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Independently Accessible Dual-Band Barrier Infrared Detector Using Type-II Superlattices

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Abstract: We report a novel dual-band barrier infrared detector (DBIRD) design using InAs/GaSb type-II superlattices (T2SLs). The DBIRD structure consists of back-to-back barrier diodes: a “blue channel” (BC) diode which has an nBp architecture, an n-type layer of a larger bandgap for absorbing the blue band infrared/barrier/p-type layer, and a “red channel” (RC) diode which has a pBn architecture, a p-type layer of a smaller bandgap for absorbing the red band infrared/barrier/n-type layer. Each has a unipolar barrier using a T2SL lattice matched to a GaSb substrate to impede the flow of majority carriers from the absorbing layer. Each channel in the DBIRD can be independently accessed with a low bias voltage as is preferable for high-speed thermal imaging. The device modeling of DBIRDs and simulation results of the current–voltage characteristics under dark and illuminated conditions are also presented. They predict that the dual-band operation of the DBIRD will produce low dark currents and 45–56% quantum efficiencies for the in-band photons in the BC with $\lambda_c = 5.58 \mu\text{m}$, and a nearly constant 32% in the RC with $\lambda_c = 8.05 \mu\text{m}$. The spectral quantum efficiency of the BC for 500 K blackbody radiation is approximately 50% over the range of $\lambda = 3\text{--}4.7 \mu\text{m}$, while that of the RC has a peak of 42% at $5.9 \mu\text{m}$. The DBIRD may provide improved high-speed dual-band imaging in comparison with NBN dual-band detectors.

Keywords: dual-band infrared detector; barrier engineering; InAs/GaSb type-II superlattices; T2SL device modeling; independently accessible; high speed dual-band thermal imaging



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1. Introduction

One of the increasingly important subjects to be developed for future infrared (IR) applications is multiband IR detection to identify the unique footprint of a target and increase the probability of detection and identification of imminent threats [1–4]. Semiconductor band architecture engineering permits various implementations of multiband IR detectors using a series of heterojunctions (HJs) that can be designed with a detailed understanding of carrier transport in the electronic band structure. Multiband IR photon detectors with HJs have been typically implemented with low bandgap (E_g) materials like HgCdTe [5–7], which has a tunable E_g and a small change of lattice constant with CdTe mole fraction. More recently, another tunable E_g material class, type II superlattices (T2SLs) [1–4], has emerged as an alternative to HgCdTe.

A T2SL is an artificial material with variable E_g , which may be controlled by the thicknesses of, for example, InAs and GaSb layers forming the superlattice. One of the interesting features of an InAs/GaSb T2SL is the small valence band offset (VBO) between the two materials while permitting the realization of various energy bandgaps [8,9], allowing the ready development of nBn unipolar barrier IR detectors. Indeed, this feature provides a major degree of freedom to design various devices, including multiband IR detectors with different E_g T2SL materials, and facilitates bandgap engineering to implement various novel devices that could open new horizons.

nBn unipolar barrier IR detectors are a recent achievement aiding the utilization of T2SLs since they can attain performance superior to conventional photoconductive detectors [8–12] and photovoltaic devices with the same materials [13–15]. The role of a unipolar barrier is to block the flow of majority carriers without hindering the photogenerated minority carriers' movement. This feature is very similar to a reverse biased p-n junction, which is a basic type of photovoltaic IR detector. A major feature of nBns in comparison with photovoltaic IR detectors is that they can suppress generation–recombination (G-R) and tunneling dark currents arising in the depletion regions of conventional p-n junctions, potentially resulting in higher sensitivity and/or a higher operating temperature with same sensitivity [8,11,13].

A sequential readout dual-band IR detector with InAs/GaSb T2SL materials is simply realized by the change of nBn to NBn, where the capital letter N means a larger E_g material than the lowercase n, both being T2SLs. An NBn bias selectable dual-band IR detector uses photogenerated minority carriers, namely holes, as the signal carriers in both n-type materials. An NBn dual-band IR detector has great simplicity in structure and operation. Its three layers are enough to form a good dual-band IR detector, and the detection band can be selected by simple bias switching. A PBp device with a unipolar hole barrier is a similar dual-band IR barrier detector, and can be seen as the twin of an NBn.

Another T2SL dual-band IR detector architecture is an NIPpin device [16–18]. Its twin PINnip has also been introduced [19]. In the epitaxially stacked PIN diodes, a wide and highly resistive intrinsic region of each diode is the IR absorber. A proper design of a band separator, a potential barrier between the two diodes, is important to reduce the electrical and spectral cross-talks. This device needs relatively high bias for operation. Another architecture with T2SL materials is NPBpN, introduced in ref. [2]. It is interesting that the barrier in this architecture is for blocking minority carriers, not for blocking majority carriers as in the NBn. The role of the barrier is a band separator. Having electrons as the minority carriers is the main advantage of the NpBPN architecture relative to the NBn since the electron mobility is greater than the holes in T2SLs. This device architecture has more unipolar barriers at each p-n junction to suppress Shockley–Read–Hall (SRH) G-R. These devices, with two terminals, can be operated via bias switching to sequentially access each band.

