

Photoluminescence of Colloidal CdSe/ZnS Quantum Dots Under Oxygen Atmosphere

Gia-Wei Shu, Wan-Zhen Lee, I.-Jen Shu, Ji-Lin Shen, James Cheng-An Lin, Walter H. Chang, Ruoh-Chyu Ruaan, and Wu Ching Chou

Abstract—The effects of oxygen versus vacuum ambients on colloidal CdSe/ZnS quantum dots (QDs) were studied using both continuous and time-resolved photoluminescence (PL) measurements. The PL intensities were found to be an order of magnitude higher in an oxygen atmosphere, which is explained by the passivation of surface defects by oxygen absorption. The decay of PL intensities can be best fitted by a biexponential function with lifetimes of approximately 1 ns for the fast decay and approximately 10 ns for the slow decay. Based on the emission-energy dependence of carrier lifetimes and of the amplitude ratio of the fast-decay component to the slow-decay component, we suggest that the fast and slow PL decay of colloidal CdSe/ZnS QDs is caused by the recombination of delocalized carriers in the internal core states and the localized carriers in the surface states, respectively.

Index Terms—Optical properties, quantum dots (QDs).

I. INTRODUCTION

SEMICONDUCTOR quantum dots (QDs) that are smaller than the bulk exciton Bohr radius provide a nearly zero-dimensional system in which carriers are confined in all spatial directions. The quantum confinement results in discrete electronic levels, which can be tuned by varying the QD size. The optical properties of the semiconductor QDs are expected to exhibit a high luminescence yield and thermal stability because the QDs have a δ -like density of states and strong quantum confinement. Their novel optical properties cause semiconductor QDs to have many applications in opto-electronic devices such as optical switches, light-emitting diodes (LEDs), and lasers [1], [2]. In recent years, colloidal semiconductor QDs have been chemically coupled to biomolecules such as peptides, DNA, and proteins [3]–[7]. These QD bioconjugates can be used as biomedical fluorescence labels for investigating biomolecular interactions and developing highly sensitive detection and imaging [3]–[7]. Although colloidal semiconductor QDs are promising materials in numerous applications, the origin of their luminescence remains

the topic of some controversy. The near-edge photoluminescence (PL) in colloidal semiconductor QDs has been attributed to the recombination of the carriers from surface states [8]–[11]. This is generally acceptable since the heterostructure interfaces, unsaturated bonds, and adsorbed foreign species on the surface create surface states with energies within the bandgap of the material. The surface states may act to localize or trap the photo-generated electrons and/or holes on the surface. However, some experiments have revealed that the near-edge PL originates from the internal core states in QDs—not the surface states [12]–[14]. The enhanced electron–hole exchange interaction and strong confinement in the core states indicates that the spin degeneracy of the band-edge exciton is lifted and a dark exciton state is formed. The presence of a dark exciton can explain the PL properties in QDs. Therefore, the origin of PL in colloidal QDs remains an open question.

This study elucidates PL in colloidal CdSe/ZnS QDs in an atmosphere of oxygen. Introducing the oxygen to QDs can enhance their PL intensity by an order of magnitude without causing photo-oxidation. Time-resolved PL decay measurements provide a complementary method for studying the PL properties of QDs, using the kinetics of electron–hole recombination as a probe. The PL decay of QDs was monitored at various emission wavelengths and in an atmosphere of oxygen, and we suggest that the fast and slow decay of PL may originate from the recombination of the internal core states and the localized surface states, respectively.

