

# Analysis of barrier parameters on the extended threshold wavelength of infrared detectors

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**Abstract**—The threshold wavelength ( $\lambda_t$ ) of spectral photoresponse of any semiconductor photodetector is determined by the minimum energy gap ( $\Delta = 1.24/\lambda_t$ ) of the material, or the interfacial energy gap of the heterostructure. It was shown before that the threshold limit can be extended beyond  $\lambda_t$  to obtain an extended threshold wavelength  $\lambda_{\text{eff}}$  ( $\lambda_{\text{eff}} \gg \lambda_t$ ) in detectors with a barrier energy offset ( $\delta E_v$ ) and a gradient. Here, in this letter, we analyze the effect of barrier parameters such as  $\delta E_v$  and gradient on the extended threshold wavelength of infrared detectors for the temperature range up to 50 K.

**Index Terms**— Infrared photodetectors, threshold wavelength, heterojunction

## I. INTRODUCTION

In general, the threshold wavelength of spectral photoresponse of any semiconductor detector is determined by the minimum energy gap ( $\Delta$ ) of the material, or the interfacial energy gap of the heterostructure detector [1, 2]. Extension of threshold wavelength beyond the typical threshold limit ( $\lambda_t = 1.24/\Delta$ ) in heterostructure based infrared (IR) photodetectors was reported recently [1]. A heterostructure detector with a graded barrier and a barrier energy offset at  $T = 5.3$  K showed extended threshold wavelength ( $\lambda_{\text{eff}} = 1.24/\Delta'$ , where  $\Delta'$  is effective activation energy,  $\lambda_{\text{eff}} \gg \lambda_t$ ) up to 55  $\mu\text{m}$  whereas the  $\lambda_t$  was 3.9  $\mu\text{m}$  [1].

A p-GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$  heterostructure consists of an absorber/emitter (p-type GaAs) sandwiched between high energy undoped  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  injector (graded or flat) barrier and low energy undoped  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  collector (flat) barrier. The barrier energy difference between these two barriers is referred as the barrier energy offset ( $\delta E_v$ ). Upon incident of infrared radiation, photo excited carriers i.e. hot carriers are generated in the injector, absorber and collector. The photo-absorption in the p-GaAs absorber excites hot

carriers from the light/heavy hole bands into the split-off band [3], and these excited carriers then escape into the barrier region, typically interact with cold carriers and are collected at the contact region. The basic model to explain the  $\lambda_{\text{eff}}$  in IR detectors is based on the hot carrier effects [4-6]. In that kind of IR detectors, for a net flow of hot carriers  $\delta E_v$  is critical and increasing  $\delta E_v$  and the gradient of the injector barrier; will increase the carrier flow. Hot carriers injected from the high energy barrier side interact with cold carriers in the absorber that leads to non-equilibrium carrier distribution to the specific momentum states and elevated carrier temperature in the absorber [5]. The hot carriers evolve towards equilibrium via momentum and energy relaxation, on a femtosecond (fs) or picoseconds (ps) time scale via elastic and inelastic scattering [7, 8]. Carrier-carrier scattering results in coulomb thermalization and allows the carrier distribution to be described by a quasi-Fermi level with carrier temperature ( $T_c$ ) > lattice temperature ( $T_L$ ). Finally, the escape of hot carriers from that quasi-Fermi level across the collector barrier when a long wavelength photon is absorbed gives the extended wavelength threshold photoresponse  $\lambda_{\text{eff}}$  ( $\lambda_{\text{eff}} \gg \lambda_t$ ) [6]. However, in conventional heterostructure detectors with  $\delta E_v = 0$ , spectral photoresponse with designed  $\lambda_t$  have been observed.

Here we discuss the effect of barrier parameters on the extended threshold wavelength of heterostructure detectors up to 50 K.

