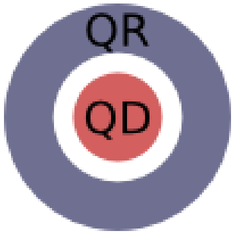
Wave function engineering in quantum dot-ring structures

Nanostructures with highly controllable electronic properties

E. Zipper, M. Kurpas, M. M. Maśka
Instytut Fizyki, Uniwersytet Sląski w Katowicach, Poland

Talk outline

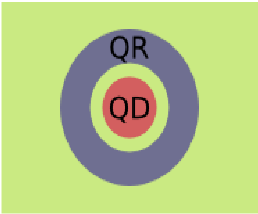


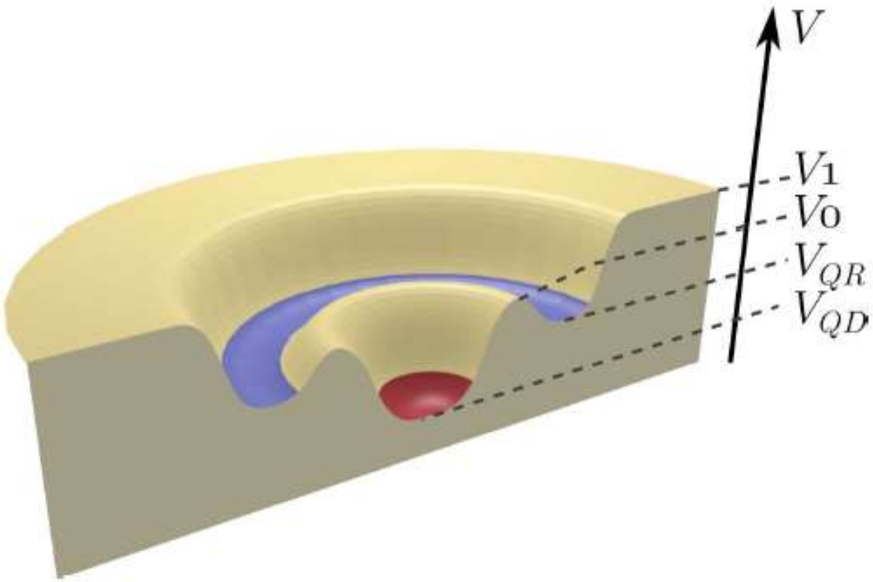
Szafran B, Peeters F M and Bednarek S 2004 *Phys. Rev. B 70 125310*

1. DRN structure - quantum dot (QD) surrounded by a quantum ring (QR).
2. Relaxation times of spin qubits and memory devices built on DRNs.
3. Engineering of optical absorption of DRNs.
4. Conducting properties of arrays of DRNs.
5. Summary.

E.Z.,M.Kurpas, M.Maśka
arXiv:1203.1025v1, New Journal of Physics 14,(2012)093029

• 2D semiconductor nanostructure (DRN) in the form of quantum dot (QD) surrounded by a quantum ring (QR).

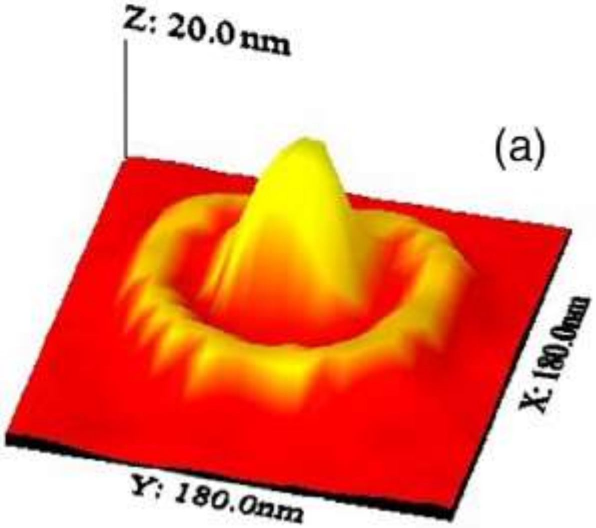




$V_1 = 50\,\mathrm{meV}$

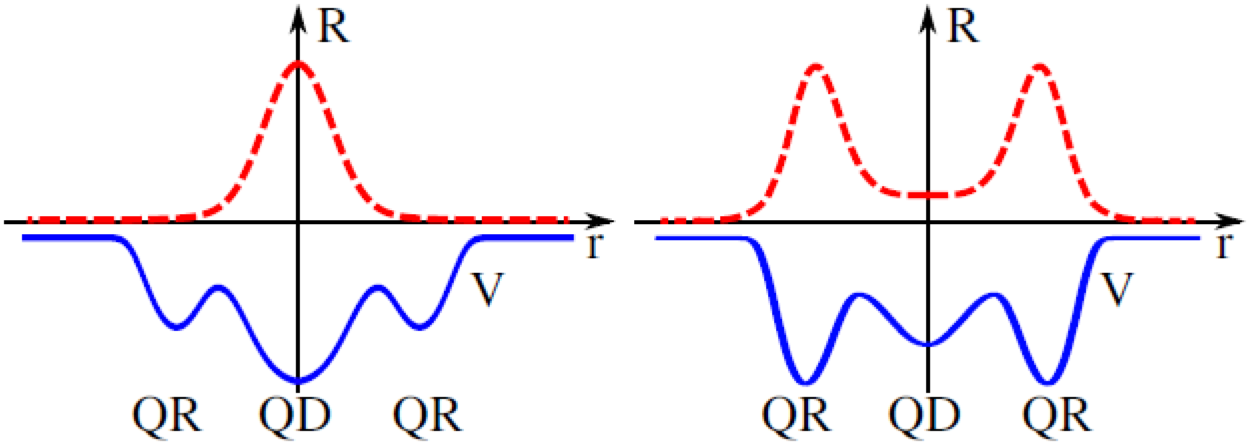
$V_{\mathrm{QR}} = 0\ \mathrm{meV}$

Electron can tunnel from QD to QR via the barrier V_0



Somaschini et al., Nanotechnology 22, 185602 (2011

•By changing the barrier parameters and/or potential well offset one changes the shape and distribution of wave functions – wave function engineering



- Such manipulations can change:
- spin relaxation times of DRNs by orders of magnitude
- cross section for optical intraband absorption from strong to negligible
- conducting properties of a DRN and of an array of DRNs from highly conducting to insulating

Basic theoretical formulas

- Single electron in a DRN in a static in-plane magnetic field B

$$H_R = \frac{\mathbf{p}^2}{2m^*} + \frac{e\hbar}{2m_e}\hat{\sigma}\cdot\boldsymbol{B} + V(r),$$

- The single electron energy spectra – set of discrete states – E_{nl}, n=0,1,…, l=0, ±1 …

$$\Delta_{nl} = E_{nl} - E_{00}$$

$$\Psi_{nl} = R_{nl}(r)\exp(il\phi)\chi_\sigma,$$

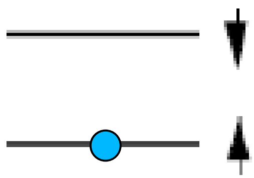
Overlap factor: $$\Xi_{nl} = \int_0^\infty R_{00}^* R_{nl} r^2 dr \qquad l = \pm 1.$$

Spin relaxation time for dot-ring nanostructure

- Nanostructure with a single electron in magnetic field B – a natural two level system – spin qubit or spin memory device

- InGaAs with R_{DRN}=80nm, $m^* = 0.067 m_e,\ |g_s| = 0.8 \quad B = 1T$

GS with E_{00} - |g>



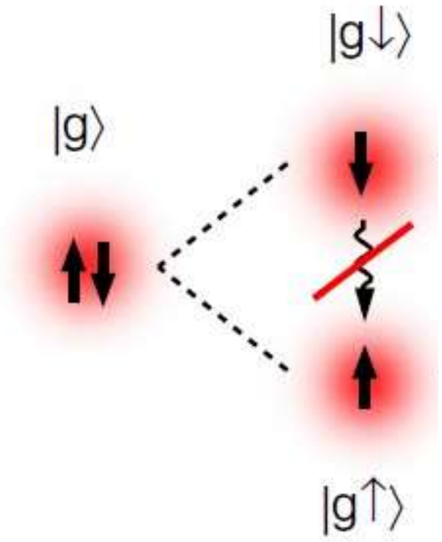
$$\Delta_Z = g_s \mu_B B,$$

$$k_B T << \Delta_Z << \Delta_{01}$$

- Modification of relaxation times in DRNs

Relaxation for spin qubit ($B_{||}$=1T)

- At 0.5T<B<10T relaxation mainly due to one-phonon admixture of orbital to spin state



Amasha et al.,PRL100, 046803, (2008)

- drastic reduction of spin relaxation rates due to strong quantum confinement ;

- T_1 calculated by Khataetski and Nazarov for circularly symmetric nanostructures with very strong confinement in the z direction

  (*A.V.Khaetskii ,Y.Nazarov, Phys.Rev. B **64**, 125316,(2001)*)

- The most important mechanism is due to spin-orbit mediated interaction with piezoelectric phonons

$$H = H_R + \frac{e\hbar}{2m^*}\hat{\sigma}\cdot B + H_{SO} + V_{ph} \qquad (1)$$

where

$$H_{SO} = \beta\left(-\hat{\sigma}_x p_x + \hat{\sigma}_y p_y\right) \qquad (2)$$

is the Dresselhaus SO interaction due to the bulk inversion asymmetry,

$$H_R = \frac{1}{2m^*}(\mathbf{p} + eA)^2 + V(r), \qquad (3)$$

- For an electron occupying the nth orbital level

$$T_1^{-1} = C_{ph}\left(\alpha_{xx}^2 + \alpha_{yy}^2\right)\Delta_z^5$$

$$\alpha_{xx} = 2e^2 \sum_{m \neq n} \frac{|\langle n|x|m\rangle|^2}{E_m - E_n} = \alpha_{yy}$$

