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COMMUNICATIONS

DESIGN AND PROPERTIES OF InGaAs/InGaAsP/InP AVALANCHE PHOTODIODE

Daniel Haško [*] — Jaroslav Kováč [**] — František Uherek [*] — Jaroslava Škriniarová [**] — Ján Jakabovič [**] — Loránt Peternai [**]

An avalanche photodiode (APD) based on an InGaAs/InGaAsP/InP structure containing separated absorption, charge and multiplication layers (SACM) was designed, fabricated and tested. The InGaAsP charge layer at the heterointerface between the InGaAs absorption and InP multiplication region allows optimization of the electric field distribution and suppression of the carrier capture at the heterointerface. The design of APD structure was verified using the semiconductor device simulation software APSYS. SACM avalanche photodiodes were characterized by measuring current-voltage and capacitance-voltage curves, the speed of response and by photocurrent spectroscopy. The designed SACM APD shows responsivity of 0.85 - 0.9 A/W at 1310 nm for reverse bias voltage 15 V and avalanche gain up to 8 near the breakdown voltage.

K e y w o r d s: InGaAs/InGaAsP/InP structure, SACM avalanche photodiode, Electrical and optical characterisation

1 INTRODUCTION

For long-haul and high bit rate optical communication systems (OCS) [1] the avalanche photodiodes (APDs) are preferred since they offer an improvement of the receiver sensitivity by several decibels [2, 3]. The most advanced APD structure enhances carrier multiplication in the InP layer while the absorbing ternary layer is separated from the binary layer by an intermediate bandgap or a graded InGaAsP layer [4]. Separation of these two layers leads to lowering of the dark current [5]. This structure is known as separate absorption and multiplication (SAM) or separate absorption, grading and multiplication (SAGM) APD [6, 7]. The APD structure with multiplication region thickness in submicron scaling results in low multiplication noise and high gain-bandwidth products. Best performances were achieved with separated absorption, grading, charge and multiplication (SAGCM) layers in APD structure [8], where only single type of carriers are transported into the multiplication region, which reduces the multiplication noise. For the modern OCS and other applications, design of new APD structures with a high gain-bandwidth product and low breakdown voltage is required [9, 10].

Our study was focused on design and properties of the separated absorption, charge and multiplication (SACM) layer APD structure based on InGaAs/InGaAsP/InP material system. The InGaAsP charge layer provides a sufficient electric field drop between the absorption and multiplication layers to secure effective avalanche multiplication. The low breakdown voltage SACM APD was designed containing a 500 nm thin InP multiplication layer and InGaAsP charge layer between InGaAs absorption and InP multiplication layers. The electrical and optical properties of realized SACM APD were investigated.

2 STRUCTURE DESIGN AND FABRICATION

For simulation of SACM APD structure properties, the APSYS software was used to investigate the electrical field distribution, carrier concentration, thickness of layers and current-voltage characteristics. In the APD structure design, the electric field higher than 4.5105 V/cm is desirable for achieving an efficient carrier avalanche multiplication in $n-$InP multiplication layer. In the $n-$InGaAs absorption layer the electric field should be lower than 1.5×10^5 V/cm because of tunnelling and reduction of the carrier capture at the heterointerface. A sufficient electric field drop in the APD structure between the multiplication and absorption layers and bandgap variation reduction are provided by an $n-$InGaAsP charge layer with appropriate thickness and carrier concentration. The simulation software does not contain tunnelling and avalanche process simulation in the structure near the breakdown, therefore optimization of structure properties was estimated only up to the punch-through voltage.

The cross-sectional view of the designed, fabricated and tested SACM APD structure with an InGaAsP charge layer is depicted in Fig. 1. The APD structure consists of five layers grown on n^+-InP substrate. In our design 300 nm thick n^+-InP $(1 \times 10^{17}\text{cm}^{-3})$ buffer layer, 1000 nm thick $n-$InGaAs $((1 \times 10^{15}\text{cm}^{-3})$ absorption layer followed by 150 nm thick n^+-InGaAsP $(1 \times 10^{17}\text{cm}^{-3})$ charge layer and 500 nm thick $n-$InP

[*] International Laser Center, Ilkovičova 3, 812 19 Bratislava, Slovakia; E-mail: hasko@ilc.sk; [**] Department of Microelectronics, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology, 812 19 Bratislava, Slovakia