## II. EXPERIMENTAL DETAILS

The three IR p-GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$  heterostructure detectors, SP1001, SP1007 and 15SP3, were grown by molecular beam epitaxy on a semi-insulating GaAs (100) substrate. Each p-GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$  IR detector structure consist of three p-type GaAs regions ( $p = 1 \times 10^{19} \text{ cm}^{-3}$ ), i.e. bottom contact, absorber (emitter) and top contact. The active region of each IR detector consists of p-GaAs of 80 nm thickness with the bottom and top contacts have the thicknesses of 80 nm and 400 nm respectively. Detector SP1001 have a flat high energy barrier and low energy flat barrier with barrier energy offset ( $\delta E_v$ ) = 0.10 eV. Detector SP1007 have a high energy barrier with graded profile and  $\delta E_v = 0.10$  eV. Detector 15SP3 have a similar structure as SP1007 except  $\delta E_v = 0.19$  eV. By varying the Al fractions, the detectors SP1007 and 15SP3 have a graded potential profile and energy offset between the barriers. For comparison, a flat barrier detector LH1002 with  $\delta E_v = 0$  was also designed with thickness of absorber 18.8 nm and the bottom and top contacts 60 nm respectively. Mesas with an electrically active area of  $400 \times 400 \mu\text{m}^2$  were fabricated by the conventional photolithography and wet etching, and the contact electrodes were formed by Ti/Pt/Au metallization. By partially etching the top contact layer, an optical window of  $\sim 260 \times 260 \mu\text{m}^2$  was opened for normal incidence optical illumination of the detector. For photoresponse measurements,

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samples were mounted in a liquid helium Dewar and a black body source with peak intensity of  $2.8 \text{ mW/cm}^2$  is used to measure the photoresponse spectra (Perkin–Elmer system 2000 Fourier transform infrared (FTIR) spectrometer) of all the detectors under study. The bias voltage in the photoresponse measurement was measured using Keithley 1600 Electrometer, and the negative bias refers to the positive voltage connected to the bottom contact, with the top contact grounded and vice versa. A bolometer with known sensitivity was used for background measurements and calibrating the responsivity. The comparison of Al fraction, thicknesses and  $\delta E_v$  for all detectors used in this study are listed in Table. I.

TABLE I

TABLE I STRUCTURAL PARAMETERS FOR ALL IR DETECTORS: ALUMINUM MOLE FRACTION, BARRIER ENERGY OFFSET ( $\delta E_v$ ) AND THICKNESSES

Sample	Al mole fraction				$\delta E_v$ (eV)	Thickness (nm)		
	$x_1$	$x_2$	$x_3$	$x_4$		$w_1$	$w_2$	$w_3$
SP1001	0.75	0.75	0.57	0.57	0.10	80	80	400
SP1007	0.45	0.75	0.57	0.57	0.10	80	80	400
15SP3	0.45	0.75	0.39	0.39	0.19	80	80	400
LH1002	0.57	0.57	0.57	0.57	0	60	18.8	60

Fig. 1(a), (b) and (c) shows unbiased valence band (VB) diagram of samples SP1001, SP1007, 15SP3 and LH1002 under dark condition. In all the detectors, the bottom contact (BC), the absorber (p-GaAs) and top contact (TC) are highly doped. The Fermi level ( $E_f$ ) in the p-doped GaAs absorber lies in the light hole (LH)/heavy hole (HH) band, with the spin-orbit split-off (SO) band separated by 340 meV from the LH/HH band near  $k = 0$  as shown in Fig. 1(d). The energy difference between the Fermi level and the top of the valence band edge is denoted as the potential energy barrier ( $\Delta$ ). The carrier transport over  $\Delta$  takes place via thermionic emission (since the barriers are thick enough, tunneling can be ignored) [9]. The dark current of a heterostructure detector is described by a 3D carrier drift

