A Novel Avalanche Free Single Photon Detector

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***Abstract* — We have conceived a novel single photon detector for IR wavelengths above 1 µm. The detection mechanism is based on carrier focalization and nano-injection. Preliminary measured data from unpassivated devices show a very high internal gain and low dark current at 1.55 µm at room temperature**

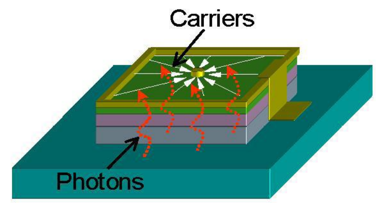
Keywords- single photon detector, infrared detector, type-II, finite element method, simulation.

INTRODUCTION

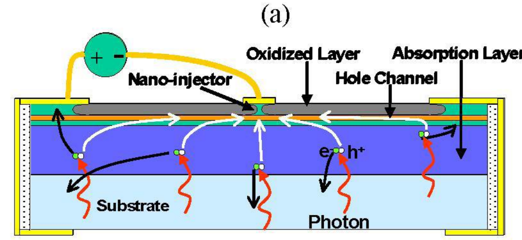
Infrared detectors have been known and developed for many years. However, a wide range of applications require single photon detectors with lower noise, better signal-to-noise ratio, faster response, and operating wavelength beyond 1 µm. These include biophotonics, tomography, non-destructive material inspection, astronomy, quantum key distribution, quantum imaging, and homeland security.

Existing devices for infrared detection are photodiodes (PIN and avalanche), phototransistors, quantum well (QWIP), and quantum dot infrared photodetectors (QDIP). However, not all of these are suitable for single-photon detection. In order to be used as a single-photon detector, an infrared detector needs to be extremely low noise while creating enough signal amplitude: generally this is only possible with quantum confinement, such as a single-electron transistor based detectors [1], or an internal gain mechanism, such as avalanche based detectors [2]. PIN photodiodes are the simplest and most mature of all IR photon detectors. However, they have no internal gain, which limit their application for single photon detection. Silicon based single photon detectors show good detection performance below 1 µm. Unfortunately, at telecom wavelengths (1.3µm, 1.55µm) silicon does not absorb efficiently. Therefore, researchers have focused on other materials for this important part of IR spectra. InGaAs/InP avalanche photodetectors have been the main candidates for single photon detection up to ~1.7 µm. However, they generate large dark currents that reduce effective single photon detection for many applications. In particular, they cannot be used in non-synchronized applications such as imaging systems [3, 4].

Here we present a novel avalanche-free single photon detector based on carrier focalization and augmentation. The principle of operation of the so-called Focalized Carrier aUgmented Sensor (FOCUS) is shown in Fig.1 schematically.



(a)



(b)

Figure 1. The schematics of FOCUS, showing (a) lateral focalization and (b) vertical transport.

Compared with the existing technologies, FOCUS is created to deliver better performance and higher SNR: when optically generated electron-hole pairs are attracted and trapped at the nano-injector. This creates a high concentration that reduces the potential barrier of the injector and leads to the injection of many electrons to the absorption layer (Fig.2). The structure features short transit time for electrons and high lifetime for holes in the nano-injector, which accounts for the high gain. Furthermore, the thick absorption layer and efficient collection of holes results in high quantum efficiency.

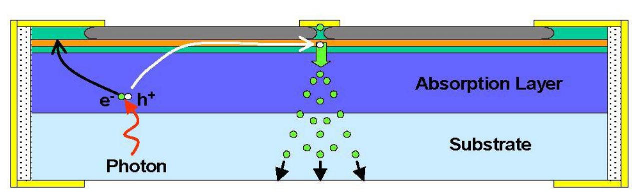


Figure 2. Electron injection resulted from entrapment of a hole.

To improve carrier injection, FOCUS is utilizing type-II band alignment in the lattice matched InP/GaAsSb/InGaAs material system. Hot electron injection is easily achieved in this system [5, 6], and is used to enhance the device gain. Unlike other low dimensional detectors, FOCUS contains a large

This work is partially sponsored by DARPA through grant # HR0011-05-1-0058

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absorption medium to increase quantum efficiency, and adds the benefit of same small sensing volume of a quantum dot. The small volume of the nano-injector produces an ultra-low capacitance that leads to a large change of potential even with entrapment of a single hole (Fig.3). The change of potential reduces the barrier between the emitter and collector, and produces a large electron injection. Our simulation results show a gain of $\sim 10^4$ is easily achievable. The structure is also designed to reduce recombination of injected electrons with the photo-generated holes by separating the electron and hole current paths.

