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NIR/LWIR Dual-band Infrared Photodetectors with Optical Addressing

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ABSTRACT

A near infrared (NIR) and long-wavelength infrared (LWIR) dual-band infrared photodetector, which can switch detection bands with light bias, is demonstrated at 77 K. The demonstrated scheme consists of series connected photodetectors for different bands. The basic operating principle of the scheme is that without light bias, shorter wavelength detector limits the total current and thus the device operates in NIR mode. With light bias on the NIR detector, the LWIR detector becomes the current limiting device and the device then operates in LWIR mode. Proposed design allows single indium-bump per pixel focal plane arrays, and in principle allows covering all tactical bands such as UV, visible, NIR, SWIR, MWIR and LWIR bands with a single pixel.

Keywords: Multicolor photodetector, multiband photodetector, multispectral imaging, FPA

1. INTRODUCTION

Third generation infrared focal plane arrays (FPA) demand small pixel pitch and multiband operation together with high pixel fill-factor. Optically-addressed photodetectors allow these with single indium bump per pixel while using conventional read-out circuits (ROIC). The architecture can be applied to all important tactical bands such as ultraviolet (UV), visible, near-infrared (NIR), mid-wave infrared (MWIR), long-wave infrared (LWIR) and very long-wave infrared(LWIR) bands.

Infrared multiband photodetectors using HgCdTe[1,2] type-II superlattices[3-4], quantum well infrared photodetectors (QWIP)[5-10] and quantum-dot infrared photodetectors (QDIP) has been reported.[11] Switching bands by changing electrical bias polarity or tuning electrical bias magnitude has been demonstrated in these reports.[12-13] Theory of band switching using multiple QWIP stacks has been investigated in the literature. Dual spectral[14] wideband detection, and NIR/LWIR FPAs with spatially separated pixels[15] with different bands has also been fabricated using QWIPs. Focal plane arrays which use multiple indium bumps per pixel have the disadvantage of using large pixel pitch. While all of the reported FPA structures are feasible for multi-band sensing, the optical-addressing offers the potential to add at least one more band to these existing multi-band FPA technologies. The optical-addressing method enables the use of an external light source to switch bands, without modifications on the ROIC.

The preliminary proof of the concept has been recently demonstrated in visible, NIR and SWIR bands using a triple-junction photodetector.[16-17] The device consists of a set of photodetectors with different cutoff wavelengths and series connected through tunnel junctions. Incident photons pass through all junctions whose bandgaps have higher energies than the photons' and are absorbed at the corresponding junction. All junctions except one are illuminated by a series of LEDs with their corresponding detection wavelengths, and the non-illuminated junction remains the only active photodetector since it limits the total current.

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A front-side illuminated NIR/LWIR optically-addressed photodetector is fabricated on GaAs substrate and its characterization results shows that the device performance is sufficient for imaging applications.[18] In this study we report NIR/LWIR band-switching threshold of the device at different temperatures and discuss the NIR response linearity of the NIR/LWIR photodetector. The photodetector consists of a NIR p-i-n sub-photodetector and a LWIR QWIP sub-photodetector connected in series. The device is a combination of a bipolar device with a unipolar device and does not need the use of tunnel junctions between them.

For front-side illumination NIR sub-photodiode is grown on top of the LWIR sub-photodetector and the incident light first passes through the shorter wavelength sub-photodetector. A backside illuminated version of the same device is also proposed in Fig. 1, which has the sub-photodetectors grown in reverse order. The photodetector can switch its detection band from NIR to LWIR under optical bias from an NIR light source such as an LED or a laser diode. The GaAs substrate is opaque in NIR optical bias wavelength range and should be removed for back-side illuminated FPA applications.

