A Novel SWIR Detector with an Ultra-high Internal Gain and Negligible Excess Noise

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ABSTRACT

Short wave infrared (SWIR) imaging systems have several advantages due to the spectral content of the nightglow and better discrimination against camouflage. Achieving single photon detection sensitivity can significantly improve the image quality of these systems. However, the internal noise of the detector and readout circuits are significant barriers to achieve this goal. One can prove that the noise limitations of the readout can be alleviated, if the detector exhibits sufficiently high internal gain. Unfortunately, the existing detectors with internal gain have a very high noise as well.

Here we present the recent results from our novel FOcalized Carrier aUgmented Sensor (FOCUS). It utilizes very high charge compression into a nano-injector, and subsequent carrier injection to achieve high quantum efficiency and high sensitivity at short infrared at room temperature. We obtain internal gain values exceeding several thousand at bias values of less than 1 volt. The current responsivity at 1.55 μm is more than 1500 A/W, and the noise equivalent power (NEP) is less that 0.5 x10 $^{-15}$ W/Hz^{½} at room temperature. These are significantly better than the performance of the existing room temperature devices with internal gain. Also, unlike avalanche-based photodiodes, the measured excess noise factor for our device is near unity, even at very high gain values. The stable gain of the device combined with the low operating voltage are unique advantages of this technology for high-performance SWIR imaging arrays.

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Introduction:

Short wave infrared (SWIR) imagers have recently found many applications due to their better discrimination against camouflage and better spectral match to the nightglow emission. Unlike the mid and long wave imagers, SWIR produces more familiar images for the users, since it shows the reflected light rather than the “thermal” images.

It can be shown that increasing the signal to noise ratio (SNR) of each element can significantly improve image quality of the existing SWIR imagers. The maximum achievable SNR in the existing technology is limited by the noise of the readout integrated circuit (ROIC), which is currently about 10 e^- rms. Unfortunately, reducing the noise below this value for high resolution imagers with small pitch size is extremely challenging, since ultra-low noise electronics with extremely low cross-talk must be implemented in very small footprints. Implementation of a high internal gain into the detector can clearly alleviate this issue, as the system SNR will not be limited by the readout, and rather the detector. Avalanche based photodetectors in the SWIR range can produce internal gain due to the avalanche multiplication. However, they have limited stable gain of less than a few hundreds[1], low quantum efficiency[2], and high excess noise[3,4].

Here we present a novel SWIR detector with a very high internal gain, and negligible excess noise. The gain mechanism of the detector is inspired by the extremely high sensitivity of the rod cells in the eye, which is capable of detecting a few photons[5]. Specialized segments in these cells are very rich in photosensitive rhodopsin molecule, which is a strong absorber of photons with peak sensitivity in blue-green spectrum. Upon light reception rhodopsin undergoes structural changes and triggers a chain of events that eventually lead to drastic changes in the ion channels. The ion channels, which control the current passing through the rod cell, change their states and alter the cell potential. The significance of this detection mechanism is that it can provide both high efficiency and high sensitivity at room temperature; a condition that is very difficult to achieve in conventional single photon detectors. Simply put, the energy of a single photon in the visible or short infrared is extremely small, less than one atto Joule, and the only reliable way of sensing this small energy is to use a very small sensing volume, for example a quantum dot. However, the wavelength of light is significantly larger than such a sensor, and hence the interaction between the photon and the sensor, or quantum efficiency, is extremely small. Any attempt to enhance the efficiency by increasing the volume would simply reduce the sensitivity. Rod cell's detection mechanism resolves this conflict by using a micron-scale absorbing volume, the outer cell, and nano-scale sensing elements, or the ion channels.

