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Publication Date 2004-08-01

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Physica E 20 (2004) 300-307



www.elsevier.com/locate/physe

Narrow band gap group III-nitride alloys

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Abstract

Recent results on the properties of narrow gap group III-nitrides and their alloys are reviewed. It is shown that InN with the energy gap of 0.7 eV exhibits classical characteristics of a narrow gap semiconductor with strongly nonparabolic conduction band and an energy dependent electron effective mass. With the new discovery, the direct band gaps of the group III-nitride alloys span an extremely wide energy range from near infrared in InN to deep ultraviolet in AlN offering possibilities for new device applications of these materials. We also discuss properties of dilute group III-N–V alloys in which incorporation of a small amount of nitrogen results in a dramatic band gap reduction. All the unusual properties of the alloys are well described by a band anticrossing model that considers an interaction between localized nitrogen states and the extended states of the conduction band.

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PACS: 72.80.Ey; 78.66.Fd; 71.20.Nr; 78.40.Fy; 71.10.Fd

Keywords: InN; Group III-nitrides; Nonparabolic bands; Bowing parameters; Dilute nitrides; Band anticrossing; Electron effective mass; Highly mismatched alloys

1. Introduction

Wide gap group III-nitrides and their alloys are now one of the most extensively studied classes of semiconductor materials. The interest in these materials has been generated by a successful implementation of the Ga-rich $In_xGa_{1-x}N$ alloys for short wavelength light emitters and a variety of electronic devices [1]. Until recently, all group III-nitrides were qualified as wide gap semiconductors since it was commonly accepted that even InN, the narrowest gap member of the nitride family had a relatively wide gap of 1.9 eV [2,3]. This gap was determined from optical absorption studies of polycrystalline thin films. In a surprising recent discovery it has been shown that InN has a gap of only

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0.7 eV [4,5]. This expanded the range of the direct band gaps covered by the group III-nitride alloys into a near infrared region.

It has been demonstrated more than 10 years ago that alloying of standard III–V compounds with small amounts of group III-nitrides leads to a dramatic reduction of the band gap of the resulting $IIIN_xV_{1-x}$ alloys [6]. Thus it has been shown that the gap of $In_yGa_{1-y}N_xAs_{1-x}$ can be reduced by several hundreds of meV bringing the band gap of these alloys into the mid-infrared region [6]. Significant, N-induced band gap reductions have been also reported in other group $IIIN_xV_{1-x}$ materials (see, for example, Ref. [7]) including narrow gap InN_xSb_{1-x} alloys [8]. The group $IIIN_xV_{1-x}$ materials belong to a much broader class of highly mismatched alloys (HMA) in which metallic (electronegative) atoms are partially replaced by more electronegative

^{1386-9477/\$ -} see front matter @ 2003 Elsevier B.V. All rights reserved. doi:10.1016/j.physe.2003.08.023

(metallic) atoms [9]. Group $IIO_x VI_{1-x}$ materials in which column VI anions are partially replaced with O are a representative example of group II–VI HMAs [10].

In this paper these two types of narrow gap nitride materials will be considered. Our recent work on InN and In-rich $In_xGa_{1-x}N$ alloys will be reviewed. These materials show electronic properties characteristic to narrow gap semiconductors with a large interaction between conduction and the valence band states. The origin of the large band gap reduction in dilute group $IIIN_xV_{1-x}$ nitrides will be discussed. The electronic properties of these materials are described by the band anticrossing between localized states of nitrogen and extended conduction band states.

2. Electronic properties of InN

Early efforts to synthesize thin films of InN using a variety of sputtering techniques and recent progress in MBE grown films have been recently reviewed by Nanishi et al. [11]. The sputter deposited films were polycrystalline and in most instances highly conducting with electron concentrations as high as 10^{21} cm⁻³. The band gaps of these films determined from the absorption measurements ranged from 1.7 to 3.1 eV [11] with a majority of the results falling close to about 1.9 eV. This value of the band gap has been widely accepted and frequently used as the end point value for the extrapolation of the band gap in $In_xGa_{1-x}N$ alloys [12]. It should be emphasized that despite extensive efforts, no light emission associated with the energy gap near 1.9 eV has ever been reported in these early studies of InN. This is in contrast to GaN and Ga-rich $In_x Ga_{1-x} N$ alloys which are known to be very good light emitters despite large densities of structural defects typically found in these materials.

