Long-wave infrared nBn photodetectors based on InAs/InAsSb type-II superlattices

H. S. Kim, O. O. Cellek, Zhi-Yuan Lin, Zhao-Yu He, Xin-Hao Zhao, Shi Liu, H. Li, and Y.-H. Zhang

Citation: [Applied Physics Letters](#) **101**, 161114 (2012); doi: 10.1063/1.4760260

View online: <http://dx.doi.org/10.1063/1.4760260>

View Table of Contents: <http://scitation.aip.org/content/aip/journal/apl/101/16?ver=pdfcov>

Published by the [AIP Publishing](#)

Articles you may be interested in

[Bias-selectable dual-band mid-/long-wavelength infrared photodetectors based on InAs/InAs_{1-x}Sb_x type-II superlattices](#)

Appl. Phys. Lett. **106**, 011104 (2015); 10.1063/1.4905565

[InAs/InAs_{1-x}Sb_x type-II superlattices for high performance long wavelength infrared detection](#)

Appl. Phys. Lett. **105**, 121104 (2014); 10.1063/1.4896271

[High performance long-wave type-II superlattice infrared detectors](#)

J. Vac. Sci. Technol. B **31**, 03C122 (2013); 10.1116/1.4798485

[Performance improvement of longwave infrared photodetector based on type-II InAs/GaSb superlattices using unipolar current blocking layers](#)

Appl. Phys. Lett. **96**, 231107 (2010); 10.1063/1.3446967

[Molecular beam epitaxy growth and characterization of type-II InAs/GaSb strained layer superlattices for long-wave infrared detection](#)

J. Vac. Sci. Technol. B **28**, C3G13 (2010); 10.1116/1.3276429

Long-wave infrared nBn photodetectors based on InAs/InAsSb type-II superlattices

H. S. Kim, O. O. Cellek, Zhi-Yuan Lin, Zhao-Yu He, Xin-Hao Zhao, Shi Liu, H. Li, and Y.-H. Zhang^{a)}

Center for Photonics Innovation and School of Electrical, Computer, and Energy Engineering, Arizona State University, Tempe, Arizona 85287, USA

(Received 27 August 2012; accepted 4 October 2012; published online 18 October 2012)

Long-wave infrared InAs/InAsSb type-II superlattice nBn photodetectors are demonstrated on GaSb substrates. The typical device consists of a $2.2\ \mu\text{m}$ thick absorber layer and has a 50% cutoff wavelength of $13.2\ \mu\text{m}$, a measured dark current density of $5 \times 10^{-4}\ \text{A}/\text{cm}^2$ at 77 K under a bias of $-0.3\ \text{V}$, a peak responsivity of $0.24\ \text{A}/\text{W}$ at $12\ \mu\text{m}$, and a maximum resistance-area product of $300\ \Omega\ \text{cm}^2$ at 77 K. The calculated generation-recombination noise limited specific detectivity (D^*) and experimentally measured D^* at $12\ \mu\text{m}$ and 77 K are $1 \times 10^{10}\ \text{cm}\ \text{Hz}^{1/2}/\text{W}$ and $1 \times 10^8\ \text{cm}\ \text{Hz}^{1/2}/\text{W}$, respectively. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4760260>]

Mid-wave infrared (MWIR) and long-wave infrared (LWIR) photodetectors have broad applications in environmental monitoring, imaging, and scientific instrumentation. Currently, many of these infrared applications need to use high-performance HgCdTe photodetectors which operate around 200 K or below to reduce the dark current and to provide the necessary performance.¹ Due to higher cost limitations of the HgCdTe materials, antimonide based type-II superlattices (T2SL) have been proposed as an alternative^{2,3} to HgCdTe with potentially lower manufacturing cost on large substrates⁴ and better device performance with low dark current density due to suppressed Auger recombination rate and tunneling current.^{5–7} These advantages of T2SLs enable them to operate at higher temperatures, which is highly desirable for photodetector applications.^{8,9}

