LM-04K032
May 11, 2004

Effects of Radiative Recombination and Photon Recycling on Minority Carrier Lifetime in Epitaxial GaInAsSb Lattice-matched to GaSb

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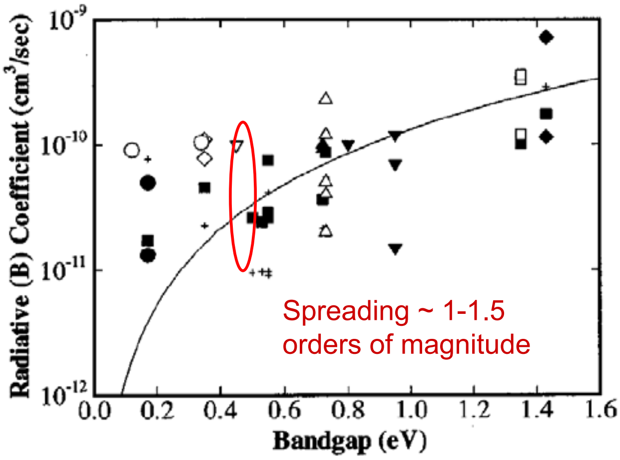
12th International Conference on Metal Organic Vapor Phase Epitaxy

Radiative coefficient (B) is a fundamental recombination parameter which is of importance for a variety of optoelectronic minority carrier devices. Radiative recombination was comprehensively studied for wide-bandgap III-V compounds, while for 0.5-0.6 eV materials experimental data are quite limited and demonstrate significant spreading.

Here we report excess carrier lifetime in isotype double heterostructures (DHs) of 0.54-eV p-GaInAsSb capped with p-AlGaAsSb, and grown lattice-matched to GaSb. Lifetime was measured by time-resolved photoluminescence (dynamic lifetime) as well as by optical response to sinusoidal excitation (static lifetime). Wide range of GaInAsSb layer thickness was used to separate contributions from interface and radiative recombination processes. Radiative coefficient and recombination velocity at GaInAsSb/AlGaAsSb heterointerface were determined. Temperature dependence of lifetime demonstrated significant contribution of radiative effects to the total recombination rate.

This work was done in collaboration with MIT Lincoln Laboratory and Lockheed Martin Corporation.

Data review on radiative recombination coefficient (B) for III-V compounds (T=300 K)



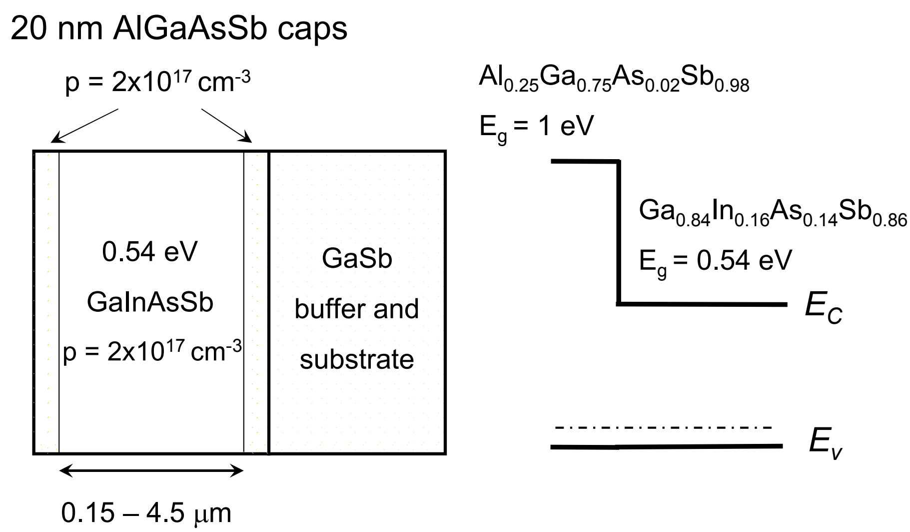
For 0.5-0.55 eV materials:

B ~ 10^{-10} - 10^{-11} cm^3/s

G. W. Charache et al., J.Appl.Phys. ***85****, 2247 (1999)*

The figure presents review of experimental and theoretical data on radiative coefficient B for III-V compounds. For 0.5-0.6 eV materials available data are quite limited and demonstrate 1-2 orders of magnitude variation. By extrapolation, the range for the values of B can be estimated as 10^{-11} – 10^{-10} cm^3/s. This uncertainty necessitates further experimental study of radiative recombination for mid-IR materials.

