# Carrier lifetime measurements in short-period InAs/GaSb strained-layer superlattice structures

Dmitry Donetsky,[1] Stefan P. Svensson,[2] Leonid E. Vorobjev,[3] and Gregory Belenky[1,a)]
[1]*Department of Electrical and Computer Engineering, Stony Brook University, Stony Brook, New York 11794, USA*
[2]*US Army Research Laboratory, 2800 Powder Mill Road, Adelphi, Maryland 20783, USA*
[3]*Department of Semiconductor Physics and Nanoelectronics, St. Petersburg State Polytechnical University, St. Petersburg 195251, Russia*

(Received 14 September 2009; accepted 3 November 2009; published online 24 November 2009)

Minority carrier lifetime and interband absorption in midinfrared range of spectra were measured in InAs/GaSb strained-layer superlattices (SLSs) grown by molecular beam epitaxy on GaSb substrates. The carrier lifetime in 200-period undoped 7 ML InAs/8 ML GaSb SLS with AlSb carrier confinement layers was determined by time-resolved photoluminescence (PL) and from analysis of PL response to sinwave-modulated excitation. Study of PL kinetics in frequency domain allowed for direct lifetime measurements with the excess carrier concentration level of $3.5\times10^{15}$ cm$^{-3}$. The minority carrier lifetime of 80 ns at T=77 K was obtained from dependence of the carrier lifetime on excitation power. © *2009 American Institute of Physics*. [doi:10.1063/1.3267103]

There is a continuous interest in development of mid-IR photodetectors and lasers based on InAs/GaSb strained-layer superlatice (SLS) structures for the 3–5 $\mu$m wavelength range.[1,2] Optimization of the device design requires better understanding of carrier recombination phenomena, and determination of carrier recombination parameters in SLS structures for adequate device modeling. Carrier lifetime studies can shed light on carrier generation-recombination (G-R) processes through Shockley–Read–Hall (SRH) centers in the depletion region of a p-n junction contributing to the detector dark current.[3] In this work it is shown that the minority carrier lifetime in undoped InAs/GaSb SLS can be determined by photoluminescence (PL) response measurements in the frequency domain. A minority carrier lifetime of 80 ns at T=77 K was obtained from the dependence of the carrier lifetime on excitation power.

In moderately doped III-V semiconductor compounds the minority carrier lifetime is typically determined by time-resolved PL (TRPL) response to a pulsed excitation. If the excess carrier concentration is small compared to the concentration of majority carriers, the PL will decay with a time constant equal to the minority carrier lifetime. In low-doped materials with background carrier concentrations in order of $10^{16}$ cm$^{-3}$ and below, the requirement on low excitation is challenging to meet because of the weak PL signal compared to noise in a broadband detection system.

The signal/noise ratio in PL measurements can be improved with reduction in the system bandwidth. We demonstrated direct measurements of the minority carrier lifetime in undoped GaSb-based materials with PL frequency response to a sinusoidal excitation.[4] This approach allows for narrow-band (<1 Hz) signal detection for a substantial reduction in noise traded for reduction in the excess carrier concentration.

In case of carrier generation with stationary rate $G_0$ modulated with amplitude $G_1 \ll G_0$ and carrier recombination with time constant $\tau$, excess carrier concentration $\Delta n(t)$ is defined by Eq. (1a) with solution Eq. (1b) containing stationary and oscillating terms

$$\frac{d}{dt}(\Delta n) = G_0 + G_1\cos(\omega t) - \frac{\Delta n}{\tau}, \tag{1a}$$

$$\Delta n(t) = G_0\tau + \frac{G_1\tau}{\sqrt{1+\omega^2\tau^2}}\cos(\omega t - \phi). \tag{1b}$$

