Theoretical Study of Midwave Infrared HgCdTe nBn Detectors Operating at Elevated Temperatures

Nima Dehdashti Akhavan, Gregory Jolley, Gilberto A. Umana-Membreno, Jarek

Antoszewski and Lorenzo Faraone

School of Electrical, Electronic and Computer Engineering, The University of Western

Australia, 35 Stirling Highway, Crawley, WA 6009

Email: nima.dehdashti@uwa.edu.au

Abstract

We report a theoretical study of mercury cadmium telluride (HgCdTe) unipolar n-type/barrier/n-type (nBn) detectors for midwave infrared (MWIR) applications at elevated temperatures. The results obtained indicate that the composition, doping, and thickness of the barrier layer in MWIR HgCdTe nBn detectors can be optimized to yield performance levels comparable with those of ideal HgCdTe p - n photodiodes. It is also shown that introduction of an additional barrier at the back contact layer of the detector structure (nBnn⁺) leads to substantial suppression of the Auger generation–recombination (GR) mechanism; this results in an order-of-magnitude reduction in the dark current level compared with conventional nBn or p - n junction-based detectors, thus enabling background-limited detector operation above 200 K.

Index Terms – Mercury cadmium telluride (HgCdTe), Unipolar barrier detector, nBn detector, nBnn⁺ detector, Device simulation, Midwave infrared (MWIR), Auger suppression, HOT detector.

I. INTRODUCTION

HgCdTe-based photodetectors operating in the mid-wavelength infrared (MWIR; 3-5 μ m) have a broad range of military and civilian applications [1, 2]. However, the low operating temperature needed for thermal noise reduction requires the use of cumbersome and energy-consuming cooling systems. Research interest in high-operating-temperature (HOT) photodetectors is motivated by the need to substantially reduce the size, weight, and power requirements of infrared imaging systems.

From the perspective of processing and materials science, high-performance MWIR detectors and imaging focal-plane arrays (FPA) have, for decades, been dominated by HgCdTe-based *p-n* photodiodes [1, 2]. The long-term success of HgCdTe-based photovoltaic detectors is because of the excellent optoelectronic properties of HgCdTe and relatively mature device-processing technology. However, the performance of these devices is susceptible to Shockley-Read-Hall (SRH) generation-recombination centers in the depletion region, non-uniformities and/or impurities, and surface leakage current. The last of these demands effective surface passivation, which adds to the complexity of the detector-fabrication process. The development of HgCdTe-based detector structures which substantially simplify device fabrication processes, or circumvent the above challenges, is of great importance, assuming such designs result in devices which perform as well as or better than state-of-the-art *p-n* junction photodetectors. Nevertheless, recently proposed unipolar barrier detector structures are particularly attractive, because, in principle, the SRH-related dark current is substantially reduced [3, 4].

Currently, among different barrier IR detectors (BIRDs), the leading position is occupied by devices called unipolar barrier infrared detectors (UBIRDs) which incorporate a single type of doping (*n* or *p*) in their structures. A^{III}B^V family compounds (e.g., GaSb, InAs_{1-z}Sb_z cap

layers, $\text{InAs}_{1-y}\text{Sb}_y$ active region, $\text{AlAs}_{1-x}\text{Sb}_x$ barrier) have become the most important in the design of UBIRDs, mainly because of a nearly zero band offset in the valence band; this group of materials does not, however, have optical and electronic properties comparable with those of HgCdTe [5-9]. Although HgCdTe -based nBn structures do not naturally have a zero valence band offset, BIRD detector designs have been successfully adapted to the HgCdTe alloy, resulting in technological advantages over the HgCdTe p - n photodiode [10]. These advantages arise from: simplification of the fabrication process, relaxed requirements for the passivation process, elimination of the potential problems with p -type in-situ doping in molecular beam epitaxial (MBE) growth, removal of dopant implantation, and its subsequent activation [11-15]. It is worth noting that some approaches may lead to reduction or even elimination of the natural valence band offset of HgCdTe -based nBn structures [16-18]. As a consequence, the performance of the HgCdTe BIRDs can be substantially improved. However, this subject does not fit within the scope of this study and will be investigated independently [19, 20].

In this paper we report a study of the performance of BIRD MWIR HgCdTe detectors with a cut-off wavelength of $\lambda_c = 5 \mu\text{m}$ and operating in the temperature range of $T = 50\text{-}300 \text{ K}$. The temperature and bias voltage dependences of the dark current and detectivity of the HgCdTe -based nBn, nBnn^+ , pn and pnn^+ photodiode detectors were studied, including all important GR mechanisms, for example SRH, Auger, radiative, trap-assisted-tunnelling (TAT), band-to-band-tunneling (BTB), and existing mobility models (temperature dependence, electric field dependence, and doping dependence) [21, 22].