Recent improvements in epitaxial growth techniques have led to the availability of InN films with considerably lower electron concentrations and much higher electron mobilities [13–15]. Electron concentrations in the mid- 10^{17} cm⁻³ with room temperature electron mobilities well in excess of 2000 cm²/V s were achieved by these methods [15]. It has been reported that those improved InN films show a relatively strong photoluminescence (PL) at energies below 1 eV [4,5,16].



Fig. 1. Optical absorption (300 K), PL (300 K), and PR (77 K) spectra of a typical InN sample [5].

Fig. 1 shows the optical absorption edge as well as photoluminescence (PL) and photomodulated reflection (PR) spectra of an InN film with the electron concentration of 5×10^{18} cm⁻³ [5]. All three measurements clearly point to an existence of the fundamental edge for optical transitions at about 0.8 eV. It should be noted that there is no discernible change of the absorption coefficient around 1.9 eV i.e. at the energy of the previously reported band gap of InN. All InN samples we have measured show a strong PL signal whose peak energy position and the linewidth depend on the electron concentration.

We have also measured the temperature dependence of the direct band gap. Positions of the absorption edge and the PL peak energies are presented in Fig. 2. The absorption edge energy shows the characteristic dependence that can be well described by the Varshni equation,

$$E_{\rm G}(T) = E_{\rm G}(0) - \frac{\gamma T^2}{T + \beta} \tag{1}$$

with $E_G(0)=0.69$ eV, $\gamma=0.41$ meV/K and $\beta=454$ K. The temperature dependence of the band gap of InN is weaker than that of other nitrides. The total change of the band gap between 0 and 300 K equals to 49 meV in InN compared to 72 meV for GaN and 92 meV for AlN [17].



Fig. 2. Temperature dependence of the PL peak energy, absorption bandgap (E_g) , and the broadening parameter (Δ) . The solid curve represents a fit to the band edge energy using Eq. (1).

Results in Fig. 2 show that the position of the PL peak energy agrees with the absorption edge energy only at higher temperatures. At lower temperature the PL peak energy falls below the absorption edge. This might indicate that a luminescence from localized states dominates the low temperature emission process. Also it strongly suggests that the PL peak position cannot be used to reliably determine the band gap energy.

The low value of the energy gap of InN has very important consequences for the electronic band structure. According to the two band Kane model of the narrow gap semiconductors the dispersion relation close to the conduction band minimum is given by [18]

$$E_{\rm C}(k) = E_{\rm G} + \frac{\hbar^2 k^2}{2m_0} + \frac{1}{2} \left(\sqrt{E_{\rm G}^2 + 4E_{\rm P} \frac{\hbar^2 k^2}{2m_0} - E_{\rm G}} \right), \qquad (2)$$

where E_G is the direct bandgap energy, m_0 is the free electron mass and E_P is an energy parameter related to the momentum matrix element between the s-like conduction band and p-like valence band states,

$$E_{\rm P} = \frac{2}{m_0} |\langle S|P_x|X\rangle|^2.$$
(3)



Fig. 3. Electron effective mass as a function of electron concentration based on results of several different reports [19]. The theoretical curve has been calculated using Eqs. (2) and (4).

For the dispersion relation given by Eq. (2) the electron effective mass defined as

$$m^*(k) = \frac{\hbar^2 k}{\mathrm{d}E_{\mathrm{C}}(k)/\mathrm{d}k} \tag{4}$$

depends on the Fermi wavevector and thus also on the electron concentration. The experimental results in Fig. 3 clearly show a large increase of the effective mass with increasing electron concentration [19–24]. The results are reasonably well described by Eqs. (2) and (4) with $E_{\rm G} = 0.69$ eV and $E_{\rm P} = 10$ eV [19]. The calculated curve extrapolated to the intrinsic case of vanishing electron concentration, n=0 gives the value of $0.07m_0$ for the conduction band edge effective mass in InN. This is significantly lower than the previously accepted and widely used value of $0.11m_0$ [17].

