Reduction of interfacial recombination in GaInAsSb/GaSb double heterostructures

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Minority carrier lifetimes in 0.55 eV band-gap GaInAsSb epitaxial layers that are double capped with GaSb or AlGaAsSb layers were determined using time-resolved photoluminescence. It was found that accumulation of electrons at the p-doped GaInAsSb/GaSb type-II interface contributes significantly to the interfacial recombination velocity S, which was measured to be 3100 cm/s. The use of heavily p-doped GaSb cap layers was proposed to eliminate the potential well of electrons and barrier for holes at the interface. Increasing the GaSb cap doping level from 1×10^{16} to 2×10^{18} cm^{-3} resulted in a 2.7 times reduction of S down to 1140 cm/s. The smallest value of S was determined to be 720 cm/s, which was obtained for structures with AlGaAsSb cap layers that have no valence band offset. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1530743]

Epitaxial GaInAsSb alloys grown lattice matched to GaSb are attractive materials for thermophotovoltaic (TPV) devices that operate in the band gap range of 0.5–0.6 eV.[1–6] Using modern growth technology, it is possible to obtain high quality epitaxial layers with large bulk lifetimes. At the same time, interfacial recombination contributes notably to the overall recombination rate and can be important even in efficient TPV cells.[7] Previous studies have shown that the interfacial recombination velocity S could be significantly reduced by incorporating a passivation (cap) layer on the emitter surface.[3,8] This layer isolates minority carriers from the front surface of the device and increases the conversion efficiency.

By producing a potential barrier for minority electrons, the cap layer should create no obstacle to majority hole transport to maintain low series resistance. It was shown that passivation with either GaSb or AlGaAsSb improves the external quantum efficiency and open-circuit voltage of GaInAsSb TPV diodes.[2,3,6] While the AlGaAsSb/GaInAsSb interface can be grown with no valence band offset, the AlGaAsSb cap is more complicated to grow. At the same time, GaSb on GaInAsSb creates a staggered (type II) band alignment that leads to the separation of holes and electrons at the p-type interface in two adjacent potential wells. The possibility of electron accumulation in TPV devices was pointed out in Ref. 3. The corresponding depletion of holes in p-GaInAsSb due to a GaSb cap can contribute to device series resistance. In this letter we show that electron accumulation at the GaInAsSb/GaSb interface contributes significantly to S and degrades the overall minority carrier lifetime. The use of a heavily doped p-GaSb cap layer is proposed to reduce the negative effect of the double potential well. Estimations have shown that near flat-band conditions can be achieved with p-doping concentrations of 2×10^{17} and 2×10^{18} cm^{-3} in the GaInAsSb and GaSb cap layers, respectively.

Measurement of photoluminescence (PL) decay after a short excitation pulse is a standard method of lifetime determination in direct band gap materials. This principle, widely used for wide-band gap structures,[9] has not been practical in the midinfrared (IR) wavelength range due to the lack of photodetectors with fast response and sufficient detectivity. A common but rather complicated way by which to achieve temporal resolution in the mid-IR is by exploiting nonlinear optical effects, such as PL wavelength upconversion followed by a photon counting system[10] or by a pump–probe method that measures transmission decay.[11] As an alternative method, a radio-frequency photoreflectance (rf PR) technique was proposed.[12] In fact, there are very few recombination lifetime studies of GaInAsSb materials. The rf PR technique was utilized to measure the photoconductivity decay in double-capped structures.[13,14]

Recently, extended InGaAs and HgCdTe mesa photodiodes for the mid-IR wavelength range have become available. These diodes are capable of providing the required time resolution and detectivity at a wavelength of 2.3 μm. With these detectors it is now possible to use the direct and reliable PL technique in the mid-IR region.

