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Growth of GaSb on GaAs/AlAs mirrors for 1.68 μm detectors

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Abstract

Distributed Bragg reflector mirrors (grown by MBE) are designed to give maximum reflectance at 1.68 μm. The DBR is incorporated into a resonant cavity enhanced (RCE) detector by growing GaSb (by MOVPE) on top of the mirror. Device results show such an RCE detector has enhanced quantum efficiency and photocurrent compared to a nonresonant detector grown at the same time. The initial nucleation and growth of GaSb on GaAs by MOVPE is studied by atomic force microscopy (AFM). Conditions are established for the nucleation of small islands of GaSb using TMGa and TMSb as precursors. However, the dark current suggests that the initial nucleation of GaSb is still not optimised. In order to nucleate smaller GaSb islands at lower temperatures, two new precursors are used. Triisopropylgallium (TIPGa) and trisdimethylaminoantimony (tDMASb) are used in combination for the first time to grow GaSb at 480°C. This results in nucleation of much smaller islands and subsequent improvement in the dark current and quantum efficiency of the nonresonant detector. Further work is needed on the equivalent (RCE) detector.

1. Introduction

GaSb is a promising material for infrared detectors based around the 1.6 μm wavelength region. It is also a candidate for a tandem solar cell, in conjunction with GaAs [1]. When alloyed with indium it has been possible to fabricate 1.6–2.5 μm detectors [2] and emitters [3]. Such wavelengths have medical, military and environmental applications that have so far not been successfully addressed by other materials systems. In this study a design wavelength of 1.68 μm was chosen, as this corresponds to the first overtone of the ν_{C-H} vibration in the infrared spectrum of methane, making the device of possible use in the detection of this gas. In our study of the growth of GaSb and InGaSb to date we have found that detectors based on homojunctions have had disappointingly high dark currents [4]. Also the room temperature background doping of GaSb is 10^{16} cm^{-3} irrespective of whether it is grown by MOVPE [5], MBE [6] or LPE [7] and this means that a thick layer of GaSb, suitable for absorbing a reasonable amount of radiation, will not be able to be depleted with an acceptable voltage. We decided to investigate whether both the above problems could be addressed by growing the GaSb on a AlAs/GaAs based distributed Bragg reflector (DBR) [8]. Previously we had successfully grown and fabricated devices with a GaSb/GaAs pn heterojunction that had superior properties to those of an equivalent GaSb

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homojunction [9]. This led us to believe that the 7% lattice mismatch at the heart of such a structure was not necessarily an insuperable problem. Also the DBR would increase the amount of radiation that passes through a layer of GaSb thin enough to be depleted with a few volts. The combination of GaSb and a DBR would give a resonant cavity enhanced (RCE) detector.

2. Initial nucleation of GaSb on GaAs

From our previous work we had established that the initial nucleation of GaSb on GaAs played an important role in the subsequent optical, electrical and structural properties of the bulk layer [10]. The 7% mismatch causes the GaSb to grow via the Stranski–Krastanov mode, that is, to initially grow a monolayer or so of pseudomorphic GaSb and then to nucleate islands that grow three dimensionally [11]. We assumed, based on other group's studies of the growth of GaAs on silicon [12] that these islands eventually coalesce and it is their size and density as they coalesce that will determine the properties of the thick layer. Fig. 1 shows the AFM images (Park Instruments) obtained after 3 min growth of GaSb on GaAs substrates at various temperatures. It can be clearly seen that the smallest islands were obtained, as expected, at the lowest growth temperatures. Thus the initial conditions for the growth of GaSb onto the DBR was to grow it at 520°C.

3. Design and growth of a resonant cavity detector

Fig. 2 shows a cross section of an RCE detector, the design and modelling of which has been reported elsewhere [13]. Briefly the GaAs/AlAs thicknesses were $\lambda/4n$ (n = refractive index) of 1.68 μm (AlAs, 145 nm; GaAs, 125 nm). These layers that form the DBR, were grown by MBE, on a GaAs:Si substrate and doped 1×10^{18} cm^{-3} n-type. There was a 250 nm buffer layer between the substrate and the 18 period DBR. After growth, reflection measurements on the mirror stacks were carried out using a quartz-halogen light source with a CVI monochromator, and the reflected light was measured with a Newport

