AIP | Applied Physics Letters

# Significantly improved minority carrier lifetime observed in a long-wavelength infrared III-V type-II superlattice comprised of InAs/InAsSb

E. H. Steenbergen, B. C. Connelly, G. D. Metcalfe, H. Shen, M. Wraback, D. Lubyshev, Y. Qiu, J. M. Fastenau, A. W. K. Liu, S. Elhamri, O. O. Cellek, and Y.-H. Zhang

Citation: Applied Physics Letters **99**, 251110 (2011); doi: 10.1063/1.3671398
View online: http://dx.doi.org/10.1063/1.3671398
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/99/25?ver=pdfcov
Published by the AIP Publishing

# Significantly improved minority carrier lifetime observed in a long-wavelength infrared III-V type-II superlattice comprised of InAs/InAsSb

E. H. Steenbergen,[1,a)] B. C. Connelly,[2] G. D. Metcalfe,[2] H. Shen,[2] M. Wraback,[2] D. Lubyshev,[3] Y. Qiu,[3] J. M. Fastenau,[3] A. W. K. Liu,[3] S. Elhamri,[4] O. O. Cellek,[1] and Y.-H. Zhang[1]

[1]*Center for Photonics Innovation and School of Electrical, Computer and Energy Engineering, Arizona State University, Tempe, Arizona 85287, USA*
[2]*U.S. Army Research Laboratory, RDRL-SEE-M, Adelphi, Maryland 20783, USA*
[3]*IQE, Inc., Bethlehem, Pennsylvania 18015, USA*
[4]*Department of Physics, University of Dayton, Ohio 45469, USA*

(Received 8 November 2011; accepted 1 December 2011; published online 22 December 2011)

Time-resolved photoluminescence measurements reveal a minority carrier lifetime of >412 ns at 77 K under low excitation for a long-wavelength infrared InAs/$InAs_{0.72}Sb_{0.28}$ type-II superlattice (T2SL). This lifetime represents an order-of-magnitude increase in the minority carrier lifetime over previously reported lifetimes in long-wavelength infrared InAs/$Ga_{1-x}In_xSb$ T2SLs. The considerably longer lifetime is attributed to a reduction of non-radiative recombination centers with the removal of Ga from the superlattice structure. This lifetime improvement may enable background limited T2SL long-wavelength infrared photodetectors at higher operating temperatures. © *2011 American Institute of Physics*. [doi:10.1063/1.3671398]

The InAs/$Ga_{1-x}In_xSb$ type-II superlattice (T2SL) is the most investigated III-V T2SL material for mid- and long-wavelength infrared (MWIR and LWIR) photodetectors. T2SLs are predicted to have a number of advantages over the currently used bulk HgCdTe, including a decreased dependence of the bandgap on compositional non-uniformity, the ability to leverage III-V manufacturing capabilities, the lower cost of substrates, a higher electron effective mass leading to smaller tunneling currents, and band-engineered lower Auger recombination rates and thus lower dark currents.[1] However, reported minority carrier lifetimes at 77 K are 50–80 ns for MWIR InAs/$Ga_{1-x}In_xSb$ T2SLs (Refs. 2 and 3) and 10–40 ns for LWIR InAs/$Ga_{1-x}In_xSb$ T2SLs (Refs. 2, 4 and 5) as compared to 1 $\mu$s for $Hg_{0.78}Cd_{0.22}Te$ ($\sim$10 $\mu$m bandgap).[2] The short minority carrier lifetime has been attributed to Shockley-Read-Hall (SRH) recombination and is detrimental to the device dark current and quantum efficiency.[6] Calculations show that a 350-ns lifetime must be reached for a LWIR T2SL *pn* homojunction photodiode to achieve background limited operation (BLIP) at 80 K with F/6.5 optics in a 300 K background.[4]

