Ultimate Performance of IB CID T2SLs InAs/GaSb and InAs/InAsSb Longwave Photodetectors for High Operating Temperature Condition

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The highest performance of interband cascade detectors optimized for the longwave range of infrared radiation is investigated in this work to include decisive electric gain contribution. Presently, A^{III}B^V-type-II superlattice systems exhibit short carrier lifetimes limited by Shockley–Read–Hall generation–recombination processes. The maximum reported carrier lifetimes at 77 K for the InAs/GaSb and InAs/InAsSb type-II superlattices in longwave range correspond to ~ 200 ns and ~ 400 ns, respectively. We estimated theoretical detectivity of interband cascade detectors versus high operating temperatures, number of stages, absorber thickness, absorption coefficient and carrier lifetime; carrier lifetime were varied up to the reported value of MCT ~ 1 μ s. It has been shown that for room temperature the utmost performance–detectivity $\sim 10^{10}$ cmHz^{1/2}/W for the optimized detector operating in the longwave range ~ 10 μ m and assuming electric gain effect could be reached.

Key words: HOT, T2SLs, InAs/GaSb, InAs/InAsSb, FSO

INTRODUCTION

Among the methods to reach higher operating temperature (HOT) conditions the proper selection of the active layer exhibiting the highest absorption coefficient and thermal generation rate ratio (α/G) must be numbered. Currently, except MCT, both type-II superlattices (T2SLs) InAs/GaSb and InAs/InAsSb must be added to the list of the materials characterized by the highest α/G ratio. T2SLs exhibit short carrier lifetimes related to the Shockley–Read–Hall (SRH) generation–recombination (GR) mechanism. Improvement in that field was theoretically and experimentally proved by “Ga-free” T2SLs InAs/InAsSb in comparison with T2SLs InAs/GaSb.

In terms of extremely HOT conditions (up to 400 K and high frequencies 1.3 GHz) the interband cascade infrared detectors (IB CIDs) have been proving to be suitable candidates to that temperature and longwave (LWIR) range and could be implemented into free-space optical communication (Free Space Optics, FSO).^{1–4} IB CID contains multiple discrete absorbers designed with a thickness being thinner than the carrier diffusion length and separated by electron and hole barriers where adjacent stages are electrically connected by interband tunneling.

Figure 1 shows a IB CID band structure with absorber based on the T2SLs InAs/GaSb. In an absorber, electrons are optically excited from state H_1 in the valence band to state C_1 in the conduction band, and then move to the left through intraband relaxation. The relaxation region is constructed with graded multiple quantum wells with discrete energy levels. Electrons return to the valence band

state in the adjacent absorber through interband tunneling.

In terms of FSO the LWIR range is mostly explored due to the limited scattering and atmospheric turbulence in comparison to the commonly used $\lambda \sim 1550$ nm range. Currently, FSO in LWIR is dominated by MCT being temperature unstable due to the weak Hg bonds reducing the material strength, resulting in a weak mechanical properties and major difficulties in a material *processing* (detectivity for MCT LWIR, $\lambda \sim 10$ μm should stay within range $\sim 9 \times 10^9$ – 3×10^{10} Jones, while time constant 4–0.3 ns to fulfill requirements of the FSO system–detectivity and time constant stay in contradiction in optimization process).^{5,6} That issue could be circumvented by the IB CID with T2SLs $\text{A}^{\text{III}}\text{B}^{\text{V}}$ active layers. In the paper the utmost detectivity of IB CID for LWIR range ($\lambda = 10$ μm , $E_g = 0.124$ eV) and HOT conditions are discussed. Moreover, IB CID exhibits electrical gain exceeding unity that is why an influence of electrical gain on the utmost detectivity is shown.^{7–10} Electrical gain allows to operate with improved performance without current matching.

The comparison of the T2SLs: InAs/GaSb and InAs/InAsSb, assuming the characteristic parameters—absorption coefficients (α), carrier lifetimes (τ) and carrier mobility (μ) and dependence of the Johnson-noise limited detectivity on the absorber thickness for a different number of stages at HOT is reported. According to the calculations, the cascade detectors based on “Ga-free” T2SLs exhibit higher performance. Lei et al. claims that LWIR IB CID architecture has not been optimized yet but cascade detector can operate at 300 K with $D^* > 10^8$ $\text{cmHz}^{1/2}/\text{W}$ exceeding the reported values of the LWIR HgCdTe operating without cooling.^{11,12}

ULTIMATE PERFORMANCE IB CID FOR LWIR

In the simulations, the IB CID architecture for LWIR, $\lambda_{\text{cut-off}} = 10$ μm (corresponding bandgap, $E_g = 0.124$ eV) was assumed and utmost D^* was calculated. Since IB CID was proved to operate above room temperature, the utmost D^* was assessed within the range 200–400 K. The detailed active layer parameters assumed in simulations include absorption coefficient, carrier lifetime, carrier

Fig. 1. Schematic drawing of an IB CID photodetector with T2SLs InAs/GaSb absorber.

