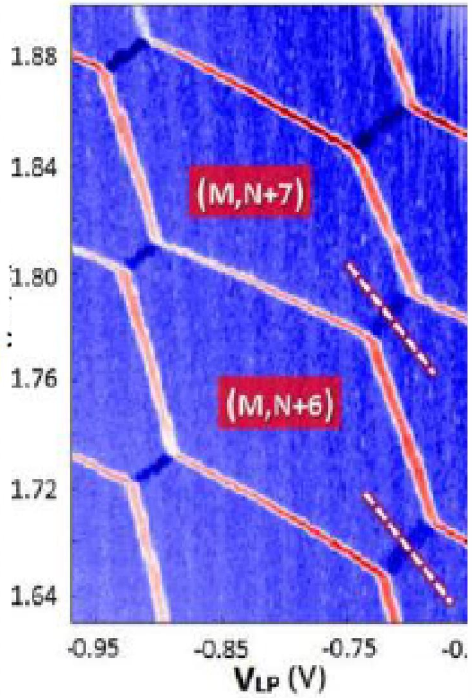

APPLIED PHYSICS LETTERS **100**, 022106 (2012)

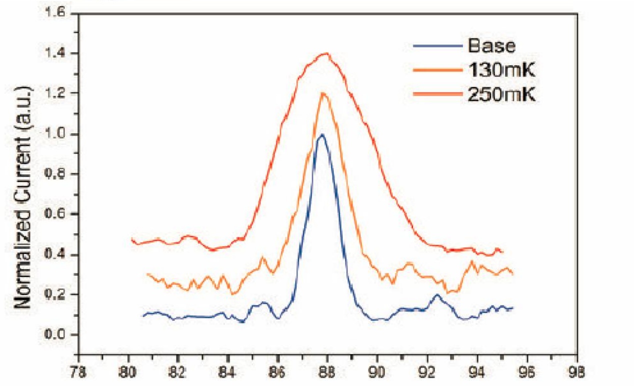
## Controllable tunnel coupling and molecular states in a graphene double quantum dot

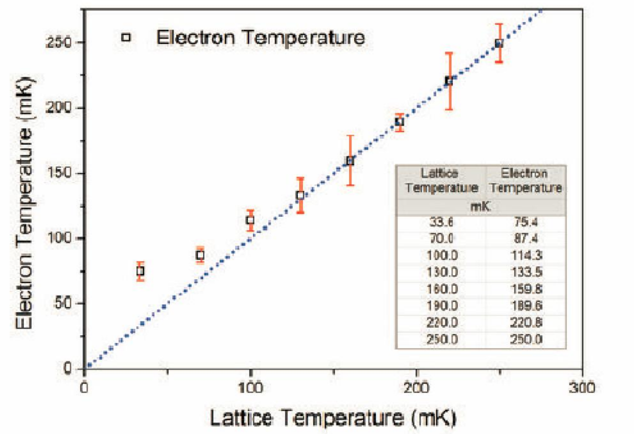
Lin-Jun Wang,[1] Hai-Ou Li,[1] Tao Tu,[1,a)] Gang Cao,[1] Cheng Zhou,[1] Xiao-Jie Hao,[1] Zhan Su,[1]
Ming Xiao,[1] Guang-Can Guo,[1] Albert M. Chang,[2] and Guo-Ping Guo[1,b)]
[1]*Key Laboratory of Quantum Information, University of Science and Technology of China, Chinese Academy of Sciences, Hefei 230026, People's Republic of China*
[2]*Department of Physics, Duke University, Durham, North Carolina 27708, USA*

# 金属电极石墨烯双量子点



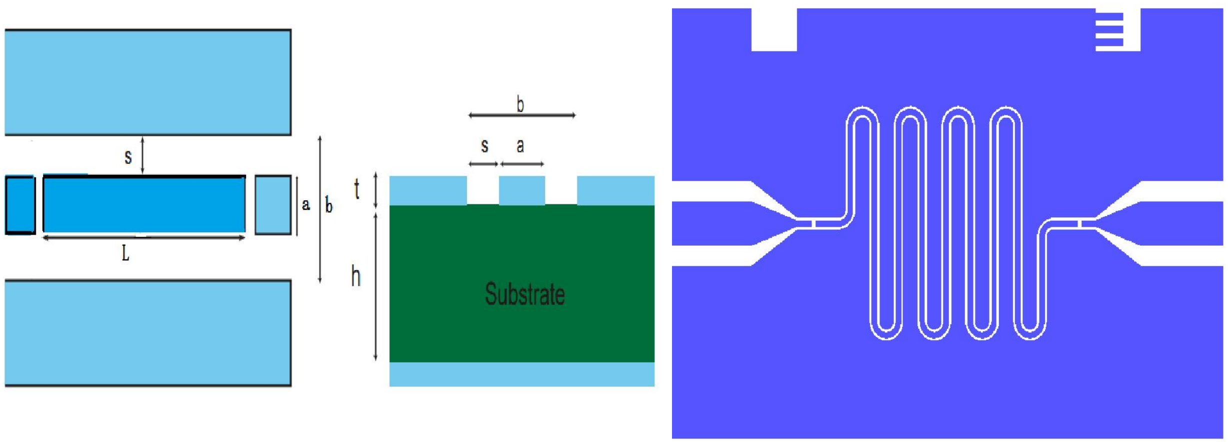




**全金属电极：克服石墨烯电极边缘态的影响**

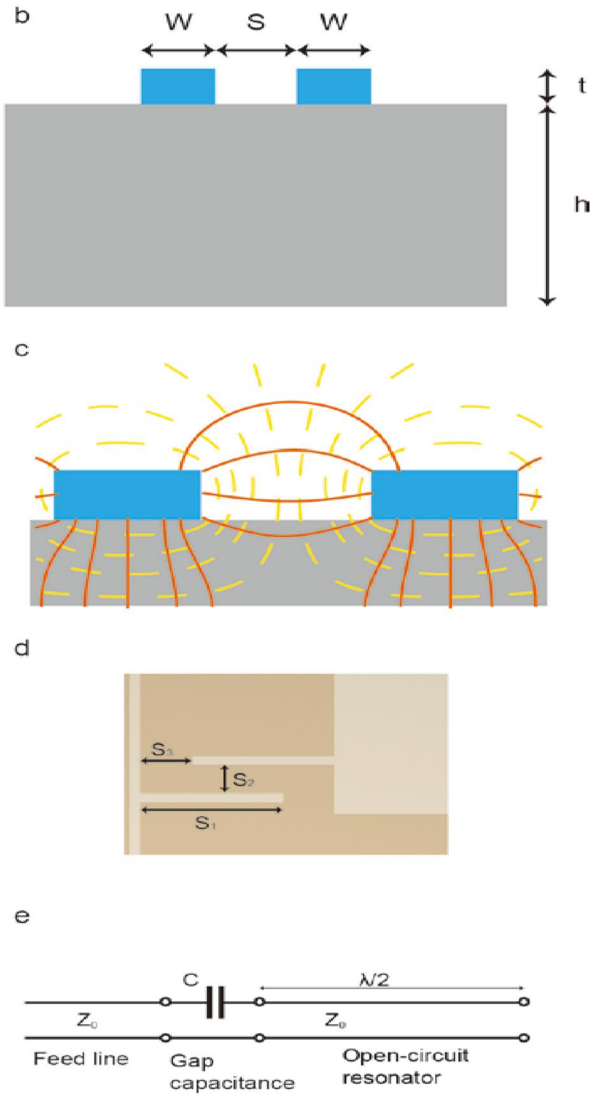
Scientific Reports 3, 3175 (2013)

# Symmetric reflection line resonator (RLR)

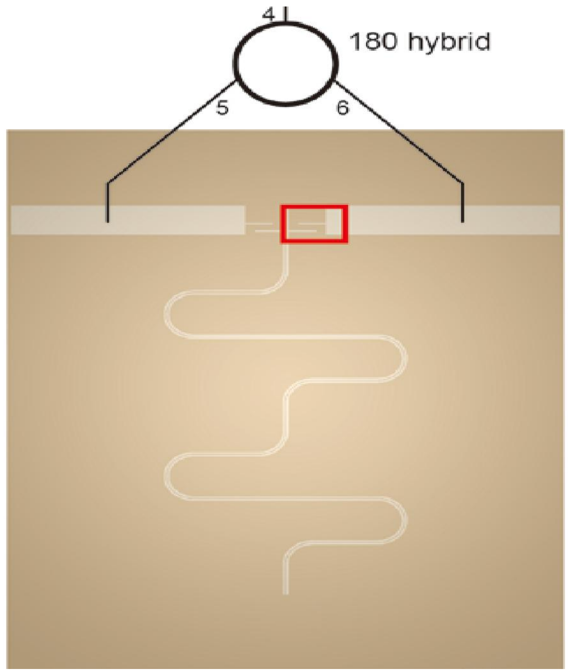
**Transmission line resonator (TLR)**



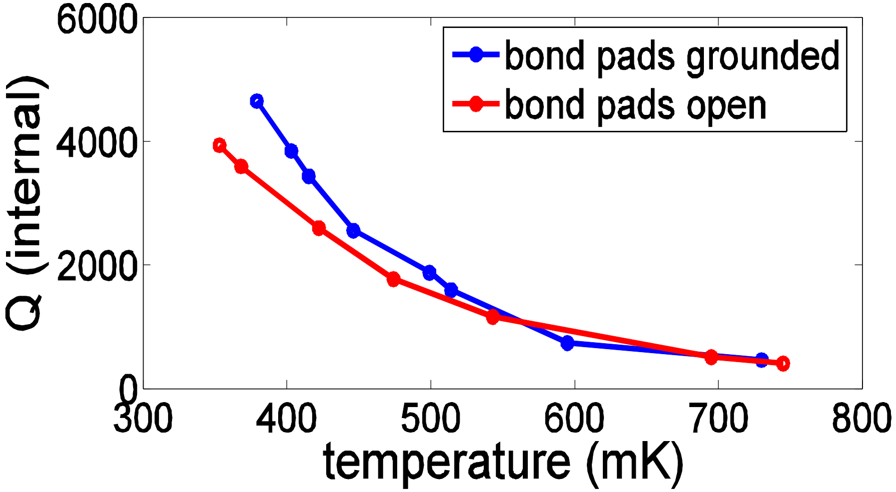

**Our reflection line resonator (RLR)**

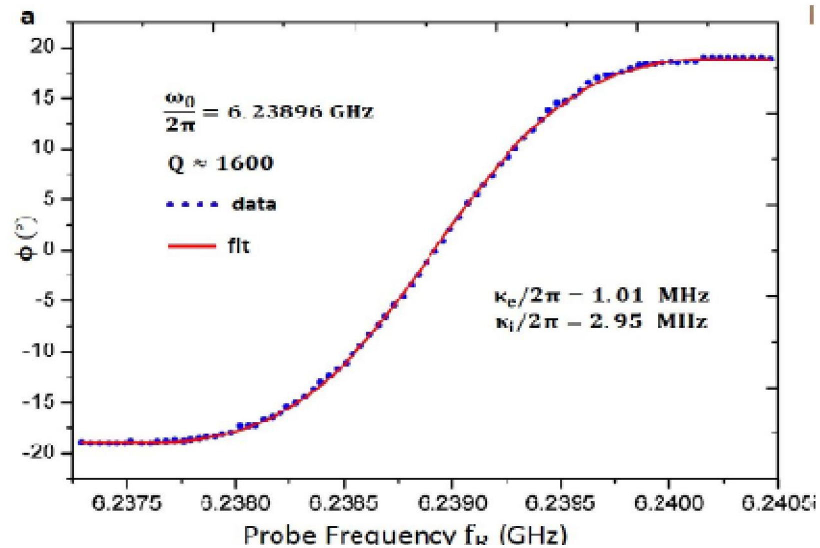


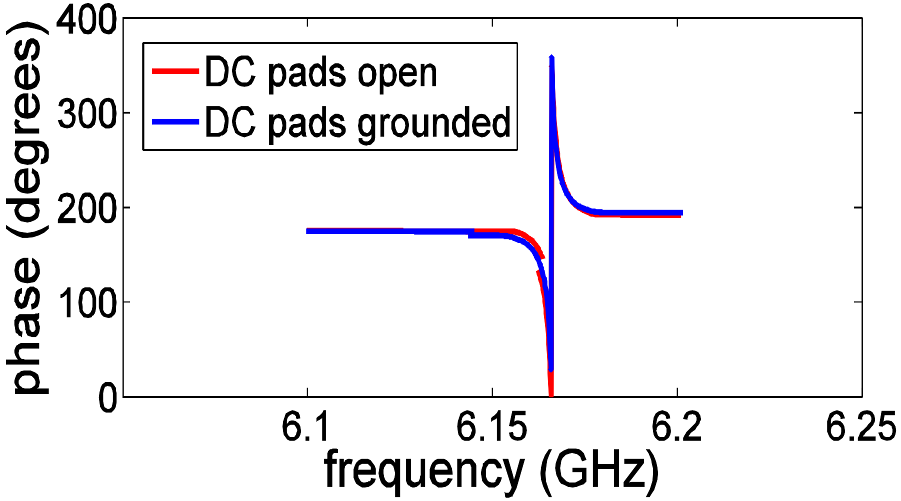

- 1/2 or 1/4 wavelength **reflection** line resonator
- **Two** coplanar strip-lines geometry
- Coupling strength is expected to be **double**
- **Bias T** for **independent** DC bias of either side