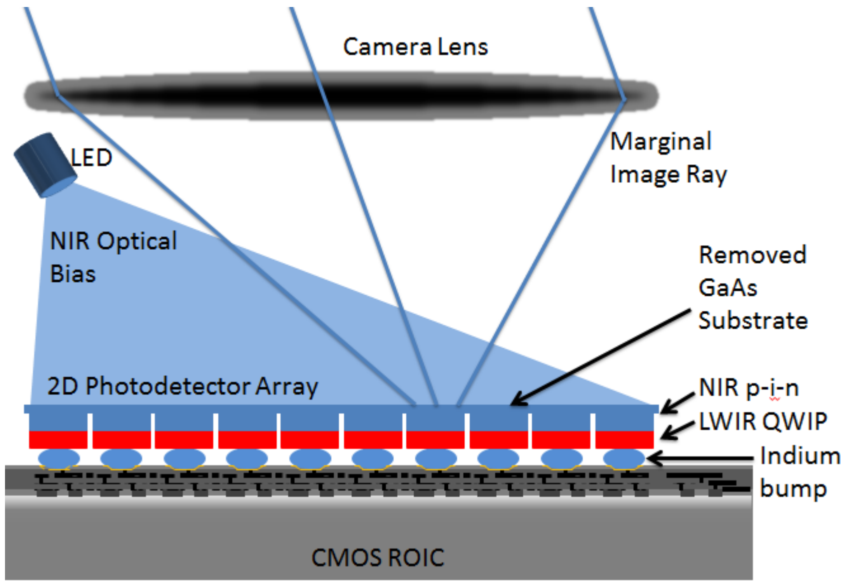

Figure 1. Cross-section of a NIR/LWIR optically-addressed FPA based on the demonstrated test detector.

2. DEVICE STRUCTURE AND OPERATION

For proof of concept in NIR and LWIR bands, the front-side illuminated optically-addressed NIR/LWIR photodetector structure is grown with MBE on GaAs substrate (Sample reference VA0411). It consists of two sub-photodetectors; an AlGaAs/GaAs LWIR QWIP and a NIR p-i-n photodiode. Bottom contact is n-type GaAs, followed by the QWIP which has 16 periods of 4.6 nm quantum wells and 50 nm $Al_{0.27}Ga_{0.73}As$ barriers. Quantum wells are n-type center doped with sheet density of $1.6x10^{16}$ cm^{-2}. The following layers are 500 nm n-GaAs, 2500 nm lightly doped n-GaAs NIR absorber and 500 nm p-$Al_{0.27}Ga_{0.73}As$ window layer. The p and n layer doping concentrations are 10^{18} cm^{-3}, except the quantum wells and the 10^{16} cm^{-3} doped GaAs NIR absorber layer. The device cap layer is 10 nm p-GaAs. The 150 µm x 150 µm mesa shaped photodetector is fabricated with wet etching without passivation and ohmic contact metals are evaporated. The packaged photodetector is installed into a cryostat with ZnSe window.

Detailed operation principle and the circuit model of the NIR/LWIR optically-addressed photodetector using AlGaAs/GaAs QWIP and p-i-n photodetectors is explained in the references.[19] The photodetector band switching relies on large impedance difference between the sub-photodetectors. The basic operating principle of the scheme is that without the optical bias, the NIR sub-photodetector limits, and determines, the photodetector current and thus the photodetector operates in NIR mode. With the NIR optical bias, the LWIR sub-photodetector becomes the current limiting device and the photodetector then operates in LWIR mode. The electrical bias is kept same during both modes of operation. The output of the device is given as[19]

$$i_{out} = i_{QWIP}\frac{r_{QWIP}}{r_{QWIP}+r_{PIN}} + i_{PIN}\frac{r_{PIN}}{r_{QWIP}+r_{PIN}} \tag{1}$$

where i_{QWIP} and i_{PIN} are the AC-currents, r_{QWIP} and i_{PIN} are the AC-resistances of the QWIP and the p-i-n sub-photodetector, respectively. The switching behavior is similar to voltage tuning in multiple QWIP stacks[17,18].

