Heavy-Hole Spin Resonance in Quantum Dots

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ABSTRACT

We propose and analyze a new method for manipulation of a heavy hole spin in a quantum dot [1]. Due to spin-orbit coupling between states with different orbital momenta and opposite spin orientations, an applied rf electric field induces transitions between spin-up and spin-down states. This scheme can be used for detection of heavy-hole spin resonance signals, for the control of the spin dynamics in two-dimensional systems, and for determining important parameters of heavy-holes such as the effective g-factor, mass, spin-orbit coupling constants, spin relaxation and decoherence times.

Effective Hamiltonian for Heavy Holes

$$H = \frac{1}{2m}(P_x^2 + P_y^2) + \frac{m\omega_0^2}{2}(x^2+y^2) - \frac{1}{2}g_\perp \mu_B B_\perp \sigma_z + H_{\rm SO},$$

$$H_{\rm SO} = i\alpha P_-^3\sigma_+ + \beta P_- P_+ P_- \sigma_+ + \gamma B_- P_-^2 \sigma_+ + h.c.,$$

where $\alpha = 3\gamma_0\alpha_R\langle E_z\rangle/2m_0\Delta$, $\beta = 3\gamma_0\gamma_1\langle P_z^2\rangle/2m_0\eta\Delta$, $\gamma = 3\gamma_0\kappa\mu_{\rm B}/m_0\Delta$, and $\Delta = E_0^{hh} - E_0^{lh}$.

$$|+\rangle = \left|0,0,+\frac{3}{2}\right\rangle + i\beta_1^+\left|1,+1,-\frac{3}{2}\right\rangle + \beta_2^+\left|3,+1,-\frac{3}{2}\right\rangle + \alpha^+\left|3,+3,-\frac{3}{2}\right\rangle + \gamma^+ B_+\left|2,+2,-\frac{3}{2}\right\rangle,$$

$$|-\rangle = \left|0,0,-\frac{3}{2}\right\rangle + i\beta_1^-\left|1,-1,+\frac{3}{2}\right\rangle + \beta_2^-\left|3,-1,+\frac{3}{2}\right\rangle + \alpha^-\left|3,-3,+\frac{3}{2}\right\rangle + \gamma^- B_-\left|2,-2,+\frac{3}{2}\right\rangle,$$

where $\beta_1^\pm = \beta(ml)^3\omega_\pm(\omega_-^2+\omega_+^2)/\hbar\omega_{\rm D}^\pm$, $\gamma^\pm = 3\sqrt{2}\gamma_0\kappa\mu_{\rm B}(ml)^2\omega_\pm^2/m_0\Delta\hbar\omega_\parallel^\pm$, $\omega_\pm = \Omega \pm \omega_c/2$, and $\Omega = \sqrt{\omega_0^2 + \omega_c^2/4}$.

Spin Relaxation and Decoherence

$$\frac{1}{T_1} = \frac{1}{T_1^{\rm DSO}} + \frac{1}{T_1^{\parallel}} + \frac{1}{T_1^{\rm RSO}},$$

$$\frac{1}{T_1^{\rm DSO}} = \frac{\beta^2\hbar\omega_{\rm Z}^3 m^2}{2^4\pi\rho}\left(N_{\omega_{\rm Z}}+\frac{1}{2}\right)\left(\frac{\omega_-}{\omega_- - \omega_{\rm Z}} - \frac{\omega_+}{\omega_+ + \omega_{\rm Z}}\right)^2 \sum_\alpha \frac{e^{-\omega_{\rm Z}^2 l^2/2s_\alpha^2}}{s_\alpha^5} I^{(3)},$$

$$\frac{1}{T_1^{\parallel}} = \frac{\gamma^2 B_\parallel^2\hbar\omega_{\rm Z}^5}{2^7\pi\rho\Omega^4}\left(N_{\omega_{\rm Z}}+\frac{1}{2}\right)\left(\frac{\omega_-^2}{2\omega_- - \omega_{\rm Z}} + \frac{\omega_+^2}{2\omega_+ + \omega_{\rm Z}}\right)^2 \sum_\alpha \frac{e^{-\omega_{\rm Z}^2 l^2/2s_\alpha^2}}{s_\alpha^7} I^{(5)},$$

$$\frac{1}{T_1^{\rm RSO}} = \frac{\alpha^2\hbar^3\omega_{\rm Z}^7}{2^8\pi\rho\Omega^6}\left(N_{\omega_{\rm Z}}+\frac{1}{2}\right)\left(\frac{\omega_-^3}{3\omega_- - \omega_{\rm Z}} - \frac{\omega_+^3}{3\omega_+ + \omega_{\rm Z}}\right)^2 \sum_\alpha \frac{e^{-\omega_{\rm Z}^2 l^2/2s_\alpha^2}}{s_\alpha^9} I^{(7)}.$$

At low temperatures ($\hbar\omega_{ph} \gg T$) [2], $T_2 = 2T_1$.

