Título:

1. **Cubic phase wide band gap materials for avalanche photodetectors**

Duration in months:

48

Free keywords:

Avalanche Photo-detector (APD), Cubic phase Wide band gap materials.

1.1 Introduction

Semiconductor photodiodes were developed in the early 'Forties approximately at the time when the photomultiplier tube became a commercial product (RCA 1939). With the invention of Geiger-mode avalanche photodiodes (APD), the sensitivity of semiconductor photodetectors has reached comparable to photomultiplier tubes [1]. The evolution started in the 'Sixties with the successful utilization of PIN photodiodes, which is still used in many detectors for high energy physics and many other applications i.e. radiation detection and medical imaging. The next step was the development of the APD leading to a substantial reduction of noise but not yet achieving single photon response. The weakest light flashes that can be detected by the PIN diode need to contain several hundreds of photons. An improvement of the sensitivity by 2 orders of magnitude was achieved by the development of the avalanche photodiode, a device with internal gain. At the end of the millennium, the semiconductor detectors evolved with the Geiger-mode avalanche photodiode into highly sensitive devices, which have an internal gain comparable to the gain of photomultiplier tubes and a response to single photons. Currently, silicon is the by far best understood and by far the most frequently used semiconductor material. Therefore, it is not surprising that nearly all manufactured types of large area PIN photodiodes, APDs and G-APDs are based on silicon [2]. There exist many other semiconductor materials, which are nowadays pursued for alternative applications, mainly on III-V materials [3, 4]. Most of the activities concentrate on developments for LEDs, laser diodes and microwave components. Industry is steadily improving the purification of these materials and the growth of high quality, cost effective crystals. It will, therefore, only be a question of time before G-APDs based on materials other than silicon will be fabricated. The main reasons are the prospects of producing G-APDs with lower noise and possibly higher sensitivity in the UV and blue spectral region. The reduction of noise is strongly correlated with a higher bandgap material and high purity materials, which also should have few lattice defects. One can even list several requirements in the search for useful semiconductor candidates:

A bandgap wider than that of silicon.

High purity intrinsic materials.

Ability to grow crystals with few lattice defects.

Suitable doping materials for both n and p structures.

A sufficiently large lifetime of the carriers.

Holes must also contribute to electron-hole pair production to start secondary avalanches.

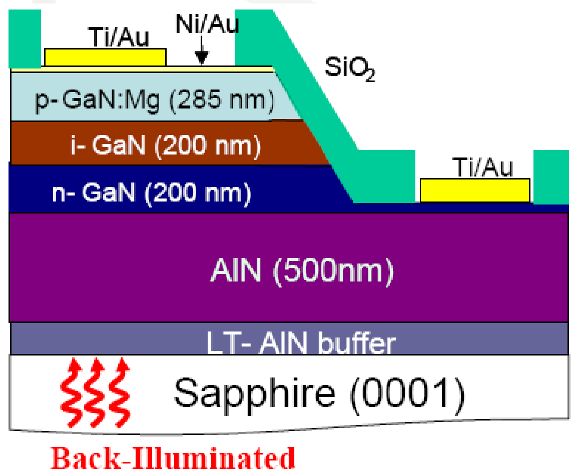
A key requirement is that the production of secondary photons in the avalanche process should be very small, i.e. it must be an indirect bandgap material.

In order to the reduce the noise related problems and enhance the response and detection speed, we propose the investigation of cubic phase GaN material as APD. To carried out this proposal we will employ Molecular beam epitaxy (MBE) provided by CINVESTAV to grow the layers with reduced lattice defects. Furthermore, for the enhancement of multiplication of the electrons in order to upgrade the internal gain (i.e. ratio of multiplication current to primary current) of the device. The structure will modify by employing staircase/step/superlattice structure in the form of alternative layers i.e. GaN/AlGaN. The above-mentioned structures are more facilitated for electron multiplication (Impact ionization coefficient) due to of large conduction band discontinuity as compared to valence band. Then, the sample processing, microfabrication and contact deposition will be carried out in a clean room provided by UTD.

1.2 Background on Prior R&D

The significant enhancement of the ionization rates ratio ($\alpha e/\alpha h$) has been demonstrated in AlGaAs/GaAs superlattice and graded gap APDs. The staircase APDs have been also disclosed where only electron multiply [5].

(a)



(b)

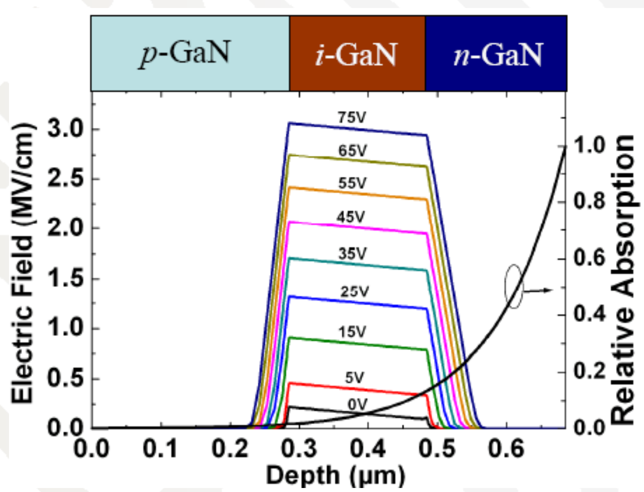


Figure:1 (a) Schematic structure of GaN-based APD and (b) Electric field across the device.

