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14. ABSTRACT

This report results from a contract tasking University Montpellier 2 as follows: The objectives of this effort are to demonstrate an electrically injected Hole Well (HoW) Laser in the 3-4µm wavelength range and to obtain continuous wave operation and a high output power (>100mW) above room temperature. The tasks will be: 1. Laser design: Simulation of the structure to optimize alloy compositions and the thicknesses of the GaInSb QWs and GaInAsSb barriers in order to achieve an emission between 3 and 4µm. 2. Growth of the HOW-Laser active zone: Optimisation of growth conditions to achieve intended compositions and thicknesses, abrupt interfaces and high quality materials that are suitable for devices. RHEED and double-crystal x-ray diffractometry will be performed. 3. Characterization of the HOW-Laser active zone: Optical characterization, including optical transmission, photoluminescence and electroluminescence studies will be done to determine the band gap of the constituent alloys. Measurements of luminescence efficiency, and the variation of photoluminescence spectra with temperature and optical power. Electrical measurements to evaluate electrical transport in the active region. 4. Growth and study of HoW-Laser diode in the 3-4µm wavelength range. Doped heterostructures for diode HOW-Laser. 5. Characterization of HoW-Laser diode: Complete laser characterization including power, efficiency, and beam quality.

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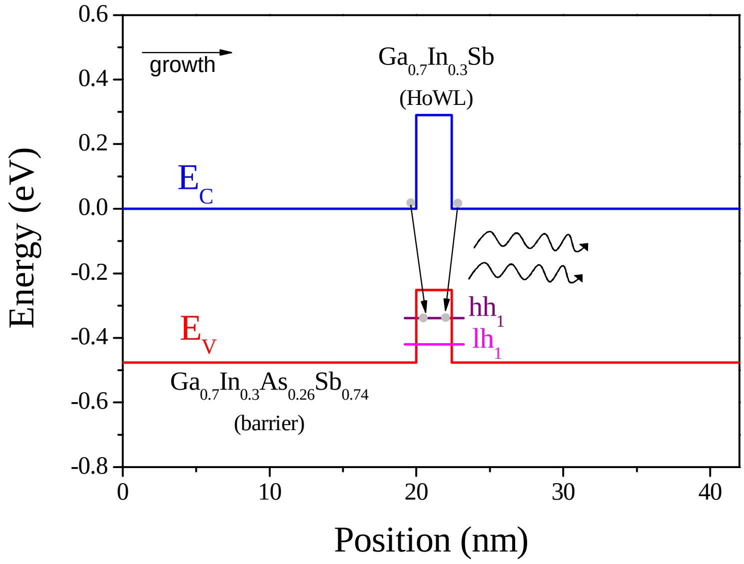

Growth and Study of Novel 3-4 µm Antimonide III-V Diode Lasers Operating at Room Temperature (Hole Well Laser)

Growth and Study of Novel 3-4 µm Antimonide III-V Diode Lasers Operating at Room Temperature
Final Report

1. Introduction

This final report is related to the work realized by CEM2, University Montpellier 2-CNRS, France during the period May 2005 – April 2006 in the framework of the EOARD Grant n° FA8655-05-1-3019 in collaboration with the team of Dr. Ron Kaspi from AFRL, Albuquerque, New Mexico, USA. The aim of this research work was to design, to fabricate and to characterize a novel kind of antimonide-based laser diodes emitting in the 3 µm to 4 µm wavelength range. The originality of these devices was the use, as light producing layers, of InGaSb/InGaAsSb multi-quantum-well (MQW) structures in which only the holes are quantum confined. Thus, in such a configuration, laser photons originate from the radiative recombinations between electrons from the InGaAsSb barriers and holes from the InGaSb holes. It was recently demonstrated by AFRL, Albuquerque, that optically-pumped devices with this kind of active zone can provide a novel solution for laser emission between 2 µm and 4 µm[1]. So, our objective was to develop lasers that employ similar multi-quantum-well active zones, but which operate under electrical excitation. The different structures fabricated during this project were grown by molecular beam epitaxy (MBE) on (001) GaSb:Te substrates.

2. Team

The persons involved at different levels in this EOARD project in CEM2 (University Montpellier 2-CNRS, France) are :
Design, MBE growths and characterization: L. Cerutti, G. Boissier, Y. Rouillard, J. Angellier and F. Genty
Laser diodes processing: P. Grech
X-Ray scans: F. Chevrier

3. Summary of the different layers and structures fabricated

The fabrication by MBE of different alloys in order to realize laser diodes needs several steps : calibration layers to optimise the compositions, the crystalline quality, the growth rate, the doping level....... of the different alloys constituting the laser structures, and obviously the whole structures for laser demonstration. Moreover, as it was described in the previous reports and as it often occured when machines and systems with a a very high level of technicity such as MBE are used, several breakdowns and time periods for normal maintenance of the MBE system perturbated our work and modified our planning of work. After each stop of the MBE machine, a new serie of calibrating layers was necessary before to be able to fabricate new laser diodes structures.

