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14. ABSTRACT

Unrelaxed InAs1-xSbx layers with lattice constants up to 2.1% larger than that of GaSb substrates were grown by molecular beam epitaxy on GaInSb and AlGaInSb compositionally graded buffer layers. The topmost section of the buffers was unrelaxed but strained. The in-plane lattice constant of the top buffer layer was grown to be equal to the lattice constant of unrelaxed and unstrained InAs1-xSbx with given X. The InAs0.56Sb0.44 layers demonstrate photoluminescence peak at 9.4 mu m at 150 K. The minority carrier lifetime measured at 77K for InAs0.8Sb0.2

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# Properties of unrelaxed InAs1−XSbX alloys grown on compositionally graded buffers

G. Belenky, D. Donetsky, G. Kipshidze, D. Wang, L. Shterengas et al.

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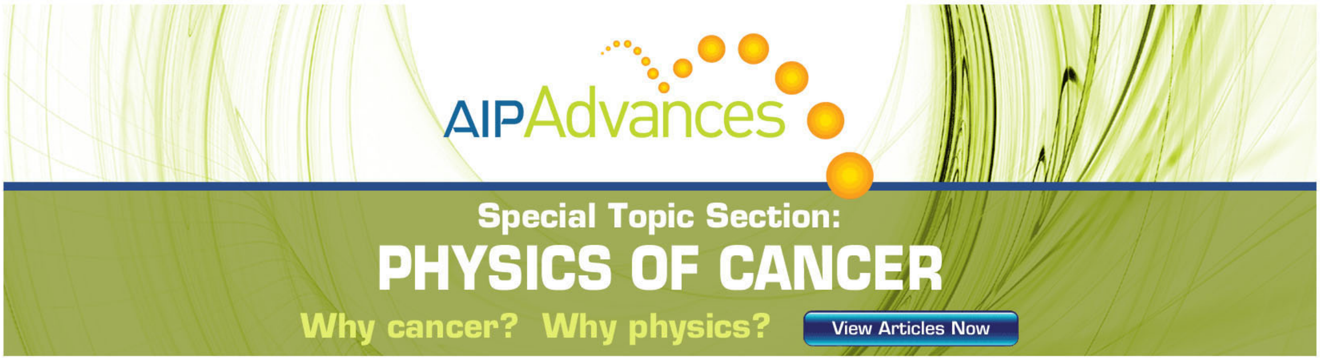

APPLIED PHYSICS LETTERS **99**, 141116 (2011)

# Properties of unrelaxed $InAs_{1-X}Sb_X$ alloys grown on compositionally graded buffers

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Unrelaxed $InAs_{1-x}Sb_x$ layers with lattice constants up to 2.1% larger than that of GaSb substrates were grown by molecular beam epitaxy on GaInSb and AlGaInSb compositionally graded buffer layers. The topmost section of the buffers was unrelaxed but strained. The in-plane lattice constant of the top buffer layer was grown to be equal to the lattice constant of unrelaxed and unstrained $InAs_{1-x}Sb_x$ with given X. The $InAs_{0.56}Sb_{0.44}$ layers demonstrate photoluminescence peak at 9.4 $\mu$m at 150 K. The minority carrier lifetime measured at 77 K for $InAs_{0.8}Sb_{0.2}$ was $\tau = 250$ ns. © *2011 American Institute of Physics*. [doi:10.1063/1.3650473]

There is a continuing interest in the development of III-V materials by molecular beam epitaxy (MBE) as an alternative to HgCdTe for the fabrication of infrared (IR) photodetectors. These photodetector structures require the development of epitaxially grown unrelaxed absorption layers that are several microns thick. This task is not easy to accomplish due to the limited availability of appropriate III-V substrates.

