Microelectronics Journal 37 (2006) 483–486

Microelectronics Journal

www.elsevier.com/locate/mejo

Avalanche photodiode with sectional InGaAsP/InP charge layer

D. Haško [a,b,*], J. Kováč [a], F. Uherek [a,b], J. Škriniarová [a], J. Jakabovič [a], L. Peternai [a]

[a] *Department of Microelectronics, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology, Ilkovičova 3, 812 19 Bratislava, Slovak Republic*

[b] *International Laser Center, Ilkovičova 3, 812 19 Bratislava, Slovak Republic*

Received 14 July 2005; received in revised form 19 September 2005; accepted 21 September 2005
Available online 4 November 2005

Abstract

An InGaAs/InP avalanche photodiode (APD) with a sectional InGaAsP/InP charge layer at the heterointerface between the InGaAs absorption and InP multiplication region has been designed, fabricated and tested. We demonstrate a new APD structure that utilizes the sectional 140 nm thin charge layer and a 500 nm thin multiplication layer. The band diagram, electrical field distribution and current–voltage (*I*–*V*) characteristics up to punch-through voltage have been simulated. The fabricated mesa structure photodiode shows responsivity 0.9 A/W at 1310 nm at 20 V and avalanche gain up to 10 near breakdown voltage 36 V. The measured results revealed that the sectional charge layer could be used for control of the electric field profile in the APD structure.

Keywords: Avalanche photodiode; InGaAs/InP SACM structure; Device simulation

1. Introduction

Wide-bandwidth photodetectors with high sensitivity are crucial components for optical communication system (OCS) in the spectral range of 0.8–1.6 μm. Avalanche photodiodes (APDs) and PIN photodiodes based on InGaAs/InP material system are two of the most widely used photodiodes for these applications. The PIN photodiodes have responsivity higher than 0.8 A/W at 1.3 μm [1] but they do not offer an internal gain in comparison with APDs [2,3]. The requirements for high-performance APDs are satisfied by photodiodes with separated absorption and multiplication (SAM) layers [4]. Separation of these two layers causes a lower dark current [5]. APDs with a separated absorption, grading, and multiplication (SAGM) layer structure have higher quantum efficiencies and gain-bandwidth product [6]. The charge layer provides a sufficient electric field drop between the absorption and multiplication layers to secure effective avalanche multiplication. Best performances were achieved with separated absorption, grading, charge and multiplication (SAGCM) layers in APD structure [7], where only single types of carriers are transported into the multiplication region, which reduces the multiplication noise. The grading layer decreases the pile-up effect in the bandgap between InGaAs and InP layers. The multiplication region width and low breakdown voltage of APDs are most important parameters for modern OCS and other applications [8,9].

In this work, we present the design and properties of a low breakdown voltage separated absorption, charge and multiplication (SACM) layer structure APD containing a 500 nm thin InP multiplication layer and an alternative sectional InGaAsP/InP charge layer between InGaAs absorption and InP multiplication layers.

2. Design and simulation of SACM APD

Cross-sectional view of the designed SACM APD structure with a low breakdown voltage is depicted in Fig. 1. The structure consists of six layers on n^+ substrate. The charge region is split into two layers of InGaAsP and InP that reduce the bandgap variation and supply a sufficient electric field drop between the multiplication and absorbing regions. In our design, an n-InP multiplication region with a thickness of 500 nm (1×10^{15} cm^{-3}) and n-InGaAs absorbing layer with thickness 1000 nm (1×10^{15} cm^{-3}) have been used. APSYS software was employed for simulations of electrical field distribution, carrier concentration, thickness of layers and current–voltage characteristics of the designed APD structure up to punch-through voltage. The simulation software does not contain the tunnelling and avalanche process simulation

* Corresponding author.
E-mail address: hasko@ilc.sk (D. Haško).

0026-2692/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.mejo.2005.09.008

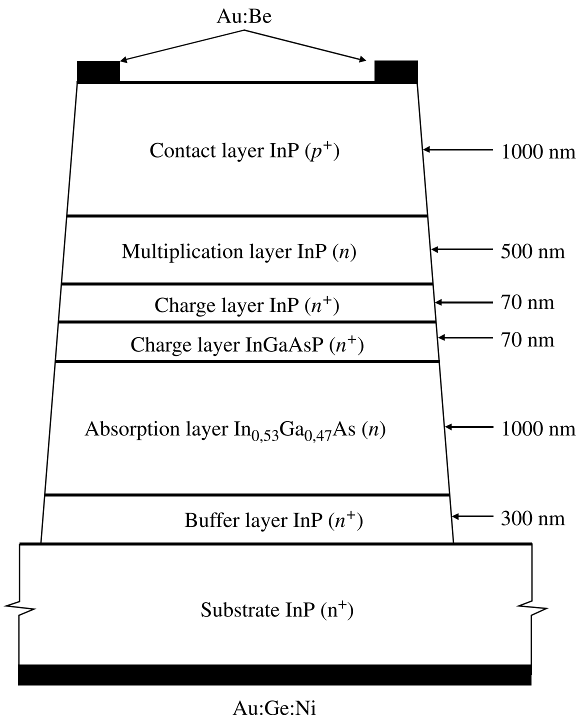

Fig. 1. Cross-sectional view of InGaAs/InP SACM APD device.