Fig. 2. LWIR utmost detectivity for IB CID T2SL InAs/GaSb (a) and T2SL InAs/InAsSb (b) versus temperature for selected number of stages: $N_s = 2, 6, 10, 20, 30$.

Table I. The nominal T2SLs InAs/GaSb and InAs/InAsSb active layers simulation parameters

T2SLs	Absorption coefficient (cm ⁻¹)	Carrier lifetime (ns)	Electron effective mass	Hole effective mass	Electron mobility (m ² /Vs)	Hole mobility (m ² /Vs)
InAs/GaSb	3000	200	$m_{II} = 0.0235$; $m_{\perp} = 0.0275$	$m_{II} = 0.0342$; $m_{\perp} = 79.8$	0.1	0.01
InAs/InAsSb	2000	400	$m_{II} = 0.016$; $m_{\perp} = 0.018$	$m_{II} = 0.033$; $m_{\perp} = 5.6$	0.1	0.01

 Fig. 3. LWIR utmost detectivity for IB CID T2SL InAs/GaSb (a) and T2SL InAs/InAsSb (b) versus number of stages for selected temperatures $T = 200$ K, 230 K, 300 K and 380 K.

mobilities and carrier effective masses (presented in Table I). Assuming equal absorber, $d = 150$ nm and gain contribution (see Eq. 2), the utmost detectivity reaches $\sim 5 \times 10^9$ (active layer T2SLs InAs/GaSb) and $\sim 9 \times 10^9$ Jones (T2SLs InAs/InAsSb) at 200 K while for 400 K, $D^* \sim 1 \times 10^9$ and $\sim 2 \times 10^9$ Jones was estimated, which are presented in Fig. 2a and b for a selected number of stages ($N_s = 2-30$).

lowering the external quantum efficiency. As can be seen, the current gain increases detectivity. With no gain, responsivity is determined by the last stage and the optimal number of stages depends on αd product according to the relation $N_s = (2\alpha d)^{-1}$ what was extracted from the equation (for equal active layers) presented by Hinkey et al.⁴:

$$D^* = (1 - R) \times (\lambda/hc) \sqrt{N_s} \frac{\alpha L / [1 - (\alpha L)^2] \times [\sinh(d/L) + \alpha L e^{-\alpha d} - \alpha L \cosh(d/L)] / \cosh(d/L) \times \exp(-\alpha d(N_s - 1))}{\sqrt{4g_{th}L \tanh(d/L)}}. \quad (1)$$

Detectivity versus number of stages ($N_s = 2-50$) simulated without gain (dashed line) and with gain contribution (solid line) is presented in Fig. 3. The fact that the equal absorbers device exhibits an equal photocurrent in all stages means that the external quantum efficiency depends on the photo-generation rate in the last stage. By the N_s increase the last stage moves away from the radiation source

Assuming gain (where responsivity is averaged over all stages) in the IB CID structure, the optimal number of stages could be assessed by solving the following expression: $e^{-x}(x + 0.5) - 0.5 = 0$ (where $x = N_s \alpha d$) yielding $N_s = (1.25\alpha d)^{-1}$ suggesting that number of stages must be nearly doubled to reach maximum detectivity in comparison to the condition where there is no gain in the structure and that was

extracted from the relation (for equal active layers) given by Huang et al.⁸:

$$D^* = (1 - R) \times (\lambda/hc) \frac{\alpha L / [1 - (\alpha L)^2] \times [\sinh(d/L) + \alpha L e^{-\alpha d} - \alpha L \cosh(d/L)] / \cosh(d/L) \times \exp(-\alpha \sum_{i=1}^{m-1} d_i) \times [1 - \exp(-N_s \alpha d)]}{\sqrt{N_s} [1 - \exp(-\alpha d)] \sqrt{4g_{th} L \tanh(d/L)}}, \quad (2)$$

where R stands for the reflectance at the device's top surface, L diffusion length, g_{th} thermal generation rate calculated as ratio of intrinsic concentration and carrier lifetime n_i/τ , d active layer thickness, N_s number of stages, α absorption coefficient, λ operating wavelength, h Planck constant, α absorption coefficient.

Figure 4 presents utmost detectivity calculated for both considered T2SLs and average carrier

lifetime for MCT, $\tau = 1 \mu s$ and selected temperatures: 230 K, 300 K and 380 K with gain contribution.