In this paper, we address this challenge by growing an $InAs_{1-X}Sb_X$ alloy on a metamorphic buffer layer. $InAs_{1-X}Sb_X$ alloys are of special interest, because the bowing effect in the band gap $E_g$ is dependent on the Sb composition (x), which allows the growth of layers having band gaps narrower than that in InSb.[1–9]

There are different approaches to fabricating metamorphic buffer layers, as they can be grown in compositionally graded steps or graded linearly.[10,11] In this work, we used the approach discussed in Refs. 12 and 13 to grow $InAs_{1-X}Sb_X$ on Ga(Al)InSb compositionally graded buffer layers on GaSb substrates. As a first step, we grew Ga(Al)InSb buffer layers with strained but unrelaxed top layers, having the desirable in-plane lattice constant. Then we grew the entire structure consisting of the graded buffer layer and the $InAs_{1-X}Sb_X$ absorption layer with given x and thickness up to 1.5 $\mu$m. At T = 77 K, the photoluminescence (PL) intensity peaks were found at 5.4, 7.6, and 9.3 $\mu$m for the Sb compositions of 20%, 30%, and 44%, respectively. The carrier lifetime up to 250 ns was obtained at T = 77 K for InAsSb with 20% of Sb. The reflection high energy electron diffraction (RHEED), reciprocal space mapping (RSM), and cross-sectional transmission electron microscopy (XTEM) techniques were used in the material development.

The heterostructures were grown by solid-source MBE utilizing crackers for As and Sb. The growth temperature was maintained near 415 °C for the InAsSb layers grown on GaSb substrates. Ga(Al)InSb graded buffer layers of 2–3.5 -$\mu$m thick were grown at temperatures from 460 to 520 °C.

Figure 1 presents an example of the structural characteristics of a 1 $\mu$m $InAs_{0.8}Sb_{0.2}$ layer grown onto a 2 $\mu$m linearly compositionally graded AlGaInSb buffer layer. The native lattice constant of the $InAs_{0.8}Sb_{0.2}$ layers is about 0.8% larger than that of GaSb. The native lattice constant of the buffer layer changed from that of GaSb to that of $Al_{0.75}Ga_{0.13}In_{0.12}Sb$ with a strain ramp rate about 0.6% per $\mu$m. The topmost section of the graded buffer with $Al_{0.75}Ga_{0.13}In_{0.12}Sb$ composition had a native lattice constant about 1.3% larger than that of GaSb, but due to compressive strain, the in-plane lattice constant is equal to the native constant of the bulk $InAs_{0.8}Sb_{0.2}$ layer. When the final structure was grown, the $InAs_{0.8}Sb_{0.2}$ layer was sandwiched between $Al_{0.75}Ga_{0.20}In_{0.05}Sb$ carrier confinement layers to assist photoluminescence experiments.

Figure 1(a) shows a XTEM image of the structure taken with a (220) bright field two-beam condition to emphasize the dislocations. The result demonstrates that the graded composition metamorphic buffer effectively accommodated the lattice mismatch between GaSb and $Al_{0.75}Ga_{0.20}In_{0.05}Sb$/$InAs_{0.8}Sb_{0.2}$ and layers. The misfit dislocation network was confined in the bottom 1.5 $\mu$m of the graded buffer. The topmost portion of the buffer as well as the epi-structure grown onto the graded buffer is free from misfit dislocations. From this image, we can estimate that the threading dislocation density is below $10^7$ cm$^{-2}$.

Figure 1(b) and 1(c), correspondingly shows the high resolution x-ray diffraction reciprocal space maps obtained near the symmetric (004) and asymmetric (335) reflections. The symmetric reflection revealed the tilt present in the epi-structure. From the measurement of the (004) RSM under several azimuth angles, we estimate the tilt angle to be 0.2° in the direction about 10° away from the [110] crystallographic direction. Asymmetric (335) RSM reflexes were measured at four different azimuth angles in order to characterize the degree of relaxation of the graded buffer layer and to confirm that the $InAs_{0.8}Sb_{0.2}$ layer is lattice-matched to the topmost part of the graded buffer. The (335) RSM was measured at an azimuth angle equal to 90°, i.e., at the minimum tilting effect (see inset to Figure 1(b)). The shift visible