- T_1 calculated by Khaetskii and Nazarov for circularly symmetric nanostructures due to spin-orbit mediated interaction with piezoelectric phonons is given by:

$$\frac{1}{T_1} = \frac{\Delta_z^5}{\eta}\left[\Gamma^{01} + \Gamma^{11}\right]^2,$$

$$\Xi_{nl} = \int_0^\infty R_{00}^* R_{nl} r^2 dr$$

$$\Gamma^{01} = \frac{\Xi_{01}^2}{\Delta_{01}}, \quad \Gamma^{11} = \frac{\Xi_{11}^2}{\Delta_{11}}.$$

$$\Delta_{nl} = E_{nl} - E_{00}$$

$$\eta = \frac{\hbar^5}{\Lambda_p (2\pi)^4 (m^*)^2},$$

$\Lambda_p = 0.007$ for GaAs type systems

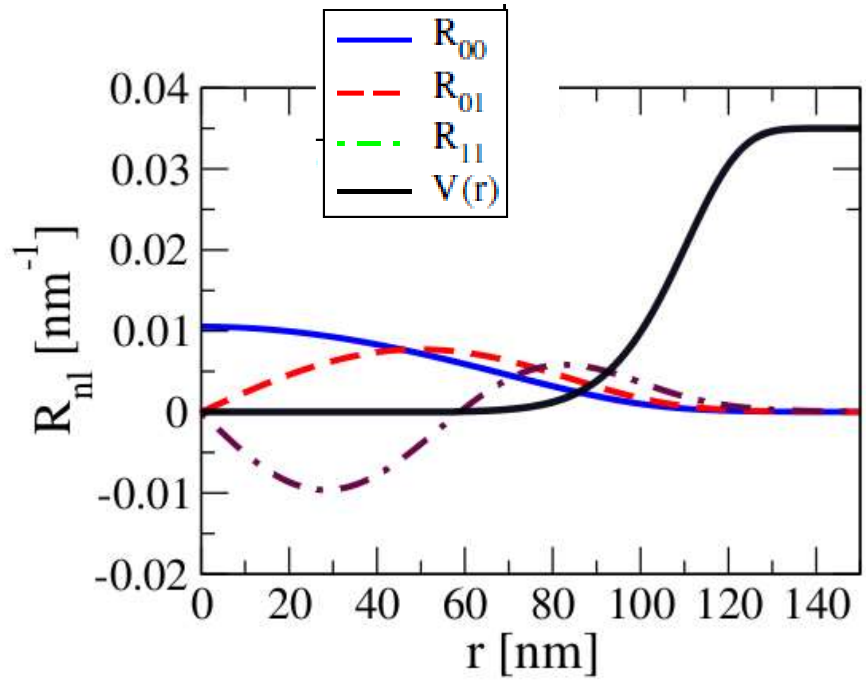
Relaxation time in DRN with $V_0 = 0$

QD

$$\frac{1}{T_1} = \frac{4\Delta_z^5}{\eta}\left(\Gamma^{01} + \Gamma^{11}\right)^2,$$

$$\Gamma^{01} = \frac{\Xi_{01}^2}{\Delta_{01}}, \quad \Gamma^{11} = \frac{\Xi_{11}^2}{\Delta_{11}}.$$

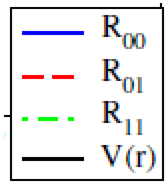
$$\Xi_{nl} = \int_0^\infty R_{00}^* R_{nl} r^2 dr$$

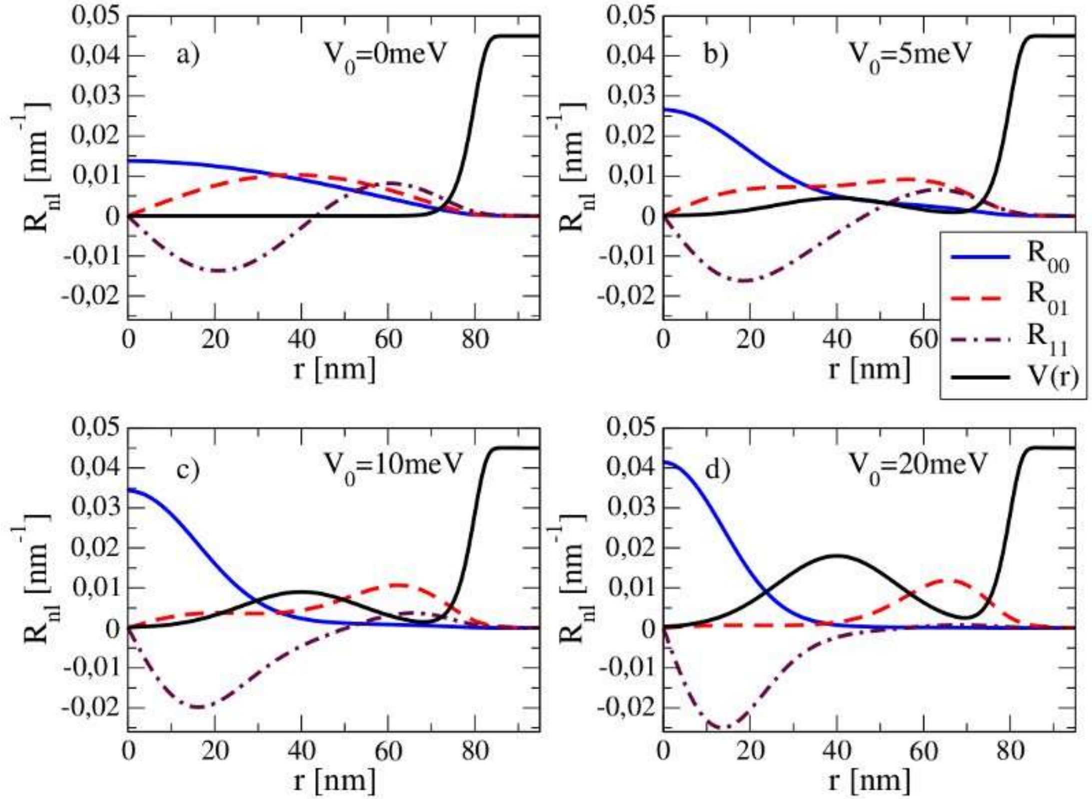


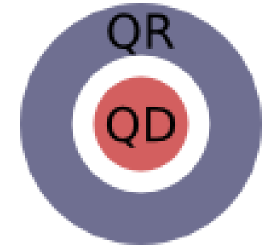
V_0	Δ_{01}[meV]	Δ_{11}[meV]	Ξ_{01} [nm]	Ξ_{11} [nm]	T_1[ms]
0	0.807	3.91	5.87	0.45	0.05

- Pure QD: T_1 is entirely determined by excitations to the first orbital state
- Small T_1 because of large Ξ_{01}

Relaxation time in DRN







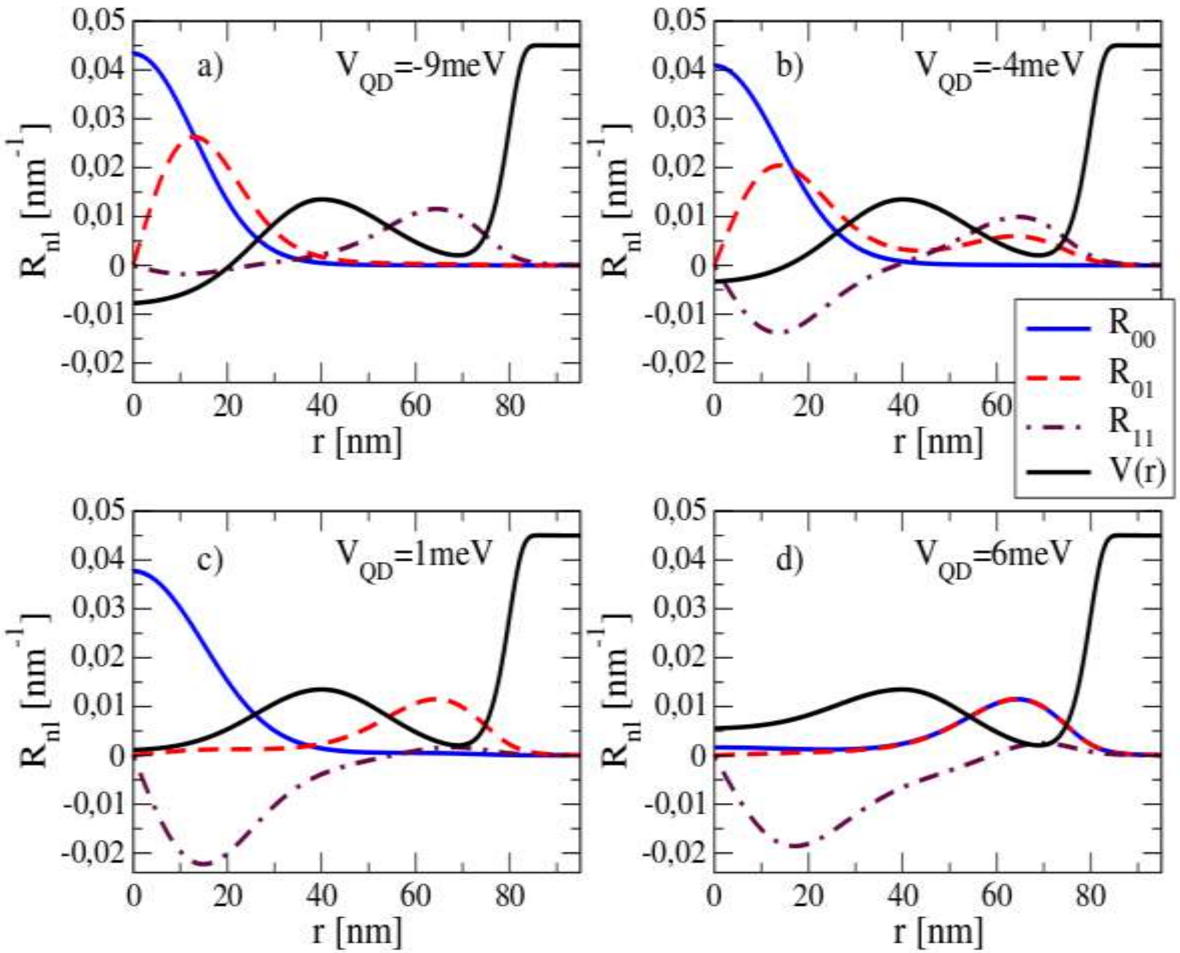
$$\Xi_{nl} = \int_0^\infty R^*_{00} R_{nl} r^2 dr$$

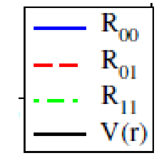
V_0	Δ_{01} (meV)	Δ_{11} (meV)	Ξ_{01} (nm)	Ξ_{11} (nm)	T_1 (ms)
0	0.807	3.91	5.87	0.45	0.05
5	1.48	3.61	3.74	1.45	0.9
10	2.29	4.30	1.47	2.34	18
15	2.85	5.26	0.53	2.30	74.2
20	3.26	6.12	0.20	2.16	151

By increasing the barrier height excitations to the second orbital state determine T_1

Wave function engineering by changing the potential well offset

$V_0 = 15\,\mathrm{meV}$ and $V_1 = 50\,\mathrm{meV}$ $\quad V_{QR} = 0\,\mathrm{meV}$

