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Electrically-based spin switching in hetero-dimensional quantum dot device

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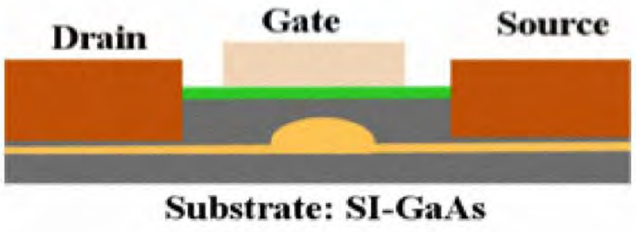
Overview

- *Back Ground*
- *Introduction of single electron transistor*
- *Introduction of 2D electron Gas in Fock-Darwin states*
- *Hamiltonian of III-V type Semiconductor*
- *Effect of Bulk Inversion symmetry (Dresselhauss Effect)*
- *Effect of Structural Inversion symmetry (Rashba Effect)*
- *Results:*
- *Illustrations of Asymmetric confining potential in III-V semiconductor (Based on DFT and Finite element method).*
- *Illustrations of few eigen states and wave functions in this realistic asymmetric confining potentials.*
- *Calculations of electron g-value in symmetric and Asymmetric confining potentials*
- *Summary and Conclusions*

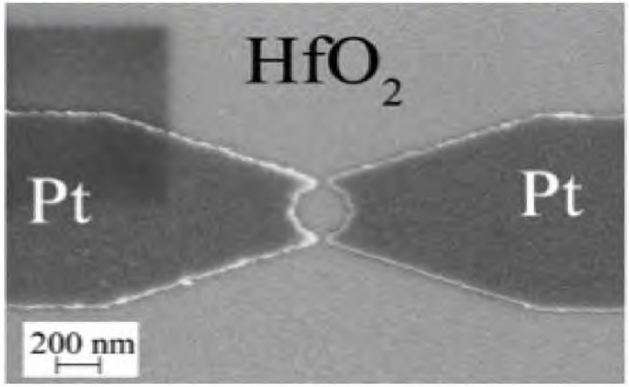
Bandyopadhyay:
Phys. Rev. B 61, 13813 (2000)

Global ac magnetic field

Possible spin-SET prototype (Oktyabrsky)



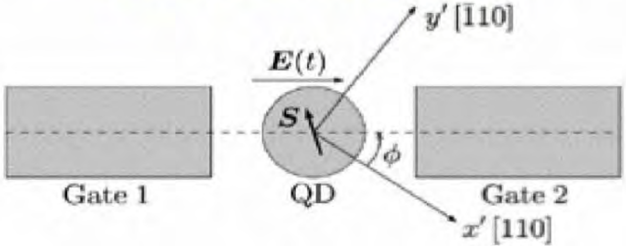
SEM of a 2D-0D heterodimensional prototype



Goal: Development for planar SET prototype using:

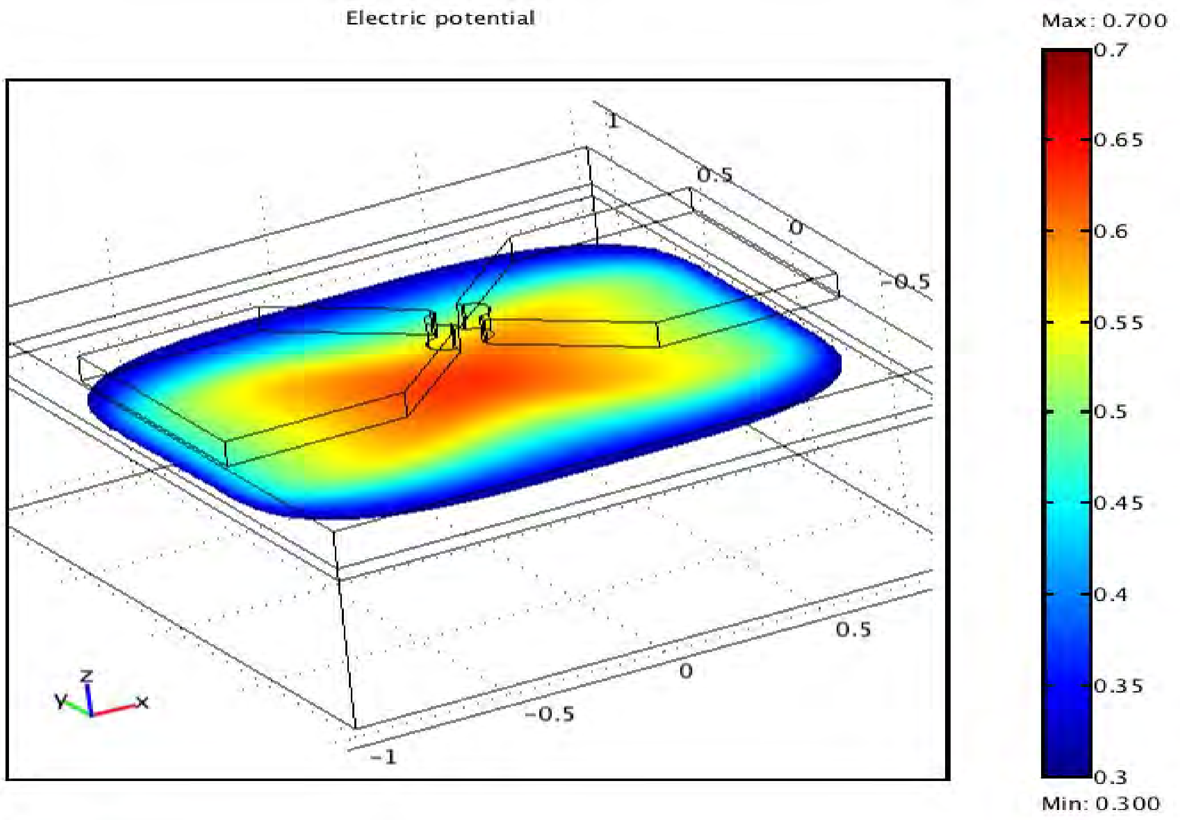
- High-k gate stack on InGaAs/AlGaAs structure
- Hetero-dimensional control of 2D-1D-0D electrons
- Eventually self-assembled InAs QD