In summary, during this project, about 35 MBE growths were performed which can be divided as follows :

- about 20 calibration layers (compositions, crystalline quality, doping, ...)
- 15 laser diodes structures

[1] A. P. Ongstad et al., J. Applied Physics, 98, 043108 (2005)

Currently, a new serious breakdown has stopped our MBE machine (a leak in the nitrogen cryopanel of the cells). Nevertheless, we have enough results to write this final report. But, we have planned to continue the work concerning this research project as soon as our MBE system will be operational again, and this even if this EOARD grant is closed.

4. Design of HOle Well Laser diodes

As it has been recently demonstrated by AFRL with optically-pumped devices, these laser structures include an active InGaSb/InGaAsSb MQW zone in which only the holes are quantum confined. The typical structure has been grown by MBE on (001) GaSb:Te substrates. The heterostructure consisted of a 100 nm thick Te-doped layer lattice-matched on GaSb with a composition gradually varying from $Al_{0.1}Ga_{0.9}AsSb$ to $Al_{0.9}Ga_{0.1}AsSb$, a Te-doped 1.5 µm thick cladding $Al_{0.9}Ga_{0.1}AsSb$, a first 420 nm thick waveguide of $In_xGa_{1-x}AsSb$ lattice-matched on GaSb followed by a $In_xGa_{1-x}Sb/In_xGa_{1-x}AsSb$ MQW zone with five or ten InGaSb hole wells. The upper part of the structure was similar to the lower one but with p-type doping (Be). A final 100 nm thick Be-doped GaSb was epitaxied as the contact layer. The schematic band diagram of such a structure is described in figure 1. During this EOARD grant, two different values for x have been tested x= 0.3 and x= 0.2. Currently, it appears that it is a 0.3 composition in Indium in the wells and in the barriers that allows us to obtain the best results. But, we think that a further improvement could be obtained with an higher In composition such as 0.4 or more.

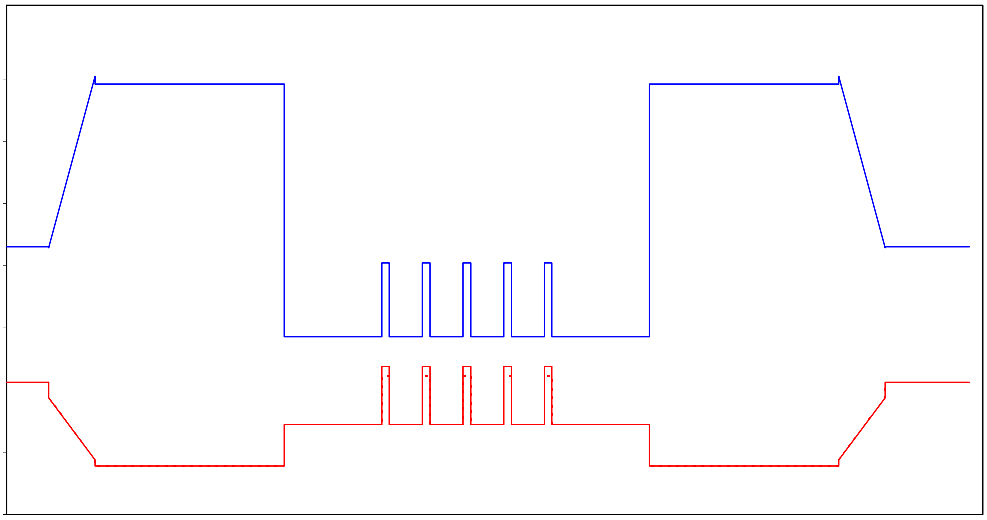

Fig. 1: Flat band diagram of the typical laser heterostructure (in blue : conduction band, in red : valence band)

