

Uncooled InAs–GaSb Type-II Infrared Detectors Grown on GaAs Substrates for the 8–12- μm Atmospheric Window

H. Mohseni, J. Wojkowski, M. Razeghi, G. Brown, and W. Mitchel

Abstract—We report on the growth and characterization of type-II infrared detectors with an InAs–GaSb superlattice active layer for the 8–12- μm atmospheric window at 300 K. The material was grown by molecular beam epitaxy on semi-insulating GaAs substrates. Photoconductive detectors fabricated from the superlattices showed 80% cutoff at about 12 μm at room temperature. The responsivity of the device is about 2 mA/W with a 1-V bias ($E = 5$ V/cm) and the maximum measured detectivity of the device is 1.3×10^8 cm $\cdot\text{Hz}^{1/2}$ /W at 11 μm at room temperature. The detector shows very weak temperature sensitivity. Also, the extracted effective carrier lifetime, $\tau = 26$ ns, is an order of magnitude longer than the carrier lifetime in HgCdTe with similar bandgap and carrier concentration.

Index Terms—Infrared detectors, photodetectors, semiconductor devices, semiconductor growth, superlattices.

I. INTRODUCTION

INFRARED detectors in the 8–12- μm wavelength range have many medical, industrial, and military applications. This is mainly due to the low atmospheric absorption in this range and the maximum radiation of a blackbody at 300 K. However, in most of the applications, cryogenic coolers are not desirable because of their short lifetime and the added power consumption, weight, volume, and cost. Commercially available infrared detectors in this wavelength range can be categorized as interband, which are HgCdTe and InAsSb, or intersubband quantum-well infrared detectors (QWIP's). Unfortunately, there are some fundamental problems, namely the fast Auger recombination in interband detectors and the high thermal generation rate in intersubband detectors, which drastically decrease their ability for near room temperature operation in the long-wavelength infrared range.

Type-II superlattices [1] have been proposed as another alternative for infrared photodetectors in the long-wavelength infrared range. In comparison to HgCdTe, the higher effective mass of electrons and holes and the slower Auger recombination rate [2]–[4] lead to lower dark current and higher operating temperature in type-II superlattices. Another advantage of a type-II superlattice is the possibility of bandgap engineering. Unlike bulk material or Type I superlattices, one

can modify the energy of the conduction and valence minibands of a type-II superlattice with a high degree of freedom. The II–VI HgTe–CdTe and the III–V InAs–Ga $_x$ In $_{1-x}$ Sb type-II superlattices have shown very promising results in the long-wavelength range [5]–[8] at low temperatures. We report on the first demonstration of uncooled InAs–GaSb type-II detectors for the long-wavelength infrared range.

II. DESIGN AND MODELING

The energy of the superlattice minibands and the optical matrix elements were calculated using an envelope function approximation containing the strain effect [9]. In comparison to previous work [10], we decreased the thickness of the GaSb layer from 48 Å to 30 Å. This increases the overlap of the electron and hole wavefunctions and, hence, the optical matrix element increases by approximately a factor of two. More importantly, the minimum energy difference between the light-hole and heavy-hole minibands is higher than the bandgap of the superlattice and, therefore, the CHLH Auger recombination is more suppressed. Table I shows the calculated energy of the minibands of the InAs–GaSb (48 Å/30 Å) and InAs–GaSb(48 Å/48 Å) superlattices at $k_{\parallel} = 0$. We assumed a 190-meV energy difference between the valence band of GaSb and the conduction band of InAs in our calculation. This value is close to the 180-meV prediction of the model-solid theory [11] but shows a better agreement with the optical response of our devices.

III. EXPERIMENT

InAs–GaSb superlattices were grown by molecular beam epitaxy (MBE) on semi-insulating (001) GaAs substrates, as described elsewhere [10]. InSb-like interfaces were used since they improve the structural quality of the superlattice [12] as they compensate the tensile effect of the InAs layers. In order to reduce the leakage current through the GaSb buffer layer, a thin layer of AlSb was grown before the superlattice. Fig. 1 shows the band structure of the superlattice and the AlSb layer. The quality of the superlattices was systematically improved by using structural, electrical, and optical characterization as the feedback for the growth optimization.