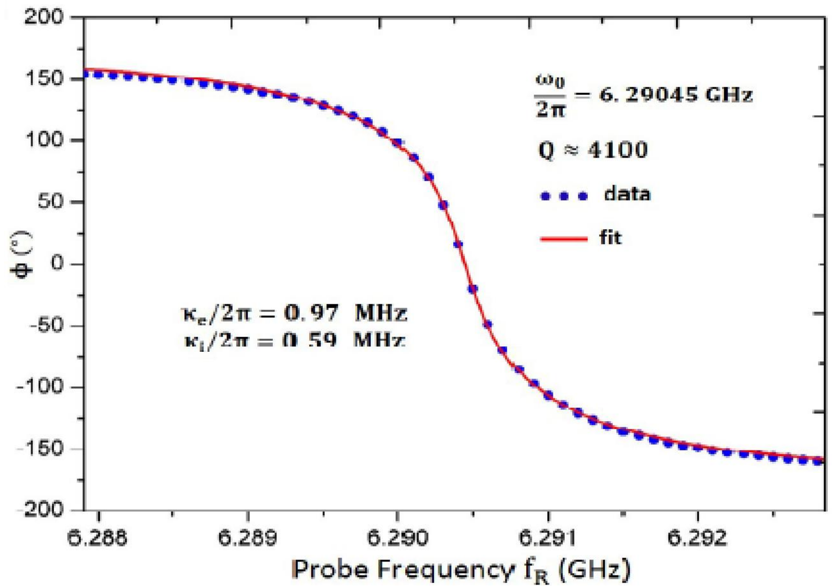


# The property of reflection line resonator



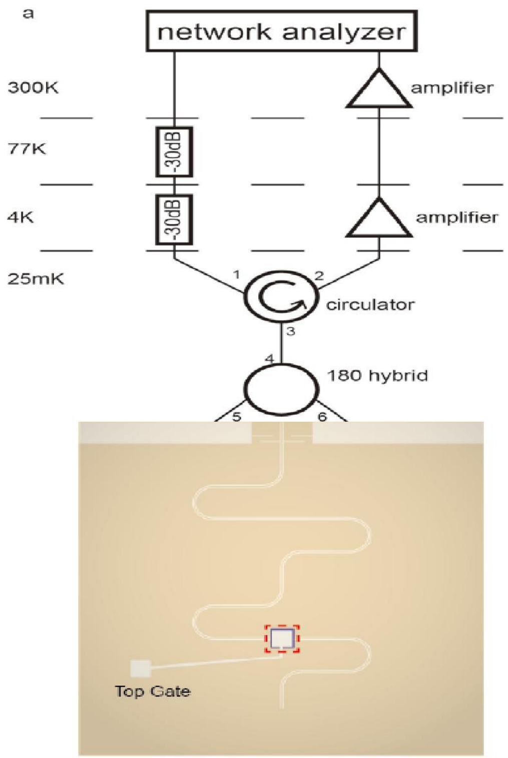



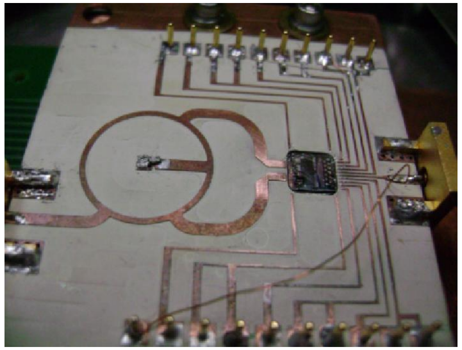



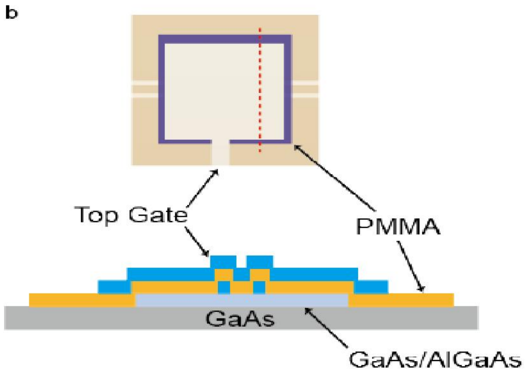



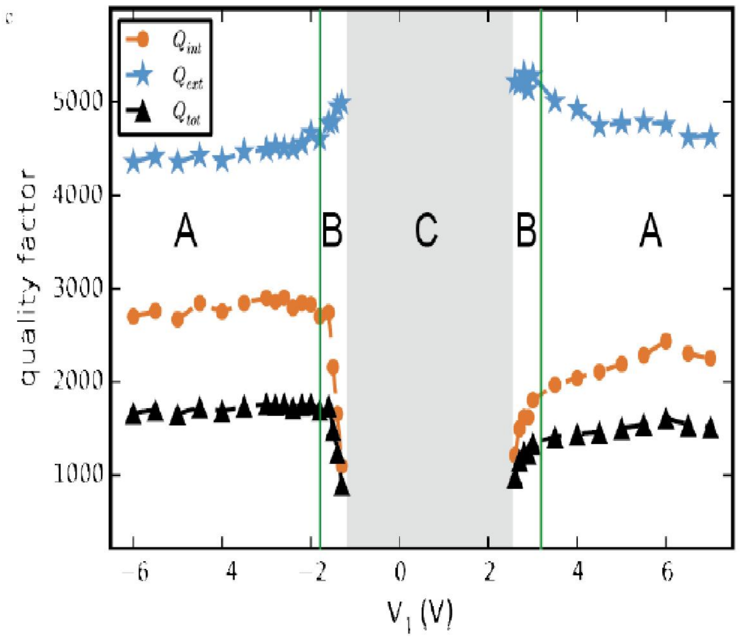

**The effect of DC pads, temperature, and dissipation to the cavity properties.**

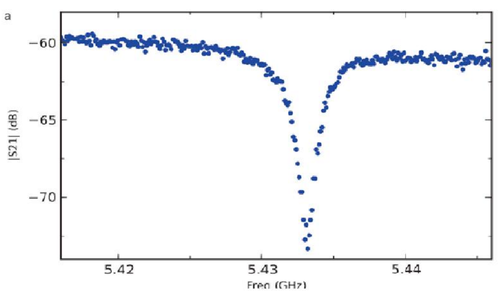
# Tuning the Q factor of Symmetric reflection line resonator

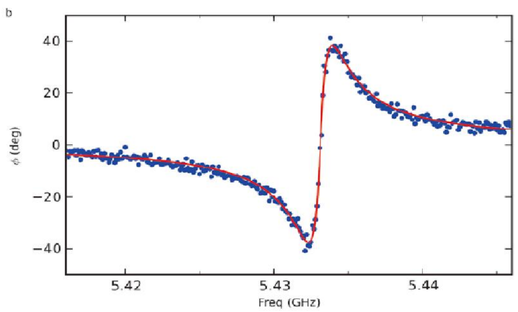


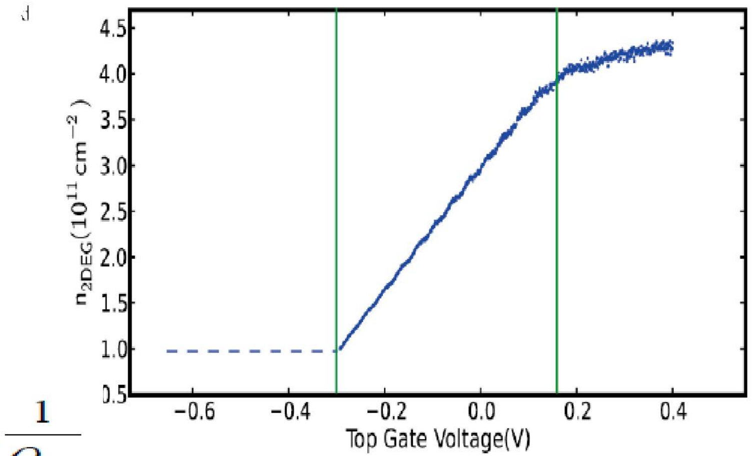






$$\frac{1}{Q_L} = \frac{1}{Q_{int}} + \frac{1}{Q_{ext}}$$

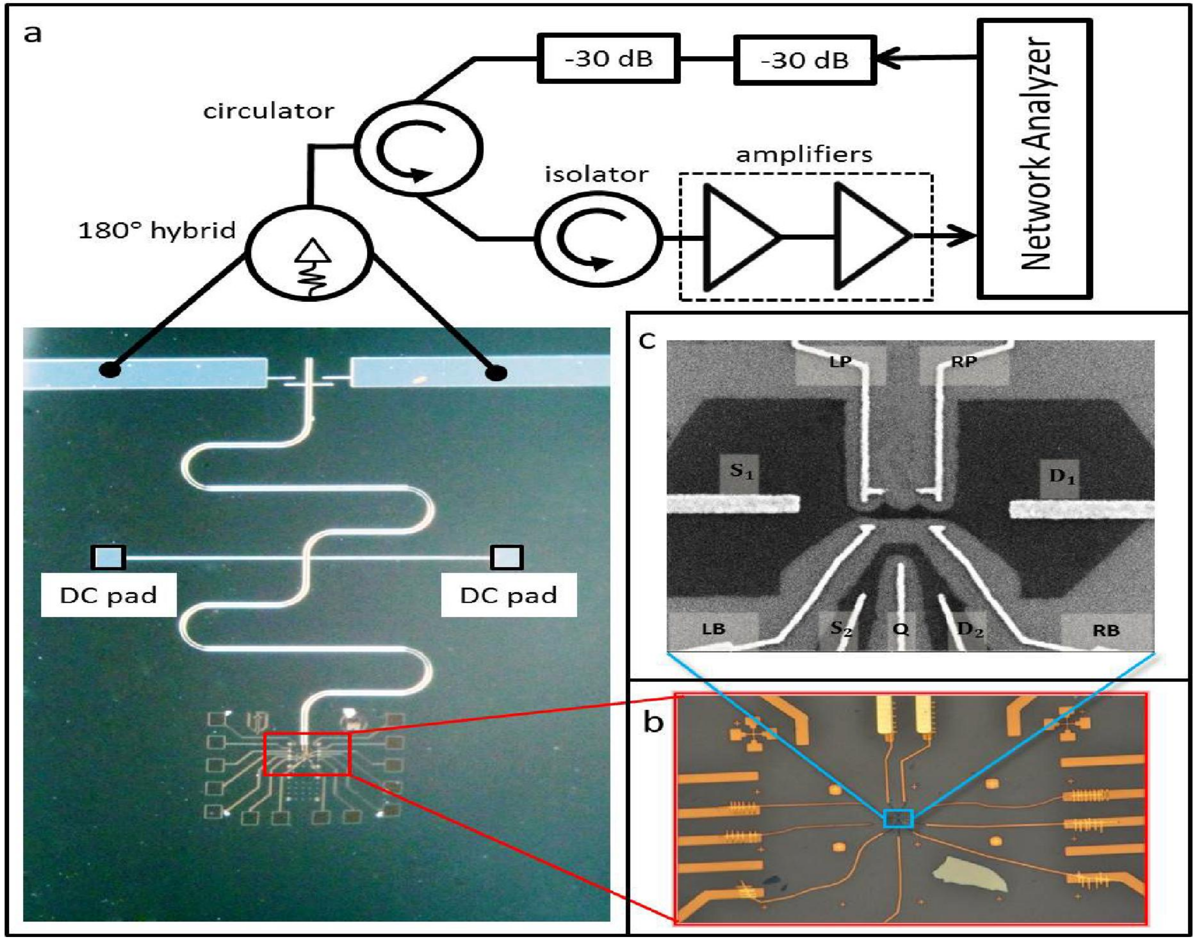
M. L. Zhang, et.al, APL 104,083511 (2014).
M. L. Zhang, et.al, APL 105,073510 (2014).