An interesting and unique feature of InN is that it shows an extreme proclivity for the n-type conduction. Electron concentrations as high as 10^{21} cm⁻³ were reported in nominally undoped layers [20]. Very large Burstein–Moss shifts of the fundamental absorption edge are expected at these high electron concentrations. The energy of the fundamental absorption edge of InN layers with different electron concentrations is shown in Fig. 4 [19]. At low electron concentration the absorption edge converges on the energy of about



Fig. 4. Room-temperature absorption edge as a function of electron concentration adopted from several different reports [19]. The solid line is the calculated band gap assuming a non-parabolic dispersion for the conduction band and including the band-renormalization effects. The dashed line represents the absorption edge calculated for the parabolic conduction band with $m^* = 0.07m_0$.

0.7 eV. The absorption edge shifts rapidly with increasing concentration reaching the energy of 2 eV for the electron concentration close to 10^{21} cm⁻³. This large Burstein–Moss shift could explain the origin of the previously observed large energy gap in the highly conducting sputter deposited samples.

The concentration dependence of the absorption band edge can be explained by Burstein–Moss shift only if the nonparabolicity of the conduction band given by Eq. (2) is included in the calculations [19]. Also, in order to obtain a good agreement with experiment it was necessary to incorporate band gap renormalization resulting from the electron–electron and electron–ion interactions [19].

3. Band gaps of group III-nitride alloys

The new, low gap of InN requires a reexamination of the composition dependence of the band gaps of $In_xGa_{1-x}N$ and $In_xAl_{1-x}N$ alloys. Unlike Ga-rich $In_xGa_{1-x}N$ alloys that were extensively studied and are used for light emitting devices much less infor-



Fig. 5. PL peak energy and the band gap determined by optical absorption as a function of alloy composition [29]. Some previously reported data on the Ga-rich side are also shown; Ref. [27] (Pereira) and Ref. [28] (Shan). The solid curve shows the fit to the band gap energies determined from absorption and photomodulated transmission using a bowing parameter b = 1.43 eV. The dashed curve is the fit to the band gap energies on the Ga-rich side assuming the band gap of 1.9 eV for InN.

mation is available on the properties of In-rich alloys. The value of the band gap bowing parameter for this alloy system is still a hotly contested issue [25]. Large band gap bowing parameters were invoked to connect the band gaps measured in Ga-rich alloys to the previously accepted value of 1.9 eV for the InN band gap [26].

Band gaps of $In_x Ga_{1-x}N$ alloys as a function of the alloy composition are shown in Fig. 5. The gap energies determined from the optical absorption increase continuously with increasing Ga content from about 0.7 eV in InN to 1.75 eV for x = 0.5. As shown in Fig. 5 the band gaps measured for the In-rich alloys connect very well with the previous measurements of the much more extensively studied Ga-rich alloys [27,28]. All the data can be well fit with the bowing parameter of 1.43 eV [29]. The results in Fig. 5 show that the position of the maximum of the PL spectrum falls below the band gap determined from the optical absorption. The difference becomes quite large at larger Ga contents. It indicates that localized states are

responsible for the emission. Also it cautions against using PL measurements to determine the energy gaps in the alloys.

The discovery of the low band gap of InN greatly expanded the spectral range covered by group III-nitride alloys. It spans the wavelength range from near infrared at about 1.8 µm in InN to deep ultraviolet at 0.2 µm in AlN. This band gap energy span is larger than that of any known, direct gap semiconductor alloy system. It is important to note that the range of the energy gaps of $In_xGa_{1-x}N$ alloys provides almost a perfect match to the solar spectrum. This offers an interesting possibility of using $In_xGa_{1-x}N$ alloys for multijunction solar cells. One of the disadvantages of the currently used Ge/GaAs/GaInP triple junction tandems is that the band gaps of the component junctions are fixed. In the case of the $In_rGa_{1-r}N$ alloys the band gaps as well as the number of the component junctions could be adjusted to maximize the solar cell performance.

4. Dilute group III-nitride alloys

4.1. Theory

Several different explanations have been proposed for the origin of the observed large N-induced band gap reduction in $IIIN_xV_{1-x}$ alloys. The first attempts to explain this unusual behavior were based on a dielectric model that predicted highly nonlinear composition dependencies of the band gap for the alloys of semiconductor compounds with very different properties [30]. The model predicted a semiconductor to semi-metal transition in some of the alloys [31]. The large band gap reduction in GaN_xAs_{1-x} alloys has also been explained by Wei and Zunger [32] in terms of a large composition dependent bowing parameter that could be decomposed into three different contributions: a volume deformation, a charge exchange and a structural relaxation. This approach has been later abandoned, and several other theoretical explanations of the large band gap reduction in III-V-N alloys have been also proposed [33-38].