Grating light coupling is not used for the QWIP sub-photodetector and the photodetector spectrum is measured with normal incident light. The photodetector spectrum at 77 K is given in figure 2. In the NIR mode of operation, with the optical bias source off, the photodetector has cut-off wavelength of 0.82 µm. In the LWIR mode of operation, the 780 nm optical bias source is turned on and its power density is 1 W/cm^2. The photodetector LWIR peak wavelength is measured as 8.2 µm. The LWIR spectrum is measured with KBr beam splitter and the NIR spectrum is measured with quartz beam splitter in an FTIR using different light sources for each band. In the NIR mode of operation the LWIR signal is below the FTIR noise floor, while in the LWIR mode of operation the NIR signal is below the FTIR noise floor. The device demonstrated successful band switching between NIR and LWIR bands.

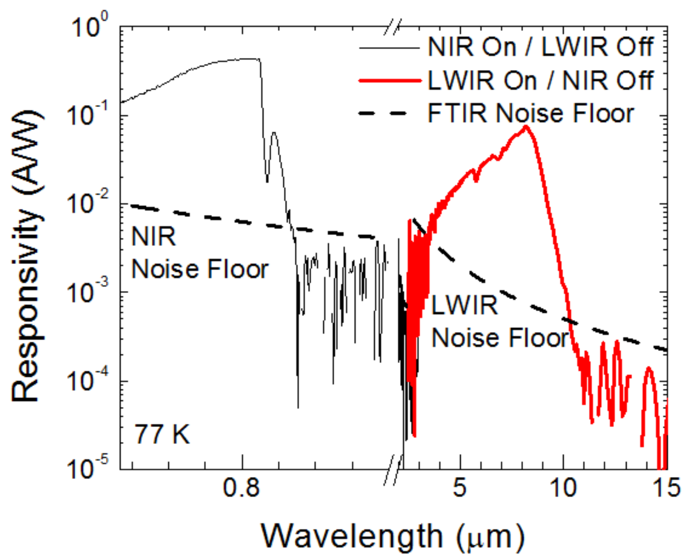

Figure 2. NIR/LWIR band-switching demonstration at 77 K temperature with a front-side illuminated NIR/LWIR optically-addressed photodetector. In each band, the off-state band signal is below the FTIR noise floor and too weak to be measured. NIR and LWIR spectra are measured with different FTIR beam splitters and different light sources.

Band switching threshold from LWIR to NIR band at 77 K is characterized using a lock-in amplifier and a chopped IR source at 150 Hz. A 780 nm CW laser diode is used as the variable optical bias source, and the LWIR signal is measured at different optical bias levels (Fig. 3). The LWIR signal stays relatively constant above optical bias threshold of 100 mA./cm^2. Below the threshold, the LWIR signal significantly decreases and becomes too weak that couldn't be measured. The band switching threshold is the optical bias level where the photodetector changes its detection band from LWIR to NIR. The threshold occurs at NIR optical bias power density level where the NIR sub-photodetector photocurrent is limited by the LWIR QWIP current. The band switching threshold is observed to decrease as the detector temperature decreases. The fabricated QWIP sub-photodetector is not 100% BLIP at 77 K and decreasing the detector temperature reduces the QWIP dark current significantly. At lower temperatures, the NIR photocurrent reaches the QWIP current at lower NIR optical bias levels.

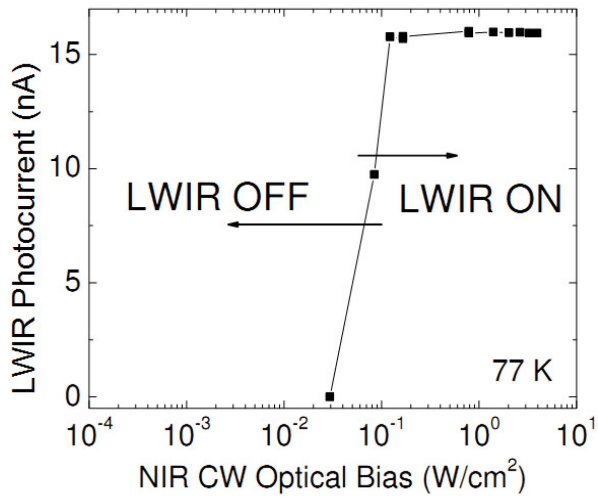

Figure 3. LWIR photocurrent vs. NIR CW optical bias is measured at 77 K. NIR to LWIR band switching threshold of 100 mW/cm^2 optical bias is measured at 77 K. Lower band-switching-threshold is observed at lower detector temperatures.