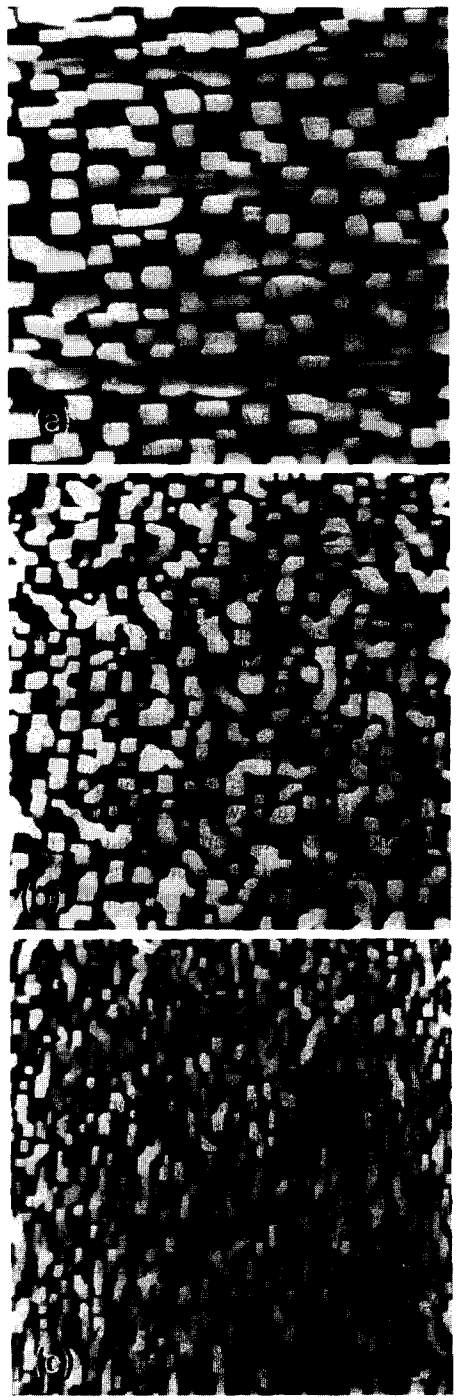

Fig. 1. AFM images of the MOVPE growth of GaSb on GaAs:Si substrates at various temperatures, together with the average height of the islands. Each image is 20 μm square: (a) 560°C, average height 350 nm, (b) 540°C, average height 200 nm, (c) 520°C, average height 100 nm.

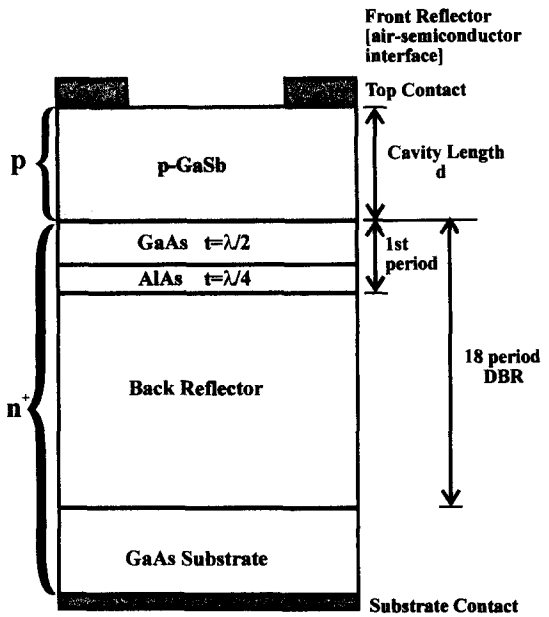

Fig. 2. Schematic cross section of the RCE detector structure.