Although the feasibility of T2SLs for IR photodetectors has been studied for decades, the T2SL materials properties and device performance still have not reached the level predicted by theory.⁶ One of the limiting factors of the most widely studied LWIR InAs/(In)GaSb T2SLs is the short minority carrier lifetime, which determines the dark current, detectivity, and ultimately the maximum operating temperature. The typical minority carrier lifetimes in LWIR InAs/GaSb T2SL measured with time-resolved photoluminescence (PL) and optical modulation response techniques are only 30 ns and 31 ns at 77 K, respectively.^{10,11} Recently, the study of another type of T2SL, namely the “Ga-free” InAs/InAsSb T2SLs grown on GaSb substrates, has been revisited and revealed very encouraging results.^{12–15} Time resolved PL measurements of the InAs/InAs_{0.72}Sb_{0.28} T2SL structures showed minority carrier lifetimes greater than 412 ns due to strong reduction of non-radiative recombination in these superlattices.¹⁶ Therefore, it is reasonable to expect that substantially better photodetector performance and higher operating temperature are achievable with the InAs/InAsSb T2SL materials.

It has been demonstrated lately that the nBn structure suppresses the dark current in infrared photodetectors effectively through band gap engineering.¹⁷ The electron transport

in nBn structures is blocked by a conduction band barrier while the hole can easily transport to the contact. Recently, an MWIR focal plane array based on an unpassivated nBn structure with an AlGaSb barrier and an InAs/GaSb T2SL n-type absorber has been reported.¹⁸ In this paper, we demonstrate LWIR nBn photodetectors with an InAs/InAsSb T2SL absorber having a cutoff wavelength of $13.2\ \mu\text{m}$.

Figure 1 shows the bandedge diagram of the device design, which consists of an n-type InAs/InAs_{0.62}Sb_{0.38} T2SL as the top contact layer, lattice-matched InAs/Al_{0.8}Ga_{0.2}As_{0.01}Sb_{0.99} T2SL as the barrier for electrons, and an InAs/InAs_{0.62}Sb_{0.38} T2SL as the absorber. A three-band Kronig-Penney model is used to calculate the electron and hole miniband energy levels in the InAs/Al_{0.8}Ga_{0.2}As_{0.01}Sb_{0.99} T2SL barrier layer. The calculated conduction band barrier height is 409 meV. The Al and As mole fractions of the barrier are carefully chosen to align the hole miniband in the InAs/InAsSb T2SL layer with that in the barrier layer to ensure optimized hole transport.

The designed nBn device is grown on a Te-doped (100) 2 in. GaSb substrate using a VG V80 solid-source MBE system.

FIG. 1. Designed energy band diagram of T2SL nBn photodetector using the three-band Kronig-Penney model calculation. The conduction band offset between the barrier and the absorber is $\sim 0.4\ \text{eV}$.

^{a)}Electronic mail: yhzhang@asu.edu.

The growth starts with a 500 nm GaSb buffer at 510 °C followed by the bottom contact layer consisting of 15 periods of 13.9 nm InAs:Si ($1 \times 10^{18} \text{ cm}^{-3}$)/4.5 nm InAs_{0.62}Sb_{0.38} T2SL layers. Then, a 120 periods un-intentionally doped 13.9 nm InAs/4.5 nm InAs_{0.62}Sb_{0.38} T2SL absorber layer is grown, followed by a barrier consisting of 17 periods of 2.8 nm InAs/2.5 nm Al_{0.8}Ga_{0.2}As_{0.01}Sb_{0.99} T2SL layers. Finally, the n-type top contact layer is grown, which consists of 8 periods of 13.9 nm InAs:Si ($1 \times 10^{18} \text{ cm}^{-3}$)/4.5 nm InAs_{0.62}Sb_{0.38} T2SL layers and a 13.9 nm InAs:Si ($1 \times 10^{18} \text{ cm}^{-3}$) top layer. The growth temperature is kept at 415 °C during the growth of all superlattice layers. The high-resolution x-ray diffraction (XRD) shows that the actual T2SL barrier consists of InAs/Al_{0.8}Ga_{0.2}As_{0.03}Sb_{0.97}, where the increase of As composition compared to the designed value is due to the incorporation of background As in the MBE chamber. The calculated hole miniband energy level in the barrier layer indicates that the sample possesses a hole barrier of $\sim 38 \text{ meV}$ in the valance band between the valance bandedge of barrier and the valance bandedge of absorber layer.

