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Detailed Numerical Modeling of a Novel Infrared Single Photon Detector for $\lambda > 1\mu m$

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Abstract — **We have designed a novel avalanche-free single photon detector for IR wavelengths above 1 µm. The detector shows high quantum efficiency and high gain. A detailed finite-element-method based three-dimensional simulation was developed to model and evaluate the nonlinear effects involved in the design.**

Keywords- single photon detector, infrared detector, type-II, finite element method, multiplication factor.

I. INTRODUCTION

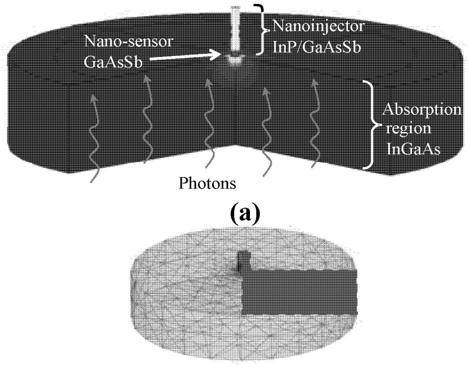
As the need for better detectors continues to grow while technology progresses, the required sensitivity of detectors are rapidly approaching the ultimate limit, a single photon. Hence, recently there has been a large amount of research done to get to single photon detectors (SPDs), which promise ultra-low noise levels and high signal-to-noise ratio.

Tracking the progress on single photon detection, one can see that specialized Si-based avalanche photodetectors (APDs) are the oldest and most mature SPDs, and they have demonstrated excellent performance. Gain values less than 100 have been shown, and as electron-to-hole ionization ratio in silicon was proved to be very small, small excess noise factors were measured at such gain values [1]. Unfortunately, single photon detection in Si APDs becomes inefficient at wavelengths above 1 µm and makes Si detectors unsuitable for longer wavelengths [2]. For near-infrared (NIR) spectrum, research has been focused mainly on InGaAs/InP APDs, but they generally suffered from several problems: In stark contrast with Si APDs, InGaAs/InP detectors have comparable electron-to-hole ionization rate, leading to high excess noise [3]. Due to deep level traps, significant afterpulsing and long deadtimes have been observed [4]. Coupled with stable gain values less than a hundred and low quantum efficiency, InGaAs/InP detectors have not been able to show satisfactory performance in asynchronous systems. Hence, their operation is yet limited to gated operation in synchronous systems [5]. As another alternative, superconductor based detectors (transition-edge detectors) have been proposed [6], but their extreme low temperature requirements severely limit them from being a mainstream option.

II. THEORY AND SIMULATIONS

To overcome the limitations of the current technologies in single photon detection beyond 1 µm, we focused on the two general requirements of a good single photon detection method: The first is high quantum efficiency which ensures any incoming photon is captured with a high probability and converted to an electron-hole pair. The other requirement is a low-noise multiplication process for any created carrier to prevent the noise contamination from proceeding circuitry.

Based on the requirements, we have designed a detector with InGaAs/GaAsSb/InP material system. The geometry and layer structure are shown in Figure 1. With type-II band alignment, this material system provides some unique properties, which we exploit to provide an avalanche free gain mechanism.



(a)

(b)

Figure 1 – (a) Three-dimensional device structure, (b) Two-dimensional cross section used in model with cylindrical symmetry

Our novel detector design is composed of two regions: a large absorptive InGaAs volume and a GaAsSb/InP sensor/nano-injector. When a photon strikes on the detector, the large InGaAs volume captures the photon with a high probability and converts it to an electron-hole pair. The hole is attracted towards the nano-injector due to the internal electric field. The tip of the nano-injector doubles as the sensor, and provides a conduction band barrier and valance band trap with type-II band alignment (Figure 2). When the optically created hole reaches the nano-injector, it becomes trapped in the small sensor region at the tip and increases the potential of the sensing layer. This potential change, in turn, lowers the conduction barrier and results in an exponential increase the flow of electrons from the nano-injector over the barrier. The nanometer size dimension of the sensor volume also amplifies

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the effect of a single hole, by creating a high charge density and altering the potential significantly. The high charge density and exponential injection leads to a low noise multiplication process that can provide stable gains more than several thousands.