II. EXPERIMENTAL DETAILS

The investigated colloidal core/shell CdSe/ZnS QDs were synthesized by the following procedure. 0.30 g of cadmium oxide (CdO), 1.30 g of tetradecylphosphonic acid (TDPA), and 25.0 g of tri-*n*-octylphosphine oxide (TOPO) were loaded into a 250-mL flask and heated to 320 °C under argon flow. After the CdO was totally dissolved in TDPA and TOPO, the solution was cooled to 300 °C and 4.45 mL of selenium stock solution (0.5 M of selenium solution in tributylphosphine, TOP) was injected. 1.5 mL of precursor solution (made by mixing a 1.75 mL of ZnMe₂ (2.0 M in toluene) and S(Si(CH₃))₂ in TBP) was then added dropwise into the mixture to cover a layer of ZnS. 20 mg of TOP/TOPO capped CdSe/ZnS QDs was mixed with a 200-mg 11-mercaptoundecanoic acid (MUA) in a reaction vessel to synthesize the carboxylated QDs. Methanol was added and the pH value was adjusted to about ten with tetramethylammonium hydroxide. The mixture was heated under reflux for 2 h. After it was cooled to room temperature,

Manuscript received December 30, 2004; revised March 8, 2005. This work was supported in part by the National Science Council under Grant NSC-93-2112-M-033-010, Grant NSC-92-2120-M-033-001, and Grant NSC-93-2120-M-033-001.

G.-W. Shu, W.-Z. Lee, I.-J. Shu, and J.-L. Shen are with the Physics Department, Chung Yuan Christian University, Chung-Li 32023, Taiwan, R.O.C. (e-mail: jlshen@cycu.edu.tw).

J. C.-A. Lin and W. H. Chang are with the Department of Biomedical Engineering, Chung Yuan Christian University, Chung-Li 32023, Taiwan, R.O.C.

R.-C. Ruaan is with the Department of Chemical and Material Engineering, National Central University, Chung-Li 32023, Taiwan, R.O.C.

W. C. Chou is with the Electrophysics Department, National Chiao-Tung University, Hsin-Chu 300, Taiwan, R.O.C.

Digital Object Identifier 10.1109/TNANO.2005.851445

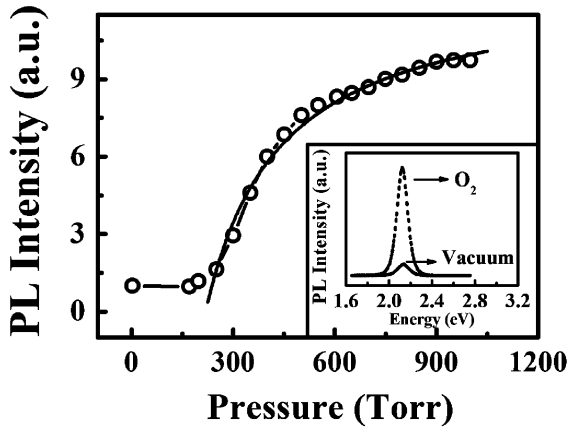


Fig. 1. PL intensity of CdSe/ZnS QDs under different oxygen pressures. The solid line displays the result calculated using (1). The PL signals in a vacuum environment (solid line) and an oxygen atmosphere (dashed line) are shown in the inset.

the resulting water-soluble QDs were precipitated with tetrahydrofuran and separated by centrifugation.

The PL measurements were obtained at room temperature using a pulsed GaN diode laser operated at a wavelength of 396 nm as the excitation source. The diode laser produced light pulses with a duration of 50 ps and a repetition rate of 1 MHz. The collected luminescence was directly projected into a grating spectrometer and then detected with a high-speed photomultiplier tube (PMT). PL decay signals were measured using the technique of time-correlated single-photon counting (TCSPC) and a PC plug-in time-correlated counting card. The overall temporal response function of the system was 300 ps.

III. RESULTS AND DISCUSSION

The solid line in the inset in Fig. 1 displays the PL signal of colloidal CdSe/ZnS QDs in a vacuum environment (at a pressure of 10^{-3} torr). The PL peak energy was centered at 2.13 eV, which is assigned to the near bandgap transition. No PL was observed from the deep trap states at energies of lower than 2.13 eV, indicating that the CdSe/ZnS QDs have good optical qualities. The dashed line in the inset of Fig. 1 shows the PL signal of CdSe/ZnS QDs in an atmosphere of oxygen at a pressure of 1 atm. The PL intensity in the oxygen atmosphere was enhanced by an order of magnitude greater than that in a vacuum. The significant role of oxygen in the fluorescence enhancement from single CdSe/ZnS QDs has also been recently demonstrated [15]. The open circles in Fig. 1 present the PL intensity of CdSe/ZnS QDs at various oxygen pressures. The PL intensity remains unchanged in the low-pressure range (10^{-3} –200 torr), increasing after 200 torr. The influence of oxygen pressure on PL intensity can be described by the quantity of the monomolecular adsorption layer and the pressure, as formulated by Zhao *et al.* [16] and Langmuir [17] as follows:

$$I(P) = A \frac{K \times P}{1 + K \times P} \quad (1)$$

where $I(P)$ is the PL intensity, P is the gas pressure, and A and K are constants [16]. The solid line in Fig. 1 plots the results calculated using (1). A good fit to experiment is found for

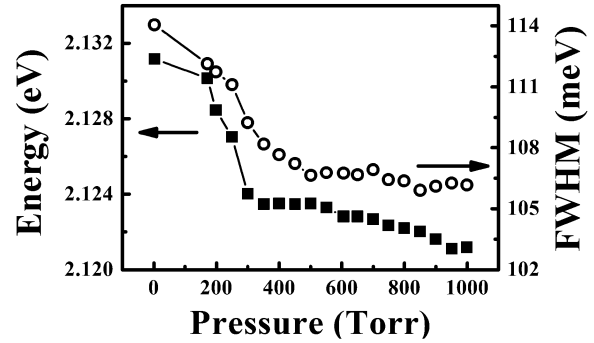


Fig. 2. PL peak energy (closed squares) and FWHM (open circles) of CdSe/ZnS QDs as a function of oxygen pressure.

the pressure range of $P > 200$ torr. In the low-pressure range, the deviation between calculations and experiments may arise from the decrease in the amount of oxygen absorbed on the surface of QDs, originating from the trapping of oxygen by MUA molecules. The good fit in Fig. 1 reveals that the enhancement of PL intensity is related to the adsorption of the first monolayer of oxygen on the surface of QDs.

Fig. 2 displays the PL full-width at half maximum (FWHM) of CdSe/ZnS QDs as a function of oxygen pressure, indicating that the FWHM decreases as the oxygen pressure increases. The enhanced PL intensity and reduced PL FWHM in the oxygen atmosphere suggest that the surface traps of QDs are passivated by introducing oxygen. Surface defects such as Se or/and Cd dangling bonds can introduce surface trap states with energies that are within the bandgap of the material. The adsorbed oxygen may interact with surface defects, which are directly involved in the nonradiative recombination of the photogenerated carriers [18]–[20]. For instance, Se dangling bonds can be passivated by introducing oxygen, reducing the main trap sites for holes [21]. If the surface defects are eliminated by oxygen, then the contribution from radiative recombination should increase, enhancing PL intensity. The reaction of oxygen with the surface defects of CdSe QDs can be of two types—chemisorbed interaction and physisorbed interaction. The chemisorbed interaction involves the surface oxidation of CdSe, whereby oxygen is irreversibly chemisorbed onto the surface defects, forming a surface oxide. The oxidation product, which can result in smaller QDs and a loss in PL efficiency, has been suggested to be SeO_2 or CdSeO_x ($x = 2$ or 3) [22]. The other one is a weakly interaction, whereby oxygen is physisorbed onto the CdSe surface. The physisorbed interaction can be eliminated by the evacuation of oxygen. PL experiments were performed after the evacuation of oxygen to identify the mechanism of oxygen passivation. The PL properties (intensity, peak position, and FWHM) in the vacuum recovered their initial values, which are consistent with the results in the inset of Fig. 1. Moreover, refilling with oxygen recovered the PL enhancement, indicating that the PL enhancement is a reversible effect and the oxygen passivation of surface defects should be attributed to the physisorbed interaction. The PL enhancement from single CdSe/ZnS QDs upon sudden exposure to air has been studied very recently [15]. Actual chemical modification, such as ligand reaction, has been suggested not to take place at the surface of QDs.