5. Fabrication of the GaInAsSb alloy lattice-matched on GaSb

5.1 Miscibility gap

As previously described in the first report of this work at T_0+3, the GaInAsSb alloy is characterized by the existence of a very large miscibility gap depending on the composition. The so-called miscibility gap defines a region delimited by an isothermal curve (the spinodal curve) where the obtention of GaInAsSb compounds with only one phase is thermodynamically impossible (in fact, it is impossible to obtain a unique liquid phase with the composition intended at the particular temperature considered). This region is surrounded by the instability gap (delimited by the binodal curve) were the growth of GaInAsSb compounds, using growth technique in thermodynamical equilibrium, should lead to polycrystalline samples constituted of 2 phases, a first one having a composition close to GaAs and a second one having a composition close to GaInSb. In practice, LPE growths carried out inside the instability and immiscibility regions lead to unusable samples constituted of 2 phases (one GaAs rich, another one InSb rich). MBE growth is a very different process. From one side, all the atomic precursors are in gas phase (there is no fabrication of liquid alloy, so in theory the miscibility gap has no influence) and from another side, at the temperatures used for MBE growth, the atoms have small diffusion lengths on the surface of the growing sample. So, at sufficiently low growth temperatures, atoms can be "frozen" on the surface and forced to arrange in a random way instead of the ordered way characteristic of the phase separation. In practice, growths carried out by MBE inside the instability region lead to monocrystalline samples exhibiting good crystallographic and optical quality but growths made inside the immiscibility region can lead (but not always) to samples having the characteristics of a phase separation. So, in this last case, it is very important to optimise the growth conditions to limit the thermodynamic influence of the phase diagram. One of the calculated curves having the best agreement with experimental data was published by Sorokin et al.[2] (figure 2).

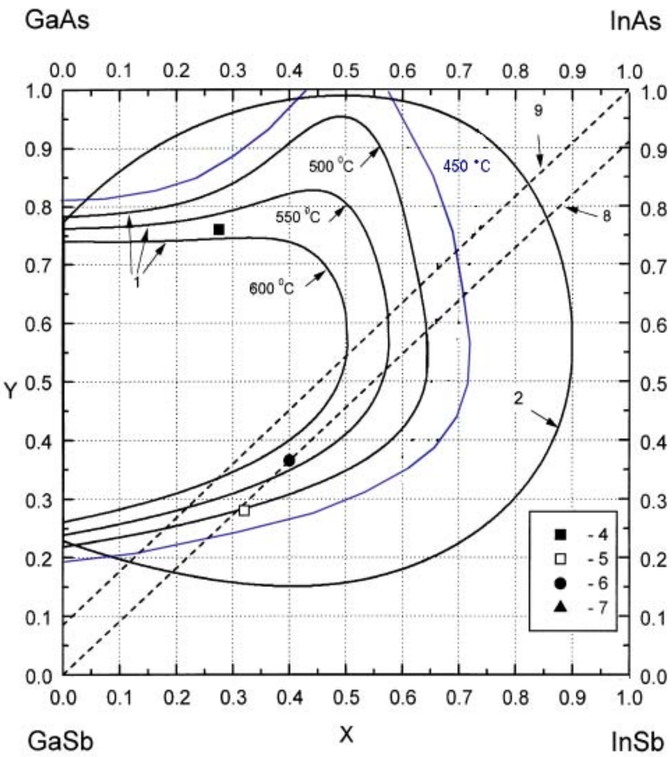

Fig. 2: Spinodal curves surrounding the miscibility gap of the $Ga_{1-x}In_xAs_ySb_{1-y}$ compound at 600, 550 and 500°C (the blue line at 450°C has been added as a line to guide the eye) [4]
Line 8: Compounds lattice matched to GaSb substrate
Curve 2:Spinodal curve calculated by Onabe et al. at 800 K (527°C)

During this project, we have fabricated $Ga_{0.70}In_{0.30}AsSb$ and $Ga_{0.80}In_{0.20}AsSb$ alloys lattice-matched on GaSb. To ensure a good composition control and a good crystalline

[2] V.S. Sorokin et al., *J. Cryst. Growth*, **216**-1-4 (2000) pp. 97-103

quality, a temperature of 420°C was chosen as MBE growth temperature for these alloys. As described by the figure 2, these alloys have compositions expected to be within the miscibility gap of this alloy system.

Since a few year, it has been demonstrated that another growth technique than the classical "bulk" one can help to obtain high quality alloys when their compositions are within a miscibility gap. This technique is called "digital" alloy growth technique and is based on the realization of very thin layers with very short periodicity (less than 8 monolayers) of alloys whose compositions are out of the miscibility gap. The compositions and the thickness of these alloys layers are chosen to obtain a "digital" alloy whose mean composition is within the miscibility gap[3].

So, in order to compare the different alloys grown, and to help improve the optical quality of the InGaAsSb layers, the classical "bulk" technique and the digital alloy technique were used during this project.

5.2 Control of the composition of the InGaAsSb alloy

The growth rate of all group-III elements (Ga, In, Al) have been determined classically using the observation of the Reflection High Energy Electron Diffraction (RHEED) specular beam oscillations. The period of these oscillations corresponds to the time needed to grow one monolayer of semiconductor. So, owing to these, it is possible to determine the flux *vs.* growth rate correspondance for each element-III, allowing the setting of the growth rate and of the composition of the antimonide alloys to be grown by a simple flux measurement.

