Verification of $\Gamma_7$ symmetry assignment for the top valence band of ZnO by magneto-optical studies of the free A exciton state

Lu Ding$^{1,5}$, Chunlei Yang$^{2,7}$, Hongtao He$^{1,6}$, Jiannong Wang$^{1}$, Zikang Tang$^{1}$, Bradley A Foreman$^{1}$, Fengyi Jiang$^{3}$ and Weikun Ge$^{1,4,7}$

1 Department of Physics, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, People’s Republic of China
2 Center for Photovoltaic Solar Cells, Shen Zhen Institute of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, People’s Republic of China
3 Institute of Materials Science, Nanchang University, Nanchang 330047, Jiangxi, People’s Republic of China
4 Department of Physics, Tsinghua University, Beijing 100871, People’s Republic of China
E-mail: phweikun@ust.hk and cl.yang@siat.ac.cn

New Journal of Physics 15 (2013) 033015 (9pp)
Received 9 January 2013
Published 13 March 2013
Online at http://www.njp.org/
doi:10.1088/1367-2630/15/3/033015

Abstract. Circularly-polarized and angular-resolved magneto-photoluminescence spectroscopy was carried out to study the free A exciton 1S state in wurtzite ZnO at 5 K. The $\Gamma_7$ symmetry of the top valence band symmetry is confirmed according to the unique selection rules of Zeeman splitting lines. The out-of-plane component $B_\|$, which is parallel to ZnO’s c-axis, leads to linear Zeeman splitting of both the dipole-allowed $\Gamma_5$ exciton state and the weakly allowed $\Gamma_1/\Gamma_2$ exciton states. The in-plane field $B_\perp$, which

$^5$ Present address: Institute of Materials Research and Engineering, Agency for Science, Technology and Research (A*STAR), Singapore 117602, Singapore.
$^6$ Present address: Department of Physics, The South University of Science and Technology of China, Shenzhen, People’s Republic of China.
$^7$ Authors to whom any correspondence should be addressed.

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is perpendicular to the \(c\)-axis, increases the oscillator strength of the weak \(\Gamma_1/\Gamma_2\) states by forming a mixed exciton state. For the \(\Gamma_7\) symmetry, the lower energy Zeeman splitting peak of the weak \(\Gamma_1/\Gamma_2\) can only be \(\sigma_+\) polarization.

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1. Introduction

The debate on the top valence band symmetry of wurtzite ZnO crystal has lasted for more than half a century. In most wurtzite semiconductors, the quasidegenerate \(p\)-like valence states at \(\Gamma\) are split by the crystal-field (\(\Delta_{\text{cr}}\)) and spin–orbit (\(\Delta_{\text{so}}\)) interactions into states of symmetry \(\Gamma_9\), \(\Gamma_7\) and \(\Gamma_7\), in order of decreasing energy [1]. For ZnO, the crystal-field splitting is about one order greater than the spin–orbit coupling [2]. As it is well accepted that \(\Delta_{\text{cr}} \gg |\Delta_{\text{so}}|\), the sign of \(\Delta_{\text{so}}\) is the subject of much debate. The controversy was first raised by Thomas [3] and Hopfield [4] by their pioneering reflectivity studies of excitonic transitions; they proposed that ZnO has a negative spin–orbit coupling, leading to a reversed \(\Gamma_7 - \Gamma_9 - \Gamma_7\) ordering. This reversed ordering is consistent with a wide variety of experimental data (see [5–12] for a few examples) and is also supported by first-principles calculations [13].

Nevertheless, some authors [14–22] have rejected this interpretation in favor of the conventional \(\Gamma_9 - \Gamma_7 - \Gamma_7\) ordering (i.e. \(\Delta_{\text{so}} > 0\)). In some cases, such a conclusion came from the misassignment of the absorption lines [23]. Many of the studies supporting reversed ordering did not directly compare the two possibilities; hence, although these studies provide cumulative evidence in favor of reversed ordering, they cannot be said to definitively resolve the controversy. Some such studies also used models with a large number of fitting parameters, leaving open the possibility that other parameter sets (perhaps consistent with a different ordering) might yield an equally good fit. A further reason for the continued skepticism toward models with \(\Delta_{\text{so}} < 0\) may be that they often depend crucially on parameters (e.g. \(k\)-linear terms [5, 6, 10, 11]) that are very small in the limit \(\Delta_{\text{cr}} \gg |\Delta_{\text{so}}|\).