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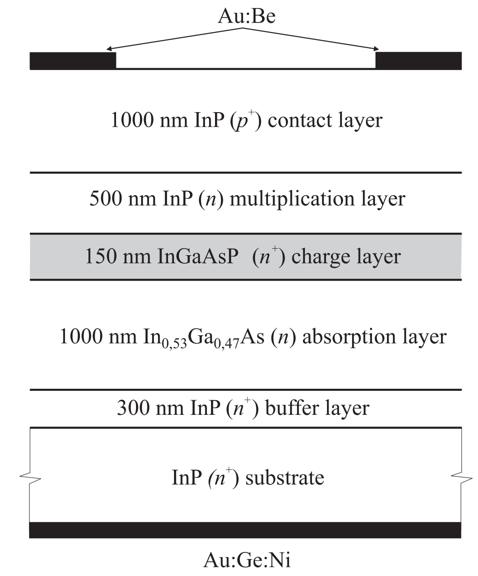

Fig. 1. Cross-sectional view of InGaAs/InGaAsP/InP SACM APD structure

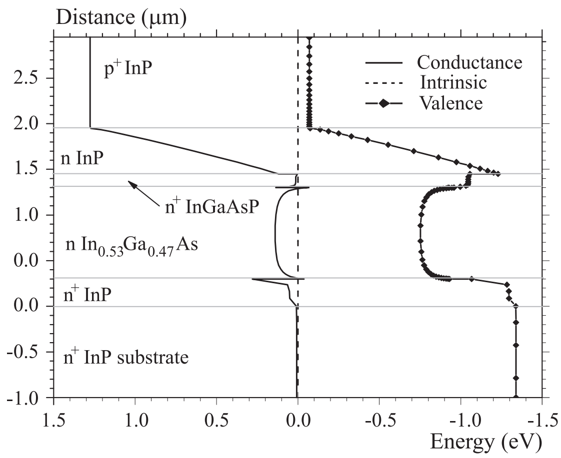

Fig. 2. Simulated band diagram of InGaAs/InGaAsP/InP SACM structure at $V_B = 0$ V

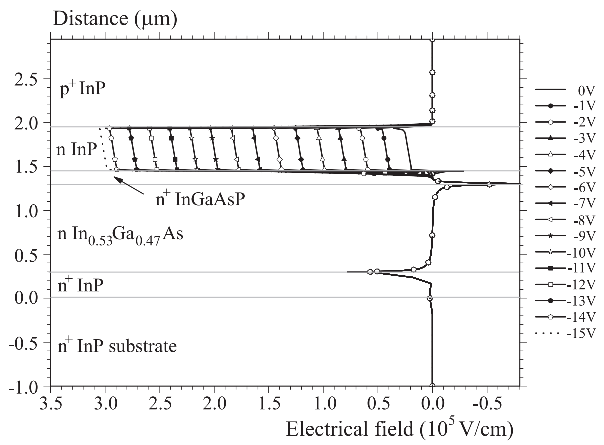

Fig. 3. Simulated electrical field distribution at different reverse bias voltage V_B in InGaAs/InGaAsP/InP SACM structure

(1×10^{15}cm^{-3}) multiplication layer, covered by 1000 nm thick p^+-InP (1×10^{18}cm^{-3}) contact layer have been used. The band diagram of the designed structure at zero reverse bias is shown in Fig. 2, where the bandgap variation is reduced by inserting n^+-InGaAsP layer betweeen InGaAs absorption and InP multiplication layer. The electrical field distribution in the structure at different reverse bias voltages for designed SACM APD is depicted in Fig. 3.

The lowest value of the electrical field correspond to zero reverse bias and the highest value to the reverse bias of $V_B = 15$ V. If the reverse bias increases over 15 V, the electrical field extends into the absorption layer and this value correspond to the punch-through voltage. The comparison between simulated and measured current-voltage ($I - V$) characteristics of the designed SACM APD up to the punch-through voltage is shown in Fig. 4. The measured $I - V$ characteristic shows a slightly increased leakage current and punch-through voltage in comparison with the simulated characteristic. For the reverse bias above the punch-through voltage the dark current increases due to the increased electric field in central active region with simultaneous extension of the reduced electrical field into the absorption layer.

SACM APD structure was grown by MOCVD in a single step and photodiodes were fabricated using standard photolithography, wet chemical etching and lift-off ohmic contacts processing. 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.