Schematic for EDSR spin control [Loss et al ., PRB 2006]



Results

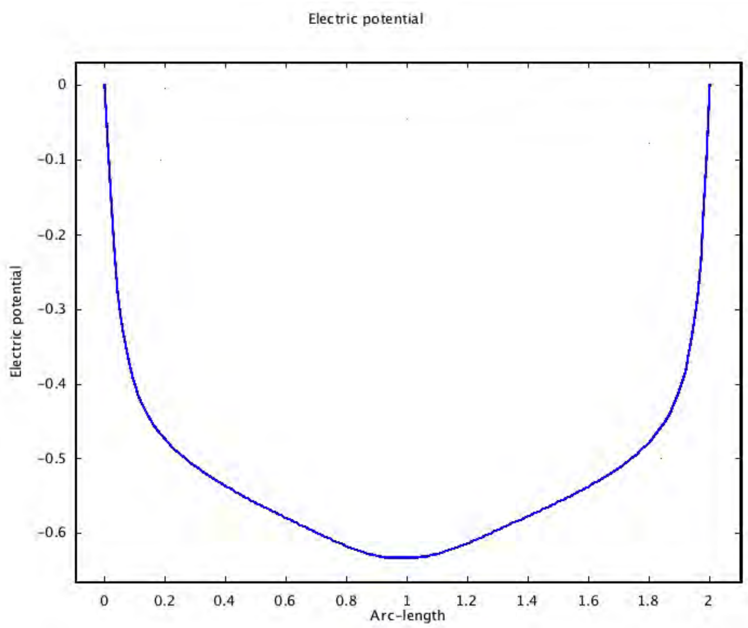
Electric potential in conducting (quantum well) layer