Large-signal NIR peak photocurrent vs. the incident NIR peak power is measured using a 780 nm laser diode with 50% duty cycle at 150 Hz (Fig. 3) at 68 K. The NIR photocurrent is measured with a lock-in amplifier and observed to linearly increase over three orders of magnitude until the band-switching threshold of ~3-6 mW/cm^2, above which the NIR photocurrent signal saturates and stays constant. Above the threshold, the photodetector enters the LWIR mode of operation and the photocurrent is determined by the LWIR flux.

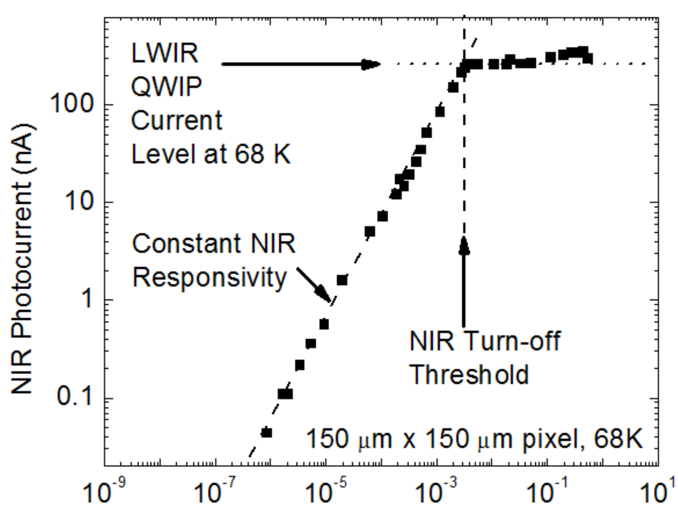

Figure 4. Large-signal NIR peak photocurrent vs. incident peak power at 68 K on a 150 μm x 150 μm sized square pixel. The NIR responsivity is constant until the NIR sub-photodetector turn-off threshold of 3 mW/cm2. Above the threshold, the photodetector enters the LWIR mode of operation and the LWIR QWIP sub-photodetector current limits the photodetector current.

Large-signal characteristics are measured with a single 780 nm laser diode at 100% modulation factor and 50% duty cycle. Small-signal characteristics are also measured with small NIR modulated light from a 780 nm LED, on top of the

CW optical bias from a 780 nm laser diode. Both the large-signal and small-signal characteristics are consistent, which shows the linearity in the NIR mode of operation on a wide range of NIR flux.

3. CONCLUSIONS

A NIR/LWIR dual-band photodetector band switching with optical-addressing is demonstrated with a front-side illuminated design. The photodetector consisted of an NIR p-i-n sub-photodetector and a LWIR QWIP sub-photodetector. The photodetector operates in NIR mode without optical bias, and operates in LWIR mode with optical bias. The dual-band photodetector photocurrent increased linearly with increasing incident optical power in NIR band over three orders of magnitude. The NIR mode maximum photocurrent is limited by the LWIR background current above band switching threshold of 3 mW/cm^2 optical bias at 68 K. When the temperature is increased to 77 K, the band-switching threshold increases to 100 mW/cm^2 due to increased QWIP dark current.

Such simple pixel structure allows FPAs with single indium bump per pixel at high pixel fill factor. The proposed FPA design enables the adding of at least one more extra detection band to the existing two-band or three-band detector architectures without the need to change the readout circuit design. Extension of the technique to three or more band detectors is possible by using more optically-addressed detector stacks or by using voltage tuning and bias polarity switching techniques.

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