Infrared Physics & Technology 61 (2013) 162–166

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Analysis of the response time in high-temperature LWIR HgCdTe photodiodes operating in non-equilibrium mode

M. Kopytko [a,*], K. Jóźwikowski [a], P. Madejczyk [a], W. Pusz [b], A. Rogalski [a]

[a] Institute of Applied Physics, Military University of Technology, 2 Kaliskiego St., 00-908 Warsaw, Poland
[b] Vigo System S.A., 129/133 Poznańska St., 05-850 Ożarów Mazowiecki, Poland

HIGHLIGHTS

- Theoretical and experimental response time in HOT LWIR HgCdTe photodiodes was done.
- 1 ns time constant is achieved for non-equilibrium operation mode.
- Low p-type doping of the absorber provides short time constant limited by the drift time of carriers.
- RC constant determines the response time of the practical devices.

ARTICLE INFO

Article history:
Received 19 April 2013
Available online 22 August 2013

Keywords:
HgCdTe photodiodes
Uncooled photodetectors
Auger suppression
Photodiode response
Time constant

ABSTRACT

The paper presents the theoretical investigation of the active region parameters, especially the influence of thickness and doping, on the response time and current responsivity of high-temperature long wavelength infrared HgCdTe photodiodes operating at 230 K in non-equilibrium mode. Results of theoretical predictions of time constant were compared to the experimental data. The response time of the devices have been characterized using Nd:YAG laser, optical parametric generator with pulse width <25 ps and fast oscilloscope with suitable transimpedance amplifier as a function of detector design, temperature and bias. The reverse bias applied to the photodiode causes Auger-suppression and improve the performances of the devices. This way the response time decreases to the value below 1 ns at the good current responsivity increased to the value of about 6 A/W and what is a promising parameter in view of potential telecommunication applications. Due to the series resistance of electrical connections, the response time of the devices is mainly limited by RC constant while the calculations show that the time constant of the Auger suppressed structures should be limited by the drift time of carriers.

1. Introduction

An ultimate goal for infrared (IR) photodetectors is achieving of the perfect, quantum noise limited performance at near-room temperature. Significant progress has been achieved with the use of heterostructure design of the devices [1–5] in which the active region (absorber) is sandwiched between wide gap layers that protect it against parasitic thermal generation at contacts, surfaces and interfaces. Moreover, the dark current in HgCdTe photodiodes is usually determined by Auger generation processes at elevated temperatures, because the low-doped absorber layer becomes intrinsic and the carrier concentration is higher than the doping level. The device structures with combination of exclusion (P^+/π or N^+/ν) and extraction (N^+/π or P^+/ν) junctions in $P^+/\nu/N^+$ and $P^+/\pi/N^+$ configurations have demonstrated suppression of Auger mechanisms by reducing the absorber carrier density below thermal equilibrium in reverse bias condition [1–5]. Practical HgCdTe heterostructures for the devices have been grown with advanced epitaxial techniques such as molecular beam epitaxy (MBE) [6] and metal organic chemical vapor deposition (MOCVD) [7].

The response time is an important parameter of infrared detectors especially used in telecommunication applications. There are still continued investigations to optimize devices where compromise between contradictory requirements of achieving high detectivity and fast response time is necessary. The best way to achieve a short response time of the detectors is a fast transport of photogenerated carriers to contacts. In this case, a special heterostructure design are developed, where p-type absorber is an advantageous material for the fast response HgCdTe detectors. p-type material is characterized by high ambipolar mobility, what is crucial to achieve fast and efficient drift collection of charge carriers.

This paper presents the theoretical investigation of influence of thickness and arsenic doping level of the active region on reverse

* Corresponding author.
E-mail address: mkopytko@wat.edu.pl (M. Kopytko).

1350-4495/$ - see front matter © 2013 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.infrared.2013.08.005

bias dark current characteristics, current responsivity, and the response time of long wavelength IR (LWIR) HgCdTe photodiodes operating at near-room temperatures.

2. Method of analysis

An advanced numerical model is used for investigation of HgCdTe LWIR photodiodes operated in time-dependent light illumination conditions. The program based on the solution of the system of the carrier transport equations in a Fourier space as well as whole spectrum of various generation and recombination processes including influence of radiative (RAD), Auger (AUG) and Shockley–Read–Hall (SRH) mechanisms connected with structural defects as well as band-to-band (BTB) and trap-assisted (TAT) tunneling mechanisms. There is considered two types of generation-recombination channels in the SRH mechanism: metal site vacancies and dislocation related centers. We have used our original model [8] to examine it in this paper. This two types of centers are characterized by different ionization energies and capture cross-sections. The vacancy concentration is assumed at the level of $N_T = 1 \times 10^{14}\,\mathrm{cm}^{-3}$ with ionization energy $0.75E_g$ above the valence band and the electron and hole captures cross-sections of $\sigma_n = \sigma_p = 5 \times 10^{-16}\,\mathrm{cm}^2$. The bulk dislocations density is assumed at the level of $G_{DIS} = 1 \times 10^7\,\mathrm{cm}^{-2}$ and the mean energy of the dislocation band is $0.1E_g$ above the valence band, with cross sections equal to $\sigma_n = \sigma_p = 2 \times 10^{-14}\,\mathrm{cm}^2$. Surface effects are also considered by introducing the surface recombination velocity parameter S. We have taken into account ohmic contacts with $S = 10^4$ cm/s similar as in Refs. [9,10]. We have calculated numerically electron and hole mobilities caused by two scattering mechanisms (ionised impurity scattering and polar optical phonon scattering). The procedures were presented in Ref. [11].