Recently, a series of studies on bound excitons (BX) provide strong evidence to support the reversed ordering, which used first-principles calculations [24] and magneto-optical spectroscopies [25] to argue that the sign of the hole \(g\) factor deduced from magneto-optical studies of free excitons (FX) in [15] is incorrect, and that the top valence band of ZnO should therefore have \(\Gamma_7\) symmetry. The result reported by Wagner et al [12] on a newly observed hole state related Zeeman fine splitting for BXs in the Voigt configuration together with angular- and polarization-dependent magneto-optical measurements also provides convincing evidence for the \(\Gamma_7\) symmetry of the top valence band. However, as pointed out by Thomas and Hopfield [26], the hole \(g\) factors derived from studies of BX may, in principle, be entirely different from the
g factors of free holes, due to mixing the quasidegenerate valence states by the defect potential. For this reason, it is not a priori obvious that results based on BX are capable of providing unambiguous evidence for the symmetry of the top valence band of ZnO.

A straightforward approach is to investigate free A excitons, in view of its simple and well defined nature. We carry out high-resolution magneto-photoluminescence (PL) spectroscopy which is a powerful technique that explicitly reveals the relationship between the fundamental optical transitions of semiconductors and the optical selection rules that are uniquely determined by the band structure symmetries. In this paper, the circular polarization property of Zeeman splitting peaks of free A excitons, where the lower-energy peak of $\Gamma_{1\beta}^2$ excitons has $\sigma_+$ polarization, unambiguously demonstrates that the hole in the A exciton 1S state (or the top valence band) in wurtzite ZnO has $\Gamma_7$ symmetry. This interpretation is also supported by the polarization dependence of the Zeeman splitting of neutral-impurity BX.

As such, we believe it is worth getting this work formally published, which is mainly motivated by the very recent claim of the conventional $\Gamma_9 - \Gamma_7 - \Gamma_7$ ordering by [22]. It is a matter of fact that even after the convincing experiments of [12], there are still other voices. We believe that our results on FX straightforwardly support the $\Gamma_7 - \Gamma_9 - \Gamma_7$ ordering with no other options.

2. Magneto-photoluminescence spectroscopy

FX involving the s-like $\Gamma_7$ conduction band and the three valence bands are labeled as A, B and C excitons, in order of increasing exciton energy [3]. Depending on the symmetry assigned to the top valence band, A excitons have two possible symmetries:

$$\Gamma_7 \otimes \Gamma_7 \rightarrow \Gamma_5 \oplus \Gamma_1 \oplus \Gamma_2, \Gamma_7 \otimes \Gamma_9 \rightarrow \Gamma_5 \oplus \Gamma_6.$$  (1)

Here the doubly degenerate $\Gamma_5$ exciton is dipole-allowed for light polarized normal to the hexagonal $c$-axis ($E \perp \vec{c}$) and the singly degenerate $\Gamma_1$ exciton is (weakly) dipole-allowed for $E \parallel \vec{c}$, whereas the doubly degenerate $\Gamma_6$ exciton and the singly degenerate $\Gamma_2$ exciton are dipole-forbidden.