germanium detector calibrated to a standard gold reflector. Fig. 3 is a typical spectrum and shows that MBE is capable of growing mirrors of a suitable wavelength. These DBRs together with GaAs:Si substrates were then transferred to an MOVPE reactor [14] where a GaSb layer was grown. This formed a resonant detector on the mirror and a nonresonant detector on the substrate. Thus subsequent measurements could compare an RCE detector, with a nonresonant detector, grown at the same time. Unintentionally-doped (p-type) GaSb was used as the active region material thus making the mirror/active region interface an n^+–p heterojunction. The GaSb active region was grown by MOVPE using (initially) trimethylgallium (TMGa) and trimethylantimony (TMSb) precursors and the thickness of the active region was ~ 1.5 μm. The exact thickness of GaSb needed was determined as follows. Assuming a refractive index for GaSb of ~ 3.8, the wavelength of operation can be calculated from $\lambda = 2nd/m$, where m is an integer and n is the refractive index, d is the thickness of the active region in the cavity. Thus d, the thickness of the GaSb, is simply 220 nm multiplied by m. In this study we took m as 7 and thus a thickness of 1.55 μm of GaSb would form a cavity that would enhance the absorption at a wavelength of 1.68 μm, but note that the value of the refractive index is only approximate. In order for the absorption to occur at the design wavelength of 1.68 μm the thickness of the GaSb would have to be within a few nanometres of the calculated thickness. To simplify the fabrication it was decided to use the inherent reflectivity of the GaSb/air interface (34%) even though this would lead to some loss of quantum efficiency. This also had the advantage of leaving an option to etch down the GaSb if it was slightly too thick or by etching to a thickness of 1.32 μm of GaSb ($m = 6$) if the MOVPE had grown slightly too thin GaSb. Fig. 4 is the reflectance spectrum of a complete RCE structure, the increase in the absorption at the desired wavelength of 1.68 μm shows that MOVPE is capable of growing accurately the required thickness of GaSb. Circular mesa structures

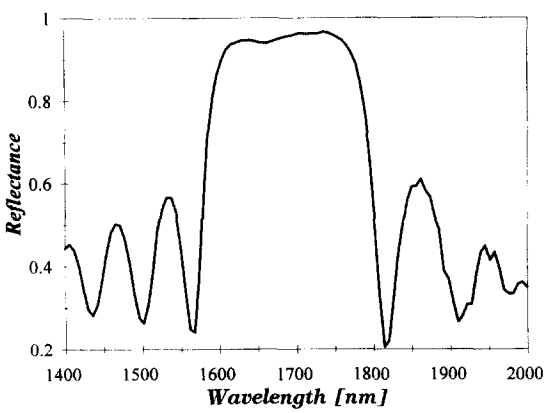

Fig. 3. Measured reflectance spectra of an 18 period GaAs/AlAs DBR designed for 1.68 μm.

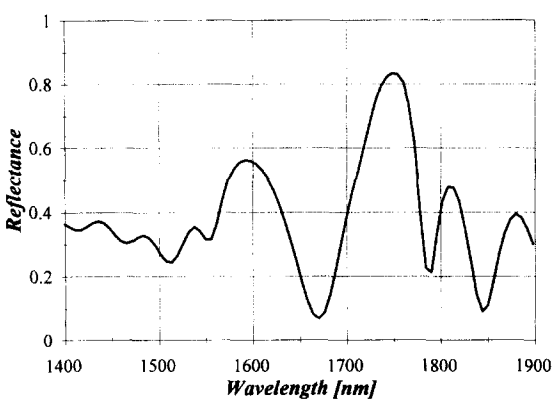

Fig. 4. Measured reflectance spectra of a complete RCE device.

of diameter 400 μm were fabricated using standard photolithography and wet etching. The top contact was Cr/Au and the broad back contact was Al, both contacts were ohmic.

4. Results

Fig. 5 shows the measured photocurrent spectra for an RCE detector and a nonresonant detector and a 3-fold enhancement in the photocurrent signal for the RCE detector at the design wavelength of 1.68 μm. Thus the basic design criterion seems to have been correct in postulating that the effective path length of light in an RCE would be increased over that in a non-RCE detector. The other results are summarised in Table 1 and are average values from a number of devices, all of which were 400 μm in diameter. The results with the trimethyl precursors show a significant increase in the quantum efficiency for the RCE over that obtained from the GaSb grown on a GaAs:Si substrate, and thus not having any resonant enhancement. However, the D^* is rather low, probably because the dark currents, even at very low reverse bias are quite high. Since the dark currents were similar for the resonant and nonresonant device it seemed likely that the problem was with the initial nucleation of the GaSb on to the GaAs. We decided to see if we could improve on this by nucleating even smaller islands of GaSb. The island size (average 100 nm height, 900 nm long, 500 nm wide) at 520°C seen in Fig. 1, is perhaps too large to act as a suitable buffer layer. Unfortunately even at 520°C the growth of GaSb is very inefficient (~ 120 μm/mole compared to 424 μm/mole at 560°C) because of the low level of pyrolysis of the commonly used precursors TMGa and TMSb at 520°C. From our pyrolysis studies [10] about 95% of the TMSb and TMGa are unreacted at this temperature in our MOVPE reactor, probably partly because it is designed to have a high mean gas velocity to ensure abrupt gas switching and good uniformity [15,16]. In order to improve growth efficiency for nucleation at 520°C and below, we used a combination of triisopropylgallium (TIPGa) and trisdimethylaminoantimony (tDMASb), both of which pyrolyse more efficiently than the trimethyl sources at 480°C [17]. Growing GaSb at 480°C from these new precursors we were able to obtain a growth efficiency of 310 μm/mole. Under those conditions a large number of small square islands (height 6 nm, 50 nm square, Fig. 6) are nucleated (note the different scale from the previous images). Thus we grew a layer of GaSb at 480°C with these new precursors and the results are again in Table 1. It is clear from a comparison of the nonresonant devices that there is a significant improvement in the dark current. These devices were able to be biased to −1 V without deleterious effect, where their dark currents were about 1 nA. This improvement in the dark current is