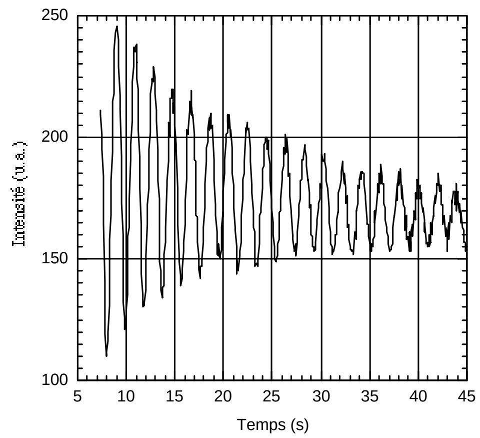

Fig 3.1: RHEED specular beam intensity oscillations for Ga rate growth on GaSb substrate

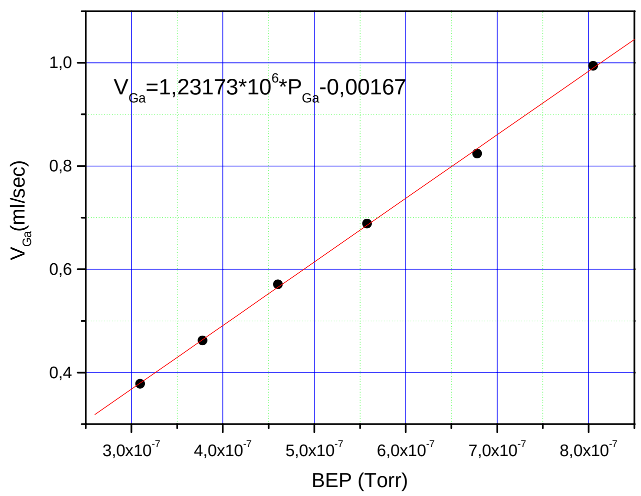

Fig 3.2: Calibration curve rate vs. Beam equivalent pressure (BEP) for Ga deduced from RHEED oscillations.

A typical RHEED oscillations record for Gallium is represented in Figure 3.1. Each oscillation corresponds to the growth of one monolayer. These oscillations are observed at different temperatures of cells (which corresponds to different Ga BEP) allowing the realization of a calibration curve showed in Figure 3.2. All group-III elements can be calibrated using this method.

For the group-V elements calibration, the RHEED oscillations method are not used. The As and Sb cells mounted on our MBE system are cracker cells equipped with a needle

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[3] R. Kaspi et al., J. Crystal Growth, 251, 2003, pp. 515-520

valve. Then, the valve opening allows to change the BEP of element-V used for the growth without changing the sublimator temperature of the cell. So, the As needed flux for lattice-matching on GaSb has been determined for each InGaAsSb alloy. While keeping a Sb flux constant (corresponding to 1.6 ml/s), three different layers have been grown with 3 different As-valve openings (*i.e.* 3 different As BEP). Each sample has been characterized by Double Crystal X-Ray Diffraction (DCXRD). The pattern obtained for $In_{0.3}Ga_{0.7}AsSb$ on GaSb substrate is shown on Figure 4. In this pattern, three peaks are visible which correspond to three lattice parameters and hence to three As compositions. Considering a linear evolution of the lattice parameter with the As valve opening, it is then possible to determine the best As valve opening (*i.e.* the best As BEP) to obtain lattice-matched materials.

