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HgCdTe PHOTODIODES FOR INFRARED MID-WAVELENGTH REGION

F. Sizov, Z. Tsybrii, M. Vuichyk, K. Andreyeva, M. Apatsка, S. Bunchuk,
N. Dmytruk, M. Smolii

V. E. Lashkaryov Institute of Semiconductor Physics, Ukrainian Academy of Sciences
E-mail: tsybrii@isp.kiev.ua
sizov@isp.kiev.ua, tsybrii@isp.kiev.ua, vuychik@isp.kiev.ua, ev_andreeva@bk.ru, amv54@ukr.net,
dmytruknd@gmail.com

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Abstract. HgCdTe photodiodes of relatively large area (Ø = 0.5 mm) for mid-wave infrared region (MWIR) were fabricated on the base of liquid phase epitaxial layers. Characteristics of these photodiodes were estimated to be applicable as those working in background limited performance (BLIP) mode. It was shown that in spectral range of atmospheric transparency $\lambda = 3$ to 5 μm obtained dynamical resistance of HgCdTe photodiodes allow to realize their detectivity D* that are restricted by fluctuations of background radiation with specific power of photon fluxes $W_{eff} \approx 3.3\cdot10^{-4} - 4.4\cdot10^{-5}$ W/cm^2.

Keywords: photodiode, HgCdTe, infrared, BLIP mode

ФОТОДІОДИ HgCdTe СЕРЕДНЬОХВИЛЬОВОГО ІЧ ДІАПАЗОНУ СПЕКТРА

Ф. Ф. Сизов, З. Ф. Цибрій, М. В. Вуйчик, К. В. Андрєєва, М. В. Апатська, С. Г. Бунчук, Н. В. Дмитрук, М. І. Смолій

Анотація. Виготовлено фотодіоди HgCdTe середньохвильового інфрачервоного (ІЧ) діапазону спектра з великою площею чутливого елемента (Ø = 0.5 мм) з довгохвильовою межею фотовідгуку $\lambda_{co} \approx 5$ мкм та досліджено їхні характеристики на структурах, вирощених методом рідкофазної епітаксії. Оцінено характеристики таких фотодіодів, які необхідні для їх функціонування в режимах, обмежених флуктуаціями потоку фотонів фонового випромінювання (BLIP режим, BLIP - background limited performance).

Ключові слова: фотодіод, HgCdTe, інфрачервоний, BLIP режим

ФОТОДИОДЫ HgCdTe СРЕДНЕВОЛНОВОГО ИК ДИАПАЗОНА СПЕКТРА

Ф. Ф. Сизов, З. Ф. Цибрий, Н. В. Вуйчик, Е. В. Андреева, М. В. Апатская, С. Г. Бунчук, Н. В. Дмитрук, М. И. Смолий

Аннотация. Изготовлены фотодиоды HgCdTe средневолнового инфракрасного (ИК) диапазона спектра большой площади (Ø = 0.5 мм) с длинноволновой границей фотоответа $\lambda_{co} \approx 5$ мкм и исследованы их характеристики на структурах, выращенных методом жидкофазной эпитаксии. Оценены характеристики таких фотодиодов, необходимые для их функционирования в режимах, ограниченных флуктуациями потока фотонов фонового излучения (BLIP режим, BLIP - background limited performance).

Ключевые слова: фотодиод, HgCdTe, инфракрасный, BLIP режим

1. Introduction

MWIR HgCdTe photodiodes (λ = 3-5 μm, T ≈ 80 K) together with InSb photodiodes (cut-off wavelength λ_{co} = 5.6 μm, T ≈ 80 K) are finding broad applications in systems of environment monitoring, fire safety, communication, space monitoring of the Earth surface, medical diagnostics, security and military applications (e.g. tracking and capture of targets) etc. (see e.g. [1-3]). IR MWIR photodiodes (on the base of HgCdTe and InSb) are basically used at matrix arrays formation with pixel dimensions up to 15×15 μm and photodiodes number in the array up to 2048×2048 (for Refs. see e.g. [3]). Along with small area detectors in a lot of applications are used large area photodiodes with dimensions Ø ≈ 1.25, 3.2×3.2 mm [4, 5].