The first epitaxially stacked dual-band IR detector architecture was introduced with HgCdTe materials [5]. The device architecture is NPn, has two terminals and is a bias selectable dual-band detector. The reported quantum efficiencies (QEs) of each band were $QE > 65\%$ at $4\ \mu\text{m}$ with $+100\ \text{mV}$ bias, and $QE > 55\%$ at $7.5\ \mu\text{m}$ with $-200\ \text{mV}$ bias. The spectral cross-talk of the red channel to blue radiation was very high. Immediately after the introduction of this architecture, an independently accessed back-to-back HgCdTe dual-band photodetector architecture, PNnp, was introduced [6]. This device provided several important achievements, including (i) the true simultaneous and independent detection and integration of blue and red channel photocurrents, which leads to the capability of tracking rapidly moving objects, and (ii) independent electrical access, which allows the bias voltages for the blue and red channel diodes to be independently selected to optimize the performance of the individual detectors in both bands and their readout circuits [6].

A switching time is needed in bias selectable dual-band IR detectors, becoming the limiting factor determining the frame rate for high-speed thermal imaging applications. Here, true independently accessible dual-band IR detectors are preferred. However, the fabrication of such detectors in a high-density FPA is challenging, mainly because of the complexity in device architecture and interconnection with a readout circuit.

In this paper, a novel dual-band barrier IR detector (DBIRD) architecture using T2SLs is introduced. The DBIRD utilizes a unipolar electron barrier to block electron flow in the blue channel and a unipolar hole barrier to block hole flow in the red one. A detailed design procedure for a DBIRD is presented. A DBIRD modeling process to simulate its performance is also described. To assure proper operation and to estimate its electrical and optical performance, a DBIRD for middle and long wavelength (MW/LW) dual-band

detection is designed and modeled. The simulations show that the DBIRD photoresponses, such as QE, responsivity and detectivity, are similar to those in previous studies of single-band IR detectors with the same T2SLs. The NBpBN DBIRD has a barrier in each channel, so each channel device becomes a photodiode with a barrier in the depletion region to suppress SRH G-R. The DBIRD is designed to be a dual-band detector that has the merits of a NBn device and a photodiode, and does not need bias switching. The DBIRD may provide a relatively simple architecture and improved high-speed dual-band thermal imaging in comparison with NBn and NIPpin bias selectable dual-band detectors.

2. Materials and Methods

2.1. DBIRD Design

A DBIRD consists of two consecutive barrier photodetectors. Each consists of three sequential T2SL regions. The blue channel (BC) device must be optically ahead of the red channel (RC) one. In the sequence of the incident IR radiation, the BC device has an n-type absorber, the same type electron barrier, and a p-type region, while the RC device has a p-type absorber, the same type hole barrier, and an n-type region, together making up $NB_n p B_p n$ as a whole, where B_x means barrier with doping type x . Capital letter N means the larger band gap n-type T2SL material. Figure 1 shows the schematic energy band profiles and photogenerated carriers transport schemes with a back-to-back diode representation of the DBIRD.

As shown in Figure 1a, IR radiation absorbed in the blue channel absorber (BCA) produces photogenerated electron–hole pairs, of which the holes may flow across the electron barrier (EB) to the p-type red channel absorber (RCA), resulting in a contribution to the BC signal. Similarly, IR radiation absorbed in the RCA produces photogenerated electron–hole pairs, of which the electron may flow across the hole barrier (HB) to the n-type electron collection layer (ECL), resulting in a contribution to the RC signal. Figure 1b shows a similar energy band profile that has a different ECL and the contact positions. Here, the BC device $NB_n p$ may be accessed through the contacts C1 and C2, while the RC one $p B_p n$ is accessible through C2 and C3. The access to one channel is independent of the other, which means that each channel of the DBIRD can be independently accessed; this is highly preferable for high-speed IR imaging applications. Each channel device may be independently biased to optimize its performance. Hence, the DBIRD is appropriate for high-performance and high-speed dual-band thermal imaging. It can also provide operational flexibility, such as variable integration times and sequential access to the two channels.

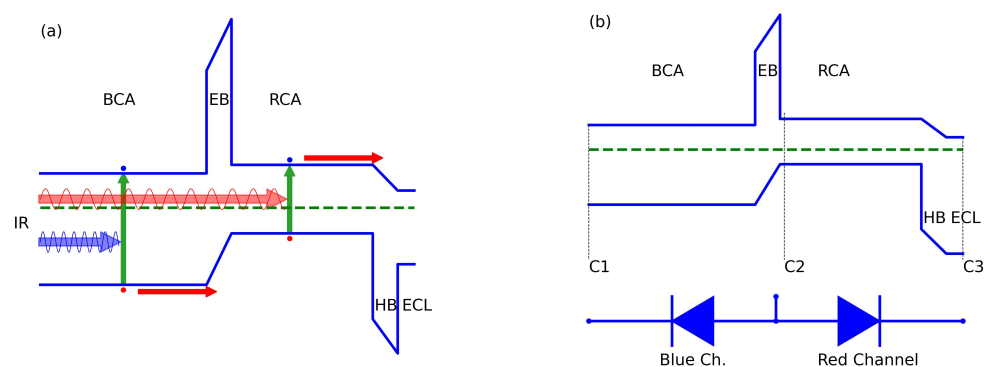


Figure 1. (a) Schematic band profile of a DBIRD with representation of photogenerated minority carriers and their transport to form a signal for each channel. (b) Schematic band profile with three contact positions C1, C2, and C3 (top) and a circuit symbol representation of back-to-back diodes (bottom) of a DBIRD. Note that in (b) ECL is made of the same material as HB with a different doping type. Since ECL is the top layer of this design, it is highly preferred to be a higher energy band gap material.

