Two-micron detector development using Sb-based material systems

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Abstract **- NASA Langley Research Center (LaRC), in partnership with the University of Delaware (UD), developed AlGaAsSb/InGaAsSb custom-designed phototransistors in the 0.6 – 2.5 µm wavelength range for applications to laser remote sensing. The phototransistor's performance greatly exceeds the previously reported results at this wavelength range in the literature. The performances of the custom-designed phototransistor, such as responsivity, detectivity, and gain, are improved significantly as compared to the previously published detectors as well as commercial detectors. Detection in the 0.6- to 2.5-µm broadband with a single phototransistor will result in reduction or elimination of heavy and complex optical components now required for multiple wavelength detection in atmospheric remote sensors resulting in smaller, lighter, simpler instruments with higher performance. This high performance broadband phototransistor will eliminate the need for high power laser for active remote sensing and also the Si (1.0-µm cutoff) and InGaAs (extended 2.3-µm cutoff) detectors. The developed broadband phototransistor will be applicable for the next generation of space-based Earth observations and other planetary instruments for active and passive remote sensing with substantial reduction in size, complexity, and weight to measure water vapor, methane, and carbon dioxide in planetary atmospheres as well as aerosol, cloud, water vapor, O_2, CO, and CO_2 for a broad range of applications to Earth and Space Science Missions under Science Mission Directorate (SMD) research programs.**

I. INTRODUCTION

There is a great interest in broadband detectors for numerous critical applications such as temperature sensing, process control, and atmospheric monitoring (e.g., CO_2, O_2, H_2O). To address the Earth science areas, NASA's Science Mission Directorate (SMD) has formulated a methodology of scientific research and observation. Active lidar remote sensing enables better characterization of aerosols, clouds, trace gas species, greenhouse gases, surface topography, biomass, and winds, which are essential elements in understanding major Earth system processes. Development of high sensitivity and low noise detector technology in the visible to near infrared region is critical and one of the important components for the successful development of such active remote sensing capability. On the other hand, these measurements are essential to better understand the Mars and other planetary atmosphere.

The 0.6 to 2.5 µm spectral region has a large number of principle absorption lines, which enable active and passive remote sensing of O_2, CO_2, CH_4, H_2O, CO, NH_3, and a number of hydrocarbons in the atmosphere [1-2]. This spectral range is covered by a single phototransistor. In particular the CO_2 and CH_4 are key greenhouse gases that play a key role in climate and linked to the global carbon cycle. CO_2 is the widely accepted and most abundant contributor toward warming of the Earth. A critical issue in understanding climate change and its prediction is to understand the global CO_2 processes. Development of space-based active remote sensors with high sensitivity and low noise detectors will considerably reduce the requirements for high power lasers. This will greatly reduce the risk, cost, and volume of future active remote sensors.

When selecting a detector, key parameters, such as spectral response, quantum efficiency, detectivity, and signal-to-noise ratio must be considered in order to satisfy the requirements of the Earth and planetary remote sensing systems. Besides p-i-n photodiodes and avalanche photodiodes (APD), antimonide (Sb)-based heterojunction phototransistors (HPT) satisfy many of the detector requirements for applications to the active remote sensing systems without excess noise and high bias voltages [3-6]. HPT has an internal gain mechanism that allows increasing the output signal and signal-to-noise ratio (SNR). However, further reduction of gain related noise is desirable, and research on different HPT structures indicates some important design considerations that can minimize device noise and further increase SNR.

Earlier reports on phototransistors are made of Si [7], Ge [8], InGaAs/InP [9], and InGaAsP/InP [10] indicated that none of these materials is suitable for detection in (over the entire spectral range) the 0.6- to 2.5-µm range. Si has an upper limit wavelength at approximately 1.1-µm. Absorption in Ge also terminates before 2 µm, with an upper wavelength of approximately 1.9-µm. InGaAs/InP HPT operates in the 0.9- to 1.6-µm and quaternary InGaAsP on InP HPTs operates in the 0.9- to 1.3-µm wavelength range.

On the other hand, APDs are an integrated solid-state semiconductor device and the most common APDs, based on III-V compounds are fabricated using InGaAs on InP, and are operational in the range of 900 - 1600 nm [11-13]. Recently, a group from DRS Technologies has demonstrated responsivity of ~ 15 A/W in HgCdTe electron (e-) APD at short wave infrared (SWIR) wavelength (biased at -7 V and 20 ^{o}C) [14]. HgCdTe e-APDs have demonstrated high responsivity in the 3- to 5-µm, but low responsivity at the SWIR region [14]. Even though HgCdTe detectors are efficient in the infrared range, due to the technology limitations of the HgCdTe system, researchers have looked to other III-V systems that provide much higher yield by manufacturing and higher operability. It is necessary to explore alternative material systems, which can absorb radiation in the 0.6- to 2.5-µm range and are compatible with the general requirements of a low-noise phototransistor. GaInAsSb/AlGaAsSb III-V compound material system presents a strong candidate and published results show Sb-based HPTs with record responsivitites [5,15-19] for a single element phototransistor using liquid phase epitaxy (LPE) growth technique.