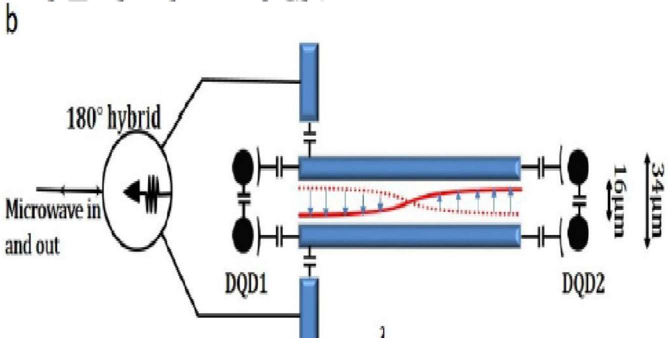
# 石墨烯量子点与超导谐振腔复合系统

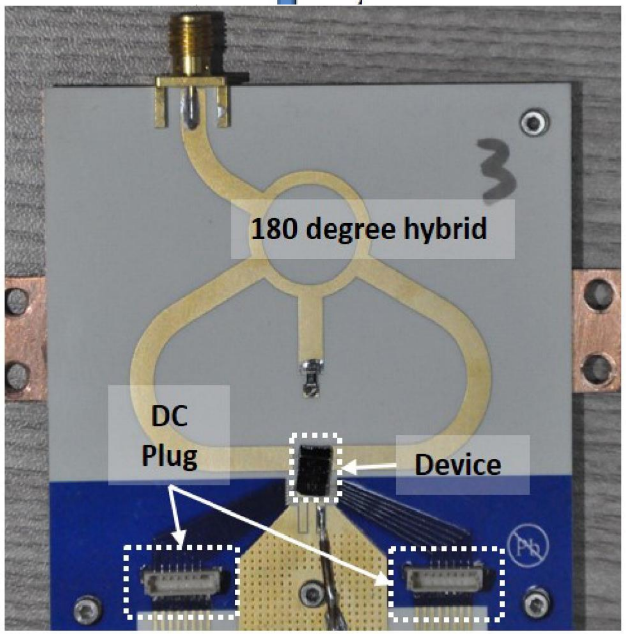
PRL 115, 126804 (2015) PHYSICAL REVIEW LETTERS week ending 18 SEPTEMBER 2015

**Charge Number Dependence of the Dephasing Rates of a Graphene Double Quantum Dot in a Circuit QED Architecture**

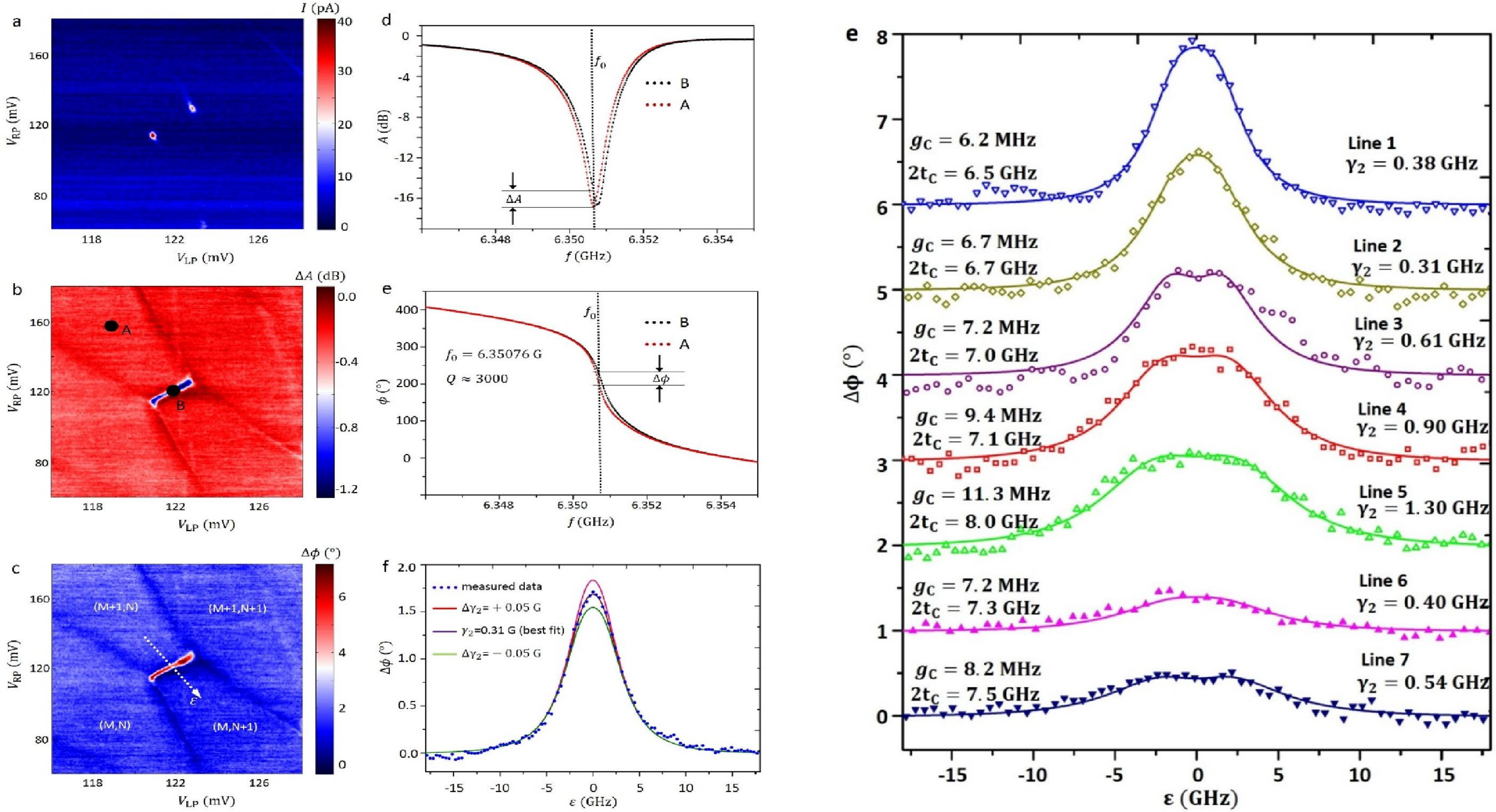
Guang-Wei Deng,[1,2] Da Wei,[1,2] J. R. Johansson,[3] Miao-Lei Zhang,[1,2] Shu-Xiao Li,[1,2] Hai-Ou Li,[1,2] Gang Cao,[1,2] Ming Xiao,[1,2] Tao Tu,[1,2] Guang-Can Guo,[1,2] Hong-Wen Jiang,[4] Franco Nori,[5,6] and Guo-Ping Guo[1,2,*]



# 石墨烯量子点与超导谐振腔复合系统

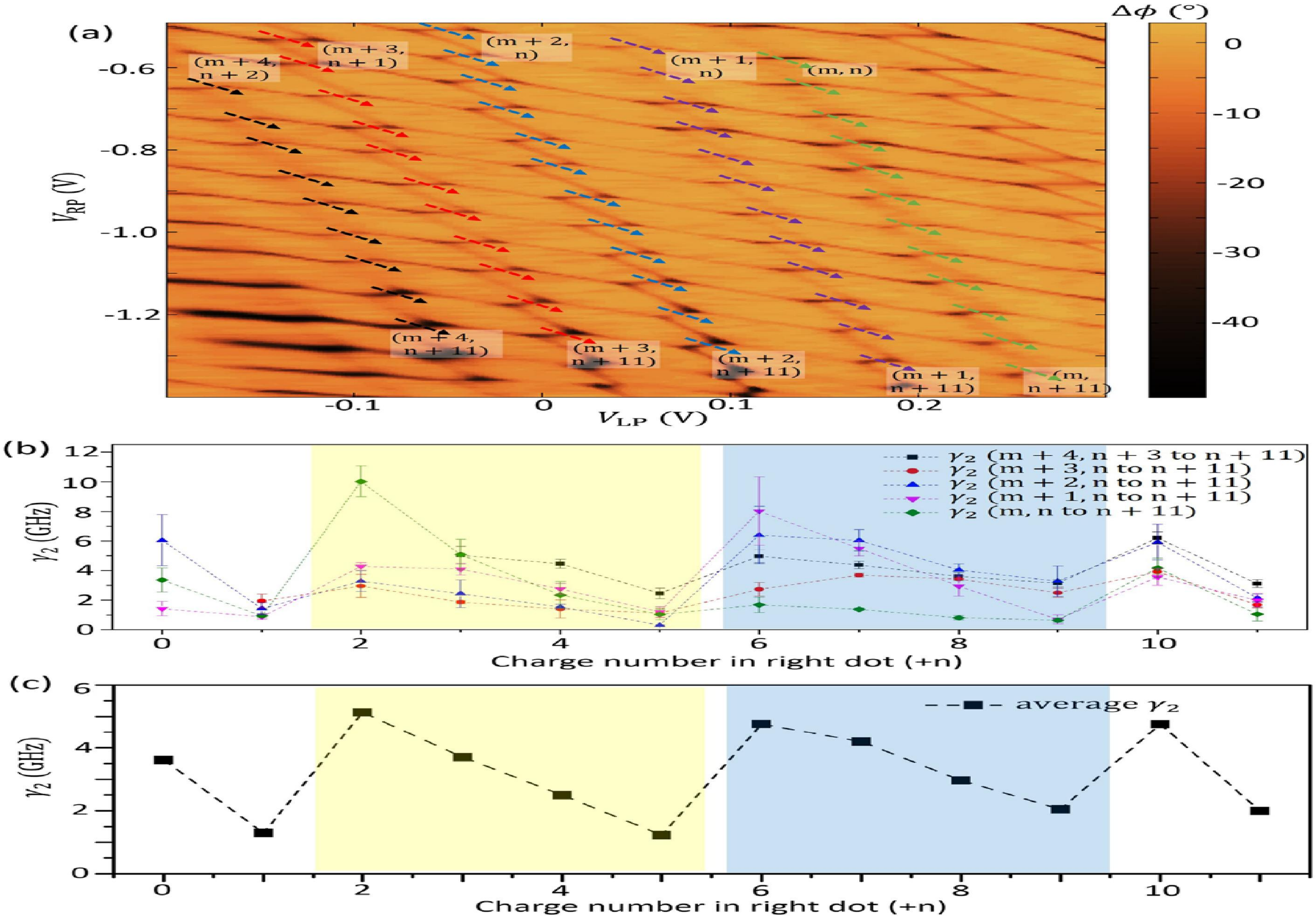



$$S_{11} = \frac{a_{\text{out}}}{a_{\text{in}}} = -\frac{i(\omega_0 - \omega) + g_{\text{eff}}\chi + \frac{\kappa_i - \kappa_e}{2}}{i(\omega_0 - \omega) + g_{\text{eff}}\chi + \frac{\kappa_i + \kappa_e}{2}},$$

$$g_{\text{eff}} = g_C \frac{2t_C}{\Omega}$$

$$\chi = \frac{g_{\text{eff}}}{i(\Omega - \omega) + \frac{1}{2}\gamma_1 + \gamma_2}. \quad \Omega = \sqrt{(2t_C)^2 + \epsilon^2}$$

# 石墨烯量子点与超导谐振腔复合系统



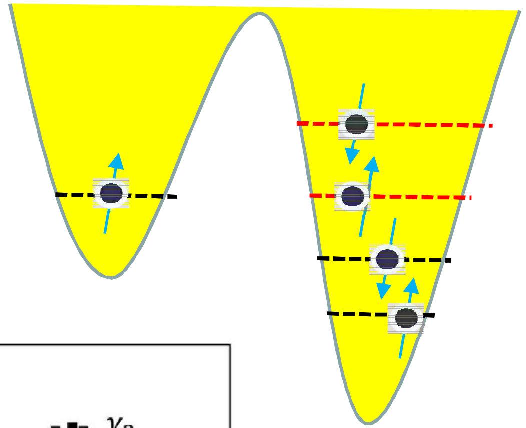
# 石墨烯量子点与超导谐振腔复合系统

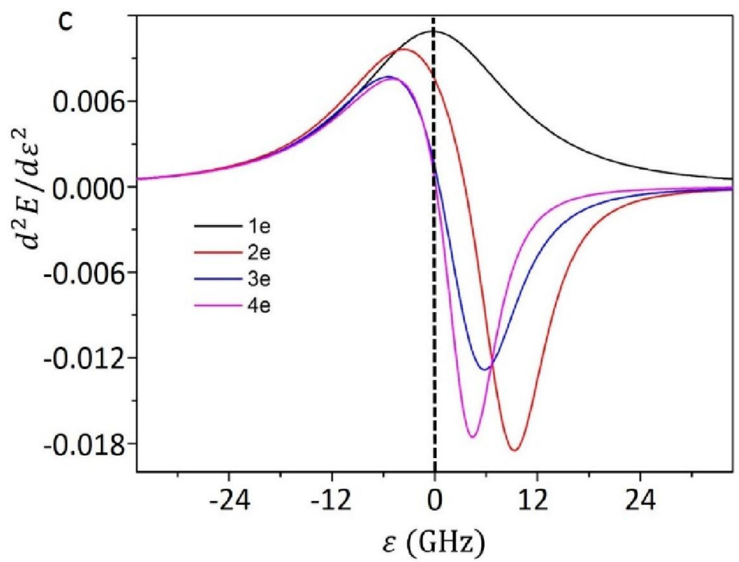
## 相干时间与能级差的偏倒数成正比：

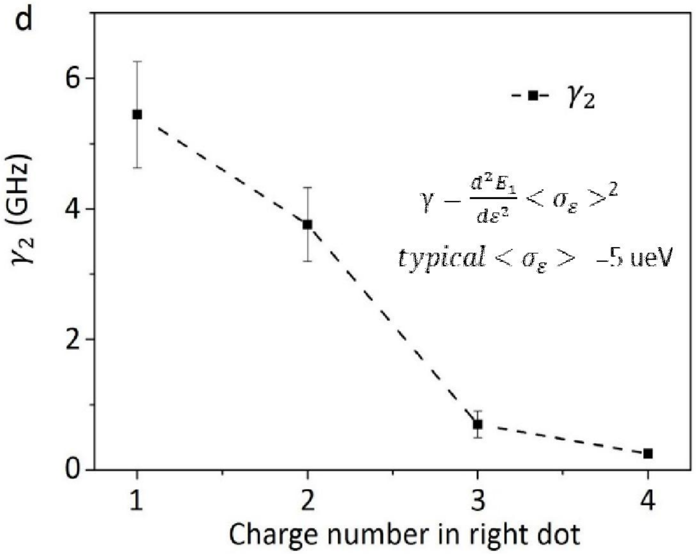
**PRL 108, 046807 (2012), PPL 105,063105 (2014), PRB 89, 165404 (2014)**

$\Omega(\delta, t) = \sqrt{\delta^2 + (2t)^2)}$ dephasing rate via the

$\gamma_\varphi / 2\pi \approx \frac{d^2\Omega}{d\delta^2}|_{\delta=0} S_\delta(\nu = 1\,\mathrm{Hz}) = S_\delta(\nu = 1\,Hz)/2t.$