in the structure near breakdown and the optimisation of the structure properties was estimated only up to punch-through voltage. After the simulation optimised parameters of other layers are as follows: 70 nm thick n-InP ($1.5\times10^{17}\,cm^{-3}$), 70 nm thick n-InGaAsP ($1.5\times10^{17}\,cm^{-3}$) charge layer, 300 nm thick n-InP buffer layer ($1\times10^{17}\,cm^{-3}$) and 1000 nm thick p-InP contact layer ($1\times10^{18}\,cm^{-3}$). The bandgap diagram of SACM APD structure at zero reverse bias is shown in Fig. 2, where the bandgap variation is reduced by inserting n-InGaAsP layer within InGaAs and InP heterointerface. The electrical field distributions in the structure under different reverse bias voltages are depicted in Fig. 3.

The lowest value of the electrical field corresponds to zero reverse bias and the highest value to the reverse bias

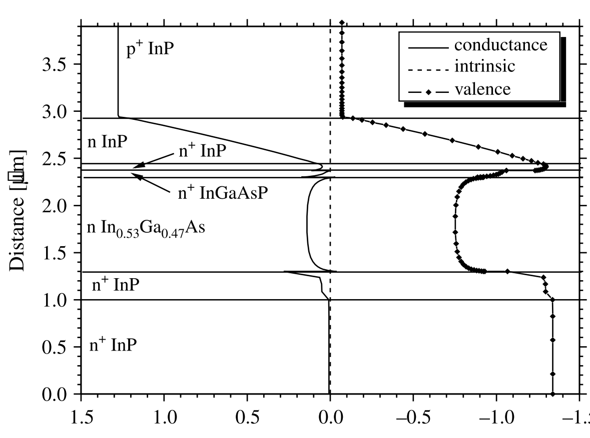

Fig. 2. Simulated band diagram of InGaAs/InP SACM structure at $V_B=0$ V.

of $V_B=15$ V. The electric field in the central active region of the junction is enhanced by selectively increased charge density under that region. For the range of reverse bias between 0 and 15 V, the absorption InGaAs layer is not depleted. In Fig. 4 are compared the simulated and measured *I–V* characteristic of the SACM APD up to punch-through voltage. The measured *I–V* characteristic shows slightly increased leakage current and punch-through voltage in comparing with simulated characteristic. For the reverse bias above punch-through voltage the avalanche process will occur due to increased electric field in central active region over critical level with simultaneous extension of reduced electrical field into the absorption layer.

3. Experimental

The designed structure was grown by MOCVD technique in one step. For investigation of electrical and optical properties of designed structure the avalanche photodiodes were mesa formed by using standard photolithography and wet chemical etching. Special care has been devoted to the mesa processing and passivation of the edges by polyimide to reduce leakage current and avalanche breakdown on mesa edges. The upper contact metallization was formed by lift-off process. Contact metallization consist of 15 nm sputtered Pt followed by sequential evaporation of 200 nm AuBe alloy onto p-type InP cap layer. The bottom contact metallization was formed by evaporation of 200 nm AuGeNi alloy onto InP substrate (Fig. 1) followed by annealing at 400 °C. The active area of mesa shaped diode is 0.007 mm^2. The current–voltage (*I–V*), capacitance–voltage (*C–V*) and spectral characteristics were measured and analysed on selected devices. *I–V* dark current and photocurrent characteristics were measured by using Keithley 2400 and calibrated 1310 nm illumination source.

4. Results and discussion

The measured *I–V* dark current and photocurrent characteristics up to breakdown are shown in Fig. 5. The step in *I–V* characteristic near 19 V is due to extension of the electrical field into the absorption layer. Within this mode of operation, the entire charge sheet and absorption layer are depleted. The measured photoresponsivity of the photodiodes without antireflection coating at 20 V was determined as 0.9 A/W at 1310 nm. The photocurrent is flat just above punch-through, indicating that the device is operating near unity gain in this regime. By increasing the bias voltage over 25 V, the carriers generated within the InGaAs absorption layer can drift into the multiplication region with high electric field thus providing an internal gain. The maximum measured avalanche gain 10 was reached for mesa shaped SACM APD near breakdown voltage of 36 V. The spectral characteristics at different applied reverse bias voltages in the range from 5 to 35 V are shown in Fig. 6. The SACM APD spectral sensitivity at reverse bias 5 and 15 V correspond to generation of carriers in the InP multiplication and InGaAsP charge region. At bias voltages higher than 25 V increase of the sensitivity is originated due to the avalanche