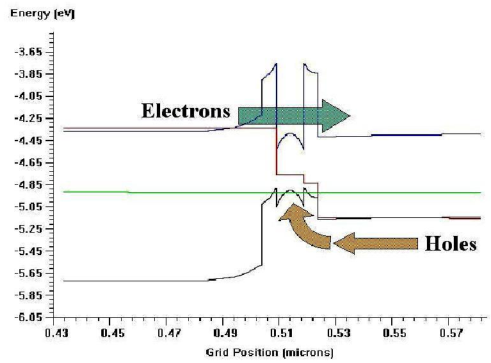

Figure 3. The band diagram at the center of device (vertical).

SIMULATION MODEL

A simulation tool was created using Comsol Multiphysics [7], which uses Finite Element Method (FEM) to simulate physical environment. The model incorporates the Poisson's equation along with the diffusion-drift equations using appropriate boundary conditions and cylindrical symmetry. To improve performance and lower the complexity, the simulation of a radial cross-section of FOCUS is performed instead of the whole 3-dimensional volume (Fig.4). The model incorporates several nonlinear effects such as incomplete ionization of dopants, surface recombination, impact ionization, nonlinear mobility, and hot electron effects.

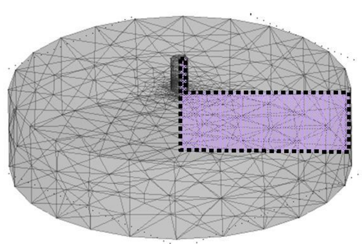

Figure 4. The radial cross section used in FEM simulation

As the device contains highly nonlinear dynamics, stability of the model was a problem. Consequently, there were convergence issues which needed to be addressed: First, forced boundaries in the form of ohmic or Schottky contacts (i.e. Dirichlet boundary conditions) imposed infinite recombination and created stress on the domains they are attached to. In addition to this, the heterojunctions in the device resulted in jumps in the carrier concentrations, which made current continuity harder to sustain. The most effective method to overcome these problems was to build up the simulation in steps. Starting with a less constrained model (i.e. without nonlinear effects or forced boundaries), then using that solution as initial condition increased convergence and stabilized the simulation.

Other than convergence issues, accurate modeling of surfaces needed special attention: The nano-injector region was extremely sensitive to any surface effect due to its high surface-to-volume ratio. It was important to accurately depict surface recombination physics. Further, to improve the results of FEM simulation, weak constraints were used in current calculations. Weak constraints ensured that predicted currents are correct and free of the inherent boundary flux calculation problem in FEM.

RESULTS

Simulation results show a high gain and low dark current, which correspond to a high SNR in this device. Comparing to InGaAs phototransistor and photodiode, although the gain of phototransistor is higher and the dark current of photodiode is lower than FOCUS, SNR ratio of both is still lower than FOCUS. The current components within the device are also as expected: the electron injection is mainly under the nano-injector, and hence recombination with photo-generated holes is minimized (Fig. 5) Current-voltage characteristics of a 5 µm wide device at different optical powers are shown in Fig.6. The device is capable of detecting very weak optical powers even at room temperature, while demonstrating a respectable internal gain of about 4×10^3 even with a small multiplication region.

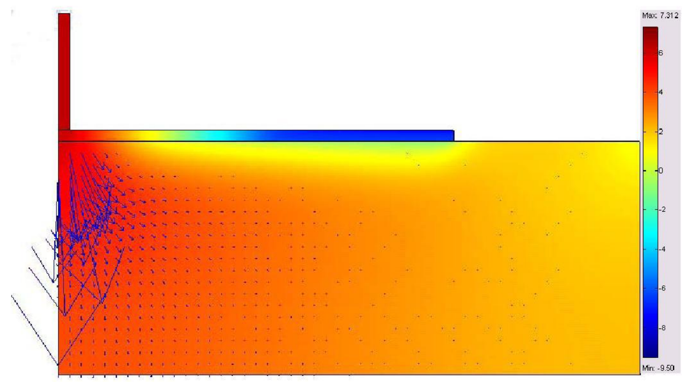

Figure 5. Simulated electron injection density (arrow) and electrostatic potential (color) of the device at T=300 K and under a bias value of ~0.5 volts.

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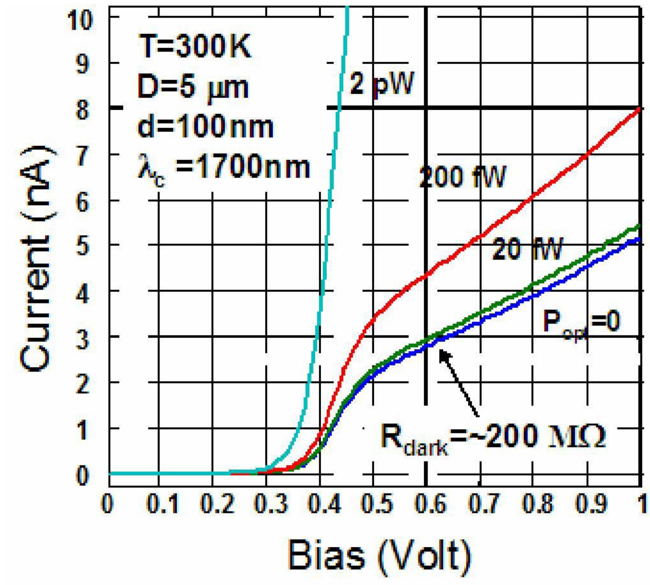

Figure 6. Current-voltage characteristics of a 5 μm wide device at T=300 K and different optical powers. The device shows an internal gain of ~4000.