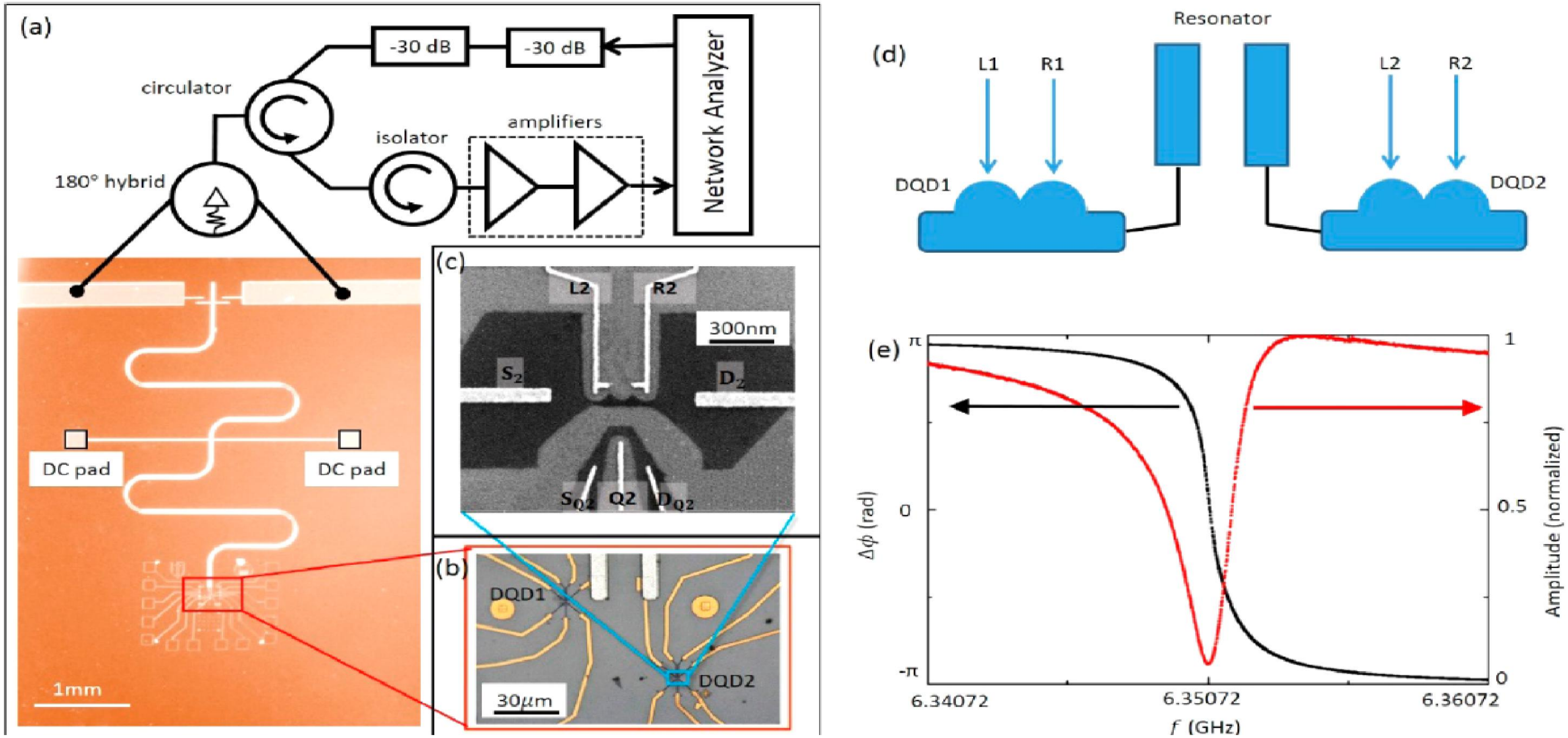



# 石墨烯量子比特的长程耦合

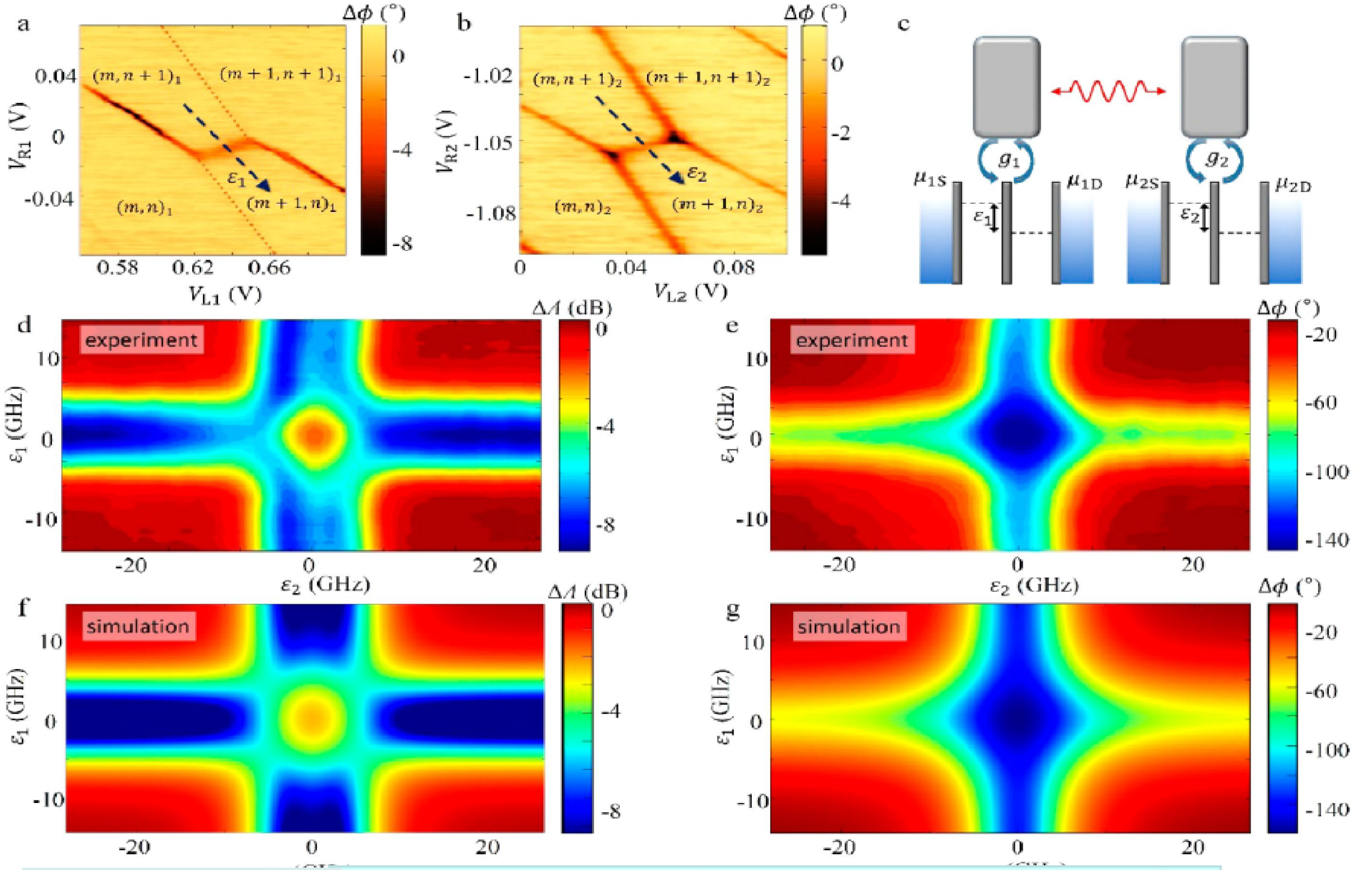
NANO LETTERS
Letter
pubs.acs.org/NanoLett

## Coupling Two Distant Double Quantum Dots with a Microwave Resonator

Guang-Wei Deng,[†,‡] Da Wei,[†,‡] Shu-Xiao Li,[†,‡] J. R. Johansson,[§] Wei-Cheng Kong,[†,‡] Hai-Ou Li,[†,‡] Gang Cao,[†,‡] Ming Xiao,[†,‡] Guang-Can Guo,[†,‡] Franco Nori,[∥,⊥] Hong-Wen Jiang,[#] and Guo-Ping Guo[*,†,‡]

