The role of antimony on properties of widely varying GaInNAsSb compositions

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(Received 15 November 2005; accepted 24 January 2006; published online 11 May 2006)

Antimony has been used as a surfactant to improve the quality of GaInNAs/GaAs quantum wells for long-wavelength optoelectronics. We demonstrate the importance of antimony as a reactive surfactant and the proper usage of it with dilute nitrides in order to tailor the properties of solar cell and laser devices. The effects of the addition of antimony to low indium concentration (~8%) and low strain GaInNAs material (for 1.0 eV solar cell applications) were investigated. It was assumed previously that adding antimony helped all GaInNAs alloys, but the validity of this was not previously tested. The addition of antimony to high indium concentration (~32%) and high strain GaInNAs samples led to a dramatic improvement in optical quality and a widening of the growth window, while it led to a degradation in the low indium (low strain) composition samples. The addition of indium under constant antimony flux also improved the optical quality of the GaInNAs material. Variations in the indium and antimony compositions revealed a competition in atomic incorporation into the GaInNAsSb alloy. This interaction will be discussed. Increasing indium and/or strain confirmed the reactive surfactant properties of antimony on GaInNAsSb alloys. [DOI: 10.1063/1.2191745]

I. INTRODUCTION

The introduction of nitrogen to GaAs led to the surprising revelation that both the band gap and the lattice parameter could be simultaneously reduced, contrary to the behavior of most III-V semiconductors.[1] Kondow *et al.* added nitrogen to InGaAs to create GaInNAs,[2] enabling a class of GaAs-based materials and devices that emit light at wavelengths of 1.6 μm or longer. GaInNAs of different compositions has found great interest in two applications: high-efficiency solar cell junctions operating at 1.0 eV (1.1 μm)[3–5] and lasers operating at the telecommunication wavelengths of 1.3 and 1.55 μm.[6–8] With concentrations of 6%–8% indium and 2%–3% nitrogen, GaInNAs has a band gap corresponding to a 1.0 eV with little or no strain when grown on GaAs. The ability to grow thick coherent layers ($\geqslant$1 μm) is extremely important for high-quality absorption-based devices, such as solar cells and detectors. Before GaInNAs, GaAs-based devices requiring thick layers of 1.0 eV band gap materials necessitated techniques such as graded strain relaxation layers or wafer bonding that introduced performance degrading defects. At higher concentrations of 30%–40% indium and 2%–3% nitrogen, GaInNAs has enabled the realization of GaAs-based long-wavelength edge-emitting and vertical-cavity surface-emitting lasers (VCSELs) at 1.3 and 1.55 μm.[6–8] Before the development of GaInNAs, it was impossible to obtain these wavelengths from a coherently grown material on GaAs due to the very high strain found within the active region. With nitrogen, although the strain is still very high ($\geqslant$2.0%), it is low enough that one to three quantum wells (QWs) may be grown.

The growth of high-quality dilute nitrides is quite difficult; the incorporation of nitrogen can degrade the optical properties due to ion damage,[9,10] nonradiative traps,[5,11] and/or phase segregation.[12] These issues become increasingly apparent when the indium and nitrogen concentrations in GaInNAs are increased to extend the wavelength to 1.6 μm. The addition of antimony as a surfactant[13,14] and constituent dramatically improves the material and optical qualities in dilute nitrides,[15–18] reduces the band gap, and enables the lowest threshold GaAs-based edge-emitting lasers at 1.55 μm.[19] However, adding antimony has made an already complex alloy even more complicated, forming a five-element quinary system. Growth interactions between indium, nitrogen, and antimony are undoubtedly present. Although antimony improved GaInNAs's material quality and surface morphology, it provided little improvement to the indium-free GaNAs material;[20,21] this may be due to the nature of antimony incorporation and the effects of adding indium. It is believed that a reactive surfactant, such as antimony on GaAs, behaves differently in low strain versus high strain materials.[22,23] This may lead to a difference in observed properties when utilizing antimony in the high strain GaInNAsSb alloys for laser applications as opposed to the low strain alloys for 1.0 eV solar cell applications.