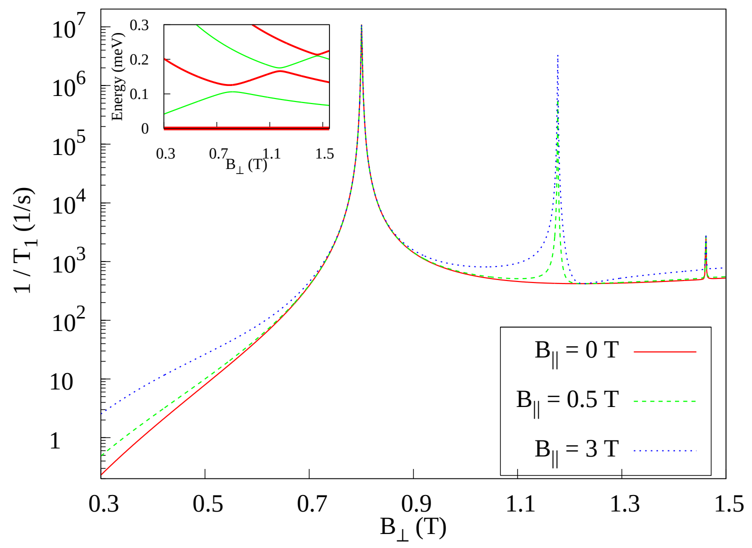

Fig. 1. Heavy hole spin relaxation rate $1/T_1$ in a GaAs QD versus an applied perpendicular magnetic field $B_\perp$ (the height of a QD is $h = 5$nm, the lateral size $l_0 = \sqrt{\hbar/m\omega_0} = 40$ nm, $\kappa = 1.2$, $\gamma_0 = 2.5$, $g_\perp = 2.5$). Inset: Energy differences of lowest excited levels with respect to the ground state $E_{0,0,+3/2}$.

Interaction of HHs with RF Electric Fields

$$\mathbf{E}(t) = E(\sin\omega t, -\cos\omega t, 0),$$

$$\langle H^E(t)\rangle = {\rm Tr}(\rho H^E(t)) = -\mathbf{d}_{\rm SO}\cdot\mathbf{E}(t), \quad \text{(coupling energy)}$$

$$d_{\rm SO} = \frac{\beta|e|m\hbar\omega_0^2}{\omega\Omega^2}\left(\frac{\omega_-^2}{\omega_- - \omega_Z} + \frac{\omega_+^2}{\omega_+ + \omega_Z}\right) \quad \text{(effective dipole moment)}.$$

RF Power Absorbed by the System

$$P = -\frac{d\langle H^E(t)\rangle}{dt} = \frac{2\omega(d_{\rm SO}E)^2 T_2\rho_z^T/\hbar}{1 + \delta_{\rm rf}^2 T_2^2 + (2d_{\rm SO}E/\hbar)^2 T_1 T_2}.$$