Double-capped isotype heterostructures



The double heterostructures were grown by organometallic vapor phase epitaxy at T=525 C. Active $Ga_{0.84}In_{0.16}As_{0.14}Sb_{0.86}$ epilayers were undoped and doped p-type at $2x10^{17}$ cm^{-3} and the thickness was varied from 0.15 to 4.5 um. The GaInAsSb alloy composition corresponds to 300 K photoluminescence peak at 2.3 um. 20-nm-thick AlGaAsSb confinement layers (caps) were nominally undoped with background hole concentration of $2x10^{17}$ cm^{-3}. Al content of 25 % was chosen to obtain almost zero valence band offset between AlGaAsSb and GaInAsSb, resulting in no band bending near the interface. This type of band alignment minimizes carrier trapping at the hetero-interface, while significant conduction band offset suppresses thermionic carrier leakage from the active area.

Static and dynamic lifetime measurements

$$\frac{dn}{dt} = G - \frac{n}{\tau}$$

Pulsed excitation:

$$G(t) = \delta(t)$$

$$n(t) = n(0)\exp\left(-\frac{t}{\tau}\right)$$

Sinusoidal excitation:

$$G(t) = G_0 + G_1\cos(\omega t)$$

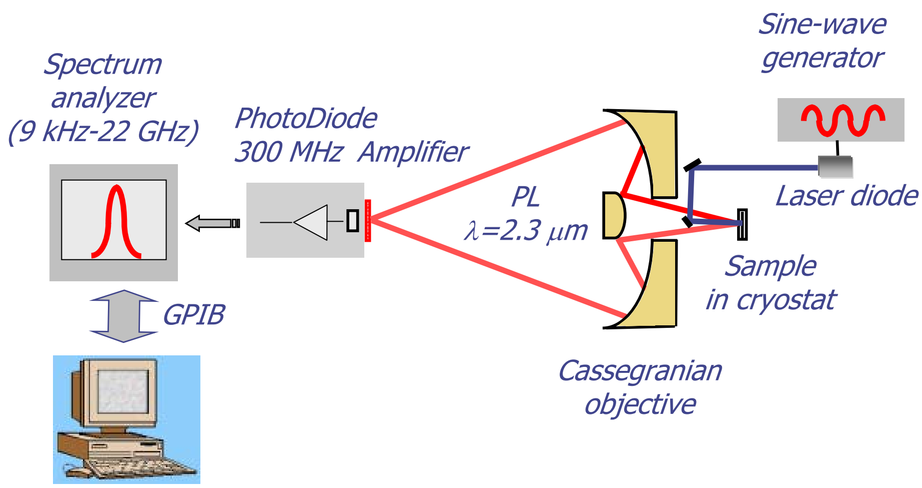
$$n(t) = n_0 + n_1\cos(\omega t - \phi)$$

$$n_1 = \frac{G_1\tau}{\sqrt{1+\omega^2\tau^2}}$$

$$\tau = 1/\omega_{-3dB}$$

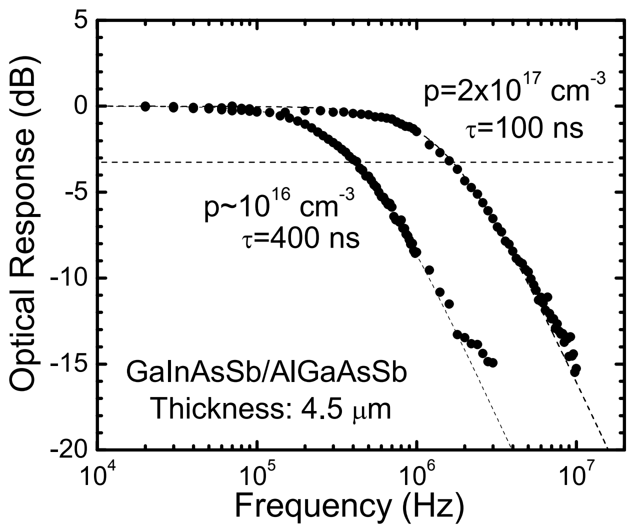
Carrier recombination lifetime was measured by time-resolved photoluminescence (dynamic lifetime) as well as by optical PL response to sinusoidal excitation (static lifetime). In the first case photoluminescence kinetics after pulsed excitation was recorded. The recombination lifetime is given by decay constant of transient PL emission. The second technique measures modulation bandwidth of optical signal with -3 dB frequency corresponding to carrier lifetime. For studied structures both techniques provide identical results. However, modulation response method can be more effective in terms of noise suppression due to narrow-band filter/amplifier at the input of detection system.