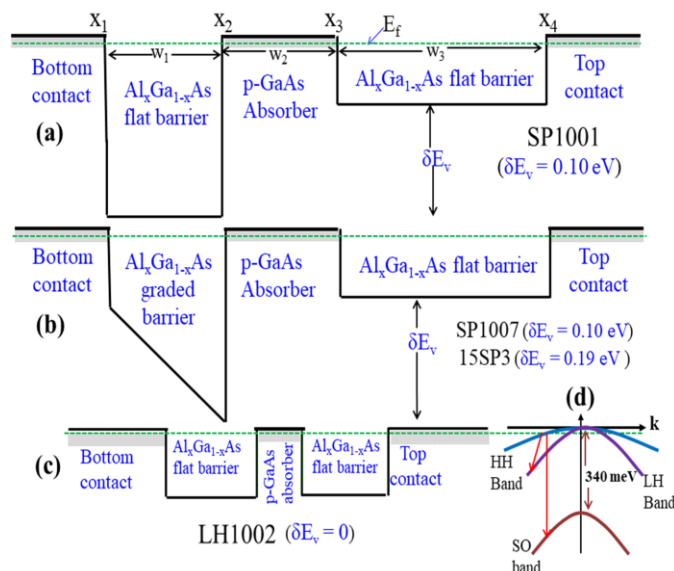


Fig.1. Unbiased schematic VB diagram of (a) Detector SP1001 with p-GaAs absorber, flat high energy  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  barrier, flat low energy  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  barrier and  $\delta E_v = 0.10 \text{ eV}$  (b) detector SP1007 have similar structure as SP1001 except graded barrier with  $\delta E_v = 0.10 \text{ eV}$  and detector 15SP3 have similar structure as SP1007, except  $\delta E_v = 0.19 \text{ eV}$  (c) LH1002 consists of a p-GaAs absorber and bottom contact and top contact of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  with  $\delta E_v = 0$ . (d) A schematic of the valence band of the p-GaAs absorber shows hole transition from LH/HH band, to SO band which is separated from LH/HH band by 340 meV.

model [9, 10], and for a given value of the electric field, the  $I_{\text{dark}} \propto T^{3/2} \exp\left(-\frac{\Delta}{kT}\right)$  and  $\Delta = 1.24/\lambda_t$ . Therefore the dark current of all the detectors is determined by the designed value of  $\Delta$  and remains unaffected.

Upon incidence of light from an external optical source, holes transitions taking place either between different bands (intervalence-band absorption) or within the same band (free-carrier absorption)[3] Holes surmounting the barrier are ‘hot’ because of their excess energies relative to the valance band-edge of the absorber. In SP1001 and SP1007, 15SP3 [fig. 1 (a) and fig. 1(b)] a net flow of hot holes observed owing to the difference in barrier heights,  $\Delta E_v$  even at zero bias and an extended threshold wavelength  $\lambda_{\text{eff}} = 1.24/\Delta'$  where  $\lambda_{\text{eff}} \gg \lambda_t$  is observed. For LH1002 as shown in Fig. 1(c), no net flow of hot holes observed due to the symmetry of the detector. However upon application of bias,  $\lambda_t = 1.24/\Delta$  observed with slight variation in  $\lambda_t$  with increasing bias due to image force induced barrier lowering effect [10]. The interaction of hot holes and cold holes (holes which are already present in p-GaAs absorber due to doping) in the absorber leads to mechanism responsible for extended threshold wavelength in detectors SP1001, SP1007 and 15SP3 as already mentioned in details in Ref [6].

In general, by increasing thickness of p-GaAs absorber, the absorption in material increases which can change the position of the peak responsivity and spectral width of photoresponse up to a certain limit [9, 11]. Since, the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  barriers are undoped and will not produce any photo carriers; therefore the thickness differences don’t have any contribution in the extension of threshold wavelength beyond  $\lambda_t$ . In this work, samples with different thicknesses of barrier and absorber have compared; thus, all the photoresponse spectra have analyzed at the close value of the electric field.

