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Modelling of MWIR HgCdTe complementary barrier HOT detector

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ABSTRACT

The paper reports on the photoelectrical performance of medium wavelength infrared (MWIR) HgCdTe complementary barrier infrared detector (CBIRD) with *n*-type barriers. CBIRD nB_1nB_2 HgCdTe/$B_{1,2}$-*n* type detector is modelled with commercially available software APSYS by Crosslight Software Inc. The detailed analysis of the detector's performance such as dark current, photocurrent, responsivity, detectivity versus applied bias, operating temperature, and structural parameters (cap, barriers and absorber doping; and absorber and barriers compositions) are performed pointing out optimal working conditions. Both conduction and valence bands' alignment of the HgCdTe CBIRD structure are calculated stressing their importance on detectors performance. It is shown that higher operation temperature (HOT) conditions achieved by commonly used thermoelectric (TE) coolers allows to obtain detectivities $D^* \approx 2 \times 10^{10}$ cm $Hz^{1/2}$/W at $T = 200$ K and reverse polarisation $V = 400$ mV, and differential resistance area product $RA = 0.9\ \Omega cm^2$ at $T = 230$ K for $V = 50$ mV, respectively.

Finally, CBIRD nB_1nB_2 HgCdTe/$B_{1,2}$-*n* type state of the art is compared to unipolar barrier HgCdTe nBn/B-*n* type detector, InAs/GaSb/B-$Al_{0.2}Ga_{0.8}Sb$ type-II superlattice (T2SL) nBn detectors, InAs/GaSb T2SLs PIN and the HOT HgCdTe bulk photodiodes' performance operated at near-room temperature ($T = 230$ K). It was shown that the *RA* product of the MWIR CBIRD HgCdTe detector is either comparable or higher (depending on structural parameters) to the state of the art of HgCdTe HOT bulk photodiodes and both $A^{III}B^{V}$ 6.1 Å family T2SLs nBn and PIN detectors.

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1. Introduction

Hitherto, the infrared radiation (IR) industry is conquered by HgCdTe bulk photodiodes [1–3] and GaAs/AlGaAs intersubband quantum well infrared photodetectors (QWIP) [4,5]. The requirement of the infrared detectors' cryogenic cooling is a major impediment preventing from their extensive application that is why detector's cooling push boundaries to increase device operating temperature. It is known that the critical condition which must be fulfilled to construct the HOT IR detector is to achieve both low dark current and high values of the quantum efficiency. Among the mechanisms generating the dark current in detector's structure the following must be enumerated: band-to-band (BTB) tunnelling, trap assisted tunnelling (TAT), Schockley-Read-Hall (SRH) generation-recombination (GR) process, Auger GR process, and leakage currents.

It was found that an incorporation of the type II superllatice (T2SLs) e.g. InAs/GaSb 6.1 Å $A^{III}B^{V}$ family into detector architecture allows to reduce adverse BTB/TAT currents and GR Auger's contribution to the total dark current. Therefore T2SLs could be considered as an alternative to the bulk HgCdTe HOT detectors and GaAs/AlGaAs IR material systems [6]. Unfavourable SHR GR and leakage dark current's components could be limited by the properly selected barriers incorporated into detectors structure. The barrier's selection plays crucial role due to the lattice constant matching of the detectors' constituent layers, the barrier's height in both conduction and valance bands connected directly to the band alignment. It must be stressed that band alignment playing important role in design of the barrier IR structures is often fortuitous and extremely difficult to control from technological perspective [7].

The very first barrier structures were commonly known $A^{II}B^{VI}$ and $A^{III}B^{V}$ heterostructures invented to increase device's performance by suppression of the diffusion currents from the detector's active region. The next stage in IR detector's development was double layer heterojunction (DLHJ) allowing reducing both majority and minority carriers diffusion currents in comparison to the homojunction IR detectors. Another variation of the DLHJ was a graded gap structure incorporated between hole blocking layer and absorber to suppress tunnelling and GR currents [8].