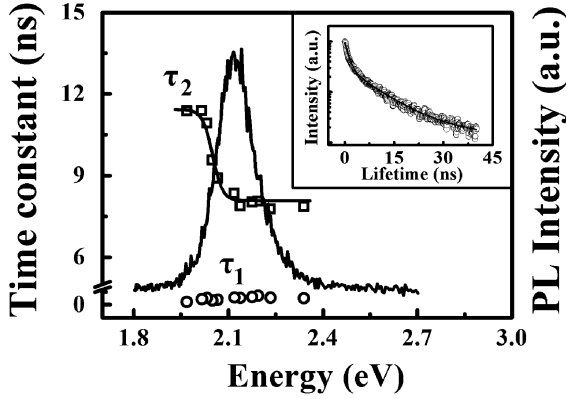


Fig. 3. Mission energy dependence of τ_1 (open circles) and τ_2 (open squares). The solid line displays the calculated τ_2 using (3). The spectrum of CdSe/ZnS QDs is also shown. PL decay profile of CdSe/ZnS QDs in a vacuum environment is shown in the inset. The solid line in the inset displays the calculated result using (2).

Fig. 2 also shows the PL peak position of CdSe/ZnS QDs as a function of oxygen pressure. The peak energy decreases as the oxygen pressure increases. Oxygen has been reported to be able to interact with CdSe under light illumination, producing evaporating oxides [8], [21]–[23]. This photooxidation of QD reduces the effective core diameter of QDs to decrease and causes the PL peak to undergo a blue shift. The red shift of the PL peak in Fig. 2 indicates that no photooxidation occurred in the sample. The red shift of the PL peak can be also explained by the passivation of surface defects. Oxygen had already eliminated the nonradiative surface defects so the carriers had more opportunities to recombine radiatively on the surface. The radiative recombination on the QD surface can occur at some energy potential minima because of the carrier localization (as will be demonstrated later) [24], leading to a red shift of the PL peak. Additionally, the electronic confinement effect may contribute to the PL red shift. Oxygen, which is very electronegative, can adsorb onto the surface of QDs via a transfer of electrons from the semiconductor to the oxygen [18]. Accordingly, the electron wave function confined in the CdSe core can extend toward the ZnS shell layer as oxygen adsorbs on QDs. In an analogous effect, the core diameter of QDs electronically increases, causing the PL peak to be red-shifted.

The inset of Fig. 3 displays the normalized PL decay profile of CdSe/ZnS QDs in a vacuum environment. The decay can be well fitted by a biexponential function

$$I(t) = A_1 e^{-\frac{t}{\tau_1}} + A_2 e^{-\frac{t}{\tau_2}} \quad (2)$$

where τ_1 (τ_2) represents the fast (slow) decay time, and A_1 (A_2) represents the amplitude of the fast-decay (slow-decay) component at $t = 0$. The solid line in the inset of Fig. 3 shows the fitted result, which is in good agreement with the experimental results. The PL decay mechanism of CdSe/ZnS QDs can be further analyzed by the emission energy dependence of the lifetimes. The open squares and circles in Fig. 3 show the measured lifetimes of slow and fast decay, respectively, for different emission energies. As shown in Fig. 3, the lifetimes of slow PL decay fall as the emission energy increases, the relationship of which is

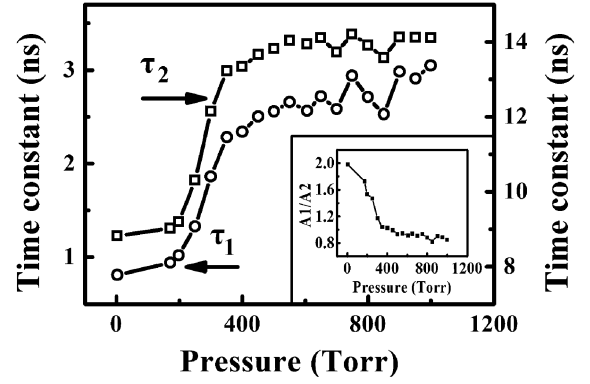


Fig. 4. τ_1 (open circles) and τ_2 (open squares) as a function of oxygen pressure. The inset shows the PL amplitude ratio A_1/A_2 as a function of oxygen pressure.