Quaternary AlGaAsSb/InGaAsSb heterojunction phototransistors in the 0.6- to 2.2-µm wavelength range have been developed and fabricated using LPE at AstroPower, Inc. in collaboration with NASA Langley Research Center. These devices have been characterized at NASA Langley Research Center, and encouraging results including high responsivity, high detectivity, and relatively low dark current have been obtained [5,15-19]. Figure 1 shows the spectral response of such devices. Recently, similar devices with longer cutoff wavelength (around 2.4-µm at room temperature) have been fabricated at the University of Delaware using Molecular Beam Epitaxy (MBE) technique [20].

There is no commercially available broadband detector in the 0.6- to 2.5-μm spectral range. Again, this spectral range is suitable for sounding of the earth and planetary atmosphere. As a result, such phototransistors would prove extremely valuable to NASA's Earth and planetary atmospheric remote sensing programs, allowing critical measurements at improved accuracy with greatly reduced system complexity, weight, and cost.

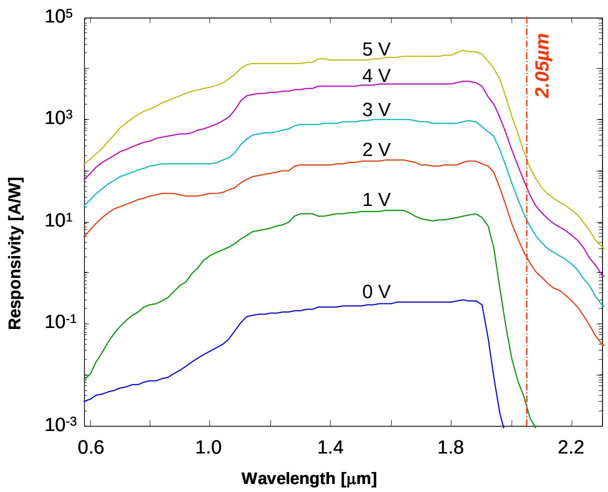

Figure 1. Spectral response variation with bias voltage for LPE sample A1-d2 at 80.1K.

II. Sb-BASED MULTILAYER GROWTH AND DEVICE FABRICATION

A. Multilayer growth

The growth of multilayer structures was carried out using the Molecular Beam Epitaxy (MBE) technique [20]. Multilayer structures were grown from top to bottom as n-GaSb contact layer/n-AlGaAsSb emitter/p-AlGaAsSb base/p-InGaAsSb base/n-InGaAsSb collector layer on n-GaSb substrate. In Figure 2, two different compositions of the quaternary alloys were used to provide the cutoff wavelength (50% QE of peak signal) of 2.4- μm. The HPT was composed of $Al_{0.25}Ga_{0.75}As_{0.02}Sb_{0.98}$ and $In_{0.18}Ga_{0.82}As_{0.17}Sb_{0.83}$ layers with room-temperature bandgaps of $Eg \approx 1.0$ eV and $Eg \approx 0.54$ eV, respectively. The layers are lattice-matched to a GaSb substrate. The growth started with a 0.15μm-thick n^+-GaSb buffer layer and was completed with a 0.1μm-thick n^+- GaSb contact layer doped with Te. The HPT structure includes a 0.5μm-thick n-type AlGaAsSb emitter, 0.8 μm-thick p-type composite base consisting of AlGaAsSb (0.3 μm) and InGaAsSb (0.5 μm) layers, and a 1.5μm - thick n-type InGaAsSb collector.

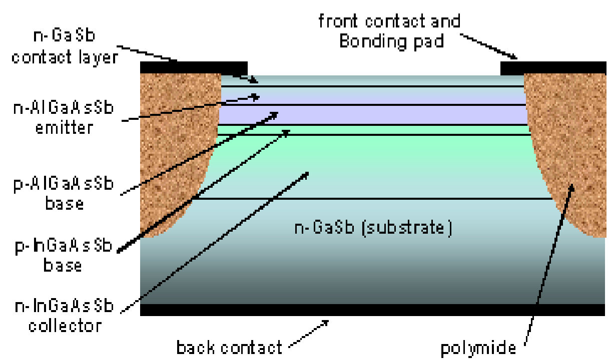

Figure 2. The multilayer structures of AlGaAsSb/InGaAsSb HPTs. Different InGaAsSb compositions were used for MBE-grown HPT.

