Utmost response time of long-wave HgCdTe photodetectors operating under zero voltage condition

P. Martyniuk*, P. Madejczyk, M. Kopytko, W. Gawron, J. Rutkowski
Institute of Applied Physics, Military University of Technology, 2 Kaliskiego Str., 00-908 Warsaw, Poland (✉piotr.martyniuk@wat.edu.pl, +48 261839215)

***Abstract*–The paper reports on the long-wave infrared HgCdTe detector for short response time operating for unbiased and room temperature condition. The response time was calculated at the level of ~ 220−520 ps for zero bias condition. It was shown that depending on architecture extra series resistance ≤ 20 Ω related to the *processing* allows to reach response time within the range ~ 220 ps. The highest detectivity of the simulated structure was assessed at the level of ~ 10^8 Jones.**

I. Introduction

Applications requiring frequencies > 1 GHz and operating under zero voltage and room temperatures contribute to the development of the new device architectures. That trend is also visible in the long-wave (8−12μm, LWIR) range HgCdTe detectors. Reaching the utmost response time (τ_s), the detectivity (D^*) will be reduced without any prospect of the background limited photodetection (BLIP) condition. According to experimental data the LWIR $N^+pP^+n^+$ based photodetectors reach response time in several nanoseconds range operating under non-equilibrium condition, zero voltage and room temperature. Figure 1 presents measured response time for the LWIR $N^+pP^+n^+$ detector versus voltage with nominal active layer composition, x_{Cd} = 0.196 and doping N_A = 5×10^{16} cm^{-3} confirming that for zero voltage, τ_s stays within the range 5−10 ns for operating temperature, T ~ 200−300 K. At the same time, assuming that detector is immersed, those devices exhibit D^* ~ 10^9 Jones [1−3].

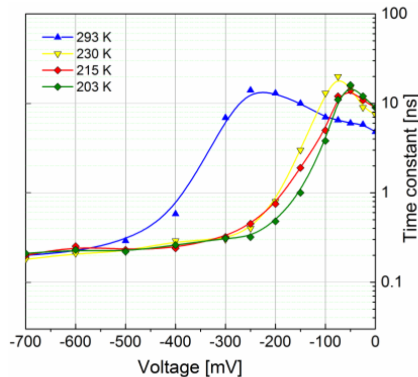

Fig. 1. Measured response time of the LWIR HgCdTe $N^+pP^+n^+$ structure versus voltage (nominal active layer x_{Cd} = 0.196 and N_A = 5×10^{16} cm^{-3}).

II. Simulation Procedure and Results

Our approach to maximize response time in comparison with the three-layer N^+pP^+ structure invented and introduced by Elliot *et al.* for non-equilibrium conditions is lowering of the P^+ barrier layer by composition gradient within p^+-n^+ transition layer (gradient-contact layers) [4,5]. The nominal HgCdTe multi-layer graded gap structure with doping and composition gradients is presented in Fig. 2. The highly doped N_A = 10^{17} cm^{-3} active layer with thickness d = 1 μm was implemented. Device architecture was changed by composition gradient of the p^+-n^+ transition layer. Low frequency resistance was calculated to be at the level of ~ 1.5 Ω for all analyzed structures. Detector structure was simulated with software APSYS by Crosslight Inc. [6,7]. Photocurrent time dependence was calculated based on Li *et al.* model [8].

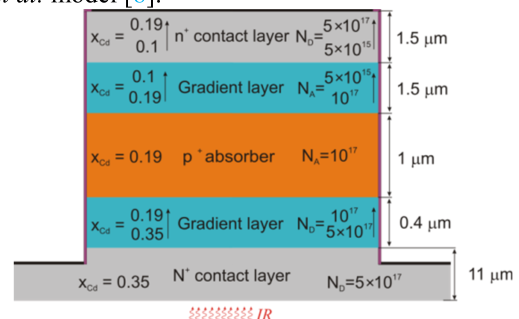

Fig. 2. LWIR HgCdTe structure exhibiting response time, τ_s < 1 ns for unbiased condition and room temperature operation.

Energy band diagrams for selected p^+-n^+ transition layer composition within the range x_{Cd} = 0.1−0.19 is presented in Fig. 3 (a−d).