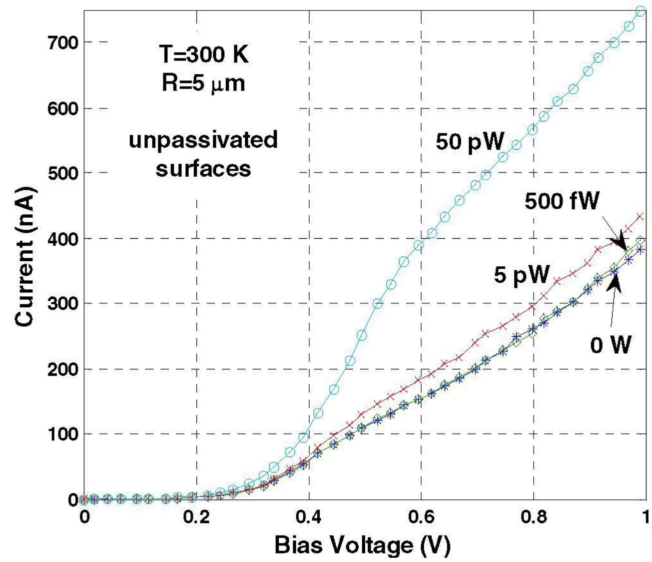

Figure 7. Measured current-voltage data at different illumination powers of 5 μm diameter device without any surface passivation (T=300 K)

The results show that slightly increasing the radius of nano-injector is quite effective in further separation of electron and hole currents. The simulation also confirmed that the routing of the carriers towards the narrow nano-injector region reduces the radial diffusion length compared to the axial diffusion length. This reduction was expected due to the congestion of carriers around the center of FOCUS device.

EXPERIMENTAL RESULTS

We have started processing and fabricated devices grown on InP substrates. Circular devices of 2.5 μm and 5 μm radius and square shaped devices of 10 μm, 40 μm and 100 μm side length were patterned using photolithography. The metal contacts were then formed using lift-off technique and were used as hard-mask for etching.

The tested devices showed a very high gain (more than 10000) even for smaller devices. Dark current calculations show that the effective collection radius is 1.5 μm larger than the device size, on average. The tested devices have relatively high bandwidth of more than 70 kHz, reaching to 400 kHz at 1.2 volts.

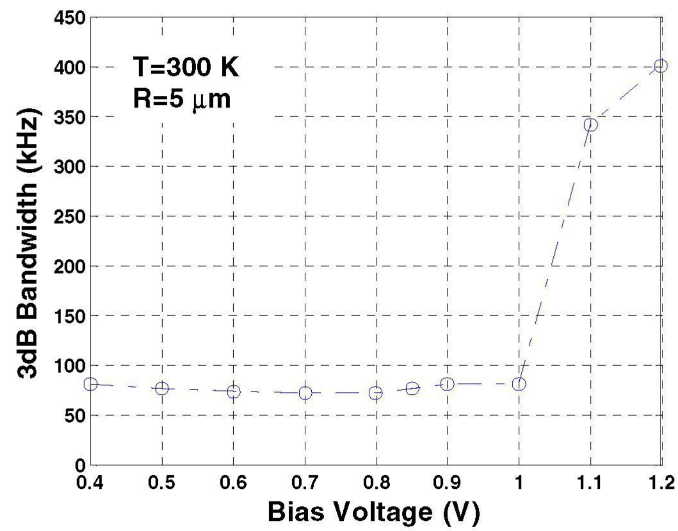

Figure 8. Measured bandwidth of 5 μm diameter device at different voltages.

Note that the measured devices were not passivated. We believe that a significant reduction in dark current can be achieved using conventional passivation methods.

CONCLUSION

We have designed and realized a novel single photon detector. It incorporates a nano-injector region on top of a large absorption layer. It has several features to reduce the noise level while maintaining a high gain. The design was created while taking into account the fabrication and processing technology limitations.

Furthermore, we created a three-dimensional non-linear simulation tool for accurate modeling of the proposed detector. The model enables us to see and compare performances among different types of photon detectors, and optimize the structures. We believe that there is much more room for improvement for

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the simulation: we are currently adding quantum effects and Monte Carlo analysis to the existing model.

The optimized epitaxial layer structure and device geometry, provided by the simulation tool, was used for epitaxial growth and processing mask design. First batch of devices have been fabricated and tested. These unpassivated devices show a high internal gain at small bias values, high frequency bandwidth, and low dark current at room temperature.

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