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Heterojunction phototransistor for highly sensitive infrared detection

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ABSTRACT

In this work, we have proposed a model for the ultimate physical limit on the sensitivity of the heterojunction bipolar phototransistors (HPTs). Based on our modeling we have extracted the design criteria for the HPT for high sensitivity application. HPT with the submicron emitter and base area has the potential to be used for the low number photon resolving in near-infrared (NIR) wavelength. However, in practice, the quality of materials, processing, and the passivation plays an important role in the realization of the highly sensitive HPT. For short wave infrared (SWIR) HPTs based on lattice matched InGaAs to InP is studied. For these devices, conditions to reach to the highest possible sensitivity is examined. We have made an HPT based on InGaAs collector and base on the InP substrate. After developing proper processing combination of wet and dry etching and the surface passivation for the device we made an imager with 320x256 pixels based with a 30m pixel pitch. The imager shows the sensitivity less the 30 photons for each pixel with the frame rate more than 1K frames per second.

Keywords: Electron Injection Detector, Infrared Sensor, FPA

1. INTRODUCTION

A single photon is the quanta of electromagnetic energy, so single photon detection is the ultimate goal of enhancing the sensitivity of detectors. So far, single photon detectors (SPDs) for near infrared (NIR) have found numerous applications, such as in quantum cryptography, LIDAR, astronomical imaging and photoluminescence.[1] SPDs like other photon detectors convert the energy of an absorbed photon to the electrical signal. In this process noise is the main obstacle to detect weak light. There are three main sources for noise in any photon detection system, photons noise, dark noise and read noise. Photon noise is the photons statistical noise that obeys Poisson statistics. Dark noise is the noise associated with the detector and read noise is the noise of the electronic circuitry that is needed to read the generated electric signal. The lower the overall noise of the SPD, the higher the performance of it. Sensitivity can be simply defined as the minimum number of photons that produce electric eld equal to the total noise.

Reducing the temperature of the detector reduces the contribution of its shot noise on the overall noise level. For detectors without internal gain, e.g., PIN detector, lowering the temperature from a certain level no longer reduces its noise level. The reason is that the sensitivity becomes limited to the read noise. An internal low noise amplifier needs to be added to the detector to address this issue. This amplifier can be extremely low noise since it works at the same low temperature as the detector. The read noise contribution will reduce by a factor equal to the value of internal gain. There are few mechanisms to add internal gain to the detector such as avalanche and transistor action. Avalanche photodetector (APD) is a high-speed detector that uses impact ionization as its internal gain mechanism. APDs has been widely used to increase the sensitivity of detection systems. Drawbacks of the avalanche mechanism are its excess noise, high voltage operation and low gain[2] . The voltage of operation for APDs is higher than the operating voltage for standard CMOS electronics, so special circuitry is usually needed to drive them. These drawbacks impose some limitations on using APD for low light detection.

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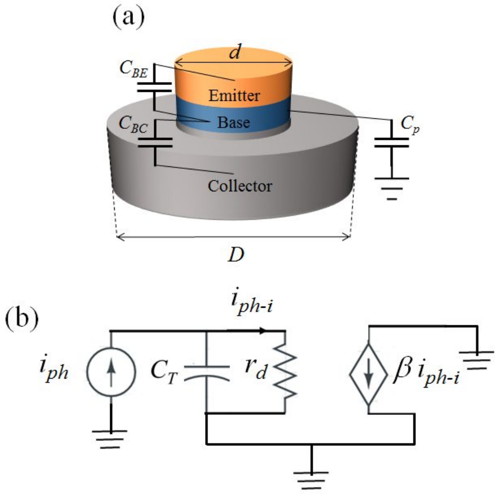

Figure 1. Schematic diagram of a 2-port npn PTD and its small signal circuit model.

Phototransistor detector (PTD) uses bipolar transistor action for its internal gain. Because of PTD's low voltage operation and high gain, it has been investigated by many researchers for numerous applications, especially in optical communication. Due to the advances in CMOS technology that enabled creating low noise, high-speed and low-cost amplifiers, attention to the PTD gradually reduced. For ultra-fast applications, a PIN photodiode combined with a CMOS read circuit became a better solution. PTD is an inherently slow device and not suitable for telecommunication especially when it is used in the two-port mode. In telecommunication, speed is the most important parameter and usually, the power level is far more that what could be considered a low light level.[3–6] In addition to speed, the other main problem of the PTD is its gain drop in low power levels, which has imposed huge restrictions on its application. By demonstrating the advance in III-V semiconductor material quality and addressing the gain drop problem,[7] here we show that PTD has great potential to be used for weak light detection.