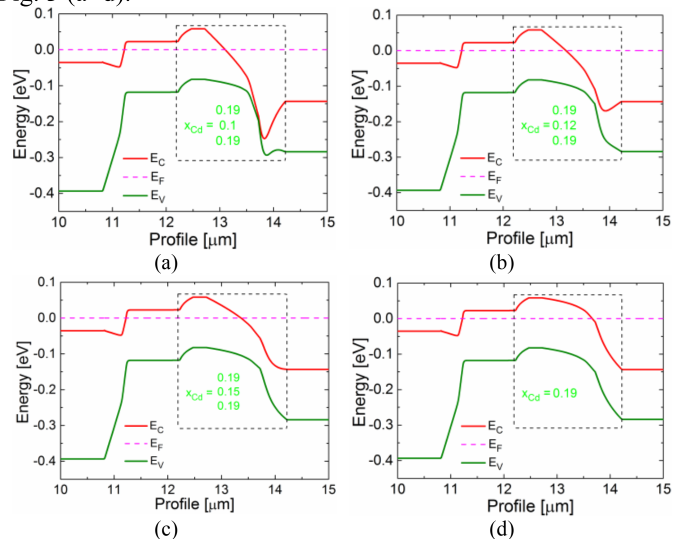

Fig. 3. Energy band diagram for LWIR HgCdTe structure for short response time for selected p^+-n^+ transition layer composition, x_{Cd} = 0.1 (a); x_{Cd} = 0.12 (b); x_{Cd} = 0.15 (c); x_{Cd} = 0.19 (d).

Corresponding electric field drop along the simulated LWIR HgCdTe structure for short response time and selected p^+-n^+

transition layer composition, x_{Cd} = 0.1−0.19 was presented in Fig. 4.

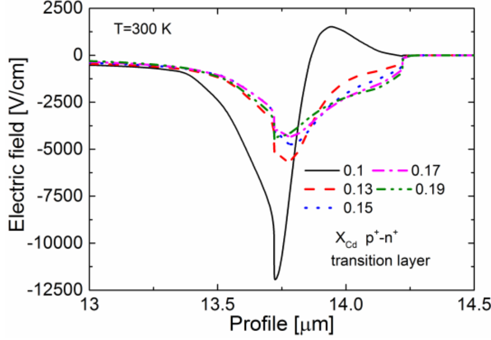

Fig. 4. Electric field drop along LWIR HgCdTe structure for short response time and selected p^+-n^+ transition composition, x_{Cd} = 0.1−0.19.

Response time was derived from photocurrent dependence on time where time for *1*/e drop from photocurrent's maximum value was assessed. Simulated photocurrent versus time was presented in Fig. 5. Since detector operates under zero bias, it was assumed that detectivity was limited by thermal Johnson-Nyquist noise and assessed according to the relation:

$$D^* = \frac{n^2 R_i}{(4k_B T/R_o A)^{0.5}} \quad (1)$$

where: R_i, k_B, R_o, A, n stands for current responsivity, Boltzmann constant, resistance at zero bias, detector's electrical area and GaAs substrate refractive index respectively. D^* for immersed detector was assessed at the level of ~ 10^8 Jones.

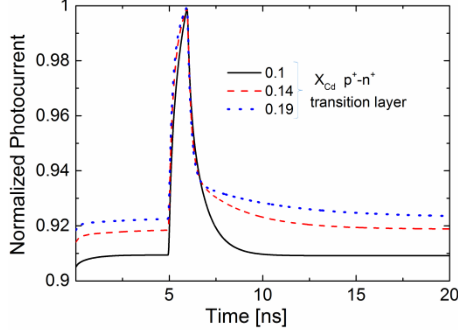

Fig. 5. Normalized photocurrent versus time and selected p^+-n^+ transition layer composition, x_{Cd} = 0.1−0.19.

Figure 6 presents simulated response time versus p^+-n^+ transition layer composition for selected extra series resistance R_{Series} = 0−20 Ω.