II. SIMULATION AND DEVICE DESIGN

Numerical calculations were performed by use of the commercially available software Synopsys Sentaurus device-simulation framework. The one-dimensional (1D) model incorporates electrical and optical material properties of HgCdTe from previously published models, and SRH, Auger, radiative, BTBT, and TAT GR mechanisms. Temperature-dependent, field-dependent and doping-dependent mobility models were included in the steady-state drift–diffusion model at all locations within the device [21, 22]. Dirichlet boundary conditions were implemented at the ohmic contacts, where charge neutrality and equilibrium conditions were assumed. The simulations assume step doping and compositional profiles; series resistance and surface recombination effects were assumed to be negligible. Specific equations and relationships used for calculation of carrier lifetimes and recombination rates are detailed in the Appendix I and Table I. The model was validated by fitting the calculated current–voltage characteristics of the p - n photodiode device to those of established experimental measurements [23-26] and models were developed on the basis of measured data [23, 27, 28]. Furthermore, the generation-recombination rates, and mobility values obtained from 1D modeling were compared with analytical models and available published data for HgCdTe with $x=0.30$ [28, 29] .

Schematic representations of the UBIRD and photovoltaic structures used in this study, with their energy band profiles, are shown in Figs. 1 and 2. Similar HgCdTe-based UBIRD designs have previously been reported by Velicu *et. al*, Itsuno *et. al*. and Martinuk *et. al*. [25, 30-33]. In this study we included all important GR and mobility models. Optimized data were obtained for MWIR $nBnn^+$ and pnn^+ detectors and it will be shown that the performance of the $nBnn^+$ detector can be similar to that of the best available pnn^+ detector technology.

The simulated nBnn⁺ detector for MWIR applications consists of an n-type contact layer of thickness of 1 μm , *n*-type barrier layer (e-Barrier) of 50 nm, to block the majority carrier (electron) flow, an In-doped ($N_D=10^{15}\text{cm}^{-3}$) *n*-type HgCdTe absorber layer of thickness of 10 μm and composition $x = 0.30$, and an *n*-type doped exclusion barrier of thickness of 1 μm and $x=0.40$ which blocks minority carrier (hole) injection from the ground contact at all temperatures.

Table I. Parameters taken in modeling of MWIR BIRD HgCdTe detectors				
	Contact	e-Barrier	Absorber	h-Barrier
Donor concentration, N_D (cm^{-3})	1×10^{15}	1×10^{15}	varies	5×10^{17}
Composition, x	0.30	0.60	varies	$x_{\text{abs}} \rightarrow 0.4$
Geometry, d (μm)	1	0.050	10	1
Overlap matrix, $F_1 F_2$	0.2			
SRH lifetime τ_{n0}, τ_{p0} (μs)	10, 1			
Trap energy level, E_{Trap}	$0.25 E_g$			
Trap concentration, N_{Trap} (cm^{-3})	5×10^{13}			
Capture cross-section, σ_n, σ_p (cm^2)	$10^{-15}, 10^{-16}$			
Target incident power density, ϕ (W/cm^2)	50			
Background temperature T_B , FOV	300K, 20°

Figure 1. Schematic representation of the p - n photodiode structure and associated energy band diagrams for (a) a p - n photodiode detector, and (b) an HOT pnn^+ detector with an exclusion junction to block minority carriers.

Figure 2. Schematic representation of the UBIRD structure and associated energy band diagrams for (a) an nBn detector, and (b) an HOT $nBnn^+$ detector with an exclusion contact.

2.1. Background-Limited Infra-red Performance (BLIP)

The optical responsivity (R) and detectivity (D^*) were calculated from the following analytical expressions based on current–voltage characteristics. The responsivity (R) was determined by the photocurrent density J_{photo} , because of the incident power density φ :

$$R = \frac{J_{photo}}{\varphi} \quad (1)$$

The noise current calculation includes current contributions from thermal Johnson–Nyquist noise and electrical and optical shot noise and is expressed as a quadrature sum:

$$i_n(V_{Bias}) = \sqrt{\left(\frac{4k_B T_d}{R_d A} + 2q(J_{Dark} + J_{Scene}) \right) A} \quad (2)$$

where k_B is Boltzmann’s constant, q is electron charge, T_d is the detector temperature, A is the detector area, and R_d is the dynamic resistance for a given reverse bias. J_{dark} is the dark current density and J_{scene} is the wavelength-dependent, scene-induced photocurrent due to the background scene, typically modeled as black-body radiation at 300 K, which can be calculated as follows [25, 32]:

$$J_{Scene} = 2\pi c q \times \sin^2\left(\frac{\theta}{2}\right) \int_0^{\lambda_c} \frac{1}{\lambda^4} \frac{1}{\exp\left(\frac{hc}{T_s k_B \lambda}\right) - 1} \eta(\lambda) d\lambda \quad (3)$$

