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Citation: Appl. Phys. Lett. 76, 2247 (2000); doi: 10.1063/1.126310

View online: http://dx.doi.org/10.1063/1.126310

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Temperature dependent polarization switching and band-gap anomalies in strained Ga\textsubscript{x}In\textsubscript{1-x}As quantum wire heterostructures

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(Received 29 December 1999; accepted for publication 16 February 2000)

We report on the polarized photoluminescence (PPL) properties of strained Ga\textsubscript{x}In\textsubscript{1-x}As quantum wire (QWR) heterostructures formed \textit{in situ} by the strain-induced lateral-layer ordering process. It is found that the PPL spectra of these QWRs have unique properties that depend on temperature and orientation of the pump polarization with respect to the QWR direction. In particular, the dominant polarization switches when the sample is warmed from 77 to 300 K provided the pump polarization is parallel to the QWRs. This indicates that the light-hole (LH) and heavy-hole (HH) bands cross with increasing temperature, which implies that the multiaxial strain in this material is a function of temperature. Furthermore, this effect is only observed in Ga\textsubscript{x}In\textsubscript{1-x}As QWR heterostructures that display anomalous band-gap stability with respect to temperature. It is believed that the strain induced temperature dependent LH–HH crossing as evidenced by the polarization switching effect is responsible for this anomaly. © 2000 American Institute of Physics.

The change in band gap with respect to temperature of III–V bulk semiconducting crystals typically follows the Varshni equation.\textsuperscript{1} However, exceptions do exist in spontaneously ordered InGaP (Ref. 2) and phase separated InGaAlAs (Ref. 3) and InGaAsP.\textsuperscript{4} Using photoluminescence (PL) spectroscopy at temperatures ranging from 4 to 300 K, deviations from the Varshni equation are observed up to around 100 K. Some authors have shown this to be due to exciton localization\textsuperscript{3,4} or crystal defects.\textsuperscript{5} Similar deviations from the Varshni equation have also been observed in the InGaAs quantum dot structures grown on GaAs.\textsuperscript{6,7} Anomalies in the PL energy have also been found in the InGaP quantum dots (QDs) and quantum wires (QWRs) grown by the strain-induced lateral-layer ordering (SILO) process.\textsuperscript{8,9}

The most striking deviation in PL behavior with respect to temperature, however, has been observed in the Ga\textsubscript{x}In\textsubscript{1-x}As QWRs grown by the SILO process.\textsuperscript{10,11} Specifically, a temperature stabilized PL wavelength for temperatures near and above 300 K is observed in these structures.\textsuperscript{11} For temperatures well below 300 K, the PL behavior with respect to temperature varies with the degree of strain in the QWR region.\textsuperscript{10} For moderately strained structures the 77 K peak PL wavelength is relatively invariant with respect to the 300 K peak wavelength; whereas strongly strained structures have a 77 K peak wavelength larger than the 300 K peak. In this letter, we provide polarized PL (PPL) spectra as evidence that this behavior is due to the unique multiaxial strain (and the subsequent light-hole–heavy-hole crossing) that exists in the QWR regions of these structures as previously suggested.\textsuperscript{10} Furthermore, we will show that this effect is somewhat material dependent in that Ga\textsubscript{x}In\textsubscript{1-x}As QWRs display this interesting behavior more readily than other species of SILO grown QWRs and QDs.

The structures studied here were grown using the SILO process during molecular beam epitaxy growth. This is a one step all \textit{in situ} method that is used to fabricate QWRs with a high linear density of \(~1\times10^6\) cm\textsuperscript{-1} on GaAs\textsubscript{0.66}P\textsubscript{0.34}, GaAs, and InP substrates that emit in a large spectral range of 600–1600 nm.\textsuperscript{8,12,13} Specifically, the SILO process entails the deposition of a nearly strain balanced short-period superlattice (SPS) on exact (100)-oriented substrates to form a lateral composition modulation across the [110] direction.\textsuperscript{14} The lateral composition modulation exists as alternating regions of Ga-rich Ga\textsubscript{x}In\textsubscript{1-x}As and In-rich Ga\textsubscript{x}In\textsubscript{1-x}As where X can be As, P, or AsP. The variation across the [110] direction typically results in QWRs that are \(~100–200\) Å wide depending on the degree of composition modulation as determined by cross-sectional transmission electron microscopy (XTEM).\textsuperscript{15} Also depending on the degree of lateral composition modulation, the indium composition of the alternating Ga- and In-rich QWRs can be as much as 30% and 70%, respectively.\textsuperscript{16} QWR heights are controlled in the same way as QWs, and they vary from 75 to 100 Å. Moreover, (GaAs\textsubscript{m}/InAs\textsubscript{n})\textsubscript{m}/InP typically result in QWRs that display the temperature stable PL discussed above. In fact, there exists a correlation between the degree of lateral composition modulation, the strain, and the temperature dependent PL behavior of Ga\textsubscript{x}In\textsubscript{1-x}As QWRs.\textsuperscript{17} Using XTEM, the degree of the lateral composition modulation can be determined.\textsuperscript{15}

