

Available online at www.sciencedirect.com



Surface Science 600 (2006) L110-L115

SURFACE SCIENCE

www.elsevier.com/locate/susc

Surface Science Letters

Electronic structure of HgTe nanocrystals: An observation of p–d weakening

S. Rath, S.N. Sahu *

Institute of Physics, Cluster and Nanostructure Laboratory, Sachivalaya Marg, Bhubaneswar 751 005, India

Received 17 August 2005; accepted for publication 23 February 2006 Available online 20 March 2006

Abstract

Photoemission studies to identify the electronic structure of the HgTe nanocrystals revealed a new phenomenon of p–d weakening, as a consequence of size quantization effect associated with the mean crystalline size, 5.35 ± 0.83 nm. The weakening of the p–d hybridization by a factor of 0.33, to that of the bulk HgTe suggests the valence band maxima and core level shifts toward higher binding energy. The widening of the band gap due to size quantization is confirmed from optical absorption and photoluminescence measurements. The upward and downward shift of the conduction band minima and the valence band maxima with respect to the bulk value of HgTe are found to be 1.6 eV and 0.54 eV respectively.

© 2006 Elsevier B.V. All rights reserved.

Keywords: Electronic structure; Nanocrystals; Semiconductor; Quantum confinement effect

1. Introduction

Mercury-telluride (HgTe) belongings to the II-VI group have been studied considerably over the past decade [1,2]. However, the electronic structural study of the nanocrystalline Hg-VI semiconductor which is distinguished by a cation d-band inside the main valence band is important for its wide applications in optoelectronic [3], spintronic [4] and quantum devices [5]. Bulk HgTe is an inverted narrow band gap semiconductor. At the gap, the fully occupied valence band maximum (VBM) has Γ_{15} symmetry and the empty conduction band minimum (CBM) has Γ_1 symmetry. Taking spin degree of freedom into account, the symmetry of the band can be described within the double-group representation such as the Γ_{15} level splitting into a fourfold degenerate, Γ_8 level and a twofold Γ_7 , with the Γ_8 level above the Γ_7 of the p states. Similarly, the Γ_1 level splits into a twofold degenerate Γ_6 level of the s state. Since, bulk HgTe has tetrahedral symmetry, $T_{\rm d}$, hence, the valence p-d orbital interactions between the central atom, mercury, d states and the ligand, tellurium, p states are permitted [6]. For conventional symmetry representation, the anion p state has t_2 symmetry and the cation d state has t_2 and e symmetry. The above is shown schematically in Fig. 1(a). The details of Fig. 1(b-f) is to be discussed in a later section. From the symmetry point of view, the hybridization between t_2 symmetry of the p state and t_2 symmetry of the d state is allowed which results in the shift of Γ_8 level. However, the Γ_6 level remains unchanged due to the symmetry forbidden nature of hybridization between t_2 symmetry state of the p orbital and e symmetry state of the d orbital [6]. This results in an inverted narrow band gap feature of HgTe with $E_{\rm g} = f_6 - f_6$ $\Gamma_8 = -0.15$ eV at room temperature [7–9] (300 K). The negative band gap is due to the large partial delocalization of the Hg d state which is attributed to the attractive potential of Hg ion and pertains to the Γ_6 level below Γ_8 [10,11]. Notably, the band gap of Hg-VI compound is based on three factors: (1) the chalcogen (Te) p spin-orbit (SO) splitting, (2) the Hg d SO splitting and (3) the strength of the pd hybridization [4]. Since p-SO and d-SO splittings are an atomic properties, hence, the nature of band gap is solely

^{*} Corresponding author. Tel.: +91 674 2301058; fax: +91 674 2300142. *E-mail address:* sahu@iopb.res.in (S.N. Sahu).