where λ_c is the cut-off wavelength, θ is the field of view (FOV) and corresponds to the detector optics, T_s is the scene temperature, η is the normalized external quantum efficiency, and h and c are Planck’s constant and the speed of light, respectively. The electrical noise is typically dominated by thermal noise for operation near zero bias, whereas shot noise will be dominant for the nBn device operated under applied bias. The normalized external quantum efficiency is calculated as a function of the incident radiation wavelength, and can be expressed by:

$$\eta(\lambda) = \frac{J_{photo} hc}{\phi \lambda q} = R \frac{1.24}{\lambda(\mu m)} \quad (4)$$

where λ is the wavelength in μm . Finally, the detectivity (D^*) of the device as a function of incident radiation wavelength and current responsivity, is defined as:

$$D^*(\lambda) = \frac{R(\lambda) \sqrt{A}}{i_n(V_{Bias})} \quad (5)$$

where A is the area of the photosensitive region of the detector. The focal ratio $f_{\#}$ of the detector optics is given by f/D , where f is the lens focal length and D is the diameter of the entrance pupil. It is related to the FOV, such that a focal ratio $f_{\#}=0$ corresponds to 2π FOV. Typical $f_{\#}$ values in common infrared detector systems vary between 2 (FOV $\sim 30^\circ$) and 5 (FOV $\sim 10^\circ$) depending on the application. In this study FOV is assumed to be 20° ($f_{\#}=2.835$). The BLIP temperatures for dark current and detectivity of an MWIR detector considered in this study are shown in Figs. 3a and b.

Figure 3. Procedure used to identify the BLIP point in an nBn detector. (a) The intersection of the scene current and dark current correspond to a BLIP point with a BLIP current density of $2 \times 10^{-3} A/cm^2$; (b) the BLIP value of D^* is equal to $3.2 \times 10^{10} cmHz^{1/2}/W$. It is apparent that both the dark current and detectivity reach the BLIP condition at $T=166$ K.

2.2. Theory of HOT Detectors

The HOT photon detector concept originally introduced by Elliot and Ashley had a p-i-n⁺ structure in which an intrinsic region contains a *p*-type background dopant [34]. The intrinsic IR absorbing volume is connected to both a minority carrier contact and a majority carrier contact. The proposed device operates in strong non-equilibrium by reverse biasing the minority carrier contact to completely extract all the intrinsically generated minority carriers. Charge neutrality in the absorbing volume is violated, creating an electric field to sweep out the intrinsically generated majority carriers until the majority carrier concentration equals the background dopant concentration. Elimination of the minority carriers throughout the device means that minority carrier recombination processes are eliminated, and the dark current is determined entirely by generation mechanisms within the active volume of the device plus possible components related to injection from contact and surfaces. The HOT detector structures considered in this study were shown in Figs 1 and 2, and the data were specified in Table I.

III. Optimization of the nBnn⁺ Detector

3.1. *e*-Barrier Optimization

The barrier composition of UBIRD structures is important in the ultimate performance of the nBnn⁺ detectors. A barrier with a high proportion of Cd leads to a very large valence band offset (ΔE_V), which blocks the flow of minority carriers (holes) toward the contact and results in reduced detectivity. In contrast, a low proportion of Cd in the barrier leads to a very small conduction band offset (ΔE_C), compromising its blocking function and, consequently, reduced detectivity. Thus, adjusting the amount of Cd in the barrier layer is crucial to achieving a high-performance nBnn⁺ detector.

Figure 4 shows the valence band diagram of an nBnn⁺ detector for different values of the barrier width at $V_{\text{bias}}=-100$ mV and $T=100$ K. The optimum barrier width is 50 nm; a barrier layer with wider thickness will require a larger bias to eliminate the valence band offset (ΔE_V). On the other hand, a thinner barrier layer will increase quantum mechanical tunneling of the majority carriers (electrons) through the conduction band energy offset (ΔE_C) and, therefore; increase the dark current.

Figure 5 shows the energy band offsets in the barrier (ΔE_C , ΔE_V) as function of barrier doping density at a fixed voltage of $V_{\text{bias}}=-1$ mV and $T=100$ K, where it is apparent that increasing the barrier doping density results in larger ΔE_V and smaller ΔE_C which corresponds to larger dark current. The variation of (ΔE_C , ΔE_V) as a function of barrier doping density is because when the barrier doping density is increased the Fermi level in the barrier becomes closer to the conduction band and, to keep the Fermi energy of the barrier aligned with the Fermi energy in both the absorber layer and contact layer, the top of the conduction band and bottom of the valence band should shift to lower energies.

Figure 6a shows D^* as a function of barrier Cd composition and for $T=100$ K and $T=200$ K. It is apparent that the Cd composition should be set to $x=0.60$ to achieve the highest detectivity at both low and high temperatures. Figure 6b shows D^* as a function of barrier composition and for different bias values. For a maximum flow of minority carriers and, therefore, maximum D^* , a minimum bias of $V=-300$ mV should be applied to the detector.