Campaigns to improve the minority carrier lifetime have led to investigations of the InAs/$Ga_{1-x}In_xSb$ T2SL interface type[7] and density,[8,9] as well as doping concentration,[2,10] but have thus far resulted in minor or no improvements in the carrier lifetime. It is hypothesized that a native defect associated with InAs or GaSb limits the carrier lifetime.[9] The measured lifetimes of bulk InAs ($\sim$325 ns) (Ref. 9) and bulk $InAs_{0.80}Sb_{0.20}$ (250 ns) (Ref. 2) are longer than that of bulk GaSb ($\sim$100 ns),[9] suggesting that defects associated with GaSb and other Ga-related bonds limit the lifetime of InAs/$Ga_{1-x}In_xSb$ T2SLs and that InAs/$InAs_{1-x}Sb_x$ T2SLs should have a longer minority carrier lifetime than InAs/$Ga_{1-x}In_xSb$ T2SLs. Furthermore, InAs/$InAs_{1-x}Sb_x$ T2SLs have been successfully demonstrated for MWIR lasers and proposed for LWIR photodetectors.[11] A theoretical comparison between LWIR InAs/$InAs_{1-x}Sb_x$ and InAs/$Ga_{1-x}In_xSb$ T2SLs, which excludes SRH recombination, found that the ideal detectivities of the two types of T2SL devices are comparable and are both greater than that of HgCdTe devices.[12] This letter reports an order-of-magnitude improvement of the minority carrier lifetime for a LWIR InAs/$InAs_{1-x}Sb_x$ T2SL over that of a LWIR InAs/$Ga_{1-x}In_xSb$ T2SL. We observe a carrier lifetime of >412 ns at 77 K under low excitation for an InAs/$InAs_{0.72}Sb_{0.28}$ T2SL as determined by time-resolved photoluminescence (TRPL) measurements. This improvement in minority carrier lifetime could now enable LWIR T2SL BLIPs at higher operating temperatures.

The InAs/$InAs_{0.72}Sb_{0.28}$ T2SL was designed with AlSb barriers for TRPL measurements. The AlSb barriers ensure that the measured photoluminescence (PL) decay time is due to carrier recombination in the T2SL and the influence of carrier transport, surface recombination, or any junction fields within the sample is minimized. Studies of a T2SL homojunction have shown that the restoring current in a narrow-bandgap junction results in an ostensibly long PL lifetime.[7] The sample was grown by molecular beam epitaxy on an undoped 2-in. GaSb substrate with a 500-nm GaSb buffer layer. The T2SL consists of 20 periods of InAs (173 Å) and $InAs_{0.72}Sb_{0.28}$ (72 Å), with a total thickness of $\sim$500 nm. The T2SL is unintentionally doped *n*-type ($\sim 3 \times 10^{16}$ $cm^{-3}$ at 10 K) as determined by Hall measurements. AlSb barrier layers (100 Å), above and below the T2SL, are used to confine the electrons to the superlattice as well as to provide an adequate heavy-hole barrier of over 100 meV. The entire structure is capped with 100 Å of $p^+$ InAs. PL measurements show peak emission at 8.2 $\mu$m (150 meV) at 77 K.

TRPL measurements were performed on the InAs/$InAs_{0.72}Sb_{0.28}$ T2SL sample at 11, 40, 77, 110, 150, 200, and 250 K. An ultrafast laser with $\sim$100 fs pulses at a 250 kHz

a)Electronic mail: Elizabeth.Steenbergen@asu.edu.

 

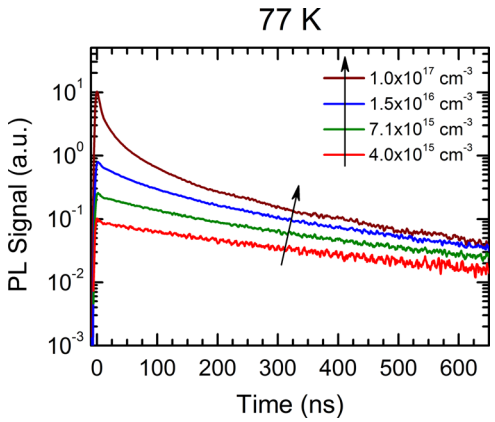


FIG. 1. (Color online) Time-resolved photoluminescence measurements on an InAs/$InAs_{0.72}Sb_{0.28}$ T2SL at 77 K for initial excess carrier densities ranging from $4.0 \times 10^{15}$ to $1.0 \times 10^{17}\,cm^{-3}$.

repetition rate with 2 $\mu$m (0.62 eV) emission was used to excite carriers in only the T2SL region to excess carrier densities between $10^{15}$ and $10^{17}\,cm^{-3}$. The carrier concentrations were calculated using an absorption coefficient of $10^4\,cm^{-1}$ from published *n*-type InAs room-temperature absorption data at 0.62 eV.[13] This is a reasonable absorption coefficient value given that the laser pump energy is well above the SL band edge energy. The PL was detected with an HgCdTe detector operating at 200 K with a 3 ns temporal resolution and a $1 \times 1\,mm^2$ detector area. A 3.6 $\mu$m longpass filter isolated the PL signal from the pump laser scattering. Further details of the experimental technique can be found in Ref. 5.