In this work, we investigated the effects and behavior of antimony on GaInNAsSb alloys with widely varying compositions of antimony and indium. The addition of antimony to the low strain GaInNAs material (for 1.0 eV solar cell applications) has never been studied. In addition, a detailed study of interactions between indium and antimony is useful to help understand the role of antimony in dilute-nitride materials and how to use it properly. We examined two sets of samples in which the antimony fluxes were varied under two

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different indium compositions corresponding to the two different primary applications of GaInNAs: ~8% indium for the low strain (1.0 eV solar cell application) and ~32% indium for the high strain (telecommunication quantum well laser application). In addition, we varied the indium under a constant antimony flux to further study the interactions between indium and antimony and help connect the results found from the two studies with varying antimony fluxes and with different indium compositions. Secondary-ion mass spectrometry (SIMS) showed a significant interplay between indium and antimony with varying GaInNAsSb compositions. High-resolution x-ray diffraction (HRXRD) showed that most samples were of good quality. Strain quantities were also obtained from the scans and were correlated with SIMS results to understand the properties of antimony with varying amounts of strain. Finally, photoluminescence (PL) measurements were performed to obtain a general understanding of the optical quality of the material. The addition of antimony to a high strain material improved the optical quality, while antimony in a low-strain material degraded the luminescence. These results confirm the reactive surfactant properties of antimony in GaInNAsSb alloys and show how these dilute-nitride-antimonide alloys must be grown under different conditions in order to optimally tailor the properties of solar cells and laser devices.

II. EXPERIMENTAL DETAILS

The GaInNAs(Sb) QW samples used in this study were grown on *n*-type (100) GaAs substrates by solid-source molecular beam epitaxy (MBE) in a Varian Mod. Gen-II system. Gallium and indium were supplied by SUMO effusion cells. A valved arsenic cracker supplied As_2 and an unvalved antimony cracker supplied monomeric antimony. The GaInNAs(Sb) QWs were grown at a substrate temperature of 440 °C measured by pyrometry. An arsenic-to-gallium overpressure of 20× and an antimony flux of $2.0-10.0 \times 10^{-8}$ torr beam equivalent pressure (BEP) were supplied during the GaInNAsSb QW growth. Nitrogen was supplied by a modified SVT Associates plasma cell operating at a rf of 13.56 MHz. Nitrogen gas of a 5N (99.999%) purity was filtered through a <1 ppb Pall Mini-Gaskleen purifier to minimize oxygen contamination. The cell was operated with a 300 W input power and a nitrogen gas flow of 0.5 SCCM (standard cubic centimeter per minute). Nitrogen incorporation into (In)GaAs is directly controlled by the group-III growth rate and obeys the equation

$$[N\,\%] = \frac{K}{\{GR\}}, \quad (1)$$

where [N%] is the percentage of nitrogen desired, K is a constant obtained from calibrations, and $\{GR\}$ is the group-III growth rate in μm/h.[24] The constant K is a function of the nitrogen gas flow[10] into the rf plasma cell and the amount of antimony[20,21,25] present in the dilute-nitride layer.

To determine the effects and behavior of widely varying compositions on the structural, optical, and electronic properties of GaInNAsSb, several samples were grown at a variety of indium and antimony fluxes. A summary of the samples described below is shown in Table I. The first series consisted of GaInNAs(Sb) QWs which were intended to contain 32% indium and 2.0% nitrogen, a typical composition for a 1.3 μm wavelength emission. These samples are considered to be in the "high indium" and high lattice strain regime. The antimony flux was varied from zero to 1.0×10^{-7} torr BEP, while all other growth parameters were held constant. The 1.0×10^{-7} torr BEP is the typical flux we have used for all GaInNAsSb laser devices.[19] Next, a series of GaInNAs(Sb) QWs grown with much lower indium and with 8% and 2.0% nitrogen were analyzed for their properties with varying amounts of antimony. These "low indium" and low lattice strain regime samples correspond to the composition typically used to obtain a 1.0 eV band gap for solar cell applications. Finally, a set of samples with a constant 1.0×10^{-7} torr BEP antimony flux and varying indium concentrations from the low to high indium regimes was studied to connect the properties of the two previous series into a comprehensive understanding on the role of antimony. The total group-III flux (gallium and indium) was held constant such that the nitrogen composition remained the same for all samples in this series. The structure for all samples consists of a 7.5 nm GaInNAs(Sb) QW grown on a 300 nm GaAs buffer capped by a 50 nm GaAs layer. For each run, samples were grown out of order to eliminate source drift effects on the compositions. The compositions of the samples were determined by HRXRD and SIMS. The HRXRD was obtained with a Philips X'Pert Pro four crystal high-resolution x-ray diffractometer, and the SIMS analysis with a Physical Electronics ADEPT 1010 quadrupole analyzer. PL measurements, used to obtain emission wavelength and intensity, were performed at room temperature with an argon ion laser and an InGaAs detector.

TABLE I. A summary of the growth conditions for the samples described in this study. The intended indium composition and the applied antimony fluxes are listed. Series A denotes the series in which antimony was varied under a constant "high" indium flux. Series B indicates the series in which antimony was varied under a constant "low" indium flux. Series C illustrates the series in which indium was varied under a constant 1.0×10^{-7} torr BEP antimony flux.