^{0039-6028/\$ -} see front matter @ 2006 Elsevier B.V. All rights reserved. doi:10.1016/j.susc.2006.02.037



Fig. 1. Schematic representation of the p-d hybridization occurring during HgTe crystal formation and resulted the band gap as $E_g = -0.15 \text{ eV}$, at room temperature is shown in (a) and (b) respectively. The quantum size effect attributing the band gap opening and observation of the p-d weakening are shown in (c) and (d) respectively. The downward and upward arrow indicated in (e) represents the shifting of the levels towards higher binding energy side. The shift of conduction band (ε_c) and valence band (ε_{HHV}) with respect to the Fermi energy is illustrated in (f).

depends upon p–d hybridization [12]. As a result of which the Γ_8 level exhibits both p and d character whereas Γ_6 exhibits the s character (schematic is shown in Fig. 1(a)) [6]. With the above consideration, the present work describes the studies on the electronic structure of the HgTe nanocrystals and their associated unique optical properties through X-ray photoelectron spectroscopy (XPS), optical absorption and photoluminescence (PL) measurements.

2. Experimental

HgTe nanocrystalline thin films have been synthesized under galvanostatic condition with an electro-deposition current density, 1.5 mA/cm² for a period of 2 min using a solution containing HgCl₂ (0.028 M) and TeCl₄ (0.052 M) at temperature, 278 K and at pH 0.6. The substrates were indium tin oxide (ITO) coated glass, carbon coated Cu grid and titanium (Ti) used respectively as cathode and platinum as anode for sample synthesis. Near stoichiometric HgTe nanocrystals (NCs) could be obtained by the above mentioned electro-deposition parameters [13]. The stoichiometry, and size of the NCs deposited on three different substrate were tested through Rutherford back scattering and optical absorption studies. The measurements reveal the composition and/or absorption spectrum do not vary appreciably which suggests that the results are independent of substrates under consideration. Shown in Fig. 2(a) is the transmission electron microscopy (TEM) (Jeol 2010 TEM machine operated at 200 keV) micrograph of the HgTe NCs. The NCs appeared as black points in the micrograph have the mean crystalline size as 5.35 ± 0.83 nm. Fig. 2(b) shows the high resolution TEM (HRTEM) image of a typ-



Fig. 2. TEM micrograph (a), high resolution image (b) and the electron diffraction pattern (c) of the HgTe NCs.



ical HgTe NC (black point). It should be noted that in the HRTEM image (Fig. 2(b)), the boundary of the NC is not resolvable. Further, there is a small size distribution in deposited NCs. Hence, a typical NC was chosen for HRTEM image for getting the structure (lattice spacing) of the NC. The lattice spacing, d (difference between two consecutive bright or dark fringes) calculated from HRTEM is found to be 0.62 nm which corresponds to the cubic phase of the HgTe as compared to standard JCPDS data with 3% lattice contraction. The cubic phase of the HgTe NCs have been verified with different NCs (black points). As to the selected area electron diffraction (SAD) measurements, shown in Fig. 2(c), the exposed sample diameter under electron beam is around 150 nm. Whereas the mean size of the NCs is 5.35 nm. Hence, the SAD is the contribution from all the NCs under the beam giving the ring patterns. The ring like SAD patterns (Fig. 2(c)) corresponding to the crystallographic planes, (220), (311) and (222) reveal the polycrystalline cubic phase character of the deposit. The structure of the HgTe NC is also verified using grazing angle X-ray diffraction (GXRD) measurements (figure is not shown) and shows consistent results (cubic phase) as observed from TEM [13].

