Minority carrier lifetime studies of narrow bandgap antimonide superlattices

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ABSTRACT

In this study optical modulation response and photoluminescence spectroscopy were used to study mid-wave Ga-free InAs/InAsSb superlattices. The minority carrier lifetimes in the different samples varied from 480 ns to 4700 ns, partly due to different background doping concentrations. It was shown that the photoluminescence intensity can be used as a fast non-destructive tool to predict the material quality. It was also demonstrated that it is crucial to use a low excitation power in the photoluminescence measurements in order to get a good correlation between the photoluminescence intensity and the minority carrier lifetime.

Keywords: photoluminescence, heterostructure, infrared, superlattice, minority carrier lifetime

1. INTRODUCTION

The lifetime of minority carriers is a key parameter that defines both the dark current and quantum efficiency of photodetectors. Among the detector materials currently used for mid wave infrared (IR) detectors, HgCdTe and InSb have the longest lifetimes (in the order of 10μs) [1,2] while InAs has a much shorter lifetime (~300ns) [3]. Achievement of a long lifetime material is an important task for superlattice detector development that will advance the current state-of-the-art technology and will enable high performing detectors and focal plane arrays. Recently, lifetimes up to 9 μs have been demonstrated in Ga-free mid-wave InAs/InAsSb superlattices, which makes them promising candidates as IR detector material [4]. The long lifetime is partly due to a significant increase in the Shockley Read Hall lifetime as compared to Ga-containing superlattices [5,6]. Another crucial factor is the low background doping concentration that has been reported for these superlattices. To enable accurate monitoring of the material quality and background doping, different optical and electrical characterization methods can be used, such as photoluminescence (PL) to get information about the band gap and the material quality (from PL intensity and full-width-half-max), optical modulation response to extract the minority carrier lifetime and capacitance measurements for background doping.

In this paper, three mid-wave superlattices will be studied using these different characterization techniques. We will compare the information obtained from spectral PL measurements with minority carrier lifetime measurements. It will be shown that PL measurements alone can give sufficient information about the quality of the epi-grown material, however, the excitation power used in the PL measurements is critical for obtaining a correct measure of the material quality and prediction of the minority carrier lifetime.

2. EXPERIMENTAL DETAILS

2.1 Material

Three different not intentionally doped mid-wave InAs/$InAs_{0.55}Sb_{0.45}$ superlattices grown on GaSb wafers were studied. The samples were grown at different occasions during the growth cycle of the MBE and consequently had different background doping levels. The background doping levels were estimated from capacitance voltage measurements to ~1×10^{16} cm^{-3} and ~4×10^{14} cm^{-3} for sample A and C, respectively, while the background doping in sample B was estimated to 1.5×10^{15} cm^{-3} using a PL technique [5].

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2.2 Photoluminescence measurements

Spectral PL measurements were carried out at 77 K using a Bruker IFS-V Fourier transform (FT) spectrometer. Investigated samples were mounted on the cold finger of a liquid flow cryostat with the temperature controlled by a Lakeshore temperature controller. A laser diode (emission wavelength 643 nm) with both continuous wave (CW) and sine-wave modulation was used as excitation source. For the spectral measurements, the magnitudes of the sine-wave modulation (P_1) and CW excitation powers (P_0) were varied from 0.375 mW to 15 mW, resulting in peak to peak intensities between 0.75 mW and 30 mW. The step-scan mode of the FT spectrometer was utilized, combined with lock-in technique to improve the signal to noise ratio and to achieve a reliable way to separate the background radiation from the PL emission. The PL signal was detected by a cooled HgCdTe detector.

2.3 Lifetime measurements

The PL frequency response was studied by varying the frequency of the excitation source from 50 kHz to 5 MHz while the PL intensity was recorded. A 643 nm laser source with a CW excitation power P_0 and a modulated excitation power P_1 was used to excite carriers in the material. The laser excitation gave rise to the excess carrier density given in equation (1), where τ is the recombination carrier lifetime and ω is the angular frequency [7].

$$\Delta n = P_0\tau + \frac{P_1\tau}{\sqrt{1+\omega^2\tau^2}}\cos(\omega t - \phi) \tag{1}$$

In the frequency response measurements, the CW- and the modulated excitation powers were generating excess carrier densities less than or approximately equal to the doping density and the modulated excitation power, P_1, was kept much smaller than P_0. The laser was focused to an area of $2.5\text{x}10^{-4}$ cm^{-2}. The generated PL signal was collected by reflective optics and detected by a HgCdTe detector and a lock-in amplifier, both with bandwidths of 200 MHz.

