2.4 μm cutoff wavelength AlGaAsSb/InGaAsSb phototransistors

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We report the first AlGaAsSb/InGaAsSb phototransistors with a cutoff wavelength (50% of peak responsivity) of 2.4 μm operating in a broad range of temperatures. These devices are also the first AlGaAsSb/InGaAsSb heterojunction phototransistors (HPT) grown by molecular beam epitaxy (MBE). This work is a continuation of a preceding study, which was carried out using LPE (liquid phase epitaxy)-grown AlGaAsSb/InGaAsSb/GaSb heterostructures. Although the LPE-related work resulted in the fabrication of an HPT with excellent parameters [1-4], the room temperature cutoff wavelength of these devices (≈ 2.15 μm) was determined by fundamental limitations implied by the close-to-equilibrium growth from Al-In-Ga-As-Sb melts. As the MBE technique is free from the above limitations, AlGaAsSb/InGaAsSb/GaSb heterostructures for HPT with a narrower bandgap of the InGaAsSb base and collector – and hence sensitivity at longer wavelengths (λ) - were grown in this work. Moreover, MBE - compared to LPE - provides better control over doping levels, composition and width of the AlGaAsSb and InGaAsSb layers, compositional and doping profiles, especially with regard to abrupt heterojunctions. The new MBE-grown HPT exhibited both high responsivity R (up to 2334 A/W for $\lambda = 2.05$ μm at –20ºC.) and specific detectivity D^* (up to $2.1\text{x}10^{11}\text{cmHz}^{1/2}/\text{W}$ for $\lambda = 2.05$ μm at –20ºC).

Introduction: The spectral range 2.0 – 2.4 μm wavelength is of great interest for several important applications, including profiling of atmospheric CO_2 using light detection and ranging (LIDAR) techniques [5,6], and non-invasive monitoring of blood glucose using absorption spectroscopy [7]. In this work, the MBE-grown AlGaAsSb/InGaAsSb solid alloys are used for the first time to fabricate HPT providing a high internal gain at the wavelength as long as 2.4 μm. Moreover, the new high-gain phototransistors operate at low bias (less than 1.5 volts).

Experimental: The HPT mesa structure (Fig.1) fabricated and studied in this work is 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* ≈ 1.0 eV and *Eg* ≈ 0.54 eV, respectively. The layers are lattice-matched to a GaSb substrate and were grown at 500°C on an n^+- GaSb (001) substrate using a Riber 32 solid source MBE. A valved cracker source for arsenic (As_4) and a conventional effusion source for antimony (Sb_4) were used. 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, 0.8μm-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. Mesa HPT with a 400-μm diameter total area and a 300-μm diameter active area were defined using photolithography and wet chemical etching. A backside planar and frontside annular ohmic contact (together with a bonding pad) were deposited by electron-beam evaporation of Au/Ge. A polyimide coating (HD Microsystems PI-2723 photodefinable polyimide resin) 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.

Results: Spectral response, dark current and noise measurements were performed for MBE-grown phototransistors. Measurements of spectral response were carried out using the equipment described in Ref. [4]. Fig.2 shows spectral response of an AlGaAsSb/InGaAsSb HPT at the specified bias voltage and +20^{o}C. As can be seen in Fig.2, responsivity R rapidly increases with applied bias voltage and at 1.4 V reaches 1128 A/W for λ = 2.04 - 2.08μm. Even higher values of R (up to 2334 A/W) were measured at -20^{o}C at 1.4 V for λ = 2.05 μm. Fig. 3 shows responsivity R of an AlGaAsSb/InGaAsSb HPT at λ = 2.05 μm vs. bias voltage at temperatures from -20^{o}C to +100^{o}C. One can distinguish two parts of the graph: at very low voltage (< 1V) higher R was measured at higher temperatures, while at higher voltages the opposite dependence was observed. This complicated behavior can be explained by temperature dependencies of minority-carrier (electrons) diffusion length in the base, and by the as-yet-unexplored temperature-sensitive band discontinuities of AlGaAsSb/InGaAsSb heterojunctions, which can affect the minority carrier injection at the emitter-base junction and consequently the gain of the HPT. On the other hand, the dark current and hence the noise current I_n of the HPT are also dependent on applied voltage and temperature. All the above dependencies are considered in specific detectivity $D*$, which is one of the main figures of merit for any photodetector:

$$D*(T,V) = R(T,V)\cdot\sqrt{A}\big/I_n(T,V)\,, \tag{1}$$

where A is the detector area.

Fig. 4 exhibits a 2.05-μm detectivity *D** of an AlGaAsSb/InGaAsSb HPT at –20ºC and +20ºC vs. bias voltage. D* value as high as 2.1×10^{11} cmHz$^{1/2}$/W was determined at –20ºC and 1.3 V.

We believe the significant performance levels achieved with the first MBE-grown HPT structures bode well for the AlGaAsSb/InGaAsSb HPT approach to mid-infrared detectors, as well as for the materials and device fabrication technology described here. Moreover, we believe there is much room for further improvements in both *R* and *D** of the AlGaAsSb/InGaAsSb HPT through continued optimization of the design and fabrication.