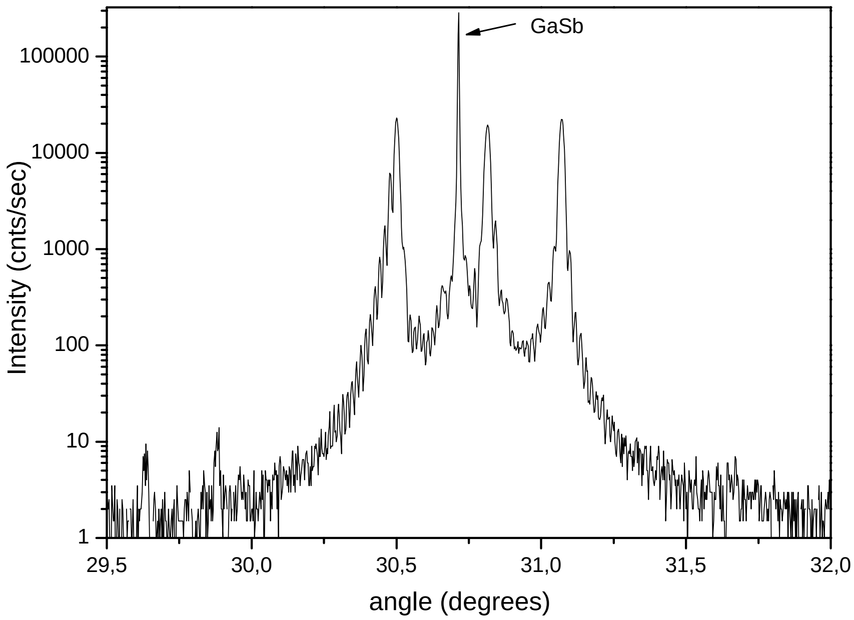

Fig. 4: *DCXRD pattern of 3 different $In_{0.3}Ga_{0.7}AsSb$ layers grown on GaSb substrate with 3 different As BEP while Sb BEP was keeping constant*

$In_{0.3}Ga_{0.7}AsSb$ alloys were also grown on GaSb substrate with the digital alloy technique. The growth conditions used in this case are reported in the table 1.

	1 period GaInAsSb (8sec: 1.536nm)	Pause 30sec	GaInSb QW (13sec)	1 period GaInAsSb (8sec)
Ga	Open Closed			
In	O C			
Sb	O C			
As	O 5sec C 3sec			5 sec 3sec

Table 1 : *Digital alloy growth conditions of InGaAsSb on GaSb substrate. O and C corresponds of the time of opening and closing of the different shutters of MBE.*

The $In_{0.3}Ga_{0.7}As_{0.26}Sb_{0.74}$ lattice-matched on GaSb was then obtained from the growth of successive layers of $In_{0.3}Ga_{0.7}AsSb$ with a very high As proportion and of layers of

$In_{0.3}Ga_{0.7}Sb$. As described by figure 2, the high proportion of As in the InGaAsSb quaternary allows to obtain a composition out of the miscibility gap. With these digital alloy growth conditions, the As-flux needed for lattice-matching is then obtained with the same process than previously described but with higher As BEP. The figure 5 represents the DCXRD pattern obtained from a sample containing two 300 nm-thick (200 digital alloy periods) layers of $In_{0.3}Ga_{0.7}AsSb$ digital alloys fabricated with two different As BEP. Two peaks are visible on this pattern corresponding to two As composition in $In_{0.3}Ga_{0.7}AsSb$ digital alloys. Then, the correct As BEP can be deduced from linear extrapolation.

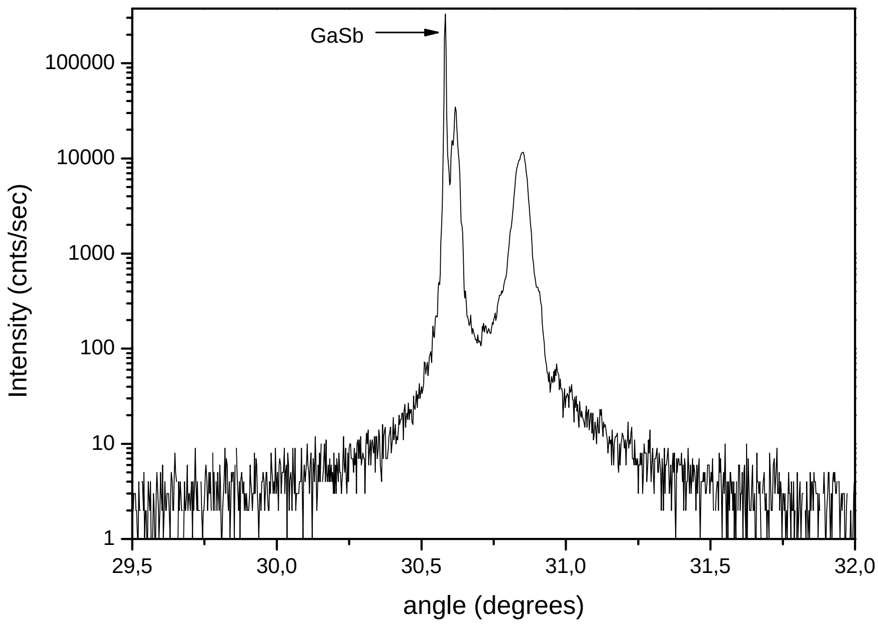

Fig. 5: *DCXRD pattern of 2 different $In_{0.3}Ga_{0.7}AsSb$ layers grown on GaSb substrate using the digital alloy technique with 2 different As BEP while Sb BEP was keeping constant*

6. Laser diodes characterization

As already reported in paragraph 3, 15 laser diodes structures were fabricated for this project. The thickness of such a typical heterostructure was about 5 µm (considering all the layers and the buffer layer realized just after the substrate deoxidation) and the typical growth rate used was about 0.6 µm/h. So the time of fabrication of one laser structure was about 8 hours without considering the time needed to heat the cells up to the right temperature and to deoxidate the substrate. Two compositions of InGaAsSb quaternary lattice-matched on GaSb (waveguide and barriers) have been tested ($In_{0.3}Ga_{0.7}AsSb$ and $In_{0.2}Ga_{0.8}AsSb$), and thus two compositions of wells ($In_{0.3}Ga_{0.7}Sb$ and $In_{0.2}Ga_{0.8}Sb$). Two growth methods have been used for InGaAsSb quaternary, the classical "bulk" one and the "digital" alloy one. Different kinds of results have been obtained which are described in the following.