### III. RESULTS AND DISCUSSIONS

The heterostructure detectors operate based on the internal photoemission process (IPE) process where carriers are photoexcited and escape from one material to another by passing through an absorber/barrier interface [9, 12]. The photoemission efficiency is proportional to  $(\varepsilon - \Delta)$ , where  $\varepsilon$  is the energy of the photo-excited holes and  $\Delta$  is the potential energy barrier at the interface.

The quantum yield defined as the number of collected photo carriers per incident photon can be described by the following expression

$$Y(h\nu) = Y_0(kT) + C_0 \int_{\Delta}^{\infty} \rho(\varepsilon, h\nu) f(\varepsilon, h\nu) P(\varepsilon, \Delta) d\varepsilon \quad (1)$$

which takes into account two essential processes during IPE, photo excitation in the absorber [described by an energy distribution function  $\rho(\varepsilon, h\nu)$ ] and the transmission of carriers over a barrier [describe by probability distribution function  $P(\varepsilon, \Delta)$ ]. In this work, the  $\Delta$  of spectral photoresponse is determined by temperature-dependent internal photoemission spectroscopy (TDIPS) method [13], where the quantum yield is proportional to the multiplication of spectral responsivity and photon energy. Thus to obtain  $\Delta$ , the quantum yield (x-axis) plotted as a function of photon energy (y-axis) and fittings to this spectrum were carried out in the near-threshold regime by using Eq. (1) where  $Y_0$ ,  $C_0$ , and  $\Delta$  are regarded as fitting parameters.

**A. Heterostructure detectors with and without barrier energy offset**

The photoresponse spectra of detectors LH1002 ( $\delta E_v = 0$ ) and SP1001 ( $\delta E_v = 0.10$  eV) are compared at 5.3 K and  $E \sim -10.41$  kV/cm as shown in Fig. 2(a). At  $T = 5.3$  K, SP1001 have detectable  $\lambda_{eff} \sim 36 \mu\text{m}$  (due to noise at the threshold end) which is much longer than the designed  $\lambda_t \sim 3.1 \mu\text{m}$  of SP1001. However, the photoresponse spectra of LH1002 shows threshold wavelength of  $4.3 \mu\text{m}$  which is close to the designed  $\lambda_t = 4.1 \mu\text{m}$ . Therefore, it is clear that extended threshold wavelength observed only for SP1001 at 5.3 K.

Now, the photoresponse spectra of LH1002 and SP1001 are compared at 50 K and  $E \sim -20.83$  kV/cm as shown in Fig. 2 (b), inset of fig. 2(b) shows the TDIPS fitting results for LH1002 and SP1001 at 50 K. A close value of threshold wavelength of  $4.2 \mu\text{m}$  for LH1002 and  $4.1 \mu\text{m}$  for SP1001 is observed at 50 K. By comparison of photoresponse spectra of both samples at 5.3 K and 50 K, it is observed that as the temperature goes up from 5.3 K to 50 K, the  $\lambda_{eff}$  comes down closer to the  $\lambda_t$  for SP1001 whereas for LH1002, not much change in  $\lambda_t$  is observed as temperature changes from 5.3 K to 50 K. This observation suggests that the  $\delta E_v$  is critical to obtain  $\lambda_{eff} (>> \lambda_t)$  in IR detectors for a given value of temperature. However, it may also be noted here that the observation of  $\lambda_{eff}$  is also depended on temperature. In this view, the dependence of  $\lambda_{eff}$  on the temperature up to 90 K was already reported as mentioned in Ref [12].