3. Results and discussion

Fig. 3 shows the optical absorption spectrum (left arrow) and photoluminescence spectrum (right arrow) of the HgTe NCs prepared on ITO substrate. Note that both the spectra are normalized to the same scale. Optical absorption measurements of the HgTe NCs were carried out using a dual beam Shimadzu UV-3101PC spectrophotometer. The absorption spectrum shows the striking excitonic features around 578.5 nm and 550 nm marked by A_1 and A_2 respectively, in the optical absorption. According to



Fig. 3. Optical absorption (left arrow) and photoluminescence (right arrow) spectra of the HgTe NCs.

the energy band diagram of the bulk HgTe (Fig. 1(b)), the energy difference between heavy hole valence (HHV) band to light hole valence (LHV) band is around 0.15 eV at temperature, T = 300 K and the conduction band (CB) touches the HHV band because of the relativistic effect [9] (i.e., strong valence electron-nucleus interaction). As a result, the band gap of the bulk HgTe is considered as -0.15 eV [8,9] and such inverted narrow band gap nature of bulk HgTe has been verified from magnetoreflection, optical absorption, photoluminescence and photovoltaic studies by several groups [1,2,14–17] since decade. Hence, bulk HgTe is known as infrared sensitive material. Further, the characteristic optical absorption of the HgTe NCs in the visible regime (shown in Fig. 3) reveals the widening of the band gap by shifting the CB, HHV and LHV bands due to the quantum-confinement effect (QCE) and is schematically shown in Fig. 1(c). Hence, the peaks, A_1 and A_2 are attributed to the HHV band-conduction band (CB) and LHV band-CB transitions respectively. Such strong QCE (i.e., shifting of VBM and CBM) is expected as the mean crystalline size, 5.35 nm is much less than the Bohr exciton radius, $a_{\beta} = 40$ nm. A similar type of excitonic features have also been observed from CdS passivated HgTe NCs by Rogach et al. [18]. It should be noted that the pronounced well resolved absorption spectrum predicts good crystallinity in the sample. Photoluminescence (PL) measurements were carried out at room temperature (300 K) using Oriel PL set up with wavelength, $\lambda = 369$ nm as an exciting radiation available from a Hg-Xe lamp and the spectrum is shown in Fig. 3 (marked by the right arrow). The PL spectrum in the wavelength range 500-700 nm, shows a broad peak with a small shoulder towards lower wavelength. Deconvoluting the PL spectrum using Gaussian function, we get two bands, P_1 and P_2 at 579.5 nm and 588 nm respectively. Since, the energy difference between P_1 and P_2 is around 30 meV which can be considered as the localization energy of exciton and the energy corresponding to the room temperature is 26 meV, hence, some of the excitons are thermally released from the bound state as free exciton. Thus, peak P_1 and P_2 are ascribed to the luminescence corresponding to the free-exciton and bound-exciton transition [19] respectively. Further, as the PL peak, P_1 position is very close to the first excitonic transition, A_1 in the absorption spectrum (Fig. 3) hence, the origin of P_1 can be ascribed to the band edge luminescence providing the band gap as $E_g = 2.14 \text{ eV}$ and confirms the semiconducting nature of the HgTe NCs. One possibility of such large band gap opening (2.14 eV) can be ascribed to the change in the electronic structure and discretization of energy levels as the crystalline size approaches to the quantum limit. It may be noted that the hybridization is a ground state property. However, as the surface to volume ratio is very large, the majority of the atoms on the HgTe NCs do not experience a true bulk-like environment. As a result, the impact of atomic-coordination number imperfection provides the change in crystal potential of the nano-solid which is given by [20]

$$V(\Delta_{\rm l}) = V_{\rm atom}(r) + V_{\rm crystal}(r)[1 + \Delta_{\rm l}]$$
(1)

where $V_{\text{atom}}(r)$ is the intra-atomic trapping potential, $V_{\text{crystal}}(r)$ is the crystal potential and

$$\begin{aligned} \Delta_{1} &= \sum_{i \leq 3} \gamma_{ij} \Delta_{i} \\ \gamma_{ij} &= \frac{D_{\text{out},i}^{\tau} - D_{\text{in},i}^{\tau}}{D_{j}^{\tau}} \sim \frac{\tau c_{i}}{K_{j}}, \quad K_{j} = D_{j}/2d_{0} \\ c_{i}(z_{i}) &= d_{i}/d_{0} = \frac{2}{1 + \exp[(12 - z_{i})/8z_{i}]} \end{aligned}$$
(2)

