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Design and Simulation of N-Substrate Reverse Type Ingaasp/Inp Avalanche Photodiode

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Abstract:- An avalanche photodiode (APD) based on an InP /InGaAsP structure containing separated absorption, chargeand multiplication layers was designed, simulated and tested. The InP charge layer at the heterointerface between the InGaAsP absorption and InGaAsP multiplication region allows optimization of the electric field distribution and suppression of the carrier capture at the heterointerface. In this simulation, both process and device simulations of APD have been done by using a 2D simulation package, Athena and Atlas, from Silvaco International. The purpose of this simulation is to investigate optimal design parameters to meet device performance requirement. The results of N-substrate reverse type avalanche photodiode(APD), which internally amplifies the photocurrent by an avalanche process, with
the epitaxial method is presented.

Keywords:- InGaAsP/InP structure, avalanche photodiode, Electrical and optical characterization

I INTRODUCTION

For long-haul and high bit rate optical communication, particle detection, astronomical observations, optical range finding, ultra-sensitive fluorescence and many other applications the avalanche photodiodes (APDs) are preferred since they offer high speed and improvement of the receiver sensitivity by several decibels [2, 3]. The growing interest in applications of APDs in experimental physics and nuclear medicine [2]–[4] prompted recently an intensive study of device performance in scintillation detection.

The compact muon solenoid (CMS) experiment at CERN and positron emission tomography (PET) scanner have done much work on characterization of Hamamatsu APDs. RMD Inc. has announced an improved structure of large area APDs replacing the beveled-edge construction by a planar one .New reverse reach-through APDs produced by EG&G have been proposed for PET scanners as well.

An Avalanche photodiode has improved low-noise characteristics, high speed response characteristics ad sensitivity. It has improved sensitivity compared to conventional pin photodiode. However APDs at high electric fields is inevitably subject to multiplication noise, restricting the device performance and maximum gain.

The most advanced APD structure enhances carrier multiplication in the InGaAsP layer while the absorbing layer is separated from the multiplication layer by an intermediate bandgap or a graded InP layer. Separation of these two layers leads to lowering of the dark current . This structure is known as separate absorption and multiplication or separate absorption, grading and multiplication APD . 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 layers in APD structure , 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.

This study was focused on design and properties of the separated absorption, charge and multiplication layer APD structure based on InGaAsP/InP material system. This study has been divided into two phases: Process Simulation and Device simulation.

Process simulation deals with the modeling of the fabrication steps of APD using the process simulation tool ATHENA from Silvaco International. Device Simulation deals with simulation of electrical characteristics like gain, breakdown voltage, external Quantum efficiency and responsivity using device simulation tool ATLAS from Silvaco International.

II STRUCTURE DESIGN AND FABRICATION

For simulation of APD structure and properties, Silvaco's ATLAS and ATHENA software has been used to investigate the electrical field distribution, carrier concentration, thickness of layers and current- characteristics.

The principle of operation of an APD is based on the conversion of the energy of the photon into free charge carrier in the semiconductor bulk and their further multiplication via the process of impact ionization. The basic element of the structure is the pn junction. One incident photon is sufficient to cause an avalanche breakdown. Under ideal conditions almost every incident photon is absorbed, creating a electron-hole pair. Both carriers are accelerated under the influence of a strong electrical field. Upon acceleration the carriers continuously collide with the lattice structure.

The avalanche photodiode for optical communications using InGaAsP and InP in the light absorbing layer is widely used. In this avalanche photodiode, electron-hole pair generated in the light absorbing layer is accelerated by an electric field and injected into the multiplication layer. A high electric field in the multiplication layer, accelerates the electron – hole pairs which are eventually ionized. The important characteristics of APD's noise are decided by the ionization process of the carriers in this multiplication process.

The dark current and illuminated current is very dependent on the absorbed layer and the doping profile. The multiplication layer thickness is a key parameter for the breakdown voltage and position of the avalanche.