	8% In	16% In	24% In	32% In
0 Sb	B			A
2.0×10^{-8} torr BEP Sb	B			A
6.0×10^{-8} torr BEP Sb	B			A
1.0×10^{-7} torr BEP Sb	B, C	C	C	A, C

III. RESULTS

A. Varying antimony in the high indium regime

The first series of samples studied contained a single GaInNAs(Sb) QW with nominal 32% indium and antimony fluxes which varied between 0 and 1.0×10^{-7} torr BEP. These QWs are typically used for 1.3 μm light emitters and have relatively high amounts of indium. The strain in the QWs is large, but usually not large enough to cause the QW to relax. Figure 1 contains the HRXRD spectra from these four samples. As will be discussed later, all of the QWs

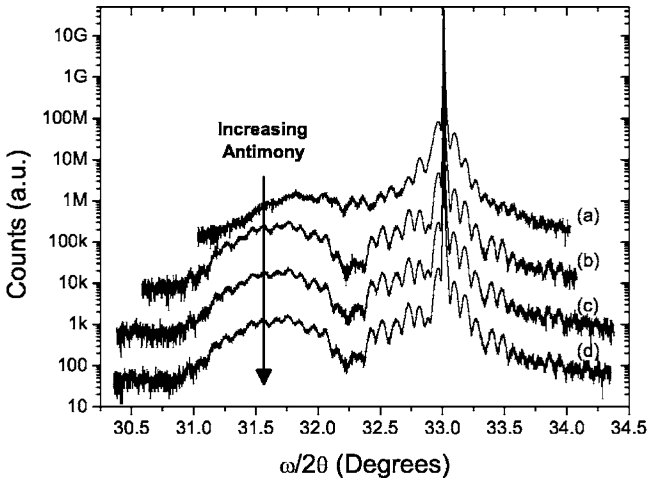

FIG. 1. HRXRD spectra of the (004) GaInNAs(Sb)/GaAs QWs with "high" indium compositions. (a) GaInNAs QW, (b) GaInNAsSb QW with 2.0×10^{-8} torr BEP antimony, (c) GaInNAsSb QW with 6.0×10^{-8} torr BEP antimony, and (d) GaInNAsSb QW with 1.0×10^{-7} torr BEP antimony.

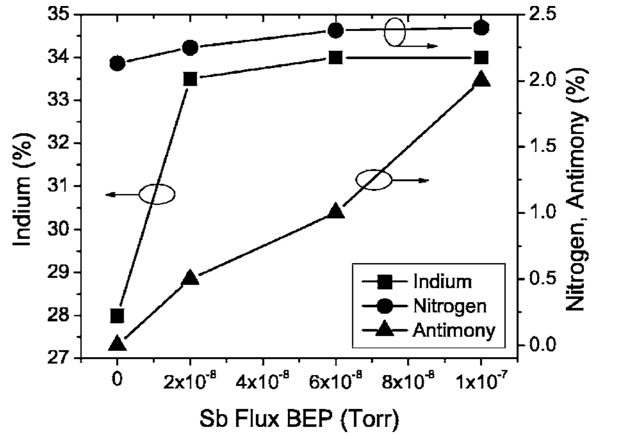

FIG. 2. Indium, nitrogen, and antimony compositions as functions of antimony flux.

contained 34% indium rather than 32% indium due to flux miscalibration. Figure 1(a) represents a GaInNAs QW which is of poor quality. The QW Pendellösung fringes are severely degraded, the peak intensity is very low, and the strain is much lower than expected. This indicates a loss of structural quality due to phase segregation. It has been a challenge to obtain high-quality GaInNAs with indium compositions greater than 34%–35% due to phase segregation and relaxation, and this difficulty is apparent in this sample. Figures 1(b)–1(d) are from GaInNAsSb QWs which have recovered their structural quality in the presence of an antimony flux. The three spectra, with a +2.1% strain, are almost identical except for a very small compressive shift of the QW with increasing antimony flux. The origin of this small shift requires a detailed compositional analysis in order to accurately determine the cause. For this compositional range of high indium and high strain, the addition of antimony greatly improved the structural quality of the GaInNAs. However, from HRXRD, there was no significant difference in the QWs with different antimony fluxes.

SIMS was used to determine the composition of the four samples in this series. Although it is relatively straightforward to obtain depth profiles, obtaining exact compositional values requires previous calibration due to artifacts, including matrix effects. The SIMS analysis was calibrated using parameters obtained from past growths analyzed with the nuclear reaction analysis Rutherford backscattering (NRA-RBS) for nitrogen and with the particle-induced x-ray emission RBS (PIXE-RBS) for antimony.[18] The compositions were consistent with HRXRD data and simulations. Figure 2 shows the indium, nitrogen, and antimony compositions as functions of the antimony flux. It is unclear if the data from the antimony-free GaInNAs sample is believable since the QW itself had phase segregated and relaxed, thus changing the bonding structure and possibly the incorporation kinetics of the alloy. These changes may alter SIMS sputtering statistics. The indium concentration is much lower than anticipated compared to previous growths which were of good quality. Nitrogen is also higher than expected compared to past growths and the other three samples which have antimony. Antimony enhances nitrogen incorporation and has been seen previously in several studies.[20,21,25,26] As expected, for increasing antimony fluxes, the antimony concentration in the QW rose from 0.5% to 2.0%. Indium was ~34% (higher than intended due to flux miscalibration), while nitrogen was 2.3%–2.4%. There was not much change in the indium or nitrogen concentrations with varying antimony flux.