The minority carrier lifetime is mainly influenced by the radiative lifetime (τ_R), the Shockley Read Hall lifetime (τ_{SRH}) and the Auger lifetime (τ_{Auger}) as given by equation (2) [8].

$$\frac{1}{\tau} = \frac{1}{\tau_{SRH}} + \frac{1}{\tau_R} + \frac{1}{\tau_{Auger}} \tag{2}$$

When excess carriers are present and the excess carrier density, n_e, is not negligible as compared to the doping density, the effective radiative lifetime of the material varies as in equation (3) and the Auger lifetime will vary as in equation (4) for an n-type sample [9].

$$\frac{1}{\tau_R} = \frac{B}{\phi}(n_0 + n_e) \tag{3}$$

$$\frac{1}{\tau_{Auger}} \approx C(n_0 + n_e)^2 \tag{4}$$

In these equations B is the radiative recombination coefficient, ϕ is the photon recycling coefficient, n_0 is the background carrier concentration and C is the Auger recombination coefficient.

3. RESULTS

3.1 Minority carrier lifetime

The minority carrier lifetime of the three different samples were obtained using an optical modulation response technique. Frequency response curves for the samples were measured at different CW excitation powers, while keeping the modulation excitation power approximately constant (Figure 1). For each CW excitation power, the frequency response curve was fitted to the theoretical expression of the PL frequency response in equation (5) [7].

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$$I_{PL}(\omega) \propto \frac{P_1 \tau}{\sqrt{1+\omega^2\tau^2}} \tag{5}$$

, with the recombination lifetime as one of the fitting parameters. The deduced inverse recombination lifetime was then plotted as a function of the excess carrier density (estimated using Equation (1)), see insets in figure 1. By extrapolating the inverse recombination lifetime to zero excess carrier density, the minority carrier lifetimes were obtained.

The resulting minority carrier lifetimes are presented in table 1 alongside with the background doping concentrations of the superlattices. This shows a large spread of minority carrier lifetimes from the different samples from 480 ns to 4700 ns. This can partly be explained by different background doping concentrations in the samples. Radiative lifetime which is dominating in these superlattices is inversely proportional to the background doping level [5].