P-GaInAsSb double-capped heterostructures were specially grown to investigate the effects of the capping layer material and doping level on electron lifetimes. The GaInAsSb double heterostructures (DHs) consisted of a GaInAsSb active narrow-gap (0.55 eV) layer and either GaSb or AlGaAsSb cap layers. All DHs were grown lattice matched to GaSb substrates by organometallic vapor phase epitaxy.[6] The GaInAsSb layer thickness was varied from 1.2 to 5 μm and was p doped with Zn at 2×10^{17} cm^{-3}. The GaSb cap layers were 50 nm thick and were either nominally undoped

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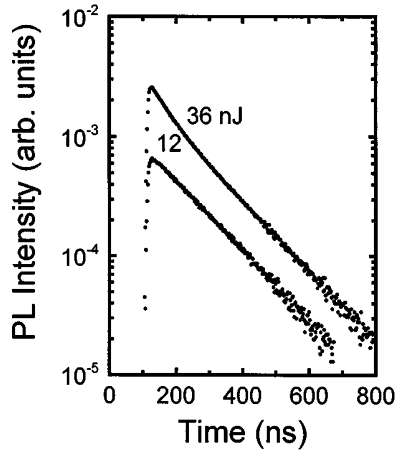

FIG. 1. Photoluminescence decay of 5-μm-thick GaInAsSb with AlGaAsSb cap layers at excitation levels of 12 and 36 nJ. The doping in the active and cap layers was 2×10^{17} cm^{-3}.

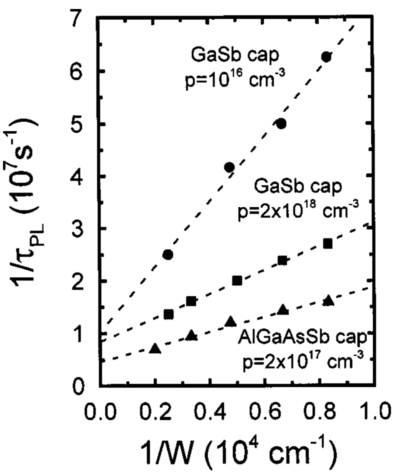

FIG. 2. Inverse photoluminescence decay $1/\tau_{PL}$ vs inverse structure thickness $1/W$ for three sets of GaInAsSb structures doped to 2×10^{17} cm^{-3} with different cap layers: undoped GaSb with $p=1\times10^{16}$ cm^{-3}; p-doped GaSb with $p=2\times10^{18}$ cm^{-3}; and AlGaAsSb with $p=2\times10^{17}$ cm^{-3}.

with $p=1\times10^{16}$ cm^{-3} or p doped with Zn at 2×10^{18} cm^{-3}. The AlGaAsSb cap layers were 20 nm thick and nominally undoped with $p=2\times10^{17}$ cm^{-3}. For structures with AlGaAsSb cap layers, a 2.5-nm-thick GaSb layer was grown between the GaInAsSb and AlGaAsSb layers to improve the interfacial quality.

The nonequilibrium carriers were excited by a 0.98 μm diode laser driven by a pulsed current source with fall time of 2 ns. The laser pulse energy was in the range of 4–40 nJ, which corresponds to an excess carrier concentration ranging approximately from 10^{16} to 10^{17} cm^{-3}. Absorption in the thin GaSb window layer was estimated to be 12%. The PL emission was collected using an ellipsoidal reflector with the DH and detector placed at the two focal points of the ellipsoid. A small excitation area allowed exploration of the homogeneity of the structure parameters. The overall time resolution of the detection system was better than 5 ns. The signal was digitized at a rate of 5 Gsamples/s and averaged in a computer.

Figure 1 shows typical measured PL decay curves for two different excitation levels. The PL response shows an unvarying time constant within two orders of carrier concentration, which is a critical aspect for reliable lifetime determination. Decay with a single time constant is indicative of a monomolecular type of recombination. In this regime, the effective lifetime is a material characteristic. At the higher excitation level, the PL response demonstrates transition to bimolecular recombination.