The background limited (BLIP) detectivity for $\lambda = 10 \mu m$, scene temperature, $T_B = 300$ K and field of view (FOV) 2π is estimated at the level of $\sim 5 \times 10^{10}$ Jones. Comparing BLIP performance to D^* at 300 K (presented in Fig. 4), T2SLs technology offers more than five times lower detectivity (using an average MCT carrier lifetime $1 \mu s$) while for $\tau < 10$ ns (see Fig. 5), D^* is two orders of magnitude lower.

Detailed D^* analysis versus carrier lifetime within the range 3 ns– $1 \mu s$ for selected temperatures 230 K, 300 K, 380 K was presented in Fig. 5. In simulations the active layer thickness, $d = 150$ nm and $N_s = 15$ were assumed. The characteristic absorption coefficients, 3000 cm^{-1} for InAs/GaSb and 2000 cm^{-1} for InAs/InAsSb active layers were assumed. Improvement in carrier lifetime from 3 ns to $1 \mu s$ increasing detectivity by one order of magnitude.

Absorption coefficient influences D^* and determines the IB CID optimal number of stages. The detailed analysis for selected carrier lifetimes $\tau = 4$ ns, 40 ns, 200 ns and 400 ns for $T = 300$ K is shown in Fig. 6. Absorption coefficient was assumed to be varying within the range 10^3 – 10^6 m^{-1} contributing to the change of αL product from 0.0097 to 9.7 (where diffusion length for $T = 300$ K and electron and hole mobilities $\mu_e = 0.1$ and $\mu_h = 0.01$ assumes $9.7 \mu m$) where the reported diffusion lengths (according to Hinkey et al.) reach $L = 0.6$ – $20 \mu m$ in LWIR and D^* enhancement is observed

Fig. 4. LWIR utmost detectivity for IB CID T2SL InAs/GaSb and InAs/InAsSb versus number of stages for selected temperatures, $T = 230$ K, 300 K, and 380 K calculated using a MCT average carrier lifetime value ($\tau = 1 \mu s$). T2SLs InAs/GaSb ($\alpha = 3000 \text{ cm}^{-1}$), T2SLs InAs/InAsSb ($\alpha = 2000 \text{ cm}^{-1}$).

(a)

(b)

Fig. 5. LWIR utmost detectivity for IB CID T2SL InAs/GaSb (a) and InAs/InAsSb (b) versus carrier lifetime for selected temperatures $T = 230$ K, 300 K, and 380 K. T2SLs InAs/GaSb ($\alpha = 3000 \text{ cm}^{-1}$), T2SLs InAs/InAsSb ($\alpha = 2000 \text{ cm}^{-1}$).

Fig. 6. LWIR utmost detectivity for IB CID T2SL InAs/GaSb (a) and InAs/InAsSb (b) versus absorption coefficient for $T = 300$ K. T2SLs InAs/GaSb/T2SLs InAs/InAsSb: $d = 150$ nm and $N_s = 15$.

Fig. 7. LWIR utmost detectivity for IB CID T2SL InAs/GaSb (a) and InAs/InAsSb (b) versus absorber thickness for selected temperatures $T = 230$ K, 300 K, and 380 K. T2SLs InAs/GaSb/T2SLs InAs/InAsSb: $d = 150$ nm and $N_s = 15$.

mainly for the αL product < 1 .^{4,13–16} The diffusion lengths are expected to drop at high temperature due to reduction of the interband carrier lifetime.

The absorber's thickness contribution to D^* for $\tau = 200$ ns and selected $T = 230$ K, 300 K and 380 K are presented in Fig. 7. Active layer thickness ranges from 50 nm to $1 \mu\text{m}$ while the same number of stages, $N_s = 15$ were assumed for both T2SLs. When gain is included in simulations, the absorber should be thicker reaching ~ 290 nm for InAs/GaSb while for InAs/InAsSb ~ 420 nm assuming 230 K.

The active layer thickness maximizing D^* slightly increases for higher temperatures. Diffusion length is higher for InAs/InAsSb due to higher carrier lifetime increasing diffusion coefficient versus temperature.

CONCLUSION

The carrier lifetime is still a factor limiting LWIR T2SLs InAs/GaSb and InAs/InAsSb HOT detector's performance. At HOT conditions the carrier lifetime is reported to be < 100 ns allowing to reach 10^9 Jones at 300 K. The prospect is seen for $T > 300$ K where MCT could not operate for FSO.

ACKNOWLEDGMENTS

This paper has been done under financial support of the National Centre for Research and Development—Project DOB-BIO8/01/01/2016.

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