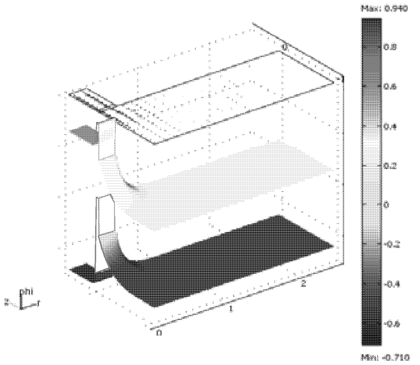

Figure 2 – Two dimentional band structure under 1 V biasing for InGaAs/GaAsSb/InP material system.

Before the designed devices were fabricated, a finite-element-method based three-dimensional simulation model was custom developed in *Comsol Multiphysics* [7] to evaluate the performance. The model has full 3-D simulation capability and 2-D cross-section modeling capability with cylindrical symmetry. It incorporates several nonlinearities including nonlinear mobility, impact ionization, thermionic emission, hot electron effects, temperature effects and surface recombination.

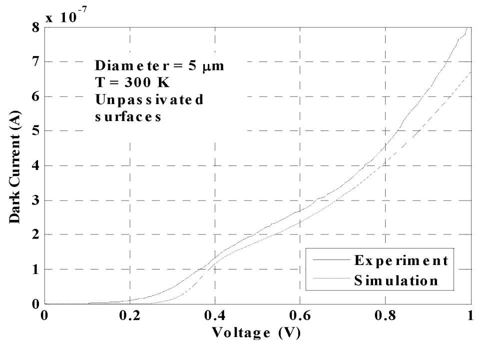

Figure 3 – Comparison of simulation results and experimental measurements for a 10µm detector.

Simulations have been done for devices ranging from 100 nm to 10 µm nano-injector diameter. The results show gain values exceeding 100 for devices with poor surface quality to several thousands for surface passivated devices. The predicted dark current density is in the order of 100 nA – 1 µA with gain values more than several thousands. Comparing the simulation results with experimental data, the measured devices show a behavior very similar to predicted performance (Figure 3).

Being a nano-scale detector with a high surface to volume ratio, the performance of our new detector strongly depends on the surface quality. To evaluate and gain insight into the surface effects and passivation we used our simulation model. Figure 4 demonstrates the influence on a 100 nm nano-injector diameter device. The results show orders of magnitude higher gain at improved surface quality. Experimentally, fabricated devices confirmed the importance of surface passivation, showing drastic changes with different types of passivation.

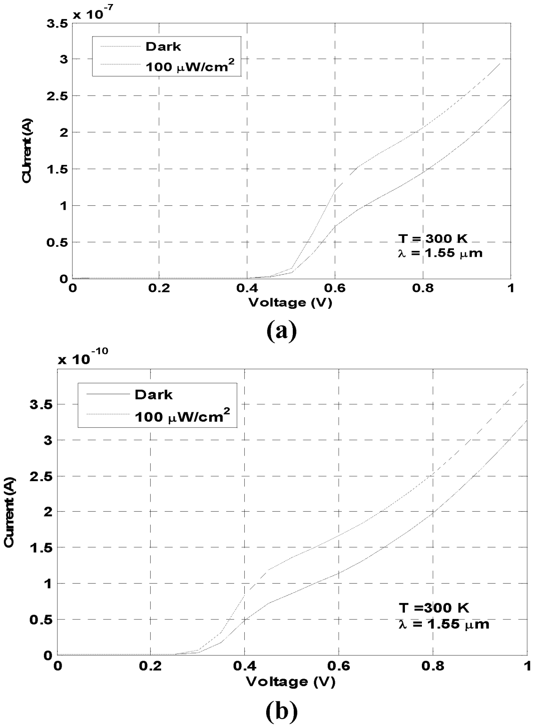

Figure 4 – Comparison of unpassivated (a) and passivated (b) devices at same voltages and optical powers.

III. CONCLUSION

We have designed and developed a novel NIR single photon detector based on InGaAs/GaAsSb/InP material system. A custom-made nonlinear three-dimensional FEM simulator was written. The simulation was used to predict the performance of the new detector and the predictions were confirmed with experimental results. To further improve performance, simulations were used to model the effects of surface passivation.

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