6.1 First laser diode results

The first laser diode obtained during this project was constituted as described in the paragraph 4 with 5 $In_{0.3}Ga_{0.7}AsSb$/ $In_{0.3}Ga_{0.7}Sb$ wells embedded in $In_{0.3}Ga_{0.7}AsSb$ waveguide layers. Modeling has shown that such 2.4 nm thick wells embedded in 50 nm thick barriers should result in room temperature emission near 3.3 µm. The well/barrier band diagram considered in this case is represented in figure 6. For this sample the $In_{0.3}Ga_{0.7}As_{0.26}Sb_{0.74}$

alloy was fabricated with the digital alloy technique and its energy band gap was estimated to be 0.47 eV.

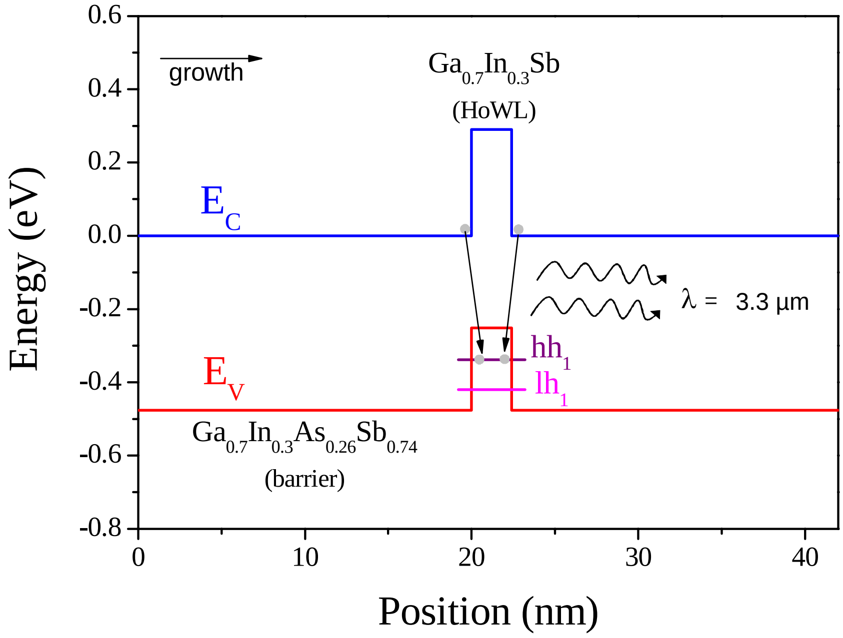

Fig. 6: *Schematic band diagram of* $In_{0.3}Ga_{0.7}Sb$ *wells embedded in* $In_{0.3}Ga_{0.7}AsSb$ *barriers. The energy band gap of* $In_{0.3}Ga_{0.7}AsSb$ *lattice-matched on GaSb is estimated to be about 0.47 eV and an emission near 3.3 µm is estimated.*

The DCXRD pattern obtained from this structure is reported in figure 7.