For structural characterization of the material, a high-resolution five-crystal X-ray diffractometer was used. X-ray diffraction simulations have also been performed to verify the thickness of the layers (Fig. 2). The average lattice constant

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TABLE I
CALCULATED ENERGIES OF THE MINIBANDS IN THE InAs-GaSb (48 Å/30 Å) AND InAs-GaSb (48 Å/48 Å) SUPERLATTICES.
THE ENERGY UNIT IS ELECTRON-VOLT, AND THE REFERENCE IS THE BOTTOM OF InAs CONDUCTION BAND

Superlattice Structure	C ₂ miniband energy (ev)	C ₁ miniband energy (ev)	HH ₁ miniband energy (ev)	LH ₁ miniband energy (ev)	HH ₂ miniband energy (ev)	Minimum energy for C ₁ -HH ₁ transition	Minimum energy for LH ₁ -HH ₁ transition
InAs/GaSb (48Å/30Å)	0.573 to 0.692	0.223 to 0.317	0.1120 to 0.1121	-0.0177 to -0.0966	-0.116 to -0.1162	0.111 ev	0.129 ev
InAs/GaSb (48Å/48Å)	0.597 to 0.644	0.250 to 0.298	0.1520 to 0.1521	0.0571 to -0.0019	0.0374 to 0.0376	0.098 ev	0.095 ev

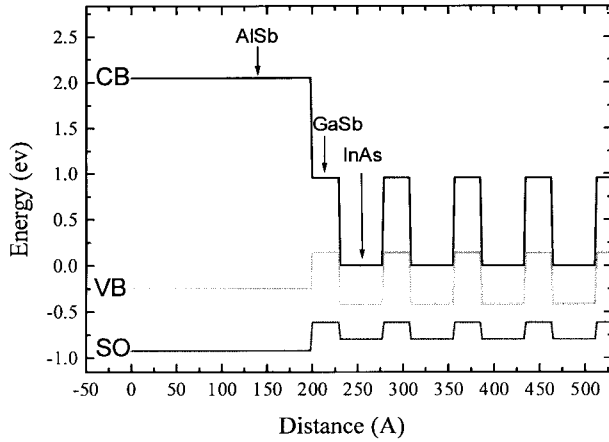


Fig. 1. The band structure of the superlattice and the AlSb layer.

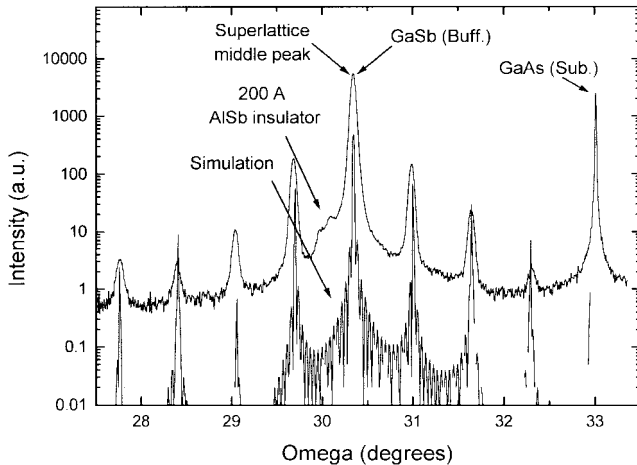


Fig. 2. High-resolution X-ray diffraction pattern of the grown material. The simulation result for the superlattice shows good agreement with the measurement.

of the superlattice is nearly equal to the lattice constant of the GaSb buffer layer, which indicates a good strain compensation in the superlattice.