3 RESULTS AND DISCUSSION

On the selected SACM APD devices with 0.007 mm^2 active area the electrical and optical characteristics were measured and analyzed. $I - V$ dark current and photocurrent characteristics under 1310 nm calibrated source illumination are shown in Fig. 5. The current steps on the $I-V$ characteristic near 16 V correspond to the extension of the electrical field into the absorption layer. Within this mode of operation, the entire charge sheet and absorption layer are depleted. The photocurrent is flat just above the 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 a high electric field thus providing an avalanche gain. The breakdown voltage was estimated near 35 V and avalanche gain up to 8 was reached for mesa shaped devices. The measured photoresponsivity of the photodiodes without antireflection coating at 1310 nm was evaluated in the range of 0.85 - 0.9 A/W at a reverse bias voltage of 20 V. Figure 6 shows the capacitance-voltage characteristic, where the ripples on the curve fit to the extension of the electric field through heterointerfaces in the structure equally

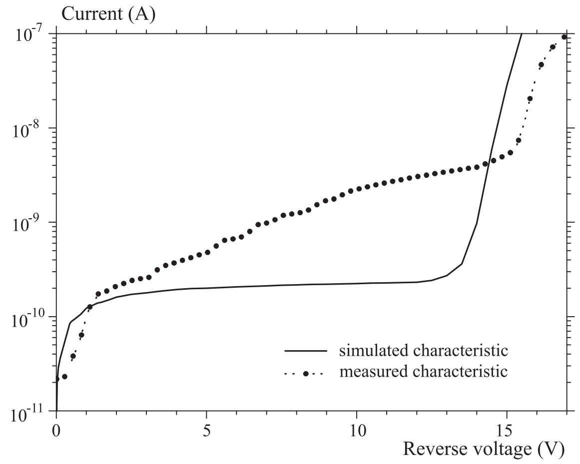

Fig. 4. InGaAs/InGaAsP/InP SACM structure I-V characteristics, simulated and measured