The parameters, Δ_i , τ , D_j , d_0 and z_i are the contribution from interlayer bond contraction, dimensionality of the nano-solid (e.g., $\tau = 1$, 2 and 3 correspond to the dimensionality of a thin plate, a rod, and a spherical dot respectively), diameter of the nano-solid in *j*th layer, bulk bond length, atomic coordination number of the *i*th layer respectively. This leads to the localization of the charge in relaxed surface region and helps to modify the bond formation during hybridization and is reflected on the electronic structure by shifting of the valence and core levels [21].

In pursuit of the change in the electronic structure and the band opening phenomena associated with HgTe NCs, XPS measurements were carried out at 2×10^{-9} mbar pressure using VG Microtech XPS setup incorporated with 300 W Mg/Al X-ray source and a hemispherical analyzer with a channeltron detector (resolution 0.9 eV) at room temperature. The exciting radiation was 1256.4 eV Mg K_{α} X-ray source. After removal of few mono-layers of the adsorbed impurities and surface oxides by Ar ion sputtering, the XPS scan has been made for the HgTe NC sample. The valence and core level spectra were calibrated against the C 1s peak and the background (due to inelastic scattering of the secondary electrons) corrections have been carried out by a polynomial fitting of experimental data using VG Microtech software. The valence band spectrum of the HgTe NC as shown in Fig. 4(a) consists of six peaks, r_1 (4.40 eV), r_2 (6.42 eV), r_3 (8.41 eV), r_4 (10.27 eV), r_5 (12.89 eV) and r_6 (14.87 eV) where r_3 and r_4 represent the Hg 5d_{5/2} and 5d_{3/2} levels with BE shift, $\Delta E5d_{5/2} = E_{5d_{5/2}}^{N} - E_{5d_{5/2}}^{B} = 0.88 \text{ eV}$ and $\Delta E5d_{3/2} = E_{5d_{3/2}}^{N} - E_{5d_{3/2}}^{B} = 0.83$ respectively. Note that the full width of half maxima (FWHM) of Hg $5d_{3/2}$ is large compared to Hg $5d_{5/2}$ and is due to the effect of orbital-hybridization leading rearrangement of density of states (DOS) as a result of the size quantization. Peaks, r_1 and r_2 corresponds to the Te 5p derived DOS and a hybrid, Hg 6s-Te 5p derived DOS respectively [22]. Similarly, peaks, r_5 and r_6 are due to the Hg 5d-Te 5s derived DOS and Te 5s state respectively. Since, the band position and the width reflect the degree of overlapping and the strength of the hybridization [11], hence, the values of $E_p^{N-B} = E_p^N - E_p^B = 0.71 \text{ eV}$ and $E_d^{N-B} = E_d^N - E_d^B = 0.91 \text{ eV}$ suggests that the d level of Hg is shifting more towards higher BE with narrow line width compared to the low shift and long tail of Te 5p state. The superscript N and B stand for nanocrystal and bulk respectively. The results suggest a significant weakening of p–d hybridization in the HgTe NCs. The magnitude of the p–d hybridization (ΔE_{pd}) can be estimated perturbatively [6], as

$$\Delta E_{\rm pd} \sim \frac{V_{\rm pd}^2}{\epsilon_{\rm d}^{\rm c} - \epsilon_{\rm p}^{\rm a}} \tag{3}$$

where V_{pd} , ϵ_d^c and ϵ_p^a are p–d orbital interaction potential, cation, d orbital energy and anion, p orbital energy respectively in the valence level.