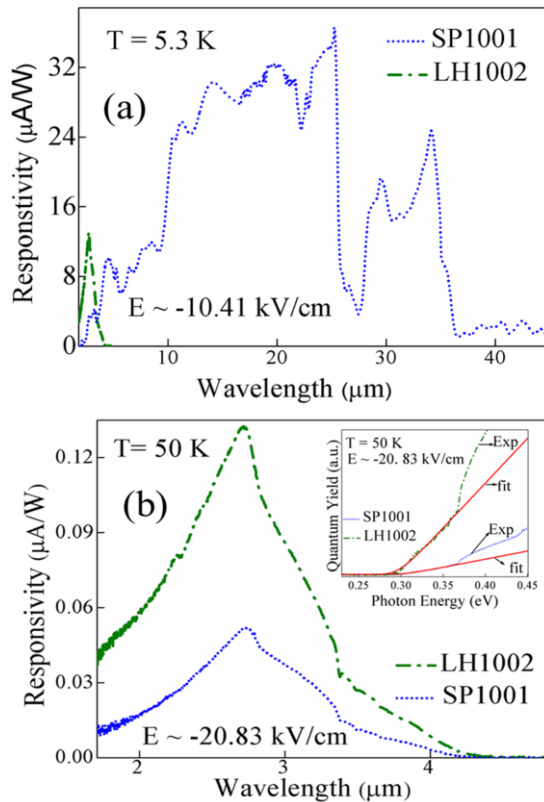


Fig. 2. Photoresponse spectra of SP1001 and LH1002 (a) at 5.3 K, SP1001 shows  $\lambda_{eff} \sim 36 \mu\text{m}$  whereas LH1002 which shows  $\lambda_{eff} \sim 4.3 \mu\text{m}$  close to  $\lambda_t$ , (b) at 50 K, SP1001 and LH1002 shows  $\lambda_{eff} \sim \lambda_t$ ; inset shows TDIPS fitting of LH1002 and SP1001 that confirm that the threshold wavelength remains almost same, solid (red) and dashed lines represent TDIPS fitting and experimental curves.

**B. Heterostructure detectors (similar barrier energy offset) with flat and graded barrier**

The photoresponse spectra of two detectors with a similar value of  $\delta E_v$  but one with a flat injector barrier (SP1001) and other with a graded injector barrier (SP1007) have compared in Fig. 3(a) at 50 K and  $E \sim -20.83$  kV/cm. From the VB diagram of Fig. 1(a) and (b), it is observed that due to the graded high energy barrier, hot holes of varying energy can overcome the injector/absorber barrier. However, with flat high energy barrier, hot holes with energy corresponding to only higher potential barrier can overcome the barrier. Thus, it is expected that efficiency of the hot - cold hole interaction in the absorber decreases for SP1001 which could be the prime mechanism of extended threshold wavelength in SP1001 and SP1007 [6]. Therefore, photoresponse with clear  $\lambda_{eff}$  observed in SP1007 even at a small value of the electric field as compared to SP1001.

The photoresponse spectra of SP1007 shows a clear  $\lambda_{eff} = 8.9 \mu\text{m}$ , however the designed  $\lambda_t = 3.1 \mu\text{m}$ . However, SP1001 shows  $\lambda_{eff} = 4.1 \mu\text{m}$  very close to the designed  $\lambda_t = 3.1 \mu\text{m}$ . The TDIPS fitting for SP1007 are shown in the inset of Fig. 3(a) where for SP1001 is already in the inset of Fig. 2(b). Thus, a clear extension observed in threshold wavelength for SP1007 at 50 K. This implies that by changing the high energy barrier from flat to graded (without changing the  $\delta E_v$ ), a clear  $\lambda_{eff}$  can be observed at 50 K. It may be noted here, since the responsivity of SP1001 data is order of  $\sim 0.05 \mu\text{A/W}$  (see Fig. 2 b), and SP1007 is of  $\sim 108 \mu\text{A/W}$  and for comparison in single Fig, we have multiplied responsivity of SP1001 by  $\times 120$  to just show visibility of data in one spectra.