We incorporated these principles in our novel semiconductor platform. Figure 1 shows the mechanism of photon detection in our device. Upon absorption, photons generate an electron-hole pair in the large absorption region. The electron and hole are immediately separated because of the internal electric field. Holes are attracted to the nano-injector that has a type-II band alignment and presents a trap for holes. A single photo-generated hole in the absorption region is equivalent to a charge density of 1.4×10^{-3} C/m^3. However, when trapped inside the 50 nm thick by 100 nm wide nano-injector, the same hole creates a charge density of more than 400 C/m^3. Therefore, the impact of the hole increases by more than 5 orders of magnitude. Equivalently, the small volume of the trap represents an ultra-low capacitance, and hence the entrapment of a single hole leads to a large change of potential and produces an amplified electron injection, similar to a single electron transistor (SET)[6]. Detailed simulations and potential calculations show that a single hole can alter the potential by more than 52 mV. This value is significantly higher than the thermal fluctuation energy of carriers at 300 K, and hence a high signal to noise ratio is possible even at room temperature.

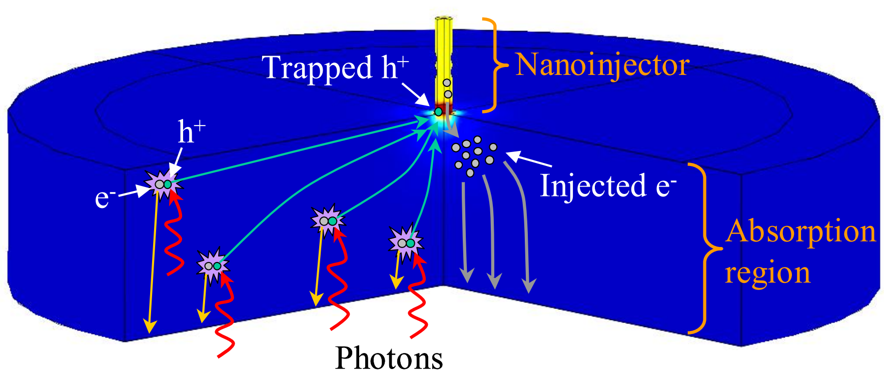

Figure 1. Schematic of our semiconductor base single photon detector showing the large absorption region, and the nanoinjector. The ultra small volume of the hole trap makes the device sensitive to a single charge.

We used a three-dimensional simulation model to design the epitaxial layer thickness, doping level, and composition. The layers are grown using conventional epitaxial growth on InP substrates. Wafers were patterned with e-beam lithography (EBL) to form nanometer size pillars. Conventional metallization with e-beam evaporation was used to form multi-layer metal contacts. Etching process consisted of dry etching with methane and hydrogen in a reactive ion etcher (RIE), followed by a mild wet etching with sulfuric acid and hydrogen peroxide. Samples were passivated and planarized with polyimide to provide planar surfaces for metal contact pads. Photolithography was used to produce liftoff patterns. Final metallization was used to form reliable top contacts to the submicron features (see Figure 2).

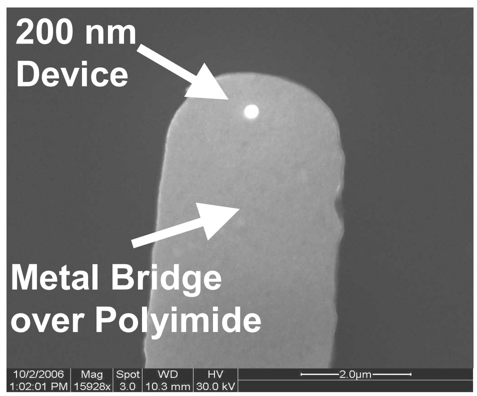

Figure 2. SEM image of the processed device showing the metal bridge that connects the nanoinjector to a large metal pad.

Fabricated devices are tested using computerized setups. The measured dark current shows a fairly good agreement with the modeling results. The gain of the device increases with the device bias, and beyond ~1 volt the device shows a stable gain of more than several thousand (see Figure 3). Compared to existing avalanche-based detectors, our devices show more than an order of magnitude higher stable gain, and much better dark current values.