Device processing starts with photolithography to define the mesas ($410 \mu\text{m} \times 410 \mu\text{m}$), which have open optical apertures ranging from $50 \mu\text{m}$ to $200 \mu\text{m}$ diameter. Wet etching is done with citric acid solution (1 g citric acid:1 ml water): H₂O₂:DI water solution with ratio of 1:1:10. The etching is stopped at the middle of the n-type bottom contact, resulting in an etch depth of $2.53 \mu\text{m}$. The bottom and top metal contacts (50 nm Ti/50 nm Pt/300 nm Au) are deposited using an e-beam evaporator. The front-side illuminated device does not have any anti-reflecting coating and passivation. The fabricated devices are wire bonded to a ceramic package with the bottom n-type InAs/InAsSb T2SL layer connected as a common ground, and external bias is applied to the top contact of each mesa.

The spectral response is measured using a Fourier transform infrared spectrometer with a KBr beam splitter and SRS-570 low-noise current preamplifier. The LWIR spectral response is measured at -0.5 V , while the detector temperature is swept from 8 K to 77 K (Fig. 2). The cutoff wavelength at 8 K is $12.5 \mu\text{m}$, which red-shifts to $13.2 \mu\text{m}$ at 77 K.

FIG. 2. Front side illuminated single pass spectral responsivity spectrum for an nBn photodetector under the applied bias of -0.5 V , measured at 8 K and 77 K.

FIG. 3. Measured responsivity and specific detectivity as a function of applied bias at 50 K and 180° field of view conditions.

The responsivity and detectivity are measured under 180° field of view using an 800°C blackbody source with a 1 in. aperture, chopped at 130 Hz, at a distance of 91 cm, with a $7.3 \mu\text{m}$ long-pass IR filter with 90% transmission. The peak responsivity at $12 \mu\text{m}$ wavelength is measured as 0.3 A/W at -0.5 V bias at 77 K. The responsivity drops to $\sim 0.2 \text{ A/W}$ at 8 K which is attributed to reduced mobility of the holes at lower temperatures and shorter carrier lifetime.¹⁶

Figure 3 shows the bias dependent responsivity and specific detectivity (D^*) at $12 \mu\text{m}$. The responsivity increases with bias and reaches 0.36 A/W at 50 K at a bias of -0.8 V . The peak D^* is $3 \times 10^8 \text{ cm Hz}^{1/2}/\text{W}$ under a bias of -0.3 V . Figure 4 shows the temperature dependence of the peak responsivity and D^* , which is 0.24 A/W and $1 \times 10^8 \text{ cm Hz}^{1/2}/\text{W}$, respectively, at 77 K and $12 \mu\text{m}$ under the fixed bias of -0.3 V with 180° field of view. The quantum efficiency (QE) under these conditions is 2.5%.

To compare with the theoretical limit, theoretical D^* is calculated using the following equation:

$$D^* = \frac{\frac{q}{E_g} \eta \sqrt{A}}{\sqrt{(4kT/R) + 4qI}}, \quad (1)$$

FIG. 4. Measured responsivity and specific detectivity as a function of device temperature under the applied bias of -0.3 V and 180° field of view conditions.