Alternatively, the band structures of HMAs have been explained in terms of the two-level band anticrossing (BAC) model. The model has been developed to explain the pressure and composition dependencies of the band gap of $In_yGa_{1-y}N_xAs_{1-x}$ alloys [39]. Later it was successfully applied to other HMAs [40,41]. Furthermore, it has predicted several new effects, such as a N-induced enhancement of the electron effective mass [42], an improvement in the donor activation efficiency [43] in $In_yGa_{1-y}N_xAs_{1-x}$ alloys, and the change in the nature of the fundamental band gap from indirect to direct in $GaP_{1-x}N_x$ [44]. In the meantime, all these predictions have been experimentally confirmed.

In the BAC model, the restructuring of the conduction band is a result of an anticrossing interaction between highly localized A_1 states of the substitutional N atoms and the extended states of the host semiconductor matrix. The newly formed subbands, named E_+ and E_- , have dispersion relations given by [39]

$$E_{\pm}(k) = \frac{1}{2} \{ [E^{C}(k) + E^{N}] \\ \pm \sqrt{[E^{C}(k) - E^{N}]^{2} + 4V^{2}x} \},$$
(5)

where $E^{C}(k)$ is the energy dispersion of the lowest conduction band of the host, and E^{N} is the energy of the localized states derived from the substitutional N atoms. The coupling between the localized states and the band states of the host is described by the adjustable hybridization parameter V. The BAC model provides a simple, analytical expression to calculate the electronic and optical properties of $IIIV_{1-x}N_x$ alloys.

The two-level BAC model is a result of degenerate perturbation theory applied to a system of localized and extended states. The interaction between these two types of states has been treated in the simplest possible manner that does not account for expected severe level broadening effects. A more advanced model has been developed based on concepts originally put forward by Anderson [45] who considered an isolated transition metal impurity in a metal. In Anderson's s-d exchange model [45], the electron system is separated into a delocalized part of the matrix metal that is described in terms of band theory, and a localized level of the d shell electrons of the impurity atom. A dynamical mixing term is introduced into the Hamiltonian of the system to describe the hybridization between the band states and the localized impurity states.

Later the Anderson model has been extended to consider a system of randomly distributed transition



Fig. 6. Nitrogen-induced restructuring of the conduction band of $GaAs_{0.995}N_{0.005}$ alloy [48]. The shaded area represents the broadening of the conduction band states. All the energies are referenced to the top of the valence band of GaAs.

metal impurities [46,47]. The electronic structure of such system can be described within the coherent potential approximation (CPA). The approximation restores the periodicity of the crystal lattice at the cost of introducing an energy level broadening. The model has been applied to consider the electronic structure of HMA [48]. The results of the model calculations are shown in Fig. 6. The energy of the localized N level, $E^{\rm N} = E^{\rm C} + 0.23$ eV, used in these calculations is known from the photoluminescence experiments under high hydrostatic pressure [49]. A characteristic anticrossing behavior between localized N-states and the delocalized states of the GaAs matrix is clearly observed. It should be noted that the dispersion relations for the lower, $E_{-}(k)$ and upper, $E_{+}(k)$ subband are exactly the same as those obtained from the simple BAC model represented by Eq. (5). The broadening represented by the shaded area depends on the location of the energy states relative to the localized $E^{\rm N}$ level.

4.2. Comparison with experiment

The change in the electronic structure has a profound effect on many properties of the alloys. The fundamental band gap is determined by the location of the lowest subband edge at $E_{-}(k = 0)$. As is shown



Fig. 7. Energy gap of $GaAs_{1-x}N_x$ as a function of N concentration. The experimental data adopted after Uesugi et al. [50], Keyes et al. [51], Malikova et al. [52] and Bhat et al. [53]. The solid curve has been calculated using Eq. (5) of the BAC model.

in Fig. 7 the composition dependence of the band gap of GaN_xAs_{1-x} alloys is well explained by the BAC model with a single adjustable parameter, the coupling constant V = 2.7 eV.

