Interband infrared photodetectors based on HgTe–CdHgTe quantum-well heterostructures

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We calculate the characteristics of interband HgTe–CdHgTe quantum-well infrared photodetectors (QWIPs). Due to a small probability of the electron capture into the QWs, the interband HgTe–CdHgTe QWIPs can exhibit very high photoconductive gain. Our analysis demonstrates significant potential advantages of these devices compared to the conventional CdHgTe photodetectors and the A 3 B 5 heterostructures.

I. INTRODUCTION

The intersubband quantum-well infrared photodetectors (QWIPs) 1–4 based on the A 3 B 5 heterostructures have been developed since 1960s 5–8. These photodetectors are still the subject of intensive theoretical and experimental studies 9–15. Using different materials for the QWs and the inter-QW barrier layers, and varying the QW width, one can adjust the QWIP operation from near-infrared to terahertz frequencies. The main advantage of QWIPs is associated with the maturity of the material and processing technology allowing to produce the QWIPs and QWIP-based large arrays with desirable spectral characteristics, including multi-color systems. Another advantage is the ease of integration with other devices. Due to the mature technology, the QWIP-based large arrays exhibit stability and high pixel-to-pixel uniformity. The cost of the A 3 B 5 QWIP based devices and systems is much less than of those based on CdHgTe and InSb. The intersubband QWIP disadvantages include the large thermal dark current at elevated temperatures, which prevents the room operation 1, 2 and the need for the radiation coupling structures (for the n-type QWIPs). Therefore, the standard A 3 B 5 QWIPs cannot compete with the interband CdHgTe photodiodes (PDs) 2 in performance. The recent progress in the fabrication of CdHgTe QW heterostructures 16–19 provides an opportunity for a further enhancement of the CdHgTe photodetector technology. In this paper, we propose and evaluate the QWIPs using the interband transitions in the CdHgTe heterostructures, in particular, with the HgTe QWs. The interband HgTe–CdHgTe QWIP operation is associated with the photoexcitation of the electrons in the QWs followed by their escape. These processes result in the redistribution of the device potential, varying the electric field at the emitter and the electron injection current from the emitter. The electric potential distribution in question is governed by the balance of the photoexcitation from the QWs and the electron capture into the QWs similar to what takes place in the standard QWIPs 20–24. Due to the features of the energy spectrum in the QWs, these interband QWIPs can operate at the normal IR radiation incidence. In this regard, the interband HgTe–CdHgTe QWIP operation is akin to the operation of the vertical graphene-layer infrared photodetectors (GLIPs) 25–27.

The interband electron transitions in the HgTe–CdHgTe QWIPs can provide a rather strong absorption. A weak capture of the electrons into the QWs leads to a high photoconductive gain (phototransistor effect). The required spectral characteristics of the interband QWIPs can be obtained by a proper choice of the CdHgTe composition and the QW width. The possibility of the QW engineering enables the fabrication of the interband HgTe–CdHgTe QWIPs with desirable spectral characteristics (by using, for example, the HgTe QWs with different width). We compare the QWIPs under consideration with the standard p-i-n CdHgTe photodiodes (PDs) and discuss the advantages of the former.
II. INTERBAND QWIP DEVICE MODEL

The QWIP structure under consideration consists of a number of the undoped HgTe QWs \((N = 1, 2, 3, \ldots)\) with the energy gap, \(\Delta_{QW}\), between the top of the highest hole subband and the bottom of the lowest electron subband. The QWs are separated by a material with the energy gap \(\Delta_B > \Delta_{QW}\) (CdTeHgTeTe with \(0 < x < 1\)), so that the barrier of the height \(\Delta_B\) is formed for electrons (see Fig. 1). The structure is sandwiched between the emitter and collector n-doped layers. For the definiteness we assume that both these layers are the same QWs (as the inner QWs) but highly doped by donors. Figures 1(a) and 1(b) show the QWIP device composition and the band diagram under sufficiently strong bias voltage \(V \gg V_{bi}, k_B T/e\) (where \(V_{bi}\) is the built-in voltage between the n-doped contact and the undoped inner QWs, \(T\) is the temperature, \(k_B\) is the Boltzmann constant, and \(e\) is the electron charge).