The PL response obtained at frequency $\omega$ with a narrow-band system is linearly dependent on the oscillating portion of excess carrier concentration. It allows for adequate determination of carrier recombination constant $\tau$ from PL response measured in a broad frequency range

$$I_{PL}(\omega) \propto \frac{G_1\tau}{\sqrt{1+\omega^2\tau^2}}. \tag{2}$$

Measurement of PL decay constant versus excitation $\tau(G_0)$ is informative for determination of minority carrier lifetime $\tau_0$ in the limit $G_0 \to 0$. Assuming p-type material with background hole concentration $p_0$, under low excitation condition $\Delta n \ll p_0$ the minority carrier lifetime can be presented as follows:

$$\frac{1}{\tau_0} = A + \frac{B}{\phi}p_0. \tag{3}$$

Here $A$ and $B$ denote the SRH and radiative recombination coefficients, respectively; $\phi$ is the photon recycling factor due to PL reabsorption. Auger recombination term can be neglected due to low carrier concentrations and low temperature range.

Since the steady-state PL intensity and harmonics are filtered out with a narrow-band amplifier, the PL response at frequency $\omega \ll 1/\tau$ is described by oscillating concentrations of electrons and holes both equal to $G_1\tau$ and the corresponding steady-state concentrations of holes $p_0+G_0\tau$ and electrons $G_0\tau$ [Eq. (4)].

a)Electronic mail: garik@ece.sunysb.edu.

 

$$I_{PL}(G_0)|_{\omega\to 0} \propto \frac{B}{\phi}(p_0 + 2G_0\tau)G_1\tau. \quad (4)$$

This dependence can be used for determination of background carrier concentration $p_0$. The latter parameter is critical for optimization of growth parameters, for determination of the SRH term of the minority carrier lifetime directly related to the G-R portion of a p-n junction dark current at low temperatures, for study of the SRH recombination specifics with change in the quasi-Fermi level.

The SLS structures were grown by molecular beam epitaxy on low-doped p-GaSb substrates. The active regions consisted of 200 periods of 7 ML of InAs and 8 ML of GaSb enclosed between 20-nm-thick AlSb carrier confinement layers. A 20-nm-thick GaSb cap layer was grown on the top. The wide-bandgap confinement layers prevented possible losses of excess carriers from the SLS active region due to carrier diffusion into the substrate and losses due to recombination of excess carriers at the structure surface. The overall thickness of the active region was 0.9 $\mu$m. Two SLS structures, K0687 and K0688, were grown with the same target layer thicknesses and slight variation in the shutter sequences. High resolution x-ray diffraction (XRD) spectra indicated low residual strain and sharp interfaces. The best XRD simulation fits were obtained with a thin InSb layer incorporated between the InAs and GaSb layers. For K0687 the results were: $W_{InAs}=19.28$ nm, $W_{InSb}=1.93$ nm, and $W_{GaSb}=24.24$ nm. Similar data were obtained for the other structure.

The PL responses were measured with the setup similar to one described in Ref. 4. The excess carriers were excited either by a 1064 nm Q-switched neodymium doped yttrium aluminum garnet laser with a pulse width of $\Delta t=0.5$ ns ($\Delta t < \tau$) and repetition rate of 7.5 kHz for TRPL measurements or by a fiber-coupled current-modulated 1.3 $\mu$m laser diode for PL frequency response measurements. The PL was collected with reflective optics and focused on an InSb photodiode with a response time constant of 2.5 ns. The PL decays were sampled by a digital scope with an acquisition rate of 5 GS/s and averaged. The PL responses in the frequency domain were measured with a 200 MHz bandwidth lock-in-amplifier.