Determination of the hybridization parameter V fully defines the electronic structure of the conduction band and allows calculating other experimentally measured effects. In particular one can calculate the pressure dependencies of the edges of the E_- and E_+ subbands. The comparison of the calculations with the experimental data on $In_{0.05}Ga_{0.95}N_{0.012}As_{0.988}$ alloys is shown in Fig. 8. Note that the excellent agreement between theory and experiment has been obtained without any adjustable parameters as the pressure dependencies of the localized N-level and the conduction band edge of the $In_{0.05}Ga_{0.95}As$ matrix are well known.

One of the striking features of the electronic structure of GaN_xAs_{1-x} alloys shown in Fig. 6 is the prediction of a strongly nonparabolic dispersion relation for the lower subband. Consequently, according to Eq. (4), one expects an increase of the electron effective mass with increasing Fermi energy and thus also with increasing doping level. This prediction has been fully confirmed by experiments [42,54]. Fig. 9 shows the electron effective mass as a function of the Fermi wavevector in In_{0.03}Ga_{0.97}N_{0.01}As_{0.99} alloy. The



Fig. 8. Energies of the E_+ and E_- transitions obtained from PR experiments as a function of hydrostatic pressure [39]. The solid lines represent the subband edges calculated using the BAC model. Pressure dependencies of the N-level (E_N) and conduction band edge of the In_{0.05}Ga_{0.95}As matrix ($E_C(0)$) are also shown.



Fig. 9. Electron effective mass as a function of the Fermi wavevector in $In_{0.03}Ga_{0.97}N_{0.01}As_{0.99}$ alloy [54]. The solid line represents the dependence calculated using the BAC model. The analogous dependence in GaAs is shown for a comparison.

mass was determined by measuring the plasma reflection edge for samples with the electron concentrations ranging from 1.4×10^{17} to 2.1×10^{19} cm⁻³ [54]. The experimentally observed large increase of the effective mass with the Fermi wavevector is in excellent agreement with the prediction of the BAC model represented by the solid line in Fig. 9. It is also seen in Fig. 9 that the increase of the effective mass in $In_yGa_{1-y}N_xAs_{1-x}$ alloys is attributable to effects of nitrogen, as a much smaller increase of the effective mass is observed in GaAs.

5. Conclusions

We have reviewed recent experimental results that provide irrefutable evidence that the energy gap of InN amounts to only 0.7 eV. The electronic properties of InN exhibit features characteristic of narrow gap semiconductors. A nonparabolicity of the conduction band resulting from $k \cdot p$ interaction manifests itself in a strong dependence of the electron effective mass on the Fermi energy. We have also shown that the properties of dilute group III-N–V alloys are determined by the anticrossing interaction between localized nitrogen states and the extended states of the conduction band semiconductor matrix.

Acknowledgements

The author gratefully acknowledges contributions of his collaborators from Lawrence Berkeley National Laboratory, UC Berkeley, Cornell University, National Renewable Energy Laboratory, Unipress and UC San Diego. This work is supported by the Director, Office of Science, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering, of the US Department of Energy under Contract No. DE-AC03-76SF00098.

References

- [1] S. Nakamura, G. Fasol, Blue Laser Diode, Springer, Berlin, 1997.
- [2] K. Osamura, K. Nakajima, Y. Murakami, Solid State Commun. 11 (1972) 617.
- [3] T.L. Tansley, C.P. Foley, J. Appl. Phys. 59 (1986) 3241.
- [4] V. Yu. Davydov, A.A. Klochikhin, R.P. Seisyan, V.V. Emtsev, S.V. Ivanov, F. Bechstedt, J. Furthmuller, H. Harima, A.V. Mudryi, J. Aderhold, O. Semchinova, J. Graul, Phys. Stat. Solidi (b) 229 (2002) R1.
- [5] J. Wu, W. Walukiewicz, K.M. Yu, J.W. Ager III, E.E. Haller, H. Lu, W.J. Schaff, Y. Saito, Y. Nanishi, Appl. Phys. Lett. 80 (2002) 3967.
- [6] M. Weyers, M. Sato, H. Ando, Jpn. J. Appl. Phys. 31 (1992) L853.
- [7] Semiconductor Science and Technology, Vol. 17, Institute of Physics, Bristol, 2002 (Special Issue: III-N–V semiconductor alloys).