Figure 2 shows a schematic cross-sectional view of a MW/LWIR DBIRD. Each absorber layer thickness should be less than the diffusion length of the minority carrier, and longer than the absorption length $1/\alpha$ for in-band photons in each channel with absorption coefficient α . The diffusion length of holes, the minority carrier of the BCA, may be estimated as follows:

$$L_p = \sqrt{D_p \tau_p} \quad (1)$$

$$D_p = \mu_p \frac{k_B T}{q} \quad (2)$$

where k_B is the Boltzmann constant, q is the electron charge, and L_p , D_p , τ_p , and μ_p are the hole diffusion length, diffusion coefficient, lifetime, and mobility, respectively. For the BCA of an InAs 10 MLs(mono-layers)/GaSb 10 MLs T2SL with a hole mobility of $450 \text{ cm}^2/\text{Vs}$ and hole lifetime of 100 ns [3,17], the estimated hole diffusion length is approximately $5.4 \text{ }\mu\text{m}$ at 77 K. The absorption length of the in-band photon is about $3.3 \text{ }\mu\text{m}$. So the optimal thickness of the BCA is about $5 \text{ }\mu\text{m}$, producing approximately 77% absorption in the BCA. Similarly, for the RCA of an InAs 14 MLs/GaSb 7 MLs with an electron mobility of $1000 \text{ cm}^2/\text{Vs}$ and electron lifetime of 17 ns [14,20–22], the estimated electron diffusion and absorption length are 3.3 and $4 \text{ }\mu\text{m}$, respectively, so the thickness of the RCA is about $3 \text{ }\mu\text{m}$, producing approximately 53% absorption. A low dopant concentration of each absorber is preferable in high-quality materials to produce long minority carrier lifetimes.

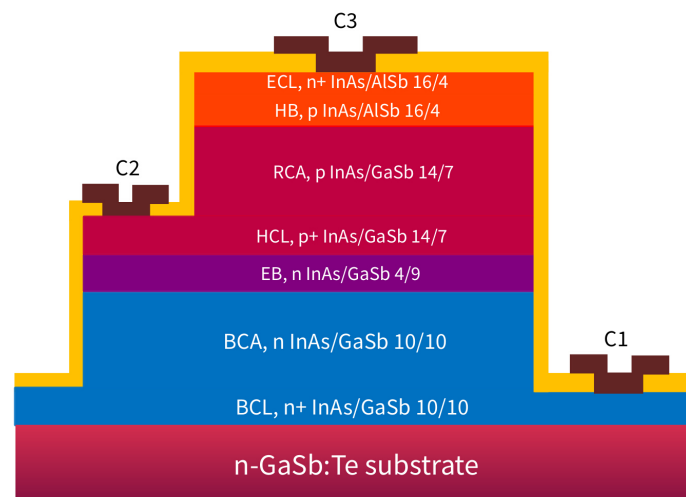


Figure 2. Cross-sectional view of an MW/LWIR DBIRD design. IR is incident from the substrate side. C1, C2, and C3 presented by dark brown are metal pads for electrodes.

The unipolar barrier design is the most important part of a DBIRD. It is interesting and complex. Three features in the barrier design are essential to make the device operate properly. The first is the band offsets, which are the valence band offset (VBO) in the BC, a minority hole device, and the conduction band offset (CBO) in the RC, a minority electron device. As shown in Figure 1, the VBO between the EB and its adjacent layers should be minimized, while the CBO between the HB and its adjacent layers should likewise be minimized. The VBO and CBO may be controlled via the InAs/GaSb T2SL design. The second feature is the doping type and concentration of each barrier layer. The doping type of the barrier should be the same as that of the absorber to place the metallurgical junction at the position where the unipolar barrier meets the signal carrier collection layer, the hole collection layer (HCL) on which C2 is based and the ECL on which C3 is based as shown in Figure 2. Each barrier doping concentration should be determined to confine the depletion region within that layer. The third feature is the height of each barrier, which may affect the SRH G-R rate in the depletion layer. A good rule of thumb is to have the barrier height, namely, its bandgap energy, be greater than twice the E_g of the absorber

layer. The thickness of the barrier is also important, namely, to prevent the tunneling of majority carriers.

The design of each minority carrier collection layer may seem simple at first, but there are some alternatives in considering its role. As shown in Figure 1a,b, there are two choices of the ECL material. The first is the same material as the RCA with n-type doping. Since the ECL is not involved in IR absorption but acts as an electron collector, it can be made of the same material as the barrier, such as an InAs/AlSb T2SL but with a different doping type. This choice of ECL material gives two additional benefits: (i) ease of growth of the ECL, and (ii) a self-passivation effect with a wide E_g material. The choice of HCL is the RCA material with a high doping concentration for contact formation.

Table 1 presents a detailed layer design for the MW/LWIR DBIRD shown in Figure 2.

Table 1. T2SL layers design summary for MW/LWIR DBIRD.

Name	Material	MLs ¹	Thickness ²	N_D/N_A ³	etc
ECL	InAs/AlSb	16/4	200	$N_D/3 \times 10^{18}$	C3
HB	InAs/AlSb	16/4	200	$N_A/5 \times 10^{15}$	
RCA	InAs/GaSb	14/7	3000	$N_A/1 \times 10^{16}$	
HCL	InAs/GaSb	14/7	200	$N_A/1 \times 10^{18}$	C2
EB	InAs/GaSb	4/9	200	$N_D/5 \times 10^{15}$	
BCA	InAs/GaSb	10/10	5000	$N_D/1 \times 10^{16}$	
BCL	InAs/GaSb	10/10	200	$N_D/3 \times 10^{18}$	C1
Sub.	GaSb:Te				

¹ MLs: mono-layers, ² Thickness in nm, ³ Doping type and concentration in cm^{-3} .