PL measurements were performed to study the optical properties of the GaInNAs(Sb) QWs. Figure 3 shows the room-temperature PL intensity of the four GaInNAs(Sb) QWs after an *ex situ* rapid thermal annealing (RTA) of 780 °C for 1 min. The relative peak intensities of the samples were all comparable before and after RTA. Additional details on the annealing behavior of the samples in this paper and their relevance for laser applications may be found elsewhere.[27,28] As expected, the GaInNAs QW that showed a poor structural quality in HRXRD produced a weak emission centered at 1.32 μm. The addition of a small antimony flux

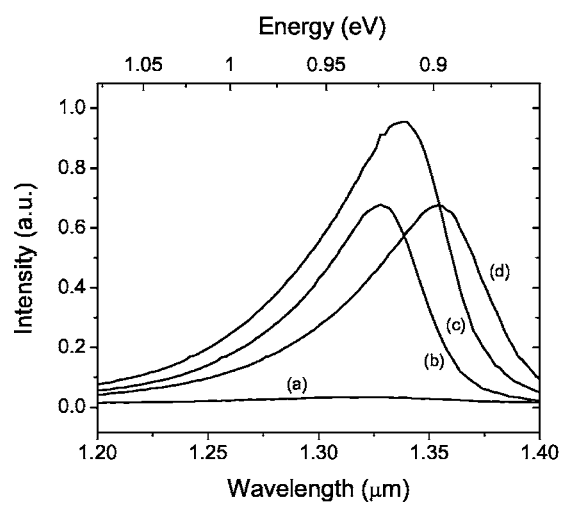

FIG. 3. PL spectra of GaInNAs(Sb) samples under high indium and high strain conditions with varying antimony flux. (a) GaInNAs QW, (b) GaInNAsSb QW with 2.0×10^{-8} torr BEP antimony, (c) GaInNAsSb QW with 6.0×10^{-8} torr BEP antimony, and (d) GaInNAsSb QW with 1.0×10^{-7} torr BEP antimony.

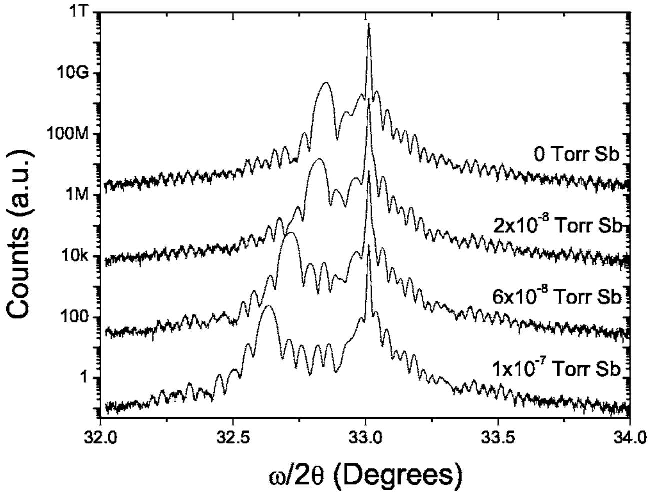

FIG. 4. HRXRD spectra of the (004) GaInNAs(Sb)/GaAs layers with "low" indium compositions.

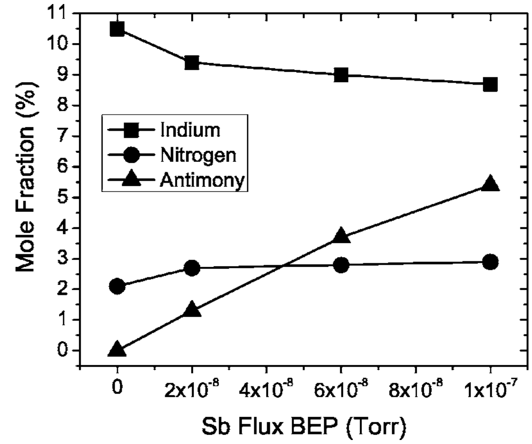

FIG. 5. Indium, nitrogen, and antimony compositions as functions of antimony flux utilized during the QW growth in the "low" indium composition range.

of 2.0×10^{-8} torr BEP during the QW growth dramatically improved the optical quality. Adding 6.0×10^{-8} torr BEP further increased the PL intensity, but adding the typical 1.0×10^{-7} torr BEP used in GaInNAsSb laser growths actually decreased the optical quality. This indicates that there is an optimal antimony flux which produces the highest optical quality GaInNAsSb QWs. A red shift of the peak wavelength was seen with higher antimony fluxes due to the increasing antimony incorporation into the QW.