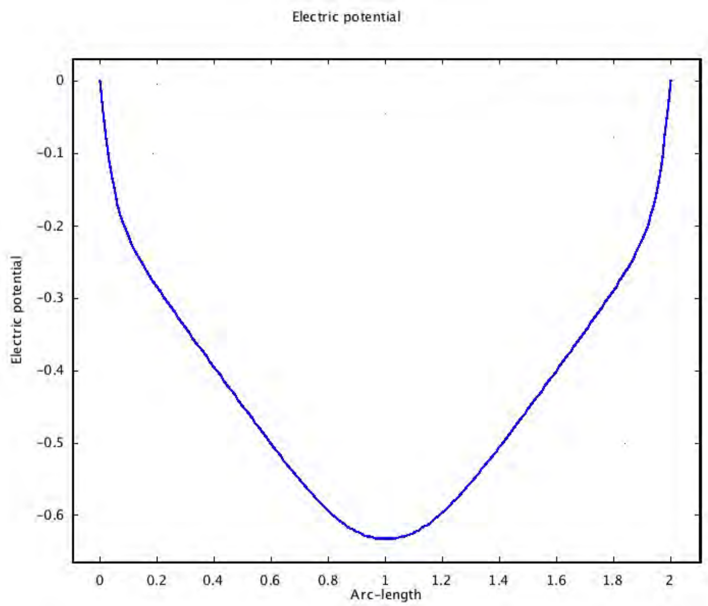


Anisotropic confining potentials

potential along symmetry axis

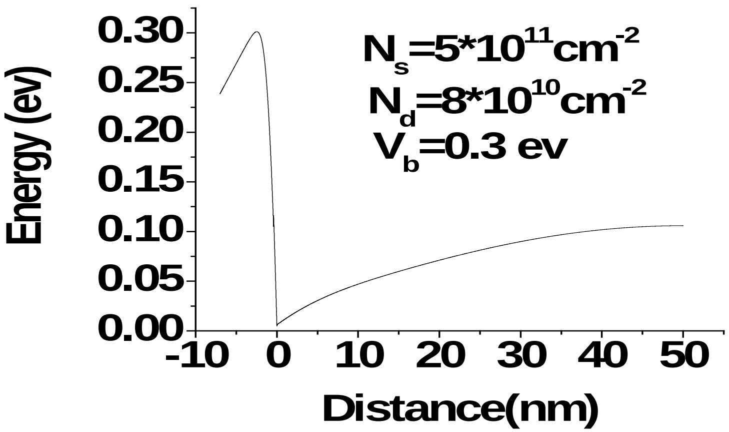
potential normal to symmetry axis

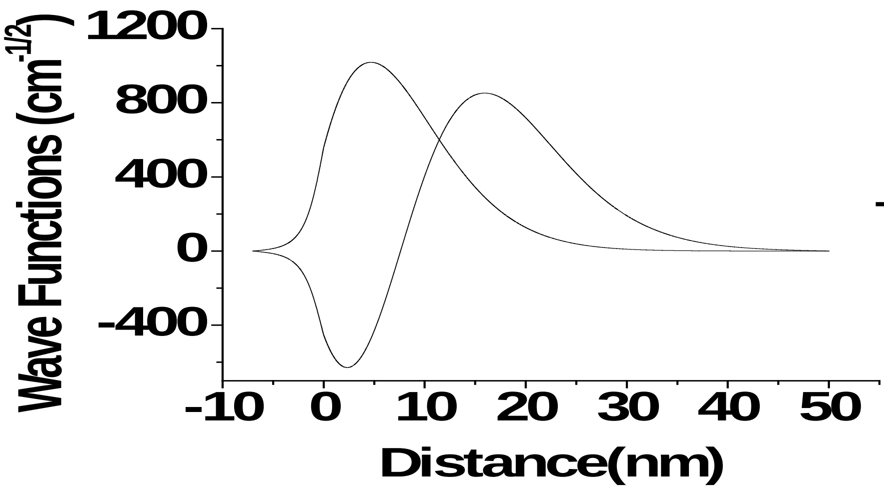




Results: Based on DFT and Finite element method

- Realistic confining potential along growth direction
- Illustration of wave functions in the realistic asymmetric confining potential





Electron moves in an effective potentials

$$V(z) = -e\,\phi(z) + V_{xc}(z)$$

$$-\frac{\hbar^2}{2}\frac{d}{dz}\frac{1}{m(z)}\frac{d\psi_i(z)}{dz} + V(z)\psi_i(z) = E_i\,\psi_i(z)$$

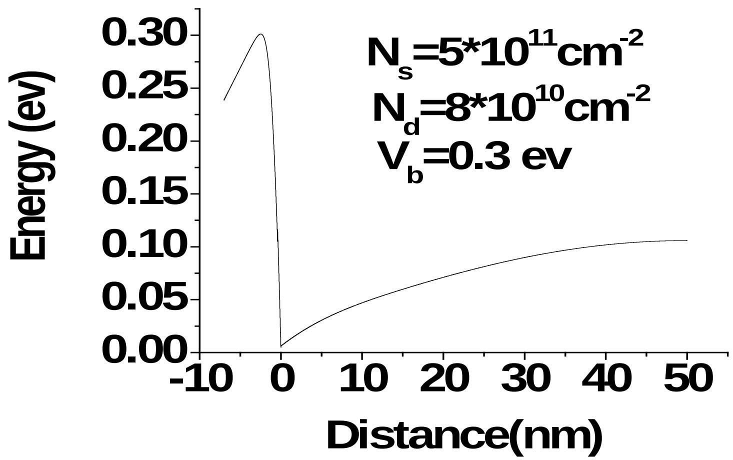
$$\frac{d}{dz}\varepsilon_0\kappa(z)\frac{d\phi(z)}{dz} = e\sum N_i\,\psi_i^2(z) - \rho_I(z)$$

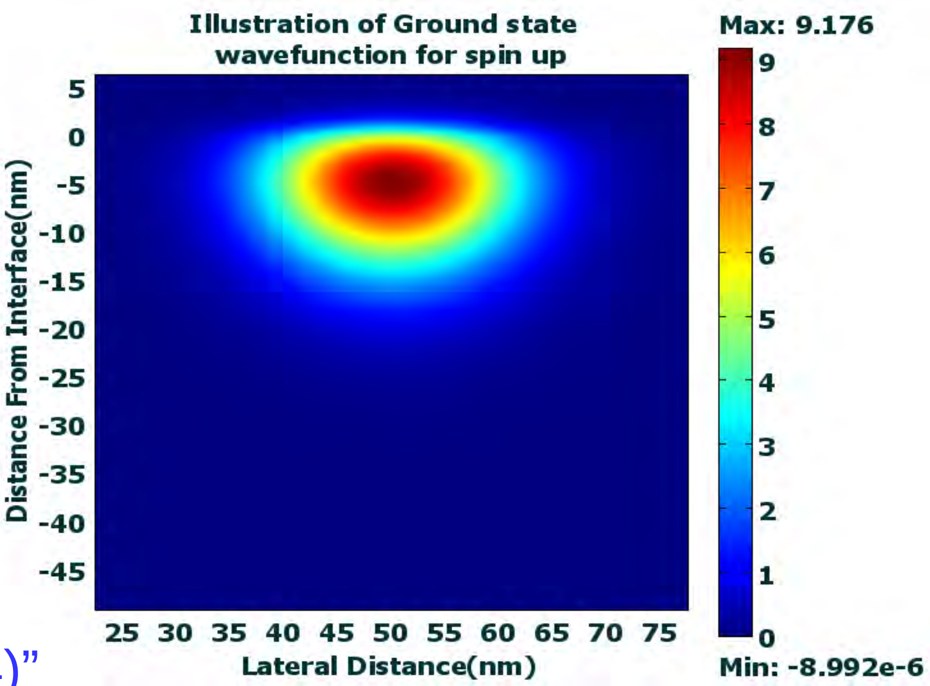
Also See PRB Vol 30,840 (1984)