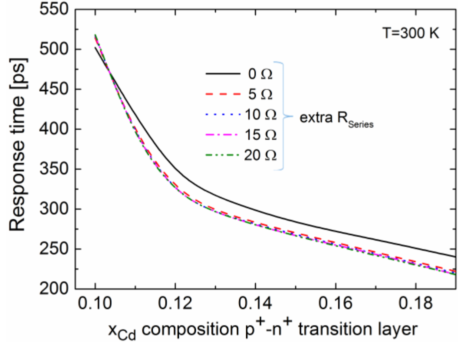

Fig. 6. Simulated response time LWIR HgCdTe structure for short response time versus p^+-n^+ transition layer composition for selected extra series resistance, R_{Series} = 0−20 Ω.

For each extra R_{Series} drastic drop of the τ_s ~ 500−325 ps is observed within the range x_{Cd} ~ 0.1−0.12. Response time exhibits two slope behavior where response time dependence on x_{Cd} of the p^+-n^+ transition layer is nearly linear.

Only for p^+-n^+ transition x_{Cd} = 0.1 the time response increases versus extra R_{Series} within the range 500−520 ps (R_{Series} = 0−20 Ω). For p^+-n^+ transition x_{Cd} > 0.1 the extra series resistance lowers response time and for extra R_{Series} > 6 Ω response time saturates for all analyzed p^+-n^+ transition layer compositions what was presented in Fig. 7.

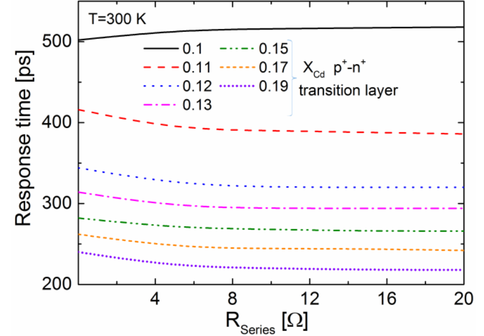

Fig. 7. Simulated response time of the LWIR HgCdTe structure for short response time versus extra series resistance for selected p^+-n^+ transition layer compositions, x_{Cd} = 0.1−0.19.

III. Conclusions

Theoretical utmost short response time $\tau_s \leq$ 520 ps LWIR HgCdTe structure exhibiting D^* ~ 10^8 Jones was presented. Further improvement in response time could be achieved by increasing composition of p^+-n^+ transition layer, however D^* will be reduced.

Acknowledgment

This paper has been completed with the financial support of The National Centre for Research and Development-the grant no. TANGO1/2665576/NCBR/2015.

References

[1] P. Madejczyk, W. Gawron, P. Martyniuk, A. Kębłowski, A. Piotrowski, J. Pawluczyk, W. Pusz, A. Kowalewski, J. Piotrowski, A. Rogalski, "MOCVD grown HgCdTe device structure for ambient temperature LWIR detectors", Semicond. Sci. Technol. 28, 10, 105017-1−7 (2013).

[2] P. Madejczyk, W. Gawron, P. Martyniuk, A. Kębłowski, W. Pusz, J. Pawluczyk, M. Kopytko, J. Rutkowski, A. Rogalski, J. Piotrowski, "Engineering steps for optimizing high temperature LWIR HgCdTe photodiodes", Infrared Phys. Technol., 81, 276–281 (2017).

[3] J. Pawluczyk, J. Piotrowski, W. Pusz, A. Koźniewski, Z. Orman, W. Gawron, A. Piotrowski, "Complex behavior of time response of HgCdTe HOT photodetectors", J. Electron. Mater., 44, 3163–3173 (2015).

[4] T. Ashley, C.T. Elliot, "Non-equilibrium mode of operation for infrared detection", Electron. Lett., 21, 451–452 (1985).

[5] C.T. Elliot, N.T. Gordon, R.S. Hall, T.J. Philips, A.M. White, C.L. Jones, C.D. Maxey, N.E. Metcalfe, "Recent results on MOVPE grown heterostructure devices", J. Electron. Mater., 25, 1139–1145 (1996).

[6] APSYS Macro/User's Manual ver. 2011. Crosslight Software, Inc. (2011).

[7] P. Capper, Properties of narrow gap cadmium-based compounds Inst. Elect. Eng., London, U.K., 1994.

[8] Q. Li, R.W. Dutton, "Numerical small-signal AC modeling of deep-level-trap related frequency-dependent output conductance and capacitance for GaAs MESFET's on semi-insulating substrates", IEEE Trans. Electron Devices, 38, 1285–1288 (1991).