Experimental setup for optical response measurements



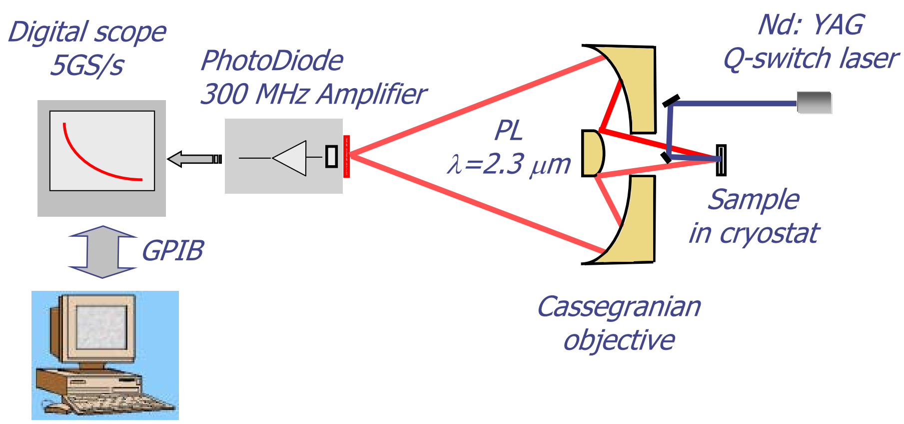
The figure shows schematic of the experimental setup for optical response measurements. Excitation source is AC modulated laser diode operating at 1.3 um. PL emission of the sample at λ=2.3 um was collected by Cassegranian reflective optics and focused to small-area IR photodiode followed by 300 MHz preamplifier. Modulation PL response was recorded by a spectrum analyzer.

Modulation photoluminescence response



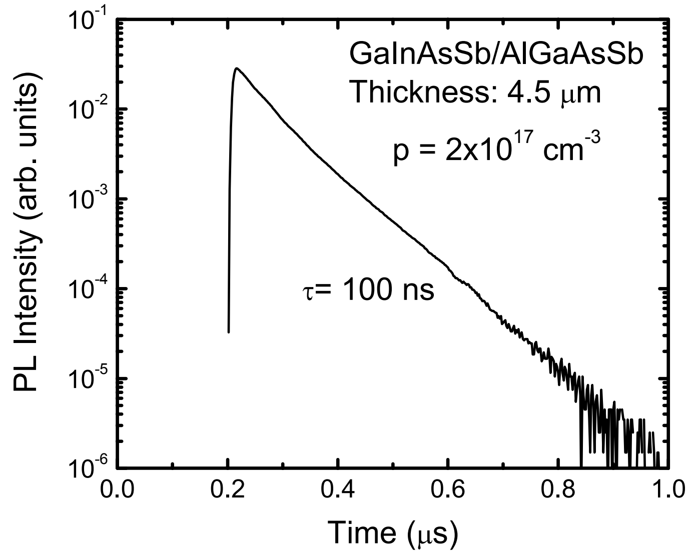
The graph presents optical responses measured in 4.5-um-thick AlGaAsSb/GaInAsSb/AlGaAsSb undoped and doped samples. PL signal in dB is plotted versus excitation source modulation frequency. -3 dB point corresponds to the frequency of 1.6 MHz which gives recombination lifetime value of 100 ns for the doped structure and 400 ns for the undoped one.

Experimental setup for time-resolved measurements



Dynamic carrier lifetime was measured by time-resolved photoluminescence. The transient IR emission was measured by a fast, small-area IR photodiode followed by 300 MHz preamplifier and visualized by the digital scope with 5 GS/s sampling rate . The non-equilibrium carriers were excited by sub-ns pulses from a passive Q-switched Nd:YAG laser. High collection efficiency was provided with reflective optics. More than 10^5 times averaging was used to achieve signal-to-noise ratio of at least two orders of magnitude required for accurate lifetime measurements.

Transient photoluminescence response

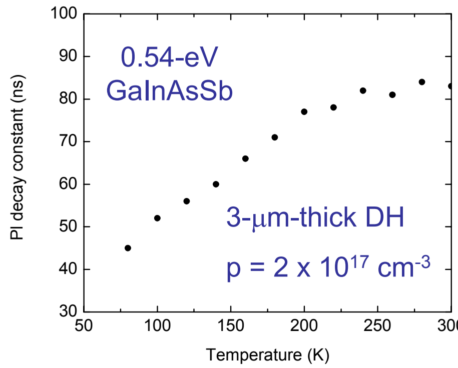


The figure shows typical transient photoluminescence response measured in 4.5-um-thick AlGaAsSb/GaInAsSb/AlGaAsSb structure. The PL intensity was recorded within several orders of minority carrier concentration which is critical for reliable lifetime determination. Dynamic lifetime of

100 ns obtained by TRPL corresponds to static lifetime measured by optical response.