Larger band gap in $Hg_{1-x}Cd_xTe$ (x ≈ 0.3, λ_{co} = 5 μm at 80 K) compared with the band gap of InSb (λ_{co} = 5.6 μm) allows realize much lower dark currents in HgCdTe photodiodes. But technologies of getting high quality large area homogeneous layers give the opportunity to get InSb photodiodes that are restricted only by fundamental mechanisms of current transport. In HgCdTe large area photodiodes there exist some additional mechanisms of “fault” currents connected with structural and metallurgical defects in layers and depletion regions (e.g heterogeneities, Te inclusions and dislocation clusters) which limit obtaining small dark currents in them that in turn restrict the ultimate parameters of photodiodes on the base of this semiconductor. It concerns mainly long wavelength $Hg_{1-x}Cd_xTe$ photodiodes (λ_{co} ≈ 12 μm) with chemical composition x ≈ 0.2.

The purpose of investigations of current-voltage characteristics, dynamical resistance and spectral dependencies of MWIR HgCdTe photodiodes performed was determination of the minimum values of parameter R_0A_d that basically defines the detectivity values of photodiodes operating in BLIP mode. Here R_0 is the dynamical resistance of diodes without bias, A_d is the photodiode sensitive area.

2. Experiment and estimations

Planar *n*-on -*p* HgCdTe photodiodes were fabricated by B^+ ion doping into epitaxial layers with thickness d ≈ 15 μm grown by liquid-phase epitaxy method on $Cd_{1-y}Zn_yTe$ (y ≈ 0.03 - 0.05) substrates. In this case, the lattice parameters are close to each other that allows obtaining structures with relatively low dislocation densities (< 10^5 cm^{-2}) at the metallurgical boundary of HgCdTe and CdZnTe. Those values of dislocation densities weakly influence on R_0A_d parameters and excess noises at typical photodiodes operation temperatures T ≈ 80 K [6].

With the assumption of photo-response spectral characteristics of ideal photodiode for current responsivity $S_{I,\lambda}$ it follows an expression [7, 8]

$$S_{I\lambda} = \eta \cdot q \cdot \lambda / h \cdot c = \eta \cdot q / h\nu = 0.806 \cdot \eta \cdot \lambda, \text{ A/W}, \quad (1)$$

where q is the electron charge, h is the Planck constant, *ν* and λ are the radiation frequency and wavelength, respectively.

For MWIR ideal photodiode with $\lambda_{co} = \lambda_{max}$ = 5 μm the maximum value of current responsivity with typical for HgCdTe photodiodes quantum efficiency $\eta = 0.5$ is $S_{I\lambda}^{max}$ ≈ 2 A/W. For ideal photodiode the spectral responsivity

$$S_I(\lambda) = \frac{\lambda}{\lambda_{max}} \cdot S_{I\lambda}^{max}. \quad (2)$$

Spectral responsivities of real photodiodes differ from those for ideal ones, due to dependence on the surface quality, the depth of depletion layer, the thickness of diode structures, etc. However, those differences are not very substantial and for estimations of upper limit performance of photodiodes detectivity one can use expressions that are valid for ideal photodiodes.

For single MWIR and LWIR (long wavelength IR) photodiodes the ultimate detectivity values

$$D^* = (A_d \cdot \Delta f)^{1/2}/NEP = S_I \cdot (A_d \cdot \Delta f)^{1/2}/I_{ph}, \quad (3)$$

are limited by background fluctuation noise [7,9]. Here Δf is the electronic bandwidth and noise equivalent power NEP = I_{ph}/S_I, the current value defined by the background fluctuation noise.

Other one of the important noise in IR photodiodes current is the thermal noise (Johnson-Nyquist noise) I_T that is defined by dynamical photodiode dark resistance $R_0 = -[dI/dU(I)]^{-1}_{U=0} = \beta k_B T/qI_0$, where U is the bias voltage, β is the non-ideality factor.