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 1.5×105 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 fabrication process is simulated using the Process simulation tool ATHENA to simulate the structure of APD. The electrical characteristics are checked using device simulation tool ATLAS.

III PROCESS SIMULATION

The process simulation of APD is simulated using ATHENA from Silvaco International. The proposed n-substrate reverse type APD structure is designed as fig 1.

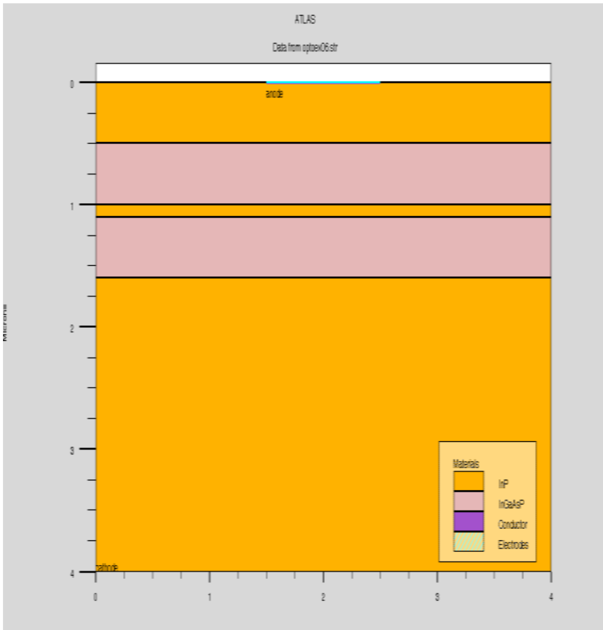

Fig 1. A schematic diagram of N-substrate reverse type InGAsP/InP Avalanche photodiode.

The simulated bulk material is a 2.5 μm thick n-type wafer. Since the fixed oxide charge and the interface trapped charge in <111> wafer are larger than those in <100> wafer, we choose the <100> wafer for the simulation study.

A thick InGaAsP absorption layer with very low donor type is on the InP. The APD structure consists of five layers grown on n type InP substrate. In our design 2500 nm thick n type InP (2×10^{18} cm^{-3}) substrate layer, 500 nm thick n type InGaAsP (2×10^{18} cm^{-3}) absorption layer followed by 100 nm thick p type InP (1×10^{15} cm^{-3})charge layer, followed by 500nm thick ptype InGaAsP ($1\times10^{15}cm^{-3}$) multiplication layer, covered by 500nm thick p type InP ($1 \times 10^{15}cm^{-3}$) contact layer have been used. The bandgap variation is reduced by inserting n type InP layer betweeen InGaAsP absorption and InGaAsP multiplication layer. The speed of the APD depends on the thickness of the absorption layer. This is due to the reduction in the transit time when this absorption layer is reduced.

To simulate the avalanche photodiodes, the recombination rate can be used to obtain an estimate of the recombination current contribution to the reverse diode leakage current. For the purpose of numerical simulation, the parameters for the InP and InGaAsP are given in table1.

Parameter	Units	InGaAsP	InP
Electron Auger Coefficient	Cm6/s	8.3 x 10^{-32}	8.3 x 10^{-32}
Hole Auger Coefficient	Cm6/s	1.8 x 10^{-31}	1.8 x 10^{-31}
Electron SRH recombination lifetime	sec	10 x 10^{-9}	2 x 10^{-9}
Hole SRH recombination lifetime	sec	10 x 10^{-9}	2 x 10^{-9}
Electron low field mobility	cm2/(V·s)	4600	2400.0
Hole low field mobility	cm2/(V·s)	150	80.0
Photon transition from valence band to conduction band		1.5 x 10^{-10}	1.5x 10^{-10}

Table 1: List of material parameters used for simulation

IV DEVICE SIMULATION

On the selected APD device laser simulation is done over the selected active area of 1µm. Fig 2 shows the structure plot of simulated APD. The emission spectrum of photons is shown in fig 3. Simulation results of radiative recombination rate in the carrier layer is shown in Fig. 4. The current distribution as a function of bias voltage is shown in fig 5. The breakdown voltage is estimated to be around 500 volts as seen from curve in fig 5. Atlas does not work well at or above the breakdown; in the figures all currents past the breakdown are meaningless and the curves should be stopped at Vb.