To further analyze the effect of the gradient on  $\lambda_{eff}$ , the

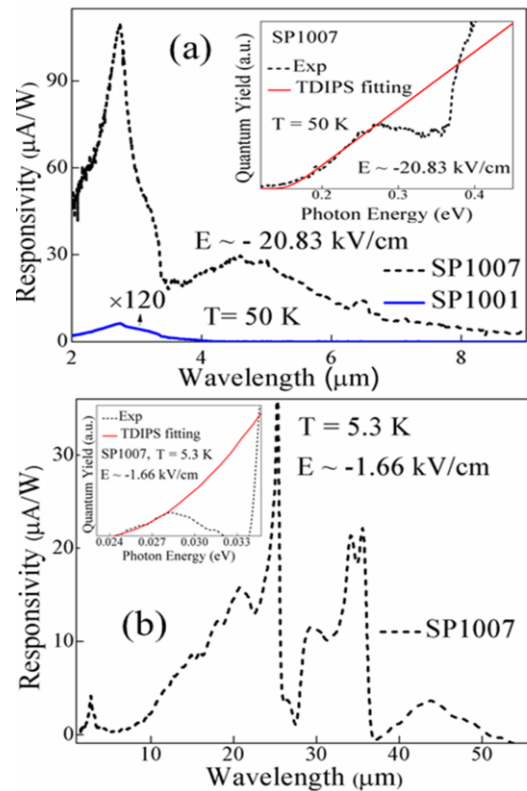


Fig. 3 (a) Photoresponse spectra of SP1001 and SP1007, as barrier changes from flat to graded, the  $\lambda_{eff}$  increases from  $4.1 \mu\text{m}$  to  $8.9 \mu\text{m}$ , inset shows TDIPS fitting for photoresponse spectra of SP1007 at 50 K, solid and dashed lines represent fitted and experimental curves (b) Photoresponse spectra of SP1007 at 5.3 K, a clear  $\lambda_{eff} = 55 \mu\text{m}$  is observed as compare to SP1001 of  $\lambda_{eff} \sim 36 \mu\text{m}$  at 5.3 K (see the Fig. 2(a)), inset shows TDIPS fitting for SP1007.



photoresponse spectrum of SP1007 is shown in Fig. 3(b) at  $T = 5.3$  K with inset shows TDIPS fitting of the data. The data is recorded at the  $E \sim -1.66$  kV/cm, for SP1007 the  $\lambda_{\text{eff}}$  started at a very small electric field and with the application of an electric field it shows a very slight increase in  $\lambda_{\text{eff}}$ . Thus for SP1007, a clear  $\lambda_{\text{eff}} = 55$   $\mu\text{m}$  at  $E \sim -1.66$  kV/cm observed; whereas in SP1001 an extended photoresponse is clearly observable, but  $\lambda_{\text{eff}}$  is detectable only up to  $\sim 36$   $\mu\text{m}$  (as already shown in Fig. 2(a)) even at higher  $E \sim -10.41$  kV/cm. This comparison shows that although extended photoresponse is observed for both detectors, i.e., SP1001 and SP1007, the clear  $\lambda_{\text{eff}}$  only observed for SP1007 at 5.3 K. Therefore, the graded barrier across injector barrier along with barrier energy offset is needed for observation of clear  $\lambda_{\text{eff}}$  at a higher temperature.