2.2. Material Growth and Device-Processing Technology

T2SLs are typically grown on GaSb (001) substrates by molecular beam epitaxy (MBE). The strengths of MBE include precise compositional control and abrupt interfaces. Solid III-V sources are employed, and Group V usually has valved cracking cells. The growth initiates with a GaSb buffer layer to reduce the influence of any impurities or surface defects on the substrate. This is followed by the growth in the T2SL, which is designed to have an average lattice constant matched to that of the substrate. In situ material quality monitoring during growth is often undertaken with reflection high energy electron diffraction (RHEED). Recent papers containing growth and material characterization details include references [23,24].

Device processing starts with epitaxial T2SL materials. The device-processing steps include passivation, mesa etching, metal–semiconductor contacts formation, and metallization. Photolithography is frequently used to delineate areas on the T2SL material to selectively etch or deposit. The first step of device processing is the formation of a passivation layer to protect the T2SL materials. An additional passivation layer is necessary whenever the material surface will be exposed to air. This is followed by a deep mesa etch to achieve pixel isolation, in which the etch stop must be near the BCL as shown in Figure 3. The next step is forming metal–semiconductor contacts, one to the HCL and another to the ECL. A contact to the BCL is also necessary. The following are the metallization steps to make metal lines from the contacts to the bump pads, which are placed on the same level on the mesa area. After the metallization steps, the processed DBIRD chip needs to be hybridized to a Si-fanout or read-out integrated circuit to test its electro-optical properties. Figure 3 shows schematic diagrams of the selected processing steps. Recent papers describing the device processing of T2SL infrared detectors include references [25–28].

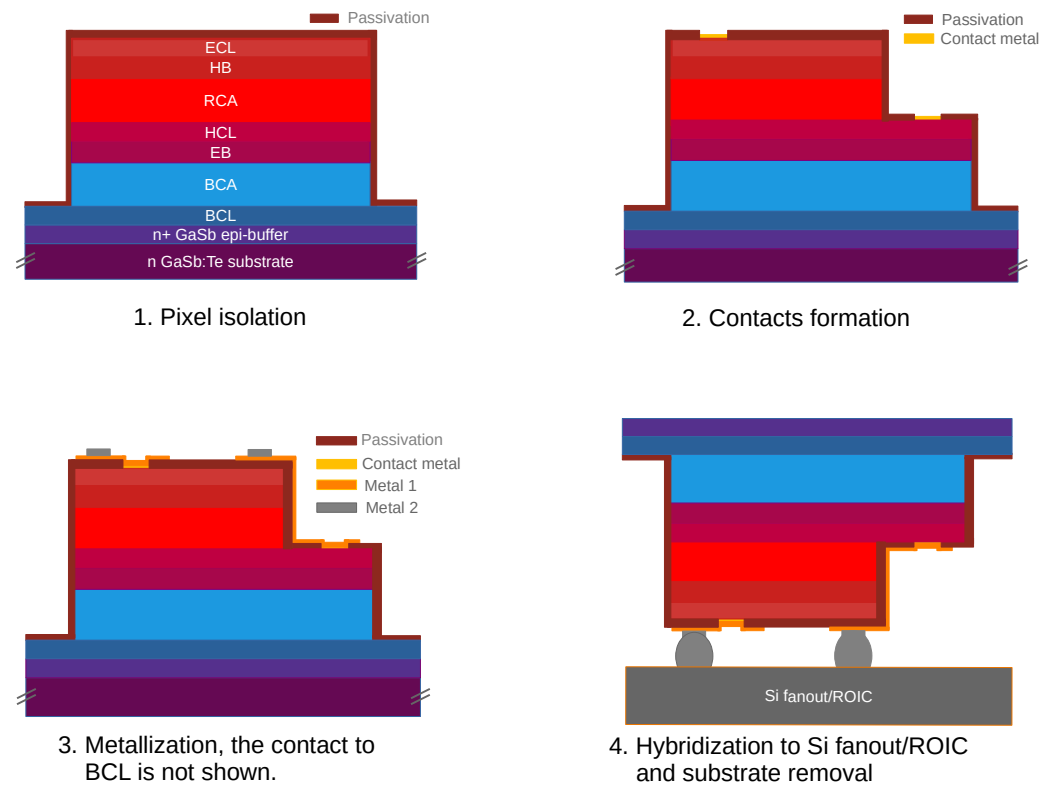


Figure 3. Schematic diagram of fabrication steps for a DBIRD.

2.3. DBIRD Modeling and Simulation

To assure correct device operation and to predict the electrical and optical performance, a series of modeling efforts was undertaken on the DBIRD shown in Figure 2. Each T2SL layer was treated as an equivalent semiconductor material having a fixed E_g . Then hetero-junction theory was applied to calculate the CBO and VBO between adjacent layers. Table 2 lists the employed T2SL material properties at 77 K used in this study [3,4,8,12,20,21,29].

Table 2. T2SL materials properties at 77 K used for the modeling of MW/LWIR DBIRD in Figure 2.

Name	Material	MLs	E_g	ϵ_s	χ	m_n^*	m_p^*
ECL	InAs/AlSb	16/4	0.514	14.52	4.785	0.054	0.506
HB	InAs/AlSb	16/4	0.514	14.52	4.785	0.054	0.506
RCA	InAs/GaSb	14/7	0.154	15.33	4.775	0.027	0.202
HCL	InAs/GaSb	14/7	0.154	15.33	4.775	0.027	0.202
EB	InAs/GaSb	4/9	0.488	15.53	4.393	0.036	0.182
BCA	InAs/GaSb	10/10	0.222	15.42	4.654	0.035	0.206
BCL	InAs/GaSb	10/10	0.222	15.42	4.654	0.035	0.206
Sub.	GaSb:Te						

E_g in eV, ϵ_s : relative permittivity, χ : electron affinity in eV calculated from VBO relative to InSb, m_n^* , m_p^* : growth-axis effective masses of electrons and holes. The growth-axis mobility μ_n and μ_p are assumed to be 1000 and 450 cm²/Vs for all T2SL layer after refs. [20,21].