The TRPL signal at 77 K is shown in Fig. 1 for a sampling of initial excess carrier densities, $\delta p_{t=0}$, between $4.0 \times 10^{15}$ and $1.0 \times 10^{17}\,cm^{-3}$. For the highest $\delta p_{t=0}$, $1.0 \times 10^{17}\,cm^{-3}$, a fast initial decay is observed in the PL signal, and the instantaneous PL lifetime increases significantly as the signal decays. At the lowest initial excess carrier density of $4.0 \times 10^{15}\,cm^{-3}$, the PL signal approaches a single exponential decay, indicating excitation levels are much lower than the background doping density (approximately an order of magnitude lower), and we are approaching the low-excitation regime. As described in Ref. 5, at a given temperature the PL intensity is only a function of the excess carrier density, $\delta p$. Therefore, the PL data taken at lower $\delta p_{t=0}$ can be shifted in time to overlap with the data taken at higher $\delta p_{t=0}$. This shifting process provides a combined PL decay signal with an improved signal-to-noise ratio. Figure 2 shows combined curves for temperatures from 11 to 250 K with initial excess carrier densities of $1.0 \times 10^{17}\,cm^{-3}$. At each temperature, the decay rate of the PL signal shows a strong dependence on $\delta p$, evolving from a faster decay in the first 100 ns, which corresponds to excess carrier densities $>5 \times 10^{16}\,cm^{-3}$, to a slower, almost single exponential decay at the tail end of the decay, which corresponds to excess carrier densities $<5 \times 10^{15}\,cm^{-3}$. This strong dependence of the carrier lifetime on the excess carrier density cannot be explained by SRH recombination alone. Contributions from radiative or Auger recombination, which vary strongly with excess carrier density, must also be considered.

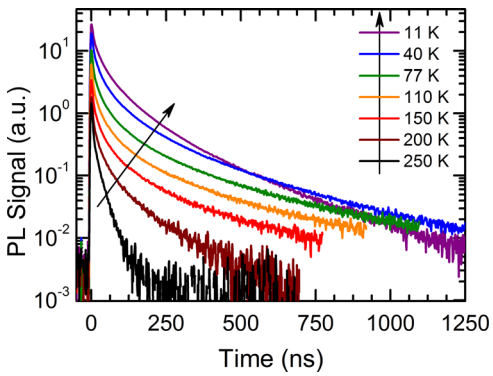


FIG. 2. (Color online) Combined temperature-dependent time-resolved photoluminescence decay measurements on the sample from Fig. 1.

Under typical detector operating conditions, only very small excess carrier densities on the order of $10^{12}\,cm^{-3}$ are expected,[14] so it is important to determine the carrier lifetime in the low-excitation regime where the lifetime is independent of the excess carrier density to predict device performance. We, therefore, fit the tail of the TRPL data, where the excitation level is low ($\sim 10^{15}\,cm^{-3}$) compared to the background doping density ($\sim 10^{16}\,cm^{-3}$), with a single exponential decay to obtain the lifetime, $\tau$, at each temperature. The resulting PL lifetimes from the fit are plotted in Fig. 3 (points) as a function of inverse temperature. When the PL decay rate reaches a single exponential decay in the low-excitation regime, the PL lifetime is equivalent to the minority carrier lifetime. At higher excitation levels, however, the PL lifetime is shorter than the minority carrier lifetime. Since the lowest excitation levels used in this study are just approaching the low-excitation regime, the measured PL lifetime represents a lower limit of the minority carrier lifetime.