Figures 7a and b show J_{dark} and J_{photo} as a function of bias and for different values of Cd composition, x_B , at $T=100$ K and $T=200$ K. It is apparent that high x_B values reduce J_{dark} by increasing the valence band offset whereas small values of x_B result in a small conduction band offset and hence large J_{dark} .

Figure 4. Valence band diagram in for different values of barrier width at $V_{\text{bias}}=-100$ mV and $T=100$ K.

Figure 5. Variation of ΔE_C and ΔE_V as a function of barrier doping density at a fixed applied voltage of $V_{\text{bias}}=-1$ mV. Increasing the barrier doping density will modify the barrier energy bands in such a way that large ΔE_V and small ΔE_C will be observed at very high doping levels.

3.2. Absorber Optimization

Having optimized the barrier composition for the MWIR nBnn⁺ detector, we investigated the effect of absorber layer doping density. In our calculations we assumed the barrier and contact layer doping density at $N_{\text{abs}}=10^{15} \text{ cm}^{-3}$ and $V_{\text{bias}}=-400 \text{ mV}$ (this V_{bias} is in the range where BTBT is negligible and the same time ΔE_V is minimum). Figure 8a shows D^* as a function of barrier doping density in the presence of a tunneling mechanism at $T=100 \text{ K}$ and $T=200 \text{ K}$. It is apparent that the absorber doping density should be kept below $2 \times 10^{15} \text{ cm}^{-3}$ to keep D^* above the BLIP limit at $T=200 \text{ K}$. When $T=100 \text{ K}$ the detectivity is well above the BLIP limit. Figure 8b shows D^* as a function of absorber doping density for different values of bias at $T=200 \text{ K}$. A minimum bias of -200 mV should be applied to the detector to reduce ΔE_V and enable the flow of minority carriers.

Figure 9a shows J_{dark} and J_{photo} as a function of absorber doping at $T=200 \text{ K}$; it is apparent that the BTBT component starts to increase significantly for doping densities higher than $2 \times 10^{15} \text{ cm}^{-3}$. Figure 9b shows J_{dark} and J_{photo} as a function of bias for different absorber doping levels at $T=200 \text{ K}$; a reverse bias $>200 \text{ mV}$ is required to reduce the valence band offset and enable the flow of minority carriers, whereas absorber doping densities higher than $2 \times 10^{15} \text{ cm}^{-3}$ result in strong BTBT.

Figure 6. (a) D^* as a function of barrier Cd composition for $T=100\text{ K}$ and $T=200\text{ K}$ for the nBnn^+ detector. (b) D^* as a function of e-barrier Cd composition for different values of applied bias for $T=200\text{ K}$ in the nBnn^+ detector.

Figure 7. J_{dark} and J_{photo} as a function of applied bias for different Cd composition in the barrier for (a) $T=100\text{ K}$ and (b) $T=200\text{ K}$.

Figure 8. (a) D^* as a function of absorber doping density for $T=200\text{ K}$ and $T=100\text{ K}$; (b) D^* as a function of absorber doping density for different values of bias at $T=200\text{ K}$.

Figure 9. (a) J_{dark} and J_{photo} as a function of absorber doping density at $T=200\text{ K}$ and $x_B=0.6$ for different values of bias; (b) J_{dark} and J_{photo} as a function of applied bias for different absorber doping densities.

IV. Optimization of the pnn^+ HOT Detector

4.1. Optimization of the Depletion Layer

Unlike the nBnn^+ detector, for which performance is determined by the properties of the barrier, pnn^+ detector performance is determined by the pn junction depletion region. Hence, optimization of the contact layer and absorber layer doping densities in p - n photodiode were the main objectives in this part of the work. Figures 10a and b show D^* and J_{dark} at $T=100$ K and $T=200$ K as a function contact layer doping density (p -type), assuming a fixed absorber doping density of $N_{\text{abs}}=10^{15} \text{ cm}^{-3}$. It is apparent that the contact layer doping density should be larger than $5 \times 10^{16} \text{ cm}^{-3}$ if D^* is to be higher than the BLIB limit. Setting the contact layer doping density above this minimum value creates a depletion region wide enough to collect the photogenerated minority carriers (holes) in the absorber region. Figures 11a and b show D^* and J_{dark} as a function of absorber doping density in the presence of different tunneling mechanisms at $T=100$ K and $T=200$ K. For $T=200$ K, it is apparent that, without considering BTBT, the Auger-1 recombination mechanism will reduce D^* for absorber layer doping densities higher than $2 \times 10^{15} \text{ cm}^{-3}$. Addition of BTBT reduces D^* even further.

Figures 12a and b show D^* and J_{dark} as a function of temperature and for different values of contact layer doping density assuming a fixed absorber doping density of 10^{15} cm^{-3} for the pnn^+ detector. As already discussed, reducing the contact doping density will reduce the detectivity of pnn^+ detectors by reducing the depletion layer width.