For these two noises the current noise is defined by

$$< I^2_{\text{noise}} > = U_I \cdot \Delta f = 2 \cdot q \cdot (I_{ph} + I_T) \cdot \Delta f =$$

$$= (2 \cdot q^2 \cdot \eta \cdot N_{\lambda,T} \cdot A_d + 4k_B T / R_0) \cdot \Delta f \,. \quad (4)$$

Here k_B is the Boltzmann constant, noise current connected with the background fluctuations of the number photon fluxes $<I_\phi>^2 = 2 \cdot q^2 \cdot \eta \cdot A_d \cdot N_{\lambda,T} \cdot \Delta f$ and thermal noise $I_T = (4k_B T / R_0) \cdot \Delta f$, and the background number of photon fluxes (see e.g. [7,8])

$$N_\phi = \frac{\Omega_i}{\pi} \cdot \int_{\lambda_1}^{\lambda_{co}} \frac{2 \cdot \pi \cdot c}{\lambda^4 \cdot [\exp(\frac{hc}{k_B T \cdot \lambda}) - 1]} \cdot d\lambda \,, \quad (5)$$

where c is the light speed, λ_{co} = 5 μm and λ_1 = 3 μm define the spectral range of photodiode sensitivity, the $\Omega_i = \pi \times \sin^2(\theta_i/2)$ is the (field of view (FOV) that is defined by cold diaphragm and θ_i is the plane angle of view. For Ω_i = 1.57 ($\theta_i = 90^0$) the background flux $N_{ph} \approx 6.5 \cdot 10^{15}$ $cm^{-2} \cdot s^{-1}$ at background temperature (of the black body) T = 300 K, and for Ω_3 = 0.21 sr ($\theta_i = 30^0$) $N_{ph} \approx 8.8 \cdot 10^{14}$ $cm^{-2} \cdot s^{-1}$.

For these two type of noises for ideal photodiode it follows

$$D^*_{\lambda_{co}} = \frac{\eta q \lambda_{co}}{hc} \cdot [\frac{4k_B T}{R_0 A_d} + 2q^2 \eta N_\phi]^{-1/2} \,. \quad (6)$$

For the angles of view pointed out the detectivity at λ_{co} = 5 μm is $D^*_{\lambda_{co}} \approx 1.5 \cdot 10^{11}$ cm·Hz$^{1/2}$/W $D^*_{\lambda_{co}} \approx 4.2 \cdot 10^{11}$ cm·Hz$^{1/2}$/W, respectively, and specific detectivity for spectral region λ = 3-5 μm $D^* \approx 2 \cdot 10^{10}$ cm·Hz$^{1/2}$/W and $D^* \approx 5.5 \cdot 10^{10}$ cm·Hz$^{1/2}$/W, respectively.

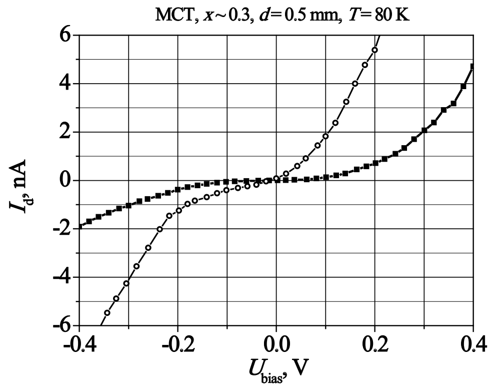

Fig. 1. Current-voltage characteristics of typical $Hg_{1-x}Cd_xTe$ (x ≈ 0.3, λ_{co} = 5 μm) photodiodes at T = 80 K. (Ø = 0.5 mm).

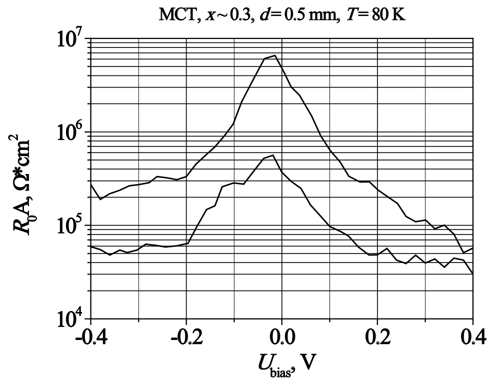

Fig. 2. Dynamical resistance of typical $Hg_{1-x}Cd_xTe$ (x ≈ 0.3, λ_{co} = 5 μm) photodiodes, T = 80 K, Ø = 0.5 mm.

