Numerical analysis of impact ionization in HOT HgCdTe avalanche photodiodes

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Abstract—**Semiconductor avalanche photodiodes enable individual photons to be detected when the incident flux of light is very low. This is possible thanks to the use of the avalanche multiplication phenomenon. Consequently, the obtained gain of photocurrent is from a few to several million times.**

The avalanche multiplication effect in semiconductors is determined by the generation rate caused by impact ionization. This paper describes the results of research aimed at investigation of the impact ionization mechanism in HgCdTe photodiodes operating at 230 K and in the medium-wave infrared range. Numerical analyses were used for the study.

I. Introduction

Among many types of infrared (IR) detectors, some of them enable (for example) individual photons to be detected when the incident flux of light is very low. For many years, photomultiplier tubes (PMTs) have been used to detect very weak signals. Despite the high sensitivity and high gain amounting of at several million, they have a significant deficiency, such as a low quantum efficiency, incorrect operation in the presence of magnetic fields, have a large size and not persistent design.

Semiconductor devices, particularly avalanche photodiodes (APDs), are alternatives to photomultipliers. Avalanche photodiodes can detect electromagnetic radiation of extremely low intensity. By applying a high reverse bias voltage, APDs show an internal current gain effect due to impact ionization (avalanche effect). Under the influence of a high electric field, the electrons/holes in the depletion region of an APD are accelerated and gradually acquire sufficient kinetic energy to impact ionize other electrons/holes leading to the junction break-down. It results in current gain of even several million times (depending on the applied voltage – the higher the reverse voltage, the higher the gain). Avalanche photodiodes with the highest operating gain allow detection of single photons. Due to the ability of very weak signals detection in a short time intervals, APDs are widely used in laser rangefinders, optical radars, long-range free space or optic telecommunication and ultrasensitive spectroscopy.

Present APDs are as sensitive as photomultipliers, and at the same time are much smaller and more convenient to use. The highest performance of the mid-wavelength infrared (MWIR) HgCdTe APDs has been obtained at low temperatures (77 K) with high gain at low reverse bias, low excess noise factor, and low dark currents. HOT conditions of MWIR APDs can be achieved in architecture so-called separate absorption and multiplication heterostructure APDs (SAM-APDs), so far implemented in III-V technology [1] and in HgCdTe in the near-infrared (NIR) radiation (1–2 μm) [2].

In this paper we present some designs of HgCdTe APDs proposed for high-operating temperature (HOT) conditions – IR detectors operated close to room temperature or thermoelectrically cooled. We use numerical simulations to investigate impact ionization process in HgCdTe photodiode to determine the ability of avalanche process.

II. Impact ionization in semiconductors

The number of electron-hole pairs generated by a carrier per unit distance travelled is called the ionization coefficient of charge carrier. The ratio of ionization coefficients of hole and electron is defined as $k = \alpha_h/\alpha_e$, which is often used to characterize excess noise. In the local-field theory, the electron-hole pair generation rate due to impact ionization is [3]:

$$G_{ION} = \frac{1}{q}\alpha_e j_n + \frac{1}{q}\alpha_h j_p, \tag{1}$$

where q is the elementary charge, α_e and α_h are functions only of the electric field. Experimentally, it has been found that the electron and hole ionization coefficients, in the limit of low field ε, can be represented by the expressions:

$$\alpha_e = a_e \exp\left(-b_e/\varepsilon^{m_e}\right), \tag{2}$$

$$\alpha_h = a_h \exp\left(-b_h/\varepsilon^{m_h}\right), \tag{3}$$

where m_e and m_h are close to unity at least at low field. Current density (j_n and j_p) is usually expressed as functions of quasi-Fermi levels.

Impact ionization can proceed in two ways:
(i) ionization caused by both types of charge carriers;
(ii) ionization caused by one carrier type.

In some semiconductors electrons ionize more efficiently than holes (Si, GaAsSb, InGaAs, for which $\alpha_e > \alpha_h$), while in others the reverse is true (Ge, GaAs, where $\alpha_h > \alpha_e$). In $Hg_{1-x}Cd_xTe$, the electron to hole impact ionization ratio is dependent on the Cd composition. The hole ionization is favourable for the short wave infrared HgCdTe detectors ($0.5 < x < 0.7$). The electron ionization is favourable for the middle and long wave infrared detectors ($x < 0.5$) which based on one-band transitions.

III. Devices design

First photodiode (N^+-p-P^+ type) is a classical $Hg_{1-x}Cd_xTe$ design built on the basis of two heterojunctions. The Cd molar composition in the active area of $x = 0.36$ was chosen to obtain

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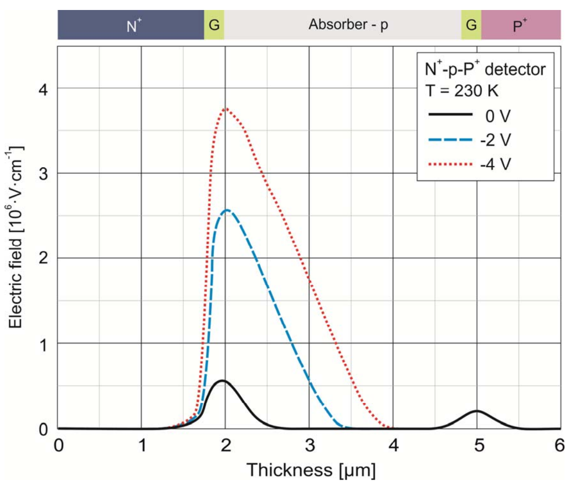
a long-term sensitivity limit ($\lambda_{cut\text{-}off}$) of about 3.5 µm at 230 K. It was assumed that the absorber is a p-type layer doped with arsenic at the level of 5×10^{15} cm^{-3}. Contacts are wide-bandgap layers with the Cd molar composition of x = 0.45: bottom contact layer is n-type doped with iodine at the level of 2×10^{17} cm^{-3} and cap contact layer is p-type doped with arsenic at the level of 5×10^{17} cm^{-3}. At the absorber and contact layers interfaces we assumed the x-graded regions created by interdiffusion processes during HgCdTe growth.