Furthermore, the Si~3C-SiC Multiple Quantum Barrier High Speed, wide-Band Avalanche Photodiodes have also been theoretically studied for influence of the number of barriers on performance of the device [6]. The defects in the material have also greatly influence on their internal gain because of these defects acts as recombination center. Therefore, the improved quality of the crystal and lattice friendly layers will lead to better results [7]. The conventional structure of GaN-based APD with respect to their electric field is shown in figure:1. The p-GaN quality is low due to (1) trade-offs in growth conditions since those at which Mg incorporation is maximized may degrade GaN quality; and (2) the high activation energy of Mg requires that the Mg incorporation in the lattice be almost 100 times higher than the desired carrier concentration leading to a disruption of the GaN lattice. However, one advantage of cubic phase GaN is that the Mg ionization energy is expected to be lower than the most familiar hexagonal GaN [8]. Therefore, cubic GaN is a better candidate to implementing an APD. Moreover, in order to upgrade the performance of device with low dark current and high gain, we will modify the structure by employing additional layers. By inserting i.e. superlattice layers, the active region become more effective for multiplication process. Meanwhile, the use of a novel δ-doping technique for the realization of high-quality p-GaN

1.3 Justification and importance

The radiation detection event presents very low efficiency. For nuclear material detection an insolate single photon detection event is needed. So, the issues are: the difficulty to catch a single photon and the louse's mechanism such as high leakage current and junction capacitance. Therefore, APD presents one of the best choices to overcome the event louses due to its multiplication properties and its high sensibility. Moreover, GaN is high energy tolerant material is comparison with the well know Si and in addition, cubic GaN has an extra advantage due its low Mg ionization energy useful to achieve p-type materials. Finally, it is worth to mentioning that: to the best of our knowledge there is a lack of scientific reports about cubic GaN APDs. Thus, we want to attend this lack of knowledge and contribute with new experimenters and results.

1.4 Hypothesis/Predictions

Hypothesis 1: The hypothesis related to the R&D proposed here is that the development of wide band gap materials with reduced lattice defects is able to detect thermal neutrons.

Hypothesis 2: From Mg doped cubic phase GaN is expected to achieve a high free hole concentration due its low activation energy in comparison with more familiar hexagonal GaN.

Prediction 1: The detection of thermal neutrons by the proposed APD.
Prediction 2: Due the low activation energy of Mg in cubic GaN. We expect that similar results will be obtaining with and without Mg δ-doping.

1.5 General Objective

The general objective is to perform a well-controlled growth technique by MBE to increase the quality of crystal. In general, we will study the effect of wide band gap material as APDs. Then with the optimized quality of layer, we will fabricate and characterize an APD.

Specific Objectives.

Modeling and design each layer of APD structure. It includes the p-type, intrinsic and n-type layer. Here, will obtain the optimized carrier concentrations and thickness of the each layer.

The systematically Growth and doping of p-type and n-type cubic phase GaN.

The electrical, optical and structural characterization of each layer.

The fabrication of complete APD structure by MBE.

The ohmic contact deposition of the structure.

The IV characterization of the device.

The device processing in a clean room.

Neutron test of the final device.

1.5 Goals

We expect a single high energy photon detection capability by employing cubic phase wide band gap materials.

We expect three JCR research papers (Related to sensitivity range, single photon emission, engineered design by control of composition).

One oral presentation in an international conference.

Deliverables for the Proposed Project.
The full research thesis.
3 published JCR research papers.

1.7 Materials and Methods
The Cubic GaN synthesis will be performed on an MBE lab located at CINVESTAV-ZACATENCO. The owner of the MBE lab is Dr. Maximo Lopez who is Researcher in Physics department at CINVESTAV. Dr. Maximo is an MBE specialist and also a SNI level III member. The idea is to send the student at least two year after global pandemic ends. Then the student has to learn MBE, RHEED, Hall effect at CINVESTAV. From now we are considering the materials and all the resources are available. In Addition, in the case of a possible pandemic extension, we consider to focused on theoretical modeling and design of the APD device.

1.8 Activity program

Activity	First Year	Second Year	Third Year	Fourth year
State of the art analysis	■			
Modeling and Simulations	■			
MBE growth		■	■	
Material Characterization		■	■	
Device Processing			■	
Device Characterization			■	
Write papers		■	■	■
Write Thesis			■	■

1.9 Link with the Productive Sector or other research center

We do not have any link with any company. Moreover, we plant to be in narrow collaboration with CINVESTAV trough Dr. Maximo Lopez. CINVESTAV is going to provide all the resources to use the MBE. Therefore, in the scientific products such as research paper: the thesis Directors and Dr. Maximo Lopez will be included.

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