Lifetime Temperature dependence

$$1/\tau_{PL} = Bp/\phi + 1/\tau_{NR}$$



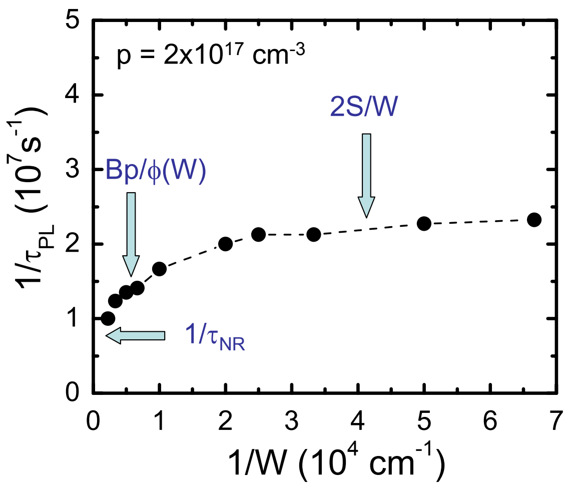
In structures where radiative recombination dominates, total recombination rate should decrease with T. The graph shows lifetime data for 3-um-thick AlGaAsSb/GaInAsSb/AlGaAsSb DH with p=2 x 10^17 1/cm^3 measured in the temperature range from 80 to 300 K. Increase of PL decay time with temperature indicated significant role of radiative recombination.

Recombination lifetime vs. GaInAsSb layer thickness

PL decay time in p-doped material:

$1/\tau_{PL} = 1/\tau_{NR} + Bp/\phi(W) + 2S/W$

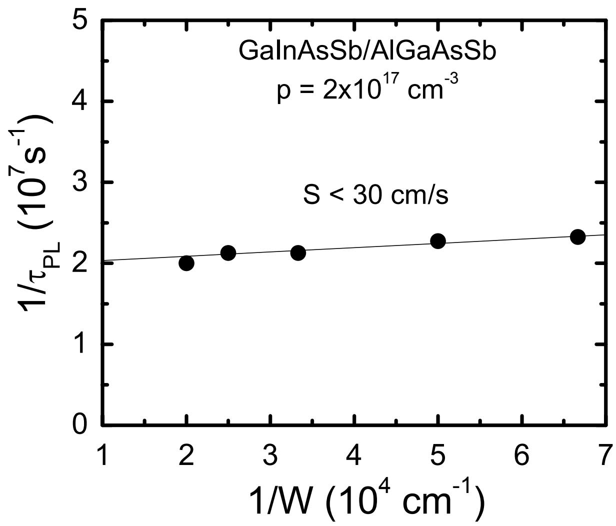
B - radiative coefficient
ϕ - photon recycling factor
S - interface recombination velocity
W - GaInAsSb layer thickness



Using wide range of GaInAsSb layer thickness interface and radiative recombination effects can be separated

The graph plots inverse PL decay constant ($1/\tau_{PL}$) versus inverse GaInAsSb layer thickness (1/W) at room temperature. There are two reasons for increase of lifetime with sample thickness: surface/interface recombination effects (described by the term 2S/W in the expression above) and thickness-dependent radiative bulk lifetime due to photon recycling effect (term $Bp/\phi(W)$). For interface recombination dominated structures ($2S/W >> Bp/\phi$), ($1/\tau_{PL}$) increases linearly with (1/W). We observed, however, that lifetime thickness dependences are essentially different for thin (W < 1 um) and thick (W >1 um) samples. Relatively slow increase of ($1/\tau_{PL}$) with (1/W) can be explained by small value of S. Therefore, inverse PL decay time for structures with W >1 um can be expressed by $1/\tau_{NR} + Bp/\phi(W)$. In order to extract radiative coefficient B from the lifetime data, recycling factor should be calculated.

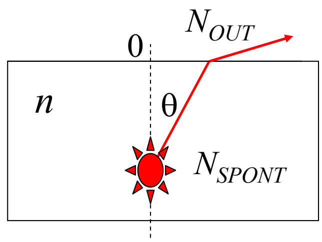
Recombination velocity at AlGaAsSb/InGaAsSb heterointerface



The figure plots inverse PL decay constant ($1/\tau_{PL}$) vs. inverse GaInAsSb epi-layer thickness (1/W) for thin (W < 1 um) samples. Since bulk recombination lifetime (τ_{bulk}) and "interface recombination" lifetime (2S/W) are both thickness dependent, precise determination of S is not straightforward. However, one can estimate S from the slope of ($1/\tau_{PL}$) vs. (1/W) for thin DHs since those DHs are the most sensitive to interface recombination and the least sensitive to photon recycling. This procedure somewhat overestimates S because it ignores thickness dependence of $\tau_{bulk.}$

The resulted upper limit for the S is presented in the graph. The relatively small value of interface recombination velocity can be attributed to good confinement properties of AlGaAsSb capping layers and low recombination velocity at the lattice-matched interface.