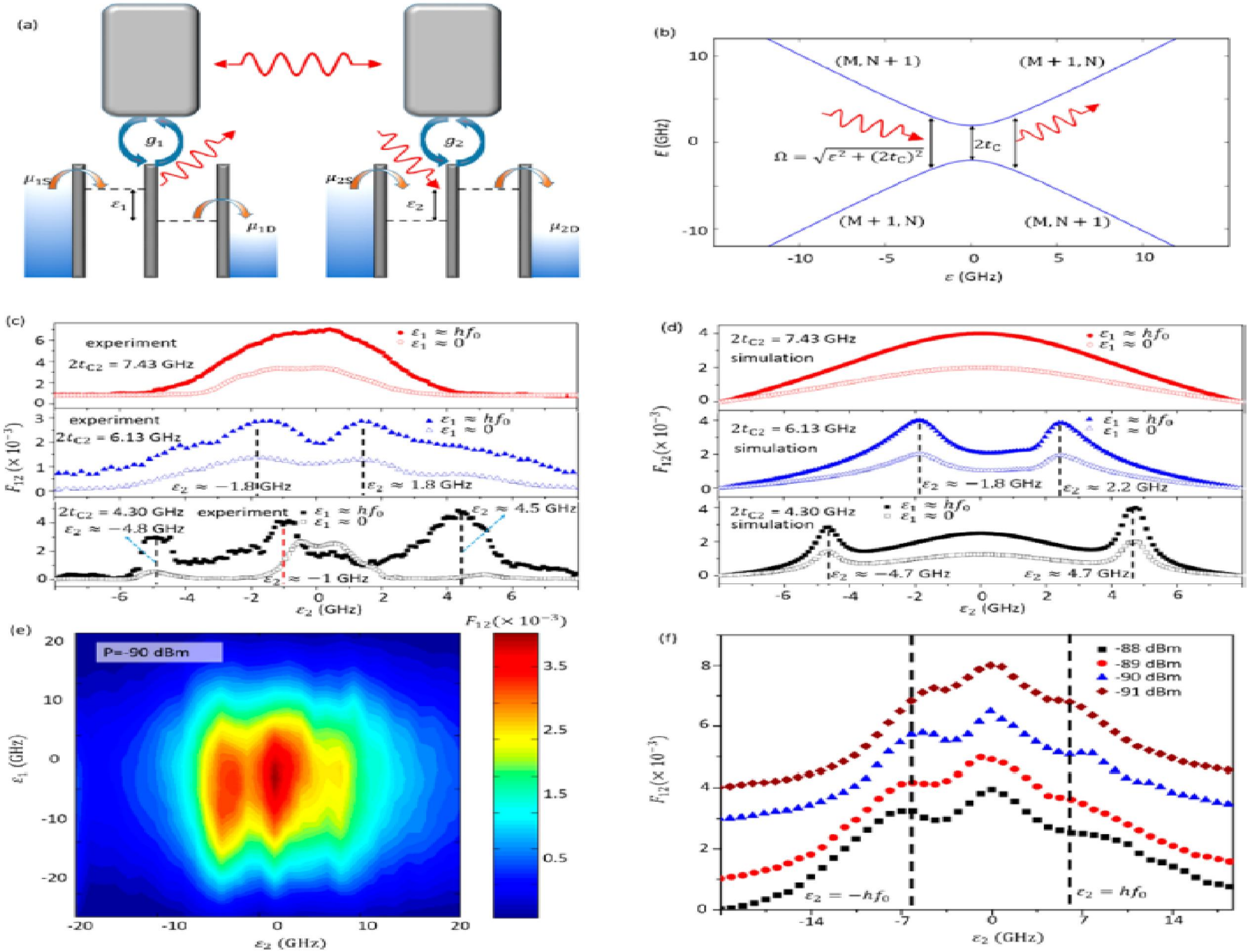


# 石墨烯量子比特的长程耦合

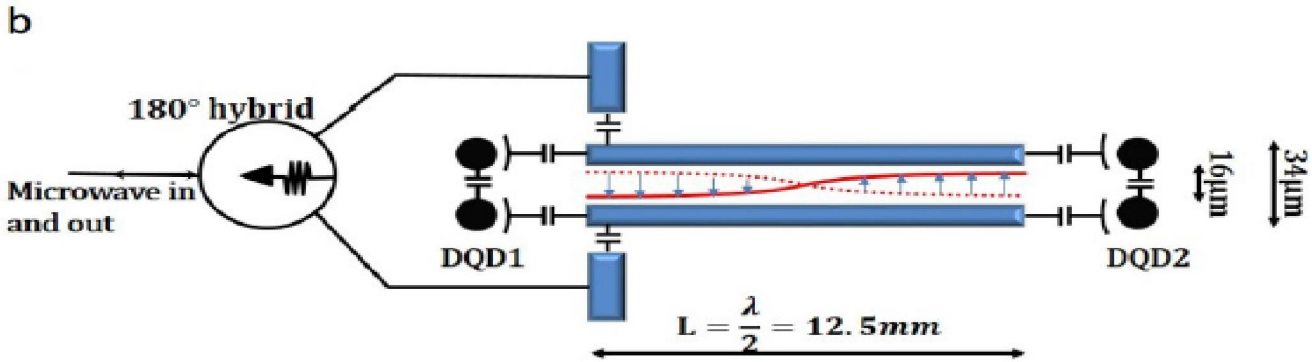


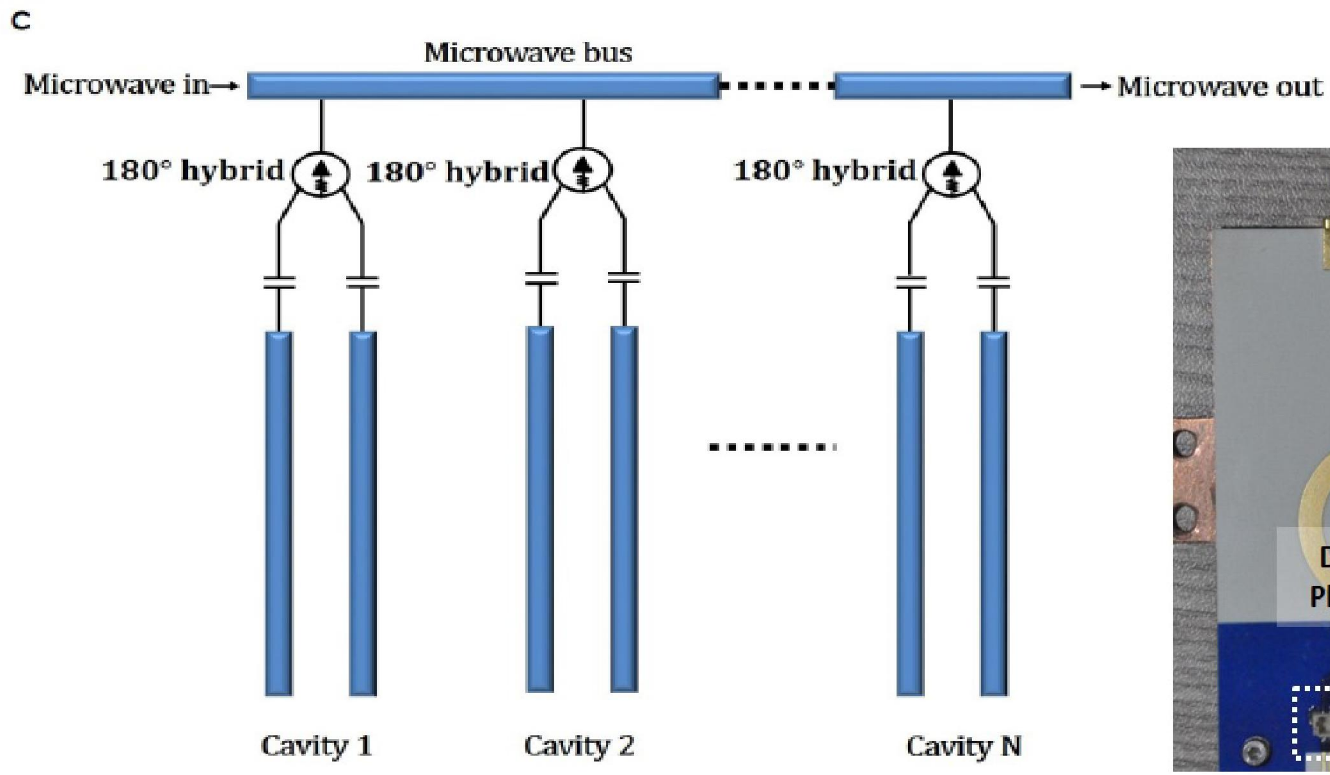

**T-C Hamiltonian:** $H = \omega_0 a^\dagger a + \sum_{i=1,2} \left[ \frac{1}{2}\Omega_i \sigma_{zi} + g_i(\sigma_{+i} a + \sigma_{-i} a^\dagger) \right]$