Comparing the experimental ΔE_{pd} value with bulk and that of nano we get

$$\frac{\Delta E_{\rm pd}^{\rm N}}{\Delta E_{\rm pd}^{\rm B}} = \frac{(\epsilon_{\rm d}^{\rm c})^{\rm B} - (\epsilon_{\rm p}^{\rm a})^{\rm B}}{(\epsilon_{\rm d}^{\rm c})^{\rm N} - (\epsilon_{\rm p}^{\rm a})^{\rm N}} = 0.33 \tag{4}$$

Hence, the p-d hybridization in case of the HgTe NCs is weakened by a factor of 0.33 to that of the bulk (schematically it has been illustrated in Fig. 1(d)). The weakening of p-d hybridization is consistent with the transfer of non – d electrons from Hg to Te [11]. Note that in explaining the above behavior, we have assumed that the background contribution to the valence band spectrum is negligible. However, in order to quantify the results one need to record the XPS spectrum at resonance X-ray photon energy for which the work is in progress. From the valence level XPS analysis, we have observed that there is a shift in VBM to higher BE. The shift of VBM can be determined from a linear extrapolation of the leading valence band edge [23] as marked by an arrow shown in the inset of Fig. 4 and found to be 1.13 eV. The possible explanation of the VBM shifting of the HgTe NCs can be due to the rearrangement of the DOS leading to a change in electronic structure because of size quantization where the crystal (in nanoform), does not exhibit true bulk like behavior [24]. Fig. 4(b) shows the Te core level spectrum of the HgTe NCs. It consists of four peaks namely s_1 , s_2 , s_3 and s_4 . The peaks, s_2 and s_3 represent the $4d_{5/2}$ and $4d_{3/2}$ respectively of 4d level. For the HgTe NCs, we have observed that the $4d_{5/2}$ level is at 40.79 eV with a BE shift of 1.11 eV from its bulk value. Similarly, the peak, s₃ appearing at 42.25 eV shows the BE shift of 1.13 eV from its bulk counter part. The prominent peaks s_1 and s_4 appeared at BE, 37.32 eV and 45.81 eV can be accounted to the Te 4d_{5/2}–O and 4d_{3/2}–O hybrid levels respectively. Similarly, the spectrum in the range 570-595 eV illustrated in Fig. 4(c) is the Te 3d core level spectrum which consists of four peaks t_1 , t_2 , t_3 and t_4 . The peaks, t_1 and t_3 appearing at 573.27 eV and 583.59 eV are the $3d_{5/2}$ and $3d_{3/2}$ core levels of Te with BE shift of 0.57 eV and 0.55 eV respectively to that of bulk Te. The appearance of the peak, t_2 at 578.21 eV can be ascribed to the contribution from Te $3d_{5/2}$ –O derived DOS. Similarly, the peak, t_4 appearing at 588.56 eV is due to Te $3d_{3/2}$ –O. The Hg core 4f level has been observed in the BE range 94-114 eV as shown in Fig. 4(d). The SO splitting of 4f level $(4f_{7/2} \text{ and } 4f_{5/2})$ is illustrated by the peaks, u_2 (100.75 eV) and u_3 (105.21 eV) L114



Fig. 4. (a) Valence band XPS spectrum of the HgTe NCs and the inset is the linear extrapolation of valence band edge to evaluate the valence band maxima as indicated by the downward arrow. Core level spectrum of Te 4d state (b), Te 3d state (c) and Hg 4f state (d) of the HgTe NCs.

with BE shift of 1.05 eV and 1.40 eV respectively. Apart from u_2 and u_3 , two other peaks, u_1 and u_4 are also appearing at BE, 96.50 eV and 109.79 eV respectively. Moreover, the intensity of $4f_{7/2}$ should be higher than $4f_{5/2}$ whereas the intensities of the above two (u_2 and u_3) are approximately same here. It indicates that the satellite feature of Hg 4f at lower binding energy side namely, u_1 can be due to the transformation of DOS to ligand, Te [11]. The peak u_4 appear in the higher energy side can be ascribed to the Hg–O hybrid level.