characteristic of the localization effect [25]. Localization associated with the structural disorder or surface states may generate localized states with different energies. Accordingly, localized carriers can be transferred from higher energy sites to lower energy sites through a relaxation process. The decay rate of localized carriers is expressed as the radiative recombination rate plus the relaxation rate to lower energy sites. Thus, the decay time decreases as the emission energy increases, as displayed in Fig. 3. Assuming the density of localized tail states is proportional to $\exp(-E/E_0)$, the emission energy dependence of τ_2 can be fitted with the function [26]

$$\tau(E) = \frac{\tau_{\text{rad}}}{1 + \exp[(E - E_{\text{me}})/E_0]} \quad (3)$$

where τ_{rad} is the radiative lifetime, E_{me} is the energy similar to the mobility edge, and E_0 is a characteristic energy that represents the depth of the tail states. τ_2 , described by (3), is plotted as a solid line in Fig. 3. A good fit with experiment confirms the effect of carrier localization.

The PL amplitude ratio of the fast-decay component A_1 to the slow-decay component A_2 was analyzed to explore further the origins of the fast and slow PL decays. The inset of Fig. 4 plots the PL amplitude ratio A_1/A_2 as a function of oxygen pressure, indicating that the PL amplitude ratio A_1/A_2 decreases (the slow-decay component increases) as the oxygen pressure increases. Accordingly, the slow PL decay should involve the *surface-related* PL since its lifetime increases with the pressure of oxygen, which is adsorbed onto the surface of QDs. Additionally, the amplitude of the slow-decay component increases while the PL intensity is enhanced (as shown in Fig. 1), revealing that the slow-decay component is related to the *radiative* recombination. The results in Fig. 3 and the inset in Fig. 4 suggest that the slow-decay component of PL in (2) originates from the recombination of carriers in the *surface localized states*. However, τ_1 is independent of emission energy (as shown in Fig. 3) and shorter than τ_2 , which is associated with the surface states, thus, τ_1 is suggested to involve the recombination of delocalized carriers in the internal core states. Fig. 4 plots the lifetimes of the PL decay of CdSe/ZnS QDs as a function of oxygen pressure. Both τ_1 and τ_2 increase with increasing the oxygen pressure. The removal of the surface traps by introducing oxygen reduces the nonradiative recombination and enables the carriers on the

surface to survive longer, a fact which accounts for the increase of τ_2 with the oxygen pressure. The increase of τ_1 with an increase in the oxygen pressure can be explained by the electronic confinement effect. As the electronic confinement decreases due to oxygen adsorption, the wave-function overlap between electrons and holes is reduced accordingly, leading to an increase of the carrier lifetimes in the core states.

IV. CONCLUSION

In summary, the PL of colloidal CdSe/ZnS QDs in an oxygen atmosphere was studied using PL methods. The intensity of PL increased by an order of magnitude as the pressure of oxygen increased from vacuum to 1 atm. This enhancement is explained by the passivation of the surface defects by oxygen. Based on the emission energy dependence of the lifetimes and the PL amplitude ratio A_1/A_2 , we suggest that the fast and slow PL decay of colloidal CdSe/ZnS QDs involves the recombination of the delocalized carriers in the internal core states and the localized carriers in the surface states, respectively.