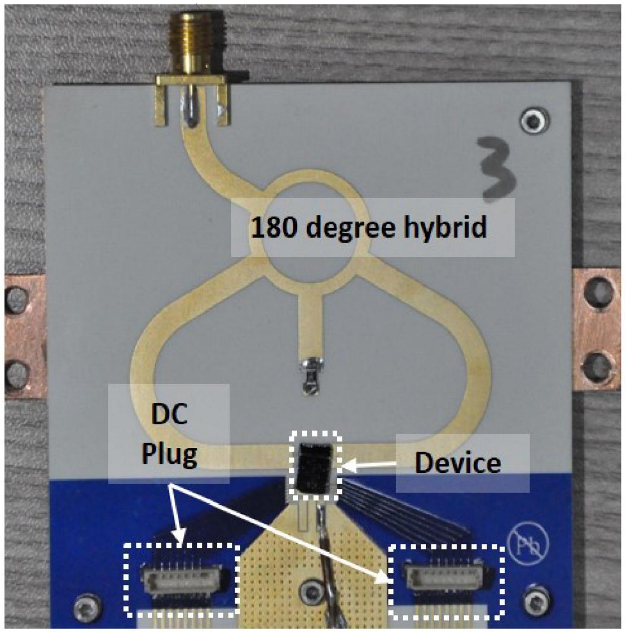
# 石墨烯量子比特的长程耦合



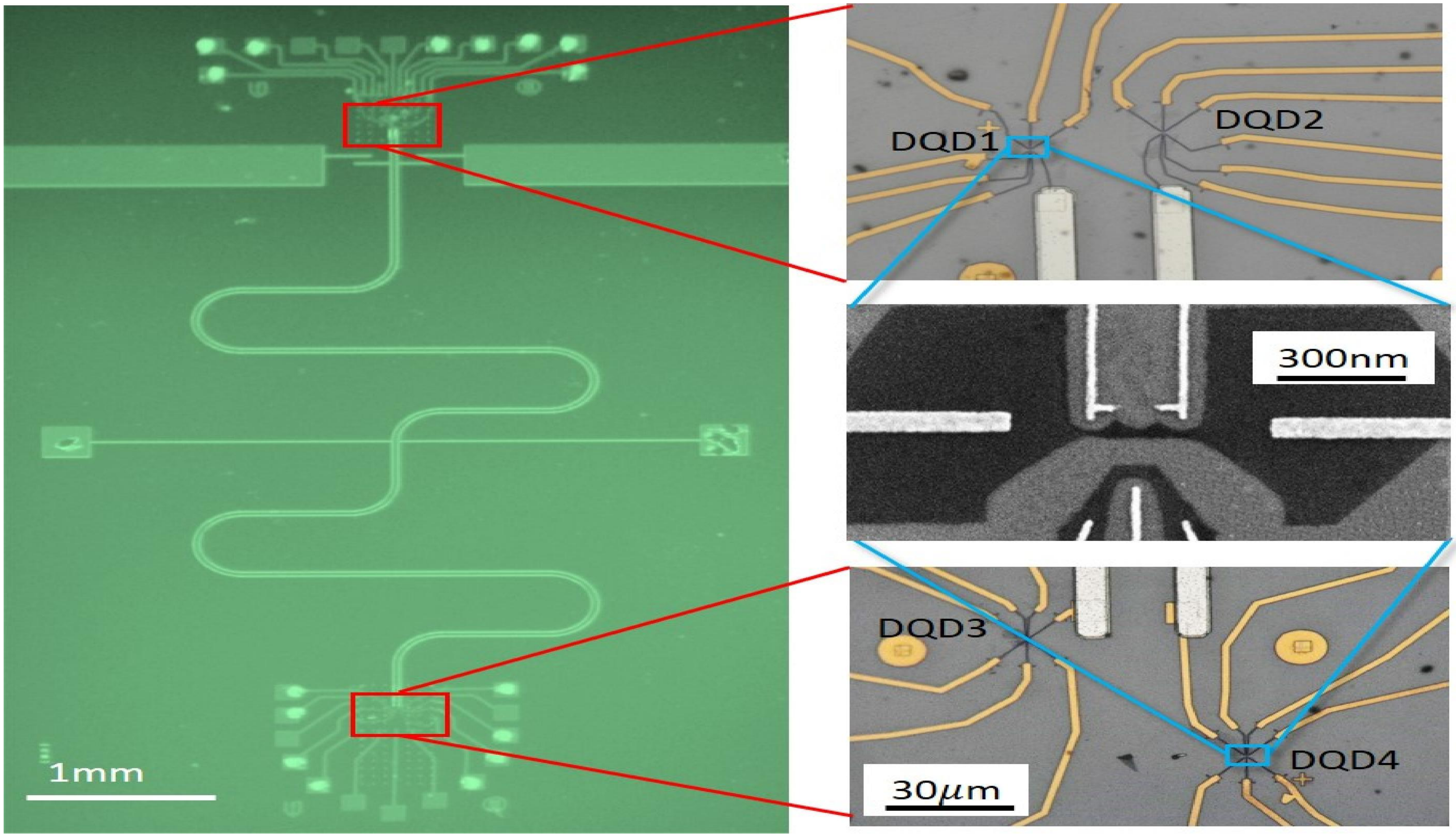
# 量子数据线和量子比特的长程耦合



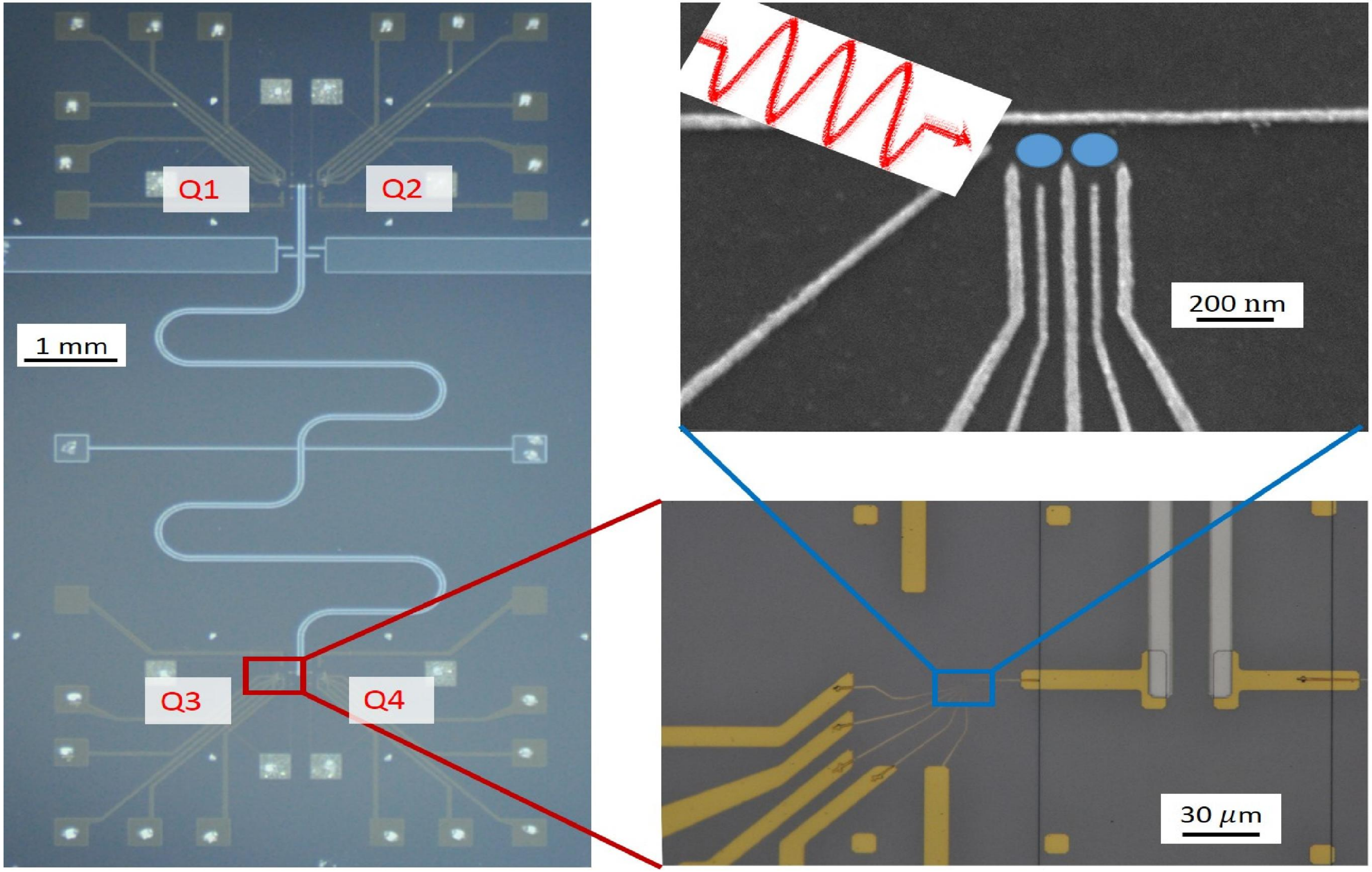



# 量子数据线和量子比特的长程耦合

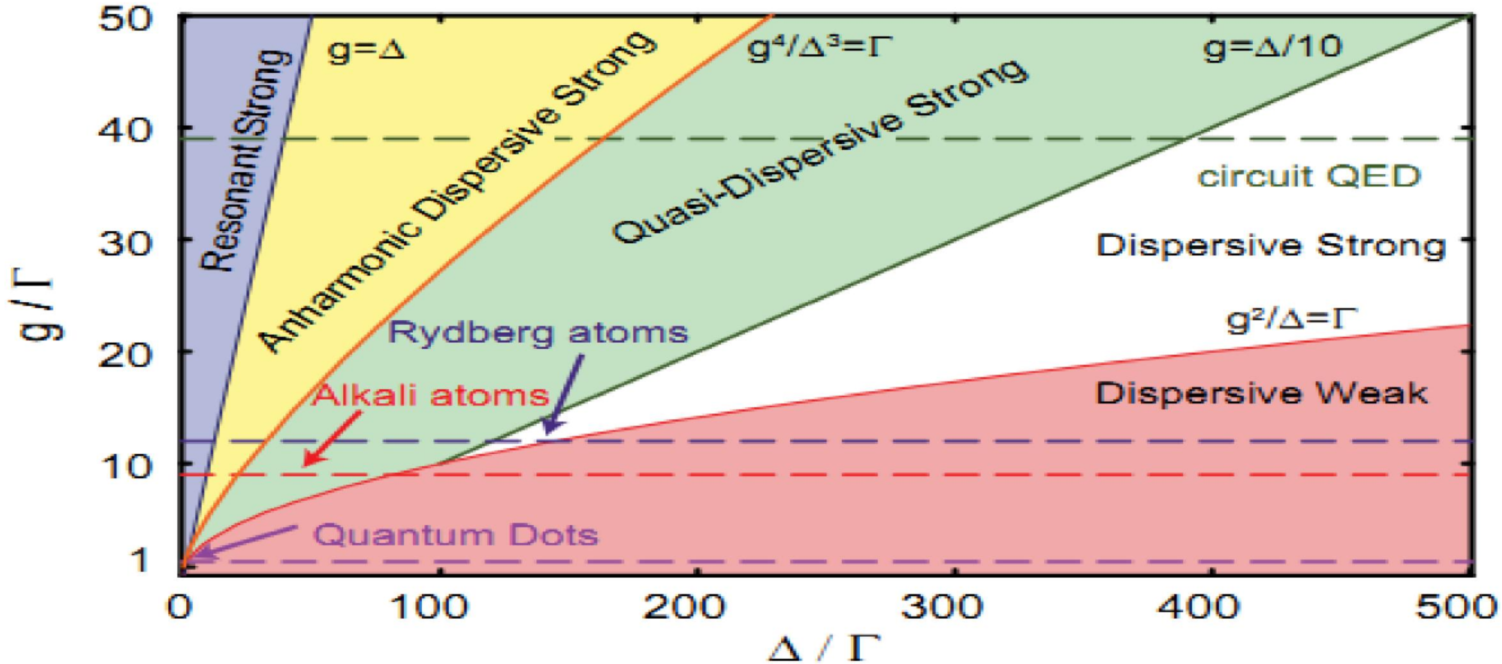


# 量子数据线和量子比特的长程耦合



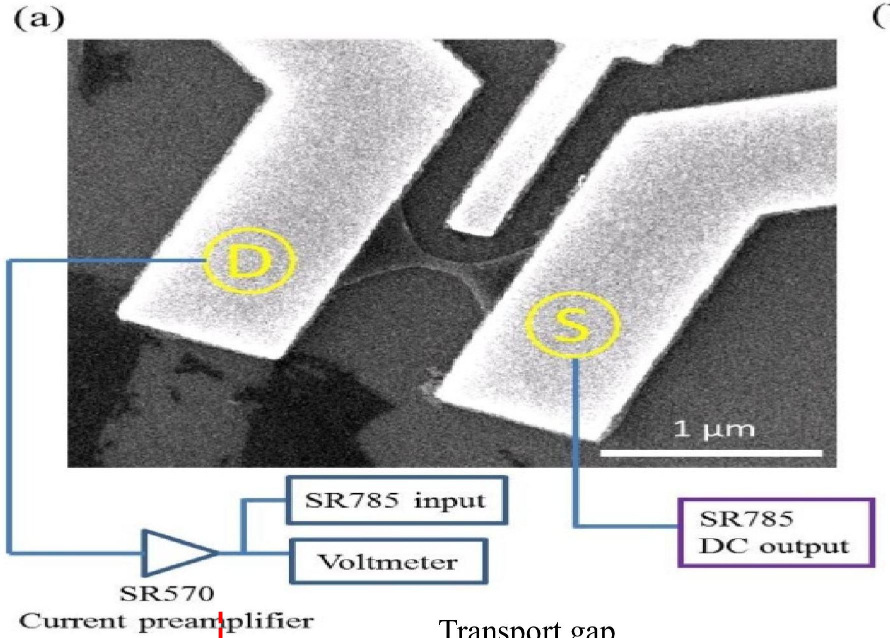
# 量子数据线和量子比特的长程耦合

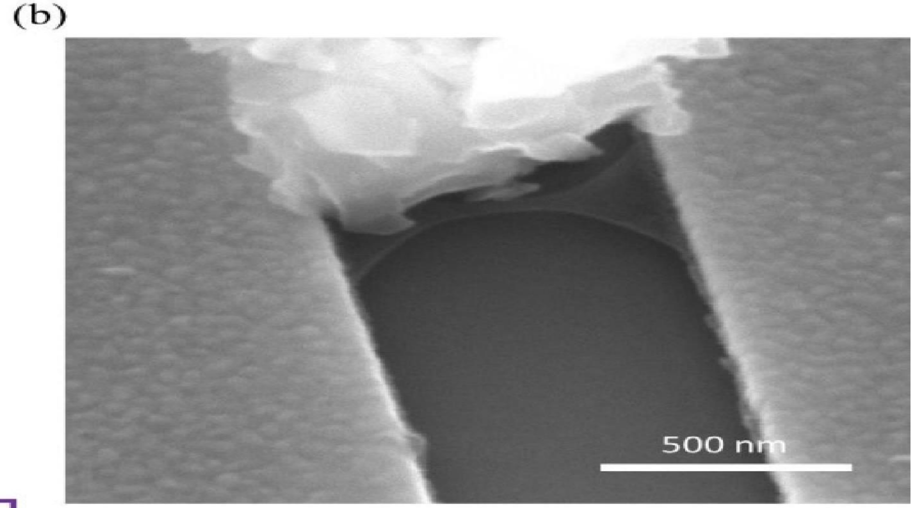
- Cavity decay $\kappa$～～3 MHz
- Quantum dot: **T1 ~~ 10ns, T2 ~~ 1ns**
- (**Where is transmon mode for QD ?** )
- Coupling strength g ~~50M



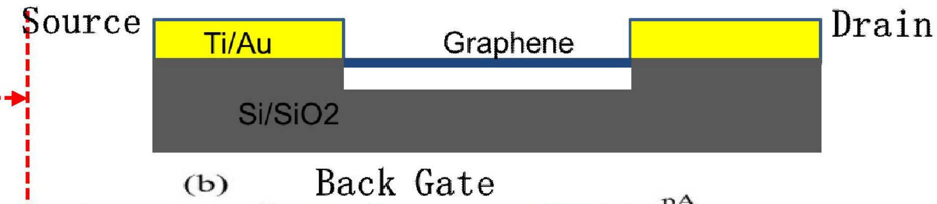

**Quantum Information in dispersive region for QD CQED ?**
G.-P. Guo, Phys. Rev. A 78, 020302 (2008). Phys. Rev. Lett. 101, 230501 (2008).

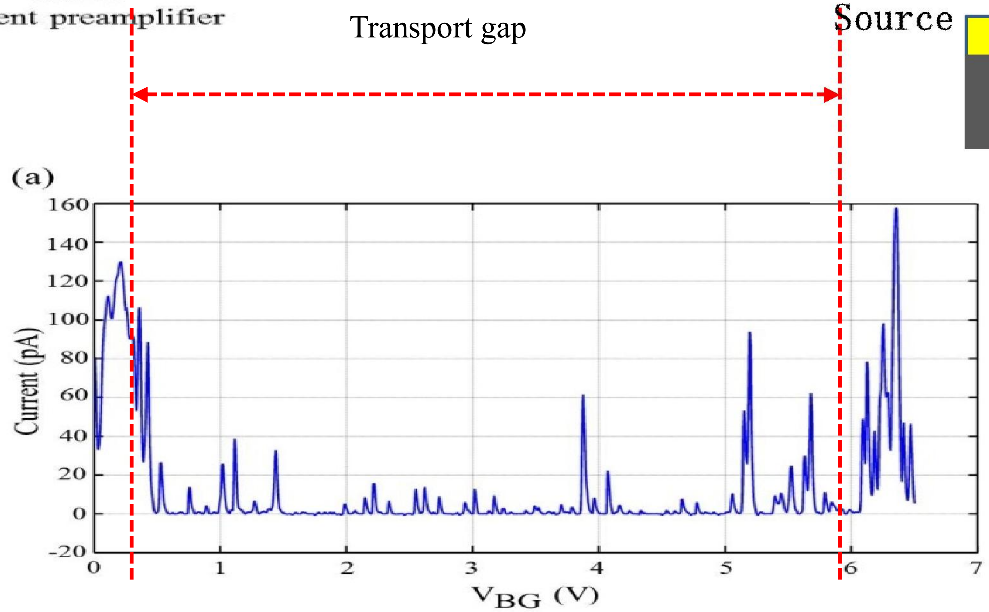
# 悬浮石墨烯量子点

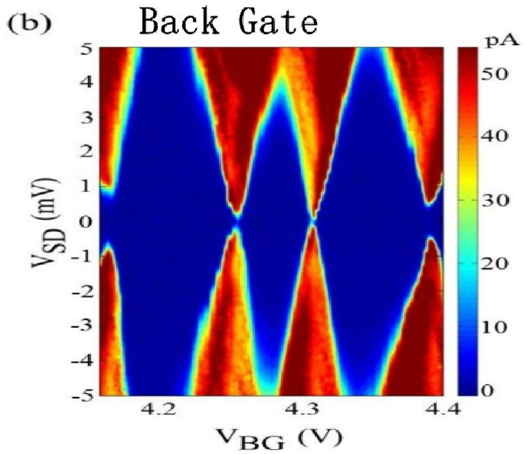



**Floating graphene noise measurement**



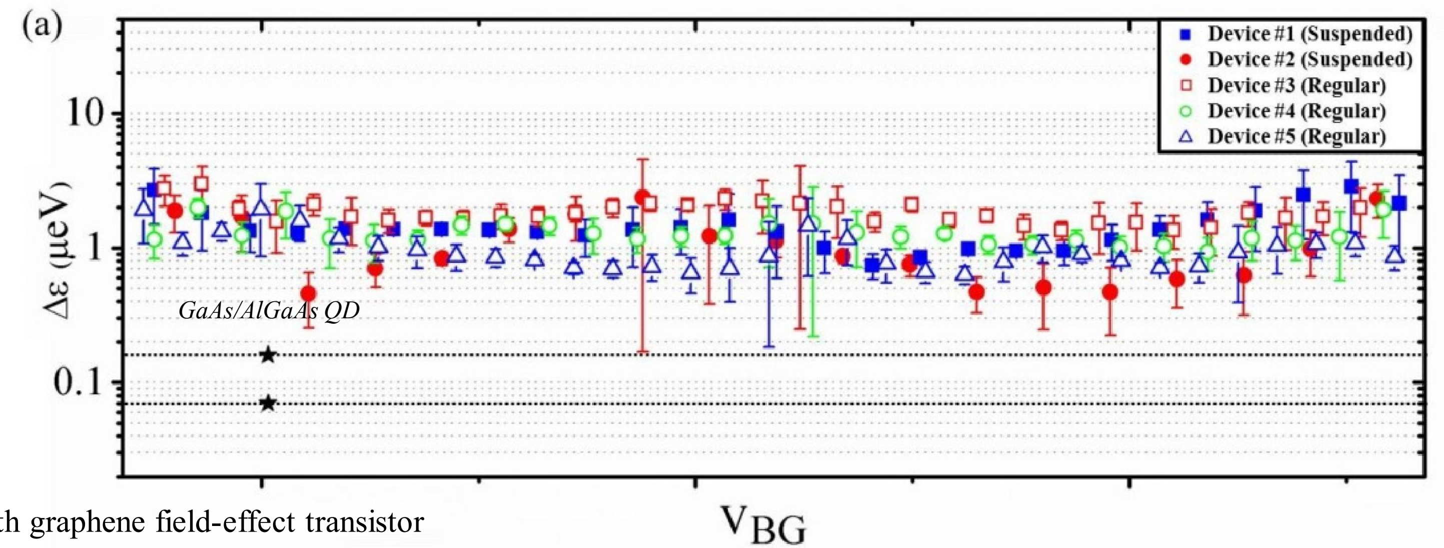



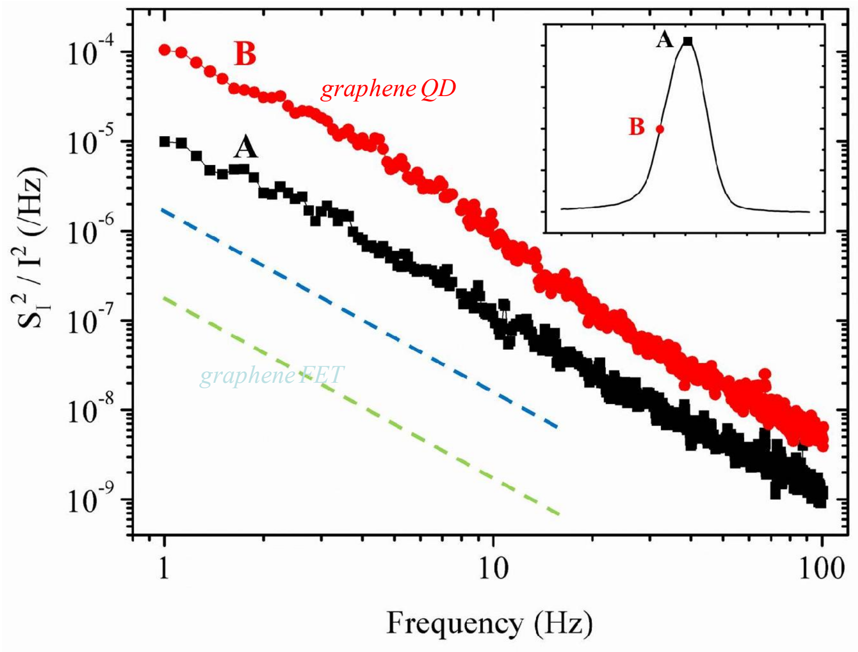

SCIENTIFIC REPORTS 5, 8142 (2015).

