Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp1223-1224

Inherently fast spin relaxation of exciton in photo-excited self-assembled quantum dots

Yu-Huai Liao[1], Juan I. Climente[2] and Shun-Jen Cheng[1]

[1] Department of Electrophysics, National Chiao-Tung University, Hsinchu, Taiwan
[2] Departament de Quimica Fisica i Analitica, Universitat Jaume I, Castello, Spain

1. Introduction

Exciton spin dynamics in self-assembled quantum dots (QDs) have attracted considerable attention for years owing to both of fundamental interest and possible applications in dot-based quantum photonic devices. In the applications, the spin relaxation between two nearby exciton states has a determinate influence on the performance of dot-based photonic devices [1, 2] and control over it would be desirable.

For a long time, it has been widely believed that the discrete nature of QDs can suppress the coupling to the electronic structures from phonon bath and make the spin relaxation times of particles long enough for further application. Indeed, the spin relaxation times of electrons confined in QDs have been experimentally confirmed to reach up to 1 s.[3] However, the measured times of the DX-to-BX spin relaxation in InAs self-assembled QDs have been reported so short as only $\sim 10^2$ ns.[4]

The lifetime of a photo-generated spin exciton in a QD is limited not only by the spontaneous electron-hole (*e-h*) recombination, but also by the spin relaxation between the bright exciton (BX) and dark exciton (DX) states, split typically by hundreds of μeV due to the *e-h* exchange interaction.[5] Although that time scale is 1-2 orders of magnitude longer than the radiative lifetime of the exciton, the spin relaxation between BX and DX has been confirmed as a severe interference source limiting the performance of dot-based single-photon devices.[6,7] Another interesting but still puzzling feature is that the size effect was not obviously evidenced in experiments to increase spin relaxation times of exciton in smaller QDs, as observed in electronic QDs. [4] Building a solid theoretical framework is clearly necessary for further development in this field.

2. Theory and results

In this work, we present a comprehensive study of various possible involved spin flip mechanisms, including electron hyperfine interaction, electron-Rashba and -Dresselhaus spin-orbit interaction, hole-linear and hole-Dresselhaus spin-orbit interaction. With the assistance of phonon coupling, the DX states are allowed to transit to BX ones via the spin-scattering mechanisms such as spin-orbit interaction or hyperfine interaction.[8-13] .We theoretically evaluate the rate of spin-state transition from a DX state to BX states via acoustic phonon interaction in self-assemble quantum dots by using exact diagonalization techniques. Further analysis is conducted using perturbation method. The theoretical studies confirm that the exciton spin relaxation rate of a self-assembled quantum dot is so fast as $\sim 10^{-2}$ ns^{-1}, consistent with recent observations. [14]

Figure 1 presents the numerically calculated total rates τ_{tot}^{-1} of single excitons in QDs of fixed thickness d_z=3 nm but with varying lateral sizes characterized by the characteristic lateral length of the ground state wavefunction l_0. It can be seen that the total spin relaxation rate of the exciton is at the scale of $10^{-3} \sim 10^{-2}$ns^{-1} . We explain the fast exciton spin relaxation observed in QDs in terms of pronounced hole-Dresselhaus SOCs and *e-h* exchange interactions. Another remarkable feature of Fig.1 is that the spin relaxation rates of an exciton confined in a QD are not really suppressed by the reduced dot sizes. Instead, the size effect of QD makes the spin relaxation rate even faster. That feature manifests itself as a complex and unique interplay between the *e-h* exchange interactions and the SOC in photo-excited QDs, and implies that the spin relaxation of excitons in small dots is inherently fast.

3. Conclusions

In conclusion, we have calculated the relaxation rates between DX and BX states in InGaAs QDs for a wide number of spin-flip mechanisms and shown that hole-Dresselhaus SOC assisted by single-phonon processes is the dominant channel. The *e-h* exchange splitting acts as an internal magnetic field enhancing SOC mechanisms. Since the splitting grows with the confinement, the smaller the dot the faster the exciton spin relaxation. This is contrary to the well-known behavior of individual electron or holes, for which relaxation is suppressed by the confinement.