B. Device Fabrication

After the MBE growth of the multiplayer structures, mesa was patterned by using the standard photolithographic technique and the transistor structures were generated with wet chemical etching. A backside planar and front side annular ohmic contacts (together with a bonding pad) were deposited by electron-beam evaporation of Au/Ge. A polyimide coating was spun on the front of the device. The polyimide served several functions including planarization of the top surface, mesa isolation, and edge passivation. After dicing, 1-mm^2 pieces with a single device in the middle of each square were mounted to TO-18 headers using silver conducting epoxy and wire bonded. No antireflection coatings were applied.

III. DEVICE CHARACTERIZATION RESULTS AND DISCUSSIONS

MBE-grown phototransistor has been characterized to measure the responsivity, dark current, and noise. Responsivity of the phototransistor is obtained in the 1.0- to 2.5-μm by using a PbS calibrated detector. The output signal of the phototransistor is acquired and then compared with the calibrated PbS detector. The spectral responsivity, $R_T(\lambda)$ (in A/W), of the phototransistor is determined by using the following equation [17]:

$$R_T(\lambda) = \frac{V_T(\lambda)}{V_{PbS}(\lambda)} \cdot \frac{A_r}{g} \cdot R_{PbS}(\lambda) \qquad (1)$$

where V_{PbS} is the PbS photodiode response (in V), V_T is the phototransistor output (in V), A_r is the ratio of the PbS detector area to the phototransistor area, g (in V/A) is the preamplifier gain setting, and R_{PbS} (in V/W) is the spectral responsivity of the PbS detector.

Figure 3 shows the spectral response of the AlGaAsSb/InGaAsSb phototransistor (HPT) as a function of applied bias voltage at 20 ^{o}C. Due to the relatively low bandgap value of InGaAsSb layers in the MBE-grown phototransistors (0.54 eV), a longer cutoff wavelength around 2.4 μm is obtained. Responsivity R_T increases with bias voltage and at 1.4 V reaches 1128 A/W for λ = 2.05-μm. Even higher values of R_T (up to 3441 A/W) were measured at -20^{o}C at 1.4 V for λ = 2.05 μm. This value is comparable to 2650 A/W at the same wavelength and temperature achieved in LPE-grown HPTs with a shorter cutoff wavelength of 2.15 μm [15]. The maximum responsivity is measured for 2.05-μm, which demonstrates that this radiation is absorbed close to the base-collector p-n junction, where conditions for the carrier separation are the most favorable. A shorter wavelength radiation (e.g., 1.55-μm) is absorbed closer to the emitter at a larger distance from the base-collector p-n junction. Evidently, some of the carriers are lost due to a higher probability of recombination in this case. The lower value of the responsivity at 2.2 μm compared to that obtained at 2.05-μm, can be explained by a lower absorption that occurs at energies close to the bandgap of InGaAsSb used in this study. Responsivity of the HPT has a strong bias dependence and it increases by more than three orders of magnitude at 2.05 μm when increasing bias voltage, (collector-emitter voltage, V_{ce}), from 0 to 1.4 V [20].

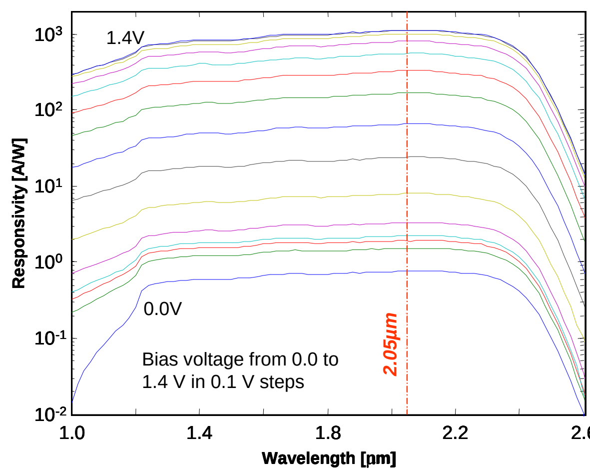

Figure 3. Spectral response of an AlGaAsSb/InGaAsSb MBE-grown HPT at the specified bias voltage and 20^{o}C.

For the measured devices, detectivity (D^*), is determined as [15]

$$D^*(T,V) = R(T,V) \cdot \sqrt{A} / I_n(T,V), \quad (2)$$

where A is the detector area, R_T is responsivity, and I_n is noise current spectral density.