Figure 10. (a) D^* and, (b) J_{dark} as a function of contact layer doping density for $T=100 \text{ K}$ and 200 K for the pnn^+ detector. It is evident that BTBT limits the maximum doping density in the contact layer.

Figure 11. (a) D^* and, (b) J_{dark} as a function of absorber layer doping density for $T=100 \text{ K}$ and 200 K for the pnn^+ detector. It is evident that maximum doping density in the absorber layer is limited by the Auger-1 mechanism.

Figure 12. (a) D^* and, (b) J_{dark} as a function of inverse temperature and for different values of contact layer doping density for the pnn⁺ detector. Absorber doping density is fixed at $N_{abs}=1\times10^{15} \text{ cm}^{-3}$.

V. Performance Comparison of HOT Detectors

In the previous sections we optimized the barrier conditions for the nBnn⁺ and contact/absorber layer conditions for the of pnn⁺ detectors. In this section we compare the performance of nBn, nBnn⁺, pn, and pnn⁺ detectors to determine whether HgCdTe-based barrier detectors have any advantages over *p-n* photodiode technology. Figures 13a and 13 show D^* and J_{dark} as a function of absorber layer doping density at $T=100 \text{ K}$ and a fixed reverse bias of 300 mV. It is apparent that nBnn⁺ and pnn⁺ photodiodes have the same D^* value for low absorber doping density, however, the onset of performance degradation in pnn⁺ because of Auger-1 and BTBT starts earlier compared with nBnn⁺.

Figures 14a and 14 show D^* and J_{dark} as a function of absorber doping density for $T=200 \text{ K}$. It is apparent that the nBn and *p-n* photodiode are not able to perform at $T=200 \text{ K}$, whereas

the D^* in $nBnn^+$ and pnn^+ can go beyond the BLIP limit and are able to operate at high temperatures. The most important point is that the absorber layer doping density for both $nBnn^+$ and pnn^+ should be kept below $3 \times 10^{15} \text{ cm}^{-3}$ and ideally close to 10^{14} cm^{-3} , to minimise the tunneling current and Auger GR current. This is because increasing the temperature also increases the intrinsic carrier density; therefore, the Auger-1 lifetime becomes smaller. This is why the absorber doping density tolerable at $T=200 \text{ K}$ is smaller than maximum allowed doping density at $T=100 \text{ K}$.

Figures 15a and b show D^* and J_{dark} as a function of temperature for a fixed absorber doping density of $N_{abs}=10^{15} \text{ cm}^{-3}$. It is apparent that $nBnn^+$ and pnn^+ photodiodes have the same level of D^* and J_{dark} at high temperatures, however pnn^+ performance starts to degrade at temperatures below 100 K, because of strong BTBT. It is also apparent that dark current in $nBnn^+$ and pnn^+ structures at high temperatures becomes very close to the values predicted by Rule-07, which implies that HgCdTe-based HOT detectors have the potential to achieve the ultimate dark current limit predicted by Rule-07 [22, 26].

Figure 13. (a) D^* and, (b) J_{dark} as a function of absorber layer doping density for different structures at $T=100 \text{ K}$ and reverse bias fixed at -300 mV .

Figure 14. (a) D^* and, (b) J_{dark} as a function of absorber doping layer density for different structures at $T=200 \text{ K}$ and reverse bias fixed at 300 mV .

Figure 15. (a) D^* as a function of inverse temperature with an absorber doping density of $N_{\text{abs}}=10^{15} \text{ cm}^{-3}$, (b) J_{dark} as a function of inverse temperature with an absorber doping density of $N_{\text{abs}}=10^{15} \text{ cm}^{-3}$. nBnn⁺ and pnn⁺ can reach the dark current predicted by Rule-07.

VI. CONCLUSIONS

We performed a theoretical study of the performance of HgCdTe-based MWIR unipolar barrier detectors for elevated temperature operation, including all the important generation recombination mechanisms (SRH, Auger, radiative, BTBT, TAT, etc.). After optimizing the barrier parameters of nBnn⁺ detector, we found that the performance of this detector is the same as that of compared to the best pnn⁺ photodiode technology for high operating-temperature conditions ($T > 200$ K). However, the nBnn⁺ detector is superior to pnn⁺ photodiode from the perspective of fabrication, because it does not involve *p*-type doping and, hence, is more uniform and requires less stringent surface passivation.

ACKNOWLEDGMENTS

The authors wish to acknowledge the Australian Research Council for financial support of this work under the Super Science Fellowship program (grant number FS110200022) and the Discovery Project program (grant number DP120104835).