2. PTD'S SENSITIVITY

Recently we have shown that the sensitivity of the PTD is limited to the total junction capacitance at its base.[8] Here we apply the the derivated formalism to analyze the newly designed and fabricated InGaAs/HPT for low light detection at short wave infrared wavelength. Fig. 1(a) shows a schematic diagram for a two-port PTD. In the model, internal dark current (I_d) is the base bias current and photocurrent (i_{ph}) is the signal. Part (b) of the figure shows the low light circuit model for the PTD. For such a circuit the rise time can be expressed by

$$t_{rise} = 2.2\frac{V_t C_T}{I_d}. \tag{1}$$

where C_T is the total capacitance at the base and V_t is the thermal voltage. If we define C_0 as the thermal fundamental capacitance as follows

$$C_0 = \frac{q}{V_t}, \tag{2}$$

minimum number of detectable photon will be given by

$$\eta N = \frac{1}{2}SNR^2(1 + \sqrt{1 + \frac{8}{SNR^2}\frac{C_T}{C_0}}) \tag{3}$$

where η is the quantum efficiency.

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3. INP/INGAAS/INGAAS HETEROJUNCTION PHOTOTRANSISTORS (HPTS)

In this section, we explore InGaAs based HPTs as SWIR low light detectors. We show that by proper design of epitaxial layers, surface friendly processing InGaAS HPTs can be used as a SWIR low light detector. $In_{.53}Ga_{.47}As$, which is lattice-matched to InP, has been extensively studied as the photo-absorption material of SWIR photodetectors. We have used low-pressure metalorganic chemical vapor deposition (LP-MOCVD) to grow the device structure on a 3-inch (001) oriented sulfur doped InP substrate. Each HPT consists of a 500-nm-thick n^+-doped ($1 \times 10^{19} cm^{-3}$) InP buffer layer, a 25-nm-thick n-doped ($5 \times 10^{15} cm^{-3}$) InGaAsP compositional graded layer, an $1.5\mu m$-thick n-doped ($10^{15} cm^{-3}$) InGaAs collector layer, a 100-nm-thick p-doped ($2 \times 10^{17} cm^{-3}$) InGaAs base layer, a 25-nm-thick undoped InGaAsP spacer layer, a 200-nm-thick n-doped ($1 \times 10^{16} cm{-}^{3}$) InP emitter layer, a 50-nm-thick n-doped ($1 \times 10^{16} cm^{-3}$) InGaAsP step graded layer, and a 300-nm-thick n^+-doped ($1 \times 10^{19} cm^{-3}$) InGaAs cap layer.[9] Zinc and Silicon are used for the p-type and n-type dopant, respectively. The undoped quaternary layer on the base layer is utilized as the ledge structure for surface passivation. The other quaternary layers are for improving the carrier transport. After growing epitaxial layers a surface friendly process is developed to fabricate the devices. Fig. 2 shows the schematic and SEM images of the final devices. Electrode and two quaternary layers are clearly visible in the SEM images. There is more than $300nm$ undercut for InGaAs capping layer and InP emitter. Fabrication begins with the definition of a $5\mu m$-diameter-emitter electrode of the HPTs. Non-alloyed Ti/Pt/Au (20/30/150 nm) metallization was evaporated and lifted off for the emitter contact. Wet etching was conducted to remove from the InGaAs cap layer to the InGaAs base layer. The diameter of the emitter-base junction is $10\mu m$. The area of the optical window mesa is $30 \times 30\mu m^2$, which defines an area of collector layer for photoabsorption. Mesa isolation etching was performed down to the InGaAs collector layer by wet (H3PO4-based solution) etches.