The PL spectra for both K0687 and K0688 structures and the absorption spectrum for K0687 structure at T =77 K are presented in Fig. 1. The PL spectra were measured at an excitation power of 1 W/cm$^2$ at a wavelength of 0.98 $\mu$m. The results confirmed that the PL was due to transitions between the bandgap edge states (C-V1). The specific point in the absorption spectrum marked (C-V2) was associated with the optical transitions between the top of the second valence subband and the bottom of the conduction band. The SLS absorption coefficients at wavelengths of 1 and 1.3 $\mu$m were estimated to be $3.4\times10^4$ and $2.1\times10^4$ cm$^{-1}$, respectively,[5] corresponding to 95% and 85% absorption of the energy of pumping sources; no PL was observed from the GaSb substrate. Carrier lifetime measurements using TRPL approach were performed. The transient PL responses to pulsed excitation for structure K0687 in a range of pulse energy from 2.3 to 23 nJ are shown in Fig. 2. The laser beam cross-section area was $3.4\times10^{-3}$ cm$^2$ full width at half-maximum (FWHM) giving the peak excitation level of $2.5\times10^{16}$ cm$^{-3}$ for the pulse energy of 2.3 nJ. For this excitation level the PL decay constants were found to be 42 ns for K0687 and 46 ns for K0688. The inset to Fig. 2 shows dependence of the PL peak intensity on the excitation pulse energy and, respectively, the excess carrier concentration. In the range of explored excitations the PL intensity was proportional to the square of the excess carrier concentration, $I_{PL}(t) \propto [\Delta n(t)]^2 \propto \exp(-2t/\tau)$. Thus, the excess carrier concentration decay constants can be estimated by multiplication of the PL decay constants by a factor of 2. The multiplication factor can be slightly less than 2 considering possible transition from quadratic to linear recombination mode at the lowest excitation. The quadratic dependence of PL intensity on excitation indicates also that the background carrier concentration in both samples was below $2.5\times10^{16}$ cm$^{-3}$.

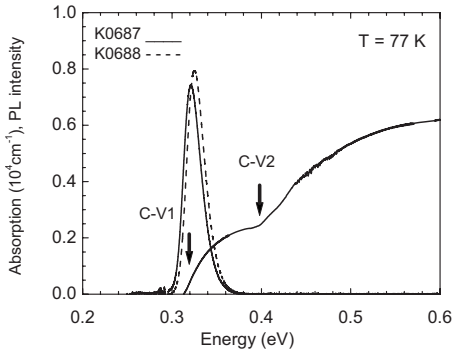


FIG. 1. The PL spectra for samples K0687 and K0688 and the absorption spectrum for K0687 measured at T=77 K with a FTIR Nicolet Magna 6700. The excess carriers were excited with a 0.98 $\mu$m diode laser at a power density of 1 W/cm$^2$. The PL spectra correspond to transitions from the bottom of the conduction band to the top of the valence subband C-V1; C-V2 in the absorption spectrum denotes transitions from the top of the second valence subband to the bottom of the conduction band.

Carrier lifetime measurements at lower than $10^{16}$ cm$^{-3}$ excitation levels were performed using PL response to modulated excitation in the frequency domain. Figure 3 shows the results obtained for structure K0687. The carrier lifetime for a given excitation power was determined by a fit of the experimental response to Eq. (2). The inset shows power dependences of both the inverse carrier lifetime and PL response at low frequency (50 kHz) obtained with the lock-in-amplifier. With the excitation area of $1.5\times10^{-3}$ cm$^{-2}$

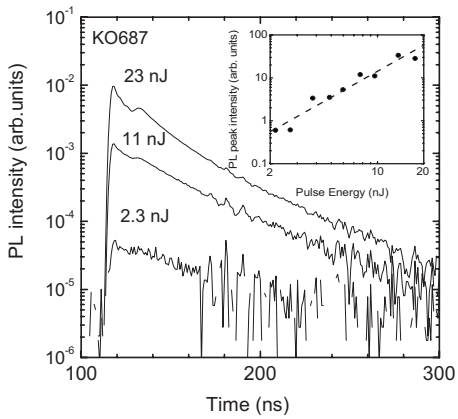


FIG. 2. The TRPL spectra for K0687 showed in a range of excitation pulse energy from 2.3 to 23 nJ. The excitation area was $3.4\times10^{-3}$ cm$^{-2}$. The peak excess carrier concentration for the lowest decay was estimated to be $2.5\times10^{16}$ cm$^{-3}$. The inset shows the dependence of the peak PL intensity on excitation energy. The quadratic dependence indicates that the excess carrier concentration was above the background doping level.