Results

Strategy: simple to complex

- ***Use Finite Element Method***
- ***Simple: Solve electrostatic problem with simplified (classical) conductors to determine confining potentials***
- ***Solve Schrödinger equation in fixed potential and effective mass approximation***
- ***Determine wave functions and electric field effects.***
- ***Complex: Self-consistent Schrödinger/Poisson***
- ***Exchange-correlation effects (DFT)***





“see also Phys. Rev. B 30, 840 (1984)”

Electrical control of "g" (physical mechanisms)

Wave function overlap: ***electric fields can "move" the wave function to sample different materials (e.g. GaAs has g = -0.44; AlGaAs has g = +0.4) see PRB 64, 041307 (2001)***

Spin-orbit: ***(see PRB 68, 155330 (2003)***

Dresselhaus: $H_{D1} \propto (-\sigma_x P_x + \sigma_y P_y)$

$$H_{D2} \propto (\sigma_x P_x P_y^2 - \sigma_y P_y P_x^2)$$

Rashba: $H_R \propto E(\sigma_x P_y - \sigma_y P_x)$

Hamiltonian of QD in III-V semiconductor

Hamiltonian for a single electron bound to a heterojunction QD

$$\mathrm{H} = \mathrm{H}_0 + \mathrm{H}_z + \mathrm{H}_R + \mathrm{H}_{D1} + \mathrm{H}_{D2}$$

$$\mathrm{H}_0 = \frac{\vec{\mathrm{P}}^2}{2\mathrm{m}^*} + \frac{1}{2}\mathrm{m}^*\omega_0^2\,\mathrm{r}^2 + \frac{1}{2}\mathrm{g}_0\,\mu_\mathrm{B}\sigma_z\mathrm{B}$$

Kinetic momentum $\vec{\mathrm{P}} = \vec{p} + \frac{e}{c}\vec{\mathrm{A}}$

Canonical momentum $\vec{p} = -i\hbar\left(\partial_\mathrm{x},\partial_\mathrm{y},0\right)$

Vector Potential $\vec{\mathrm{A}} = \frac{\mathrm{B}}{2}\left(-\mathrm{y},\mathrm{x},0\right)$

PRB 68,155330(2003)

Analytical solution of H0

$$H_0 = \hbar\omega_+\left(n_+ + \frac{1}{2}\right) + \hbar\omega_-\left(n_- + \frac{1}{2}\right) + \frac{1}{2} g_0 \mu_B \sigma_z B$$

Where $\omega_\pm = \Omega \pm \frac{\omega_c}{2}$

renormalized dot frequency $\Omega = \sqrt{\omega_0^2 + \frac{\omega_c^2}{4}}$

Cyclotron frequency $\omega_c = \frac{eB}{m^* c}$

PRB 68,155330(2003)

Fock Darwin Radius $\ell = \sqrt{\frac{\hbar}{m^*}\Omega}$

Number Operator $n_\pm = a_\pm^\dagger a_\pm$

$$H = H_0 + H_z + H_R + H_{D1} + H_{D2}$$

2nd term represents the QW confinement in growth direction

$$H_z = \frac{P_z^2}{2m^*} + V(z)$$

$$V(z) = e\,E\,z \qquad For \quad z \geq 0$$

$$= \quad \propto \qquad For \quad z < 0$$

PRB 68,155330 (2003)

$$H = H_0 + H_z + H_R + H_{D1} + H_{D2}$$

The structural inversion asymmetry in V(z) leads to the Rashba (spin orbit) interaction

$$H_R = \frac{\alpha_R \, e \, E}{\hbar}\left(\sigma_x P_y - \sigma_y P_x\right)$$

Phys. Rev. B 68,155330(2003); Phys. Rev. B 55,16293(1997)
Phys. Rev. B 50,8523 (1994)

$$\mathrm{H} = \mathrm{H}_0 + \mathrm{H}_z + \mathrm{H}_R + \mathrm{H}_{D1} + \mathrm{H}_{D2}$$

- Bulk inversion asymmetry is associated with Dresselhauss interaction
- Two Spin orbit terms -Linear in momenta
  -Cubic in momenta

$$\mathrm{H}_{D1} = \frac{0.7794\,\gamma_c k^2}{\hbar}\left(-\sigma_x \mathrm{P}_x + \sigma_y \mathrm{P}_y\right)$$

$$\mathrm{H}_{D2} = \frac{\gamma_c}{\hbar^3}\left(-\sigma_x \mathrm{P}_x \mathrm{P}_y^2 - \sigma_y \mathrm{P}_y \mathrm{P}_x^2\right) + H.c.$$