The electron photoexcitation in the QWs in question under the normally incident radiation can be associated with both the intersubband transitions within the QW conduction band and with the interband transitions. Considering that the electron density in the undoped QWs is relatively small and that the pertinent matrix elements are small, we focus on the contribution of the interband transitions.

To provide an effective escape of the photoexcited electrons from the QWs into the states above the barriers, the following conditions are assumed:

\[
\hbar \omega \gtrsim \Delta_{QW} + \left(1 + \frac{m}{M}\right) \Delta_B \simeq \Delta_{QW} + \Delta_B = \hbar \omega_{th}.
\]

Here \(m\) and \(M\) are the electron and hole effective masses in the QWs, \(\Delta_B\) is the energy separation between the bottom of the barrier conduction band and the bottom of the lowest electron subband in the QW (the barrier height for the electrons in the QWs), \(\hbar \omega_{th}\) is the threshold of the effective photoexcitation. At \(\hbar \omega > \hbar \omega_{th}\), the electrons photoexcited in the QW can easily escape. In the opposite case, the electron escape from the QWs is associated with the tunneling through the triangular barrier formed by the electric field.

Using a simplified model for the characteristics of the vertical photodetectors using the photoexcitation from the localized states in the structure and the electron injection from the emitter (used previously in the papers on the standard QWIPs as well as in the GLIPs [19–27]), one can obtain for the photocurrent density in the QWIP \(J_{\text{photo}}\) and its photodetector responsivity \(R = J_{\text{photo}}/I_{\text{th}}\).

\[
J_{\text{photo}} = \frac{e \beta_\omega \xi_N}{p_c} I_{\text{th}}, \quad R = \frac{e \beta_\omega \xi_N}{p_c \hbar \omega}.
\]

Here \(\beta_\omega\) and \(p_c\) are the probabilities of the interband electron photoexcitation between the hole and electron subbands in the QW (radiation absorption coefficient) and the capture into the QW, \(\xi_\omega\) is the probability of the escape of the photoexcited electrons from the QW, \(I_{\text{th}}\) and \(\hbar \omega\) are the incident radiation flux and the photon energy, respectively.

The factor \(\xi_N \leq 1\) describes a nonideality of the emitter (see Ref. 26 and the references therein): \(\xi_N \approx N/(\gamma^{3/2} + N)\) with \(\gamma = (\Delta_B - \varepsilon_F)/\Delta_B\), where \(N\) is the number of the inner QWs, \(\varepsilon_F\) is the electron Fermi energy in the emitter QW counted from bottom of the lowest electron subband in the QW and \(\Delta_B\) is the energy spacing between the barrier top and the bottom of this subband [see Fig. 1(b)]. Equation (2) corresponds to the net rate of the photoescape \(\beta_\omega \xi_N N\) and the photoconductive gain \(g = 1/(N p_c)\).

At \(\hbar \omega \leq \hbar \omega_{th}\) and \(\hbar \omega \gtrsim \hbar \omega_{th}\),

\[
\theta_\omega = \left(1 + \frac{\tau_{\text{esc}}}{\tau_{\text{relax}}} \exp \left[ \frac{(\omega_{th} - \omega)}{\omega_{th}} \right] \frac{E_{\text{tunn}}}{E} \right) \frac{1}{1}, \quad (3)
\]

\[
\tau_{\text{relax}} = \left(1 + \frac{\tau_{\text{esc}}}{\tau_{\text{relax}}} \right)^{-1}, \quad (4)
\]

respectively, where \(\tau_{\text{esc}}\) and \(\tau_{\text{relax}}\) are the try-to-escape and energy relaxation times, \(E_{\text{tunn}} = \)
4√2m_B(hω_{th}^3/2)/3eh and E are the characteristic tunneling field (see, for example, Ref. [28]) and the electric field in the inter-QW barriers, respectively, and m_B is the electron effective mass in the barrier material.