At $\frac{4k_BT}{R_0A_d} << 2q^2\eta N_{ph}$ (the values of R_0A_d are large) $D^*_{\lambda_{co}}$ is defined by the second term in brackets of Exp. (6) and detector is operating in BLIP mode, that is conditioned by fluctuations in background photon fluxes.

At $\frac{4k_BT}{R_0A_d} >> 2q^2\eta N_{ph}$ (low values of R_0A_d or at conditions of low background photon fluxes, e.g. in astronomical applications) the photodiode operation is conditioned by its dynamic resistance and diode operation is defined by thermal noise (Johnson noise limited operation - JOLI). Also at low R_0A_d values, due to it poor quality, through the photodiode will flow large currents.

With estimations of photon fluxes made above $N_{ph} \approx 6.6\cdot10^{15}$ cm$^{-2}\cdot$s^{-1} (Ω_1 = 1.57 sr ($\theta_1 = 90^0$) and $N_{ph} \approx 8.8\cdot10^{14}$ cm$^{-2}\cdot$s^{-1}, (Ω_3 = 0.21 sr ($\theta_3 = 30^0$), T = 300 K) the effective background load is $W_{eff} \approx 3.3\cdot10^{-4}$ W/cm^2 and $4.4\cdot10^{-5}$ W/cm^2, respectively. For assurance MWIR photodiodes operation in BLIP mode for given FOVs from (6) it follows $R_0A_d \geq 5\cdot10^3$ Ω·cm^2.

In Fig. 1 are shown dark current-voltage characteristics for two investigated $Hg_{1-x}Cd_xTe$ (x ≈ 0.3, λ_{co} = 5 μm) photodiodes of relatively large area (Ø = 0.5 mm) and in Fig. 2 their dynamical resistance characteristics in dependence of bias. It is seen that without bias in these photodiodes $R_0A_d \approx 3.5\cdot10^6$ Ω·cm^2 and $2\cdot10^5$ Ω·cm^2 and these photodiodes can operate in BLIP mode.

In Fig. 3 are shown transmission spectra of $Hg_{1-x}Cd_xTe$ epitaxial layers at T = 300 K at different parts of the chip (middle and opposite corners of epitaxial structure on CdZnTe substrate). Such kind of spectra usually are used for determination of detector photo-response long-wavelength boundary λ_{co} manufactured from these layers at 50 % of transparency T_{max} [10].

Taking widely used expression for defining $Hg_{1-x}Cd_xTe$ band gap [11]

$$E_g(x,T) = -0.302 + 1.93x - 0.81x^2 + 0.832x^3 + +5.32\cdot10^{-4}\cdot(1-2x)\cdot\left[\frac{-1822+T^3}{255.2+T^2}\right], \quad (7)$$

one can determine chemical compositions in different points of the chip investigated. From the optical transmission data of the opposite curves it follows λ_{co} = 4.1 μm and λ_{co} = 4.17 μm that corresponds to $Hg_{1-x}Cd_xTe$ band gap E_g = 0.3025 eV (x = 0.3090) and E_g = 0.2973 eV (x = 0.3045), respectively.

At T = 80 K for these chemical compositions E_g = 0.2571 eV (λ_{co} = 4.82 μm, x = 0.3090) and E_g = 0.2500 eV (λ_{co} = 4.96 μm, x = 0.3045), respectively. It means that the spectral region of these epitaxial layers at T= 80 K corresponds to the atmosphere transparency region λ = 3 - 5 μm.