APPENDIX I

Bandgap

$$E_g(x, T) = -0.302 + 1.93x - 0.81x^2 + 0.832x^3 + \left(5.3510^{-4} (1 - 2x) * T \right)$$

Electron affinity

$$\chi = 4.23 - 0.813 (E_g - 0.083)$$

Intrinsic carrier concentration

$$n_i = (5.585 - 3.82x + 0.001753T - 0.001364xT) 10^{14} E_g^{0.75} T^{1.5} \exp \left[\frac{-qE_g}{2k_B T} \right]$$

Refractive index

$$\begin{aligned} \epsilon_r &= 20.5 - 15.5x + 5.7x^2 ; & \text{low frequency} \\ \epsilon_\infty &= 15.2 - 15.5x + 5.7x^2 ; & \text{high frequency} \end{aligned}$$

Electron and hole effective masses

$$\begin{aligned} \frac{m_0}{m_e^*} &= 1 + 2F + 0.33 Ep \left[\frac{2}{E_g} + \frac{1}{E_g + \Delta} \right] \\ \Delta &= 0.893 + 0.165x ; \quad F = -0.8 ; \quad Ep = 19 ; \quad m_h = 0.5m_0 \end{aligned}$$

SRH generation-recombination rate:

$$\begin{aligned} (G - U)_{SRH} &= \frac{pn - n_i^2}{\tau_{p0} \left[n + n_i \exp \left(\frac{E_t}{k_B T} \right) \right] + \tau_{n0} \left[p + n_i \exp \left(\frac{-E_t}{k_B T} \right) \right]} \\ \tau_{n0} &= (\sigma_n v_{th,n} N_{trap})^{-1} & \tau_{p0} &= (\sigma_p v_{th,p} N_{trap})^{-1} \\ v_{th,n} &= (8k_B T / \pi m_e^*)^{1/2} & v_{th,p} &= (8k_B T / \pi m_h^*)^{1/2} \end{aligned}$$

where E_{trap} is the difference between the defect level and intrinsic level.

SRH Doping Dependence (Scharffeter relation):

$$\tau_{dop}(N_A, N_D) = \tau_{\min} + \frac{\tau_{\max} - \tau_{\min}}{1 + \left(\frac{N_A + N_D}{N_{ref}} \right)^\gamma}$$

where N_A , N_D are the acceptor, donor doping concentrations. The parameters γ and N_{ref} are equal to 1 and 10^{17} cm^{-3} .

Auger generation-recombination rate:

$$(G-U)_{Auger} = \frac{C_n n + C_p p}{pn - n_i^2}$$

$$C_n = \frac{\left(\frac{m_e^*}{m_0} \right) |F_1 F_2|^2}{2n_i^2 3.8e^{-18} \epsilon_\infty^2 (1+\mu)^{\frac{1}{2}} (1+2\mu)} \times \left(\frac{E_g}{k_B T} \right)^{-\frac{3}{2}} \exp \left[- \left(\frac{1+2\mu}{1+\mu} \right) \frac{E_g}{k_B T} \right]$$

$$C_p = C_n \left[\frac{1 - \frac{3E_g}{k_B T}}{1 - \frac{5E_g}{4k_B T}} \right]$$

where,

$$\mu = \frac{m_e^*}{m_h^*} \quad |F_1 F_2|^2 = 0.2$$

Radiative generation-recombination rate:

$$(G-U)_R = G_R (pn - n_i^2)$$

$$G_R = \frac{(2\pi)^{3/2}}{3} \frac{h(\epsilon_\infty)^{1/2} q^2}{4\pi\epsilon_0 m^2 c^2} \left(\frac{m_0}{m_e^* + m_h^*} \right)^{3/2}$$

$$\times \left(1 + \frac{m_0}{m_e^*} + \frac{m_0}{m_h^*} \right) \frac{E_g^2}{(k_B T)^{3/2} (m_0 c^2)^{1/2}}$$

Electron-hole mobility:

$$\mu_n = \frac{9 \times 10^8 b}{T^{2a}}; b = \left(\frac{0.2}{x}\right)^{0.75}; a = \left(\frac{0.2}{x}\right)^{0.6}$$

$$\mu_h = 0.01 \times \mu_n$$

Mobility field dependence (extended Canali model):

$$\mu_{n,p}(F) = \frac{\mu_{o-n,p}}{\left[1 + \left(\frac{\mu_{o-n,p} F_{hfs}}{v_{sat}}\right)^\beta\right]^{1/\beta}}$$

$$v_{sat} = 10^5 \sqrt{\frac{300}{T}} \quad \beta = \left(\frac{T}{300}\right)^{\beta_o}$$

where μ_o , v_{sat} and F_{hfs} are low-field mobility, saturation velocity and driving field, respectively. Parameter β_o is a fitting coefficient in a range of 1.2 to 1.6.