# 悬浮石墨烯量子点

Compare with GaAs/AlGaAs quantum dot



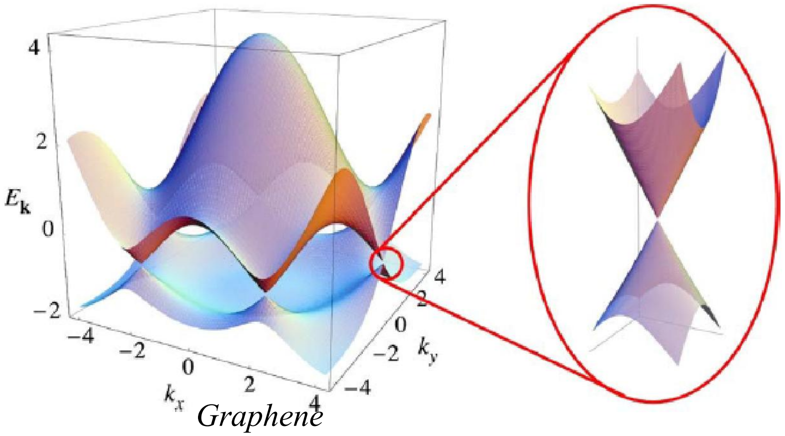

Compare with graphene field-effect transistor




***对于石墨烯纳米结构电噪声主要不是衬底应该是边缘态等缺陷***

**SCIENTIFIC REPORTS 5, 8142 (2015).**

# TMDs量子点

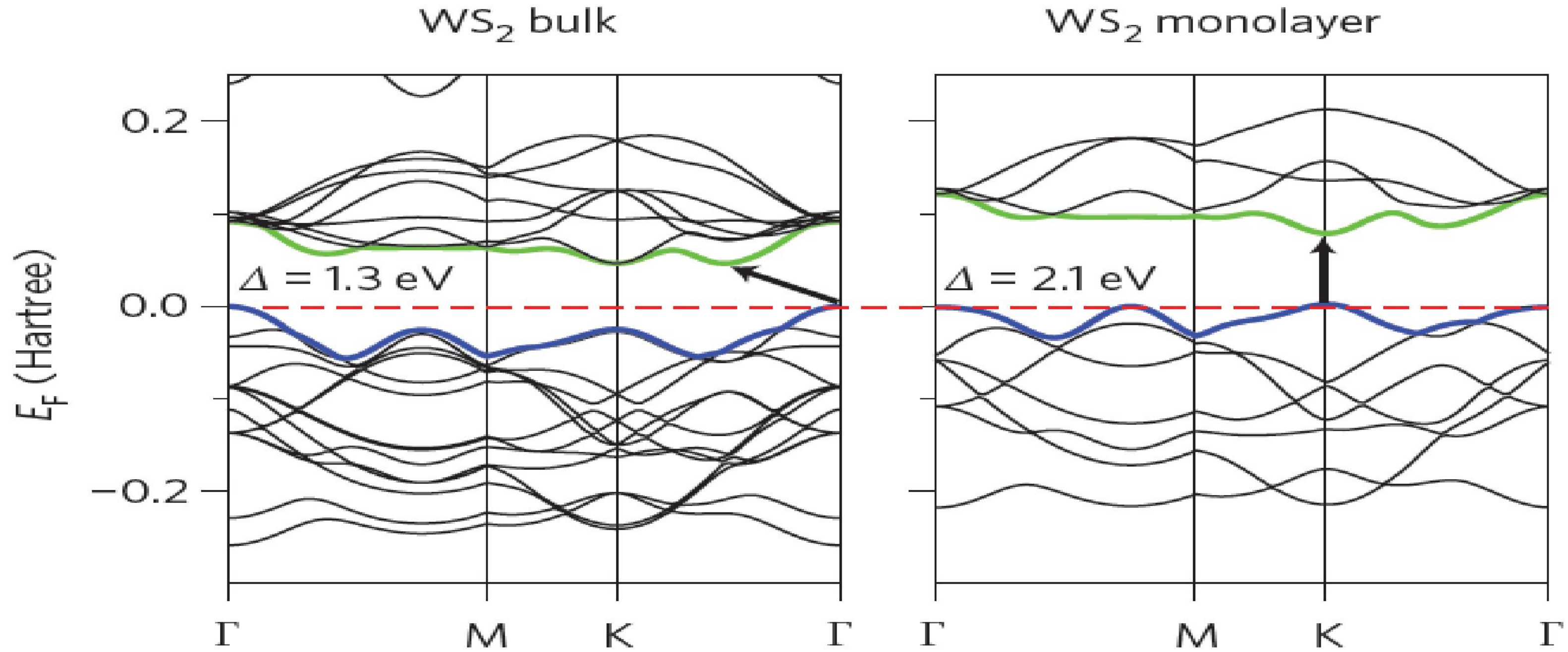



*Semimetal* → *No band gap* → *Etching steps* → ***Quantum dot***

*Etching steps* → *Edge states*

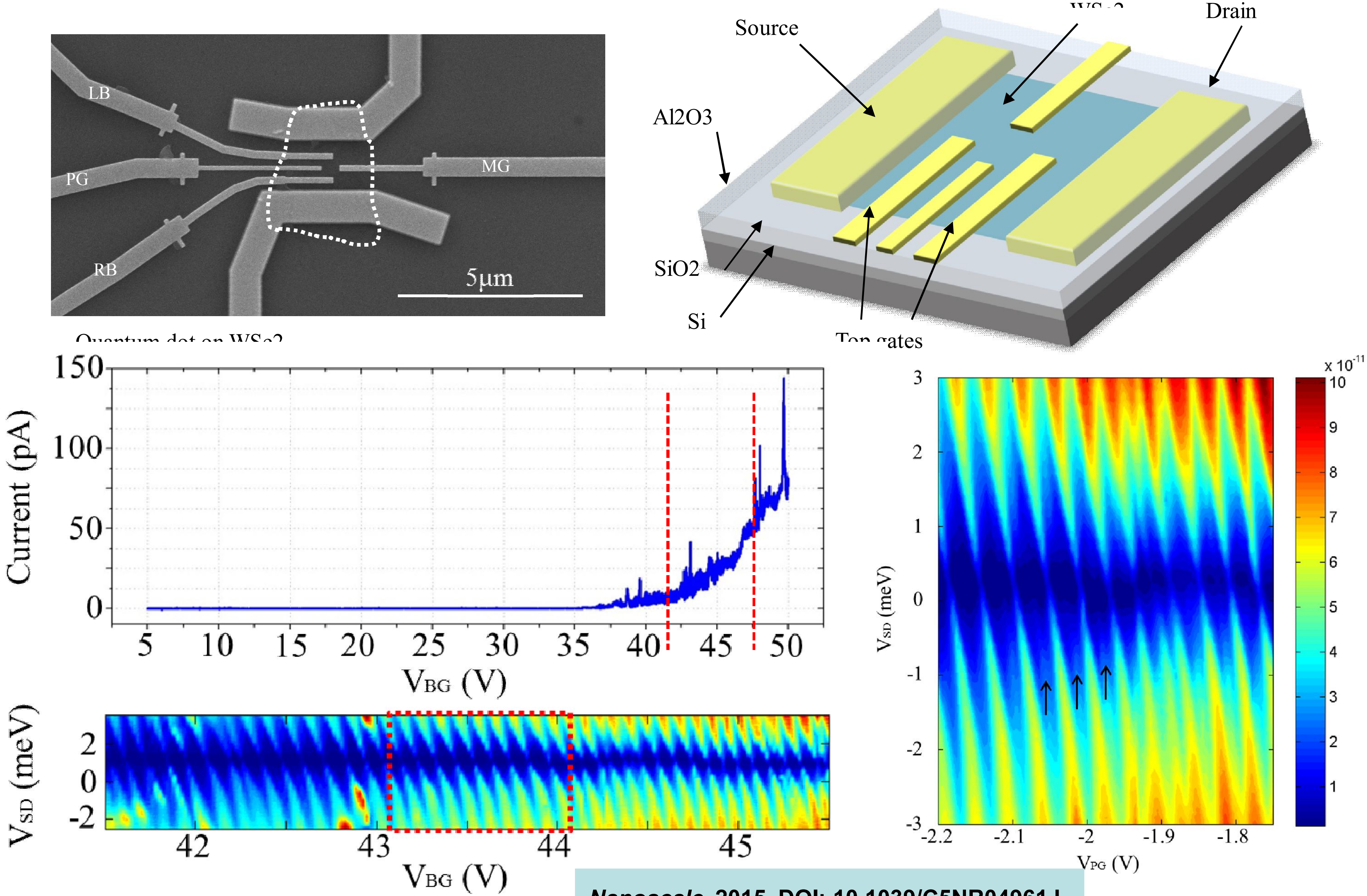
*Semiconductor* → *Band gap* → ***Quantum dot***

Why TMDCs?