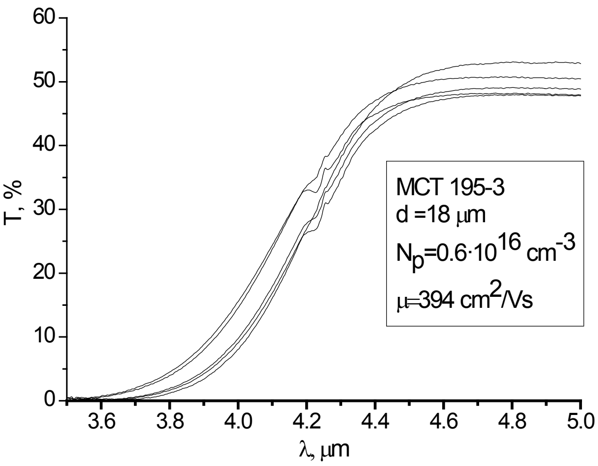

Fig. 3. Transmission spectra of one of the $Hg_{1-x}Cd_xTe/Cd_{1-y}Zn_yTe$ epitaxial structures investigated, T = 300 K.

3. Conclusions

It is shown that $Hg_{1-x}Cd_xTe$ ($x \approx 0.3$, $\lambda_{co} \approx 5$ μm at T = 80 K) photodiodes of relatively large area (Ø = 0.5 mm) that were obtained by B^+ ion doping into HgCdTe epitaxial layers on the $Cd_{1-y}Zn_yTe$ ($y \approx 0.03$-0.05) substrates can have characteristics that prove their operation in BLIP mode in λ = 3-5 μm atmospheric transparency region. In this spectral region obtained diode dynamical resistances allow realize their specific detectivities $D^* \geq 2\times10^{10}$ cm×Hz$^{1/2}$/W that are limited only by fluctuations in background photon fluxes at background loading $W_{eff} \approx 3.3\cdot10^{-4}$ - $4.4\cdot10^{-5}$ W/cm^2.

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4. References

1. M. Vuillermet, D. Billon-Lanfrey, Y. Reibel, A. Manissadjian, L. Mollard, N. Baierb O. Gravrand and G. Destéfanis, Status of MCT Focal Plane Arrays in France, Proc. SPIE, 8353, 83532K (2012).

2. N. Osia, T. Bourlai, Holistic and partial face recognition in the MWIR band using manual and automatic detection of face-based features, IEEE Int'l Conf. Technol. Homeland Security, p. 273-279 (2012), doi:10.1109/THS.2012.6459861.

3. F. Sizov, IR photoelectronics: Photon or thermal detectors? Outlooks, Sensor Electronics and Microsystem Technologies, 12, 26-52 (2015) (in Russian).

4. J.T. Wimmers, D.S. Smith, "Characteristics of InSb photovoltaic detectors at 77 K and below", Proc. SPIE, 364, 123-131 (1983).

5. J.T. Wimmers, R.M. Davis, C.A. Niblack, D.S. Smith, «Indium antimonide detector technology at Cincinnati Electronics Corporation», Proc. SPIE, 930, 125-138 (1988).

6. S.M. Johnson, D.R. Rhiger, J.P. Rosbeck, J.M. Peterson, S.M. Taylor, M.E. Boyd, "Effect of dislocations on the electrical and optical properties of long-wavelength infrared HgCdTe photovoltaic detectors", J. Vacuum Sci. Technol., B10, 1495-1506 (1992).

7. L.N. Kurbatov, Optoelectronics of visible and infrared spectral regions, Moscow, MFTI Publisher (1999) (in Russian).

8. F. Sizov, Photoelectronics for vision systems in invisible spectra regions, Kiev, Akadem-periodika (2008) (in Russian).

9. G.C. Holst, «Electro-optica imaging systems performance", Bellingham, USA: SPIE Optical Eng. Press (2003).

10. J. Chu and A. Sher, Physics and properties of narrow-gap semiconductors, Springer, N.Y., (2008).

11. J.R. Lowney, D.G. Seiler, C.L. Littler, and I.T. Yoon, "Intrinsic Carrier Concentration of Narrow-Gap Mercury Cadmium Telluride", J. Appl. Phys., 71, 1253-1258 (1992).

