Extremely low surface recombination velocity in GaInAsSb/AlGaAsSb heterostructures

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Low surface recombination velocity is critical to the performance of minority carrier devices. Minority carrier lifetime in double heterostructures (DHs) of 0.53-eV *p*-GaInAsSb confined with 1.0-eV *p*-AlGaAsSb, and grown lattice-matched to GaSb, was measured by time-resolved photoluminescence. The structures were designed to be dominated by the heterointerface while minimizing the contribution of photon recycling to minority carrier lifetime. Surface recombination velocity as low as 30 cm/s for DHs was achieved. This value is over an order of magnitude lower than that reported in previous studies. © *2005 American Institute of Physics.*
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The performance of minority carrier devices such as light-emitting diodes, photovoltaics, and heterojunction bipolar transistors is sensitive to nonradiative recombination at heterointerfaces, and numerous studies aimed at minimizing surface recombination velocity have been reported for heterostructures comprised of GaAs- and InP-based III-V alloys.[1] More recently, III-V materials based on GaSb are being developed for optoelectronic devices operating in the midinfrared wavelength range.[2] For example, GaInAsSb/GaSb and GaInAsSb/AlGaAsSb heterostructures are of particular interest since these alloys show great potential for thermophotovoltaic (TPV) devices used to generate power from a thermal source.[3] It was reported that both GaSb and AlGaAsSb window layers are effective in reducing GaInAsSb surface recombination velocity.[4,5] Either of these layers was shown to improve the external quantum efficiency and open-circuit voltage V_{oc} of GaInAsSb TPV cells, which were grown by organometallic vapor phase epitaxy (OMVPE).

From both band-structure considerations and experimental results, however, there appears to be an advantage of AlGaAsSb over GaSb as the window layer. Surface recombination velocity of *p*-GaInAsSb doubly capped with *p*-AlGaAsSb layers was reported to be 720 cm/s compared to 1140 cm/s for GaSb.[6] This lower value was attributed to a more advantageous band alignment between GaInAsSb and AlGaAsSb. The valence-band offset between 0.53-eV $Ga_{0.84}In_{0.16}As_{0.14}Sb_{0.86}$ and 1-eV $Al_{0.25}Ga_{0.75}As_{0.02}Sb_{0.98}$ is almost zero, while the GaInAsSb/GaSb interface is a staggered type-II band alignment. The former alignment minimizes carrier trapping at the heterointerface, and consequently, these heterostructures should have a comparatively lower surface recombination velocity, as was observed.[6]

Furthermore, device performance of TPV structures with an AlGaAsSb window is slightly higher compared to those with a GaSb window. GaInAsSb/AlGaAsSb/GaSb TPV cells exhibit peak internal quantum efficiency and fill factor values exceeding 94% and 70%, respectively.[7,8] These values, which are approaching theoretical limits, are achieved for structures grown with either type of window layer. The highest reported value of V_{oc}, however, is 0.33 V and was measured for devices with an AlGaAsSb window.[7] Since this value is only about 85% of the theoretical limit, further increases in V_{oc} should be possible. In principle, if the interface between GaInAsSb and AlGaAsSb can be improved with a lower surface recombination velocity, then V_{oc} should increase, and thus improve overall TPV cell performance.

While previously reported SRV values of ~720 cm/s are reasonably low,[6,7] significantly better values of over an order of magnitude lower have been reported for GaAs-based materials.[1] This work reports high interfacial quality of GaInAsSb/(Al)Ga(As)Sb double-heterostructures (DHs), and the achievement of surface recombination velocity as low as 30 cm/s. This was achieved by optimizing the heterointerface switching sequence, which is particularly critical for Sb-containing alloys.[9–13]