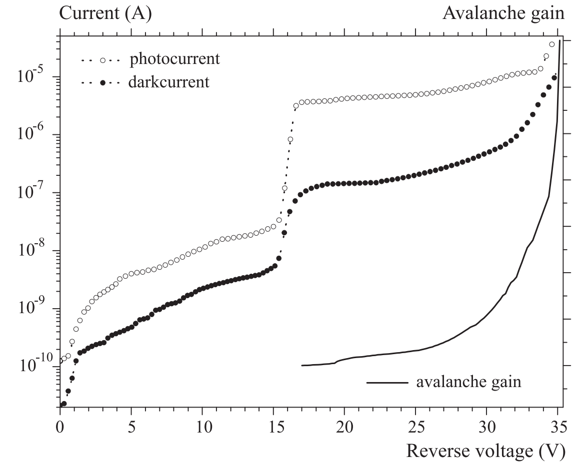

Fig. 5. Current-voltage characteristics of InGaAs/InGaAsP/InP SACM APD

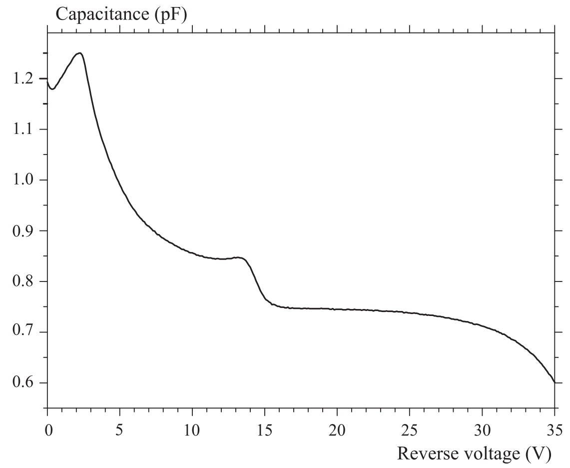

Fig. 6. InGaAs/InGaAsP/InP SACM APD capacitance-voltage characteristics

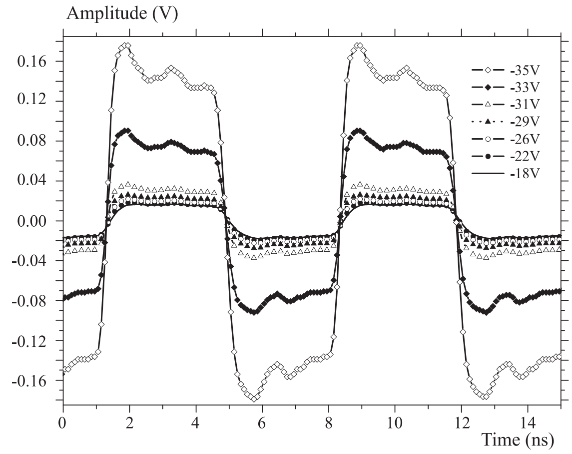

Fig. 7. Speed of response characteristics of InGaAs/InGaAsP/InP SACM APD

to the measured I-V characteristics (Fig. 5). The capacitance 0.65 pF for the bias voltage near the breakdown of APD was measured. The speed of response of SACM APD is shown in Fig. 7 in dependence on bias voltages at 1310 nm illumination. The measured rise time at breakdown was determined as 0.29 ns and fall time as 0.30 ns. The avalanche gain up to 8 was estimated from the speed of response amplitudes at the breakdown voltage. Modulation frequency bandwidth at low gain was measured as 4 GHz and gain-bandwidth product as high as 30 GHz by a microwave spectral analyzer.

4 CONCLUSION

A novel InGaAs/InGaAsP/InP structure SACM APD including a 500 nm thick InP multiplication layer and a 150 nm thick InGaAsP charge layer was simulated, fabricated and characterized. In simulations, an effective decrease of the electrical field from multiplication to absorption layer was achieved by employing an InGaAsP charge layer. The simulated and measured properties of the designed SACM APD structure exhibit good agreement up to the punch-through voltage. For tested mesa etched avalanche photodiodes with 120 μm diameter, the breakdown voltage near 35 V and avalanche gain up to 8 under 1310 nm calibrated illumination were achieved. The measured results revealed that the InGaAsP charge layer could be used to control the electric field profile in the SACM APD structure.

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Daniel Haško (Ing, PhD) was born in Piešťany, Slovakia, in 1975. He received his Ing (MSc) and PhD degrees in electrical engineering from STU, Bratislava, in 1999 and 2006. From 1999 to 2001 he worked on his PhD at Microelectronic Department of STU dealing with photodetectors. From 2002 to 2004 he worked as a research worker in the section of research and development of optoelectronic and microwave elements at Microelectronics Department of STU Bratislava. In 2005 he joined the International Laser Centre in Bratislava, where he is engaged in semiconductors materials surface characterization in the surface and materials analysis laboratory.

Jaroslav Kováč (Prof, Ing, PhD) was born in Šafárikovo, Slovakia, in 1947. He graduated from the FEI STU, Bratislava, in 1970. Since 1971 he has been engaged in the research of optoelectronic devices technology at the Microelectronics Department of FEI STU. He received a PhD degree from STU Bratislava, in 1983. Since 1991 he is the team leader of the Optoelectronic and microwave group at the Department of Microelectronics.

František Uherek (Prof, Ing, PhD) was born in Zlín, Czech Republic, in 1954. He received the Ing (MSc) and PhD degrees from FEI STU, Bratislava, in 1979 and 1989, respectively. In 1980 he joined the Microelectronics Department of FEI STU. At present he is full professor and vice-head of the department. His main interests are optoelectronics, optoelectronic devices and their applications.

Jaroslava Škriniarová (Ing, PhD) received her Ing (MSc) and CSc (PhD) degrees from the Slovak University of Technology (STU), Bratislava, in 1977 and 1986. In 1993 she joined the Microelectronics Department of STU. At present she is there engaged in the research of optoelectronic devices, especially of wet etching processes.

Ján Jakabovič (Ing, PhD) was born in Sereď, Slovakia, in 1951. He received his Ing (MSc) and PhD degrees in electrical engineering from STU, Bratislava, in 1974 and 2005. From 1974 to 1976 he worked at the Czechoslovak Metrological Institute in research of Josephson junction devices. In 1976 he joined the Microelectronics Department of STU Bratislava, where he is engaged in the research of optoelectronic devices, especially device processing and organic electronics.

Loránt Peternai (Ing, PhD) was born in Šurany, Slovakia, in 1977. He received his Ing (MSc) degree in electrical engineering from STU, Bratislava, in 2002. From 2002 to 2005 he worked on his PhD at Microelectronic Department of STU dealing with LEDs. In 2006 he joined the Microelectronics Department of STU Bratislava, where he is engaged in the research of optoelectronic devices, especially of ohmic contacts, and as a teacher.