REFERENCES

- [1] D. Bimberg, M. Grundmann, and N. N. Ledentsov, *Quantum Dot Heterostructures*. New York: Wiley, 1998.
- [2] C. P. Collier, T. Vossmeier, and J. R. Heath, "Nanocrystal superlattices," *Annu. Rev. Phys. Chem.*, vol. 49, pp. 371–404, 1998.
- [3] M. Bruchez, Jr, M. Moronne, P. Gin, and S. Weiss, "Semiconductor nanocrystals as fluorescent biological labels," *Science*, vol. 281, pp. 2013–2015, 1998.
- [4] W. C. W. Chan and S. M. Nie, "Quantum dot bioconjugates for ultrasensitive nonisotopic detection," *Science*, vol. 281, pp. 2016–2018, 1998.
- [5] H. Mattoussi, J. M. Mauro, E. R. Goldman, G. P. Anderson, V. C. Sundar, F. V. Mikulec, and M. G. Bawendi, "Self-assembly of CdSe–ZnS quantum dot bioconjugates using an engineered recombinant protein," *J. Amer. Chem. Soc.*, vol. 122, pp. 12 142–12 150, 2000.
- [6] G. P. Mitchell, C. A. Mirkin, and R. L. Letsinger, "Programmed assembly of DNA functionalized quantum dots," *J. Amer. Chem. Soc.*, vol. 121, pp. 8122–8123, 1999.
- [7] S. Pathak, S. K. Choi, N. Arnhem, and M. E. Thompson, "Hydroxylated quantum dots as luminescent probes for *in situ* hybridization," *J. Amer. Chem. Soc.*, vol. 123, pp. 4103–4104, 2001.
- [8] X. Wang, L. Qu, J. Zhang, X. Peng, and M. Xiao, "Surface-related emission in highly luminescent CdSe quantum dots," *Nano Lett.*, vol. 3, pp. 1103–1106, 2003.
- [9] S. R. Cordero, P. J. Carson, R. A. Estabrook, G. F. Strouse, and S. K. Buratto, "Photo-activated luminescence of CdSe quantum dot monolayers," *J. Phys. Chem. B*, vol. 104, pp. 12 137–12 142, 2000.
- [10] M. Nirmal, C. B. Murray, and M. G. Bawendi, "Fluorescence-line narrowing in CdSe quantum dots: Surface localization of the photogenerated exciton," *Phys. Rev. B, Condens. Matter*, vol. 50, pp. 2293–2300, 1994.
- [11] W. Hoheisel, Y. L. Colvin, C. S. Johnson, and A. P. Alivisatos, "Threshold for quasi-continuum absorption and reduced luminescence efficiency in CdSe nanocrystals," *J. Chem. Phys.*, vol. 101, pp. 8455–8460, 1994.
- [12] M. Kuno, J. K. Lee, B. O. Dabbousi, F. V. Mikulec, and M. G. Bawendi, "The band edge luminescence of surface modified CdSe nanocrystallites: Probing the luminescing state," *J. Chem. Phys.*, vol. 106, pp. 9869–9882, 1997.
- [13] M. Nirmal, D. J. Norris, M. Kuno, M. G. Bawendi, A. L. Efros, and M. Rosen, "Observation of the 'Dark exciton in CdSe quantum dots'," *Phys. Rev. Lett.*, vol. 75, pp. 3728–3731, 1995.
- [14] S. A. Crooke, T. Barrick, J. A. Hollingsworth, and V. I. Klimov, "Multiple temperature regimes of radiative decay in CdSe nanocrystal quantum dots: Intrinsic limits to the dark-exciton lifetime," *Appl. Phys. Lett.*, vol. 82, pp. 2793–2795, 2003.