Using a magneto-cryostat with magnetic field $B$ up to 7 T, the magneto-PL measurements are performed on a 3 $\mu$m thick high quality ZnO thin film deposited on a (0001) sapphire substrate using metal-organic chemical vapor deposition. Figure 1(a) depicts the magneto-PL experimental setup. The Faraday configuration ($\vec{k} \parallel \vec{B}$) is applied, where $\vec{k}$ is the wave vector of the emitted light and $\theta$ is the angle between $\vec{B}$ and the $c$-axis. $\vec{B}$ can be decomposed into an out-of-plane component $B_\parallel = B \cos \theta$ (parallel to the $c$-axis) and an in-plane component $B_\perp = B \sin \theta$ (perpendicular to the $c$-axis). In our setup, different angles $\theta$ are achieved by simply rotating the $c$-axis. The incident laser is perpendicular to the magnetic field for arbitrary $\theta$, except that the backscattering geometry is used for $\theta = 0$. The magneto-PL spectra are resolved by a monochromator (SPEX 1403) located along the $\vec{B}$ field direction with 1800 g mm$^{-1}$ double gratings and detected by a photomultiplier tube (R928). The system’s spectral resolution is about 0.1 meV. The circular polarization ($\sigma_+$ or $\sigma_-$) of the emitted light is analyzed using a quarter-wave plate and a linear polarizer. All the measurements are performed at 5 K to minimize energy shifts induced by thermal fluctuation.
3. Results and discussions

To demonstrate the magnetic field effect clearly, the angular-dependent zero-field PL as well as magneto-PL spectra of the A exciton 1S state ($\text{FX}_A^{n=1}$) are shown for comparison in figures 1(b) and (c), respectively. At $B = 0 \, \text{T}$, two resolved fine structures of $\text{FX}_A^{n=1}$ are labeled as $P_1$ (3.3757 eV, weak) and $P_2$ (3.3778 eV, strong), which correspond to the weakly allowed (or dipole-forbidden) and dipole-active excitons, respectively (see figure 1(b)). The changes of the peak positions and intensities are found to be negligible at different $\theta$, which indicates a weak dependence on the polarization direction of the incident laser. Applying a magnetic field of 7 T, rich features are found with a strong angular dependence in the PL spectra (see figure 1(c)). When $\theta = 10^\circ$, Zeeman splitting of $P_1$ is observed with a splitting energy $\Delta E_{P_1}$ as large as 1.4 meV, whereas $P_2$ remains nearly unchanged. When $\theta$ increases, $\Delta E_{P_1}$ becomes smaller. The two split peaks of $P_1$ finally merge into one at $\theta = 80^\circ$. On the other hand, the integrated intensity $I_{P_1}$ of $P_1$ increases with increasing $\theta$ and eventually dominates the $\text{FX}_A^{n=1}$ spectrum. It is worth noting that there is almost no change in the magneto-PL spectrum at $\theta = 0^\circ$ when $B$ is scanned from 0 to 7 T, which is due to the weakly allowed (or dipole-forbidden) nature of $P_1$ at $B_\perp = 0$. The in-plane magnetic field $B_\perp$ is found to significantly increase the oscillator strength of $P_1$.

Our experimental data are best explained by a perturbation model with (i) $\Gamma_7 - \Gamma_9 - \Gamma_7$ valence-band ordering (i.e. the spin–orbit splitting $\Delta_{so} < 0$) and (ii) a weak magnetic field case. In this model, uncontroversial assumptions are made that the crystal-field splitting $\Delta_{cr}$ is much greater than the spin–orbit splitting $\Delta_{so}$, which in turn is much greater than either the exchange
splitting or the Zeeman splitting (for the magnetic fields used in our experiment). All of these perturbations are assumed to be negligible in comparison to the fundamental energy gap of the crystal.

We treat $\Delta_{so}$ as a perturbation of $\Delta_{cr}$, working to first order in the energy and to zeroth order in the state vector. If we choose the $z$- and $c$-axis to be the same, the exciton states formed from the $p_x \pm ip_y$ hole states of $\Gamma_7$ symmetry (i.e. the A excitons according to Thomas [3] and Hopfield [4]) are therefore

$$|\Gamma_5^{(7)}\rangle = |\pm\rangle \pm 1, \mp \pm \left( g_{exc} = g_h^\parallel + g_e \right),$$

$$|\Gamma_{1\oplus 2}^{(7)}\rangle = |\mp\rangle \pm 1, \mp \pm \left( g_{exc} = g_h^\parallel - g_e \right).$$