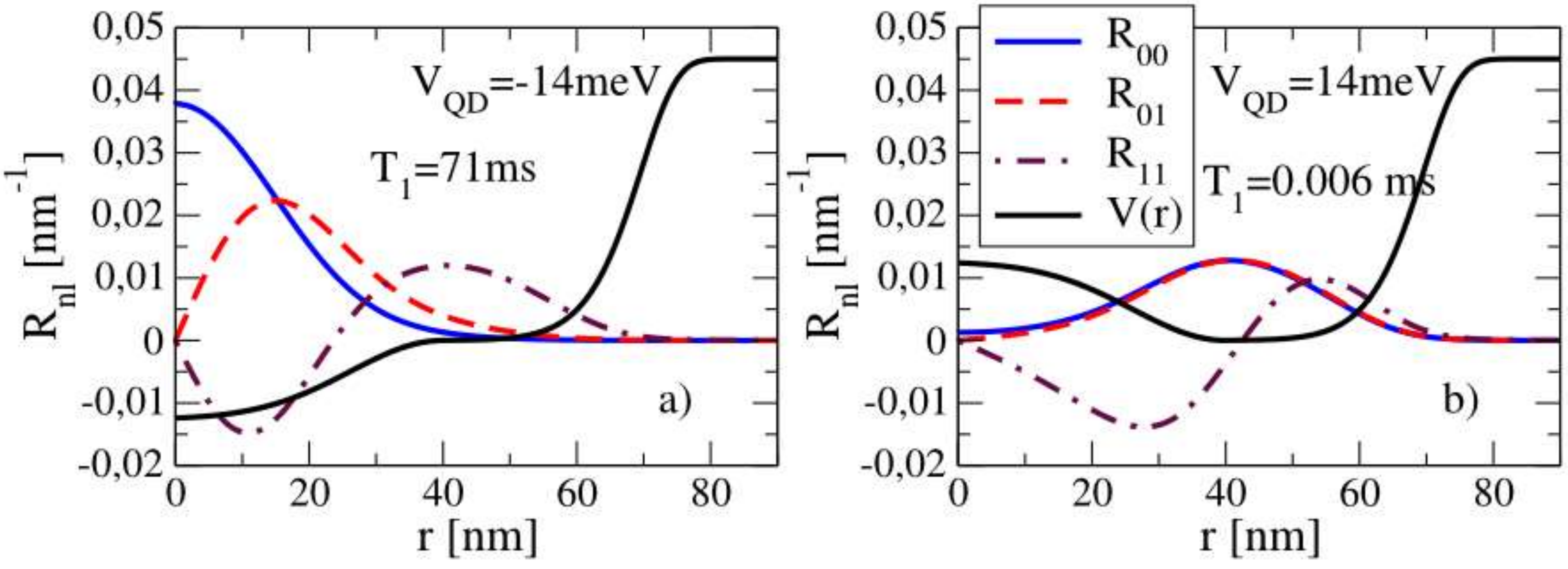




V_{QD} [meV]	T_1 [ms]
-9	240
-4	137
1	53
3	0.21
6	2.1x10-4

$$\Xi_{nl} = \int_0^{\infty} R_{00}^* R_{nl} r^2 dr$$

Wave function engineering by changing the potential well offset at $V_0 = 0$



The increase of T_1 by introducing a small disk shaped gate below a central part of initial quantum dot

Presented results for InGaAs R_{DRN}=80nm, $m^* = 0.067 m_e, \; |g_s| = 0.8$

- T_1 strongly increases with decreasing the radius of DRN

- e.g. for InGaAs R_{DRN}=40nm

$T_1(V_0=0)$ =7.5ms (0.05ms), $T_1(V_0=20meV)$ =2.5s (151ms),

- T_1 strongly increases with decreasing the g_s

e.g. for GaAs/AlGaAs with $g_s = 0.4$ R_{DRN}=80nm,

T_1 (GaAs/AlGaAs) = 32 T_1 (GaAs/InGaAs) 0.16s – 5s

- Important feature – not only the value of T_1 itself but the possibility to change T_1 by electrostatic gating

Optical intraband absorption of DRNs

$$\sigma_{i,f} = \frac{16\pi^2 \beta \hbar\omega \Xi_{i,f}^2}{n_2} \delta(E_f - E_i - \hbar\omega) F_{\rm FD}(E_i, E_f)$$

where $\beta = 1/137$ is a fine structure constant, $l_f = l_i \pm 1$,

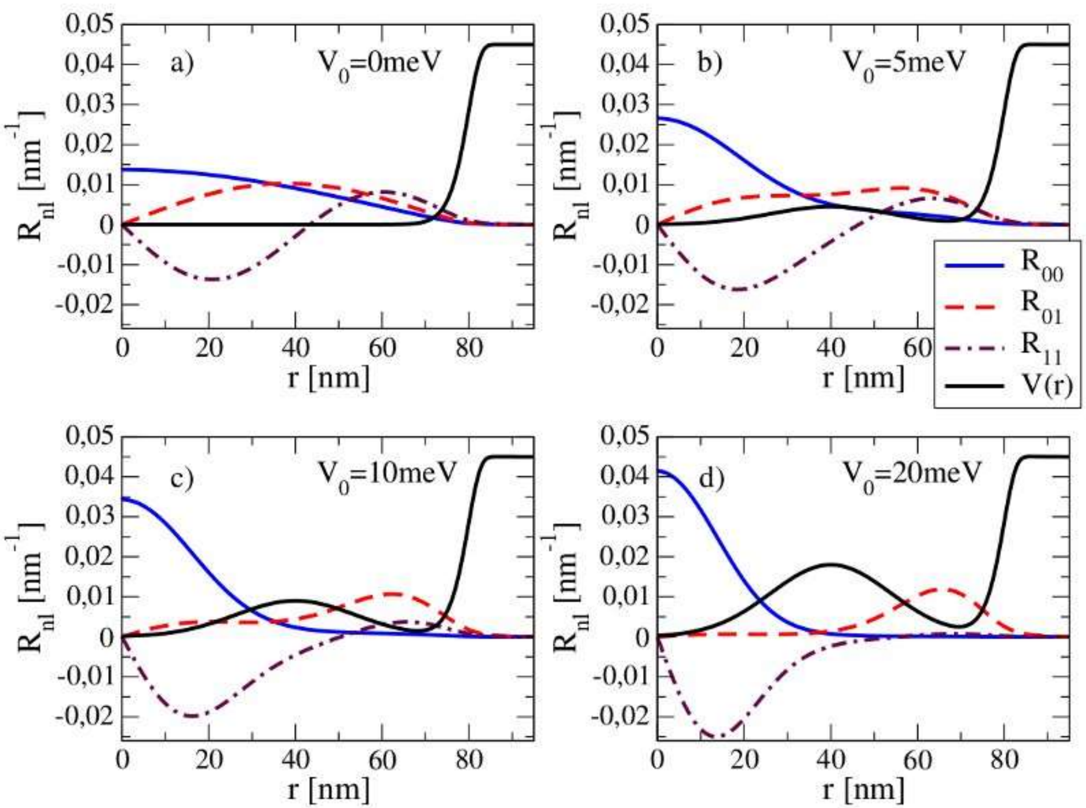
n_2 is the refractive index. B=0

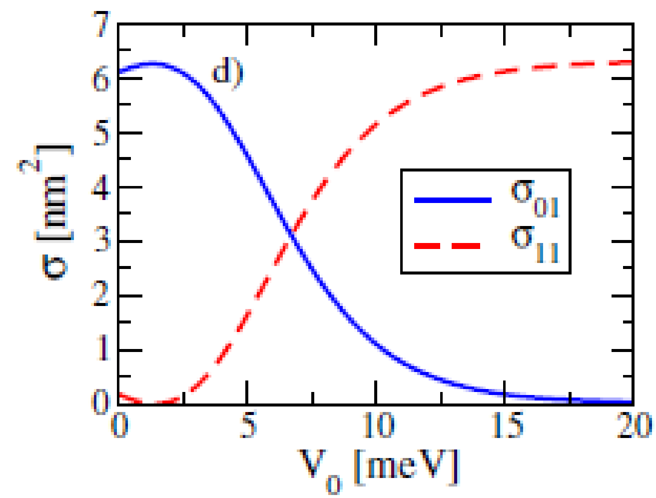
Resonant absorption at Δ_{n1} with Γ = 1meV

$$\sigma_{n1} = \frac{16\pi^2 \beta \Delta_{n1} \Xi_{n1}^2}{n_2}, \ (n = 0, 1)$$

Optical absorption of DRNs
for different V_0

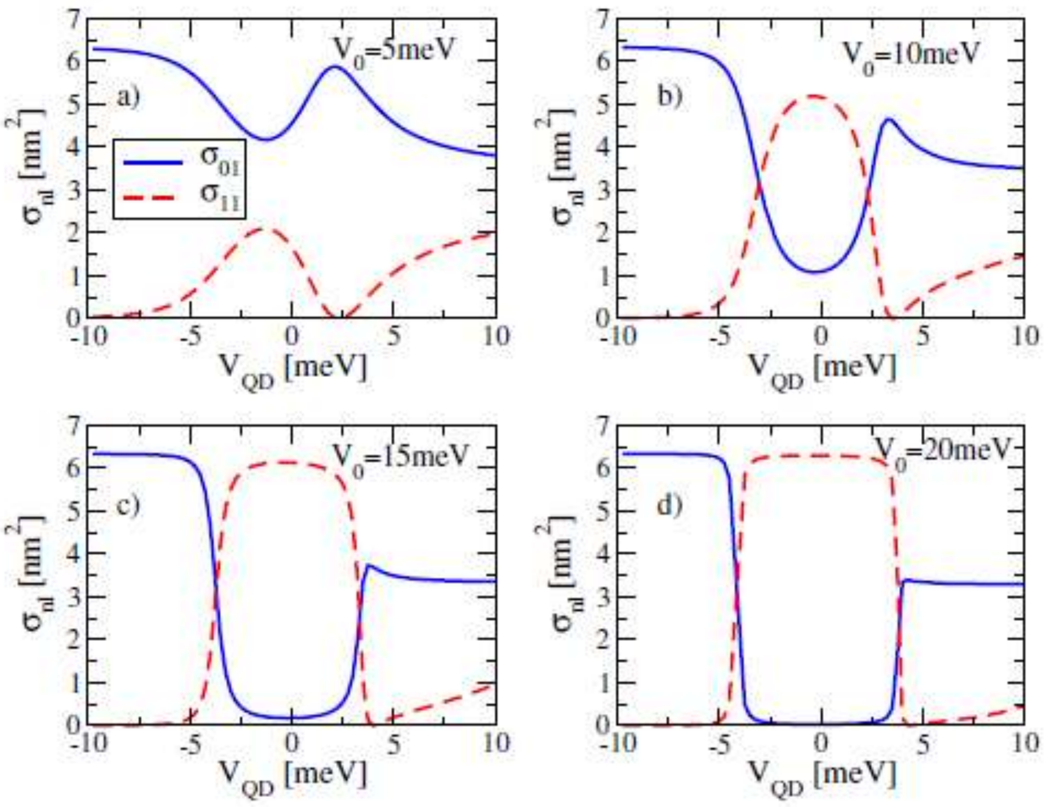
$$\sigma_{n1} = \frac{16\pi^2 \beta \Delta_{n1} \Xi_{n1}^2}{n_2}, \ (n = 0, 1)$$





Optical absorption of DRNs
for different V_{QD}

$$\sigma_{n1} = \frac{16\pi^2 \beta \Delta_{n1} \Xi_{n1}^2}{n_2}, \ (n = 0, 1)$$



One can engineer DRNs according to their applications:

1. One can design DRNs to get strong effective absorption

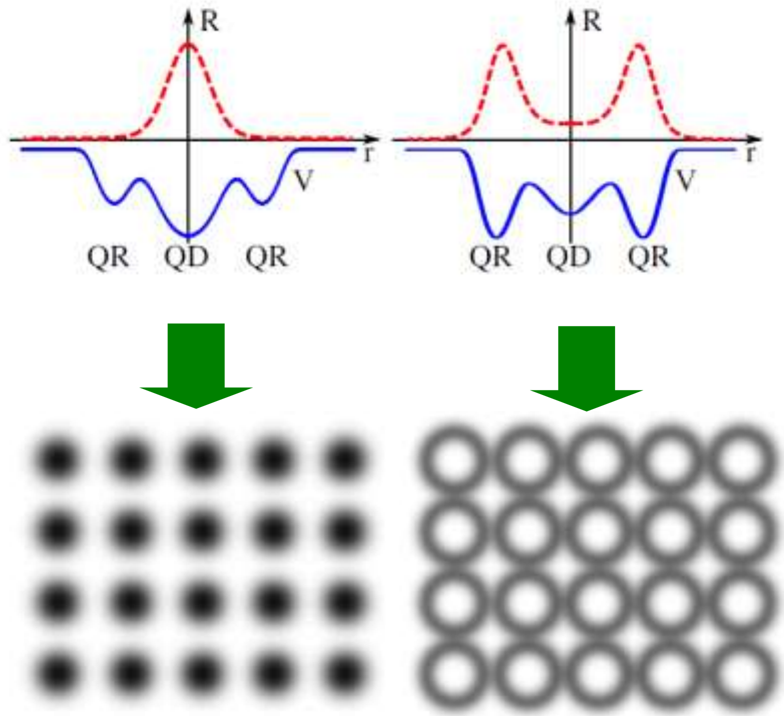
2, One can design DRNs with negligible absorption.