B. Varying antimony in the low indium regime

The next series of samples contained relatively low amounts of indium (8%) and antimony fluxes which varied between 0 and 1.0×10^{-7} torr BEP. This compositional range is used for solar cell junctions which operate at 1.0 eV. Since thick layers are required for high-efficiency solar cells, the strain must be very small or nonexistent, and thus contain a much smaller indium composition for the same nitrogen concentration. Since the strain in these QW samples would be very small, thicker 1000 Å samples of identical compositions were grown to facilitate strain determination with HRXRD. The HRXRD spectra of these thicker samples are shown in Fig. 4. The HRXRD spectra indicated that the samples possessed excellent structural quality and interfaces. In the antimony-free case, the GaInNAs layer had a strain of +0.24%. The strain increases with larger antimony fluxes, up to +0.54% with 1.0×10^{-7} torr BEP. Even with the slight increase in strain, these values are significantly lower than highly strained (2.0%–2.6%) QWs which are used for 1.3 and 1.55 μm wavelength emissions. Additional information from SIMS was required to determine the origin of the increase in compressive strain with increasing antimony fluxes.

The compositions of the four samples are shown in Fig. 5. As expected, an increase in antimony flux used during the QW growth led to a significantly higher antimony incorporation, up to 5.5%. This value is much higher than the high indium case, where there was only 2.0% incorporation at the highest antimony flux. Nitrogen composition was found to be 2.1% in the case without antimony and 2.8% in the presence of antimony. In the antimony-free case, the indium composition was found to be 10.5%. However, a 2.0×10^{-8} torr BEP antimony was applied; the composition dropped to 9.4%, even though the indium flux was held constant. The indium concentration decreased further to 8.7% at the highest antimony flux. This finding was surprising since it was unexpected that antimony would affect the incorporation kinetics of indium.

The ultimate goal of this series of samples was to determine whether antimony would improve the material and optical qualities of GaInNAs in the low indium (low strain) conditions as it did in the high indium (high strain) conditions. Figure 6 shows the PL spectra from these samples after *ex situ* RTA. Adding antimony degraded the optical quality of the GaInNAs; the higher the antimony flux, the lower the PL intensity. In addition, the full width at half maximum of the PL peaks also increased with increasing antimony flux. Also, the peak wavelength redshifted with increasing antimony concentration, despite the decrease in indium content.

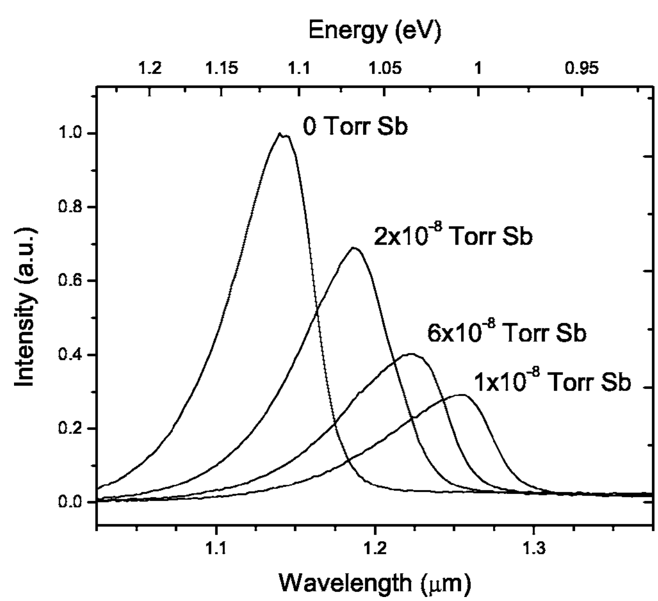

FIG. 6. PL spectra of GaInNAs(Sb) samples under low indium and low strain conditions with varying antimony flux.

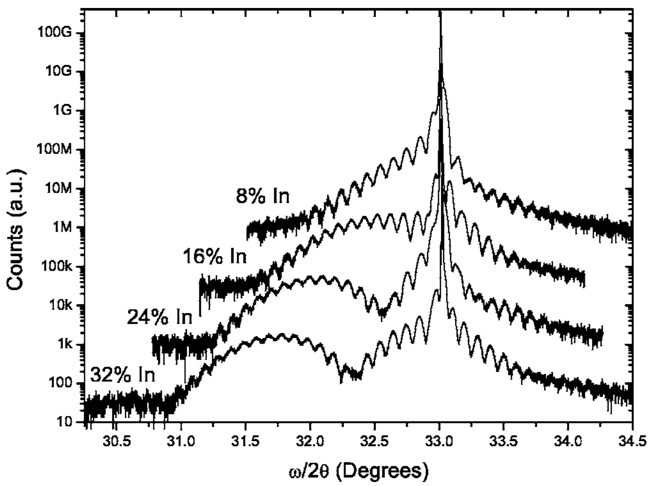

FIG. 7. HRXRD spectra of the (004) GaInNAs(Sb)/GaAs QWs with varying indium fluxes under a constant antimony flux.