(2a)

(2b)

Here $|\pm\rangle|m_h, -\rangle$ is the tensor product of a spin-up $s$ electron and a spin-down $p$ hole whose $z$ component of orbital angular momentum is $m_h$. The $\pm$ label of the exciton states is taken from the sign of $m_h$ (note that for $\Gamma_5$, $m_h$ is also the $z$ component of the total exciton angular momentum). In equation (2b), the contribution of $\Delta_{so}$ to the short-range exchange interaction is neglected, so that $\Gamma_1$ and $\Gamma_5$ form an approximately doubly-degenerate reducible representation [3, 4, 24, 25], denoted $\Gamma_{1\oplus 2}$. A small field $B_\parallel$ produces a linear Zeeman splitting with the given exciton effective $g$ factors $g_{exc}$, in which $g_e$ is the (nearly) isotropic electron $g$ factor and $g_h^\parallel$ is the hole $g$ factor parallel to the $c$-axis [25]. In the simple model of [24] we have $g_h^\parallel = 2K - g_0$, where $K = -(3\kappa + 1)$ is the magnetic Luttinger parameter and $g_0 = 2$ is the $g$ factor of a free hole. The states in equation (2b) are dipole-forbidden when $B_\perp = 0$ but they become dipole-allowed $B_\perp \neq 0$ due to mixing with $|\Gamma_5^{(7)}, \mp\rangle$ caused by $g_e$.

Likewise, the exciton states formed from the $p_x \pm ip_y$ hole states of $\Gamma_9$ symmetry (i.e. the $B$ excitons according to Thomas and Hopfield) are given by

$$|\Gamma_5^{(9)}\rangle = |\mp\rangle \mp 1, \mp \pm \left( g_{exc} = g_h^\parallel - g_e \right),$$

$$|\Gamma_{6, 7}\rangle = |\pm\rangle \pm 1, \mp \pm \left( g_{exc} = g_h^\parallel + g_e \right).$$

(3a)

(3b)

in which $g_h^\parallel = 2K + g_0$. Just as for $|\Gamma_{1\oplus 2}, \pm\rangle$, the states $|\Gamma_{6, 7}, \pm\rangle$ are dipole-forbidden when $B_\perp = 0$, but become dipole-allowed when $B_\perp \neq 0$ due to $g_e$-induced mixing with $|\Gamma_5^{(9)}, \pm\rangle$.

In figure 2, we sketch two sets of optically allowed exciton transitions in a magnetic field with arbitrary $\theta$ (so that $B_\parallel$ and $B_\perp$ are both nonzero) for the ground-state FX involving a hole of either (a) $\Gamma_7$ symmetry or (b) $\Gamma_9$ symmetry. Here $\delta$ is defined as the zero-field exchange splitting between $\Gamma_5$ and $\Gamma_{1\oplus 2}$ states in case (a) or between $\Gamma_5$ and $\Gamma_{6, 7}$ states in case (b).

The labels $\pm1/2$ and $\pm3/2$ in figure 2 refer to the $z$ component of the total angular momentum for conduction and valence electrons. The notation $\sigma_{\pm}$ indicates that these transitions are dipole-forbidden when $B_\perp = 0$, but emit photons with $\sigma_{\pm}$ polarization when $B_\perp \neq 0$. The sign of $g_h^\parallel$ would have to be negative for $\Gamma_7$ and positive for $\Gamma_9$ in order to agree with the experimental observation that the Zeeman splitting of the weakly allowed states is much larger than that of the dipole-active states.

Based on the information in equations (2) and (3) and the energy diagrams in figures 2(a) and (b), it is evident that the symmetry of the top valence band can be identified by measuring the polarization of the weakly allowed states under an applied magnetic field. For exciton transitions involving a $\Gamma_9$ hole and a $\Gamma_7$ electron, one would expect the originally dipole-forbidden states
Figure 2. Schematic representations of energy levels of A exciton transitions involving holes of (a) \(\Gamma_7\) symmetry and (b) \(\Gamma_9\) symmetry. (c) shows the circular polarization dependence of the magneto-PL of FX\(_A^{n=1}\).