Trap-assisted tunneling generation-recombination rate:

$$R_{TAT} = \frac{pn - n_i^2}{\frac{\tau_{p0}}{1 + \Gamma_p} \left[n + n_i \exp\left(\frac{E_t}{k_B T}\right) \right] + \frac{\tau_{n0}}{1 + \Gamma_n} \left[p + n_i \exp\left(\frac{-E_t}{k_B T}\right) \right]}$$

$$\tau_{n0} = (\sigma_n v_{th,n} N_{trap})^{-1} \quad \text{and} \quad \tau_{p0} = (\sigma_p v_{th,p} N_{trap})^{-1}$$

$$v_{th,n} = (8k_B T / \pi m_n^*)^{1/2} \quad \text{and} \quad v_{th,p} = (8k_B T / \pi m_p^*)^{1/2}$$

where, σ_n , σ_p are electron, hole capture cross section, and v^n , v^p are electron, hole thermal velocities. $\Gamma_{n,p}$ depends on the electron/hole effective masses.

BTBT generation-recombination rate:

$$(G - U)_{BTBT} = \frac{q^2 \sqrt{m^*} F^2}{4\sqrt{2}\pi^2 \hbar^2 E_g^{1/2}} \exp\left(-\frac{4\sqrt{2m^*} E_g^{3/2}}{3q\hbar F}\right)$$

where F is the Electric field.

REFERENCES

- [1] A. Rogalski, J. Antoszewski, and L. Faraone, "Third-generation infrared photodetector arrays," *Journal of Applied Physics*, vol. 105, p. 091101, 2009.
- [2] E. C. Piquette, D. D. Edwall, D. L. Lee, and J. M. Arias, "Precise arsenic doping of HgCdTe by MBE and effects on compositional interdiffusion," *Journal of Electronic Materials*, vol. 35, pp. 1346-1349, 2006.
- [3] S. Maimon and G. W. Wicks, "nBn detector, an infrared detector with reduced dark current and higher operating temperature," *Applied Physics Letters*, vol. 89, p. 151109, 2006.
- [4] P. Martyniuk, M. Kopytko, and A. Rogalski, "Barrier infrared detectors," *Opto-Electronics Review*, vol. 22, pp. 127-146, 2014.
- [5] L. O. Bubulac, W. E. Tennant, R. A. Riedel, and T. J. Magee, "Behavior of implantation-induced defects in HgCdTe," *Journal of Vacuum Science & Technology*, vol. 21, pp. 251-254, 1982.
- [6] A. C. Chen, M. Zandian, D. D. Edwall, R. E. De Wames, P. S. Wijewarnasuriya, J. M. Arias, *et al.*, "MBE growth and characterization of in situ arsenic doped HgCdTe," *Journal of Electronic Materials*, vol. 27, pp. 595-599, 1998.
- [7] M. Zandian, A. C. Chen, D. D. Edwall, J. G. Pasko, and J. M. Arias, "p-type arsenic doping of Hg_{1-x}Cd_xTe by molecular beam epitaxy," *Applied Physics Letters*, vol. 71, pp. 2815-2817, 1997.
- [8] L. O. Bubulac, "Defects, diffusion and activation in ion implanted HgCdTe," *Journal of Crystal Growth*, vol. 86, pp. 723-734, 1990.
- [9] A. I. D'Souza, J. Bajaj, R. E. De Wames, D. D. Edwall, P. S. Wijewarnasuriya, and N. Nayar, "MWIR DLP HgCdTe photodiode performance dependence on substrate material," *Journal of Electronic Materials*, vol. 27, pp. 727-732, 1998.
- [10] A. M. Itsuno, J. D. Phillips, and S. Velicu, "Mid-wave infrared HgCdTe nBn photodetector," *Applied Physics Letters*, vol. 100, p. 161102, 2012.
- [11] D. Z. Ting, C. J. Hill, A. Soibel, J. Nguyen, S. A. Keo, M. C. Lee, *et al.*, "Antimonide-based barrier infrared detectors," 2010, pp. 76601R-76601R-14.
- [12] A. Rogalski, "Recent progress in infrared detector technologies," *Infrared Physics & Technology*, vol. 54, pp. 136-154, 2011.
- [13] P. Klipstein, "'XBn' barrier photodetectors for high sensitivity and high operating temperature infrared sensors," in *Proc. SPIE*, 2008, p. 69402U.
- [14] A. Rogalski and P. Martyniuk, "InAs/GaInSb superlattices as a promising material system for third generation infrared detectors," *Infrared Physics & Technology*, vol. 48, pp. 39-52, 2006.
- [15] B.-M. Nguyen, D. Hoffman, P.-Y. Delaunay, and M. Razeghi, "Dark current suppression in type II InAs/GaSb superlattice long wavelength infrared photodiodes with M-structure barrier," *Applied Physics Letters*, vol. 91, pp. -, 2007.
- [16] M. Kopytko, J. Wróbel, K. Jóźwikowski, A. Rogalski, J. Antoszewski, N. D. Akhavan, *et al.*, "Engineering the Bandgap of Unipolar HgCdTe-Based nBn Infrared Photodetectors," *Journal of Electronic Materials*, vol. 44, pp. 158-166, 2015/01/01 2015.
- [17] N. D. Akhavan, G. Jolley, G. A. Umana-Membreno, J. Antoszewski, and L. Faraone, "Design of Band Engineered HgCdTe nBn Detectors for MWIR and LWIR Applications," *Electron Devices, IEEE Transactions on*, vol. 62, pp. 1-1, 2015.
- [18] N. D. Akhavan, G. A. Umana-Membreno, G. Jolley, J. Antoszewski, and L. Faraone, "A method of removing the valence band discontinuity in HgCdTe-based nBn detectors," *Applied Physics Letters*, vol. 105, pp. -, 2014.