3.By changing V_{QD} one can move over from highly absorbing to almost transparent DRNs.

4. The absorbed energy can be changed form infra-red to microwaves by changing the material, the radius of the nanostructure and the barrier parameters.

Conducting properties of arrays of DRNs

from insulating to conducting system



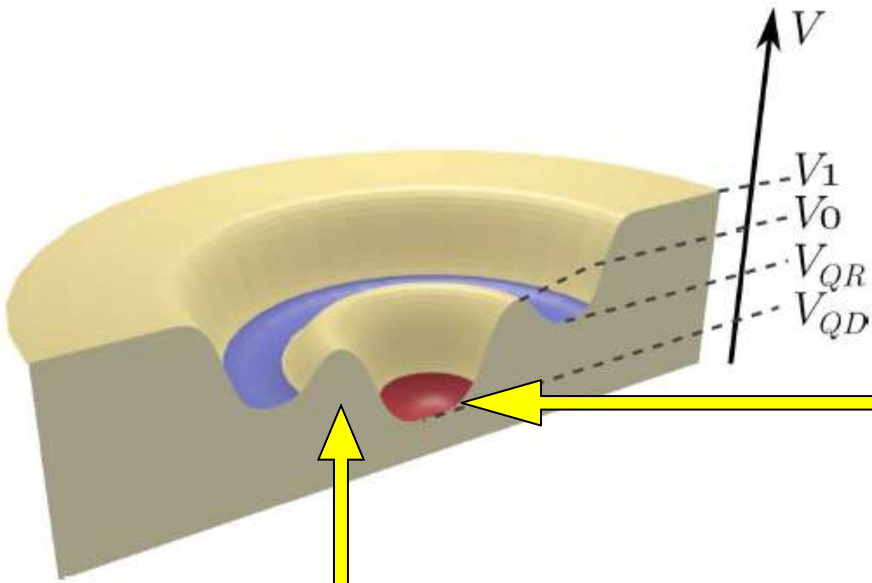
Periodic Anderson-like hamiltonian

$$\mathcal{H} = \sum_{\langle i,j\rangle\sigma} (t_{ij} - \epsilon_{\mathrm{QR}}\delta_{ij})\, c_{i\sigma}^{\dagger} c_{j\sigma} - \epsilon_{\mathrm{QD}} \sum_{i\sigma} f_{i\sigma}^{\dagger} f_{j\sigma} \quad (11)$$

$$+V \sum_{i\sigma} \left(f_{i\sigma}^{\dagger} c_{i\sigma} + \mathrm{H.c.} \right) + \frac{U_{\mathrm{QD}}}{2} \sum_{i} n_i (n_i - 1),$$

Conducting properties of arrays of DRNs

from insulating to conducting system



Controlled by V_{QD}

(position of the bottom of the QD potential)

Controlled by V_0

(height of the barrier)

Periodic Anderson-like hamiltonian

$$\mathcal{H} = \sum_{\langle i,j\rangle\sigma} \left(t_{ij} - \epsilon_{\mathrm{QR}}\delta_{ij}\right) c^{\dagger}_{i\sigma} c_{j\sigma} - \epsilon_{\mathrm{QD}} \sum_{i\sigma} f^{\dagger}_{i\sigma} f_{j\sigma} \quad (11)$$

$$+V \sum_{i\sigma} \left(f^{\dagger}_{i\sigma} c_{i\sigma} + \mathrm{H.c.}\right) + \frac{U_{\mathrm{QD}}}{2} \sum_{i} n_i (n_i - 1),$$

Array of DRNs in external electric field

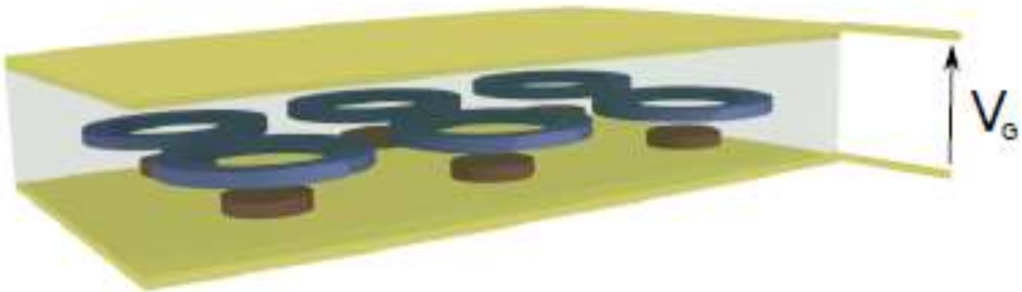


FIG. 10: (color online) Example of a spatial configuration of QR and QD that allows for controlling V_{QR} and V_{QD} by an external electrostatic field.

Controlling individual DRNs

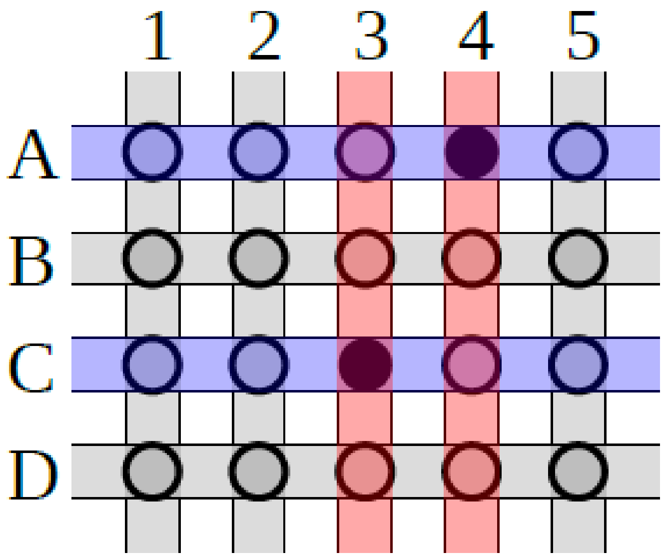
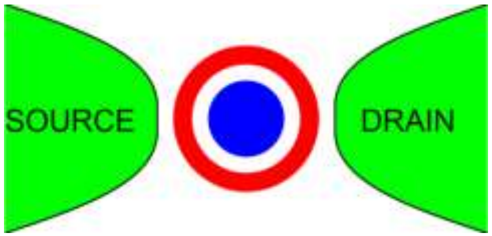
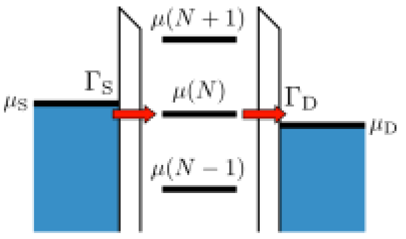


FIG. 11: (color online) Schematic illustration of the setup allowing for controlling individual DRNs. Stripes along the x axis located above the DRNs are labelled with letters, whereas the stripes along the y axis located below the DRNs are labelled with numbers. The full black circles indicate DRNs where the difference $\epsilon_{QD} - \epsilon_{QR}$ is largests when voltage is applied to pairs of stripes A4 and C3

Single electron tunneling through DRN





Current I flows through the nanostructure at low bias if:

$$\mu_D \leq \mu_N \leq \mu_S$$

$$\mu_N \equiv U(N) - U(N-1)$$

U(N) – total energy of nanostructure with N electrons including discreate quantum states separated by Δ_{nl} and charging energy $E_c = \frac{e^2}{C}$

- otherwise Coulomb blockade

$$I = -e^2 \frac{\Gamma_S \Gamma_D}{\Gamma} f'_{FD}(\mu_N - \mu)(V_S - V_D)$$

(Kouwenhoven, Beenaker)

$$\mu_{S(D)} = \mu \mp |e| V_{S(D)}, \quad \Gamma = \Gamma_S + \Gamma_D$$

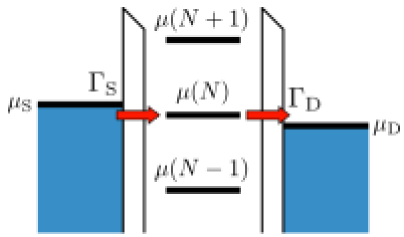
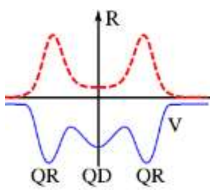


Fig.2

I depends on tunnel rates Γ_S, Γ_D

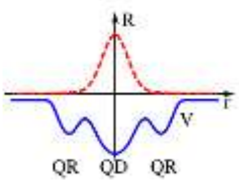
In DRN additional possibility to control transport of single electrons by changing Γ_S, Γ_D

a) GS in QR



$$\frac{I^{\text{ring}}}{I^{\text{dot}}} = 500$$

b) GS in QD



One can change the magnitude of the current and the coupling strength between DRN and S,D electrodes from large (Kondo regime) to weak by electrostatic gating

Summary

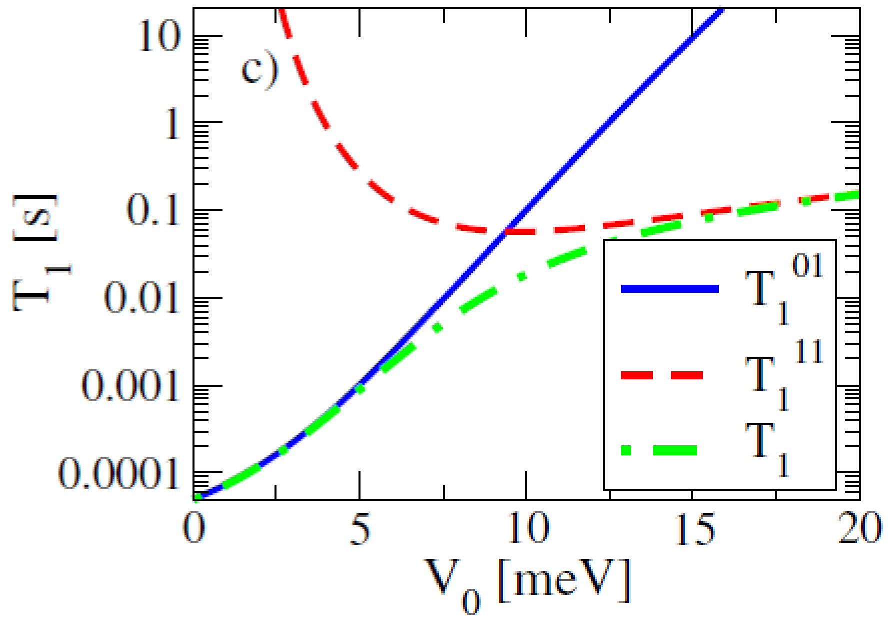
- Systematic studies of the effect of the shape and the height of the barrier and / or the potential well offset on measurable properties of DRNs.

- By manipulating the confinement parameters one can alter the overlap of the electron wave functions so that the transition probabilities will be enhanced or suppresed on demand.

- Such modifications strongly influence the relaxation times, the optical absorption spectra and the conducting properties of DRNs.