\((\Gamma_6\) excitons\) to split, with the lower-energy peak showing \(\sigma^-\) polarization. However, if both the electron and hole have \(\Gamma_7\) symmetry, the originally weakly allowed \(\Gamma_{1\oplus 2}\) excitons will show \(\sigma^+\) polarization for the lower-energy peak.

Figure 2(c) presents the polarization dependence of the magneto-PL of the A exciton state with \(B = 3\) T and \(\theta = 45^\circ\). The two dominant Zeeman-split peaks of \(P_1\) are well resolved in this figure. This clearly indicates that the lower-energy peak of \(P_1\) has \(\sigma^+\) polarization, which unambiguously demonstrates that the hole in the A exciton 1S state (or the top valence band) in wurtzite ZnO has \(\Gamma_7\) symmetry. \(P_1\) is therefore attributed to \(\Gamma_{1\oplus 2}\), whereas \(P_2\) is attributed to \(\Gamma_5\). The experimentally determined zero-field exchange splitting \(\delta\) is 2.1 meV (see figure 1(b)), which is in good agreement with [3, 29].

To get more information on the electron and hole \(g\) factors, the magnetic field dependences of the transition energies of \(P_1\) and \(P_2\) are summarized in figures 3(a) and (c) for \(\theta = 20^\circ\) and 80°, respectively. Figure 3(b) shows the \(\theta\) dependence of \(P_1\) and \(P_2\) at \(B = 7\) T. In the Zeeman splitting of \(P_1\) and \(P_2\), \(B_\parallel\) lifts the degeneracy of the \(P_1\) (\(\Gamma_{1\oplus 2}\)) states or the doublet \(P_2\) (\(\Gamma_5\)) state. The energy splitting of \(P_1\) (\(\Gamma_{1\oplus 2}\)) is fitted using \(E_{P_1\pm} = E_{P_1} \pm \frac{1}{2} \left(g^\parallel_h - g^\parallel_e\right) \mu_B B_\parallel\), where \(\mu_B\) is the Bohr magneton and \(E_{P_1} = 3.37576\) eV is the zero-field transition energy of \(P_1\) (\(\Gamma_{1\oplus 2}\)). Using \(g_e = 1.95\) [23], the hole \(g\) factor obtained from the fitting (see solid curves in figure 3) is \(g^\parallel_h = -1.6\), which agrees well with the values obtained in [5, 6] (but with a different convention for the sign of \(g^\parallel_h\)). The fact that the Zeeman splitting for \(P_2\) (\(\Gamma_5\)) could not be resolved (see the open circles in figure 3) indicates the nearly equal absolute values of \(g_e\) and \(g^\parallel_h\). The dotted
Figure 3. The magnetic field and angular dependences of the peak energies of A excitons ($P_1$ and $P_2$) and BXs ($I_6$ and $I_7$), as described in the text.

curves for $P_2$ are plotted according to $E_{P_{2\pm}} = E_{P_2} \pm \frac{1}{2} \left(g_{e}^h + g_{h}^e\right)\mu B\theta$, employing $g_e = 1.95$ and $g_h^\parallel = -1.6$.

In addition, the Zeeman splitting of BXs $I_6$ and $I_7$ has also been observed and the transition energies are shown in figure 3. The circular polarization dependences indicate that $I_6$ and $I_7$ are excitons bound to neutral impurity centers with A holes involved [28]. The dashed lines are fitted results given by $\pm \frac{1}{2}\mu B\left(g_e + g_h\right)$ and $g_h = g_h^\parallel \sqrt{\cos^2 \theta + \left(\frac{g_e^\perp}{g_h^\parallel}\right)^2 \sin^2 \theta}$, where $g_e = 1.95$, $g_h^\parallel = -1.6$, and $g_h^\perp = 0.11$. The equality of the fitted FX and BX values of $g_h^\parallel$ provides ex post facto support for the conclusions of [25] (although, as noted in the introduction, such similarity cannot be assumed to hold in general).