- [8] B.N. Murdin, M. Karmal-Saadi, A. Lindsay, E.P. O'Reilly, A.R. Adams, G.J. Nott, J.G. Crowder, C.R. Pidgeon, I.V. Bradley, J.P.R. Wells, T. Burke, A.D. Johnson, T. Ashley, Appl. Phys. Lett. 78 (2001) 1558.
- [9] J. Wu, W. Shan, W. Walukiewicz, Semicond. Sci. Technol. 17 (2002) 860.
- [10] K.M. Yu, W. Walukiewicz, J.Wu, J.W. Beeman, J.W. Ager, E.E. Haller, I. Miotkowski, A.K. Ramdas, P. Becla, Appl. Phys. Lett. 80 (2002) 1571.
- [11] Y. Nanishi, Y. Saito, T. Yamaguchi, Jpn. J. Appl. 42 (2003) 2549.
- [12] C. Wetzel, T. Takeuchi, S. Yamaguchi, H. Katoh, H. Amano, I. Akasaki, Appl. Phys. Lett. 73 (1998) 1994.
- [13] H. Lu, W.J. Schaff, J. Hwang, H. Wu, W. Yeo, A. Pharkya, L.F. Eastman, Appl. Phys. Lett. 77 (2000) 2548.
- [14] M. Higashiwaki, T. Matsui, Jpn. J. Appl. Phys. 41 (2002) L540.
- [15] D.C. Look, H. Lu, W.J. Schaff, J. Jasinski, Z. Liliental Weber, Appl. Phys. Lett. 80 (2002) 258.
- [16] T. Matsuoka, H. Okamoto, M. Nakao, H. Harima, E. Kurimoto, Appl. Phys. Lett. 81 (2002) 1246.
- [17] I. Vurgaftman, J.R. Meyer, L.R. Ram-Mohan, J. Appl. Phys. 89 (2001) 5815.
- [18] E.O. Kane, J. Phys. Chem. Solids 1 (1957) 249.
- [19] J. Wu, W. Walukiewicz, W. Shan, K.M. Yu, J.W. Ager III, E.E. Haller, H. Lu, W.J. Schaff, Phys. Rev. B 66 (2002) 201403.
- [20] D.B. Haddad, J.S. Thakur, et al., Phys. Rev. B, to be published.
- [21] T. Inushima, T. Shiraishi, V.Yu. Davydov, Solid State Commun. 110 (1999) 491.
- [22] V.A. Tygai, A.M. Evstigneev, A.N. Krasiko, A.F. Andreeva, V.Ya. Malakhov, Sov. Phys. Semicond. 11 (1977) 1257.
- [23] T. Inushima, et al., Inst. Phys. Conf. Ser. No. 142; p. 971 (Chapter 5).
- [24] A. Kasic, M. Schubert, Y. Saito, Y. Nanishi, G.W. Wagner, Phys. Rev. B 65 (2002) 115206.
- [25] K.P. O'Donnell, J.F.W. Mosselmans, R.W. Martin, S. Pereira, M.E. White, J. Phys.: Condens. Matter 13 (2001) 6977.
- [26] K.P. O'Donnell, R.W. Martin, C. Trager-Cowan, M.E. White, K. Esona, C. Deatcher, P.G. Middleton, K. Jacobs, W. van der Stricht, C. Merlet, B. Gil, A. Vantomme, J.F.W. Mosselmans, Mater. Sci. Eng. B 82 (2001) 194.
- [27] S. Pereira, M.R. Correia, T. Monteiro, E. Pereira, E. Alves, A.D. Sequeira, N. Franco, Appl. Phys. Lett. 78 (2001) 2137.
- [28] W. Shan, W. Walukiewicz, E.E. Haller, B.D. Little, J.J. Song, M.D. McCluskey, N.M. Johnson, Z.C. Feng, M. Schurman, R.A. Stall, J. Appl. Phys. 84 (1998) 4452.
- [29] J. Wu, W. Walukiewicz, K.M. Yu, J.W. Ager III, E.E. Haller,
 H. Lu, W.J. Schaff, Appl. Phys. Lett. 80 (2002) 4741.
- [30] J.A. Van Vechten, T.K. Bergstresser, Phys. Rev. B 8 (1970) 3351.
- [31] S. Sakai, Y. Ueta, Y. Terauchi, Jpn. J. Appl. Phys. 32 (Part 1) (1993) 4413.