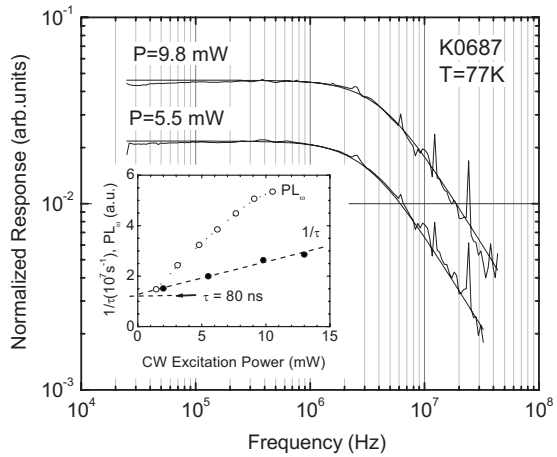


FIG. 3. The PL frequency responses of K0687 to a small-signal sin-wave modulated excitation for two continuous-wave power levels of 5.5 and 9.8 mW. The excitation area was $1.5\times10^{-3}$ cm$^{-2}$. The inset shows power dependences of both the inverse decay constant and the low-frequency PL response. The minority carrier lifetime of 80 ns was determined by extrapolation to zero excitation level. A rapid increase in the PL response indicated that the background carrier concentration was below the minimum excess carrier concentration estimated to be $3.5\times10^{15}$ cm$^{-3}$.

FWHM, the excess carrier concentration was estimated to be $3.5\times10^{15}$ cm$^{-3}$ at an excitation power of 2 mW. The minority carrier lifetime of 80 ns was obtained by extrapolation of the experimental dependence $1/\tau$ to zero excitation power. A rapid monotonic increase in the low-frequency response on power starting from the lowest excitation level indicated that the background carrier concentration was below the level of $3.5\times10^{15}$ cm$^{-3}$. A sublinear character of this dependence is expected from Eq. (4) and is due to the decrease in the carrier lifetime with excitation power. Association of the slope of dependence $1/\tau(G_0)$ with increase in the radiative recombination yielded $B/\phi=4\times10^{-10}$ cm$^3$/s at T=77 K. Subtraction of possible radiative term from the minority carrier lifetime with assumption for the background carrier concentration up to $3.5\times10^{15}$ cm$^{-3}$ would result in the SRH carrier lifetime value to be in the range from 80 to 90 ns. It can be concluded that the determined minority carrier lifetime under low excitation is dominated by the SRH carrier recombination.

The minority carrier lifetimes of 80 ns was obtained for undoped short-period SLS structure from PL frequency response to sin-wave modulated excitation. Similar results follow from analysis of the TRPL data. The dependence of PL response on excitation power indicated the background carrier concentration of $\leq3.5\times10^{15}$ cm$^{-3}$. It has been concluded that the minority carrier lifetime is limited by SRH recombination.

The authors acknowledge J. Pellegrino, M. Tidrow, and S. Bandara for support, helpful discussions and encouragement. The study was funded by NVESD and NSF (Award No. DMR071054). L.E.V. appreciates support from the RFBR.

[1]H. J. Haugan, S. Elhamri, B. Ullrich, F. Szmulowicz, G. J. Brown, and W. C. Mitchel, J. Cryst. Growth **311**, 1897 (2009).
[2]Y. Wei, A. Hood, H. U. Yau, A. Gin, M. Razeghi, M. Tidrow, and V. Natha, Appl. Phys. Lett. **86**, 233106 (2005).
[3]C.-T. Sah, R. N. Noyce, and W. Shockley, Proceedings of the IRE, 1957 (unpublished), pp. 1228–1243.
[4]D. Donetsky, S. Anikeev, N. Gu, G. Belenky, S. Luryi, C. A. Wang, D. A. Shiau, M. Dashiell, J. Beausang, and G. Nichols, AIP Conf. Proc. **738**, 320 (2004).
[5]*Handbook Series on Semiconductor Parameters*, edited by M. Levinshtein, S. Rumyantsev, and M. Shur (World Scientific, New Jersey, 1996), Vol. 1.