- [19] E. F. Schubert, L. W. Tu, G. J. Zydzik, R. F. Kopf, A. Benvenuti, and M. R. Pinto, "Elimination of heterojunction band discontinuities by modulation doping," *Applied Physics Letters*, vol. 60, pp. 466-468, 1992.
- [20] M. Kopytko, "Design and modelling of high-operating temperature MWIR HgCdTe nBn detector with n- and p-type barriers," *Infrared Physics & Technology*, vol. 64, pp. 47-55, 5// 2014.
- [21] G. Masetti, M. Severi, and S. Solmi, "Modeling of carrier mobility against carrier concentration in arsenic-, phosphorus-, and boron-doped silicon," *Electron Devices, IEEE Transactions on*, vol. 30, pp. 764-769, 1983.
- [22] C. Canali, G. Gavioli, A. Losi, and G. Ottaviani, "HOT-HOLE DIFFUSIVITY IN GE AT 77K," *Solid State Communications*, vol. 20, pp. 57-60, 1976 1976.
- [23] H. F. Schaake, M. A. Kinch, D. Chandra, F. Aqariden, P. K. Liao, D. F. Weirauch, *et al.*, "High-Operating-Temperature MWIR Detector Diodes," *Journal of Electronic Materials*, vol. 37, pp. 1401-1405, 2008.
- [24] P. Martyniuk, W. Gawron, and A. Rogalski, "Theoretical Modeling of HOT HgCdTe Barrier Detectors for the Mid-Wave Infrared Range," *Journal of Electronic Materials*, vol. 42, pp. 3309-3319, 2013.
- [25] W. E. Tennant, D. Lee, M. Zandian, E. Piquette, and M. Carmody, "MBE HgCdTe Technology: A Very General Solution to IR Detection, Described by "Rule 07", a Very Convenient Heuristic," *Journal of Electronic Materials*, vol. 37, pp. 1406-1410, 2008.
- [26] T. J. De Lyon, J. E. Jensen, I. Kasai, G. M. Venzor, K. Kosai, J. B. de Bruin, *et al.*, "Molecular-beam epitaxial growth and high-temperature performance of HgCdTe midwave infrared detectors," *Journal of Electronic Materials*, vol. 31, pp. 220-226, 2002.
- [27] W. Scott, "Electron Mobility in Hg_{1-x}Cd_xTe," *Journal of Applied Physics*, vol. 43, pp. 1055-1062, 1972.
- [28] M. Kopytko, A. Kębłowski, W. Gawron, P. Madejczyk, A. Kowalewski, and K. Jóźwikowski, "High-operating temperature MWIR nBn HgCdTe detector grown by MOCVD," *Opto-Electronics Review*, vol. 21, pp. 402-405, 2013.
- [29] J. Rothman, J. Meilhan, G. Perraïs, J.-P. Belle, and O. Gravrand, "Maximum entropy mobility spectrum analysis of HgCdTe heterostructures," *Journal of Electronic Materials*, vol. 35, pp. 1174-1184, 2006.
- [30] S. Velicu, J. Zhao, M. Morley, A. M. Itsuno, and J. D. Phillips, "Theoretical and experimental investigation of MWIR HgCdTe nBn detectors," 2012, pp. 82682X-82682X-13.
- [31] P. Martyniuk and A. Rogalski, "Modelling of MWIR HgCdTe complementary barrier HOT detector," *Solid-State Electronics*, vol. 80, p. 96, 2012.
- [32] A. M. Itsuno, J. D. Phillips, and S. Velicu, "Design and Modeling of HgCdTe nBn Detectors," *Journal of Electronic Materials*, vol. 40, pp. 1624-1629, 2011.
- [33] A. Itsuno, J. Phillips, and S. Velicu, "Design of an Auger-Suppressed Unipolar HgCdTe NBvN Photodetector," *Journal of Electronic Materials*, vol. 41, pp. 2886-2892, 2012.
- [34] S. J. Elliott and P. A. Nelson, *Algorithm for multichannel LMS adaptive filtering* vol. 21: Institution of Engineering and Technology, 1985.