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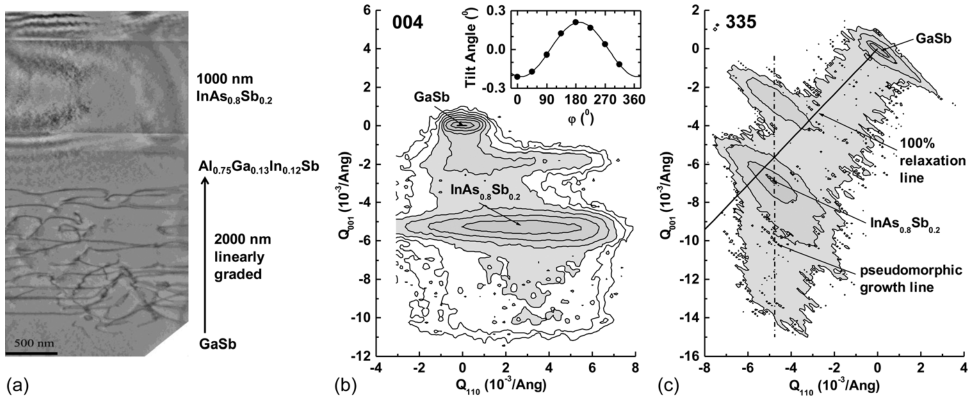

FIG. 1. XTEM (220) bright field image taken under a two beam condition (a); symmetric (004) RSM taken at the azimuth angle emphasizing the tilt in the epi-layer, the inset shows the dependence of the measured tilt angle as a function of the azimuth angle (b); (335) RSM taken at the azimuth angle equal to 90°, i.e., corresponding to the minimum tilting effect (c). Solid line denotes the location of 335 reflexes corresponding to fully relaxed material with lattice parameter gradually increasing from that of GaSb. Dashed line denotes the location of 335 reflexes of the material with further increasing native lattice parameter but grown pseudomorphically to the top of fully relaxed section.

in the (335) RSM corresponds to the transition from the strain relaxed to the pseudomorphic section of the graded buffer. For illustrative purposes, the solid line corresponds to a 100% relaxed square lattice. The observed relaxation is close to 100%. After the tilt angle is accounted for, the degree of relation in the relaxed section of the graded buffer can be estimated as 95%, i.e., nearly 100%, and within our experimental error. The pseudomorphic growth of the dislocation-free topmost section of the buffer layer is apparent from the (335) scan since the reflex from the buffer layer is nearly vertical (dashed line in Figure 1(c)). The reflection from $InAs_{0.8}Sb_{0.2}$ layer is located at the turning point and on the same vertical line as the pseudomorphic section of the buffer which confirms lattice matching to the in-plane lattice constant of the graded buffer layer. The amount of strain in $InAs_{0.8}Sb_{0.2}$ layer is below 0.1%; therefore, no strain relaxation is expected. This corresponds to the absence of dislocations in the TEM images of $InAs_{0.8}Sb_{0.2}$. The reflection located above the InAsSb reflection in both the (004) and (335) RSM corresponds to the ~150 nm pseudomorphically strained auxiliary AlGaSb layer that was grown on top of the InAsSb for calibration purposes.

The surface morphology was characterized by atomic force microscopy (AFM) in tapping mode (AFM Dimension V). The cross-hatched pattern with undulation period of about 5 $\mu$m was observed in all structures. The root mean square surface roughness measured over 50 by 50 $\mu$m area was about 4–5 nm for $InAs_{0.8}Sb_{0.2}$. The surface roughness measured over 3 by 3 $\mu$m area, i.e., in between of the dips in cross-hatch pattern, was below 1 nm. Increase of Sb content led to larger peak-to-peak variation in cross-hatch pattern characterized by surface roughness up to 10 nm for $InAs_{0.56}Sb_{0.44}$ samples.