A Fourier transform infrared (FTIR) spectrometer was used to obtain the optical characteristics of the superlattices. The absorption edge of the grown material was, in general, in good agreement with the calculated energy difference of the electron and heavy-hole minibands. The absorption coefficient of the superlattices was about $\alpha = 1.8 \times 10^3 \text{ cm}^{-1}$ at a wavelength of $10.6 \text{ } \mu\text{m}$ at room temperature.

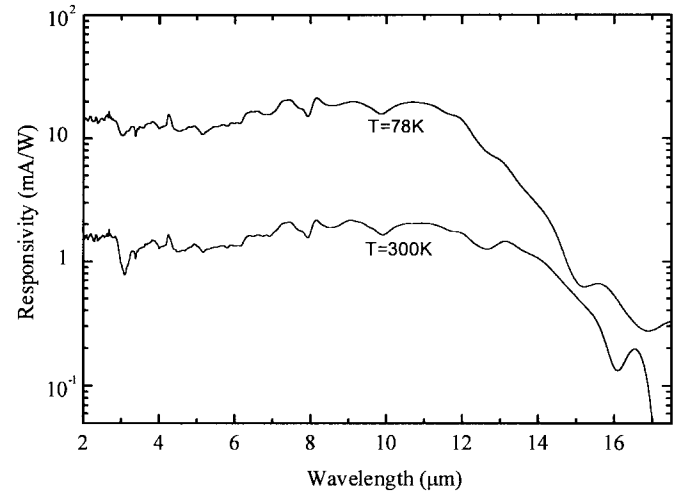


Fig. 3. The responsivity spectra of the device at 78 and 300 K with an in-plane electrical field of $E = 5 \text{ V/cm}$.

For electrical characterization, we used Hall measurements with a variable magnetic field. The field-dependent resistivity and Hall coefficient were used to extract the mobility and concentration of electrons and holes at different temperatures. The mobility and concentration of the electrons were calculated to be: $\mu_n = 4550 \text{ cm}^2/\text{V}\cdot\text{s}$ and $n = 1.29 \times 10^{17} \text{ cm}^{-3}$ and, for holes, $\mu_p = 1540 \text{ cm}^2/\text{V}\cdot\text{s}$ and $p = 1.2 \times 10^{17} \text{ cm}^{-3}$ at 300 K.

Photoconductor devices were fabricated by standard lithography and subsequent etching with a $\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ (1:1:10) solution. For ohmic contacts, Ti-Au (500 Å/2000 Å) was deposited and then the contacts were defined by a lift-off technique. No anti-reflection coating or surface passivation was employed.

The spectral photoresponse of the device was measured using a Galaxy 3000 FTIR spectrometer system. The samples were illuminated through the front side at normal incidence. The absolute response of the photodetectors was calculated using a blackbody test set, which is composed of a blackbody source (Mikron 305), preamplifier (EG&G PA-6), lock-in amplifier (EG&G 5209), and chopper system (Stanford Research System SR540). Fig. 3 shows the responsivity of the device in the 2–17- μm wavelength range at 78 and 300 K with an in-plane electrical field of 5 V/cm. The responsivity linearly increased to 10.5 mA/W at the maximum measured bias voltage of 5 V.

To assess the temperature dependence of the responsivity, the current responsivity of the device was measured at a

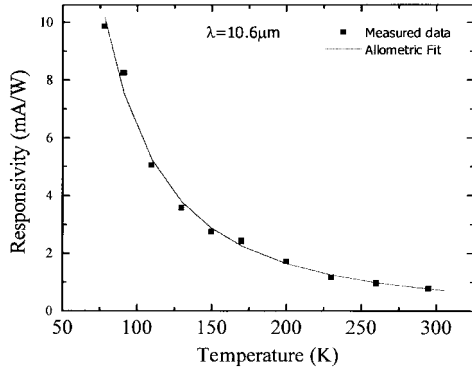


Fig. 4. The current responsivity of the device versus temperature at $\lambda = 10.6 \mu\text{m}$ at a constant voltage bias of 0.4 V. The squares are the measured points and the line is an Allometric fit (AT^B) to the points which shows that responsivity is nearly proportional to T^{-2} .