p-AlGaAsSb/*p*-GaInAsSb/*p*-AlGaAsSb DHs with varying GaInAsSb thicknesses were grown by OMVPE with trimethylindium, triethylgallium, tritertiarybutylaluminum, tertiarybutylarsine, and trimethylantimony (TMSb) as organometallic precursors, and dimethylzinc as the *p*-type doping source.[14–16] The layers were nominally lattice matched to (001) GaSb miscut 6° toward (1-11)B and the growth temperature was 525 °C. The layer structure, schematically shown in Fig. 1 consists of a *p*-GaSb buffer, *p*-AlGaAsSb, *p*-GaInAsSb, *p*-AlGaAsSb, and *p*-GaSb cap. The
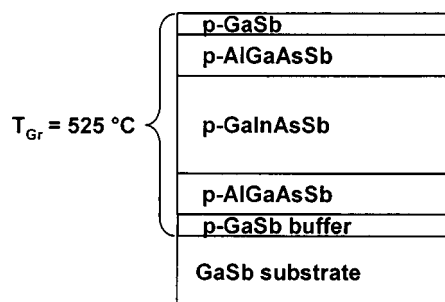

FIG. 1. Schematic AlGaAsSb/GaInAsSb/AlGaAsSb double heterostructure for measurement of minority carrier lifetime.
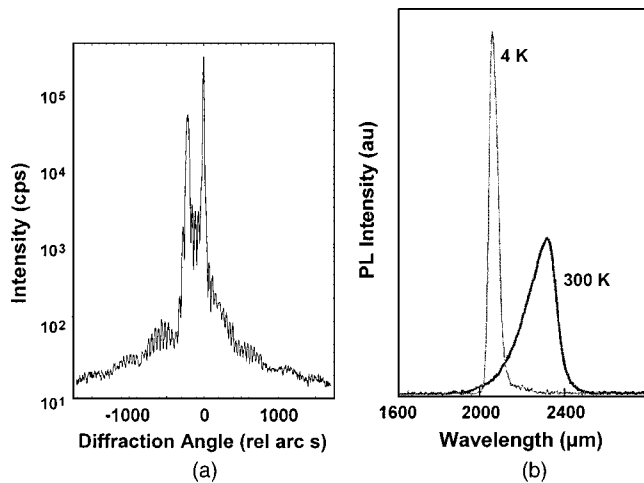
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FIG. 2. (a) High-resolution x-ray diffraction and (b) photoluminescence of AlGaAsSb/GaInAsSb/AlGaAsSb double heterostructure.
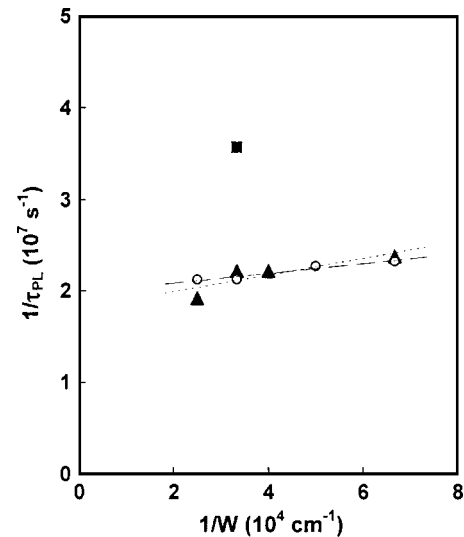

FIG. 3. Inverse PL lifetime vs inverse GaInAsSb thickness of GaInAsSb/(Al)Ga(As)Sb double heterostructures: (▲) Al content of AlGaAsSb is 0.2; (○) Al content of AlGaAsSb is 0.25; and (■) GaSb capping layers.

p-GaInAsSb active layer was doped at 2×10^{17} cm^{-3}, and GaInAsSb thickness was varied from 0.15 to 0.4 μm. The alloy composition of GaInAsSb corresponds to a 300 K photoluminescence (PL) peak emission at about 2.3 μm (0.53 eV). In contrast to previous reports,[6,7] AlGaAsSb was grown at the same temperature of GaInAsSb at 525 °C, even though the morphology of AlGaAsSb was reported to be better when grown at 550 °C.[16] The switching sequence used previously for GaInAsSb/AlGaAsSb structures decreased PL efficiency, and it is likely that those long interruption times introduced interface states where minority carriers recombine nonradiatively.[10] The V/III was 4.4, which is greater than V/III=3.2–3.4 for AlGaAsSb grown at 550 °C.[16] Nominally undoped AlGaAsSb is p-type with hole concentration dependent on Al content.[16] Two sets of DHs were grown with different Al content in AlGaAsSb. The Al is 0.2 or 0.25, which yields a hole concentration in the range $1-2 \times 10^{17}$ cm^{-3}.