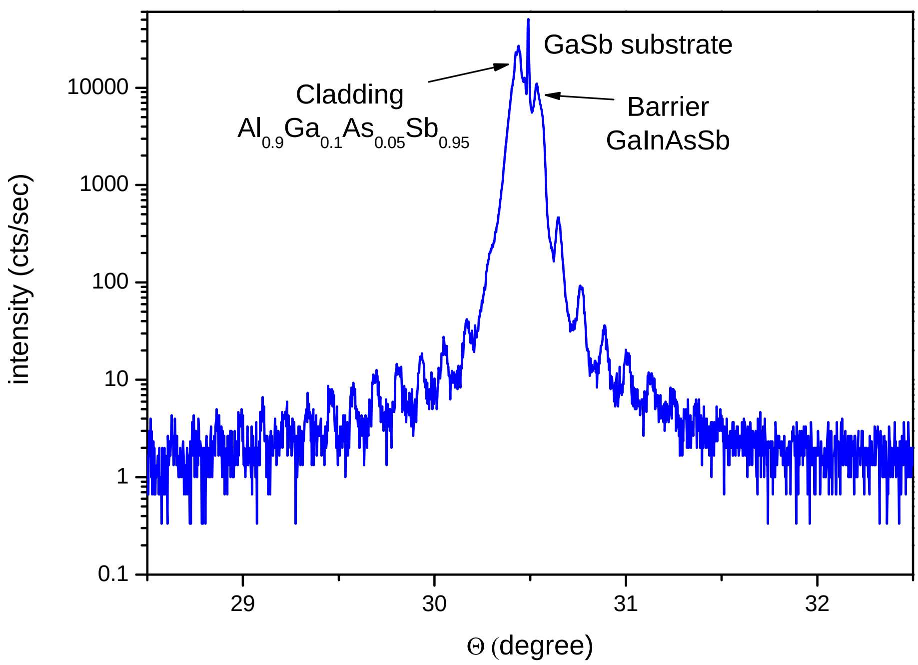

Fig.7 : DCXRD pattern of the first laser structure. Satellite peaks corresponding to a well/barrier periodicity of 42 nm are visible

In this first grown structure, DCXRD analysis indicates that the well/barrier periodicity was 42 nm, considerably thinner than the intended 52 nm. In this case, laser emission was observed at 2.65 µm up to 283 K in the pulsed regime (200 ns, 20 KHz) (figures 8a and 8b).

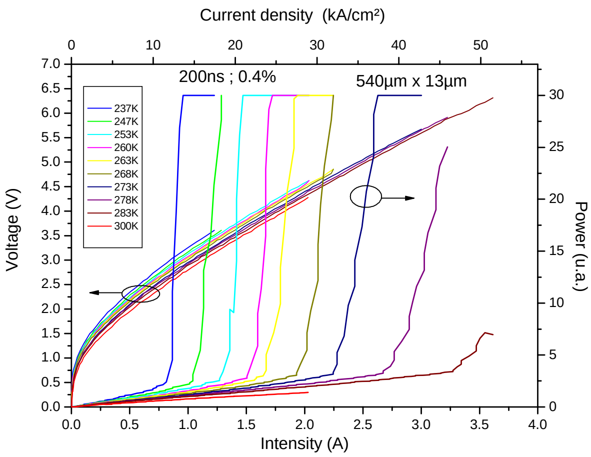

Figure 8a : P(I) and V(I) curves of the first laser structure at various temperatures

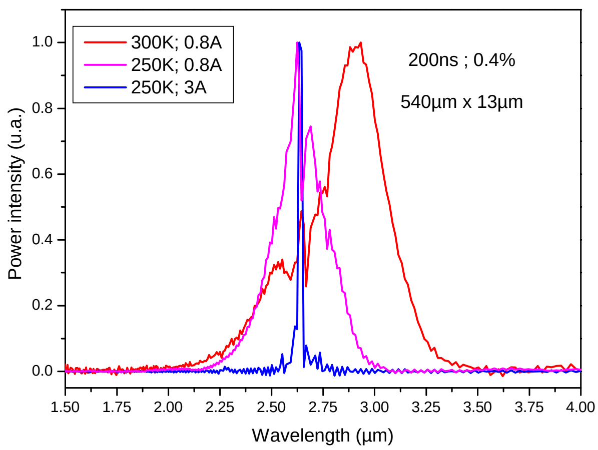

Figure 8b : Electroluminescence of the first laser structure. Laser emission near 2.65 µm at 250K is obtained

Considering the estimated value of the gap energy of the $In_{0.3}Ga_{0.7}As_{0.26}Sb_{0.74}$ alloy, 0.47 eV, it can be thought that, for this first structure, the laser emission was originating from electron-hole recombinations directly in the waveguide and not from quantum confined hole in the InGaSb wells. Indeed, in this particular case, electrons which have a high mobility sweep across the cavity without being stopped. They recombine radiatively with holes (which have a low mobility) near the p-type cladding leading to an emission at a wavelength corresponding to the gap energy of the waveguide, ie. 2.65 µm.