Analysis of valence and core level spectra of the HgTe NCs shows that the BE of the Hg 5d_{5/2}, Hg 4f_{7/2}, Te 4d_{5/2} and Te $3d_{5/2}$ levels are shifted by 0.88, 1.05, 1.11 and 0.57 eV respectively with respect to their bulk counter part. Further, it can be noted that in case of Hg cation, the core level shift is more compared to the valence level (shown in Fig. 1(e) which is due to the $(n - 1)d^{10}$ configuration of

the Hg metal where the effect of Hg nucleus on the valence electrons is stronger than the core electrons [6]. However, for Te, the case is reversed. This is because of the core level electrons are highly attracted by the nucleus than valence electrons. Since, the cationic core levels stay nearly constant [25], thus, the measured cation core level shifts must have resulted from the movement of the VBM. For the sake of clarity, the BE scale is referred to the Fermi energy, $E_{\rm f}$. In case of bulk HgTe, the $E_{\rm f}$ is lying at 0.59 \pm 0.05 eV above the VBM [22] at room temperature. However, the $E_{\rm f}$ position would change if the spectra recorded at low temperature (40 K) [7]. As we have recorded the spectra at room temperature, the $E_{\rm f}$ is assumed to be 0.59 eV above the VBM. Further, the optical absorption and PL measurements estimated the E_g of HgTe NCs as 2.14 eV. Considering both the XPS, optical absorption and PL measurements, carried out at room temperature, we found that the conduction

SUME ACCENTIC

band is shifting up by 1.6 eV and the valence band is shifted down by 0.54 eV from the Fermi level as shown in Fig. 1(f). This is due to weakening of the p–d hybridization and the discretization of the electronic energy level as a result of size quantization effect. The particle size estimated using effective mass approximation [26] from the band edge luminescence is about 5.2 nm which does not agree with the value, 5.35 nm obtained from TEM measurement. The above discrepancy can be accounted to the p–d interaction weakening and particle in a finite potential well. Hence, for the good agreement of the experimental result to that of the theory, the semi empirical relation [26] (i.e. effective mass approximation) of the confinement energy for HgTe NCs can be given by

$$E_{\rm c} = \delta E_{\rm g} + \frac{\hbar^2 \pi^2}{2m^* r^2} - \frac{1.86e^2}{\epsilon r} - \varepsilon_{\rm pol}$$
where $\delta E_{\rm g} = E_{\rm g} + \Delta E_{\rm pd}$
(5)

Taking $m^* = 0.029m_0$, $\epsilon = 21$, $\varepsilon_{pol} = 0.674$ meV of HgTe, particle size = 5.35 nm (from TEM result), $E_c = 2.14$ eV (from optical absorption data), the ΔE_{pd} value is estimated as 0.23 eV. Comparing the result with theoretical calculation, $\Delta E_{pd} = 0.68$ eV for bulk HgTe [6], we observed that

$$\Delta E_{\rm pd}^{\rm N} \simeq 0.33 \Delta E_{\rm pd}^{\rm B} \tag{6}$$

From the above observation, it can be concluded that the widening of the band gap in HgTe NCs is associated with the weakening of p–d hybridization leading to minimization of the relativistic effect (i.e. the correction of the potential energy between the valence electron and nucleus interaction due to localization of d orbital, during hybridization decreases as a result, the conduction band moves up) and the discretization of the energy levels due to QCE.

4. Conclusions

In conclusion, HgTe nanocrystals with mean size as 5.35 ± 0.83 nm have been synthesized by an electrochemical technique. The important features associated in the widening the band gap of HgTe nanocrystals are due to (1) weakening of the p–d hybridization and (2) quantization of the electronic energy levels which has been confirmed experimentally using XPS, optical absorption and PL measurements. Experimentally, it has been observed that the p–d hybridization energy is weakened by a factor of 0.33 to that of the bulk value. It further reveals that the conduction band is shifted up by 1.6 eV and valence band is moved down by 0.54 eV from the Fermi level.