- [32] Su-Huai Wei, A. Zunger, Phys. Rev. Lett. 76 (1996) 664.
- [33] E.D. Jones, N.A. Modine, A.A. Allerman, S.R. Kurtz, A.F. Wright, S.T. Tozer, X. Wei, Phys. Rev. B 60 (1999) 4430.
- [34] T. Mattila, Su-Huai Wei, A. Zunger, Phys. Rev. B 60 (1999) R11 245.
- [35] Lin-Wang Wang, Appl. Phys. Lett. 78 (2001) 1565.
- [36] N.G. Szwacki, P. Boguslawski, Phys. Rev. B 64 (2001) 161201.
- [37] A. Al-Yacoub, L. Bellaiche, Phys. Rev. B 62 (2000) 10847.
- [38] Y. Zhang, A. Mascarenhas, H.P. Xin, C.W. Tu, Phys. Rev. B 63 (2001) 161303.
- [39] W. Shan, W. Walukiewicz, J.W. Ager III, E.E. Haller, J.F. Geisz, D.J. Friedman, J.M. Olson, S.R. Kurtz, Phys. Rev. Lett. 82 (1999) 1221.
- [40] W. Walukiewicz, W. Shan, K.M. Yu, J.W. Ager III, E.E. Haller, I. Miotkowski, M.J. Seong, H. Alawadhi, A.K. Ramdas, Phys. Rev. Lett. 85 (2000) 1552.
- [41] W. Shan, W. Walukiewicz, K.M. Yu, J. Wu, J.W. Ager III, E.E. Haller, H.P. Xin, C.W. Tu, Appl. Phys. Lett. 76 (2000) 3251.
- [42] C. Skierbiszewski, P. Perlin, E. Wisniewski, W. Knap, T. Suski, W. Walukiewicz, W. Shan, K.M. Yu, J.W. Ager III, E.E. Haller, J.F. Geisz, J.M. Olson, Appl. Phys. Lett. 76 (2000) 2409.
- [43] K.M. Yu, W. Walukiewicz, W. Shan, J.W. Ager III, J. Wu, E.E. Haller, J.F. Geisz, D.J. Friedman, J.M. Olson, Phys. Rev. B 61 (2000) R13337.
- [44] W. Shan, W. Walukiewicz, K.M. Yu, J. Wu, J.W. Ager III, E.E. Haller, H.P. Xin, C.W. Tu, Appl. Phys. Lett. 76 (2000) 3251.
- [45] P.W. Anderson, Phys. Rev. 124 (1961) 41.
- [46] A.N. Kocharyan, Soc. Phys. Solid State 28 (1986) 6.
- [47] M.A. Ivanov, Yu.G. Pogorelov, Sov. Phys. JETP 49 (1979) 510;
 M.A. Ivanov, Yu.G. Pogorelov, Sov. Phys. JETP 61 (1985) 1033.
- [48] J.Wu, W. Walukiewicz, E.E. Haller, Phys. Rev. B 65 (2002) 233210.
- [49] D.J. Wolford, J.A. Bradley, K. Fry, J. Thompson, in: J.D. Chadi, W.A. Harrison (Eds.), Physics of Semiconductors, Springer, New York, 1984.
- [50] K. Uesugi, N. Marooka, I. Suemune, Appl. Phys. Lett. 74 (1999) 1254.
- [51] B.M. Keyes, J.F. Geisz, P.C. Dippo, R. Reedy, C. Kramer, D.J. Friedman, S.R. Kurtz, J.M. Olson, NCPV Photovoltaics Program Review, AIP Conf. Proc. 462 (1999) 511.
- [52] L. Malikova, F.H. Pollak, R. Bhat, J. Electron. Mater. 27 (1998) 484.
- [53] R. Bhat, C. Caneau, L. Salamanca-Riba, W. Bi, C. Tu, J. Crystal Growth 195 (1998) 427.
- [54] C. Skierbiszewski, P. Perlin, P. Wisniewski, T. Suski, J.F. Geisz, K. Hingerl, W. Jantsch, D.E. Mars, W. Walukiewicz, Phys. Rev. B 65 (2001) 035207.