Extended Abstracts of the 2015 International Conference on Solid State Devices and Materials, Sapporo, 2015, pp430-431

# Electron g-factor Engineering in GaAs Quantum Nano-Disks Fabricated by Defect-Free Neutral Beam Etching Process

Li-Wei Yang[1], Yi-Chia Tsai[1], Yiming Li[1,3,*], Oleksandr Voskoboynikov[1,*], Aiko Higo[3], Akihiro Murayama[4,5], and Seiji Samukawa[2,3,*]

[1] National Chiao Tung University, 1001 Ta Hsueh Rd., Hsinchu 300, Taiwan
[2] Institute of Fluid Science, Tohoku University, Aoba-ku, Sendai, Miyagi 9808577, Japan
[3] WPI-Advanced Institute for Materials Research, Tohoku University, Aoba-ku, Sendai, Miyagi 9808577, Japan
[4] Graduate School of Information Science and Technology, Hokkaido University, Kita 14, Nishi 9, Kita-ku, Sapporo, Japan
[5] CREST Japan Science and Technology Agency, 5 SanbanchoChiyoda-ku, Tokyo, Japan
[*]E-mail: ymli@faculty.nctu.edu.tw (Y. Li); vam@faculty.nctu.edu.tw (O. Voskoboynikov); samukawa@ifs.tohoku.ac.jp (S. Samukawa)

**Abstract**

**We study the effective *g*-factor for electrons confined in GaAs/$Al_xGa_{1-x}$As quantum nano-disk systems with different material content. Our numerical simulation results suggest that the magnitude of the effective *g*-factor is strongly controlled by the interplay between the inter-band electron state coupling and the wave function confinement in the nano-disks. The results of this study are confirmed by the recent experimental observations.**

## 1. Introduction

At non-zero magnetic field $\boldsymbol{B}$ the electron energies for different spin states are split by $\Delta\boldsymbol{E}$ and the splitting is characterized by the effective Landé factor (*g*-factor) which is defined by $\boldsymbol{g} = \Delta\boldsymbol{E}/\mu_B\mathbf{B}$ ($\mu_B$ is the Bohr magneton). Robust spin manipulations in semiconductor-based quantum computation (or more widely - in semiconductor based spintronics) using semiconductor nano-systems requires for proper (static and dynamic) techniques to control the particles' effective *g*-factors [1]. Therefore, the electron *g*-factor engineering and control are highly desirable for the realization of individual solid state qubits. The ultimate spintronics goals can be achieved only under a precise technological control of the semiconductor nano-objects material and geometrical parameters.

The newly developed bio-template and neutral beam etching fusion top-down process can immediately provide us with nano-scale structures of precisely controlled characteristics [2]. Recently, using this process, high quality GaAs/$Al_xGa_{1-x}$As quantum nano-disks (NDs) have been fabricated with a precise control of the disks' geometrical and material parameters [2-3]. Effects of the lateral quantum confinement of carriers on the actual value of the electron effective *g*-factor spin were discussed. It was suggested, that the effective *g*-factor magnitude is controlled by the interplay between the vertical (along the system growth direction) and lateral confinement of the electron wave function.

In this study, using the eight-band Kane model [4], we computationally simulate the effective *g*-factor for electrons confined in GaAs/$Al_xGa_{1-x}$As quantum ND systems with different parameters and material content. We for the first time demonstrate that, the issue of the actual dependence of the *g*-factor magnitude on the degree of vertical-lateral confinement (the wave function penetration into surrounding $Al_xGa_{1-x}$As) is rather controversial. The factor of the penetration itself cannot provide us with a comprehensive explanation of the actual change on the *g*-factor magnitude when the parameters of the system change. We suggest that the actual value of the electron effective *g*-factor (and its change) is mainly a result of the interplay between the inter-band coupling and the wave function confinement in the nano-disks.

## 2. Modeling and Simulation Results

We simulate the ground-state energy, wave function, and effective *g*-factor for the electron confined in the GaAs NDs with different structural configurations of the surrounding $Al_xGa_{1-x}$As matrix. There are 6 different NDs: D1,…, D6, as shown in Fig. 1, are investigated. The electronic structure of the quantum NDs is simulated when a weak magnetic field is applied along the structure growth direction (*z*-direction). All quantum NDs are taken of the thickness 8 nm and the lateral radius 7.5 nm, according to our experimentally characterization [2-3]. The material parameters of GaAs/$Al_xGa_{1-x}$As nano-structures adopted in the simulation follow the references [4-5]. The physical characteristics of the 3D quantum NDs are simulated within the eight-band Kane model [4] using the COMSOL MULTIPHYSICS package [6]. Notably, the structures of NDs D1 and D2 are identical to those reported and experimentally studied in the reference [3].

Right plots of Fig. 1 show the electron ground-state wave functions among six different NDs. We find that the overall 3D penetration of the electron wave functions into the surrounding matrix cannot be easily clarified. For instance, as shown in Fig. 1(b), the electron wave function of D2 penetrates along the *z*-direction which is more then that of D1 (Fig. 1(a)). However, at the same time, it is more confined in the radial direction then that of D1.

As summarized in Table I, we list the calculated effective *g*-factor: the vertical, lateral, and overall 3D effective electron radii (confinement lengths) [7]; and the simple weighted *g*-factor obtained according to the wave electron function distribution and the material change in the system ($g_{av}$). Clearly, the overall penetration of the electron wave function into the surrounding matrix for the D2 is actually smaller than that for D1 (which gives a smaller $g_{av}$ in D2). At the same time, the eight-band model (including the inter-band coupling effects) gives reasonable values for the effective *g*-factor and understandable tendencies in the *g*-factor change (which is compliant to the experimental data). Furthermore, for different possible structural configurations of the quantum NDs, as shown in Figs. 1(c)-(f), we present the similar simulation as listed in Table I. The quantum NDs systems are taken to demonstrate a potential approach to the engineering of the electron *g*-factor in the highly periodic structure and high quality GaAs/$Al_xGa_{1-x}As$ NDs fabricated by defect-free neutral beam etching process. Notably that the interplay between the inter-band coupling and wave function actual confinement generates a controllable variation in the electron effective *g*-factor magnitude.