### III. ENERGY SPECTRA, SPECTRAL CHARACTERISTICS OF THE INTERBAND ABSORPTION AND CAPTURE PROBABILITIES

The functions βω and θω depend on the QW energy spectra, which, in turn, depend on the compositions of the QWs and barrier layers materials and on the QW width, d. We calculated the energy spectra and the spectral characteristics of the absorption coefficients for the heterostructures grown on [013] CdTe surface with different content of Cd in the barrier layers at temperatures T = 77 and 200 K. The refractive index of the barrier is set to be n = 15.2.

Figure 2 shows examples of the energy spectra of the HgTe QWs surrounded by the Cd_{0.27}Hg_{0.73}Te and Cd_{0.3}Hg_{0.7}Te barriers calculated for different values of the QW width and T = 77 K and T = 200 K. The spectra shown in Fig. 2 correspond to two lowest electron subbands marked as e1 and e2 (virtually undistinguished due to a weak interface inversion asymmetry splitting) and two sets of split hole subbands marked as h1, h2 and h3, h4.

The calculations of the energy spectra and the spectral characteristics of the absorption coefficients for the heterostructures grown on [013] CdTe surface with different content of Cd are based on the framework of the 8 Kane model (see, for example, [29]), and the effective mass of the CdTe valence band.

The spectra broadening is set to be Γ = 1 meV.

In the calculations of the capture probability, p_c, we assumed that the capture of the electrons propagating over the inter-QW barriers into the QWs is primarily associated with the emission of optical phonons (with the energy hω_0 = 0.015 eV).

Figure 4 shows the spectral characteristics of the absorption coefficient (absorption probability) associated with the interband transitions in the HgTe–Cd_{0.27}Hg_{0.73}Te (at T = 77 K) and in the HgTe–Cd_{0.3}Hg_{0.7}Te (at T = 200 K) heterostructures with the HgTe QWs of different width d. The two-step increase in the absorption probability as a function of the photon energy is associated with a noticeable split of the h1, h2 and h3, h4 hole subband pairs (see Fig.2).

### IV. INTERBAND QWIP CHARACTERISTICS

Figures 5 and 6 show the spectral characteristics of the responsivity R for the interband HgTe-CdHgTe QWIPs with the same parameters as those in Fig. 4 and ξ_N = 0.738 (γ = 0.5 and N = 1) calculated using Eqs. (2) - (4) for different relative electric fields U = E/E_{tunn}. It is assumed that τ_{esc}/τ_{relax} = 0.1.

The plots in Fig. 5(a) correspond to the capture probabilities p_c = 2.5% and p_c = 1.1% of the electrons with the
average energy in the barrier layers \( \varepsilon = k_B T \approx 6 \text{ meV} \). The plots in Fig. 5(b) correspond to \( p_c = 0.36\% \) and \( p_c = 0.58\% \) (of the average electron energy \( \varepsilon = k_B T \approx 17 \text{ meV} \)).

The obtained values of the capture probability \( p_c \approx (0.36 - 0.58\%) \) are generally of the same order of magnitude (or somewhat larger) as the \( p_c \) values for the GLs.\(^{36}\) The fact that \( p_c \) in the QWIP under consideration can be larger at some QW parameters than in GLs, can be explained by large energies of the optical phonons in GLs in comparison with HgTe or CdHgTe. As a consequence, the emission of the optical phonons accompanying the electron capture into GLs requires larger variations of the electron momentum.