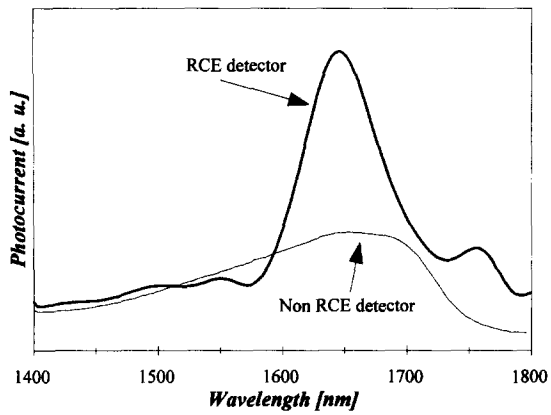

Fig. 5. Measured photocurrent spectra for RCE detector and nonresonant detector showing a 3-fold enhancement in the photocurrent signal for the RCE detector.

Table 1
Averaged device results for a number of resonant and nonresonant 400 μm devices

Substrate/Mirror	GaSb precursors	Growth temperature (°C)	Island size	Leakage at −0.1 V	Quantum efficiency	D^*
GaAs:Si	TMGa TMSb	520	Large	19 μA	2.5%	–
Mirror	TMGa TMSb	520	Large	1 μA	10%	2×10^9
GaAs:Si	TIPGa tDMASb	480	Small	1 pA	5.5%	–
Mirror	TIPGa tDMASb	480	Small	10 μA	21%	3×10^9

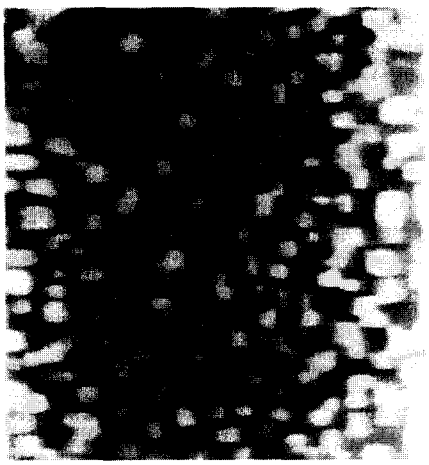

Fig. 6. AFM image of GaSb grown on GaAs:Si using TIPGa and tDMASb at 480°C, average height 6 nm.

reflected in the improved D^* for the nonresonant detector. These results would suggest that the initial nucleation of GaSb on GaAs is improved at 480°C with these new precursors. Studies using in situ laser light scattering to monitor the nucleation of the GaSb islands are underway and should lead to even bigger improvements in dark current. However, the RCE detector shows poorer dark current. This seems likely to be related to problems in cleaning the surface of this particular mirror before growth to the same high standard as that of an "epiready" substrate. Further work is in hand to solve this problem. Even so, it is still encouraging that with a 7% mismatch at a crucial part of the device, it is possible to obtain reasonable quantum efficiencies and dark currents. Other, slightly longer wavelengths, will be accessed using InGaSb on mirrors with slightly thicker periods.

5. Conclusions

RCE detectors for 1.68 μm wavelength have been successfully fabricated by growing an accurately controlled thickness of GaSb by MOVPE on an AlAs/GaAs DBR mirror grown by MBE. Despite a 7% mismatch in lattice constant between the two parts of the device a three fold improvement in quantum efficiency was achieved by using an RCE. By using new MOVPE precursors, with lower pyrolysis temperatures it was possible to nucleate smaller islands that gave nonresonant devices with much smaller dark currents compared to those grown with traditional precursors.

Acknowledgements

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