The basic semiconductor equations to be solved include Poisson's equation coupled with the continuity equations of electrons and holes. Poisson's equation is as follows:

$$-\nabla \cdot (\epsilon_s \nabla \psi) = q(p - n + N_D^+ - N_A^-) \quad (3)$$

where ϵ_s is the relative permittivity, ψ is the electrostatic potential, q is the elementary electron charge, p , n , N_D^+ , and N_A^- are the concentrations of holes, electrons, ionized donors, and acceptors, respectively.

The continuity equations of the electron and hole are as follows:

$$\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \cdot \mathbf{J}_n + (G_{ph} - R_{SRH}) \quad (4)$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q} \nabla \cdot \mathbf{J}_p + (G_{ph} - R_{SRH}) \quad (5)$$

where $\mathbf{J}_n$ and $\mathbf{J}_p$ are the electron and hole current density, G_{ph} is photogeneration rate by absorbed photons and R_{SRH} is the SRH recombination rate. The electron and hole current densities are as follows:

$$\mathbf{J}_n = -qn\mu_n \nabla \psi + qD_n \nabla n \quad (6)$$

$$\mathbf{J}_p = -qp\mu_p \nabla \psi - qD_p \nabla p \quad (7)$$

where μ_n and μ_p are the electron and hole mobilities, D_n and D_p are the electron and hole diffusivities.

To evaluate the spectral IR response of a DBIRD, the wavelength dependence of the absorption coefficient was obtained first. The absorption coefficients are modeled after references [2,30] as follows:

$$\begin{aligned} \alpha(E) &= K \frac{(E - E_g)^n}{E}, \text{ for } E \geq E_T \\ &= \alpha_T \exp\left(\frac{E - E_T}{W}\right), \text{ for } E < E_T \end{aligned} \quad (8)$$

where K , n , W , and E_T are fitting parameters with experimental data, and $\alpha_T = \alpha(E_T)$. In this work, $K = 4.45 \times 10^3 \text{ eV}^{0.4}/\text{cm}$, $W = 0.0051 \text{ eV}$, $E_T = 0.2248 \text{ eV}$, and $\alpha_T = 503.40 \text{ cm}^{-1}$ for BC, $K = 2.75 \times 10^3 \text{ eV}^{0.4}/\text{cm}$, $W = 0.0050 \text{ eV}$, $E_T = 0.1570 \text{ eV}$, and $\alpha_T = 490.73 \text{ cm}^{-1}$ for RC, respectively, and $n = 0.6$ for both BC and RC are used.

The photogeneration rate was modeled as follows:

$$G_{ph}(x, \lambda) = (1 - r)E_{q,\lambda}\alpha(\lambda)\exp(-\alpha x) \quad (9)$$

where G_{ph} is the photogeneration rate in $\text{cm}^{-3}\text{s}^{-1}$, r is the reflectance at surface, $E_{q,\lambda}$ is the photon irradiance at λ in $\text{cm}^{-2}\text{s}^{-1}$, α is the absorption coefficient, and x is a position from the surface. Here, the photon irradiance on the detector surface E_q can be expressed as the sum of two terms, one from the signal source and another from the cold shield, and was modeled as follows:

$$E_q = E_{q,s} + E_{q,cs} \quad (10)$$

$$E_{q,s} = \frac{\pi}{4(F/\#)^2 + 1} \int_{\lambda_1}^{\lambda_2} L_s(\lambda, T_s) d\lambda \quad (11)$$

$$E_{q,cs} = \frac{4\pi(F/\#)^2}{4(F/\#)^2 + 1} \int_{\lambda_1}^{\lambda_2} L_{cs}(\lambda, T_{cs}) d\lambda. \quad (12)$$

where $F/\#$ is the cold shield F-number, L_s and L_{cs} are the spectral photon radiance of the blackbody source and cold shield of the detector in $\text{cm}^{-3}\text{srad}^{-1}\text{s}^{-1}$. With Equation (10), not only the spectral photon irradiance but the in-band photon irradiance on the surface of the detector can be evaluated. For spectral photocurrents, the photon radiance of a 500 K blackbody and cold shield $F/2$ were used. Also for in-band photocurrents, the photon radiance of a 300 K blackbody and no cold shield, that is, $F/0$ were used. Figure 4 shows the modeling results of absorption coefficients and photogeneration rates for both BC and RC in this study. The spectral QE, responsivity, and normalized detectivity were evaluated as follows:

$$\eta_\lambda = \frac{J_{ph,\lambda}}{qE_{q,\lambda}} \quad (13)$$

$$R_\lambda = \frac{J_{ph,\lambda}}{E_{e,\lambda}} \quad (14)$$

$$D_\lambda^* = R_\lambda \left[\frac{2k_B T}{R_0 A} + 2qJ_{ph,\lambda} \right]^{-1/2}. \quad (15)$$

where $E_{e,\lambda}$ is the spectral irradiance at λ , and X_λ is the quantity X at wavelength λ . Equation (15) may be applied to the reverse biased photodiode, not to the zero biased situation.