As follows from Eq. (2), the dependence of the interband QWIP responsivity on the number of the inner QWs, \( N \), is determined by the factor \( \xi_N = N/(\gamma^{3/2} + N) \) with \( \gamma = (\Delta_B - \varepsilon_F)/\Delta_B \), where \( \varepsilon_F \) is the Fermi energy in the emitter QW counted from the electron subband bottom. Since \( \gamma \) varies from unity \( (\varepsilon_F \approx 0) \) to zero \( (\varepsilon_F = \Delta \text{ for a heavily doped emitter QW}) \), the factor \( 0.5 < \gamma_N < 1 \) for arbitrary \( N \). This implies that the interband QWIP responsivity is a weak function of the number of inner QWs. A similar situation occurs in the intersubband QWIPs and interband GLIPs.

Some increase (although a relatively slow) in the interband QWIP responsivity with increasing number of the QWs \( N \) is confirmed by Fig. 6 \((N = 1, 3, \text{ and } 10)\). At \( N \gtrsim 10 \), an increase in \( R \) with \( N \) becomes insignificant.

Larger values of the responsivity corresponding to the plots in Fig. 5(a) [and in Fig. 6(a)] in comparison to those shown in Fig. 5(b) [and in Fig. 6(b)] are attributed to a smaller value of the capture probability \( p_c \) for the former figure.

As follows from the above data, the interband QWIP responsivity can be fairly large.

The interband HgTe-CdHgTe QWIPs surpass the QWIPs using the intersubband (intraband) both based on similar HgTe-CdHgTe heterostructures and on the \( \text{A}_x\text{B}_y \) QW heterostructures. This is due to higher probability of the interband electron photoexcitation in the former compared to the probability of the intersubband photoexcitation. The use of the intersubband QWIPs requires a substantial donor doping of the QWs. However the latter leads to a decrease in the thermogeneration activation energy and negatively affects the detector detectivity.

Below we compare the responsivity and dark-current-limited detectivity of the interband QWIPs under consideration with the traditional interband p-i-n PDs. The operation of the latter is associated with the interband photogeneration of the electrons and holes in the depleted bulk i-layer CdHgTe and their propagating in the vertical direction.

### V. COMPARISON WITH OTHER PHOTODETECTORS

Using the above results and considering Eq. (A1) at \( \alpha_w W = \beta_w/\beta_w < 1 \), where \( \alpha_w \) and \( W \) are the interband absorption coefficient in the PD depletion layer and the thickness of the latter, for the ratio of the pertinent responsivities \( R \) and \( R_{PD} \) we find

\[
\frac{R}{R_{PD}} \approx \frac{1}{p_c \beta_w/\beta_w}.
\]

As follows from Eq. (6), a relatively small quantum efficiency in the interband QWIPs considered above can be compensated by the phoconductive gain (in the interband QWIPs, this gain \( g \propto p_c^{-1} \)). For the photon energy \( h\omega \sim 0.1 \text{ eV} \), assuming \( \beta_w = 3 \times 10^{-3} \), \( p_c = (0.4 - 0.6\%) \), \( \alpha_w = 2 \times 10^4 \text{ cm}^{-1} \), and \( W = 10^{-1} \text{ cm} (\beta_w/\beta_w = 0.2) \), Eq. (6) yields \( R/R_{PD} \approx 2.5 - 3.75 \).
equal values of the material of the p-i-n PD are chosen to provide the gain. The interband QWIP barrier layers exceed $\Delta_G$ in the p-i-n PDs under comparison. Since the energy gap in the QWs. As a result, the Auger generation in CdHgTe p-i-n PDs operating in long wavelength radiation range can result in elevated dark currents and, hence, in a lower detectivity $D^*$ (see also, Refs. 32, 33).

The QWIPs could exhibit weaker tunneling dark currents providing additional potential advantages of these detectors.

In conclusion, we proposed the interband HgTe–CdHgTe QWIPs and analyzed their characteristics. The analysis of these photodetectors demonstrates their substantial advantages over the intersubband (intraband) HgTe–CdHgTe QWIPs, the conventional p-i-n PDs, and the intersubband $\alpha^3B_5$ QWIPs.