- [15] J. Müller, J. M. Lupton, A. L. Rogach, J. Feldmann, D. V. Talapin, and H. Weller, "Air-induced fluorescence bursts from single semiconductor nanocrystals," *Appl. Phys. Lett.*, vol. 85, pp. 381–383, 2004.
- [16] T. Zhao, J. Liu, Y. Li, and D. Zhu, "C60 photoluminescence spectra related to gas adsorption," *Appl. Phys. Lett.*, vol. 61, pp. 1028–1030, 1992.
- [17] I. Langmuir, "The adsorption of gases on plane surfaces of glass, mica and platinum," *J. Amer. Chem. Soc.*, vol. 40, pp. 1361–1403, 1918.
- [18] J. E. B. Katari, V. L. Colvin, and A. P. Alivisatos, "X-ray photoelectron spectroscopy of CdSe nanocrystals with applications to studies of the nanocrystal surface," *J. Phys. Chem.*, vol. 98, pp. 4109–4117, 1994.
- [19] M. Jones, J. Nedeljkovic, R. J. Ellingson, A. J. Nozik, and G. Rumbles, "Photoenhancement of luminescence in colloidal CdSe quantum dot solutions," *J. Phys. Chem. B*, vol. 107, pp. 11 346–11 352, 2003.
- [20] N. Chestnoy, T. D. Harris, R. Hull, and L. E. Brus, "Luminescence and photophysics of cadmium sulfide semiconductor clusters: The nature of the emitting electronic state," *J. Phys. Chem.*, vol. 90, pp. 3393–3399, 1986.
- [21] W. G. J. H. M. van Sark, P. L. T. M. Frederix, D. J. Van den Heuvel, H. C. Gerritsen, A. A. Bol, J. N. J. van Lingen, C. de Mello Doneg, and A. Meijerink, "Photooxidation and photobleaching of single CdSe/ZnS quantum dots probed by room-temperature time-resolved spectroscopy," *J. Phys. Chem. B*, vol. 105, pp. 8281–8284, 2001.
- [22] D. F. Underwood, T. Kippeny, and J. R. Sandra, "Ultrafast carrier dynamics in CdSe nanocrystals determined by femtosecond fluorescence upconversion spectroscopy," *J. Phys. Chem. B*, vol. 105, pp. 436–443, 2001.
- [23] A. Y. Nazzal, X. Wang, L. Qu, W. Yu, Y. Wang, X. Peng, and M. Xiao, "Environmental effects on photoluminescence of highly luminescent CdSe and CdSe/ZnS core/shell nanocrystals in polymer thin films," *J. Phys. Chem. B*, vol. 108, pp. 5507–5515, 2004.
- [24] T. Passow, K. Leonardi, H. Heinke, D. Hommel, D. Litvinov, A. Rosenauer, D. Gerthsen, D. Litvinov, A. Rosenauer, D. Gerthsen, J. Seufert, G. Bacher, and A. Forchel, "Quantum dot formation by segregation enhanced CdSe reorganization," *J. Appl. Phys.*, vol. 92, pp. 6546–6552, 2002.
- [25] P. Malý, J. Kudrna, F. Trojánek, D. Mikeš, P. Němec, A. C. Maciel, and J. F. Ryan, "Dominant role of surface states in photoexcited carrier dynamics in CdSe nanocrystalline films prepared by chemical deposition," *Appl. Phys. Lett.*, vol. 77, pp. 2352–2354, 2000.
- [26] M. Strassburg, M. Dworzak, H. Born, R. Heitz, A. Hoffmann, M. Barteis, K. Lischka, D. Schikora, and J. Christen, "Lateral redistribution of excitons in CdSe/ZnSe quantum dots," *Appl. Phys. Lett.*, vol. 80, pp. 473–475, 2002.