Acknowledgements

Thanks are due to Prof. S.N. Behera, Dr. R.K. Choudhury, Institute of Physics, Bhubaneswar, India, for their helpful discussion and constant encouragement. Dr. P.V. Satyam and Dr. Shikha Varma, Institute of Physics, Bhubaneswar, India are acknowledged for helping in TEM and XPS measurements. The author would like to acknowledge Mr. S.N. Sarangi for his help during the experiments.

References

- R. Piotrzkowski, S. Porowski, Z. Dziuba, J. Ginter, W. Giriat, L. Sosnowski, Phys. Status Solidi B 8 (1965) K135.
- [2] G.L. Hansen, J.L. Schmit, T.N. Casselman, J. Appl. Phys. 53 (1982) 7099.
- [3] D.L. Klein, R. Roth, A.K.L. Lim, A.P. Alivisatos, P.L. McEuen, Nature 389 (1997) 699.
- [4] A. Delin, Phys. Rev. B 65 (2002) 153205-1.
- [5] T.C. McGill, D.A. Collins, Semicond. Sci. Technol. 8 (1993) S1.
- [6] S.-H. Wei, Alex Zunger, Phys. Rev. B 37 (1988) 8958.
- [7] N. Orlowski, J. Augustin, Z. Golacki, C. Janowitz, R. Manzke, Phys. Rev. B 61 (2000) R5058.
- [8] Donald Long, Joseph L. Schmit, Semicond. Semimetal 5 (1970) 190.
- [9] Isaak M. Tsidikovski, Electron Spectroscopy of Gapless Semiconductor, 116, Springer, 1997, p. 85.
- [10] Michael Rohlfing, Steven G. Louie, Phys. Rev. B 57 (1998) R9392.
- [11] C.D. Gelatt Jr., A.R. Williams, V.L. Moruzzi, Phys. Rev. B 27 (1983) 2005.
- [12] D. Khomskii, 2001, vol. 1, 11 January. Available from: arXiv: cond-mat/0101164.
- [13] S. Rath, S.N. Sahu, Eur. Phys. Lett. 67 (2004) 294.
- [14] S.H. Groves, W. Paul, Phys. Rev. Lett. 11 (1963) 194.
- [15] T.C. Harman, A.J. Strauss, D.H. Dickey, M.S. Dresselhaus, G.B. Wright, J.G. Mavroides, Phys. Rev. Lett. 7 (1961) 403.
- [16] C. Verie, J. Ayas, Appl. Phys. Lett. 10 (1967) 241.
- [17] G. Landwehr, J. Gerschutz, S. Oehling, A. Pfeuffer-Jeschke, V. Latussek, C.R. Becker, Physica E 6 (2000) 713.
- [18] M.T. Harrison, S.V. Kershaw, A.L. Rogach, A. Kornowski, A. Eychmuller, H. Weller, Adv. Mater. 12 (2000) 123.
- [19] S. Rath, A.K. Dash, S.N. Sahu, S. Nozaki, Int. J. Nanosci. 3 (2004) 393.
- [20] Chang Q. Sun, Phys. Rev. B 69 (2004) 045105.
- [21] Chang Q. Sun, Prog. Mater. Sci. 48 (2003) 521.
- [22] Xiaohua Yu, L. Vanzetti, G. Haugstad, A. Raisanen, A. Franciosi, Surf. Sci. 275 (1992) 92.
- [23] V.L. Colvin, A.P. Alivisatos, J.G. Tobin, Phys. Rev. Lett. 66 (1991) 2786.
- [24] T. van Buuren, L.N. Dinh, L.L. Chase, W.J. Siekhaus, L.J. Terminello, Phys. Rev. Lett. 80 (1998) 3803.
- [25] C.K. Shih, W.E. Spicer, Phys. Rev. Lett. 58 (1987) 2594.
- [26] L.E. Brus, J. Chem. Phys. 80 (1984) 4403.