The structural quality of epitaxial layers was characterized by high-resolution x-ray diffraction (HRXRD). Optical quality was evaluated by 300 and 4 K PL and measurement of minority carrier lifetime by time-resolved PL (TRPL). The samples were optically excited by a 0.98-μm diode laser and the excess carrier concentration ranged approximately from 10^{16} to 10^{17} cm^{-3}. The PL emission was detected by an HgCdTe photodiode, as previously described.[6] The overall time resolution of the detection system is less than 5 ns.

Figures 2(a) and 2(b) show the HRXRD and PL results, respectively, of a typical AlGaAsSb/GaInAsSb/AlGaAsSb DH. The HRXRD curve exhibits a number of intense and sharp satellite peaks, which is indicative of high structural quality and compositionally abrupt interfaces. The more closely spaced thickness fringes associated with the 0.4-μm-thick GaInAsSb are easily resolved. The 4 K PL data shown in Fig. 2(b) shows a full-width at half-maximum (FWHM) of 9.2 meV. Similar structures that had undoped GaInAsSb layers had a narrower FWHM of only ~5 meV.

Quantitative determination of interfacial quality was evaluated by analysis of minority carrier lifetime measurements to extract surface recombination velocity.[1,6] The effective lifetime was measured using time-resolved PL. This lifetime is dependent on bulk and interfacial recombination processes, and can be separated according to the equation

$$1/\tau_{PL} = 1/\tau_{BLK} + 2S/W,$$

where τ_{PL} is the lifetime measured by PL decay, τ_{BLK} is the bulk lifetime, S is the surface recombination velocity, which is assumed to be equal at the front and back heterointerfaces, and W is the active layer thickness. This approximation assumes that photon recycling effects[17] are negligible and that S is relatively small compared to the ratio of minority carrier diffusion constant D to W ($S < D/W$). These approximations are reasonable when $W < \sim 0.5$ μm.[18] Thus, S can be determined from measurements of τ_{PL} for samples with various thicknesses.

Minority carrier lifetime data measured by TRPL are shown in Fig. 3 where $1/\tau_{PL}$ is plotted as a function of $1/W$. The data for the two sets of samples with different Al content demonstrate a linear dependence, and S is determined to be about 50 and 30 cm/s for Al content in AlGaAsSb of 0.2 and 0.25, respectively. These low values are significantly smaller than the value of 720 cm/s that was previously reported for samples that were grown with interruption times on the order of minutes and similarly doped active layers.[6] That value of S did not account for photon recycling and was determined from samples with active layer thicknesses greater than 1 μm. When photon recycling is factored into the estimation of S, it is only reduced by about 200 cm/s. SIMS analysis of bulk AlGaAsSb layers indicated that O impurity levels are $\sim 8 \times 10^{18}$ cm^{-3}, which is about two times higher than that measured for layers grown at higher temperatures of 550 °C. These high levels of O do not appear to have a significant negative impact on S.

Also shown in Fig. 3 for comparison is τ_{PL} for a DH sample with p-GaSb capping layers. This value of τ_{PL} is about 40% lower than that measured for the structure with similar thickness and AlGaAsSb capping layers. This reduction is likely related to a higher S value, although it cannot be determined from this single point. The lower lifetime for GaSb capped structures is consistent with previous observations,[6] and is attributed to accumulation of electrons at the GaInAsSb/GaSb type-II interface and to thermionic

emission resulting from lower electron confinement of GaSb confining layers.[19]

In summary, surface recombination velocity in AlGaAsSb/GaInAsSb/AlGaAsSb DHs is as low as 30 cm/s. This value was determined from minority carrier lifetime measurements by PL decay, and is over an order of magnitude lower than values reported previously. Since the highest performing Sb-based TPV cells to date were fabricated from structures in which GaInAsSb and AlGaAsSb layers had SRV $\sim$720 cm/s,[6] and were grown with long interruption times,[7] it seems reasonable to expect further increases in V_{oc} in TPV devices with significantly lower SRV, as reported in this study.

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