The different contributions of the in-plane and out-of-plane magnetic field to the magneto-PL spectra are shown more specifically in figure 4. The left panel (figure 4(a)) shows the measured dependence of the Zeeman splitting $\Delta E_{P_{1\parallel}}$ of $P_1$ ($\Gamma_{1\beta\gamma}$). The data taken at $B = 7$ T for different $\theta$ (solid black dots) and those taken at fixed $\theta$ for different $B$ (hollow colored dots) fall onto the same line plotted using the equation $\Delta E_{P_{1\parallel}} = \left|g_{ex}^\parallel \mu B\theta\right|$ with $g_{ex} = g_h^\parallel - g_e = -3.55$. The zero-field splitting of the $\Gamma_1$ and $\Gamma_2$ states is zero as expected. This good linear relationship between $\Delta E_{P_{1\parallel}}$ and $B_{\parallel}$ indicates that the weak-magnetic-field condition is well satisfied and reveals that the splitting of the A exciton states depends on the out-of-plane field instead of the total magnetic field, which can be well explained by the $\Gamma_2$ symmetry of the out-of-plane field that mixes $\Gamma_1$ only with $\Gamma_2$ states [4]. Figure 4(b) shows that the intensity $I_{P_{1\parallel}}$ of $P_1$ increases monotonically with increasing $B_{\perp}$. The transition probability of the originally weakly allowed $\Gamma_1/\Gamma_2$ excitons increases significantly due to mixing with $\Gamma_5$ excitons.

It is worth mentioning that the same results are repeated on a piece of a bulk ZnO sample, which indicates that our ZnO thin film has bulk quality and is strain free. Up to now, many conclusions have been drawn based on bulk crystals. It is commonly argued that valence band
ordering may be sensitive to many extrinsic properties such as strain, piezoelectric field, etc due to the small spin–orbit splitting. Whether these conclusions are applicable to the ZnO thin films that are usually grown on a sapphire substrate has still not been carefully examined. Here, using magneto-PL, we show that the top valence band of a ZnO thin film has $\Gamma_7 - \Gamma_9 - \Gamma_7$ ordering, which is the same as that of single ZnO crystals. A crystalline ZnO epilayer is commonly deposited on substrates like sapphire (0001), silicon (111), GaN and ScAlMgO4, etc. The lattice mismatch between ZnO and these substrates is 18, −15.4, 1.8 and 0.09%, respectively. Amongst them, ZnO/sapphire has the largest lattice mismatch. The theoretical study using ab initio calculations by Schleife et al [30] reveals that only the crystal field determined valence band A-C splitting is strongly affected by biaxial strain which would, even in the case of a A-C valence band crossing for large strain fields, lead to the top valence band having $\Gamma_7$ symmetry. Therefore, it is reasonable to believe that our study is also applicable for ZnO thin films grown on other substrates, provided that strain is relaxed.

4. Conclusions

We applied magneto-PL spectroscopy on a high quality ZnO thin film and carried out circular polarization and angular-resolved analysis. The top valence band of wurtzite ZnO has been verified to have $\Gamma_7$ symmetry by directly examining the polarization of the free A exciton emission. The out-of-plane component $B_\parallel$ of the magnetic field was found to be responsible for the linear Zeeman splitting of the $\Gamma_5$ and $\Gamma_1/\Gamma_2$ states. The in-plane magnetic field $B_\perp$ increases the oscillator strength of the originally weakly allowed $\Gamma_1/\Gamma_2$ states by mixing with $\Gamma_5$ states. The hole effective $g$ factor was found to be negative and have the value $-1.6$.
Acknowledgments

The authors are grateful to Y Zhang (The University of North Carolina at Charlotte, USA) and G Q Hai (Universidade de São Paulo, Brazil) as well as Y Q Wang (Institute of Solid State Physics, Chinese Academy of Sciences, China) for their encouraging discussions. This work is funded by the Hong Kong University of Science and Technology via grants numbers DAG04/05.SC24 and DAG05/06.SC30. We would also like to acknowledge the support 973 project 2012CB933700.