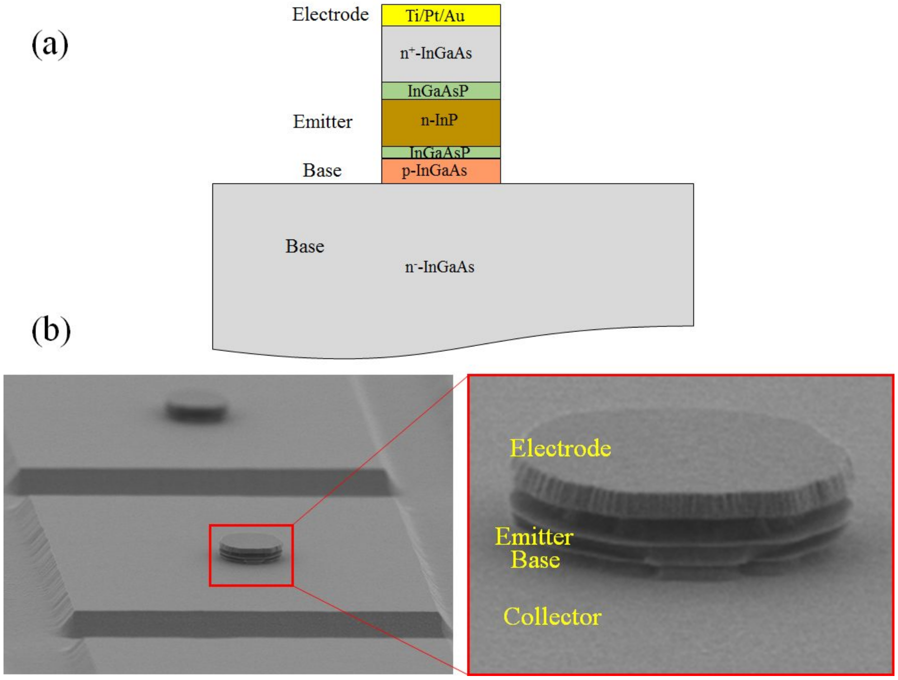

Figure 2. (a) Device schematic of InP/InGaAs HPTs and (b) SEM image of the fabricated devices

3.1 Sensitivity

Here the extracted formula for the sensitivity will be examined for the descibed HPT in the previous section . To have some estimation of the relation of the size of the PTD and the minimum number of photons that it can detect, we look at a junction capacitance versus the diameter of the electronic area, d. As it is mentioned earlier total capacitance at the base includes two junction capacitances, C_{BE} and C_{BC} and the parasitic capacitance

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of the base. In any PTD, the base-emitter junction is forward biased and the base-collector junction is reversed biased. For a p-n junction with area of A and depletion width of w_j the junction capacitance can be expressed by

$$C_j = \epsilon_0 \epsilon_r \frac{A}{w_j}. \tag{4}$$

In this formula w_j is related to the applied bias voltage and doping concentration of the both p and n sides. For a PTD the collector should have much lower doping than the emitter so the depletion width at the base-emitter junction will be smaller than that at the base-collector junction. Therefore, the total capacitance at the junction is mainly determined with base emitter capacitance. The depletion widths of our fabricated HPT for the base-emitter and base-collector junctions at the 1.2V bias voltage, are almost 200nm and 1.5μm, respectively[9] . An array of HPT detectors is fabricated and bounded to a read out circuit with >700 e noise. The time response of the detector at the temperature of 220K is shown in 4. As the figure shows this device has shown a sensitivity below 30 photons.

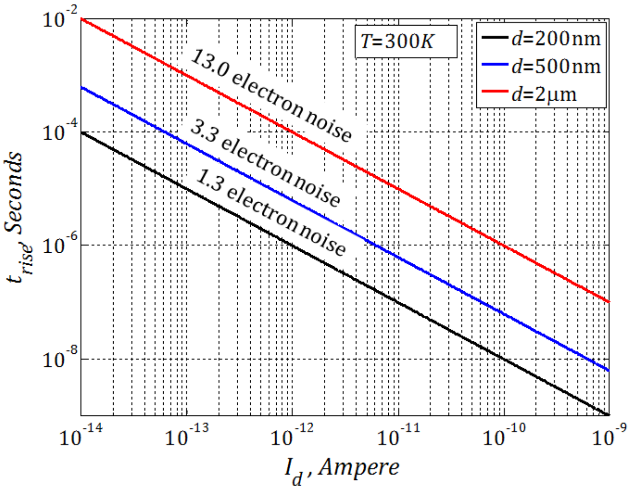

Figure 3. Rise time of the described HPT versus its internal dark current for different diameters of the junction area . The total amount of theoretical noise per read time is shown inside the figure for each diameter in the units of electrons RMS (root mean square).

Fig. 3 shows the rise time versus the internal dark current for the described HPT with different diameters of the electronic area, d . Changing the temperature changes the internal dark current, hence it changes the speed of the HPT. For each HPT the number of the electrons RMS noise is also shown in the figure.