### C. Heterostructure detectors (similar graded barrier) with different barrier energy offset.

The photoresponse spectra of two detectors having similar device structure except two different barrier energy offsets, i.e., 15SP3 ( $\delta E_v = 0.19$  eV) and SP1007 ( $\delta E_v = 0.10$  eV) are compared at 50 K and  $E \sim -20.83$  kV/cm as shown in Fig. 4(a). The TDIPS fitting for 15SP3 is shown in Fig. 4(b) and for SP1007 it is already given in the inset of Fig. 3 (a). For 15SP3 the  $\lambda_{\text{eff}} = 13.7$   $\mu\text{m}$  whereas for SP1007,  $\lambda_{\text{eff}} = 8.9$   $\mu\text{m}$  is observed, however the designed  $\lambda_t$  is 3.1  $\mu\text{m}$  for both detectors. Therefore, it is observed by increasing  $\delta E_v$  from 0.10 eV to 0.19 eV (for the similar graded barrier), the  $\lambda_{\text{eff}}$  increases from 8.9  $\mu\text{m}$  to 13.7  $\mu\text{m}$ . This suggests that the value of  $\lambda_{\text{eff}}$  can be increased, for a given graded injector barrier by optimizing value of  $\delta E_v$ . The possible reason is, by varying  $\delta E_v$ , the number of hot holes injected into the absorber and escaping across the collector barrier can be controlled which consequently control the  $\lambda_{\text{eff}}$ . Therefore, by using a higher value of  $\delta E_v$ , a much longer  $\lambda_{\text{eff}}$  can be obtained for a given temperature.

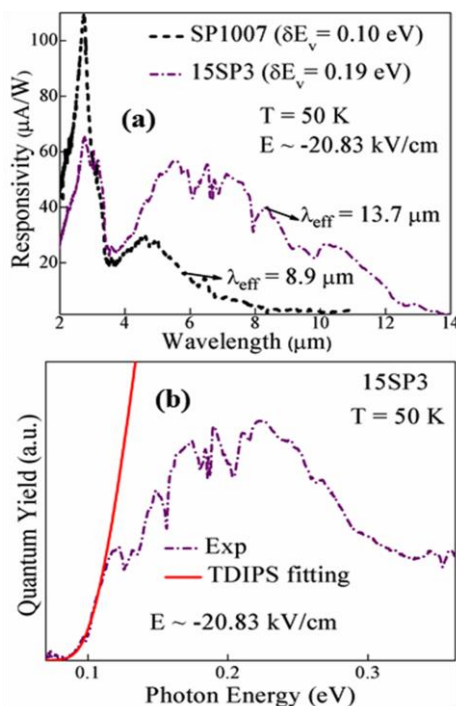


Fig. 4. (a) Photoresponse spectra of SP1007 and 15SP3 at 50 K, as  $\delta E_v$  increases from 0.10 eV to 0.19 eV the  $\lambda_{\text{eff}}$  increases from 8.9  $\mu\text{m}$  to 13.7  $\mu\text{m}$ . (b) TDIPS fitting for the photoresponse of 15SP3 to obtain the  $\Delta$  of the spectral photoresponse at 50 K, solid and dotted lines represent fitted and experimental curves, respectively.

## IV. CONCLUSION

In conclusion, the analysis of barrier design parameters on the extended threshold photoresponse of IR detectors has discussed in details up to 50 K. It is observed the  $\delta E_v$  is critical to obtain  $\lambda_{\text{eff}}$  ( $\gg \lambda_t$ ) in IR detectors at 5.3 K, however the gradient is needed to obtain  $\lambda_{\text{eff}}$  at 50 K. A conventional detector (LH1002), shows  $\lambda_t \sim \lambda_{\text{eff}}$  over operating temperature from 5.3 K and 50 K whereas the flat injector barrier and barrier energy offset detector (SP1001) shows  $\lambda_{\text{eff}} \sim 36$   $\mu\text{m}$  at 5.3 K and 4.1  $\mu\text{m}$  at 50 K. When the high energy injector barrier changes from flat (SP1001) to graded (SP1007), the  $\lambda_{\text{eff}}$  increases from 4.1  $\mu\text{m}$  to 8.9  $\mu\text{m}$  at 50 K. For a given graded injector barrier, as  $\delta E_v$  increases from 0.10 eV to 0.19 eV, the  $\lambda_{\text{eff}}$  increases from 8.9  $\mu\text{m}$  to 13.7  $\mu\text{m}$ . The results of this study indicate that by optimization of  $\delta E_v$  and the gradient, IR detectors with  $\lambda_{\text{eff}}$  ( $\gg \lambda_t$ ) can be designed to operate over a wide range of temperature for practical device applications.