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Appendix. Characteristics of the p-i-n PDs

Calculating the photocurrent density and the responsivity of the p-i-n PDs with the absorption coefficient $\alpha$, and the thickness of the depletion layer $W$, one can obtain

$$j_{\text{photo}, PD} \simeq e\beta_{\omega, PD} I_\omega, \quad R_{PD} \simeq \frac{e\beta_{\omega, PD}}{\hbar\omega}.$$  (A1)

The volume rates of the thermogeneration, $G$, in one QW and in the depletion region, $G_{PD}$, can be estimated as

$$G = \frac{m k_BT}{\pi \hbar^2 W \tau_R} \exp \left(-\frac{\hbar \omega_{th}}{k_BT} \right),$$  (A2)

$$G_{PD} = \frac{2(2\pi m k_BT)^{3/2}}{(2\pi \hbar)^3 \tau_R} \exp \left(-\frac{\hbar \omega_{th}}{k_BT} \right).$$  (A3)

Here $\tau_R$ is the recombination time (assumed to be equal in both devices). Equations (A2) and (A3) yield

$$\frac{G_{PD}}{G} = \sqrt{\frac{m k_BT W}{2\pi \hbar}}.$$  (A4)

Setting $m = 0.025 m_0$, $W = 10^{-4}$ cm, and $T = 200$ K, from Eq. (A4) we obtain $G_{PD}/G \simeq 31.6$. 

B. Dark-current-limited detectivity

One of the most important figure-of-merit of the interband QWIP is the dark-current-limited detectivity, which depends on the detector noise at moderate and elevated temperatures. The detectivity can be expressed via the dark current density and the photoconductive gain.

Compare the interband QWIP detectivity $D^*$ and the p-i-n PD detectivity $D_{PD}$ considering that $D^* \propto \beta_\omega N/\sqrt{NG}$ and $D_{PD} \propto \beta_{\omega, PD}/\sqrt{G_{PD}}$, where $G$ and $G_{PD}$ are the rates of generation in the dark conditions. We assume that the barrier material in the QWIP and the material of the p-i-n PD are chosen to provide the equal values of $\hbar \omega_{th} = \Delta_{QW} + \Delta_B = \Delta_G$ [see Eq. (1)], where $\Delta_G$ is the energy gap in the depletion region of the p-i-n PDs under comparison. Since the energy gap in the interband QWIP barrier layers exceeds $\Delta_{QW} + \Delta_B$, the former is larger than the energy gap, $\Delta_G$, in the PDs under comparison. Due to this, one can neglect the thermogeneration in the barrier layers in comparison to the thermogeneration in the QWs. As a result,

$$\frac{D^*}{D_{PD}} \simeq \frac{\beta_\omega N}{\beta_{\omega, PD} \sqrt{2G_{PD}/NG}}.$$  (7)

Using Eqs. (9) and (A4), we find

$$\frac{D^*}{D_{PD}} \simeq \frac{\beta_\omega N}{\beta_{\omega, PD} \sqrt{2NW/\hbar \omega}} \sqrt{\frac{mk_BT}{2\pi \hbar}}.$$  (8)

Assuming $m = 0.025 m_0$ ($m_0$ is the mass of bare electron), $\beta_\omega = 3 \times 10^{-3}$, $\alpha = 2 \times 10^3$ cm$^{-1}$, $W = 10^{-4}$ cm (i.e., $\beta_{\omega, PD} = 0.2$), and $T = 200$ K, we obtain from Eq. (8) $D^*/D_{PD} \simeq 0.119 \sqrt{N}$. Even at $N \sim 10 - 20$, the latter ratio is somewhat smaller than unity. However, in reality, the Auger generation in CdHgTe p-i-n PDs operating in long wavelength radiation range can result in elevated dark currents and, hence, in a lower detectivity $D^*$.