Currently, among the barrier IR detectors (BIRDs) the leading position is occupied by minority carrier devices called unipolar barrier infrared detectors (UBIRD) proposed by Maimon and Wicks [9]. Among electron-blocking UBIRD detectors the most important are these designed with $A^{III}B^{V}$ compounds (GaSb, $InAs_{1-z}Sb_z$-cap layers, $InAs_{1-y}Sb_y$-active region, $AlSb_{1-x}As_x$–barrier), T2SLs nBn

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InAs/GaSb with AlGaSb/T2SLs barriers and UBIRD nBn HgCdTe detectors, while among hole-blocking UBIRD devices should be considered a four layer architectures: InAs/GaInSb/InAs/AlGaInSb often called "W" structures and GaSb/InAs/GaSb/AlSb referenced as "M" structures [10–12]. The most sophisticated structures containing both electron and hole blocking barriers (AlSb/T2SLs barriers) were proposed by Ting et al. [13] (called either complementary barrier infrared detectors – CBIRD) or PbIbN after Gautam et al. [14] showing possible advantages in suppressing dark currents by blocking majority and minority carriers and circumventing technological problems with making ohmic contact to the wide-gap layers.

Potential interest in InAs/GaSb T2SLs results not only from unique inherited capabilities of the new artificial material with entirely different physical properties in comparison to the constituent layers (InAs and GaSb), but also from the nearly zero band offsets leading to the desirable UBIRD/CBIRD band alignments difficult to attain in HgCdTe [15]. In addition, the 6.1 Å family's capabilities to tune the position of the conduction and valance band edges in independent way and near lattice matching is extremely helpful in designing of the unipolar and complementary barrier detectors. Although the abovementioned physical properties indicates potential T2SLs' superiority over bulk materials (including HgCdTe ternary allys), the T2SLs' quantum efficiency leaves a lot of to be desired (η = 20–30% in MWIR range and η = 8–12% in LWIR range depending on nBn/pBp architecture) which stems from low level of wavefunction overlapping and technological problems connected with growth of uniform and thick enough SLs [16]. What is more, short minority carrier lifetimes (τ_{DIF}, τ_{GR} < 10 ns in temperature range >200 K) also impedes the development of the T2SLs IR devices [17]. Similarly, theoretical simulations proved quantum dot infrared detectors (QDIPs) to be an alternative to the HgCdTe, but technological problems related to the growth of self-organized QDs led to the suspension of the research on this type of the detector [18,19].

Even though, HgCdTe does not exhibit valance zero band offset, it is commonly known that bulk HgCdTe offers quantum efficiency η = 50–70%, therefore recently research groups have attempted to apply UBIRD architecture to HgCdTe alloy (n type barrier) which offers technological advantages over p–n HgCdTe homojunction (simplifying the fabrication process) [20,21]. Moving forward, it is worth applying CBIRD architecture to HgCdTe alloy incorporating n type barriers to reduce dark current in comparison to UBIRD nBn HgCdTe/B-n type detector. Taking this into consideration, this paper presents the performance estimation of the MWIR CBIRD nB_1nB_2 HgCdTe/$B_{1,2}$-n type detector with cut-off wavelength of λ_c = 5.2 μm at temperature T = 200 K. The temperature and bias voltage dependences of the dark current and RA product, responsivity, and detectivity of the CBIRD HgCdTe are analysed. Finally, near-room temperature MWIR CBIRD HgCdTe detector state of the art is compared to nBn/B-n type HgCdTe UBIRD, nBn InAs/GaSb/B-$Al_{0.2}Ga_{0.8}Sb$ T2SLs, PIN InAs/GaSb T2SL and HOT HgCdTe bulk photodiodes' performance.