References

[1] Birman J L 1959 Phys. Rev. 114 1490
[2] Mang A, Reimann K and Rübenacke St 1995 Solid State Commun. 94 251
[3] Thomas D G 1960 J. Phys. Chem. Solids 15 86
[4] Hopfield J J 1960 J. Phys. Chem. Solids 15 97
[5] Hummer K, Helbig R and Baumgartner M 1978 Phys. Status Solidi b 86 527
[6] Blattner G, Kurtze G, Schmieder G and Klingshirn C 1982 Phys. Rev. B 25 7413
[7] Fiebig M, Fröhlich D and Pahlke-Lerch Ch 1993 Phys. Status Solidi b 177 187
[8] Wrzesinski J and Fröhlich D 1997 Phys. Rev. B 56 13087
[9] Wrzesinski J and Fröhlich D 1998 Solid State Commun. 105 301
[10] Kuhnert R, Helbig R and Hüanner K 1981 Phys. Status Solidi b 107 83
[11] Haushild R, Priller H, Decker M, Kalt H and Klingshirn C 2006 Phys. Status Solidi c 3 980
[12] Wagner M R, Schulze J, Kirste R, Cobet M and Hoffmann A 2009 Phys. Rev. B 80 205203
[13] Laskowski R and Christensen N E 2006 Phys. Rev. B 73 045201
[14] Park Y, Litton C W, Collins T C and Reynolds D C 1966 Phys. Rev. 143 512
[15] Reynolds D C, Look D C, Jogai B, Litton C W, Cantwell G and Harsch W C 1999 Phys. Rev. B 60 2340
[16] Reynolds D C, Look D C, Jogai B, Litton C W, Collins T C, Harris M T, Callahan M J and Bailey J S 1999 J. Appl. Phys. 86 5598
[17] Gil B 2001 Phys. Rev. B 64 201310(R)
[18] Chichibu S F, Sota T, Cantwell G, Eason D B and Litton C W 2003 J. Appl. Phys. 93 756
[19] Chichibu S F et al 2005 Semicond. Sci. Technol. 20 S67
[20] Adachi S, Hazu K, Sota T, Chichibu S, Cantwell G, Reynolds D C and Litton C W 2005 Phys. Status Solidi c 2 890
[21] Gil B 2005 J. Appl. Phys. 98 086114
[22] Hazu K, Chichibu S F, Adachi S and Sota T 2012 J. Appl. Phys. 111 093522
[23] Reynolds D C, Litton C W and Collins T C 1965 Phys. Rev. 140 A1726
[24] Lambrecht W R L, Rodina A V, Limpijunnong S, Segall B and Meyer B K 2002 Phys. Rev. B 65 075207
[25] Rodina A V, Strassburg M, Dworzak M, Haboeck U, Hoffmann A, Zeuner A, Alves H R, Hofmann D M and Meyer B K 2004 Phys. Rev. B 69 125206
[26] Thomas D G and Hopfield J J 1961 Phys. Rev. Lett. 7 316
[27] Ding L, Li B K, He H T, Ge W K, Wang J N, Ning J Q, Dai X M, Ling C C and Xu S J 2009 J. Appl. Phys. 105 053511
[28] Ding L, Yang C L, He H T, Jiang F Y, Wang J N, Tang Z K, Foreman B A and Ge W K 2007 arXiv:0706.3965
[29] Hopfield J J and Thomas D G 1965 Phys. Rev. Lett. 15 22
[30] Schleife A, Rödl C, Fuchs F, Furchtmüller J and Bechstedt F 2007 Appl. Phys. Lett. 91 241915

New Journal of Physics 15 (2013) 033015 (http://www.njp.org/)