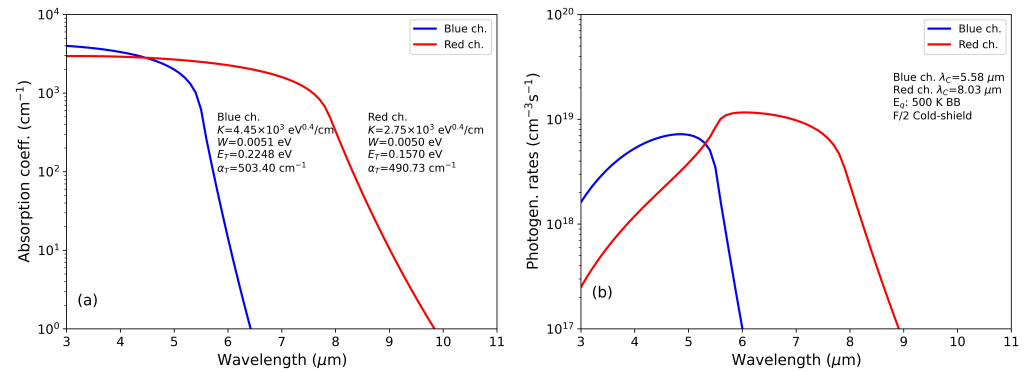


Figure 4. Absorption coefficients (a) and photogeneration rates (b) of MW/LWIR DBIRD design.

The COMSOL Multiphysics package was used to solve the basic semiconductor transport equations with and without photon illumination on the designed DBIRD. Simulations in thermal equilibrium state at 77 K were first performed with a one-dimensional model of the DBIRD design, while simulations under bias were performed on each channel device of BC and RC. Under steady-state conditions, the parametric simulations of applied bias with and without photogeneration provided the dark current density J_{dark} and photocurrent density J_{ph} . In current density simulations, SRH recombination was included with a hole lifetime of 100 ns for the BCA and an electron lifetime of 17 ns for RCA, respectively, and was assumed to be the limiting contributor to the dark current [20,21]. This assumption is thought to be valid at low reverse bias voltages, less than -0.3 V, where G-R currents through SRH recombination centers in the space charge region dominate. The J-V curves were obtained from the steady-state parametric simulations with bias voltage and photon illumination.

More detailed descriptions of the T2SL photodetector models may be found in recent published works [2,15,31].

3. Results and Discussion

Figure 5 shows the energy band and electric field profiles of the DBIRD design in thermal equilibrium at 77 K. Other than the bottom contact layer (BCL), hole collection layer (HCL) and electron collection layer (ECL), the energy band profile in Figure 5a is very similar to the schematic one shown in Figure 1. The high doping concentration layers BCL, HCL and ECL, which are necessary in a real device to make ohmic metal–semiconductor contacts, were added to produce a more realistic energy band profile. Note that there are no significant potential barriers to minority carriers in both the valence band of the BC and the conduction band of the RC as intended, so photogenerated minority carriers in the absorber layers can move freely across the barrier to collecting layer of each channel, resulting in photocurrents at the BC and RC. As shown in the insets of Figure 5a, the VBO between EB and BCA layer is found to be approximately 6 meV while the CBO between HB and RCA layer is found to be negative, approximately -10 meV. Specifically, the photogenerated holes, minority carriers in the BCA layer, can move freely across the barrier layer to the HCL, resulting in a BC signal current. At the same time, the photogenerated electrons, minority carriers in the RCA layer, can move freely to the ECL, resulting in a RC signal

current. In Figure 5b, note that most of the high electric field, of strength larger than about 10^3 V/cm, is almost completely confined within the barrier layers, which have a larger gap energy. This is expected to help suppress the dark current and result in high-performance detectors with low noise and high sensitivity.

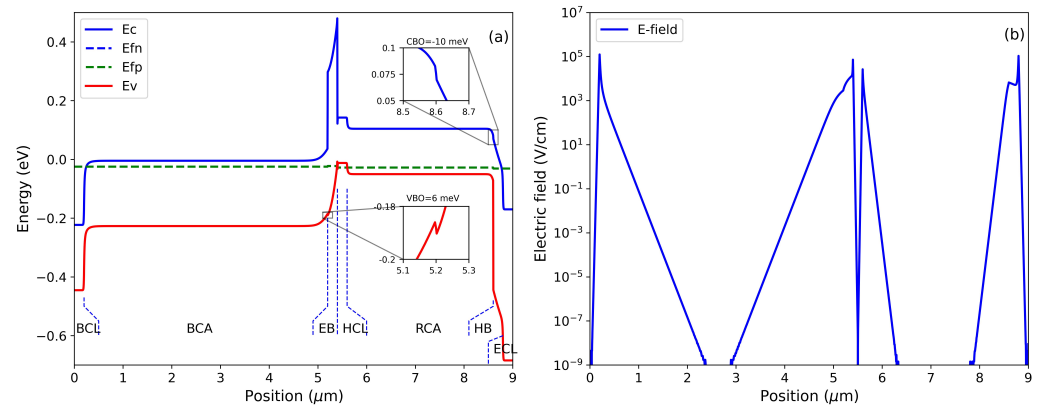


Figure 5. Energy band (a) and electric field (b) profiles of MW/LWIR DBIRD in thermal equilibrium at 77 K.