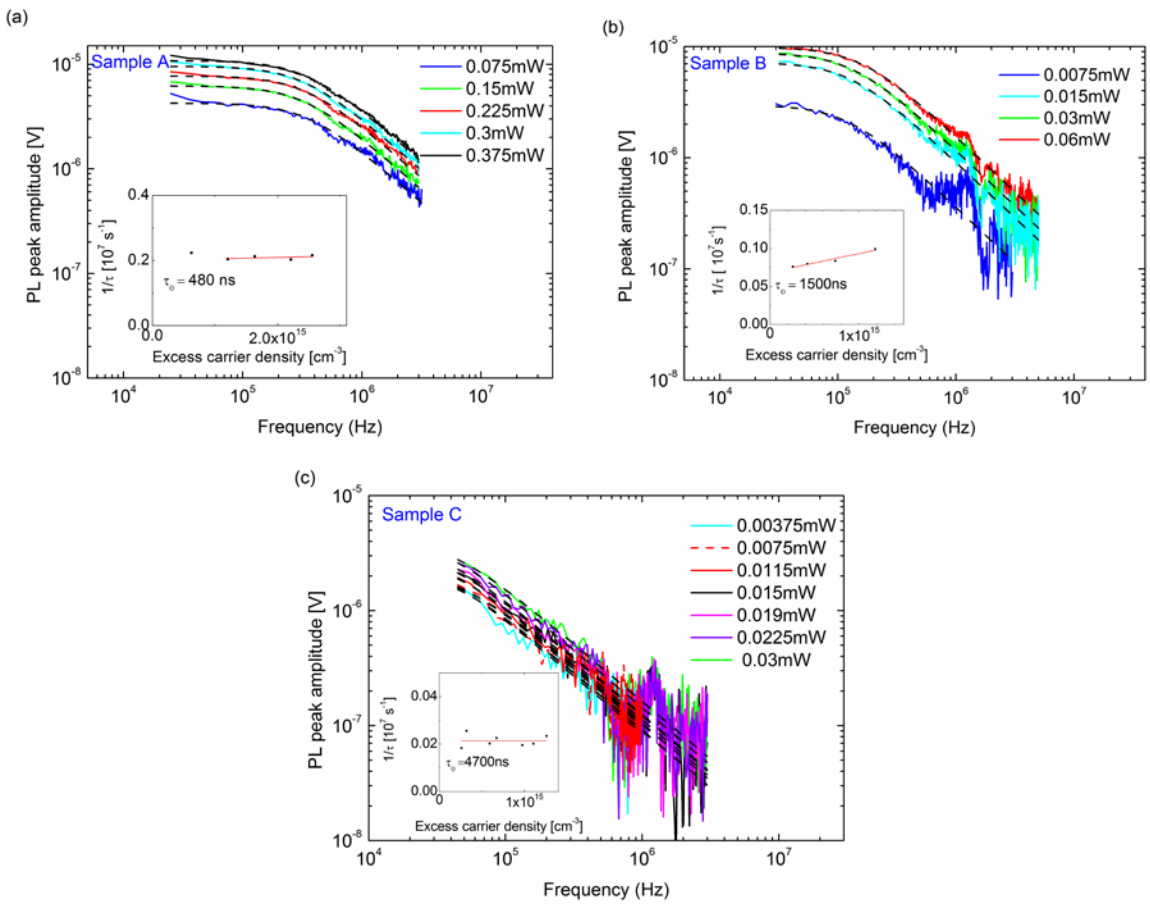

Figure 1. PL frequency response curves of three InAs/InAsSb superlattices: (a) Sample A, background doping ~ 1E16 cm^{-3} (b) Sample B background doping ~ 1.5E15 cm^{-3} and (c) Sample C, background doping ~4E14 cm^{-3}. For each frequency response curve the lifetime is extracted by fitting of the curves to equation (2) and in the insets of each figure the inverse lifetimes are plotted versus the excess carrier density. By extrapolating the inverse lifetime to zero excess carrier density, the minority carrier lifetimes are approximated to be 480 ns, 1500 ns and 4700 ns for Sample A, B and C, respectively.

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Table 1. Comparison of minority carrier lifetimes, PL intensities and background doping concentrations of three InAs/InAsSb superlattices.

Sample	Lifetime [ns]	Lowest mod. exc. power, P_1 [mW]	PL intensity, I_{PL} @ 50kHz	Normalized PL intensity, I_{PL}/P_1	Background doping [cm^{-3}]
Sample A	**480**	**0.03**	**4.3E-6**	**1.4E-4**	**~1E16**
Sample B	**1500**	**0.003**	**2.9E-6**	**9.7E-4**	**~1.5E15***
Sample C	**4700**	**0.0015**	**1.6E-6**	**1.1E-3**	**~4E14**

*The background doping in sample B could not be extracted from CV measurements, but was estimated for a similar sample from the PL intensity [5]

With the large variety in lifetime values observed, it is apparent that accurate monitoring of both the lifetime and the background doping concentration is necessary. Lifetime measurements give accurate results, however they are slightly more time consuming than spectral PL measurements, so it is valuable to get a good estimate of the optical quality of the material / lifetime directly from the PL spectrum. In the next section we will discuss in more detail which measurement conditions are required to use the PL intensity as a measure of the optical material quality.

3.2 Photoluminescence

The correlation between the PL intensity and the minority carrier lifetime was studied for different excess carrier concentrations: low ($n_e < n_0$), intermediate ($n_e > n_0$) and high ($n_e >> n_0$). The PL intensity varies according to equation (6):

$$I_{PL}(\omega) \propto \frac{B}{\phi}(n_0 + 2G_0\tau)G_1\tau \qquad (6)$$

where τ is the recombination lifetime, $G_0(\propto P_0)$ and $G_1(\propto P_1)$ are the carrier generation rates and $G_0\tau$ and $G_1\tau$ correspond to the stationary and the modulated excess carrier concentrations, respectively.