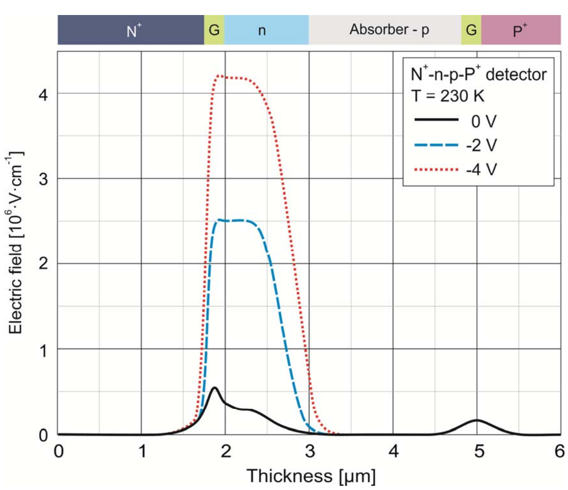
Second photodiode (N^+-n-p-P^+ type) contains an additional multiplication region introduced between the bottom contact layer and the absorber. In the proposed structure, the key item is to obtain the lowest level of doping in the avalanche multiplication area in order to reduce unfavorable tunneling processes. We assumed n-type doping in this region at the level of 5×10^{14} cm^{-3}.

IV. Results and Discussion

Figure 1 presents a spatial distribution of electric field in detectors operating at zero bias and for reverse voltage of –2 V and –4 V. Calculations were performed for the detector temperature of 230 K. In the N^+-p-P^+ detector, the electric field is deposited near the absorber and bottom contact



(a)



(b)

Fig. 1. Spatial distribution of the electric field in the HgCdTe photodiode in N^+-p-P^+ (a) and N^+-n-p-P^+ (b) configuration.

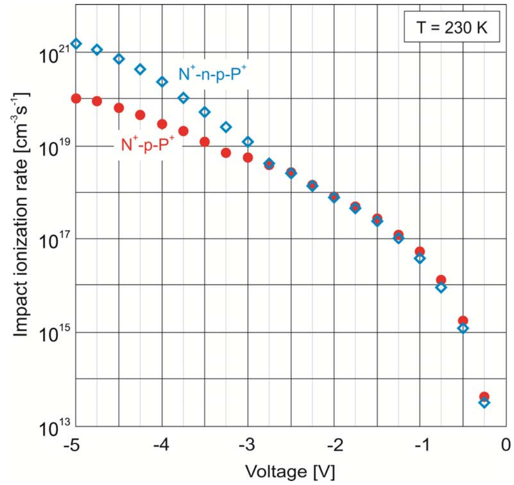


Fig. 2. Net generation rate due to impact ionization plotted as a function of the reverse bias voltage.

junction and extends into the absorber with the increasing bias voltage. In the case of the N^+-n-p-P^+ detector, the electric field reaches a higher value and is located mainly in the multiplication region. The active region remains the electric field free.

The maximum net generation rate associated with the impact ionization as a function of the bias voltage calculated for N^+-p-P^+ and N^+-n-p-P^+ detectors operating at 230 K is shown in Figure 2. At –5 V, impact ionization rate in the N^+-n-p-P^+ detector with separate multiplication region is an order of magnitude higher than in the N^+-p-P^+ detector.

V. Conclusions

Numerical analysis show that at 230 K avalanche multiplication can be achieved in a HgCdTe photodiode without a separate area for the carrier multiplication (N^+-p-P^+ configuration). However, much better results can be obtained when the carrier multiplication region and active region are separated (N^+-n-p-P^+ configuration). By reverse biasing the N^+-n-p-P^+ detector with a high voltage, the electric field is mainly distributed in the carrier multiplication region, while the N^+-p-P^+ detector, the electric field extends into the absorber area. Higher electric field in the multiplication region results in increased net generation rate associated with impact ionization.

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References

[1] X. Wang, W. Hu, M. Pan, L.Hou, W.Xie, J. Xu, X. Li, X. Chen, and W. Lu, "Study of gain and photoresponse characteristics for back-illuminated separate absorption and multiplication GaN avalanche photodiodes," *Journal of Applied Physics* 115, 013103 (2014).

[2] T.J. de Lyon, B. Baumgratz, G. Chapman, E. Gordon, A.T. Hunter, M. Jack, J.E. Jensen, W. Johnson, B. Johs, K. Kosai, W. Larsen, G.L. Olson, M. Sen, B. Walker, O.K. Wu, "MBE growth of HgCdTe avalanche photodiode structures for low-noise 1.55 lm photodetection," *J. Crystal Growth* 201/202, 980-984 (1999).

[3] M.A. Kinch, "Fundamentals of Infrared Detectors Materials," *SPIE Press Bellingham*, Washington, 110-112 (2007).