FIG. 5. Dark current density as a function of applied bias ranging from 12 K to 100 K, the solid color line shows the total current under 290 K background with $f/2$ optics at 50 K with 28% optical aperture fill-factor. The inset shows dynamic dark RA product at 77 K.

where q is the electron charge, E_γ is the photon energy, η is the quantum efficiency, A is the mesa area, k is the Boltzmann constant, T is the temperature, R is the AC resistance of the mesa, and I is the total current passing through the mesa. The $4kT/R$ term represents the Johnson noise power and the $4qI$ term represents the generation-recombination (GR) noise power with assumption of unity gain. GR noise limited D^* at $12\ \mu\text{m}$ is $1 \times 10^{10}\ \text{cm Hz}^{1/2}/\text{W}$ at 77 K. We partially attribute measured lower D^* to the unpassivated mesa sidewalls which may create excess noise and dark current. In addition, further optimization of the valance band edge energy position and doping profile will lower dark current and improve D^* .

Figure 5 shows the measured dark current density as a function of applied bias for temperatures ranging from 12 K to 100 K with a cold-shield cover. At 77 K, the dark current density is $5 \times 10^{-4}\ \text{A}/\text{cm}^2$ at an operating point of $-0.3\ \text{V}$ bias. The inset shows that the dynamic dark resistance-area (RA) product is $\sim 330\ \Omega\ \text{cm}^2$ under $-0.35\ \text{V}$ applied bias at 77 K. The room temperature background ($f/2$, 290 K) current of the nBn device is also shown in Figure 5, which has an aperture of $100\ \mu\text{m}$ diameter defined by metal contact and a 28% fill factor of optically active area. The photocurrent shows weak dependence on temperature between 50 K and 77 K. The definition of $I_{\text{total}}/I_{\text{dark}} > 5$ is used as the background limited photodetection (BLIP) condition.⁹ When the optically active area fill factor is 100%, the ratio $I_{\text{total}}/I_{\text{dark}} = 2$ at 77 K, and 13 at 70 K; the latter is claimed as the $f/2$ BLIP temperature for this $13.2\ \mu\text{m}$ cutoff photodetector.

It is worth noting that the measured dark current density $5 \times 10^{-4}\ \text{A}/\text{cm}^2$ of the devices with a cutoff wavelength of $13.2\ \mu\text{m}$ at 77 K is lower than that given by the well-known HgCdTe Rule-07,¹⁹ although it should be pointed out that the QE of the detector reported here is 2.5%, while the Rule-07 is defined for HgCdTe photodetectors with 60% QE.²⁰ The suppression of the dark current is due to blocking of the majority carriers, long minority carrier lifetime and low hole

mobility in the InAs/InAsSb absorber.^{16,17} But the device performance is still inferior to that of HgCdTe devices with similar cutoff wavelength in terms of D^* and QE due to limited absorber thickness.^{20,21}

In summary, nBn long-wave infrared photodetectors based on InAs/InAs_{0.62}Sb_{0.38} type-II strained-layer superlattice have been demonstrated. The unpassivated nBn detectors have a 50% cutoff wavelength of $13.2\ \mu\text{m}$, a dark current density of $5 \times 10^{-4}\ \text{A}/\text{cm}^2$, and a dark current GR noise limited D^* of $1 \times 10^{10}\ \text{cm Hz}^{1/2}/\text{W}$ at 77 K. Although the D^* and QE (2.5%) are still lower than those of HgCdTe devices with similar cutoff wavelength, the measured device dark current density is below the Rule-07 proposed for HgCdTe photodetectors and is the lowest value reported so far for any T2SL at similar wavelengths.²¹ These results indicate that higher operating temperature of type-II superlattice LWIR photodetectors can be demonstrated experimentally in the near future.

The authors acknowledge funding by the AFOSR under Grant No. FA9550-10-1-0129 and U.S. Army Research Office MURI program under Grant No. W911NF-10-1-0524.

¹P. Norton, Opto-Electron. Rev. **10**, 159 (2002).

²D. L. Smith and C. Mailhot, Appl. Phys. Lett. **62**, 2545 (1987).

³G. C. Osbourn, J. Appl. Phys. **53**, 1586 (1982).