- The wavelength range may be expanded from microwaves to infra-red by utilizing DRNs of different size and different material.

- The basic issues of quantum mechanics can be explored to optimize the specific properties of nanostructures by means of sophisticated design.



T_1 as a function of the barrier height :

from the first excited state (QR)

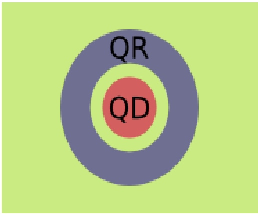
from the second excited state (QD)

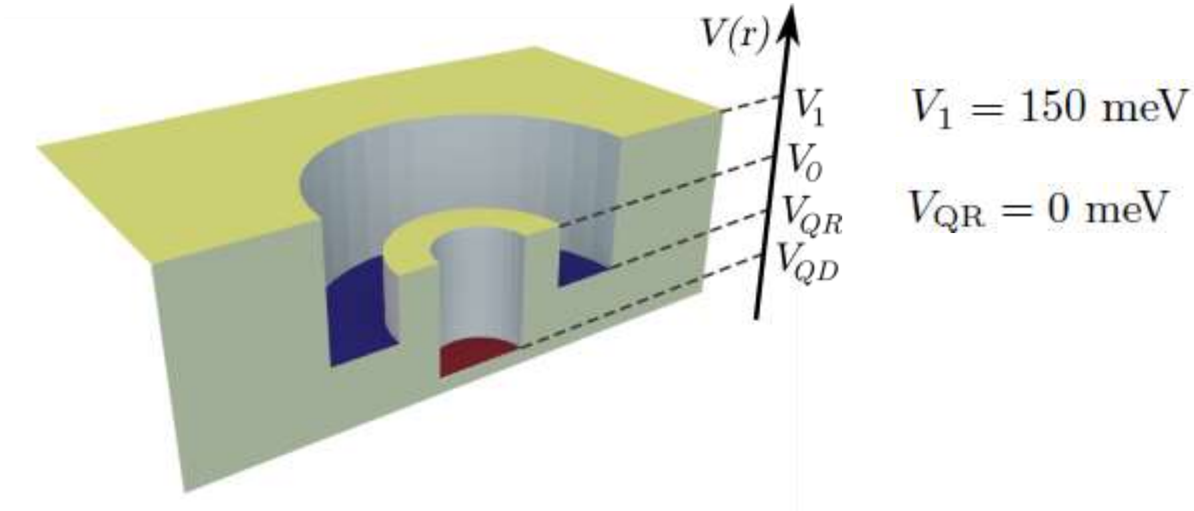
from both states

For small V_0 excitations to the first orbital state determine T_1

By increasing the barrier height excitations to the second orbital state determine T_1

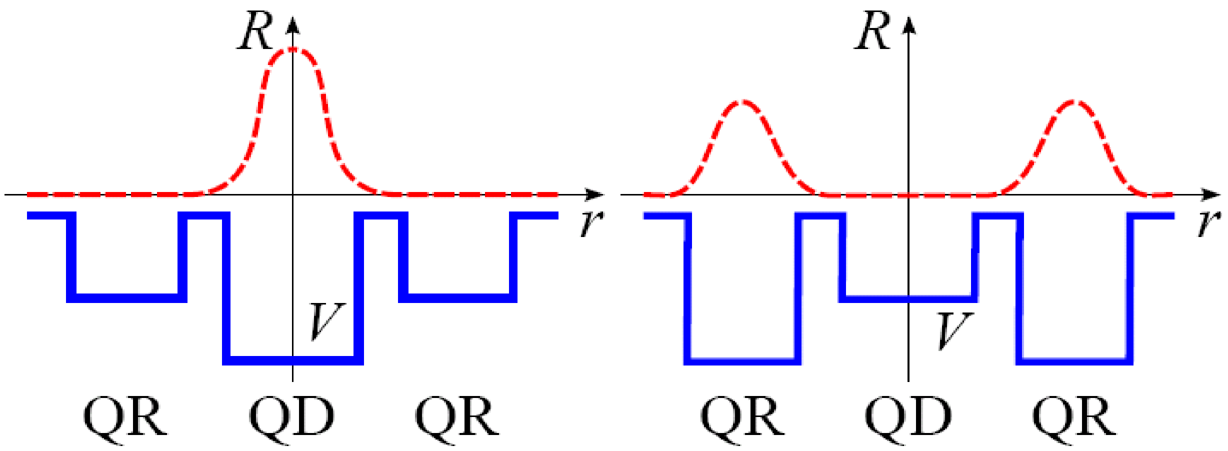
• 2D semiconductor nanostructure (DRN) in the form of quantum dot (QD) surrounded by a quantum ring (QR).





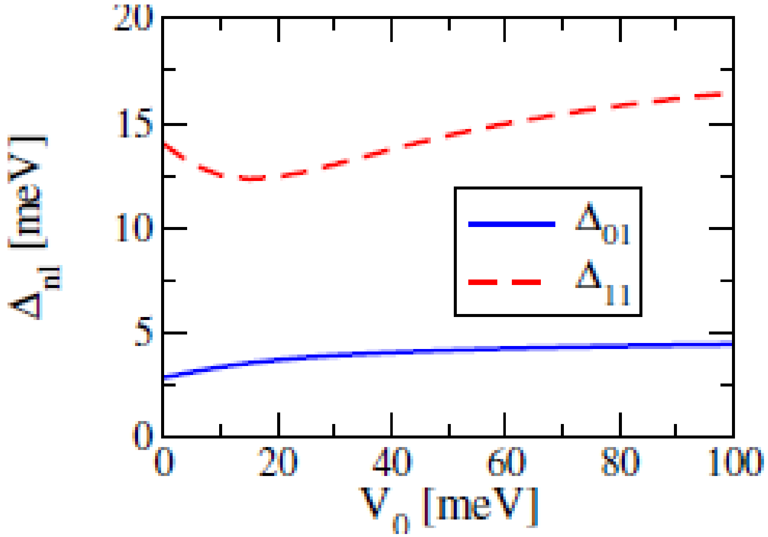
Electron can tunnel from QD to QR via the barrier V_0

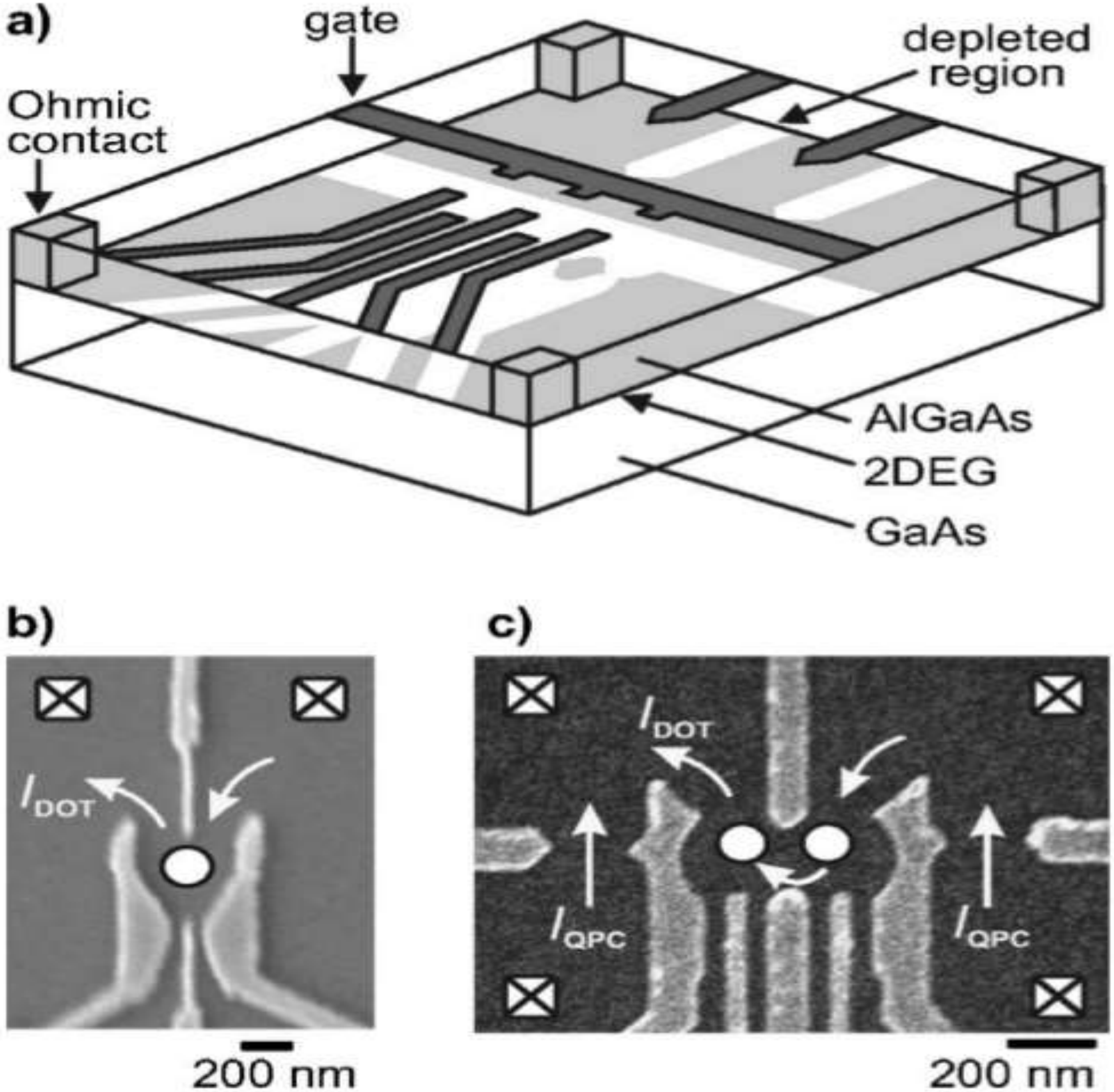
•By changing the barrier parameters and/or potential well offset one changes the shape and distribution of wave functions – wave function engineering



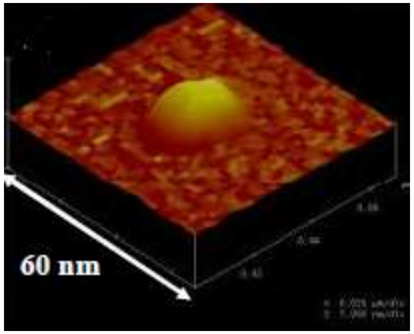
- Such manipulations can change:
- spin relaxation times of DRNs by orders of magnitude
- cross section for optical intraband absorption from strong to negligible
- conducting properties of an array of DRNs from highly conducting to insulating

Energy gaps to the first two excited states




a)
gate
depleted
region
Ohmic
contact
AlGaAs
2DEG
GaAs
b)
I_{DOT}
200 nm
c)
I_{DOT}
I_{QPC}
I_{QPC}
200 nm

Kropki kwantowe



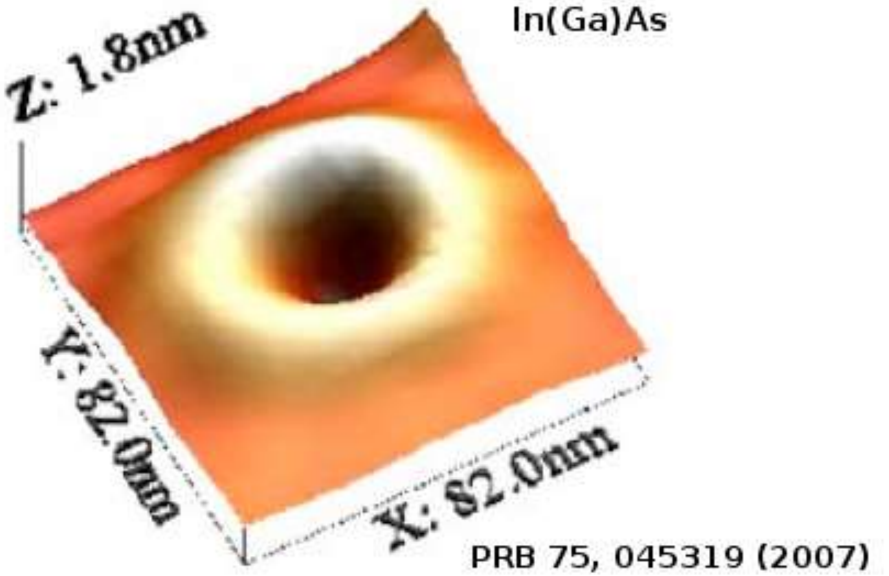
- Obiekty 0-wymiarowe (sztuczne atomy)zbudowane z półprzewodników o rozmiarach d ~ 5-100 nm
- Można precyzyjnie umieszczac zadaną liczbę elektronów
- Ciekawe zastosowania gdy w kropce 1 elektron
- Obliczenia kwantowe (quantum computing)

$|1\rangle$

$|0\rangle$

$|Q\rangle = a|0\rangle + b|1\rangle, \quad |a|^2+|b|^2 = 1$

- **Question**:
- Are quantum rings good for qubit implementations?