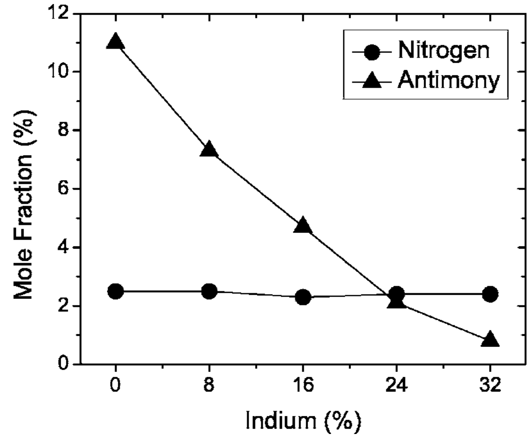

FIG. 8. Nitrogen and antimony compositions as functions of indium concentration, with the antimony flux held constant.

Antimony lowers the band gap much more rapidly than does indium in concentrations where they exist. The decrease in PL intensity is a very surprising result since this is the opposite behavior compared to samples with high indium and high strain, in which antimony dramatically improved the optical quality of GaInNAs. It may be argued that the antimony-containing samples have lower PL intensities due to the higher nitrogen content, a degradation typical of the dilute nitrides. However, the three samples with antimony contain almost the same amount of nitrogen, and thus the continuing degradation cannot be explained in that manner. Finally, it is possible that an antimony flux smaller than 2.0×10^{-8} torr BEP may improve the material quality, as it has been found that different growth alloys require different amounts of antimony.[21] The behavior is nonetheless very different than the high indium and high strain samples.

C. Varying indium with constant antimony

Finally, in an effort to connect the behaviors observed in the previous two studies, a series of samples was grown with a constant of 1.0×10^{-7} torr BEP of antimony while adjusting the indium concentration. Figure 7 shows the HRXRD spectra taken from the four samples with varying precalibrated indium concentrations. All the samples have a well defined QW peak and strong Pendellösung fringes, indicating a good structural quality. A large change in strain was also observed with the addition of more indium, as expected. The strain varied from +0.7% at the low indium composition to +2.0% in the high indium composition. These values are very similar to those observed in the previous two studies.

SIMS and HRXRD were employed to determine the compositions of the samples in this series. A summary of the data is shown in Fig. 8. A sample containing no indium (GaNAsSb) grown under nearly identical growth conditions was included in the plot for an additional comparison. The observed indium concentration in the QWs matched well with the intended compositions determined from previous calibrations. The nitrogen composition for all five indium compositions remained constant at 2.5%. The total group-III growth rate (indium and gallium) and the antimony flux were held constant, and thus the relation in Eq. (1) dictates a constant nitrogen composition as well. Different indium compositions were obtained by changing the ratio of indium and gallium fluxes. 11% antimony was found in the indium-free GaNAsSb QW sample. Interestingly, when indium was present at low composition, the antimony dropped to 7.3% in the GaInNAsSb QW. The antimony concentration continued to decrease with increasing indium fluxes down to 0.8% antimony at high indium composition. This indicates a very strong interplay of strain, resulting in competition between the indium and antimony atoms during the growth. Indium decreases antimony incorporation in GaInNAsSb.

This investigation varying the indium composition under a constant antimony flux connects the improvement in optical quality with antimony at high indium and the degradation with antimony at low indium. The PL spectra after *ex situ* RTA are shown in Fig. 9. For the sample with only 8.8% indium, the peak intensity was weak, similar to that found in the study with low indium. As evident from the plot, increasing the indium concentration (and also strain) in the GaIn-