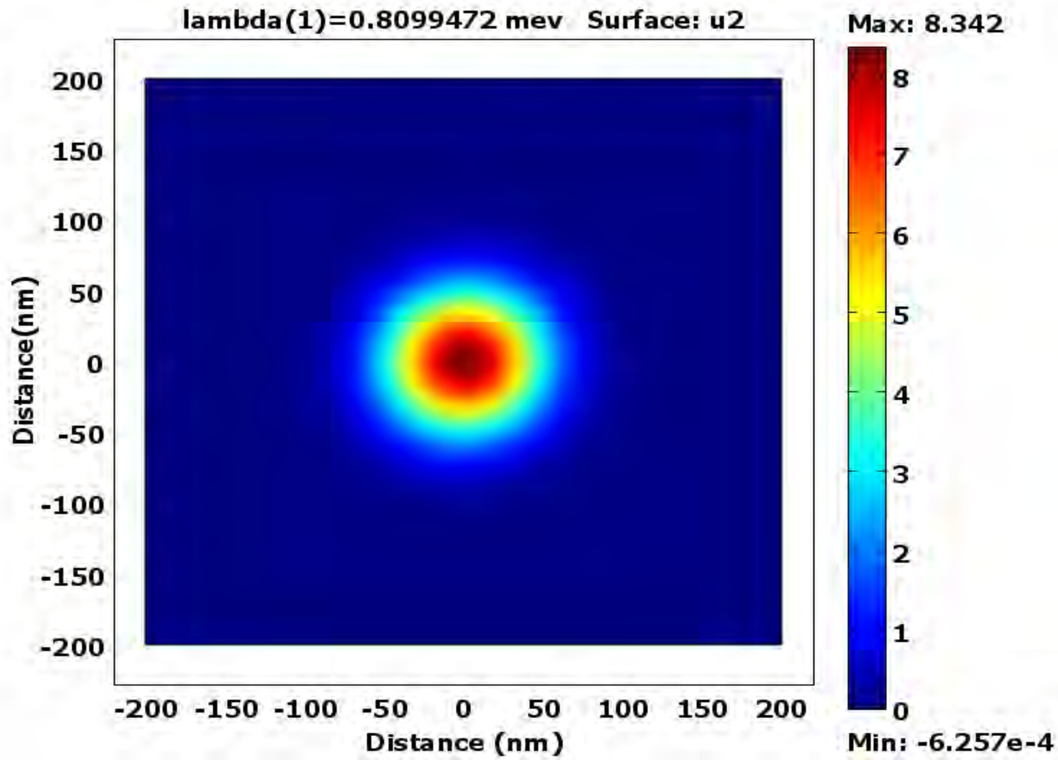
Phys. Rev. B 68,155330(2003); Phys. Rev. B 55,16293(1997)
Phys. Rev. B 50,8523 (1994)

Results

$$H = H_0 + H_z + H_R + H_{D1} + H_{D2}$$

$$H_0 = \frac{\vec{P}_x^2 + \vec{P}_y^2}{2m^*} + \frac{1}{2} m^* \omega_0^2 \left(x^2 + y^2 \right) + \frac{1}{2} g_0 \mu_B \sigma_z B$$

Illustration of QD in symmetric confining potential including spin

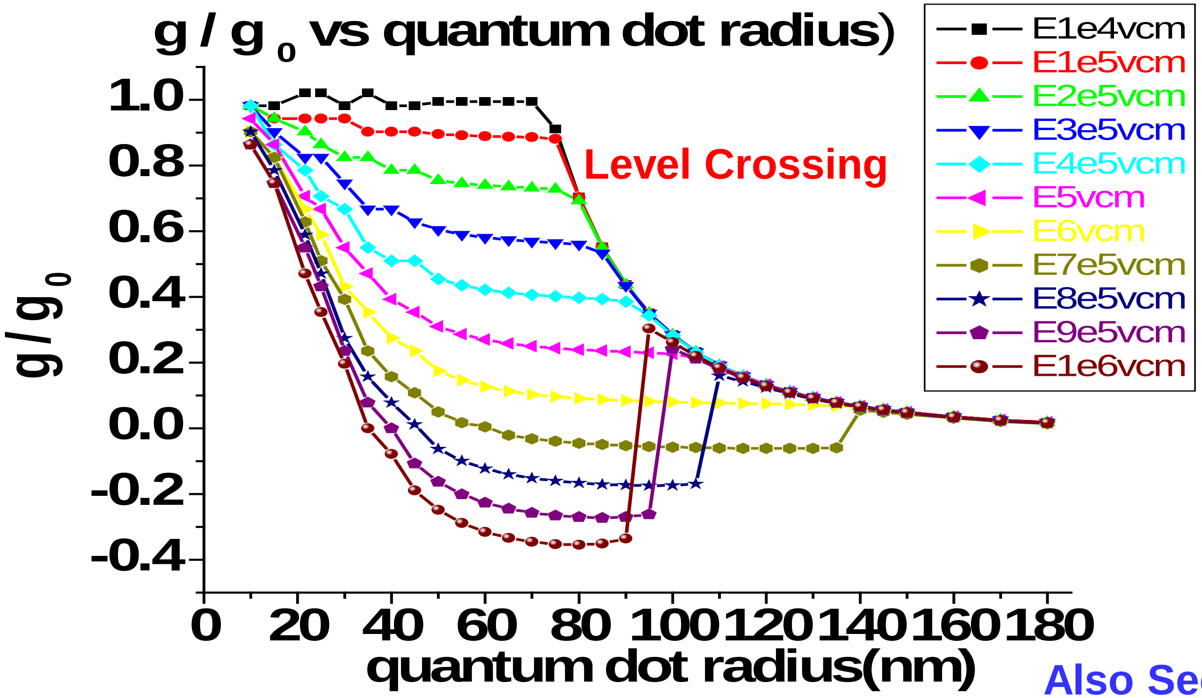


Results

Electric Field Control of Spin in Parabolic Confining Potential

$$H = H_0 + H_z + H_R + H_{D1} + H_{D2}$$

$$H_0 = \frac{\vec{P}_x^2 + \vec{P}_y^2}{2m^*} + \frac{1}{2} m^* \omega_0^2 \left(x^2 + y^2 \right) + \frac{1}{2} g_0 \mu_B \sigma_z B$$