Gia-Wei Shu received the B.S. and M.S. degrees in physics from Chung Yuan Christian University, Chung Li, Taiwan, R.O.C., in 2001 and 2003, respectively, and is currently working toward Ph.D. degree at Chung Yuan Christina University.

His research interests include bandgap engineering of semiconductors and time-resolved phenomena in nanomaterials. His current research involves the studies of semiconductor QDs by using time-resolved PL.



Wan-Zhen Lee received the B.S. degree in physics from Chung Yuan Christian University, Chung Li, Taiwan, R.O.C., in 2003, and is currently working toward the M.S. and Ph.D. degrees in physics at Chung Yuan Christian University.

Her research interest includes characterization of semiconductor materials and their devices.



I.-Jen Shu was born in Taipei, Taiwan, R.O.C., in 1967. He received the Ph.D. degree in physics from Tsing Hua University, Hsinchu, Taiwan, R.O.C., in 1999.

In 2003, he joined the faculty of the Physics Department, Chung Yuan Christian University, where he is currently an Assistant Professor. His research interests include biophotonics and nanotechnology.



Ji-Lin Shen received the B.S. degree in physics from National Central University, Taiwan, R.O.C., in 1985, the M.S. degree in applied physics from National Tsing-Hua University, Taiwan, R.O.C., in 1987, and the Ph.D. degree in physics from National Taiwan University, Taiwan, R.O.C. in 1994.

From 1995 to 1997, he was a Post-Doctoral Researcher with the Electrical Engineering Department, University of California at Los Angeles (UCLA). Since 1998, he has been with the Physics Department, Chung-Yuan Christian University, Chung-Li,

Taiwan, R.O.C., where he is currently a Professor. His current research interests include optical characterization of semiconductor materials and nanomaterials.



James Cheng-An Lin received the Bachelor degree from Chung Yuan Christian University (CYCU), Chung-Li, Taiwan, R.O.C., in 1999, and is currently working toward the Ph.D. degree in biomedical engineering at CYC.

In 2004, he set up the Core Facility Laboratory for Nano Biomedicine Technology, which is equipped with a confocal microscope, bio-atomic force microscope, cell culture room, glove-box system, etc. This laboratory enables the members of the Center for Nano Biomedicine Technology (CNBT) to work

together. For two months, he was with the Faculty of Applied Physics, Ludwig Maximillians Universität, Munich, Germany. His research has included how to synthesize QDs. His research interests are QD synthesis, surface modification, and biomedical applications.



Walter H. Chang was born in Taiwan, R.O.C., in 1943. He received the B.Sc. degree in physics from Chung Yuan Christian University, Taiwan, R.O.C., in 1966, the M.Sc. degree in electrical engineering from Yansei University, Seoul, Korea, in 1974, and the Ph.D. degree in biomedical engineering from Tokyo Denki University, Tokyo, Japan, in 2002.

Since 1983, he has been a Full Professor with the Department of Biomedical Engineering, Chung Yuan Christian University. He is listed in Marquis' *Who's Who in the World 2005*. His major research activities

are in the area of nanobiomedical technology, bone-tissue engineering, bone-fracture healing, bioeffects of electromagnetics, rehabilitation engineering, and medical instrumentation. He has authored or coauthored over 180 publications in journals, conference proceedings, abstracts, and book chapters.

Prof. Chang is a member of the American Association for the Advancement of Science (AAAS), IFMBE, the IEEE EMBS, World Academe of Biomedical Technology, and the Biomelectromagnetics Society.



Ruoh-Chyu Ruaan received the Ph.D. degree in chemical engineering from Purdue University, West Lafayette, IN, in 1991.

He is currently a Full Professor with the Department of Chemical and Materials Engineering, National Central University, Taiwan, R.O.C. He is currently focused on the study of interactions between biomolecules and artificial surfaces. His special interests lay in the orientation and conformation changes of proteins upon interactions. He is also familiar with surface modification of

polymeric and ceramic materials and nanoparticles. All of these skills ensure the immobilization of biomolecules in active forms.



Wu Ching Chou received the Bachelor of Science and Master of Science degrees from National Chiao Tung University, Hsin-chu, Taiwan, R.O.C., in 1984 and 1986, respectively, and the Ph.D. degree in physics from the State University of New York at Buffalo, in 1992. His doctoral dissertation concerned optical spectroscopy of diluted magnetic semiconductor low-dimensional structures.

Following two years of military service in the U.S. Air Force, he joined the Physics Department, State University of New York at Buffalo. In 1992, he became an Associate Professor with the Physics Department, Chung Yuan Christian University, Chung-Li, Taiwan, R.O.C. In 1997, he became a Professor. In 2003, he joined the Department of Electrophysics, National Chiao Tung University, as a Professor. His current research interests include molecular beam epitaxy and optical spectroscopy of II-VI compound semiconductors, growth, and nanoscale opto-electronic measurements of GaN-based structures, Raman scattering, and X-ray scattering of semiconductors at high pressure, and spintronics.