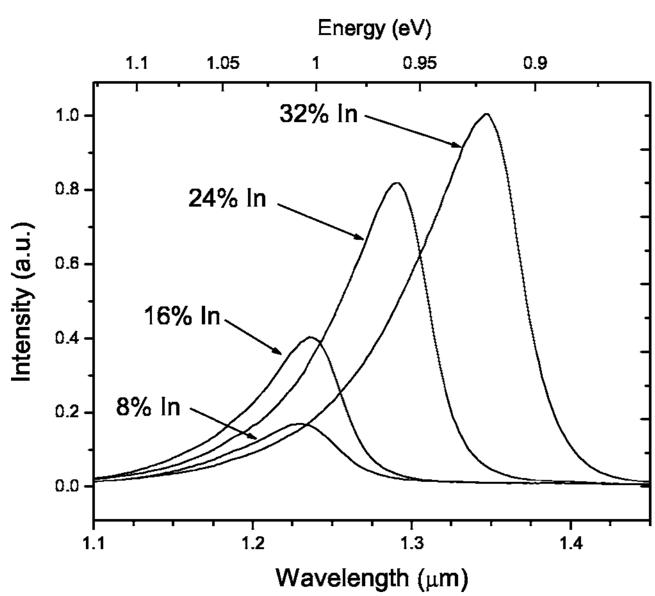

FIG. 9. PL spectra of GaInNAs(Sb) samples with a constant antimony flux with varying indium concentrations.

NAsSb QW dramatically improved the optical quality. A redshift in the peak wavelength can be attributed to the large increase in indium concentration. The shift in peak wavelength between the 8.8% and the 16.7% indium samples was very small. Indium does not decrease the band gap as rapidly as does antimony for those specific compositions. From this study, a significant decrease in antimony incorporation in the presence of indium is a result of a high amount of antimony segregation at the growth surface. Antimony limits the adatom surface diffusion and improves the quality of the strained material.

IV. DISCUSSION

When antimony was first added to GaInNAs to improve the material quality for 1.3 and 1.55 μm edge-emitting lasers and VCSELs, little attention was given to the amount used, to what situations it would be beneficial, and especially to how it would work. It was thought that antimony was a "panacea" to improving the quality of all dilute nitrides. As shown in previous studies of GaNAsSb (Ref. 21) as well as this study on GaInNAsSb, it has become apparent that antimony is not a "magical cure" to improve dilute nitrides and must be utilized correctly for different devices with different compositions.

From the studies presented in this paper, there are several factors that contribute to the improvement or degradation of GaInNAs with antimony. The typical definition of a surfactant is a species that lowers the surface free energy of the growth front. However, it was later realized that the modification of the epitaxial growth kinetics was the key effect of surfactants.[22] Massies and Grandjean[22] and Tournie *et al.*[23] proposed two classes of surfactants which were utilized in the epitaxial growth: reactive surfactants that decrease the surface diffusion length (SDL) and nonreactive surfactants that increase the SDL at the growth front. It is clear that for homoepitaxy or nonstrained heteroepitaxy, a nonreactive surfactant is preferred since increasing the SDL would improve the material quality. However, for strained heteroepitaxy in which there is a significant lattice mismatch between the layer and the substrate, minimizing the SDL would be beneficial to reduce the formation of islands and phase segregation, which are thermodynamically favored. Thus, reactive surfactants are utilized for the strained heteroepitaxial growth. The issue of nonstrained epitaxy versus strained epitaxy is particularly relevant when comparing GaInNAs used for 1 eV solar cell applications and GaInNAs used in long-wavelength optoelectronics. For the samples with high indium, and thus high strain, adding antimony improved the structural and optical quality of GaInNAs. However, the addition of any amount of antimony to the low indium and low strain GaInNAs degraded the optical quality. It was also seen that increasing the strain in the QW by increasing the indium concentration while applying identical antimony fluxes helped improve the PL intensity of the GaInNAsSb. The reduction of the SDL in the high indium and high strain case is important in minimizing the formation of islands and the three-dimensional (3D) growth due to the high strain and the tendency to phase segregate. Antimony keeps GaInNAs's growth two dimensional (2D) and reduces or eliminates phase segregation, improving the optical quality. However, for the thick lattice matched layers used in GaInNAs solar cells, the strain is minimal or zero, and a reactive surfactant is undesirable. Suppression of the SDL in this case leads to a high density of defects because there is no need to prevent strain-induced islanding.

The interplay or competition between indium and antimony in the incorporation into GaInNAs is another factor affecting the quality. In the high indium and high strain case, it was unclear whether the presence of antimony lead to a change in indium concentration since the antimony-free sample was of poor quality. Ignoring the first sample with a poor material quality, there was no observed change in indium with increasing amounts of antimony flux. It is possible that with such small percentages of antimony incorporation ($<2\%$), any effect on indium incorporation would not be detectable. A noticeable change was observed in the low indium, low strain case. By introducing a small antimony flux (V/III BEP=0.07), the indium concentration decreased. It continued to decrease with additional antimony flux. The ease of antimony incorporation with low indium concentrations was evident since there was 5.7% antimony compared to 2.0% antimony with high indium concentrations for the same maximum flux of antimony. For the samples with a constant 1.0×10^{-7} torr BEP of antimony and varying indium, the competition between indium and antimony was apparent. Without indium and at very low strain conditions, the antimony incorporated at 11% concentration. However, as the indium and strain increased, the antimony concentration steadily decreased to 0.8%. An additional investigation is required to determine the exact cause of this competition, but it is suspected that the strain associated with large atomic radii of antimony and indium in GaAs plays a major role. Both atoms induce a large local strain in the GaAs matrix, and having both atoms would not be energetically favorable due to the large strain energies they would create. Thus, one species would preferentially incorporate while the other would not. However, the fact that indium is a group-III atom and antimony is a group-V atom adds complexity to this argument and is beyond the scope of this paper. It does not appear from the findings in this study that indium or antimony has an advantage over the other. In the low indium and low strain case, there was a larger initial decrease in indium concentration with the introduction of antimony, while there was no such reduction when indium was introduced to GaNAsSb in the study, varying indium. The decrease in antimony from 11% to 0.8% is most likely because indium increased significantly from 0% to 32.7%.