PPL spectroscopy was used to characterize the QWR heterostructures. The samples were mounted with the QWRs oriented parallel and perpendicular to the pump polarization. The luminescence was excited using an Ar\textsuperscript{+} laser tuned to 5145 Å. Before the PL entered the 0.5 m focal length spectrometer, it passed through a rotatable analyzer so as to determine the dominant polarization with respect to tempera-

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A depolarizer was used to randomize the PL polarization before it could be favorably selected by the spectrometer grating. The luminescence was detected using a liquid-nitrogen cooled Ge detector using the lock-in technique.

Figure 1 shows an example of PL spectra of different QWR species taken at 77 and 300 K. Figure 1a shows spectra measured from a Ga$_x$In$_{1-x}$P QWR heterostructure grown on GaAs by the SILO process. These spectra are also representative of the temperature dependent behavior of the peak wavelength seen in GaInP QWRs grown on GaAs$_{0.66}$P$_{0.34}$ substrates, GaInP QWRs on GaAs, GaInAsP QWRs on GaAs, and GaInAsP QWRs on InP in that the 300 K wavelength is longer than the 77 K wavelength. Ga$_x$In$_{1-x}$As QWRs on InP, however, are different as seen in Fig. 1b for the case of strongly strained Ga$_x$In$_{1-x}$As QWRs grown by the SILO process. In particular, depending on the amount of strain in the QWR region, which is determined by the structure and growth conditions, different types of temperature dependent PL peak behavior may result. Figure 2 displays the three different types of PL wavelength behavior with respect to temperature of strained Ga$_x$In$_{1-x}$As QWR samples. Shown in Fig. 3 is an example of temperature dependent polarization switching observed in Ga$_x$In$_{1-x}$As QWRs. These PPL spectra are from a strongly strained Ga$_x$In$_{1-x}$As QWR heterostructure and are also representative of moderately strained QWR structure, no net shift in wavelength between 77 and 300 K is achieved. Furthermore, for strongly strained Ga$_x$In$_{1-x}$As QWRs, the peak PL wavelength blueshifts with increasing temperature. More importantly, it has been shown for strongly strained and moderately strained Ga$_x$In$_{1-x}$As QWR structures grown by the SILO process the peak PL wavelength does not shift for temperatures above 300 K.

To better understand the temperature dependent band-gap anomalies of strongly and moderately strained Ga$_x$In$_{1-x}$As QWRs, the PPL spectra of all SILO grown QWRs were studied. The dominant polarization of SILO grown Ga$_x$In$_{1-x}$P QWR heterostructures does not depend on temperature nor does it depend on the orientation of the QWRs with respect to the incident pump polarization. This type of behavior is consistent with all other SILO grown QWR species except for Ga$_x$In$_{1-x}$As QWRs. Shown in Fig. 3 is an example of temperature dependent polarization switching observed in Ga$_x$In$_{1-x}$As QWRs. These PPL spectra are from a strongly strained Ga$_x$In$_{1-x}$As QWR heterostructure and are also representative of moderately strained QWR structure, no net shift in wavelength between 77 and 300 K is achieved. Furthermore, for strongly strained Ga$_x$In$_{1-x}$As QWRs, the peak PL wavelength blueshifts with increasing temperature. More importantly, it has been shown for strongly strained and moderately strained Ga$_x$In$_{1-x}$As QWR structures grown by the SILO process the peak PL wavelength does not shift for temperatures above 300 K.