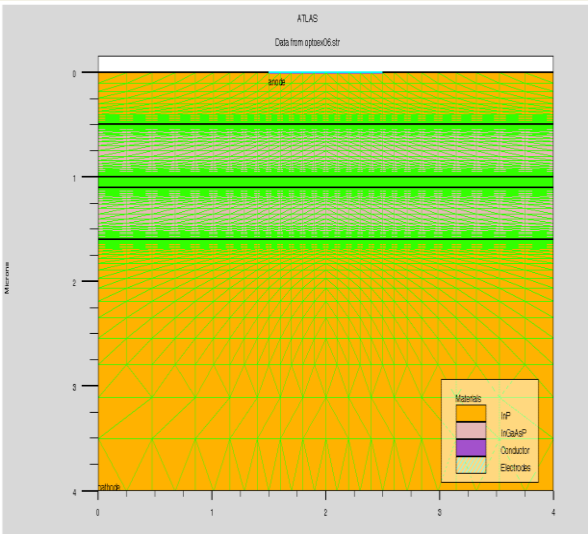

Fig 2. Structure plot of simulated APD

Photons

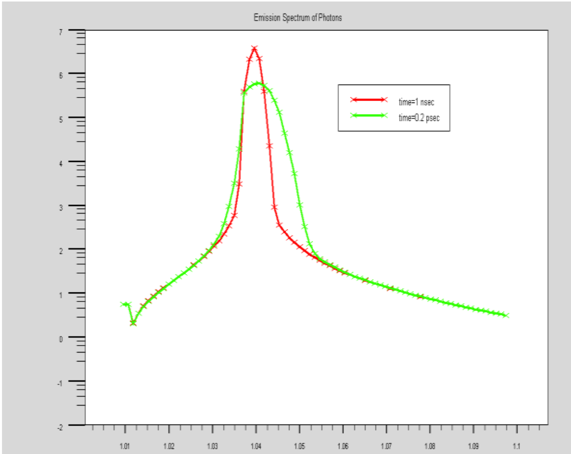

Fig 3. Emission spectrum of photons

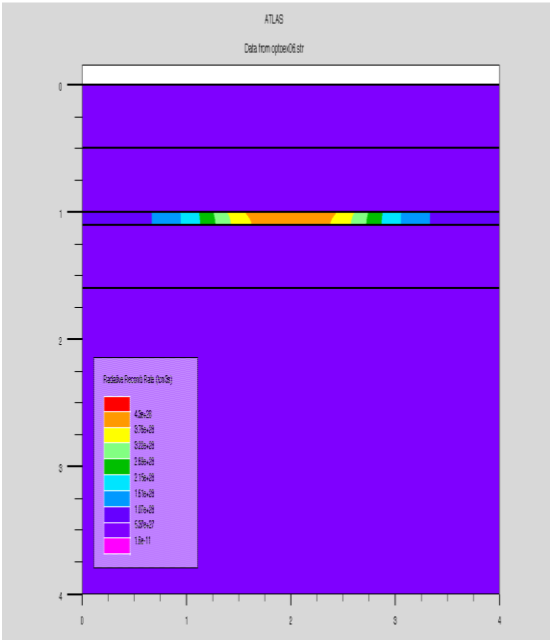

Fig 4: Radiative recombination rate in the carrier layer

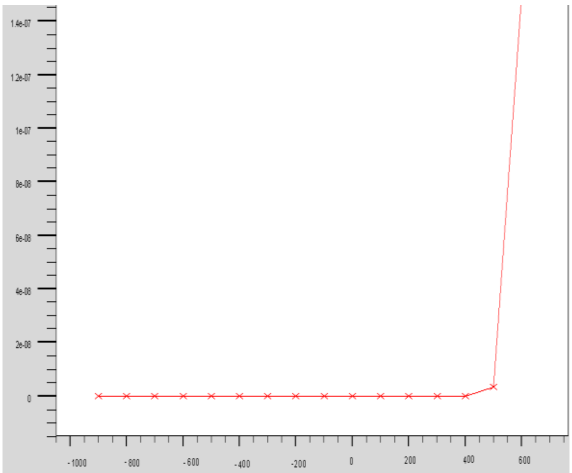

Fig 5: Current vs reverse bias voltage

The gain G is defined by

Gain G = Ic/Ia ,--(1)

Where Ic is cathode current and Ia is available photo current. The gain of ~100 for wavelength of 500 nm photon is estimated at 220V reverse bias.

Quantum efficiency (Q.E) is defined as the ratio of the number of photons contributing to the photo current to the total number of incident photons. It is given by

QE = (R/λ) * (hc/e) = 1210 * (R/ λ),-------------(2)

Where R is the responsivity in A/W, λ is the wavelength in nm, h is the Planck constant ($6.63*10^{-34}$ J.S),c is the speed of light in a vacuum ($3*10^{8}$ m/s) and e is the electronic charge ($1.6 * 10^{-19}$ C)

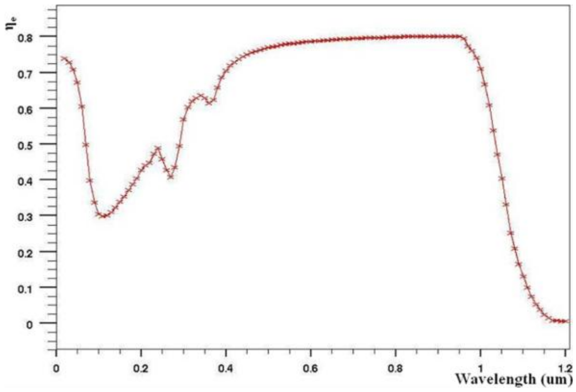

Fig. 6. External quantum efficiency as function of the wavelength for the APD