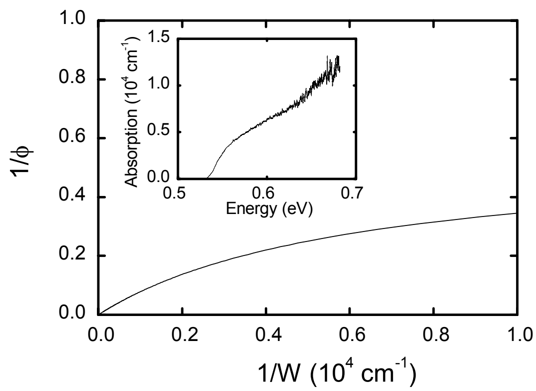
Photon Recycling Factor



$$1/\tau_{Rad} = Bp/\phi_{ph}(W)$$

$$\phi_{ph} \approx \frac{N_{SPONT}}{N_{OUT}} = \frac{\iiint S(\nu)\, d\nu\, d\theta\, dz}{\iiint S(\nu) T(\theta) e^{-\frac{\alpha(\nu)\cdot z}{\cos\theta}}\, d\nu\, d\theta\, dz}$$

P.Asbeck, J.Appl.Phys. 48, p.820 (1977)

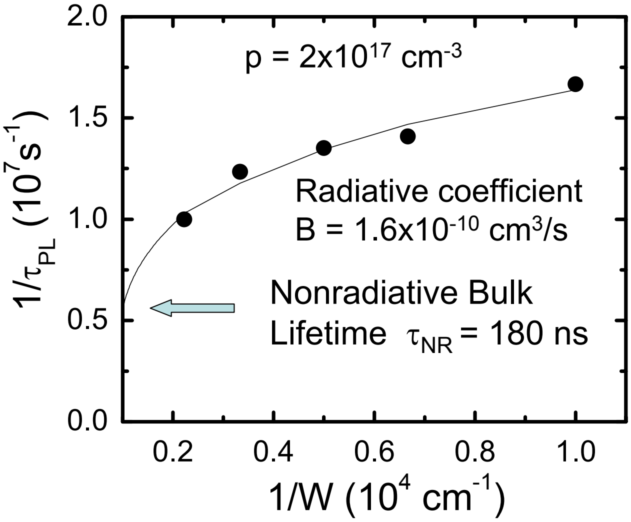


Photon recycling factor for 0.54-eV GaInAsSb DH was calculated using approach similar to that reported by Asbeck (JAP, 1977). This model does not take into account effect of multiple reflection propagation of photons, which is a reasonable approximation for samples with

W > 1 um. The graph presents inverse photon recycling factor (1/ϕ) as a function of inverse GaInAsSb active layer thickness (1/W). The measured fundamental absorption edge for GaInAsSb is shown in the inset.

Radiative recombination coefficient for 0.54 eV p-GaInAsSb at T=300 K

$$1/\tau_{PL} = 1/\tau_{NR} + Bp/\phi(W)$$



Having photon recycling factor ϕ calculated, lifetime data for 0.54 eV GaInAsSb were fitted by $1/\tau_{NR} + Bp/\phi(W)$, using nonradiative bulk lifetime τ_{NR} and radiative coefficient B as parameters. The best fit was achieved with τ_{NR} = 180 ns and B = $1.6\text{x}10^{-10}$ cm^3/s.

Summary

- Recombination lifetime in double heterostructures of 0.54-eV p-GaInAsSb confined with p-AlGaAsSb and grown lattice matched to GaSb were measured both by time-resolved photoluminescence and optical response to sinusoidal excitation.
- Recombination velocity at AlGaAsSb/GaInAsSb heterointerface was found to be as low as 30 cm/s.
- Radiative recombination coefficient B = 1.6×10^{-10} cm^3/s at T=300 K was determined for 0.54 eV p-type GaInAsSb.

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Recombination velocity at AlGaAsSb/GaInAsSb heterointerface was found to be as low as 30 cm/s.

Radiative recombination coefficient B = 1.6x10-10 cm3/s at T=300K was determined for 0.54 eV p-type GaInAsSb.