wavelength of $10.6 \mu\text{m}$ while varying the temperatures from 78 K to room temperature at constant electrical field. Fig. 4 shows the responsivity of the detector at $10.6 \mu\text{m}$ versus the detector temperature. An allometric fitting with a general form of $A \cdot T^B$, where T is the temperature and A and B are the fitting variables, shows that the responsivity of the detector is nearly proportional to $T^{-1.93}$. This behavior is unusual since the responsivity of the narrow gap material is usually an exponential function of temperature at higher temperatures where Auger recombination is the dominant recombination mechanism.

The effective lifetime of the carriers was extracted from the optical and electrical measurements with the expression

$$\tau_{ef} = \frac{lg}{E(\mu_e + \mu_p)} \quad (1)$$

where $l = 2 \text{ mm}$ is the device length, g is the photoconductor gain, and $E = 5 \text{ V/cm}$ is the electrical field. The gain of the device can be calculated from

$$g = \frac{R_i hc}{\lambda \eta q} \quad (2)$$

where $R_i = 2 \text{ mA/W}$ is the current responsivity, h is the Planck constant, c is the speed of light, $\lambda = 10.6 \mu\text{m}$ is the wavelength of the light, η is the quantum efficiency, and q is the electron charge. Assuming an internal quantum efficiency near unity and negligible reflection from the bottom of the superlattice and unpolished backside of the substrate, the quantum efficiency can be calculated from

$$\eta = (1 - r)(1 - e^{-\alpha t}) \quad (3)$$

where r is the top surface reflection coefficient, $\alpha = 1.8 \times 10^3 \text{ cm}^{-1}$ is the absorption coefficient of the superlattice, and $t = 0.5 \mu\text{m}$ is the thickness of the superlattice. Assuming $r \approx 0.3$, the quantum efficiency, photoconductive gain, and carrier lifetime can be calculated from (1)–(3) as $\eta = 6.02\%$, $g = 3.9 \times 10^{-3}$, and $\tau_{ef} = 26.8 \text{ ns}$. The effective lifetime is about an order of magnitude longer than the carrier lifetime in HgCdTe photoconductors with similar bandgap and carrier concentration at room temperature [13]. Since Auger recombination is the dominant recombination mechanism at

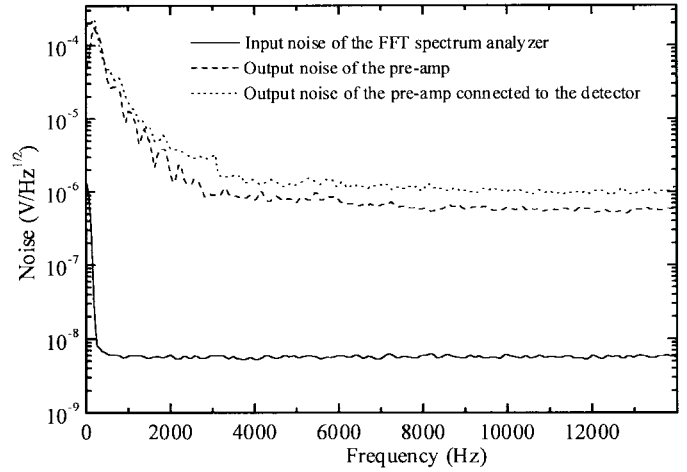


Fig. 5. The measured input noise spectrum of the FFT spectrum analyzer, the output noise spectra of the preamplifier with shorted input, and output noise spectra of the preamplifier when it is connected to the detector at 300 K.

room temperature, we believe that the enhancement of carrier lifetime is due to the suppression of Auger recombination in the type-II superlattice. Surface recombination is expected to significantly reduce the effective carrier lifetime in such a thin active layer. However, it seems that the existence of a wide bandgap cap layer (GaSb) and anisotropic carrier mobilities in the superlattice can reduce this effect.