The PL and absorption spectra were measured with a Fourier-transform infrared (FTIR) spectrometer equipped with a liquid-nitrogen cooled HgCdTe detector with a cut-off wavelength of 12 $\mu$m. The PL was excited by a 970 nm laser diode and collected by reflective optics. The absorption spectra were measured for the InAsSb layers with the Sb compositions of 20% and 30% grown on GaInSb buffers. The thicknesses of $InAs_{1-X}Sb_X$ layers were 0.5 $\mu$m for the structure with X = 0.2 and 1 $\mu$m for the structure with X = 0.3. The absorbance was determined from transmission measurements with accounting for multiple reflections. The substrate of the samples with 20% and 30% Sb was thinned to 300 $\mu$m and 55 $\mu$m, respectively, to suppress the effect of the free carrier absorption in the GaSb. The PL and absorption spectra for InAsSb X = 0.2 (grown on GaInSb buffer) measured at 77 K are presented in the insets of Figure 2 together with PL spectra measured at 150 K for samples with Sb compositions of 20% and 44% grown on AlGaInSb buffers. Since FTIR without step scan mode was utilized, the thermal background and photodetector noise limited the temperature range of PL spectral measurements to below 200 K.

The energy positions of PL maxima at T = 77 K versus Sb composition X in the InAsSb layers are presented in Figure 2. The positions of PL maxima were used to determine the bowing parameter, which was found to be 0.8 eV (the

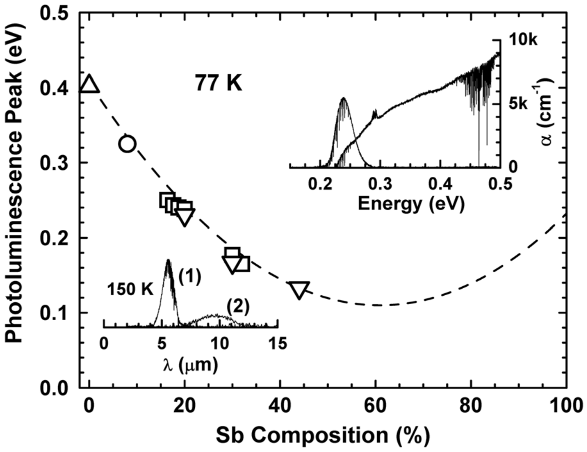

FIG. 2. Dependence of 77 K PL maxima on composition X in $InAs_{1-X}Sb_X$ epitaxial layers: InAs epilayer grown on InAs substrate (triangle), $InAsSb_{0.08}$ epilayer grown lattice matched to GaSb substrate (circle), and $InAs_{1-X}Sb_X$ epilayers grown on buffer layers InGaSb (squares) and AlGaInSb (inverted triangles) on GaSb substrate. The PL and absorption spectra for InAsSb X = 0.2 (grown on GaInSb buffer) measured at 77 K are presented in the top inset. The PL spectra measured at 150 K for InAsSb grown on AlGaInSb buffers are shown in the bottom inset. The peaks marked (1) and (2) correspond to the Sb compositions of 20% and 44%, respectively.