$$g = \frac{(E_2 - E_1)}{\mu_B B}$$

$$QD \ \ Radius \quad \ell_0 = \sqrt{\frac{\hbar}{m^* \omega_0}}$$

Where E_1 and E_2 are Ground and first excited states including spin

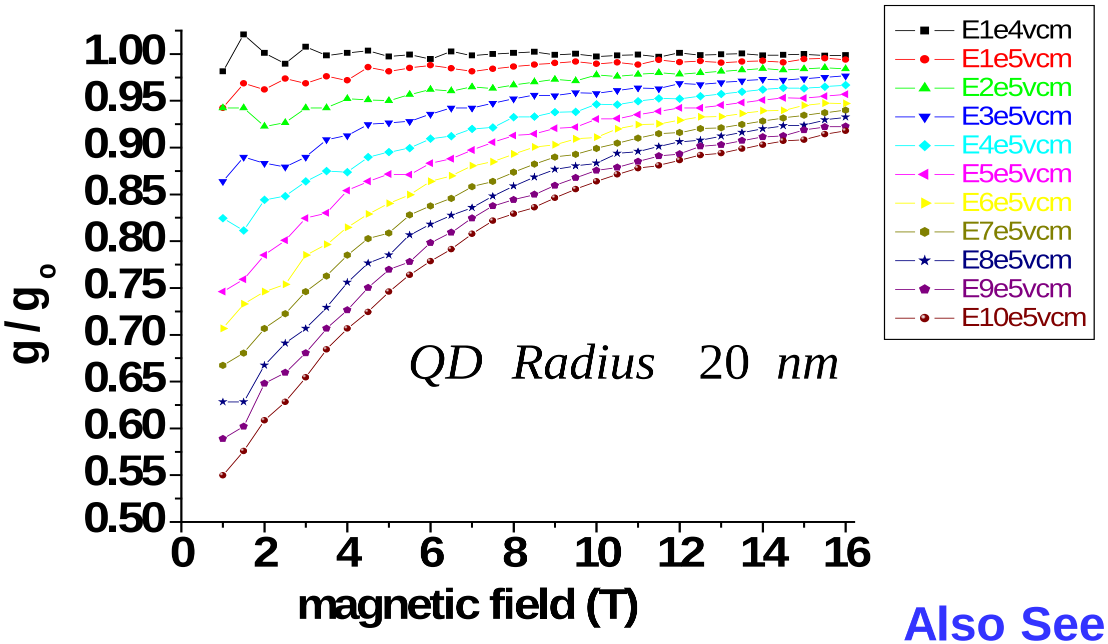
Also See Phys. Rev. B 68, 55330 (2003)

Results

Magnetic Field Control of Spin in Parabolic Potential Confining Potential

$$\mathrm{H} = \mathrm{H}_0 + \mathrm{H}_z + \mathrm{H}_R + \mathrm{H}_{D1} + \mathrm{H}_{D2}$$

$$\mathrm{H}_0 = \frac{\vec{\mathrm{P}}_x^2 + \vec{\mathrm{P}}_y^2}{2\,\mathrm{m}^*} + \frac{1}{2}\mathrm{m}^*\,\omega_0^2\left(x^2 + y^2\right) + \frac{1}{2}g_0\,\mu_\mathrm{B}\sigma_z\mathrm{B}$$



$$g = \frac{(\mathrm{E}_2 - \mathrm{E}_1)}{\mu_\mathrm{B}\,\mathrm{B}}$$

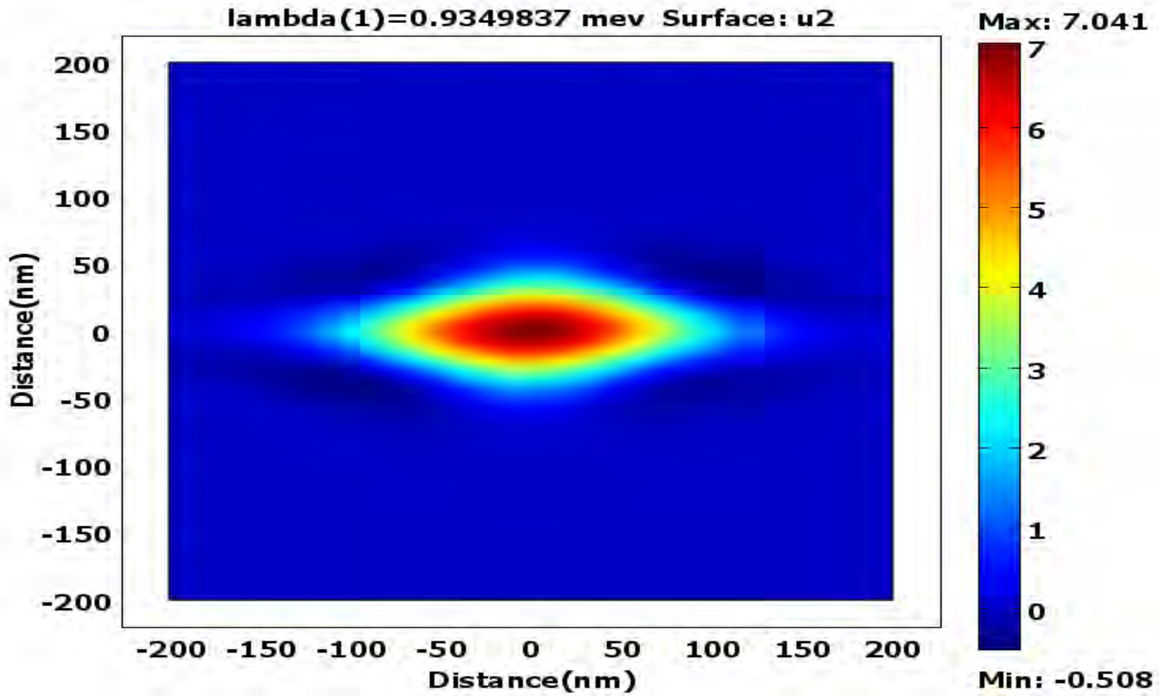
Also See Phys. Rev. B 68, 55330 (2003)