2. Simulation procedure

Theoretical modelling of the MWIR UBIRD nBn/B-n type HgCdTe detector was performed by Velicu et al. [21] and Martyniuk and Rogalski [22]. For the comparison reasons, the similar structural parameters for MWIR CBIRD nB_1nB_2 HgCdTe/$B_{1,2}$-n type detector were used. In the same way, for modelling purposes three layers electron barrier (EB–barrier I) was applied in order to mitigate the kinks emerging in energy diagrams between detector's constituent layers caused by compositional uniformity (see Fig. 1). Interdiffusion was modelled by applying gauss tail doping (dx = 0.05 μm). The modelled structure consists of the 0.16 μm thick n-type HgCdTe cap layer doped to $N_D = 7 \times 10^{14}$ cm^{-3}. After the cap layer, an n-type 0.15 μm thick HgCdTe barrier doped to $N_D = 2 \times 10^{15}$ cm^{-3} was incorporated. As mentioned, in our model the EB layer was divided on three sub-layers with composition grading fitted to the cap layer and absorber respectively (e.g. x = 0.33–0.6–0.275). The EB thickness was assumed to be thick enough to prevent electron tunnelling between the top contact layer and the absorbing layer, therefore the majority current is blocked by the barrier material under reverse applied bias. Next, n-type HgCdTe absorber with a thickness of 5–10 μm doped to $N_D = 10^{14} \rightarrow 5 \times 10^{16}$ cm^{-3} and composition x = 0.275 for MWIR range was used. Finally, 0.15–0.5 μm thick hole blocking (HB – barrier II) layer consisted of two n-type sub-layers fitted to the absorber were utilized (e.g. x = 0.275–0.6) and doped to $N_D = 10^{14} \rightarrow 5 \times 10^{17}$ cm^{-3}. Similarly to EB, interdiffusion at absorber–barrier II (HB) interface was modelled by applying gauss tail doping.

Numerical calculations were performed utilizing commercial software APSYS by Crosslight Software Inc. Specific equations and relations used in device's modelling are listed in Table 1 and Appendix. The 50% cut-off wavelength was calculated to be λ_c = 5.2 μm at T = 200 K. Detector's area was assumed to be 120 × 120 μm^2.

The noise current was calculated using the expression including Johnson–Nyquist noise, optical and electrical shot noises:

$$i_n(V) = \sqrt{(4k_BT/RA + 2qI_{DARK} + 2qI_B)}, \quad (1)$$

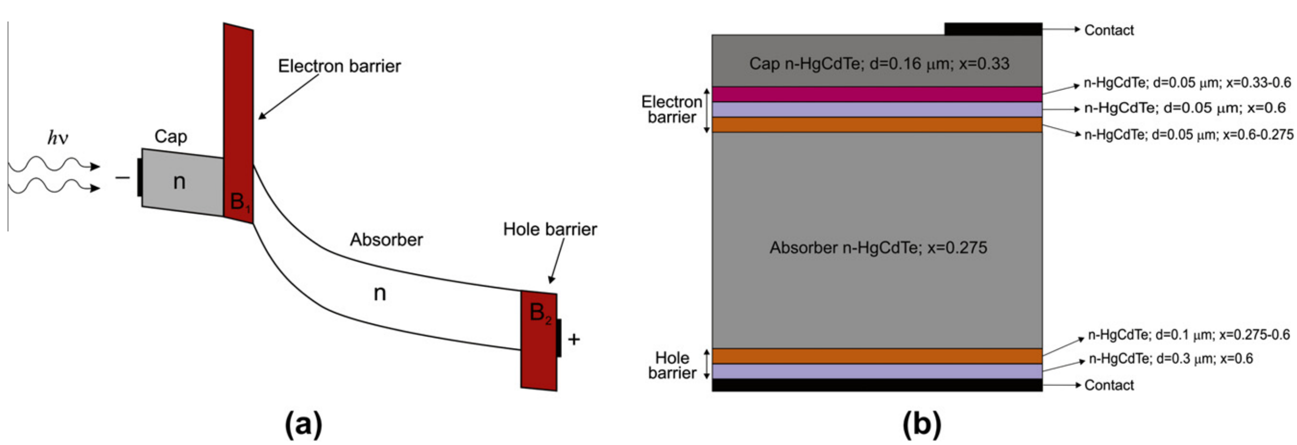

Fig. 1. CBIRD detector with the $nB_1nB_2/B_{1,2}$-n type design: (a) schematic of the heterostructure and (b) the device's structure.

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