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Ga$_x$In$_{1-x}$As QWR samples. This temperature dependent polarization switching is observed when the pump polarization is parallel to the QWRs. In this measurement geometry, the longitudinal (with respect to the QWRs) PPL is greater than the transverse PPL at 77 K. At 300 K the dominant polarization switches from longitudinal to transverse. However, when the incident pump polarization is perpendicular to the QWRs, the longitudinal PPL is dominant at both temperatures. In contrast, temperature dependent polarization switching is not observed in weakly strained Ga$_x$In$_{1-x}$As QWR samples whose band-gap dependence on temperature approaches the usual behavior of the GaInAs QW structure.

By looking at PPL spectra at different temperatures between 77 and 300 K for the pump polarization parallel to the QWRs, it was observed that the polarization switch occurs in the same temperature range as the wavelength shift ($150–200$ K) for moderately and strongly strained Ga$_x$In$_{1-x}$As QWR samples. Furthermore, of all the SILO grown QWR heterostructures studied, only the strongly strained and moderately strained Ga$_x$In$_{1-x}$As QWRs demonstrate temperature dependent polarization switching. Therefore, it seems that the temperature dependent polarization switching is related to the anomalous band-gap behavior with respect to temperature seen in Ga$_x$In$_{1-x}$As QWRs grown by the SILO process.

Unique to the SILO process grown QWRs is the multiaxial strain that exists among the wires. There exists the usual biaxial strain in the (100)-plane interface of the QWRs and the nominally lattice matched barrier material in the [100] direction. In addition, there is also biaxial strain in the (110)-plane interface between neighboring QWRs of different compositions. The polarization switching results presented in Fig. 3 imply that the multiaxial strain is temperature dependent in SILO grown Ga$_x$In$_{1-x}$As QWR heterostructures displaying anomalous band-gap behavior with respect to temperature. This is because the PPL data in Fig. 3 show that the valence bands are moving with temperature such that the change in dominant emission results from recombination with the heavy-hole band at 77 K and the light-hole band at 300 K. For this to occur, the strain itself must depend on temperature. Thus, depending on the exact functional form of this temperature dependence, a blueshift in PL wavelength with increasing temperature or even band-gap stability with respect to temperature is possible.

Finally, it should be noted that the anomalous band-gap behavior with respect to temperature described in this letter readily occurs in Ga$_x$In$_{1-x}$As QWRs grown by the SILO process. Other species such as Ga$_x$In$_{1-x}$P QWRs do not have the same temperature dependent band-gap characteristics. The obvious difference is the composition of the group-V sublattice. This results in several differences in material parameters and growth kinetics during the SILO process. First, the elastic stiffness constants are on average, larger for GaP and InP than for GaAs and InAs. Given the nature of the multiaxial strain in SILO produced QWRs, this is significant. In addition, the valence band effective masses ($m^*_{v}$) are larger for GaP and InP than for GaAs and InAs where the splitoff energy ($\Delta$) due to spin–orbit coupling is smaller.

Effective masses and splitoff band interactions are important to band structure calculations which make these differences in $m^*$ and $\Delta$ significant to the temperature dependent band-gap anomaly phenomenon based on the results of Fig. 3. For instance, it is known that it is important to include the splitoff band in band structure calculations of strained systems. Moreover, splitoff interactions are more significant for P-based crystals than for As-based ones due to smaller values of $\Delta$ for phosphides. The decreased splitoff band interaction for As-based structures may be more conducive to the temperature dependent polarization switching we have observed which gives rise to the anomalous band-gap behavior with respect to temperature.

In summary, Ga$_x$In$_{1-x}$As QWRs grown by the SILO process are known to have anomalous temperature dependent band-gap behavior. We have shown that this behavior results from the multiaxial strain that is inherent to SILO grown QWRs. This has been made clear by the observation of temperature dependent polarization switching which is only observed for Ga$_x$In$_{1-x}$As QWRs that have the anomalous temperature dependent band-gap behavior. Furthermore, the temperature dependent band-gap anomaly is more likely to occur in Ga$_x$In$_{1-x}$As QWRs than in other species of QWRs.

The authors would like to thank Y. C. Chang and L. X. Li for helpful discussions. This work was supported by the National Science Foundation (Grant No. ECS-9617153), and DARPA.

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