External quantum efficiency is calculated by defined as the ratio of the number of photons contributing to the photo current to the total number of incident photons. External quantum efficiency of the APD fabricated with the epitaxial method is shown in Fig. 5. The maximum quantum efficiency is estimated to be up to 0.8.

The responsivity of an optical detector is a measure of its response to radiation at a specified wavelength. Fig. 6 shows spectral responsivity of the device. The device is most sensitive in the 400 nm–1000 nm spectral range and cover the visible region. The peak responsivity of the device is estimated to be at around ~ 700nm.

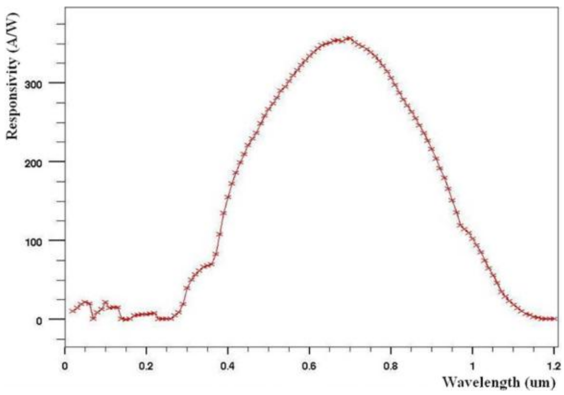

Fig 6: Responsivity of APD as a function of incident photon wavelength

V CONCLUSION

The electrical and optical characteristics were measured and analyzed. The ATHENA and ATLAS package tools were used to simulate fabrication process and device characteristics, respectively. The n-substrate reverse type InGaAsP/InP Avalanche Photodiode (APD) was simulated with the epitaxial method. Consequently the APDs electrical characteristics like breakdown voltage, current as a function of bias voltage, gain, responsivity and quantum efficiency were studied. The results reveals that the InGaAsP charge layer can be used to control the electric field profile in the APD structure.

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