Self-assambled In(Ga)As quantum rings Benito Allen et al

Further increase of T_1 by decreasing Ξ_{11} by changing the barrier shape from rectangular to gaussian

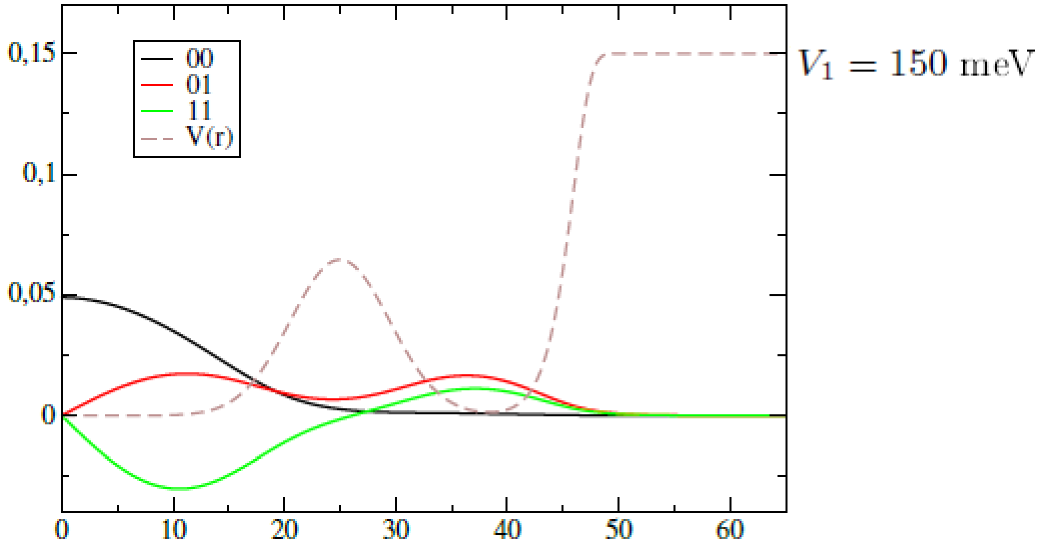


FIG. 7: The distribution of the wave functions for the first three lowest energy states for the gaussian-like confining potential. The relaxation time T_1 for DRN in this case is of the same order as for a small (inner) quantum dot.

V_0 = 30 meV, T_1 = 1.75s , (T_1 = 0.61s)

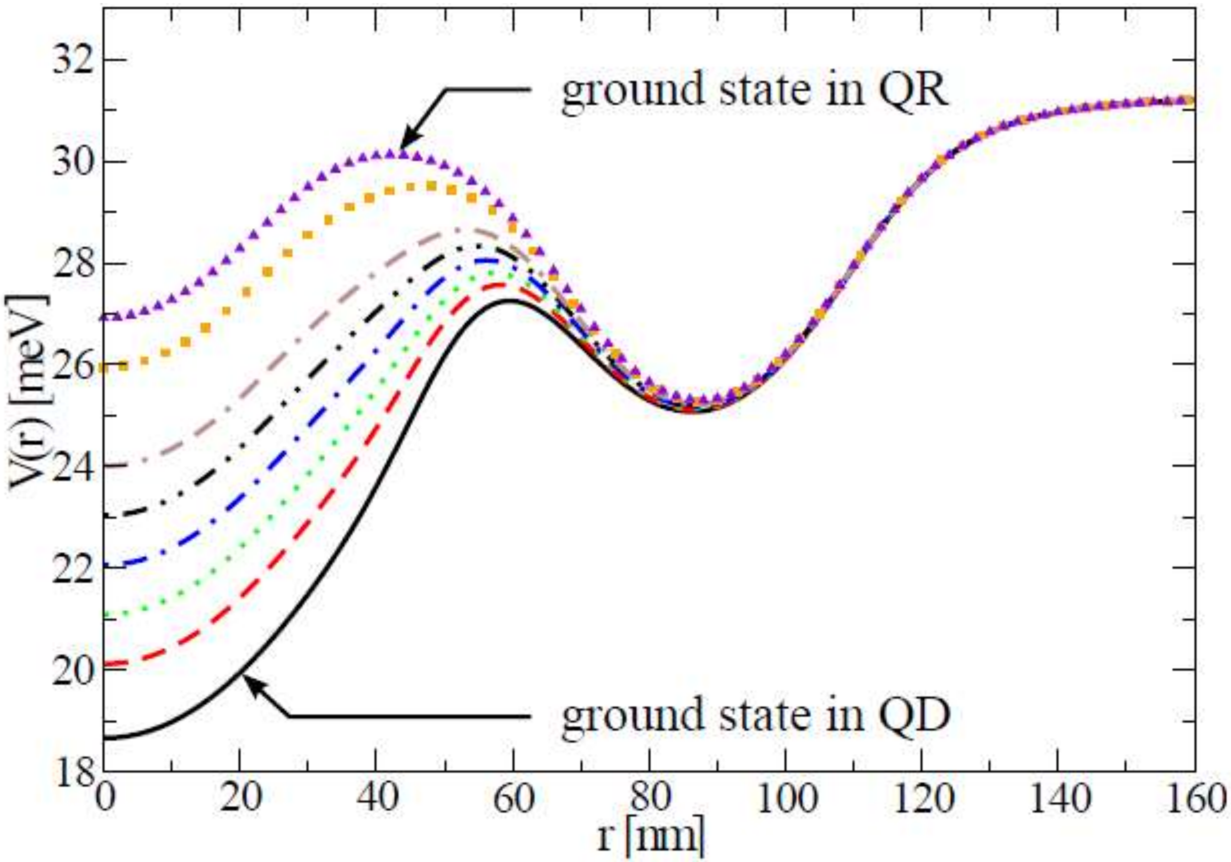
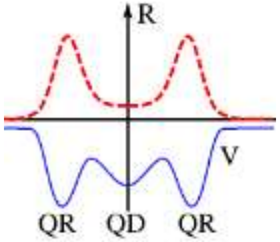


Figure 3. Cross section of the confining potential for different voltage applied to the electrodes.

$$I = -e^2 \rho f'_{\mathrm{FD}} (\mu_{\mathrm{N}} - \mu)(V_{\mathrm{S}} - V_{\mathrm{D}})$$

$$\rho = \frac{\Gamma_{\mathrm{S}} \Gamma_{\mathrm{D}}}{\Gamma}$$

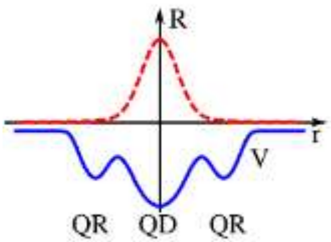
a) GS in QR



$$\Gamma^{\mathrm{ring}} \approx 0.02\,\mathrm{K}$$

$$\rho^{\mathrm{ring}} = \frac{\Gamma^{\mathrm{ring}}}{4} \approx 5 \cdot 10^{-3}\,\mathrm{K}$$

b) GS in QD



$$\Gamma^{\mathrm{dot}} \approx 4 \cdot 10^{-5}\,\mathrm{K}$$

$$\rho^{\mathrm{dot}} = \frac{\Gamma^{\mathrm{dot}}}{4} \approx 10^{-5}\,\mathrm{K}$$

$$\frac{I^{\mathrm{ring}}}{I^{\mathrm{dot}}} = 500$$

One can change the magnitude of the current and the coupling strength between DRN and S,D electrodes from large (Kondo regime) to weak by electrostatic gating

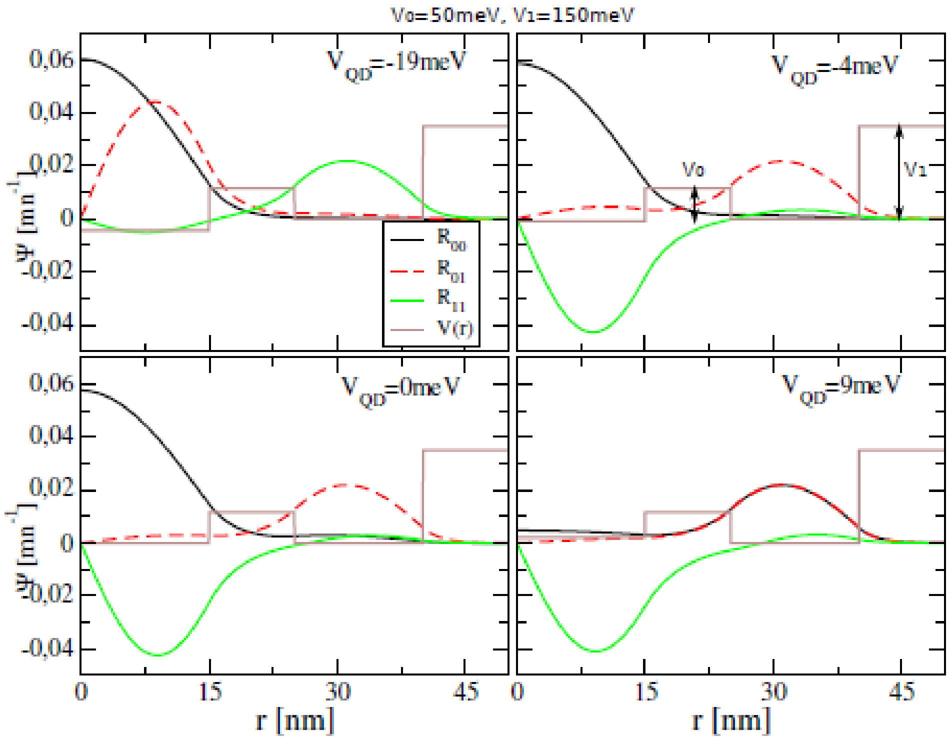
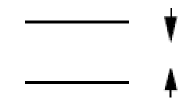


FIG. 5: The distribution of the wave functions for the first three energy states. Each panel corresponds to a different value of V_{QD}.