The Fourier analysis method for investigation of spectral characteristic was applied after illuminating biased photodiode by small harmonic optical pulse in the form of $\Phi(\omega) = \Phi_0 \exp(i\omega t)$, where Φ_0 is the amplitude of photon flux, i is the imaginary unit, ω is the frequency, and t is the time. When the photodiode is illuminated, all photoelectric parameters of the heterostructure have changed. The changes proceed with the same frequency as a frequency of the incident light. The complex amplitude of photocurrent as a function of frequency $J(\omega) = J_0 \exp(i\omega t)$ is the output parameter of calculations. The normalized photocurrent $J(\omega)/J(0)$ describes the frequency response of the photodiode. The cut-off frequency f_T, defined by −3-dB line, is inversely proportional to the time constant τ of the device:

$$2\pi f_T = \frac{1}{\tau}. \tag{1}$$

The wavelength of the incident light in all calculations was assumed $\lambda_{inc} = 7.5$ μm and the power $P_{inc} = 0.1\,\mathrm{W/cm}^2$. The detailed description of the method is in our previous paper [12].

3. Device structure

The investigated device is a photodiode based on HgCdTe multilayer heterostructures grown by MOCVD. Fig. 1 shows the high operation temperature (HOT) mesa geometric structure of analyzed HgCdTe photodiode. The architecture consists of three layers. At the bottom, about 3-μm thick highly n-type doped with iodine ($N_D = 1 \times 10^{17}\,\mathrm{cm}^{-3}$) wider-gap ($x = 0.4$) contact layer was formed. Then, the absorption π-type layer was grown with a composition $x_{abs} = 0.19$ for a cut-off wavelength of 9.6 μm at 230 K. The thickness of active region should be shorter than minority carrier diffusion length. Generally, the thickness of the absorption layer is a compromise between requirements of high absorption efficiency,

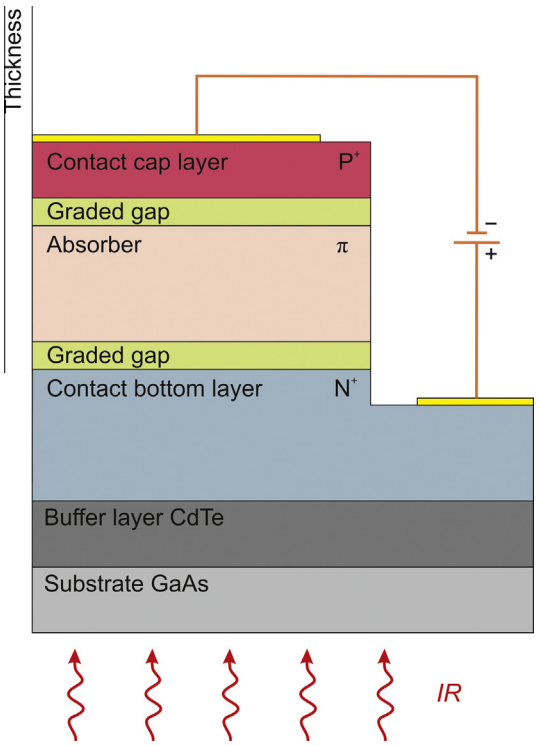

Fig. 1. The cross-section of mesa structure of the $N^+/\pi/P^+$ LWIR HgCdTe photodiode.

low thermal generation [13], as well as short response time of the device. For nonequilibrium devices this compromise formulates more precisely to the trade-off between absorption efficiency and Auger suppression [14,15]. The acceptor doping should be at possible low level just to overcompensate the donor background concentration of the material, which varied from 3×10^{15} to $6 \times 10^{15}\,\mathrm{cm}^{-3}$ in the MOCVD grown. Finally, highly p-type doped with arsenic ($N_A = 3 \times 10^{17}\,\mathrm{cm}^{-3}$) contact cap layer with a thickness of 1 μm and composition $x = 0.38$ was grown. In the π–P^+ and π–N^+ junctions are the x-graded regions and represent the real structure which profile is shaped by interdiffusion processes during $Hg_{1-x}Cd_xTe$ growth at 350 °C.

Structural parameters such as absorber doping and thickness were changed in calculations (Table 1) to obtain optimal working conditions of the device. In our calculations the thickness of the absorption layer was changed from 3 to 7 μm and acceptor concentration of the absorber material was changed from 1×10^{15} to $2 \times 10^{16}\,\mathrm{cm}^{-3}$ assuming donor background concentration at the level of $N_D = 3 \times 10^{15}\,\mathrm{cm}^{-3}$.

The theoretical composition and doping concentration profiles for $P^+/\pi/N^+$ HgCdTe heterostructure with absorber thickness of $t_{abs} = 5$ μm and arsenic dopant concentration $N_A = 8 \times 10^{15}\,\mathrm{cm}^{-3}$ are presented in Fig. 2.

4. Results and discussion

The assumed composition and doping concentration profiles permit us to calculate the bandgap structure which is presented in Fig. 3. The calculations is performed for the device operating at 230 K using zero and the 0.8 V reverse bias voltage.Theoretical and experimental response Fig. 4 presents the electron and hole concentrations at zero and 0.8 V reserve bias at 230 K. Under reverse bias, the electrons are extracted from the absorber region by positive electrode connected to bottom N^+-layer. The electrons are also excluded from the absorber near the π–P^+ junction