Acknowledgements

SJC is grateful to the National Science Council of Taiwan for supporting (contract No. NSC-98-2112-M-009-011-MY2), the National Center of Theoretical Sciences and the National Center for High-Performance Computing of Taiwan in Hsinchu for supporting. Support from MCINN project CTQ2008-03344 and the Ramon y Cajal program (JIC) is acknowledged

References

[1] Reischle M, Beirne G J, Rossbach R, Jetter M and Michler P, Phys. Rev. Lett. **101** (2008) 146402.
[2] Narvaez G A, Bester G, Franceschetti and Zunger A, Phys. Rev. B **74** (2006) 205422.

[3]S. Amasha, K. MacLean, I.P. Radu, D.M. Zumbhül, M. A. Kastner, M. P. Hanson, and A. C. Gossard, Phys. Rev. Lett. **100** (2008) 046803.
[4] J. Johansen, B. Julsgaard, S. Stobbe, J. M. Hvam, and P. Lodahl, Phys. Rev. B **81** (2010) 081304 R.
[5] M. Bayer, G. Ortner, O. Stern, A. Kuther, A.A. Gorbunov, A. Forchel, P. Hawrylak, S. Fafard, K. Hinzer, T. L. Reinecke, S. N. Walck, J. P. Reithmaier, F. Klopf, and F. Sch\"afer, Phys. Rev. B **65** (2002) 195315.
[6] S. Strauf, N. G. Stoltz, M. T. Rakher, L. A. Coldren, P. M. Petroff, and D. Bouwmeester, Nature Photon. **1** (2007) 704.
[7] M. Reischle, G. J. Beirne, R. Rossbach, M. Jetter, and P. Michler, Phys. Rev. Lett. **101**(2008) 146402.
[8] Hall K C, Koerperick E J, Boggess T F, Shcheckin O B and Deppe D G, Appl. Phys. Lett. **90** (2007) 053109.
[9] Roszak K, Axt V M, Kuhn T and Machnikowski P, Phys. Rev. B **76** (2007) 195324.
[10] Tsitsishvili E, Baltz R V and Kalt H, Phys. Rev. B **72** (2005) 155333.
[11] X. M. Dou, B. Q. Sun, Y. H. Xiong, Z. C. Niu, H. Q. Ni, and Z. Y. Xu, J. Appl. Phys. **105** (2009) 103516.
[12] J. M. Smith, P. A. Dalgarno, R. J. Warburton, A. O. Govorov, K. Karrai, B. D. Gerardot, and P. M. Petroff, Phys. Rev. Lett. **94** (2005) 197402.
[13] E. Tsitsishvili and H. Kalt, Phys. Rev. B **82** (2010) 195315.
[14] Yu-Huai Liao, Juan I. Climente, and Shun-Jen Cheng, , Phys. Rev. B **83** (2011) 165317 .

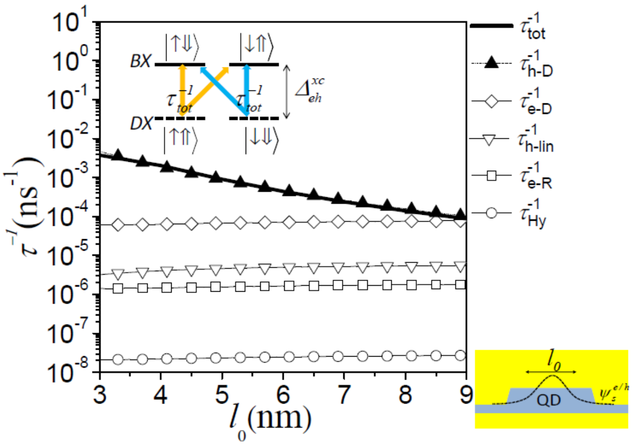

Fig. 1 Exciton spin relaxation rates in the dark exciton (DX) to bright-exciton (BX) transition, as functions of the quantum dot size (characterized by by the characteristic lateral length of the ground state wavefunction l_0), yielded by various spin-flip mechanisms, including the hole-Dresselhaus (*h-D*), electron-Dresselhaus (*e-D*), electron-Rashba (*e-R*), the linear-*k* hole (*h-lin*) spin orbital couplings and electron-nuclei hyperfine (*Hy*)interactions, respectively.