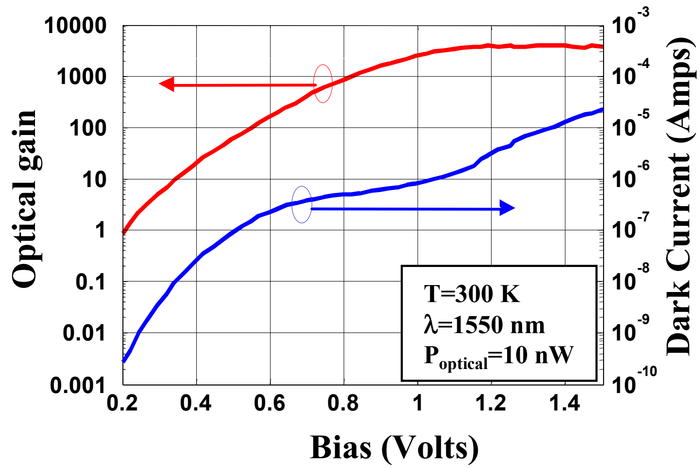

Figure 3. Measured dark current and gain of a device at room temperature and for an illumination power of 10 nW at λ=1550 nm. The gain is almost independent of the optical power below 10 nW.

Current noise of the devices was amplified with a low noise transimpedance amplifier and analyzed using a spectrum analyzer at different DC currents. The power spectral density measurements were taken at center frequency of 60 kHz and with a span of 390 Hz. In parallel, optical gain was measured at 10 nW of laser power using a calibrated p-i-n detector. The data was used to calculate excess noise factor[7] F using the relationship $I_n^2 = 2qI_{DC}M^2F\Delta f$, where I_n is the measured current noise, I_{DC} is the current, M is the gain, and Δf is the bandwidth. Figure 4 shows the measured noise performance of the device at room temperature. The device shows an excess noise factor that is less than unity up to a measured gain of 4000. This performance is in stark contrast with conventional APD, where excess noise factor grows rapidly with gain, and noise is tens of times higher than the shot noise limit at gain values below 100. Interestingly, we have measured excess noise factors that are consistently below unity, indicating shot noise suppression in our devices. Such behavior might be resulted from the nano-injector, since shot noise suppression has been predicted theoretically[8] and measured experimentally[9,10] in similar structures.

Noise equivalent power (NEP) of our detector is calculated from measured dark and photo current to be about 2×10^{-16} W/Hz^{½}, the responsivity is more than 4000 A/W at 1550 nm at 300 K. As a comparison, the best avalanche photodetectors have NEP values larger than 2×10^{-15} watt/Hz^{½} and stable responsivity of about 30 A/W at 1550 nm at room temperature[11,12].

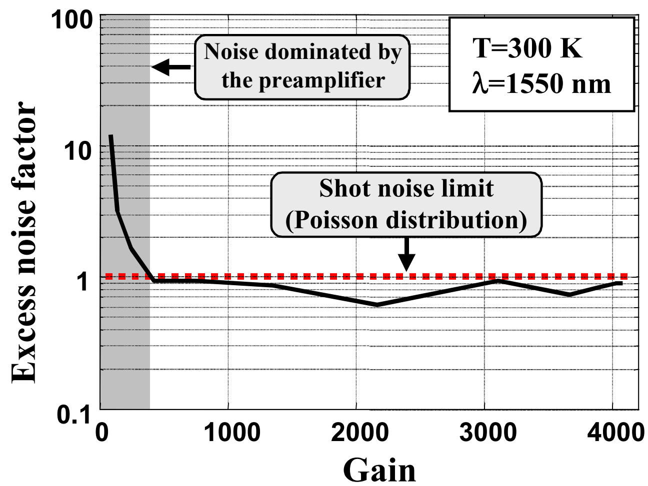

Figure 4. Measured excess noise factor of a device as a function of internal gain shows sub-Poissonian shot-noise performance up to very high gain values.

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