The measurement of the electrical noise of the detector was used to verify the above value of the carrier lifetime. The noise was measured with a fast Fourier transform (FFT) spectrum analyzer (Stanford Research System SR 760) and a low-noise wide-band preamplifier with 54-dB voltage gain (EG&G PA-100). Fig. 5 shows the input noise spectrum of the FFT analyzer, the output noise spectrum of the shorted preamplifier, and the output noise of the preamplifier when it was connected to the detector. The detector was biased by the preamplifier at $V_b = 5 \text{ V}$.

The mean-square noise of the detector can be modeled as

$$V_n^2 = V_J^2 + V_{1/f}^2 + V_{GR}^2 \quad (4)$$

where V_n is the overall noise of the detector, V_J is Johnson–Nyquist noise, $V_{1/f}$ is $1/f$ noise, and V_{GR} is the generation-recombination noise. The value of the Johnson noise can be calculated as

$$V_J^2 = 4kTR\Delta f \quad (5)$$

where k is the Boltzmann constant, T is the temperature, and $R = 76 \text{ ohms}$ is the resistance of the device. The value of Johnson noise for the device at room temperature is $1.12 \text{ nV/Hz}^{1/2}$. The $1/f$ noise can be approximated with

$$V_{1/f}^2 = V_{GR}^2 \frac{f_{1/f}}{f} \quad (6)$$

where $f_{1/f}$ is a constant which depends on the sample, and f is the frequency. This shows that at high enough frequencies $1/f$ noise can be negligible compared to the other two types of noise. Then the value of the generation-recombination noise can be extracted from the total noise of the device in this range

and the value of the Johnson noise. The noise equivalent circuit model [14] was used to extract the noise of the photodetector as $V_n = 1.7 \text{ nV/Hz}^{1/2}$ above 10 kHz. Using (4) and (5), the value of the generation-recombination noise can be calculated as $V_{GR} = 1.28 \text{ nV/Hz}^{1/2}$. The generation-recombination noise is approximated to be [15]

$$V_{GR} = \frac{2V_b}{(lwt)^{1/2}} \cdot \frac{1+b}{bn+p} \cdot \left(\frac{np}{n+p} \cdot \frac{\tau\Delta f}{1+\omega^2\tau^2} \right)^{1/2} \quad (7)$$

where $w = 4 \text{ mm}$ is the detector width, ω is the angular frequency, $\omega\tau \ll 1$ in this experiment, and b is the ratio of μ_e to μ_p . From (7), the value of the carrier lifetime can be calculated as $\tau = 17 \text{ ns}$ which is close to the value of the lifetime extracted from the optical response measurement. It should be noted that the calculation of the carrier lifetime from the electrical noise of the device is not an accurate technique and may only provide a rough estimation for the carrier lifetime.

Based on the responsivity and noise measurements, the detectivity of the device was calculated as $1.3 \times 10^8 \text{ cm}\cdot\text{Hz}^{1/2}/\text{W}$ at $11 \text{ }\mu\text{m}$ at room temperature with $V_b = 5 \text{ V}$. The power consumption of the device is about 0.05 W/mm^2 at this bias level, which ensures negligible temperature difference between the sample and the heat sink.

IV. CONCLUSION

We have obtained room-temperature operation of type-II superlattice detectors in the long-wavelength infrared range. The measured detectivity of the processed device is $1.3 \times 10^8 \text{ cm}\cdot\text{Hz}^{1/2}/\text{W}$ at $11 \text{ }\mu\text{m}$ at room temperature without any optical immersion lens or anti-reflector coatings. This value is higher than the detectivity of existing HgCdTe at $10.6 \text{ }\mu\text{m}$ at room temperature [13]. The detectors show an unusually weak temperature sensitivity and carrier lifetime of about 26 ns, which are evidences of suppression of Auger recombination in this material system.

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