Low excess carrier concentration

If the excess carrier concentration is small as compared to the background doping concentration, only the first term in equation (6) will affect the PL intensity. In that case, the PL intensity is proportional to the recombination lifetime τ, divided by the radiative lifetime τ_R, see equation (7):

$$I_{PL}(\omega) \propto \frac{Bn_0}{\phi}G_1\tau = \frac{\tau}{\tau_R}G_1 \qquad (7)$$

The PL intensity measured at very low excess carrier concentrations can consequently be used to separate samples with long lifetimes from short lifetime samples, unless the lifetime is limited by radiative recombination. From equation (7) it can be seen that samples limited by radiative recombination only are affected by the generation rate G_1 and not the lifetime.

The lowest excitation powers used during the lifetime measurements all correspond to excess carrier densities smaller than the background doping level. In this range, a big difference in the normalized PL intensity was observed between sample A and sample B. The higher PL intensity of sample B correlates well with the measured lifetime difference (see Table. 1). The big difference between the two samples implies that sample A is not only limited by radiative recombination. Between sample B and C only a small difference in the normalized PL intensities is observed, despite a large difference in measured lifetimes. This could be attributed to the dominant influence of the radiative lifetime in these samples [5], which makes it harder to detect the lifetime differences from the PL intensity at low excess carrier concentrations (equation (7)).

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Intermediate excess carrier concentration

In the spectral PL measurements it is more difficult to get a good signal to noise ratio at low excess carrier densities and consequently an intermediate excitation power need to be used. For intermediate excess carrier densities, both terms in equation (6) will affect the PL intensity and the comparison will be affected by the recombination lifetime τ which decreases with increasing excess carrier density. When comparing Sample A, B and C at an excitation power of 0.75mW (Figure 2) a good correlation is obtained between the relative PL intensities of sample A and B and their lifetimes. The PL intensity of sample C is higher than the PL intensity of sample B, however, there is not a linear dependence between the PL intensity and the lifetime. Again, this could partly be explained by the dominance of the radiative lifetime, but also by non-linear behavior of the recombination lifetime at higher excess carrier densities.

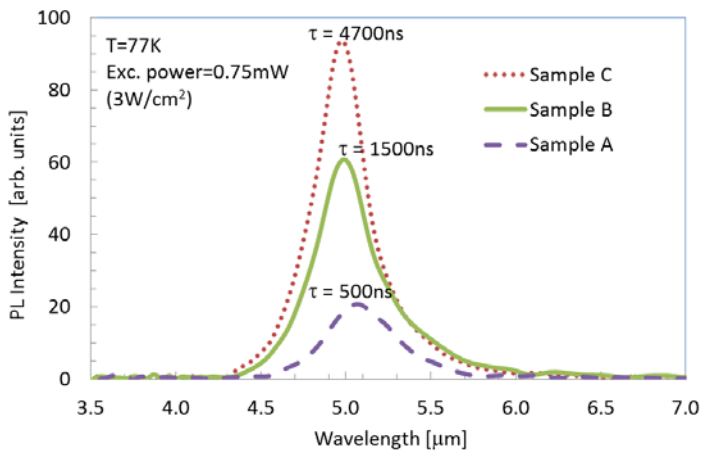

Figure 2. Comparison of the PL spectra of sample A, B and C, showing a correlation between the minority carrier lifetime and the PL intensity.

Intermediate to high excess carrier concentration

The PL spectra of Sample A and B were measured at different excitation powers to study the correlation between the PL intensity and the minority carrier lifetime for intermediate to high excess carrier concentrations (Figure 3). The excitation power was varied from 0.75 mW (3W/cm^2) to 30 mW (120 W/cm^2). At an excitation power of 0.75mW a comparison of the PL intensities of the two samples clearly show that Sample A has a much shorter lifetime than Sample B. As the excitation power is increased above 0.75 mW, the difference in PL intensities gradually decreases. At an excitation power of 30 mW, the PL intensities of the two samples look almost comparable, not revealing the lower lifetime of Sample A.

This study shows that the PL intensity alone can be used as a measure to estimate the minority carrier lifetime, however, it is critical to use low or intermediate excitation power in order to get a good correlation between the PL intensity and the lifetime.

