Student Paper

Nano-injection Infrared Photon Detectors with Record Internal Gain and Dark Current

Vala Fathipour, Omer Gokalp Memis, Sung Jun Jang, Robert Brown and Hooman Mohseni

Bio-Inspired Sensors and Optoelectronics Laboratory, Northwestern University, 2145 Sheridan Rd, Evanston, IL, USA 60208; hmohseni@northwestern.edu

Photon number resolving (PNR) detectors have recently seen an upsurge in their demand due to an explosive growth of interest in new scientific fields of research, including quantum information science [1]. More precisely, the wavelength range in the short wave infrared (SWIR) from 1.55μm to 2.5μm remains very critical for single photon counting detectors as there is a lot of applications which are utilizing this range. Among semiconductor detectors, silicon-based detectors cannot reach wavelengths beyond 1.1μm and the HgCdTe eAPDs remain strong candidates for PNR in this wavelength range [2]. Unfortunately, even though there had been great improvements there are still inherent material properties that limit their applications.

Here we demonstrate a breakthrough in reducing the dark current of the SWIR nano-injection detectors based on InP material system [3]-[5], which has enabled them to achieve photon number resolving at the SWIR at thermoelectric accessible temperatures for the first time.

HgCdTe ternary alloy (MCT) is a close to ideal infrared detector material system with PNR capability at 80°K [2], [6]. Best reported MCT eAPDs operate at SWIR (λ_c = 3μm) [2]. Compared to MWIR MCT eAPDs, they have lower dark current at constant gain and temperature. However, the minimum obtainable excess noise factor is higher and the maximum obtainable gain is lower. To benefit from the advantages of the SWIR eAPDs in FPAs, specifically designed readout integrated circuits (ROICs) capable of applying a high reverse bias and with very low noise are critical.

Compared to linear mode MCT eAPD, the nano-injection detector has 3 orders of magnitude higher gain (at same bias and temperature), and more than 3 orders of magnitude lower internal dark current density [2], [7]. Furthermore, it has the ability to form compact, large format imagers with high pixel density and its gain does not significantly change by voltage and process variation across the FPA [8].

The nano-injection detector is based on a type-II material system consisting of InP injector, GaAsSb barrier/trap, InGaAs absorber and InP substrate [3], [9]. Device schematic together with its SEM micrograph and energy band diagram along a vertical cutline through the central axis of device in darkness and under illumination is shown in Fig. 1 (a), (b) and (c) respectively. Negative bias voltage gives electrons enough energy to overcome the GaAsSb conduction band barrier and get injected from the highly n doped InP injector towards the InGaAs absorption region. Once the thermionic emission current becomes limited by current of the reversed biased n- InGaAs/ p+ GaAsSb junction, nano-injector dark current saturates. Upon photon absorption, an electron-hole pair is generated in the thick intrinsic InGaAs absorption region. Negative bias separates the electron and the hole and the hole gets trapped in the p doped GaAsSb trap layer for the period of its life time. This leads to a large change of barrier potential, producing an exponential increase in the injection of electrons towards the absorption layer and hence results in an inherent gain. Electrons have a short transit time over the GaAsSb barrier during which they lower the local potential and increase the barrier height, opposing the flow of further electrons. This results in a negative feedback mechanism which results in a stable low noise internal amplification while the device is operating at linear regime with low bias voltages.

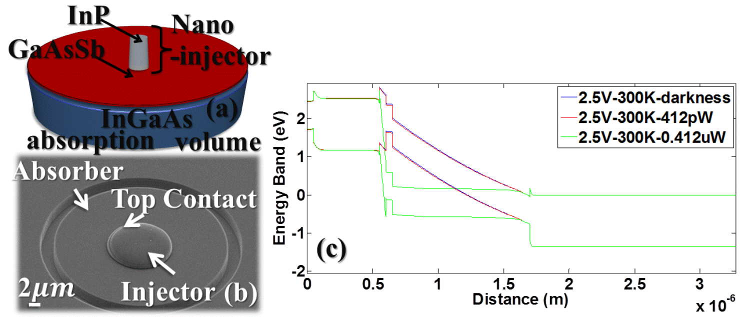

Fig. 1. **a** Device Schematic and **b.** SEM micrograph of a 10μm diameter injector showing the top metal contact, injector and absorber **c.** Energy band diagram along a vertical cutline through the central axis of device in darkness and under illumination.

Figure 2(a) shows the dark current-voltage characteristic of a 10μm injector and 30μm absorber nano-injection detector at room temperature (RT) and 260K. As shown in Fig. 2(b), at the measured temperatures, the nano-injection detector has 2 orders of magnitude lower external dark current density than the MCT eAPD[5]. The RT gain for nano-injection detector was 840 (at 3V bias) vs. 10 (at 8V bias) for the eAPD. At high illumination levels the device gain was measure to be 100. This gain reduction at high power levels is due to device saturation and reduction in collection efficiency and is depicted in Figure 1(c) by the green color line. The internal dark current density of nano-injector detector at any temperature is more than 3 orders of magnitude lower than the MCT eAPD.

Furthermore, the measured RT gain bandwidth product (GBP) yields a value of 7GHz for a 10μm injector diameter. Transient simulations yield GBP as high as THz for a 100nm diameter injector.

Based on the activation energy, simulations show the ability of photon number resolving at thermoelectric accessible temperature of ~ 200°K. This will be shown when further cooling becomes possible with our current measurement set up.

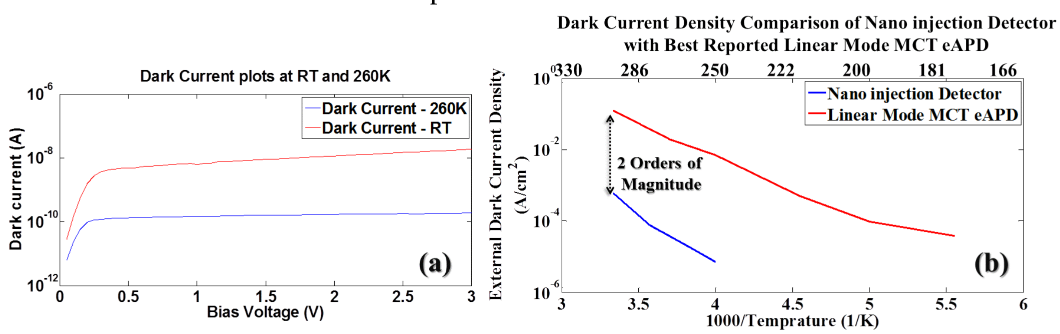

Fig. 2. **a**. Dark Current versus bias voltage for nano-injection detector at 300°K and 260°K. **b**. Comparison of dark current density for best reported linear mode MCT eAPD [5] versus the nano-injection detector at different temperatures. Operating voltage for MCT eAPD was 8V with gain of 10, while operating voltage for nano-injection detector was 3V with gain of 840 at RT. Nano-injection detector has more than 2 orders of magnitude lower dark current density at any given temperature.

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