Coherent manipulations of spin qubits



- Initialization
- Measurement by spin to charge conversion and detection by QPC
- Universal set of quantum logic gates :

❖ Single qubit rotations by ESR or electrical gates

❖ Quantum controlled CNOTgate:

- The value of T is negated if and only if C has the value 1:
- $0_C0_T \to 0_C0_T$, $0_C1_T \to 0_C1_T$
- $1_C0_T \to 1_C1_T$, $1_C1_T \to 1_C0_T$

- E.g. – two coplanar rings with the tunable barrier

$$H = J\sigma_z^{spin,1}\sigma_z^{spin,2} + \Delta_{s1}\sigma_z^{spin,1} + \Delta_{s2}\sigma_z^{spin,2})$$

Coherent manipulations of qubits

- The qubit hamiltonian

$$H_Q = -\frac{1}{2}\Delta_z\widehat{\sigma}_z - \frac{1}{2}\Delta_x\widehat{\sigma}_x.$$

where $\widehat{\sigma}_z, \widehat{\sigma}_x$ denote Pauli spin matrices.

For the orbital qubit

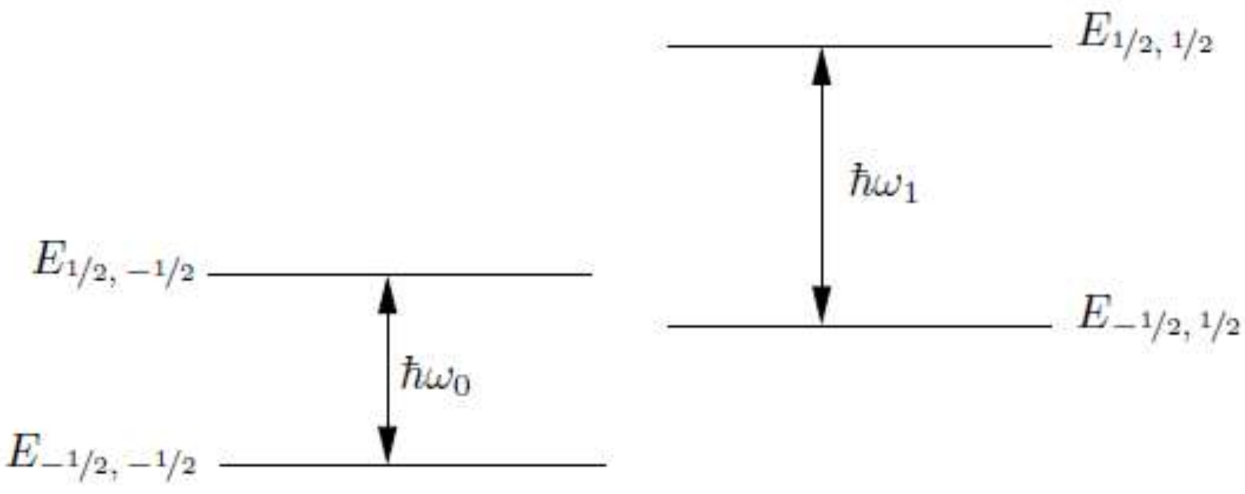
$\Delta_{z,orb}(\phi') = E_{n_\uparrow,s} - E_{m_\downarrow,s}$ can be tuned by varying the magnetic flux

$\Delta_x = \hbar\omega_{Q,orb}$ describes the amplitude of tunneling through a barrier and can be tuned by changing the barrier parameters.

For a spin qubit Δ_z and Δ_x are energy splittings in real magnetic fields B_z and B_x

Both types of qubits can be driven by microwave pulses resonant with the level separation

CNOT gate on spin qubits



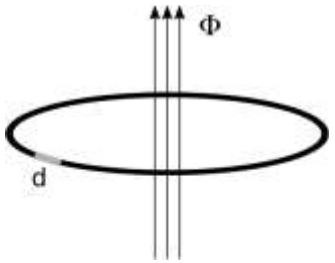
Microwave pulse of energy $\hbar\omega_1$ realizes the CNOT gate

To work with qubits one must be able to

- Prepare qubit in an initial state
- Coherently manipulate the superposition states
- Couple qubits together
- Measure their state
- Decouple from the environment that leads to decoherence

Any two state quantum system that can be addressed, controlled, coupled to its neighbors and maintained in a coherent state is potentially useful for quantum communication

Dispersion relation of an electron on the ring of radius R



$$E_{n,s} = \frac{\hbar^2}{2m^* R^2}\left[\left(n+\phi'\right)^2 + 2g_s\frac{m^*}{m_e}s\phi'\right],$$

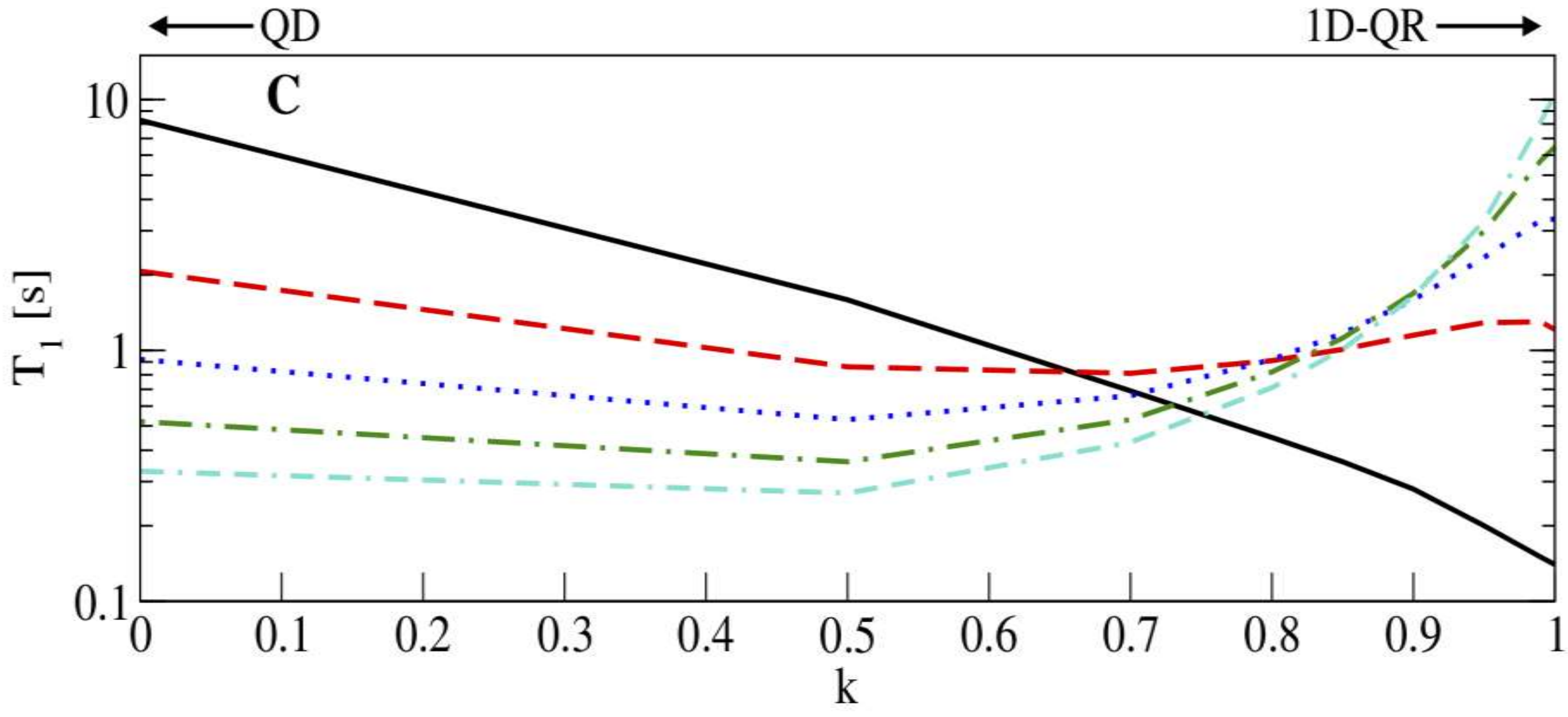
$$n = 0, \pm 1, \pm 2 \ldots \quad s = \frac{1}{2}, -\frac{1}{2} \quad \phi' = \frac{\phi}{\phi_0}, \; \phi_0 = \frac{h}{e},$$

Orbital and spin degrees of freedom to be used for quantum manipulations

1. N_e ~`200 electrons, n_F>>1 orbital states occupied successively by spin-up and spin –down electrons ;
e-e interaction well described by the constant interaction model which shifts energy spectra by $E_c=e^2/C$

E.Z. M.Kurpas, M.Szelag, J.Dajka, M.Szopa Phys. Rev. B 74, 125426 (2008),
M.Kurpas, J.Dajka, E.Z. Physica Status Solidi b244, 2470,(2007).

Single electron case *(black solid line)*



$$T_1^l = \frac{\eta}{\Delta_z^5} \frac{\Delta_l^2}{\Xi_l^4},$$

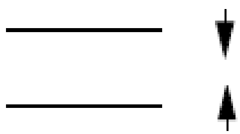
QUANTUM COMPUTING

- Prepare qubit in an initial state
- Coherently manipulate the superposition states
- Couple qubits together
- Measure their state
- Decouple from the environment that leads to decoherence

Any two state quantum system that can be addressed, controlled, coupled to its neighbors and maintained in a coherent state is potentially useful for quantum communication

Quantum dots and rings

- Quantum dot (QD)– small semiconductor quasi 2D structure
- (R~5-50nm) which can be filled with one or few electrons or holes.
- QD with single electron in magnetic field B – a natural two level system – spin qubit



$$\Delta_Z = g_s \mu_B B,$$

- We change the geometry of QD to QR – the dispersion relation changes - we get two additional (orbital – l) degrees of freedom to be used for quantum manipulations
- Applying the magnetic field B we can change the GS from l=0 to that with higher l

Decoherence

Nano-systems are expected to behave according to the laws of quantum mechanics if they are separated well from the external degrees of freedom

The important constraints on the device are relaxation and dephasing effects due to various decoherence sources.