When S is small, namely, $S \ll D/W$, where W is the active layer thickness and D is the minority carrier diffusion coefficient, the temporal response does not depend on carrier diffusion, and it is possible to separate the bulk and surface recombination phenomena according to the equation[15] $1/\tau_{PL} = 1/\tau_{bulk} + 2S/W$, where τ_{PL} is the effective lifetime measured by PL decay; τ_{bulk} is a bulk lifetime; and S is assumed to be equal at both the front and back heterointerfaces. The $1/\tau_{PL}$ vs $1/W$ measured reveals a linear dependence with slope $2S$ and offset $1/\tau_{bulk}$. A more rigorous model would include photon recycling, an effect whose contribution increases monotonically with W. Photon recycling reduces the radiative part of the recombination rate due to reabsorption of the photons emitted in the active layer.[16] Estimations have shown that this effect leads to only a minor correction of S, and therefore, the above equation was used in the present analysis.

Values of τ_{PL} were obtained by a fit of the measured PL decay. Figure 2 shows the dependence of $1/\tau_{PL}$ on $1/W$ for three different GaInAsSb/(Al)Ga(As)Sb DHs. All three plots demonstrate a linear dependence consistent with the model. The structures with undoped ($p=1\times10^{16}$ cm^{-3}) GaSb cap layers resulted in the highest S of 3100 cm/s. In structures with p-GaSb cap layers doped to 2×10^{18} cm^{-3}, S was substantially smaller at 1140 cm/s. Thus, the use of a heavily doped cap layer makes it possible to suppress the interfacial recombination by a factor of 2.7. The smallest value of S of 720 cm/s was obtained for structures with AlGaAsSb cap layers.

Calculations performed for the p-GaInAsSb/p-GaSb interface show that heavily doped p-GaSb can compensate the band bending effect to achieve near flat-band conditions [Fig. 3(a)]. The effect of electron accumulation at the interface [Fig. 3(b)] can be reduced by doping the GaSb cap.

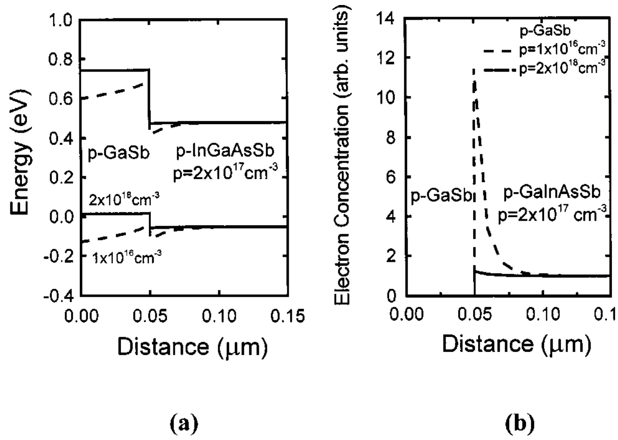

FIG. 3. Calculation of (a) the band diagram and (b) the minority carrier distribution near the GaInAsSb/GaSb interface for GaInAsSb with $p=2\times10^{17}$ cm^{-3} and two different doping concentrations in the cap layer: dashed line: undoped GaSb cap with $p=1\times10^{16}$ cm^{-3}; solid line: GaSb cap with $p=2\times10^{18}$ cm^{-3}.

Thus, the recombination rate for electrons will be essentially suppressed. In the case of AlGaAsSb cap layers, there is no valence band offset and the S observed was 1.6 times smaller compared to in heterostructures with a heavily p-doped GaSb cap.

High-performance GaInAsSb/(Al)Ga(As)Sb TPV devices demonstrate an internal quantum efficiency of close to 100% but the open-circuit voltage leaves some room for improvement.[6] Under open-circuit conditions photoelectrons remain in the emitter for a much longer time compared to in the short-circuit case and the probability for them to recombine at the interface increases.[7] Therefore interface recombination suppression is beneficial in terms of maximizing the voltage factor and can be an essential element of TPV cell design.

In conclusion, PL decay measurements of electron lifetimes in GaInAsSb/GaSb type II DHs were reported. The data indicate that interfacial recombination is sensitive to the doping level in p-GaSb cap layers. A heavily doped p-GaSb cap layer is effective in reducing the recombination velocity at the GaSb/GaInAsSb interface.

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