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F. Sizov, Z. Tsybrii, M. Vuichyk, K. Andreyeva, M. Apatsкa, S. Bunchuk, N. Dmytruk, M. Smolii

V. E. Lashkaryov Institute of Semiconductor Physics, Ukrainian Academy of Sciences
E-mail: tsybrii@isp.kiev.ua

Summary

The aim of this work is to demonstrate the possibility of realization of the photodiodes with a big area of a sensitive element based on HgCdTe epitaxial layers for middle infrared spectral region with parameters better than minimum possible values of R_0A_d (R_0 – zero biased dynamic resistance, A_d – area of photosensitive part of the photodiode), that define value of photodiode specific detectivity D*.

In this article mid wave infrared HgCdTe photodiodes of the big area of a sensitive element (Ø = 0.5 mm) with long-wavelength cutoff $\lambda_{co} \approx 5$ μm were fabricated and their characteristics on the structures grown by liquid phase epitaxy method on $Cd_{1-y}Zn_yTe$ ($y \approx 0.03$ - 0.05) substrates were investigated. Analysis of dark current-voltage characteristics of HgCdTe photodiodes manufactured by B^+ ion implantation method showed values of $R_0A_d \approx 3.5 \cdot 10^6$ Ohm·cm^2 and $2 \cdot 10^5$ Ohm·cm^2 at zero bias. Such photodiode parameters provide their operation in background limited performance mode. From measured spectral dependencies of infrared transmission of $Hg_{1-x}Cd_xTe$ epitaxial layers it was found that spectral area of photosensitivity of these epitaxial layers with $x \approx 0.3$ at T = 80 K was in atmospheric spectral window λ = 3-5 μm.

Keywords: photodiode, HgCdTe, infrared, BLIP mode

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ФОТОДІОДИ HgCdTe СЕРЕДНЬОХВИЛЬОВОГО ІЧ ДІАПАЗОНУ СПЕКТРА

Ф. Ф. Сизов, З. Ф. Цибрій, М. В. Вуйчик, К. В. Андрєєва, М. В. Апатська, С. Г. Бунчук, Н. В. Дмитрук, М. І. Смолій

Інститут фізики напівпровідників ім. В. Є. Лашкарьова НАН України
E-mail: tsybrii@isp.kiev.ua

Реферат

Мета даної роботи полягає в тому, щоб показати можливість реалізації фотодіодів з великою площею чутливого елемента на основі епітаксійних шарів HgCdTe для середньохвильового спектрального діапазону з параметрами кращими, ніж мінімально необхідні значення R_0A_d (R_0 – динамічний опір діодів при нульовому зміщенні, A_d – площа фоточутливої частини фотодіода), які визначають значення питомої виявної здатності фотодіода D*.

В даній роботі виготовлено фотодіоди HgCdTe з великою площею чутливого елемента (Ø= 0.5 мм) з довгохвильовою межею фотовідгуку $\lambda_{co} \approx 5$ мкм та досліджено їхні характеристики на структурах, вирощених методом рідкофазної епітаксії на підкладках $Cd_{1-y}Zn_yTe$ (y ≈ 0.03 - 0.05). Аналіз темнових вольт-амперних характеристик фотодіодів HgCdTe, сформованих методом іонної імплантації B^+, показав, що при відсутності напруги зміщення для таких фотодіодів значення $R_0A_d \approx 3.5\cdot10^6$ Ом·см^2 і $2\cdot10^5$ Ом·см^2. Такі параметри фотодіодів забезпечують їх функціонування в режимах, обмежених флуктуаціями потоку фотонів фонового випромінювання (BLIP режим, BLIP - background limited performance). Із виміряних спектральних залежностей оптичного пропускання в інфрачервоній ділянці спектра епітаксійних шарів $Hg_{1-x}Cd_xTe$, на основі яких виготовлялись фотодіоди, встановлено, що спектральна область фоточутливості цих епітаксійних шарів складу x ≈ 0.3 при T = 80 K перебуває у вікні прозорості атмосфери λ = 3-5 мкм.

Ключові слова: фотодіод, HgCdTe, інфрачервоний, BLIP режим