3.2 Gain

As discussed in the previous sections, the reduction of the total junction capacitance at the base is a centerpiece toward reaching high sensitivity of PTDs. We need to decrease the base diameter, d, to achieve the small junction capacitance (see Fig. 1). However, a main issue is maintaining an enough gain at low power of light incident. Effective read noise is given by

$$N_{r,eff} = \frac{N_r}{G\beta}. \tag{5}$$

where G is related to the ratio between measurement bandwidth and the PTD time constant. It is necessary to have enough gain to decrease the effective read noise to a value less than the PTD's shot noise.[8,10]

Fig. 5 shows the comparison of the gain versus incident light power at 1550nm wavelength for three different HPTs. The most recent HPT (2016) is the HPT with the described epitaxial layer and fabrication process in

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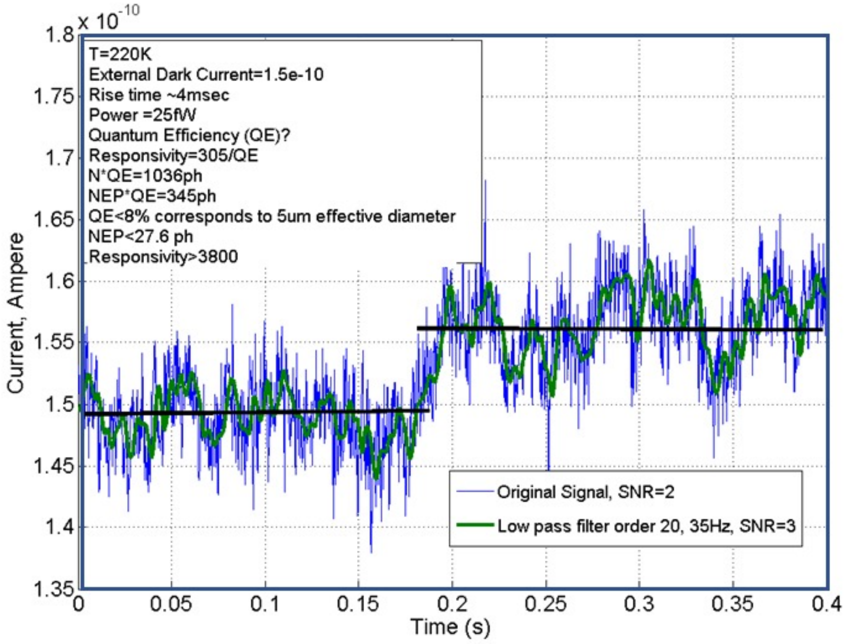

Figure 4. Measured time response for a pulse of light at 1550nm wavelength for the bounded InGaAs/InP HPT at 220K. The read out circuitry has more than 700 e noise.

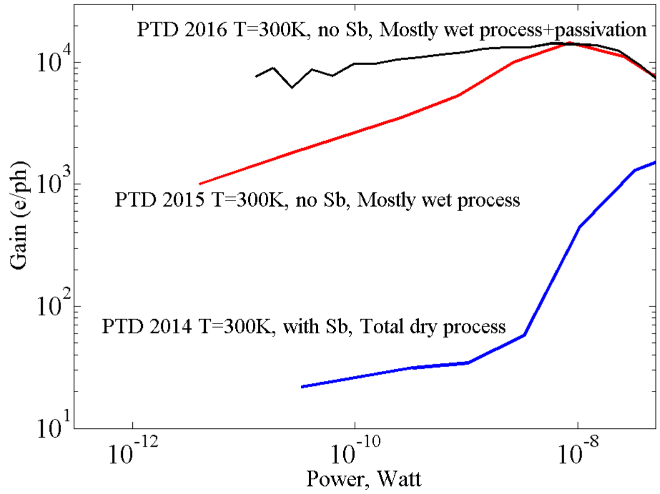

Figure 5. Gain versus incident power for three different PTD with different process and material system.

previous section. The gain performance of the HPT with GaAsSb as the base layer is also shown in this figure. GaAsSb at the base layer, because of its type-II band alignment with InP and InGaAs, adds many advantages to the HPT design and performance in high speed and high power. Despite these advantages, this figure shows that the gain of the HPT with GaAsSb base layer drops to almost 30 at power levels less than 1nW. Details about the material system and fabrication is described by Movasaghi et. al.[11] The main consideration in choosing material and process for fabrication of highly sensitive HPTs are the quality of the grow which includes low bulk defects

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and low interface traps. Specially the defects at the interface between emitter and base can extremely reduce the gain at low power.

4. CONCLUSION

In conclusion, we show that the minimum number of detectable photons for a PTD is mainly dependent on its total capacitance at the base junctions. Our experimental results show that our modeling is well predicting the sensitivity of InGaAs/InP detectors. An array of HPTs with 5μm diameter has shown less than 30 photons sensitivity for each detector.

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