Acknowledgement: This work was partially funded by NASA contract #NAS1-02117 through NIA Task Order # NNL04AC40T .

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Figure captions:

Figure 1. Structure (cross-section) of the fabricated AlGaAsSb/InGaAsSb HPT

Figure 2. Spectral response of an AlGaAsSb/InGaAsSb HPT at the specified bias voltage and +20°C

Figure 3. Responsivity of an AlGaAsSb/InGaAsSb HPT at $\lambda = 2.05$ µm vs. bias voltage at specified temperatures

Figure 4. A 2.05-µm detectivity D* of an AlGaAsSb/InGaAsSb HPT at –20ºC and +20ºC vs. bias voltage

Figure 1

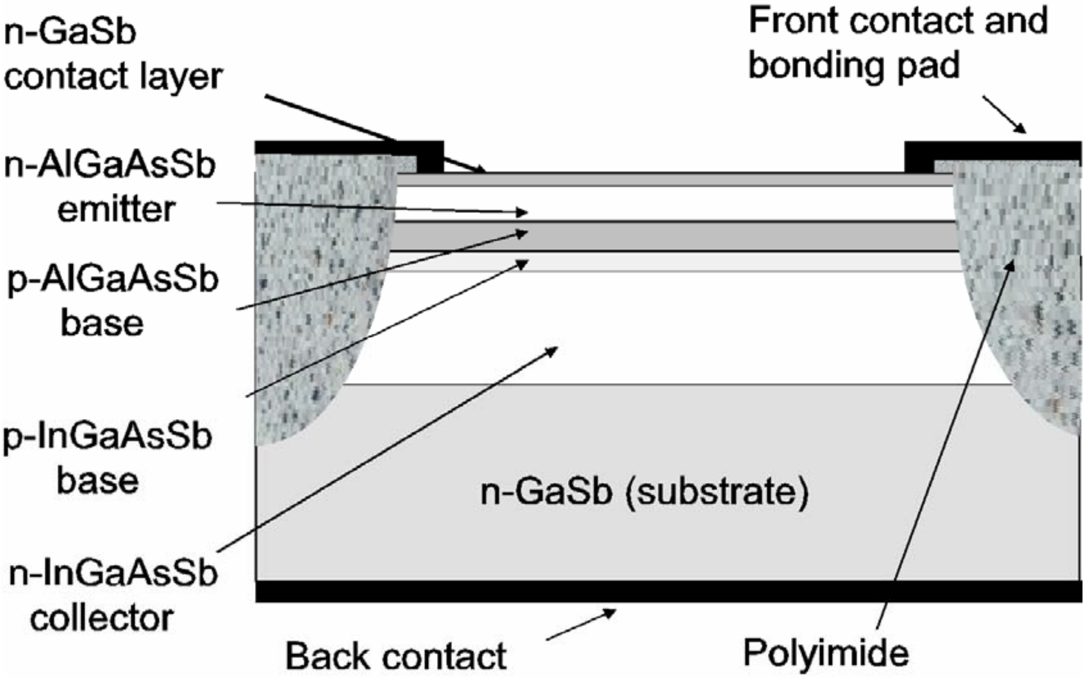
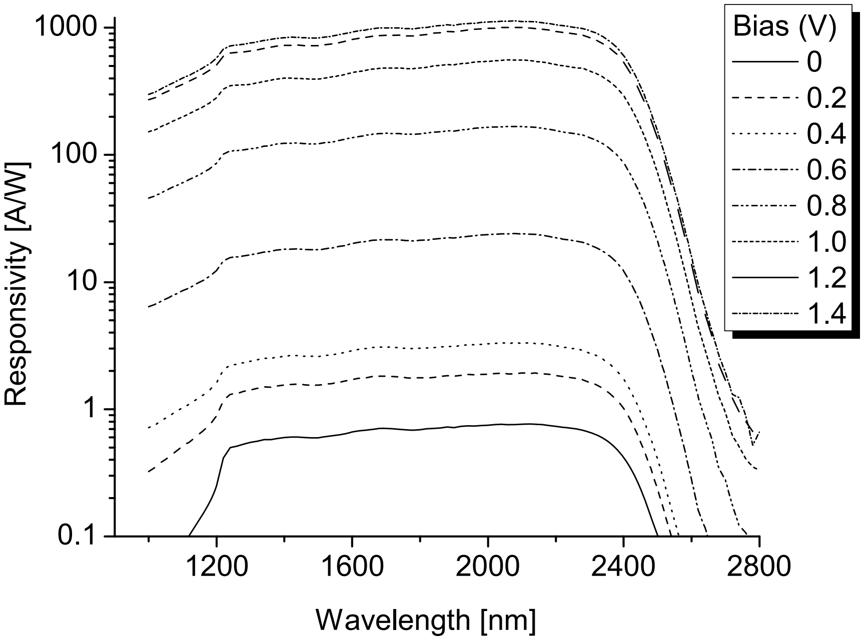

n-GaSb
contact layer
Front contact and
bonding pad
n-AlGaAsSb
emitter
p-AlGaAsSb
base
p-InGaAsSb
base
n-GaSb (substrate)
n-InGaAsSb
collector
Back contact
Polyimide