Figure 6 shows the current density–voltage (J–V) curves of the BC and RC devices of the DBIRD at 77 K; with and without incident photons. As shown in Figure 6, the dark current of the BC is almost flat up to the reverse bias of -1 V, while that of the RC slightly increases with increasing reverse bias up to -1 V. The dark currents of the BC and RC are 1.56×10^{-7} and 3.01×10^{-6} A/cm² at a reverse bias of $V = -0.2$ V, respectively. These values are comparable with the recent published experimental results, approximately 4×10^{-8} and 4×10^{-6} A/cm² at $V = -0.2$ V, at 80 K, respectively, in an NBn dual-band IR detector [28]. Considering also that the theoretically estimated dark current density of T2SL InAs/GaSb nBn at 77 K is less than 10^{-9} A/cm² for $\lambda_c = 5$ μm and 10^{-6} A/cm² for $\lambda_c = 10$ μm, respectively [32], the dark current of DBIRD seems to be as good as from a well-passivated T2SL InAs/GaSb single-band nBn device. In-band photoresponses may be evaluated from the photocurrents under photon irradiance E_q of the 300 K blackbody with no cold shield, which is the typical irradiance from a low-temperature probe station. The QE, responsivity, and D^* of the BC are evaluated as 48%, 1.90 A/W, and 7.04×10^{10} cm Hz^{1/2}W⁻¹ at -0.2 V reverse bias, while those of the RC are 32%, 1.87 A/W and 3.3×10^{10} cm Hz^{1/2}W⁻¹. These values of photoresponses are thought to be reasonable. In the BC, the absorption of incident photons was 78%, then 48% contributed to the detection signal current. The J–V curves together with the energy band and the electric field profile in Figure 5 strongly suggest that the DBIRD operates as a dual-band detector as designed. In addition, the dark current levels are reasonable in comparison with experimental results from devices with the same [28,33] and similar materials [14,20].

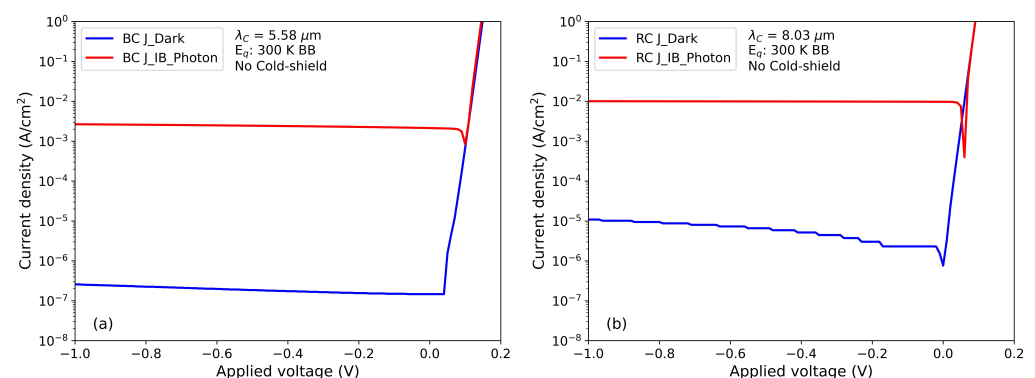


Figure 6. Current density–voltage curves of BC (a) and RC (b) at 77 K.

Figure 7 shows the spectral QE, responsivity, and normalized detectivity of the two channels in the DBIRD. The spectral photoresponses were evaluated from the photocurrent density at -0.2 V reverse bias. The QE of the BC decreases with increasing wavelength from 54% at $3\text{ }\mu\text{m}$, while that of the RC has a peak of 42% at $5.9\text{ }\mu\text{m}$. These values of QE are comparable with previous studies [14,20,33]. The responsivity of the BC has its peak of 1.7 A/W at $4.5\text{ }\mu\text{m}$, while that of the RC has its peak of 2.0 A/W at $6.2\text{ }\mu\text{m}$. Figure 7 also shows that the normalized detectivity of the BC is $2.5 \times 10^{11}\text{ cm Hz}^{1/2}/\text{W}$ at $3\text{ }\mu\text{m}$, and decreases as the wavelength increases, while that of RC has a peak value of $1.6 \times 10^{11}\text{ cm Hz}^{1/2}/\text{W}$ at $6.5\text{ }\mu\text{m}$. Note that these values are fairly high in comparison with the in-band ones.