⁴P. Manurkar, S. Ramezani-Darvish, B.-M. Nguyen, M. Razeghi, and J. Hubbs, Appl. Phys. Lett. **97**, 193505 (2010).

⁵E. R. Youngdale, J. R. Meyer, C. A. Hoffman, F. J. Bartoli, C. H. Grein, P. M. Young, H. Ehrenreich, R. H. Miles, and D. H. Chow, Appl. Phys. Lett. **64**, 3160 (1994).

⁶C. H. Grein, P. M. Young, M. E. Flatté, and H. Ehrenreich, J. Appl. Phys. **78**, 7143 (1995).

⁷J. R. Meyer, C. L. Felix, W. W. Bewley, I. Vurgaftman, E. H. Aifer, L. J. Olafsen, J. R. Lindle, C. A. Hoffman, M.-J. Yang, B. R. Bennett, B. V. Shanabrook, H. Lee, C.-H. Lin, S. S. Pei, and R. H. Miles, Appl. Phys. Lett. **73**, 2857 (1998).

⁸J. L. Johnson, L. A. Samoska, A. C. Cossard, J. L. Merz, M. D. Jack, G. R. Chapman, B. A. Baumgratz, K. Kosai, and S. M. Johnson, J. Appl. Phys. **80**, 1116 (1996).

⁹D. Z. Ting, C. J. Hill, A. Soibel, S. A. Keo, J. M. Mumolo, J. Nguyen, and S. D. Gunapala, Appl. Phys. Lett. **95**, 023508 (2009).

¹⁰B. C. Connelly, G. D. Metcalfe, H. Shen, and M. Wraback, Appl. Phys. Lett. **97**, 251117 (2010).

¹¹D. Donetsky, G. Belenky, S. Svensson, and S. Suchalkin, Appl. Phys. Lett. **97**, 052108 (2010).

¹²D. Lackner, O. J. Pitts, M. Steger, A. Yang, M. L. W. Thewalt, and S. P. Watkins, Appl. Phys. Lett. **95**, 081906 (2009).

¹³E. H. Steenberg, Y. Huang, J.-H. Ryou, L. Ouyang, J.-J. Li, D. J. Smith, R. D. Dupuis, and Y.-H. Zhang, Appl. Phys. Lett. **99**, 071111 (2011).

¹⁴E. H. Steenberg, K. Nunna, L. Ouyang, B. Ullrich, D. L. Huffaker, D. J. Smith, and Y.-H. Zhang, J. Vac. Sci. Technol. **B 30**, 02B107 (2012).

¹⁵O. O. Cellek, H. Li, X.-M. Shen, Z. Y. Lin, E. H. Steenberg, D. Ding, S. Liu, Q. Zhang, H. S. Kim, J. Fan, M. J. DiNezza, W. H. G. Dettlaff, P. T. Webster, Z.-Y. He, J.-J. Li, S. R. Johnson, D. J. Smith, and Y.-H. Zhang, Proc. SPIE **8353**, 83533F (2012).

¹⁶E. H. Steenberg, 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, Appl. Phys. Lett. **99**, 251110 (2011).

¹⁷S. Maimon and G. W. Wicks, Appl. Phys. Lett. **89**, 151109 (2006).

¹⁸H. S. Kim, E. Plis, J. B. Rodriguez, G. D. Bishop, Y. D. Sharma, L. R. Dawson, S. Krishna, J. Bundas, R. Cook, D. Burrows, R. Dennis, K. Patnaude, A. Reisinger, and M. Sundaram, Appl. Phys. Lett. **92**, 183502 (2008).

¹⁹W. E. Tennant, D. Lee, M. Zandian, E. Piquette, and M. Carmody, J. Electron. Mater. **37**, 1406 (2008).

²⁰W. E. Tennant, J. Electron. Mater. **39**, 1030 (2010).

²¹D. R. Rhiger, J. Electron. Mater. **40**, 1815 (2011).