Detectivity calculation was obtained using noise measurements in the dark conditions and spectral response data (detail discussion in ref. 15). Figure 4 shows the detectivity comparison results of a phototransistor as a function of bias voltages at two different temperatures 20°C and -20°C, and also a 2.05 µm incident radiation. Cooling down the device reduces the dark current, which allows for higher voltage operation that increases the responsivity. Therefore, higher detectivities are observed at lower temperatures and higher bias. *D** value as high as 2.1×10^{11} cmHz$^{1/2}$/W was determined at –20°C and 1.3 V. This value is slightly lower than that achieved for the same wavelength and temperature from LPE-grown HPTs with a shorter cutoff wavelength of 2.15 µm (3.9×10^{11} cmHz$^{1/2}$/W) [15]. The reason for lower *D** in an MBE-grown HPT is the higher noise, caused by a lower bandgap of the InGaAsSb collector and the extended wavelength range of the device.

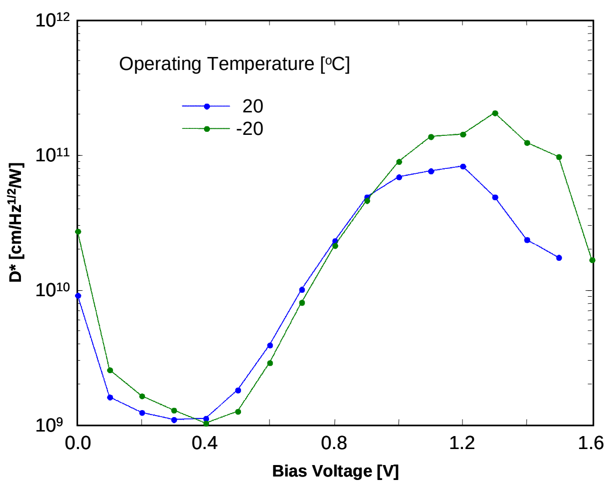

Figure 4. Detectivity (*D**) of an AlGaAsSb/InGaAsSb MBE-grown HPT at different temperatures vs. reverse bias voltage with incident radiation of 2.05-µm.

Gain of the HPT was determined as a function of bias voltage at different temperatures with incident radiation of 2.05 µm wavelength. This gain was calculated by measuring the responsivity (R_T) of the HPT as a function of bias voltage at a specific wavelength and temperature. This gain (g) can be determined using the following equation:

$$g = R_T(\lambda, V, T) / R_T(\lambda, 0, 20^oC) \qquad (3)$$

where $R_T(\lambda,V,T)$ is the responsivity, which depends on incident photon wavelength (λ), applied bias voltage (V), and temperature (T).

Figure 5 shows gain (g) versus bias voltage (V) for HPT calculated using equation 3. A gain of about 2000 is obtained at 1.4-V input voltage for HPT. It is observed that the gain of HPT is dependent on bias voltage and temperature. From low-to-high temperatures, the gain is found to have small temperature dependence with bias of around 0.9 V.

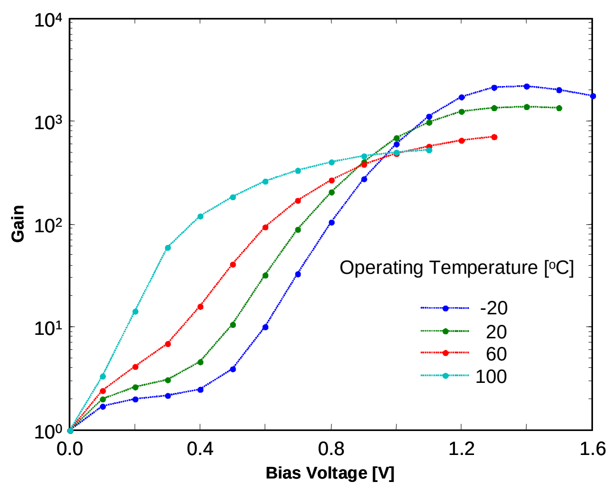

Figure 5. Gain variation of an AlGaAsSb/InGaAsSb MBE-grown HPT with bias voltage at selected temperatures and 2.05-µm incident radiation.

IV. CONCLUSIONS

Sb-based phototransistors have been developed for the 0.6- to 2.5-µm wavelength range. The custom-designed MBE-grown phototransistors, developed at the University of Delaware, have been characterized at NASA LaRC to measure the responsivity, dark current, and noise. Results from a HPT show high responsivity of 1128 A/W corresponding to an internal gain of 2000, high detectivity (D*) of $2.1x10^{11}cmHz^{1/2}/W$ that is lower than the LPE-grown phototransistor of $3.9x10^{11}cmHz^{1/2}/W$ for the same wavelength and temperature. This is the highest responsivity ever reported in the 0.6- to 2.4-µm wavelength range for the Sb-based material system [19]. These phototransistors may have great potential for lidar remote sensing applications and this technology will improve the capabilities to measure atmospheric pollutants for future Earth Science measurements. This technology has also tremendous applications to NASA's Human and Robotic Exploration Program for use in 3-D imaging by developing 2-D arrays for planetary mapping and robotics navigation.

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