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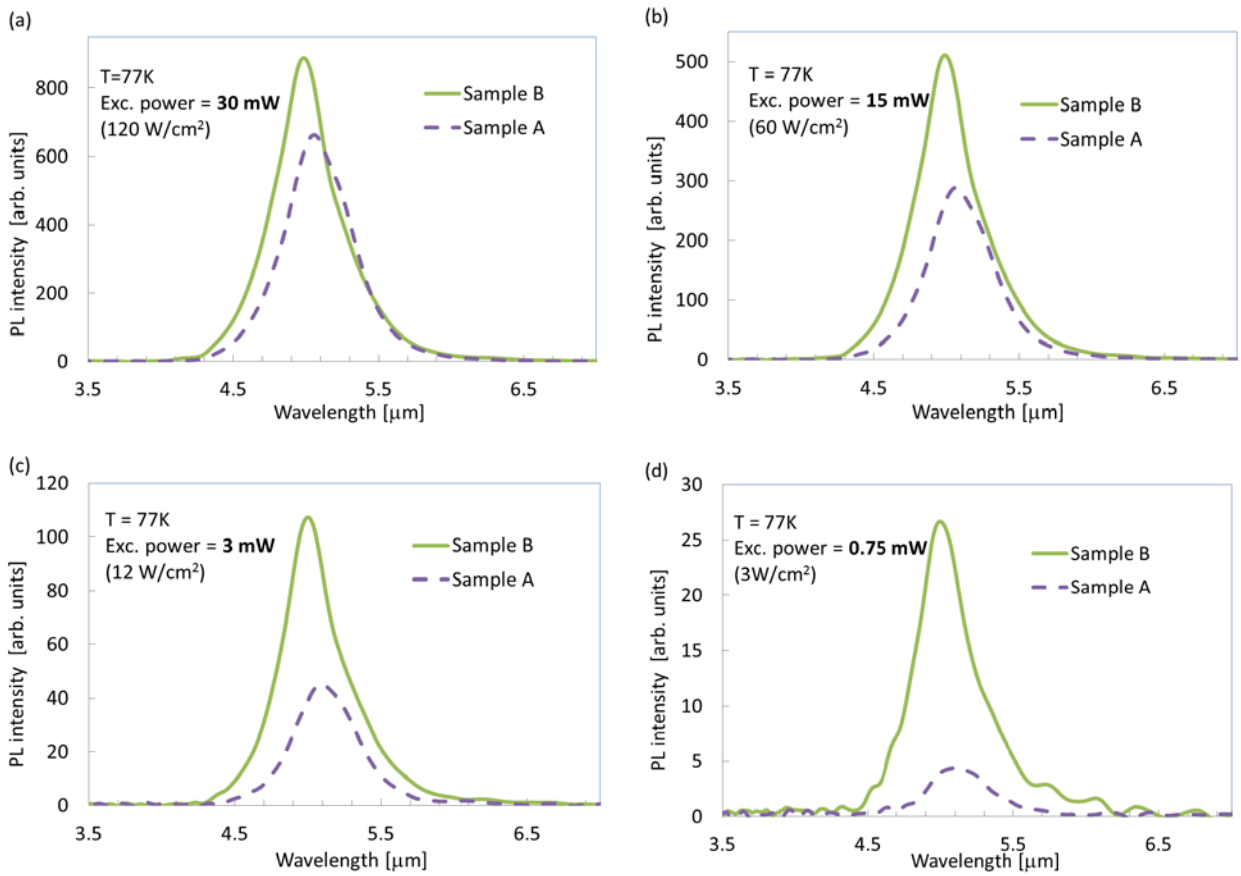

Figure 3. Comparison of the PL intensities of Sample A (τ = 480ns) and Sample B (τ = 1500ns) at different excitation powers: (a) 30mW, (b) 15mW, (c) 3 mW (d) 0.75mW. At the lowest excitation power the difference in lifetimes between the two samples can be seen by comparing the PL intensities, however as the excitation power is increased, the PL intensities are more comparable and a comparison of the PL intensities no longer reveal the differences in minority carrier lifetimes of the two samples.

4. SUMMARY

PL intensities and minority carrier lifetimes of three Ga-free InAs/InAsSb superlattices were studied. The lifetimes varied between 480 ns and 4700 ns, which was attributed to differences in background doping levels. Correlation between the PL intensity and the minority carrier lifetime were observed for low to intermediate excitation powers, however not for high excitation powers. This shows that the PL intensity can be used as a measure of the optical quality of the material, if the excitation power is chosen in the low to intermediate range.

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