The PL lifetime is observed to increase from low temperature (11 K) to a maximum of 412 ns at 77 K. This lifetime is an order-of-magnitude longer than the SRH-limited lifetime of ~30 ns that was previously observed in LWIR InAs/$Ga_{1-x}In_xSb$ T2SL absorber layers at 77 K.[2,4,5] The temperature dependence of the lifetime can be attributed to a combination of both SRH and radiative recombination. For illustration, the temperature dependence of the SRH lifetime

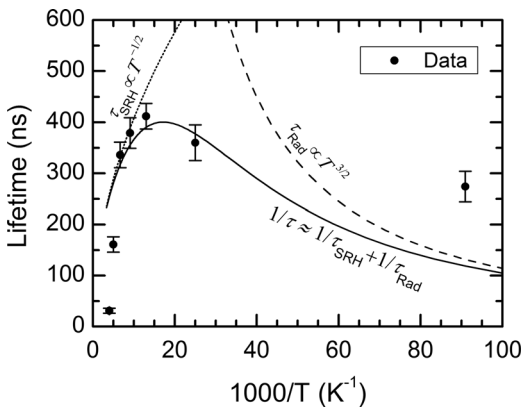


FIG. 3. Carrier lifetimes extracted from the fits in Fig. 2 of the PL decay are shown as points as a function of 1000/T. Also plotted is the temperature dependence of the SRH lifetime ($\tau_{SRH} \propto T^{-1/2}$, dotted line), radiative lifetime ($\tau_{Rad} \propto T^{3/2}$, dashed line), and a combination of both SRH and radiative lifetimes (solid line).

($\tau_{SRH} \propto T^{-1/2}$, dotted line), radiative lifetime ($\tau_{Rad} \propto T^{3/2}$, dashed line), and a combination of SRH and radiative lifetimes (solid line) are plotted along with the data in Fig. 3.[15] At temperatures below 77 K, the PL lifetime increases with increasing temperature, indicating that the lifetime is dominated by radiative recombination and that the radiative lifetime is shorter than the non-radiative (SRH) lifetime. At temperatures above 77 K, the PL lifetime decreases with increasing temperature, signifying that the PL lifetime is dominated by SRH recombination and the radiative lifetime is longer than the SRH lifetime. Around 77 K, both radiative and SRH recombination contribute significantly to the lifetime.

The improved lifetime observed in this InAs/$InAs_{0.72}Sb_{0.28}$ T2SL sample offers evidence that the constituent InAs and InAsSb layers have excellent crystalline properties, and the sample possesses a low density of non-radiative recombination centers at the interfaces and in the layers. It is important to note that this sample gives a strong PL signal and has excellent structural properties with an x-ray diffraction zero-order satellite peak FWHM of 40 arc sec, ruling out the possibility of a long carrier lifetime due to strong localization of photogenerated carriers by interface roughness or layer thickness fluctuations. The InAs/$InAs_{0.72}Sb_{0.28}$ T2SL has a longer lifetime than even bulk InAs at 77 K due to the decreased radiative transition probability compared to that of a direct bandgap bulk material resulting from a decrease in the wave function overlap in the type-II structure. These results also shine some light on the origin of the relatively short carrier lifetime (~30 ns) in LWIR InAs/$Ga_{1-x}In_xSb$ T2SLs, which could be due to the non-radiative recombination centers associated with Ga atoms. Furthermore, the "stabilized Fermi level" due to intrinsic point defects in bulk GaSb and GaAs is near the valence band edge or the midgap, respectively,[16] leaving mid-gap trap states available for SRH recombination. In comparison, in bulk InAs, the stabilized Fermi level is above the conduction band edge,[16] rendering any mid-gap defect states inactive for SRH processes, as demonstrated by relatively high photoluminescence efficiencies in As-rich InAs/InAsSb T2SLs.[17]