New Results

$$H = H_0 + H_z + H_R + H_{D1} + H_{D2}$$

$$H_0 = \frac{\vec{P}_x^2 + \vec{P}_y^2}{2m^*} + \frac{1}{2} m^* \omega_0^2 \left(\alpha x^2 + \beta y^2 \right) + \frac{1}{2} g_0 \mu_B \sigma_z B$$

Illustration of QD in Asymmetric confining potential including spin



$\beta = 2\alpha$

QD Radius 20 *nm*

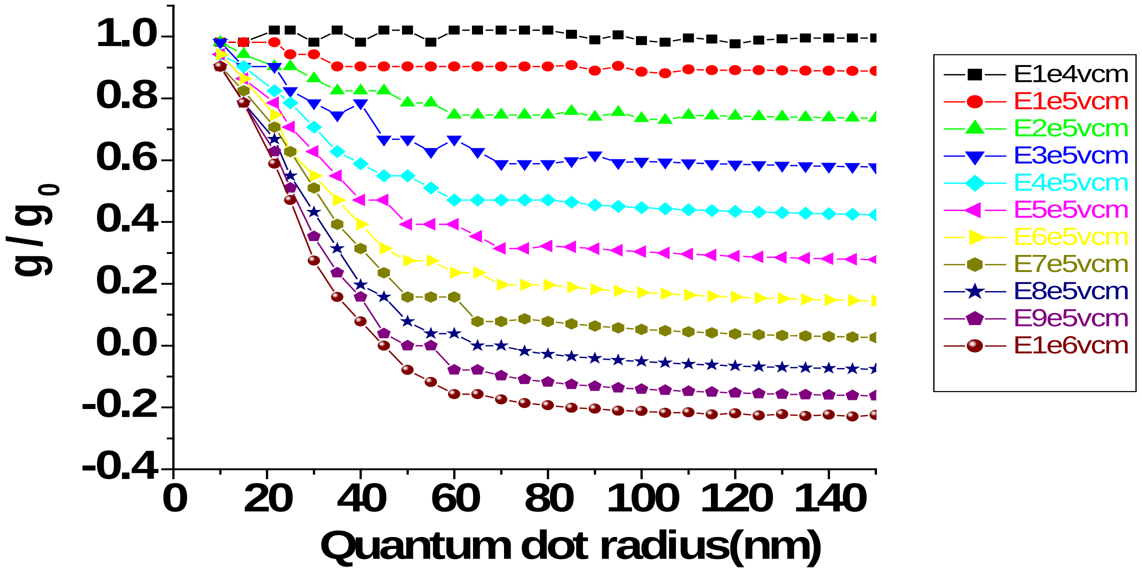
New Results

Electric Field Control of Spin in Asymmetric Confining Parabolic Potential

$$H = H_0 + H_z + H_R + H_{D1} + H_{D2}$$

$$H_0 = \frac{\vec{P}_x^2 + \vec{P}_y^2}{2m^*} + \frac{1}{2} m^* \omega_0^2 \left(\alpha x^2 + \beta y^2\right) + \frac{1}{2} g_0 \mu_B \sigma_z B$$

$\beta = 2\alpha$ *and QD Radius* 120 *nm*



$$g = \frac{(E_2 - E_1)}{\mu_B B}$$

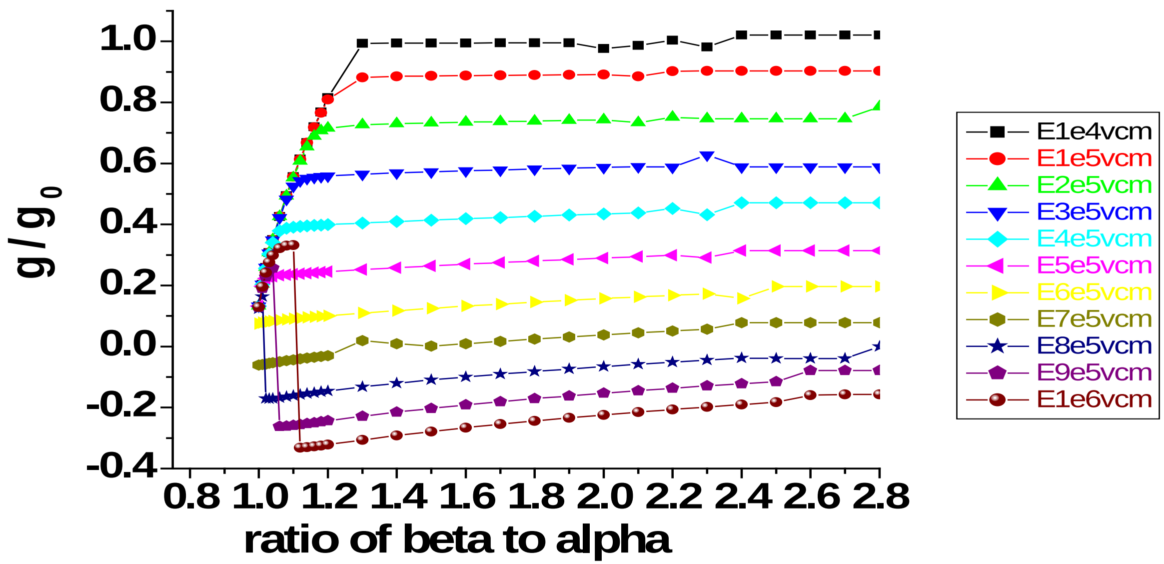
QD Radius $\ell_0 = \sqrt{\frac{\hbar}{m^* \omega_0}}$