Figure 2


Bias (V)
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Responsivity [A/W]
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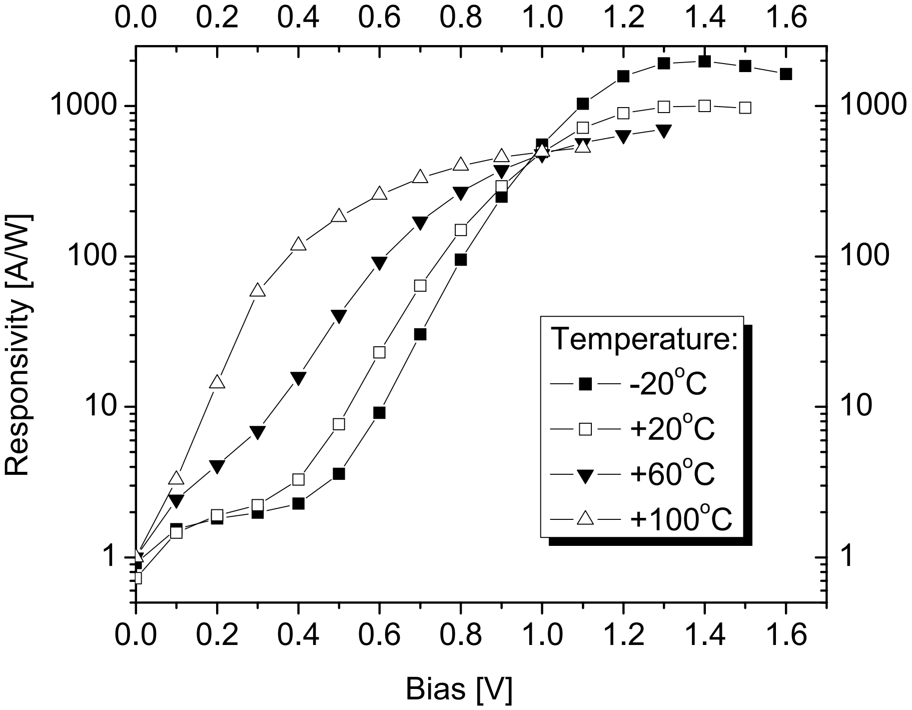
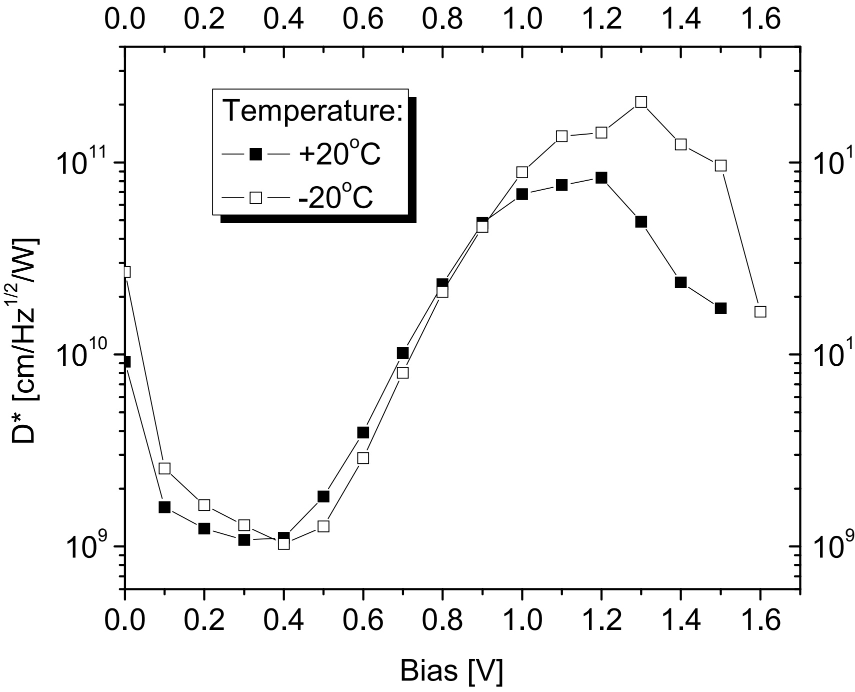
100
10
1
0.1
1200
1600
2000
2400
2800
Wavelength [nm]

Figure 3



0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1000
100
10
1
Responsivity [A/W]
Bias [V]
Temperature:
-20°C
+20°C
+60°C
+100°C

Figure 4


Temperature:
■ +20°C
□ -20°C
D* [cm/Hz^1/2/W]
10^9
10^10
10^11
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Bias [V]