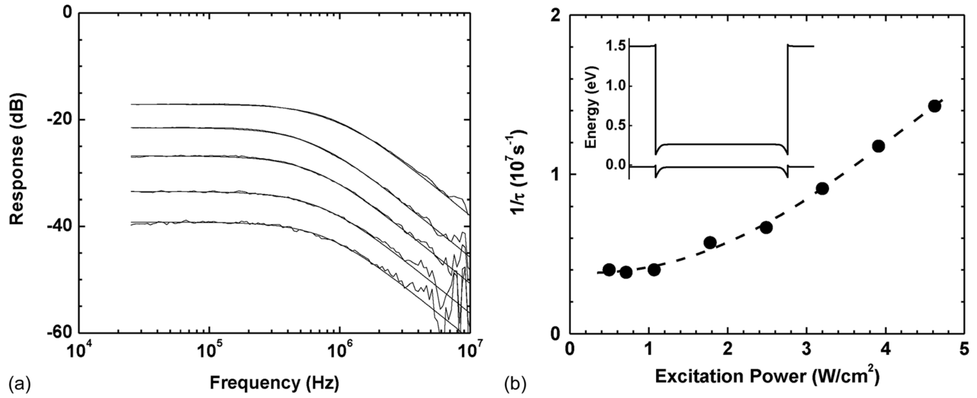

FIG. 3. Carrier lifetime measurements at T = 77 K on a 1-$\mu$m-thick InAsSb layer with a 20% of Sb, grown on an AlGaInSb buffer on a GaSb substrate. The PL responses and fits are presented for continuous wave excitation power levels of 0.8, 1, 1.4, 3, and 5 mW from bottom to top, respectively. The PL was excited at the wavelength of 1.31 $\mu$m, and the excitation area was $2 \times 10^{-3}$ cm$^2$ FWHM (a). The reciprocal carrier lifetime is plotted versus continuous–wave excitation power density (b). A schematic band diagram of the InAsSb heterostructure used for carrier lifetime measurements is shown in the inset.

dashed line in Figure 2). It is recognized that the actual energy gap for InAsSb can be lower than the energy of the PL maximum. The derived bowing value of 0.8 eV is considerably greater than that of the nearly 0.7 eV, as observed in works on InAsSb grown with various degrees of residual strain.[1]

Carrier lifetime measurements for the 1-$\mu$m thick InAsSb layer with 20% Sb grown on a AlGaInSb buffer layer on a GaSb substrate were performed at T = 77 K using a modulation response technique.[14] To minimize the effects of carrier separation on the carrier lifetime in undoped InAsSb layers, the $Al_{0.25}Ga_{0.70}In_{0.05}Sb$ barriers were doped with Be to the level of $p = 1 \times 10^{17}$ cm$^{-3}$. The dependence of the carrier lifetime on the excitation power is shown in Figure 3. Simulation of the band diagram showed that the minority holes remain confined under low excitation (inset of Figure 3(b)). The carrier lifetime was determined from the PL response to a small signal modulation of excitation in the frequency domain. The PL response spectra in a range of continuous-wave excitation power are shown in Figure 3(a). The carrier lifetime $\tau$ corresponding to the cut-off frequency ($-3$ dB point) was obtained by fitting the response in the entire frequency range to the dependence $PL_\omega \propto [1 + (2\pi f \times \tau)^2]^{-0.5}$. A 250 ns carrier lifetime under low excitation condition was measured. The excess carrier concentration was estimated to be in the range (2-4) $\times 10^{15}$ cm$^{-3}$ at the excitation power in the range of 0.5-1 W/cm$^2$.

In summary, we conclude that the technique of growth of the compositionally graded buffers (Ga(Al)InSb on GaSb substrates) with a strained but unrelaxed top layer allows the fabrication of bulk $InAs_{1-X}Sb_X$ layers (0.5–1.5 $\mu$m thick). These films have characteristics that are promising for the development of IR detectors operating within the spectral range from 5 to 12 $\mu$m. The critical element of the technology is control of the in-plane lattice constant of the topmost section of the buffer. The in-plane lattice constant of this layer must be equal to the lattice constant of $InAs_{1-x}Sb_x$ with given **X**. The unrelaxed $InAs_{1-X}Sb_X$ structures grown on top of such buffers demonstrate photoluminescence in the spectral range from 5.2 to 9.4 $\mu$m within the temperature range of 77–150 K. The carrier lifetime of $\tau = 250$ ns was obtained at T = 77 K for InAsSb with 20% Sb.

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