New Results

Electric Field Control of Spin in Asymmetric Confining Parabolic Potential

$$H = H_0 + H_z + H_R + H_{D1} + H_{D2}$$

$$H_0 = \frac{\vec{P}_x^2 + \vec{P}_y^2}{2m^*} + \frac{1}{2} m^* \omega_0^2 \left(\alpha x^2 + \beta y^2\right) + \frac{1}{2} g_0 \mu_B \sigma_z B$$



$\alpha = 1, \beta = Variable$ and

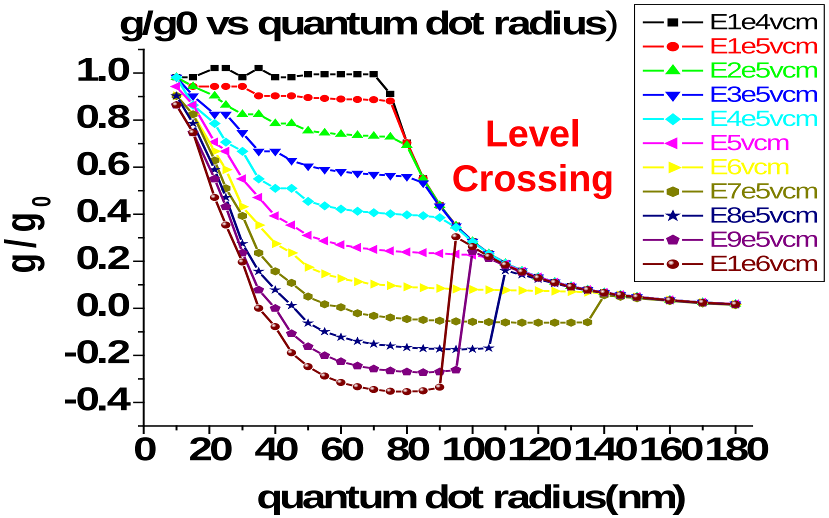
QD Radius 120 nm

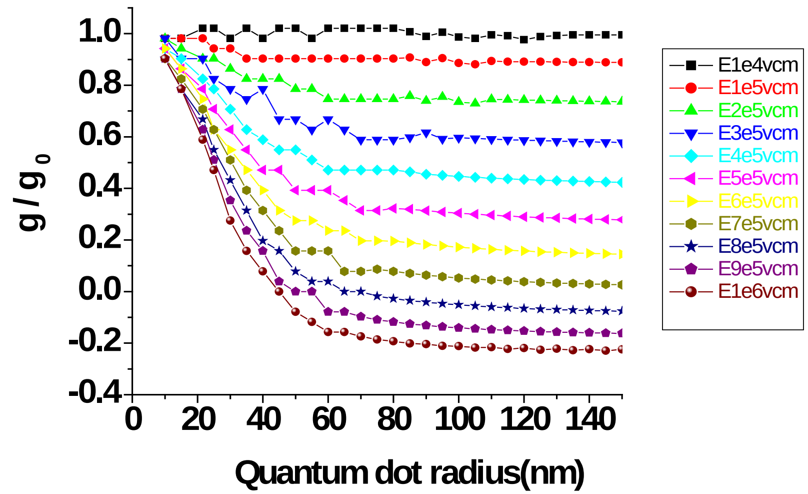
$$g = \frac{(E_2 - E_1)}{\mu_B B}$$

Results *Electric Field Control of Spin in Parabolic Confining Potential*

$$H = H_0 + H_z + H_R + H_{D1} + H_{D2}$$

$$H_0 = \frac{\vec{P}_x^2 + \vec{P}_y^2}{2m^*} + \frac{1}{2} m^* \omega_0^2 \left(x^2 + y^2\right) + \frac{1}{2} g_0 \mu_B \sigma_z B$$





$$g = \frac{(E_2 - E_1)}{\mu_B B} \quad \textit{and} \quad \textit{QD Radius} \quad \ell_0 = \sqrt{\frac{\hbar}{m^* \omega_0}}$$

Where E_1 and E_2 are Ground and first excited states including spin

See also Phys. Rev. B 68, 55330 (2003)

Summary and Conclusions

- *A 3D finite-element simulation strategy to study electrical spin control is being pursued*
- *E-field effects on electron "g" value due to spin orbit interactions in symmetric and asymmetric confining potentials have been demonstrated.*
- *Anisotropic confining potentials for realistic device enhance spin-orbit effects*