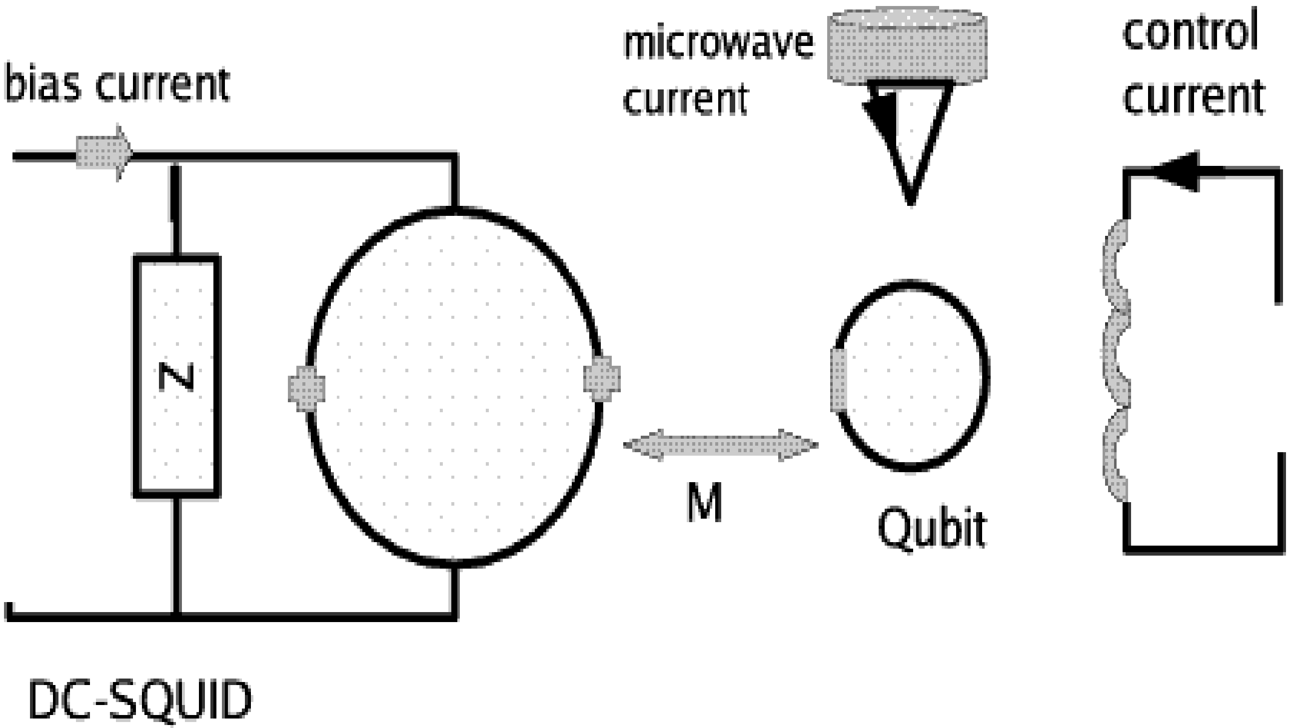
We have assumed that:

$$kT \ll \hbar\omega_{\alpha,\beta} \ll \Delta$$

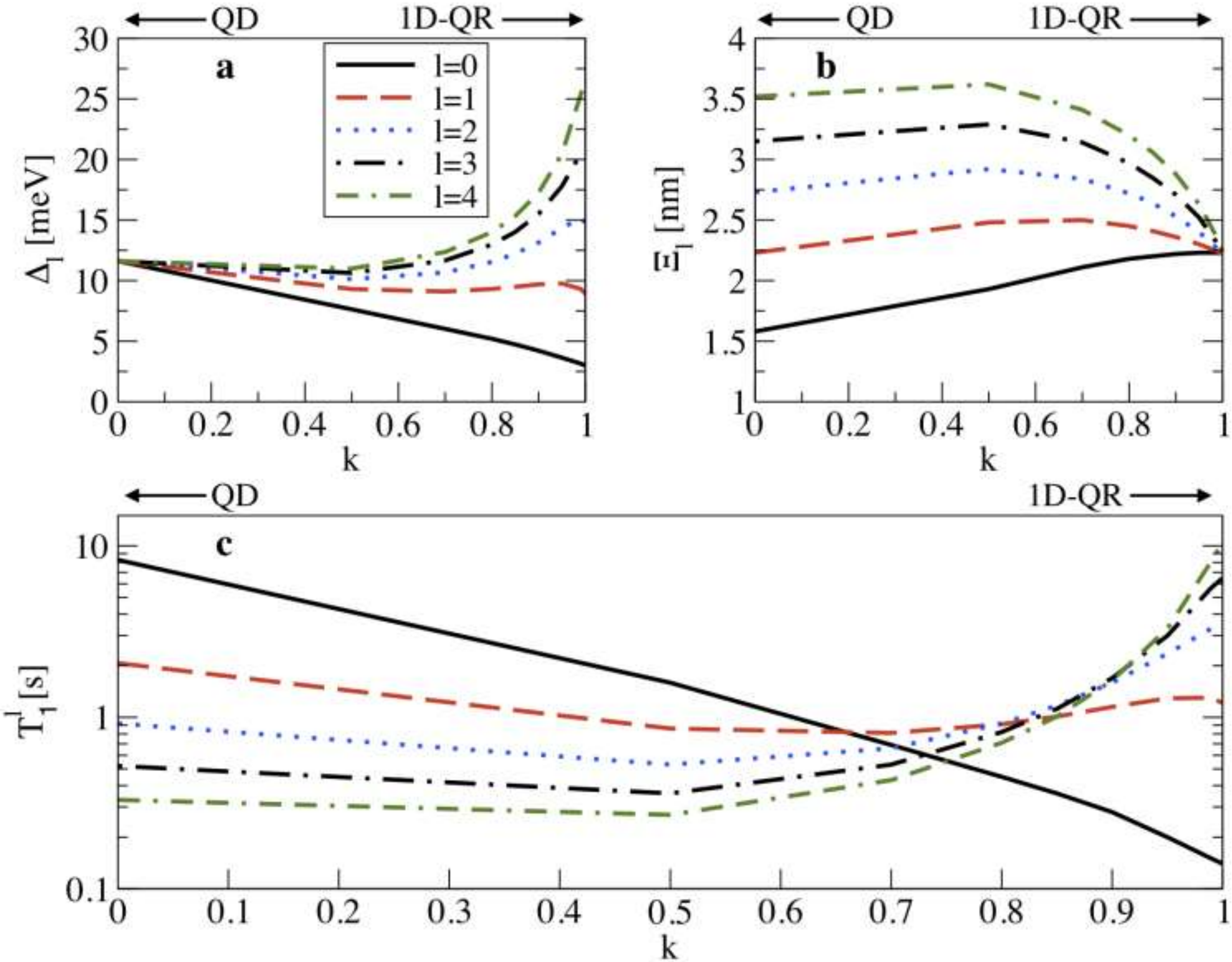
system is put in a shield, that screens it from unwanted radiation.

Decoherence

- Main decoherence mechanism for electron spins is the interaction with nuclear spins, T_2~10 -100μs;
- Several strategies to reduce randomness of the nuclear-spin system (Hanson et al., 2007);
- For qubit on a single hole spin T_2~1000μs due to the p-symmetry;
- For semiconductors of group IV (e.g.Si, SiGe) and CN with zero nuclear spin decoherence time should be longer (of the order of the relaxation time);
- Time of coherent spin manipulations ~ ns
- During T_2 more than 10^4 coherent operations can be performed allowing for QEC beeing efficient



Experimental setup for measurements on flux qubit.
(Caspar H.van der Wal et al, Eur.Phys.J.31, 111,(2003))



r_0=14nm

$$T_1^l = \frac{\eta}{\Delta_z^5}\,\frac{\Delta_l^2}{\Xi_l^4},$$

$$\left.\begin{array}{l}\hbar\omega_0 > \Delta_0,\\ \Xi_0^{\rm dot} < \Xi_0\end{array}\right\} \Rightarrow T_1^0 < T_1^{0,{\rm dot}},$$

$$\alpha_{xx} = \alpha_{yy} = 2e^2 \sum_{nl} \frac{\Xi_{nl}^2}{\Delta_{nl}}$$

n=0,1,…, l=0, ±1 …

The formula for the relexation time:

$$\Delta_{nl} = E_{nl} - E_{00}$$

$$\frac{1}{T_1} = \frac{4\Delta_z^5}{\eta} \left(\Gamma^{01} + \Gamma^{11}\right)^2,$$

$$\Xi_{nl} = \int_0^\infty R_{00}^* R_{nl} r^2 dr \quad l = \pm 1$$

$$\Gamma^{01} = \frac{\Xi_{01}^2}{\Delta_{01}}, \quad \Gamma^{11} = \frac{\Xi_{11}^2}{\Delta_{11}}.$$

$$\eta = \frac{\hbar^5}{\Lambda_p (2\pi)^4 (m^*)^2}, \quad \Lambda_p = 0.007$$

for GaAs based systems

Conclusions

- Quantum rings with one or few electrons can be effectively reduced to a two- state system with two external control parameters.

- Orbital qubit:

- The two states carry opposite persistent currents and are coupled by tunneling which leads to a quantum superposition of states.

- The qubit can be driven by microwave pulses .

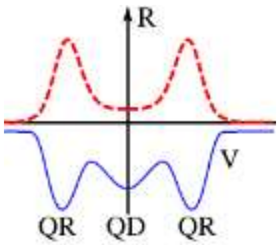
- Flux state can be measured by a separate SQUID magnetometer.

- Two or more qubits can be coupled by the flux the circulating currents generate.

$$I = -e^2 \rho f'_{\mathrm{FD}} \left(\mu_{\mathrm{N}} - \mu\right) \left(V_{\mathrm{S}} - V_{\mathrm{D}}\right)$$

$$\rho = \frac{\Gamma_{\mathrm{S}} \Gamma_{\mathrm{D}}}{\Gamma}$$

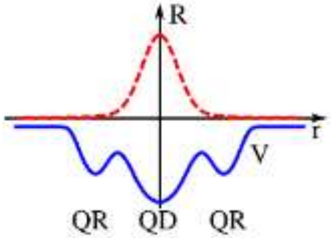
a) GS in QR



$$\Gamma^{\mathrm{ring}} \approx 0.02\,\mathrm{K}$$

$$\rho^{\mathrm{ring}} = \frac{\Gamma^{\mathrm{ring}}}{4} \approx 5 \cdot 10^{-3}\,\mathrm{K}$$

b) GS in QD



$$\Gamma^{\mathrm{dot}} \approx 4 \cdot 10^{-5}\,\mathrm{K}$$

$$\rho^{\mathrm{dot}} = \frac{\Gamma^{\mathrm{dot}}}{4} \approx 10^{-5}\,\mathrm{K}$$

$$\frac{I^{\mathrm{ring}}}{I^{\mathrm{dot}}} = 500$$

One can change the magnitude of the current and the coupling strength between DRN and S,D electrodes from large (Kondo regime) to weak by electrostatic gating

$$I = -e^2 \frac{\Gamma_S \Gamma_D}{\Gamma} f'_{FD}(\mu_N - \mu)(V_S - V_D)$$

(Kouwenhoven, Beenaker)

$$\mu_{S(D)} = \mu \mp |e| V_{S(D)}, \quad \Gamma = \Gamma_S + \Gamma_D$$

I depends on tunnel rates Γ_S, Γ_D

via $\rho = \frac{\Gamma_S \Gamma_D}{\Gamma}$

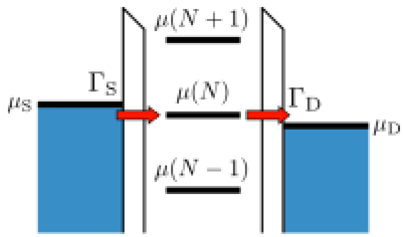
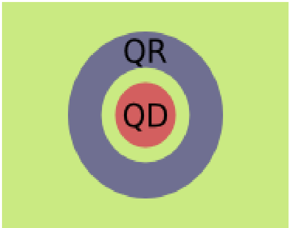


Fig.2

In DRN additional possibility to control transport of single electrons by changing Γ_S, Γ_D

$$\Gamma_S = \Gamma_D = \frac{\Gamma}{2}, \quad \Gamma \ll T, \Delta, E_C$$



We assume:

• *Fig.2* with e.g. N =1, T~ 0.1K

Electrical control of optical, coherent and conducting properties of quantum nanostructures

E. Zipper, M. Kurpas, M. M. Maśka

Instytut Fizyki, Uniwersytet Sląski w Katowicach, Poland