## 3. Conclusions

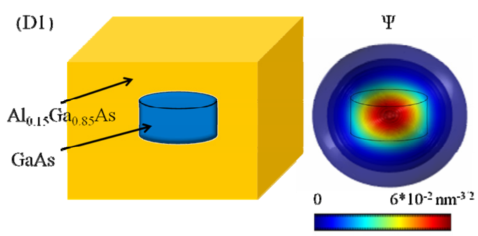
In this work, using the eight-band Kane model, we have performed 3D finite-element simulations of the effective *g*-factor for electrons confined in GaAs/$Al_xGa_{1-x}As$ quantum nano-disks fabricated by the bio-template and neutral beam etching fusion top-down process. We have clarified the impact of the inter-band coupling and the electron wave function distribution in the nano-disks on the effective *g*-factor. Not shown here, our results are in good agreement with experimental observations [3]. In addition, we further gave an insight on the different promising engineering of the electron effective g-factor for the neutral beam etching manufactured high quality quantum nano-disks.


## Acknowledgements

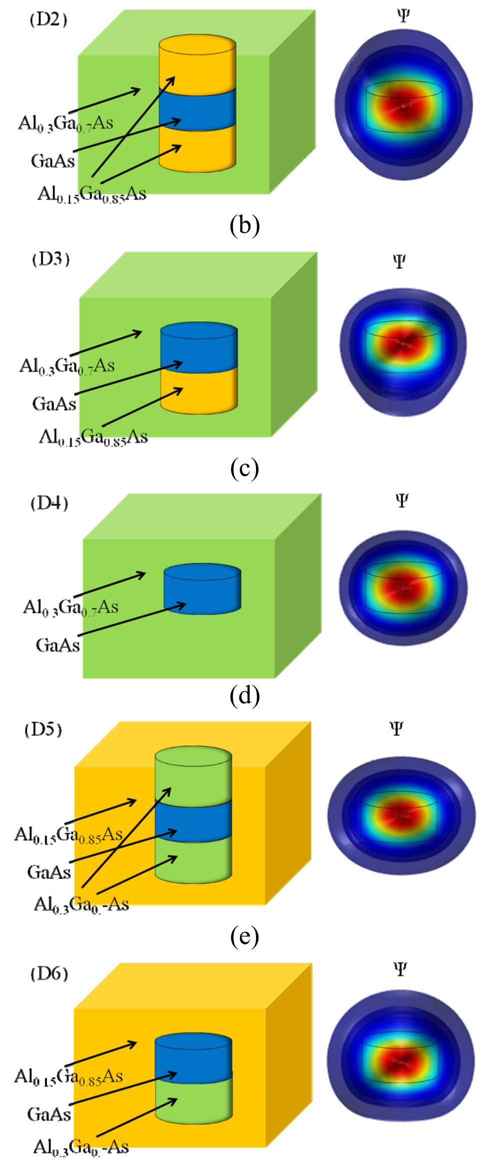
This work is supported in part by the Ministry of Science and Technology (MOST) of Taiwan under Contracts No. NSC 102-2112-M- 009-003-MY2 and No. MOST-103-2221-E-009-180, and Aiming for the Top University Program of the National Chiao Tung University.


## References


[1] J. Xia, W. Ge, and K. Chang, *Semiconductor Spintronics*, World Scientific Publishing, NJ, USA (2012).
[2] S. Samukawa, ECS Journal of Solid State Science and Technology, **4** (2015) N5089.
[3] T. Tanaka *et al*., Journal of Crystal Growth, *Available online*: http://dx.doi.org/10.1016/j.jcrysgro.2015.02.066 (2015).
[4] A. A. Kiselev, E. L. Ivchenko, and U. Rossler, Phys. Rev. B **58** (1998) 16353.
[5] I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, J. Appl. Phys. **89** (2001) 5815.
[6] www.comsol.com
[7] O. Voskoboynikov, W. T. Chiu, and L. M. Thu, Phys. Rev. B 88 (2013) 085310.


(a)




(f)

Fig. 1 GaAs NDs and the electron ground state wave function with respect to different structural configurations and surroundings.

Table I. List of the simulated characteristics quantum NDs, where the vertical radius is $r_z$, the lateral radius is $r_{\perp}$, and $r$ is the overall 3D effective electron radii (confinement lengths). The simple weighted **g**-factor is obtained according to the wave electron function distribution and the material change in the system is $g_{av}$.

| | ***g*-factor** | $r_z$ (nm) | $r_{\perp}$ (nm) | $r$ (nm) | $g_{av}$ |
|---|---|---|---|---|---|
| **D1** | -0.040 | 3.96 | 7.20 | 8.22 | -0.322 |
| **D2** | 0.031 | 3.82 | 6.36 | 7.42 | -0.330 |
| **D3** | 0.051 | 3.90 | 6.36 | 7.46 | -0.329 |
| **D4** | 0.078 | 3.20 | 6.36 | 7.12 | -0.329 |
| **D5** | 0.007 | 3.32 | 7.26 | 7.98 | -0.320 |
| **D6** | -0.019 | 3.39 | 7.23 | 7.98 | -0.320 |