Finally, we point out the minimizing the antimony incorporation and optimizing the SDL lead to the best optical quality in GaInNAsSb. This is the common trend observed in all three studies. It has also been observed in studies on GaNAsSb in which dilute antimony incorporation increased the optical quality.[21] Although a surfactant is technically defined as a surface segregant that does not incorporate, a reactive surfactant does bond substitutionally.[22] The surfactant atom then exchanges places with an impingent adatom and continues to segregate to the surface in that manner. However, it does bond to the matrix, and coupled with the fact that dilute-nitride alloys are grown at relatively low temperatures, the antimony atom does not always continue to surface segregate and thus incorporates. In the high indium and high strain case, adding antimony up to 1% mole fraction improved the optical quality, while 2% antimony degraded it. For the low indium and low strain case, the behavior was much different. Adding antimony, even at 1.3% mole fraction, decreased the PL intensity from the antimony free case. In the study varying indium, although the antimony flux itself was not varied, the antimony concentration dropped with increasing indium concentrations. The sample with the lowest antimony concentration of 0.8% had the highest PL intensity. The amount of antimony flux used during the QW growth is not the key parameter since many factors must be considered, including composition and strain. The PL intensity improved by increasing the indium concentration, forcing the antimony concentration to decrease indirectly. An antimony flux is required in the high strain case as it is needed to improve the material and optical qualities with antimony's reactive surfactant qualities in dilute nitrides. However, either no antimony or a flux much smaller than the ones studied in this paper is required for the low strain samples since reactive surfactants are not helpful in nonstrained heteroepitaxy. The amount of antimony incorporated in the GaInNAsSb is a function of surface kinetics during the growth, including surface segregation. The optimization of the SDL is important to obtain high quality GaInNAsSb materials.

V. CONCLUSION

We grew three sets of GaInNAs(Sb) samples which were representative of compositions found in 1.3 and 1.55 μm edge-emitting lasers and VCSELs and 1.0 eV solar cell junctions to determine the role of antimony as well as its proper usage. An improvement in the optical quality for GaInNAs containing high (~32%) indium and high strain was observed with the addition of antimony. The effect of antimony on near-lattice-matched GaInNAs typically used for solar cells was examined and was found to degrade the optical quality. Finally, we observed an improvement of the optical quality in GaInNAsSb QWs with increasing indium concentrations under a fixed antimony flux. A competition in incorporation between indium and antimony was also observed in the compositional analysis of the different sets of samples. This competition is probably due to the large atomic radii of indium and antimony in GaAs, but the local strain inhibits the simultaneous incorporation of both atoms. An additional investigation is required, however, to fully examine the scenario. We believe that antimony is a reactive surfactant in the dilute-nitride growth and is useful for the long-wavelength devices since those active regions contain a high strain. Conversely, antimony degrades the luminescent quality for the GaInNAs typically used for 1.0 eV solar cell junctions. Finally, the main parameter which affects the optical quality of the material is the concentration of antimony that actually incorporates into the material, not the antimony flux. By minimizing the antimony incorporation to concentrations of ~1% in highly strained materials and thus optimizing the SDL, it is possible to obtain high-performance long-wavelength lasers on GaAs. These findings are of great importance to the design, growth, and creation of high-performance lasers and high-efficiency solar cells.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Charles Evans & Associates in Sunnyvale, CA for performing SIMS measurements, the Sumitomo Electric Industries Ltd. for the donation of substrates and SIMS in this study, and Dr. Akihiro Moto from the SEI Innovation Core for useful discussions. One of the authors (H.B.Y.) would also like to thank the Stanford Graduate Fellowships for funding assistance. This work was supported under DARPA and ARO Contract Nos. MDA972-00-1-024, DAAD17-02-C-0101, and DAAD199-02-1-0184, ONR Contract No. N00014-01-1-00100, and High-Power Laser MURI contract. The authors also acknowledge support from Stanford Network Research Center (SNRC)

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