In summary, we observe an order-of-magnitude longer minority carrier lifetime (>412 ns at 77 K) in the LWIR InAs/$InAs_{0.72}Sb_{0.28}$ T2SL sample studied compared to that observed in LWIR InAs/$Ga_{1-x}In_xSb$ T2SLs. In addition, the observed carrier lifetime in InAs/$InAs_{0.72}Sb_{0.28}$ is longer across all measured temperatures than that previously reported in InAs/$Ga_{1-x}In_xSb$ T2SLs. Measurements on several other InAs/InAsSb T2SLs similar to the sample presented here also show substantially longer minority carrier lifetimes (100's of ns). We attribute the recombination mechanism to both SRH and radiative recombination, with comparable contributions from both near 77 K. This minority carrier lifetime improvement may now enable background limited T2SL LWIR *pn* photodetectors at higher operating temperatures. It should be noted that the InAs/$InAs_{0.72}Sb_{0.28}$ T2SL sample growth and material properties have not been optimized yet, suggesting that there is still room for improvement in the InAs/$InAs_{1-x}Sb_x$ T2SL minority carrier lifetime. Since the non-radiative recombination rate has now been significantly reduced, future studies can examine the tradeoff between radiative and non-radiative recombination, and sample designs can be optimized to balance lowering the wave function overlap to decrease the radiative recombination rate with increasing the wave function overlap to increase the absorption coefficient.

The authors acknowledge funding by the U. S. Army Research Laboratory and the U. S. Army Research Office MURI program under Grant No. W911NF-10-1-0524 and by the AFOSR under Grant No. FA9550-10-1-0129. E.H.S. appreciates the DOD SMART, ARCS, and SFAz scholarships and acknowledges funding from the ASU Office of the Vice-President for Research and Economic Affairs, the Graduate Research Support Program, and the Graduate College.

[1]D. R. Rhiger, J. Electron Mater. **40**, 1815 (2011).
[2]G. Belenky, G. Kipshidze, D. Donetsky, S. P. Svensson, W. L. Sarney, H. Hier, L. Shterengas, D. Wang, and Y. Lin, Proc. SPIE **8012**, 80120W (2011).
[3]D. Donetsky, S. P. Svensson, L. E. Vorobjev, and G. Belenky, Appl. Phys. Lett. **95**, 212104 (2009).
[4]J. Pellegrino and R. DeWames, Proc. SPIE **7298**, 72981U (2009).
[5]B. C. Connelly, G. D. Metcalfe, H. Shen, and M. Wraback, Appl. Phys. Lett. **97**, 251117 (2010).
[6]S. Bandara, P. Maloney, N. Baril, J. Pellegrino, and M. Tidrow, Infrared Phys. Technol. **54**, 263 (2011).
[7]B. C. Connelly, G. D. Metcalfe, H. Shen, and M. Wraback, Proc. SPIE **8155**, 81550L (2011).
[8]S. P. Svensson, D. Donetsky, D. Wang, P. Maloney, and G. Belenky, Proc. SPIE **7660**, 76601V (2010).
[9]S. P. Svensson, D. Donetsky, D. Wang, H. Hier, F. J. Crowne, and G. Belenky, J. Cryst. Growth **334**, 103 (2011).
[10]S. Bandara, P. Maloney, N. Baril, J. Pellegrino, and M. Tidrow, Opt. Eng. **50**, 061015 (2011).
[11]Y.-H. Zhang, in *Optoelectronic Properties of Semiconductors and Superlattices: Antimonide-Related Strained-Layer Heterostructures*, edited by M. O. Manasreh (Gordon, Breach, 1997), Vol. **3**, pp. 461–500, and references therein.
[12]C. H. Grein, M. E. Flatte, and H. Ehrenreich, in *Proceedings on the Third International Symposium on Long Wavelength Infrared Detectors and Arrays: Physics and Applications III, Chicago, Illinois, 8-13 October 1995* (The Electrochemical Society, Inc., Pennington, NJ, 1995), p. 211.
[13]J. R. Dixon and J. M. Ellis, Phys. Rev. **123**, 5 (1961).
[14]J. D. Vincent, *Fundamentals of Infrared Detector Operation and Testing* (Wiley, New York, 1990).
[15]R. K. Ahrenkiel, in *Semiconductors and Semimetals*, edited by R. K. Ahrenkiel and M. S. Lundstrom (Academic, New York, 1993), Vol. **39**, pp. 39–150.
[16]W. Walukiewicz, Proc. Mat. Res. Soc. Symp. **148**, 137 (1989).
[17]C. M. Ciesla, B. N. Murdin, C. R. Pidgeon, R. A. Stradling, C. C. Phillips, M. Livingstone, I. Galbraith, D. A. Jaroszynski, C. J. G. M. Langerak, P. J. P. Tang *et al.*, J. Appl. Phys. **80**, 2994 (1996).