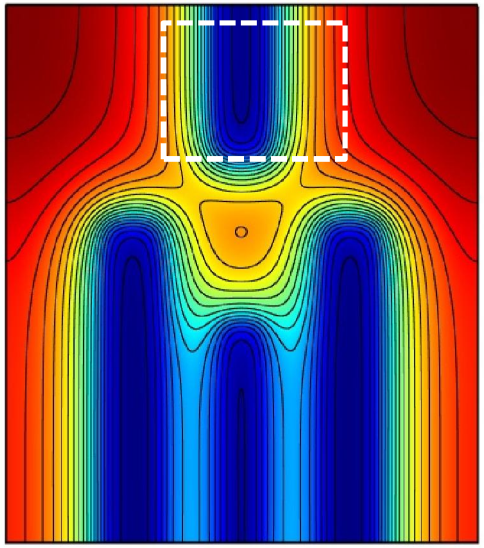

***Transition metal dichalcogenides (TMDCs)***

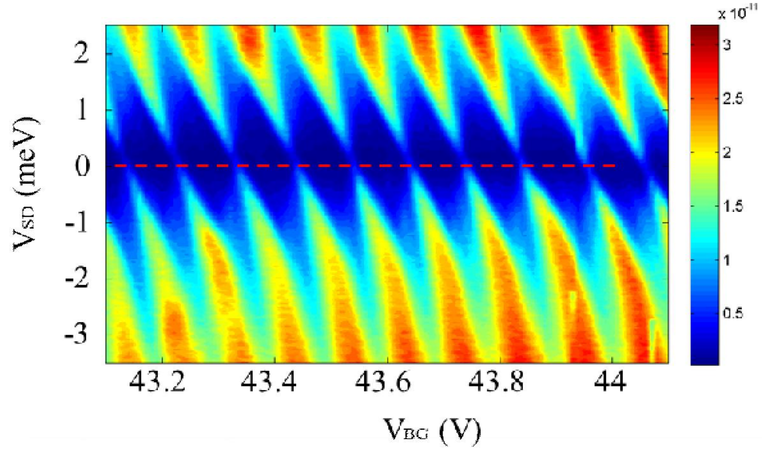
# TMDs量子点

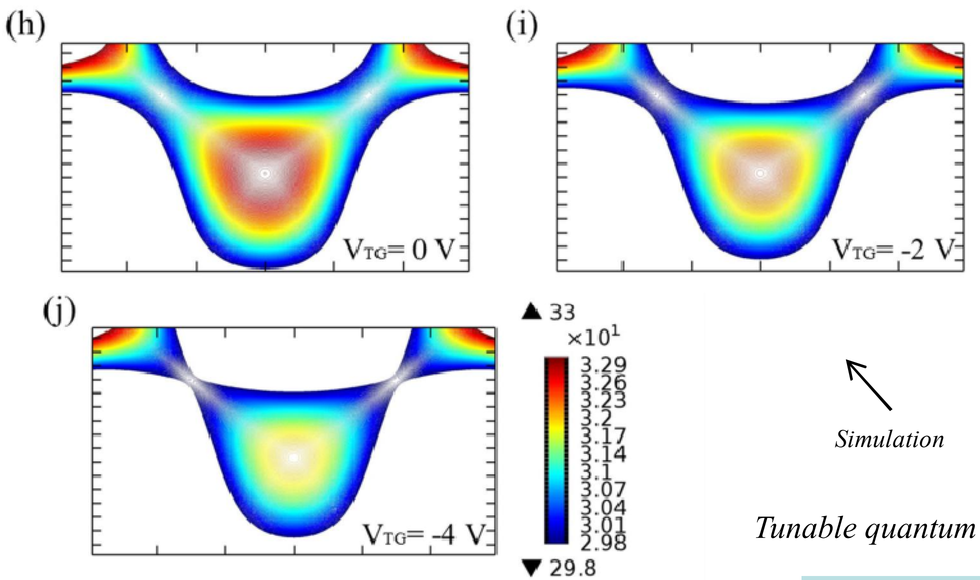


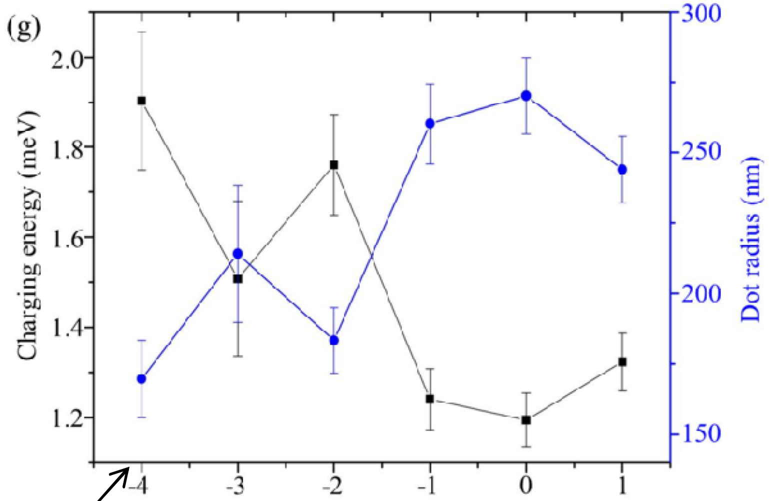

*Nanoscale*, 2015, DOI: 10.1039/C5NR04961J

# TMDs量子点





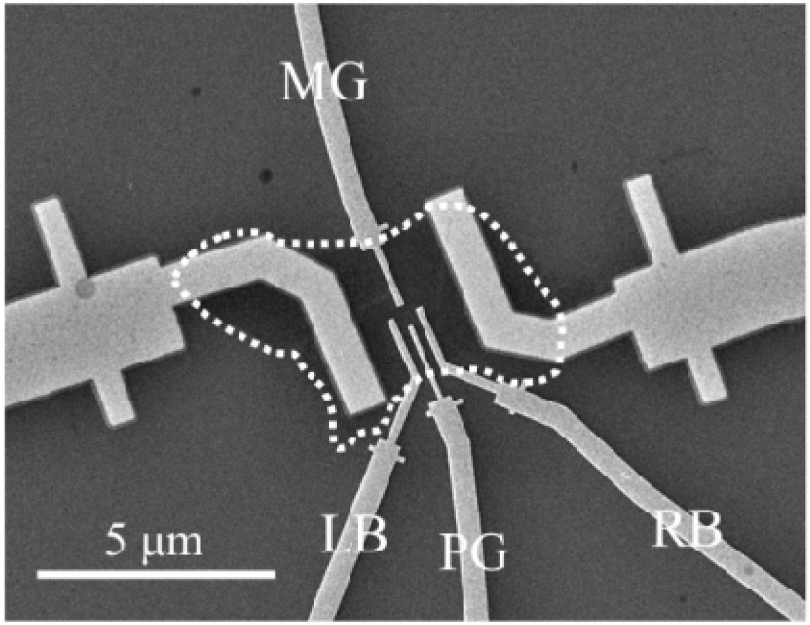



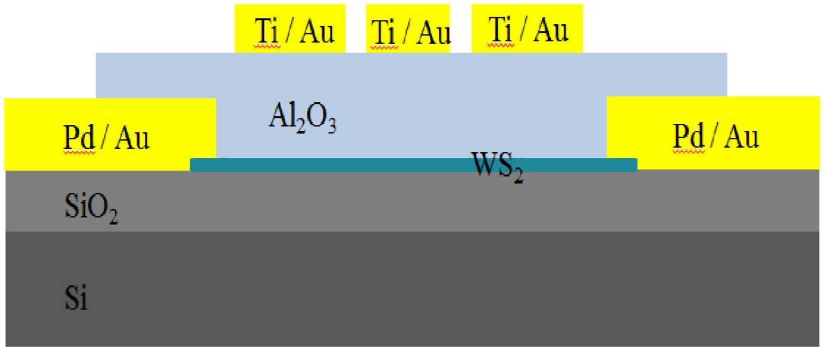

*Simulation* *Experiment*

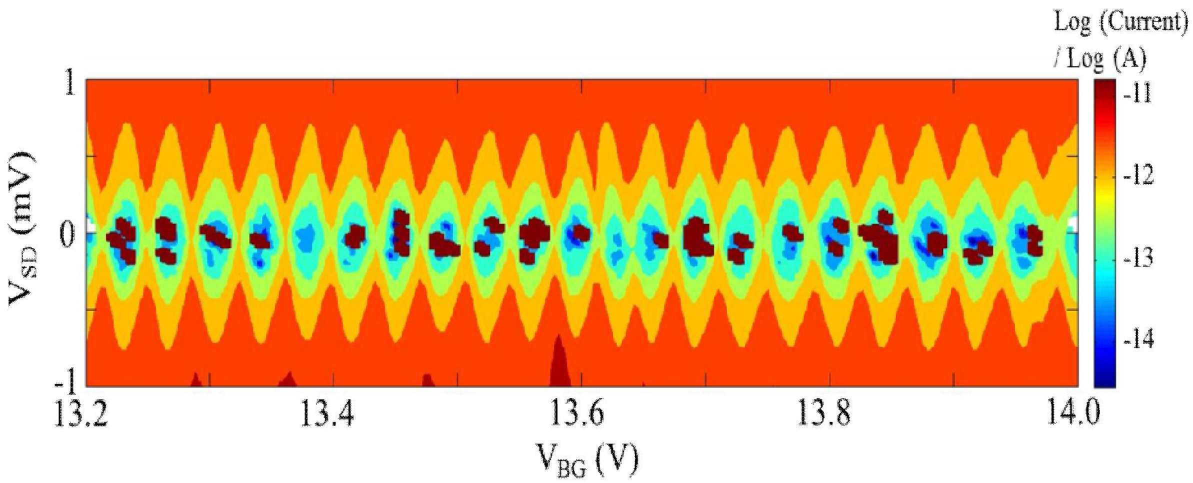
*Tunable quantum dot on TMDCs*

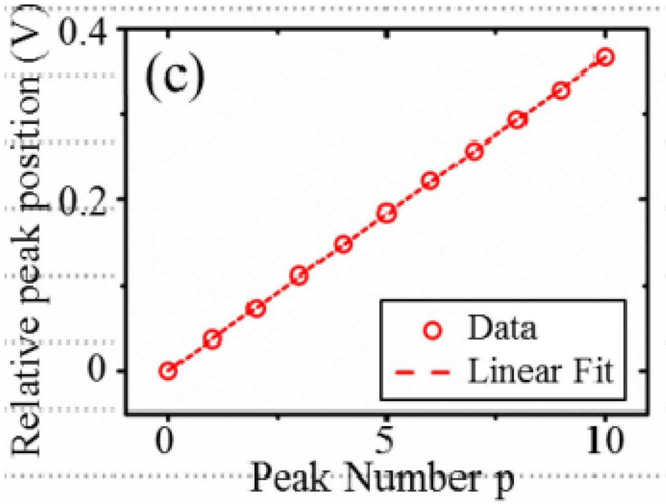
***Nanoscale*, 2015, DOI: 10.1039/C5NR04961J**

# TMDs量子点



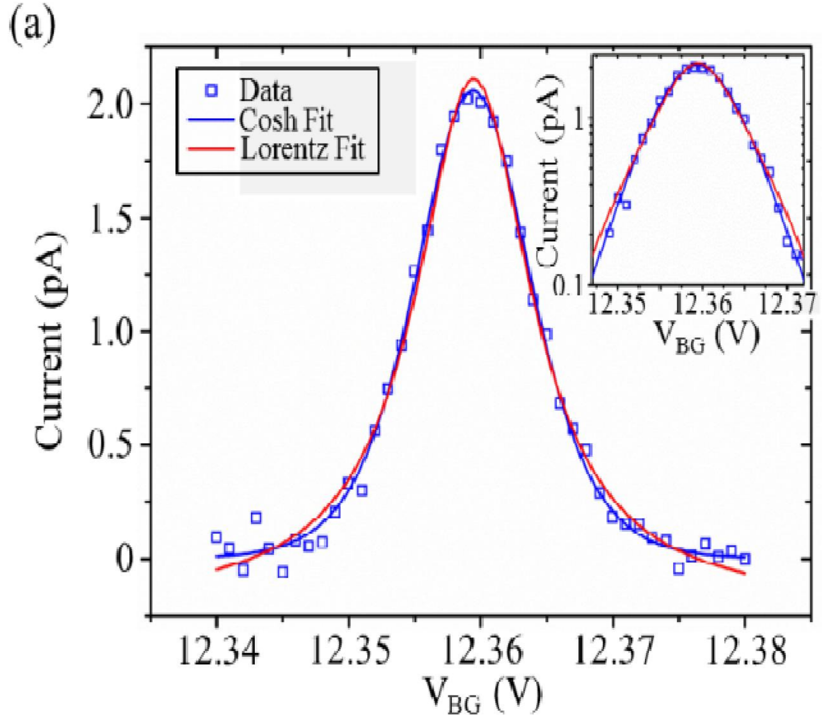



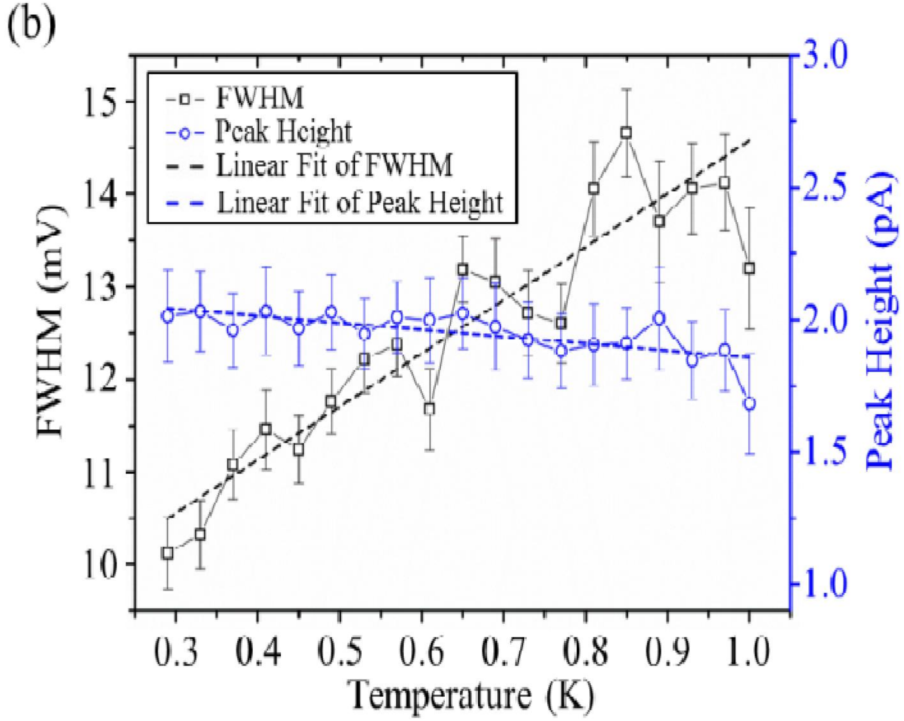



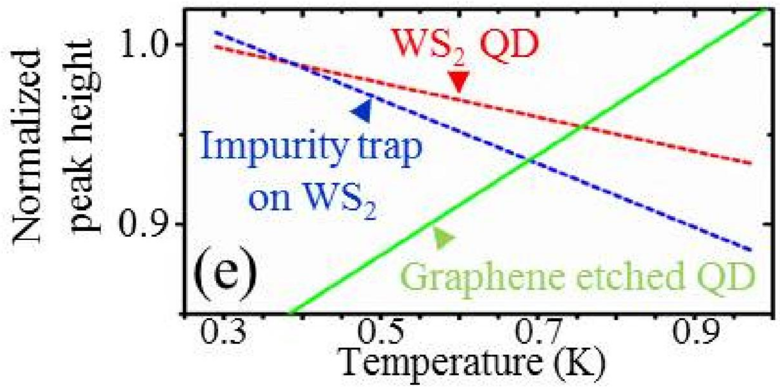




Scientific Report, Accepted 2015

# TMDs量子点

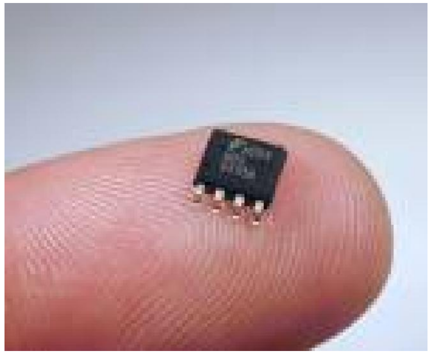


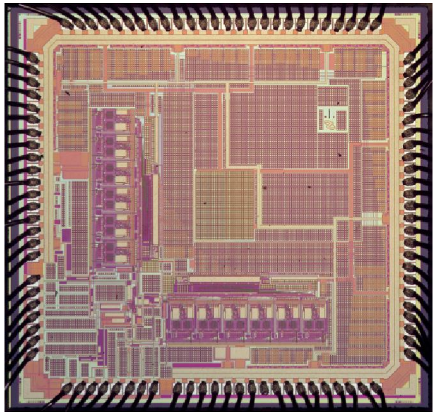



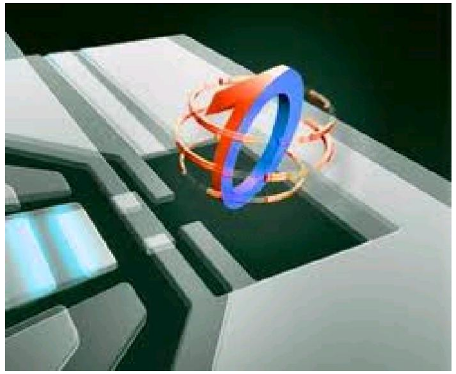




***Disordered confining potential* is *absent* in TMDCs quantum dot, which is different from graphene etched QD.**

Scientific Report, Accepted 2015







# 谢　谢！


中国科学院量子信息重点实验室
Key Lab of Quantum Information, CAS
量子计算与量子输运研究组