## REFERENCES

- [1] Y.-F. Lao, A. G. U. Perera, L. H. Li, S. P. Khanna, E. H. Linfield, and H. C. Liu, "Tunable hot-carrier photodetection beyond the bandgap spectral limit," *Nat. Photon.*, vol. 8, pp. 412-418, 2014.
- [2] D. Chauhan, A. G. U. Perera, L. Li, L. Chen, S. P. Khanna, and E. H. Linfield, "Extended wavelength infrared photodetectors," *Opt. Eng.*, vol. 56, pp. 091605-091605, 2017.
- [3] Y. F. Lao, P. K. D. P. Pitigala, A. G. U. Perera, H. C. Liu, M. Buchanan, Z. R. Wasilewski, *et al.*, "Light-hole and heavy-hole transitions for high-temperature long-wavelength infrared detection," *Appl. Phys. Lett.*, vol. 97, pp. 091104, 2010.
- [4] J. Shah, "Hot carriers in quasi-2-D polar semiconductors," *IEEE J. Quantum Electron.*, vol. 22, pp. 1728-1743, 1986.
- [5] M. L. Brongersma, N. J. Halas, and P. Nordlander, "Plasmon-induced hot carrier science and technology," *Nat. Nano.*, vol. 10, pp. 25-34, 2015.
- [6] D. Somvanshi, D. Chauhan, Y. F. Lao, A. G. U. Perera, L. Li, S. P. Khanna, *et al.*, "Analysis of Extended Threshold Wavelength Photoresponse in Nonsymmetrical p-GaAs/AlGaAs Heterostructure Photodetectors," *IEEE J. Sel. Top. Quantum Electron.*, vol. 24, pp. 1-7, 2018.
- [7] D. J. Erskine, A. J. Taylor, and C. L. Tang, "Femtosecond studies of intraband relaxation in GaAs, AlGaAs, and GaAs/AlGaAs multiple quantum well structures," *Appl. Phys. Lett.*, vol. 45, pp. 54-56, 1984.
- [8] J. Shah, A. Pinczuk, A. C. Gossard, and W. Wiegmann, "Energy-Loss Rates for Hot Electrons and Holes in GaAs Quantum Wells," *Phys. Rev. Lett.*, vol. 54, pp. 2045-2048, 1985.
- [9] D. G. Esaev, M. B. M. Rinzan, S. G. Matsik, and A. G. U. Perera, "Design and optimization of GaAs/AlGaAs heterojunction infrared detectors," *J. Appl. Phys.*, vol. 96, pp. 4588-4597, 2004.
- [10] D. Chauhan, A. G. U. Perera, L. H. Li, L. Chen, and E. H. Linfield, "Dark current and photoresponse characteristics of extended wavelength infrared photodetectors," *J. Appl. Phys.*, vol. 122, pp. 024501, 2017.
- [11] S. G. Matsik, R. C. Jayasinghe, A. B. Weerasekara, A. G. U. Perera, E. H. Linfield, S. P. Khanna, *et al.*, "Effect of emitter thickness on the spectral shape of heterojunction interfacial workfunction internal photoemission detectors," *J. Appl. Phys.*, vol. 106, pp. 014509, 2009.
- [12] Y.-F. Lao, A. G. U. Perera, L. Li, S. P. Khanna, E. H. Linfield, Y. Zhang, *et al.*, "Mid-infrared photodetectors operating over an extended wavelength range up to 90 K," *Opt. Lett.*, vol. 41, pp. 285-288, 2016.
- [13] Y.-F. Lao and A. G. U. Perera, "Temperature-dependent internal photoemission probe for band parameters," *Phys. Rev. B*, vol. 86, p. 195315, 2012.