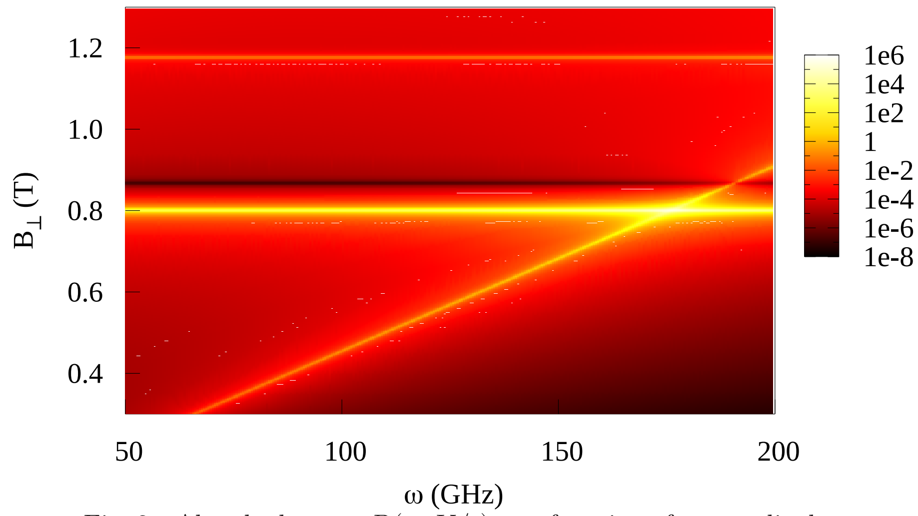

Fig. 2. Absorbed power P (meV/s) as a function of perpendicular magnetic field $B_\perp$ and rf frequency ω ($T_2 = 2T_1$, $E = 2.5$ V/cm, $B_\parallel = 1$ T).

$$B_\perp^{\rm r,1} = \hbar\omega/g_\perp\mu_{\rm B}, \quad B_\perp^{\rm r,2} = \hbar\omega_0/g_\perp\mu_{\rm B}\sqrt{1+2m_0/g_\perp m},$$

$$B_\perp^{\rm r,3} = 4\hbar\omega_0/g_\perp\mu_{\rm B}\sqrt{1+4m_0/g_\perp m}, \quad B_\perp^{\rm d} = (\hbar\omega_0/2g_\perp\mu_{\rm B})\sqrt{2m_0/g_\perp m}.$$

Rabi Oscillations

$$\langle S_z\rangle = S_z^T + e^{-(T_1^{-1}+T_2^{-1})t/2}\left\{\left(\frac{3}{2} - S_z^T\right)\cos\omega_{\rm R}t + \left[\frac{(d_{\rm SO}E)^2 T_2}{\hbar^2\omega_{\rm R}}S_z^T - \frac{T_1^{-1} - T_2^{-1}}{2\omega_{\rm R}}\left(\frac{3}{2} - S_z^T\right)\right]\sin\omega_{\rm R}t\right\},$$

where $\omega_{\rm R} = \sqrt{(d_{\rm SO}E/\hbar)^2 - (T_1^{-1} - T_2^{-1})^2/4}$ is the Rabi frequency and $S_z^T = (3/2)\rho_z^T/[1 + (d_{\rm SO}E/\hbar)^2 T_1 T_2]$.

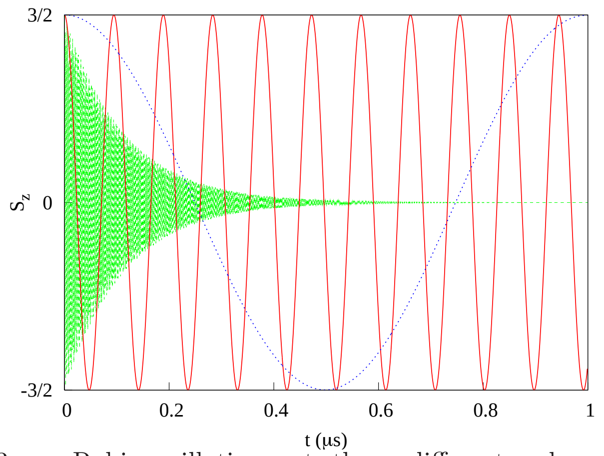

Fig. 3. Rabi oscillations at three different values of the perpendicular magnetic field: $B_\perp = 0.8$ T (damped fast oscillations), $B_\perp = 0.865$ T (dotted line), and $B_\perp = 0.5$ T (solid line). $B_\parallel = 0$, $\delta_{\rm rf} = 0$, $E = 1.5$ V/cm.

Conclusions

- Spin-orbit coupling is suppressed for flat QDs
- Spin relaxation time T_1 can be milliseconds
- Coherent spin manipulation by RF electric fields
- Strong dependence of Rabi oscillations on $B_\perp$

References

[1] Denis V. Bulaev, Daniel Loss. *Electric Dipole Spin Resonance for Heavy Holes in Quantum Dots*, cond-mat/0608410.

[2] Denis V. Bulaev, Daniel Loss. *Spin Relaxation and Decoherence of Holes in Quantum Dots*, Phys. Rev. Lett. **95**, 076805 (2005).