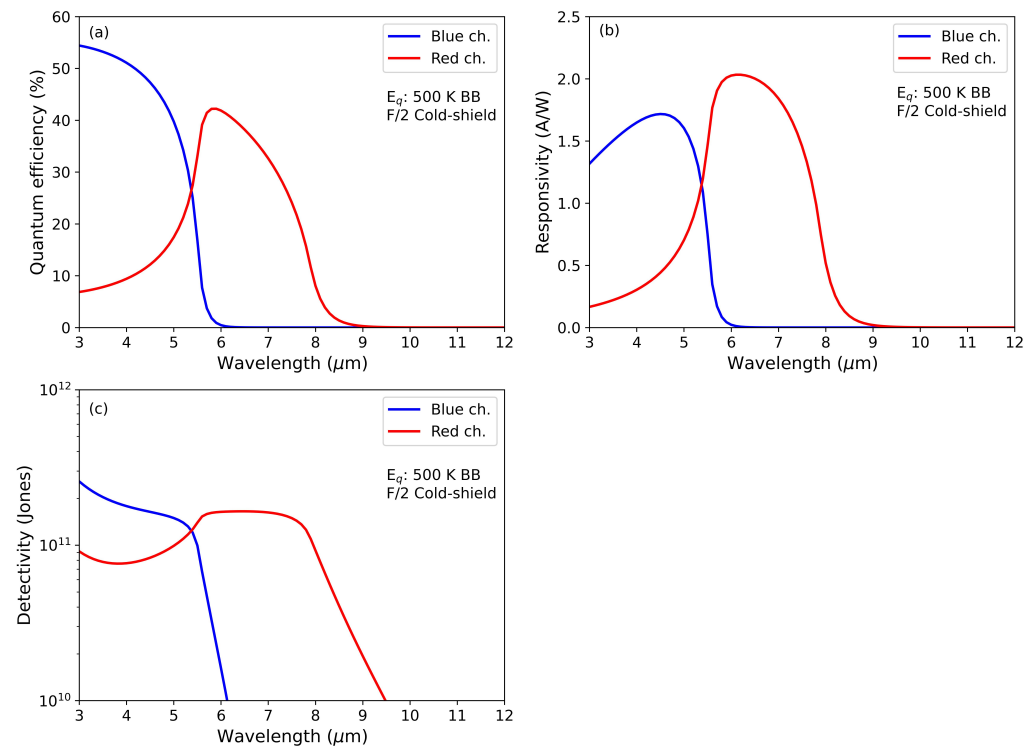


Figure 7. Spectral QE (a), responsivity (b), and detectivity (c) of DBIRD at 77 K. The photoresponses are evaluated at reverse bias $V = -0.2$ V.

The unabsorbed blue band photons in the BCA are transmitted to the RCA and absorbed, contributing the cross-talk of the RC to photons in the BC wavelength range. Figure 8 shows the spectral photocurrent densities of the two channels and the cross-talk of the RC in the DBIRD. The spectral cross-talk of the RC in the blue band is defined as the ratio of the photocurrent generated by absorbing the residual blue band IR in RCA $J_{RC}(\text{blue band})$ to the total photocurrent generated by the RC $J_{RC}(\text{blue} + \text{red band})$ [2],

$$SCT = \frac{J_{RC}(\text{blue band})}{J_{RC}(\text{blue} + \text{red band})}. \quad (16)$$

The photocurrents $J_{RC}(\text{blue band})$ and $J_{RC}(\text{blue} + \text{red band})$ can be evaluated by integrating the spectral photocurrent curve of the RC. As shown in Figure 8, $J_{RC}(\text{blue band})$ is the area of the shaded region over $\lambda = 3\text{--}5.58\text{ }\mu\text{m}$, while $J_{RC}(\text{blue} + \text{red band})$ is the total area under the spectral current density curve of the RC.

The evaluated spectral cross-talk of the RC in the blue band may be 24.1%. This suggests that 24.1% of the RC photocurrent under illumination with a 500 K blackbody may come from the contributions from the blue band. This value is high in comparison with that in the same dual-band detector using HgCdTe.

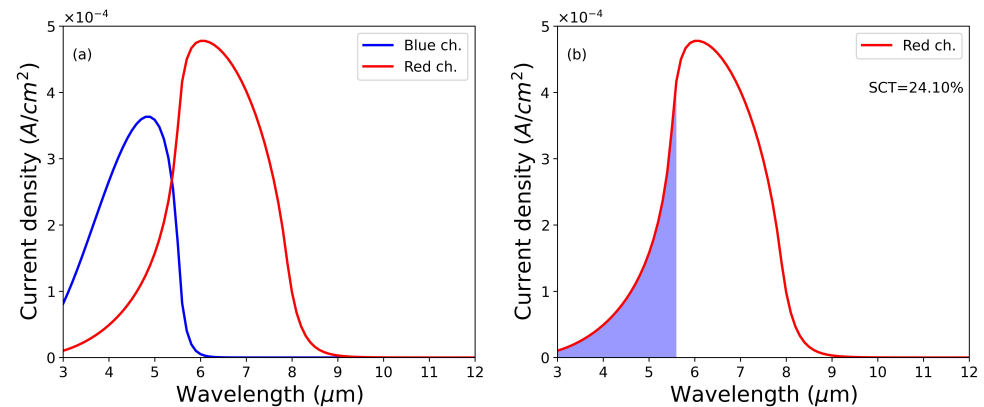


Figure 8. Spectral photocurrent of BC and RC in DBIRD (a) and RC cross-talk in blue band (b) at 77 K.

4. Conclusions

We have reported a novel dual-band barrier IR detector using InAs/GaSb T2SLs, named DBIRD. The structure of the DBIRD is NBpBN. It utilizes unipolar barriers to make each channel independently accessible, and to suppress generation–recombination current in the space charge region of each channel. A specific DBIRD has been designed and explored. Device modeling and the estimation of dark current and photocurrents were carried out. The estimated performance suggests that the DBIRD will perform as a dual-band detector per design. The performance of the DBIRD shows low dark currents in each channel device, in-band QE of 48% in the BC and 32% in the RC, and spectral QE of 54.4% in the BC and 42.2% at its peak in the RC. The DBIRD may provide a significantly improved capability and operational flexibility for high-speed dual-band imaging in comparison with NBn and NIPpin dual-band detectors.

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Abbreviations

The following abbreviations are used in this manuscript:

DBIRD	Dual-band Barrier IR Detector
T2SLs	Type-II Superlattices
BC, RC	Blue, Red Channel
HJs	Heterojunctions
VBO	Valence Band Offset
CBO	Conduction Band Offset
MW/LW	Middle and long wavelength
BCA	Blue Channel Absorber
RCA	Red Channel Absorber
EB	Electron Barrier

HB	Hole Barrier
ECL	Electron Collection Layer
HCL	Hole Collection Layer
SRH	Shockley–Read–Hall
G-R	Generation–Recombination
ROIC	Read-Out Integrated Circuit
QE	Quantum Efficiency
SCT	Spectral Cross-talk

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