According to this first result, it appears that the quantum confinement of holes in InGaSb wells was not efficient enough. So, two ways of investigations were followed in order to obtain an emission in the intended wavelength range :

- To change the well/barrier composition in order to readjust the band diagram and to obtain an efficient hole confinement in the well
- To optimise the well/barrier periodicity in order to improve the hole confinement in InGaSb wells and to obtain a higher wavelength of emission than 2.65 µm

6.2 $In_{0.2}Ga_{0.8}AsSb$/ $In_{0.2}Ga_{0.8}Sb$ laser structures

In order to check out if electrons can be more effectively blocked by the well, a test structure was grown containing a unique 10 nm-thick GaInSb well, a thickness significantly higher than that of first structure wells. This thickness should alleviate the occurrence of tunnelling effect. A composition expected to be outside of the miscibility gap for the $Ga_{1-x}In_xAs_ySb_{1-y}$ waveguide was chosen for an intended better control of the composition during the growth. This structure was constituted by a 800 nm-thick $Ga_{0.83}In_{0.17}As_{0.15}Sb_{0.85}$ waveguide (lattice-matched on GaSb) and a unique 10 nm-thick $Ga_{0.83}In_{0.17}Sb$ well. Claddings were made of 1 µm-thick $Al_{0.90}Ga_{0.10}As_{0.07}Sb_{0.93}$ layers. This structure was grown at 480°C for the claddings and 410°C for the active zone. Due to reasons detailed in the T_0+3 report, a slight lower arsenic content than targeted was obtained for the waveguide. This lead to a layer with a composition of $Ga_{0.83}In_{0.17}As_{0.11}Sb_{0.89}$. Lowering of the arsenic content has for effect an increase of the gap energy of the quaternary alloy.

Broad area laser diodes with a stripe width of 80 µm were made from this heterostructure. These laser diodes operated in pulsed mode up to 260 K with threshold currents of 50 mA at 80 K and 500 mA at 250 K (J_{th} = 85 A/cm² and 850 A/cm²) (figure 9).

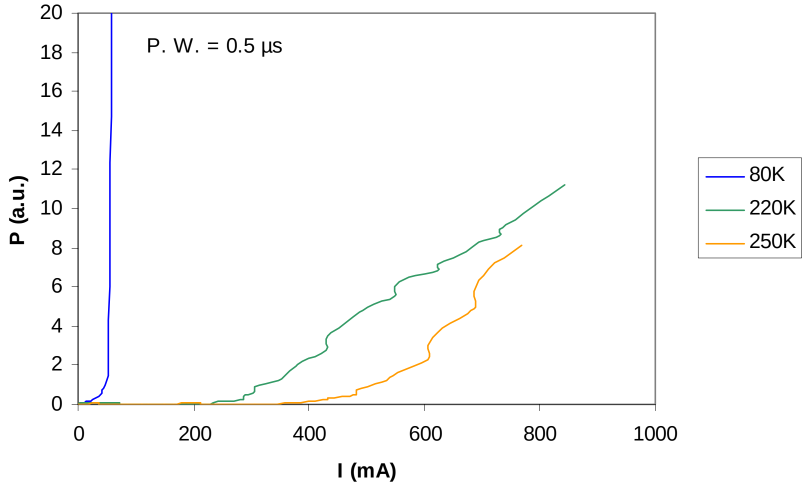

Fig. 9: L-I curves of a 80 µm-wide 730 µm-long laser diode

The lasing spectrum at 260 K is shown on figure 10.

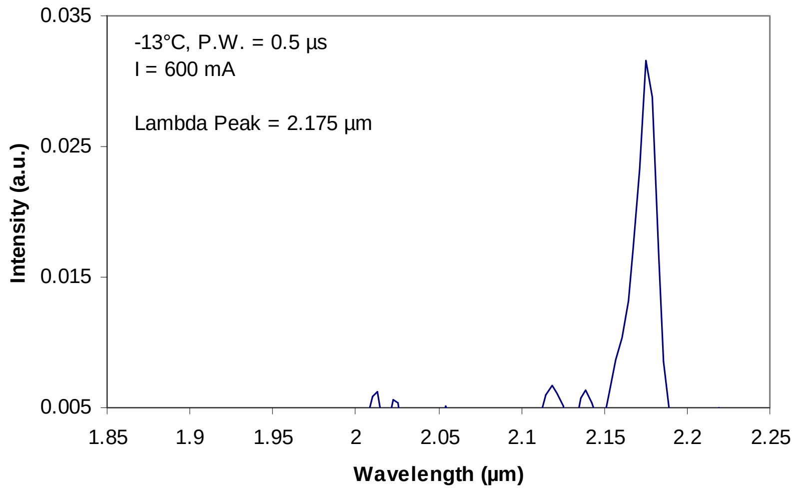

Fig. 10: Typical spectrum of a laser diode at 260K

Once again, one can note that the wavelength of the lasing peak is very low (2.175 µm) and can be thought to correspond to a band-to-band recombination in the waveguide.

Nevertheless, another interesting result can be observed from this sample. The low power photoluminescence (PL) spectrum of this structure is represented in figure 11. The wavelength of PL peak emission is different and significantly higher than the laser emission wavelength. So, the wavelength displayed on the figure 10 (2.68 µm) can correspond to a transition between electrons and holes confined in the GaInSb well. The intensity of this PL peak is really weak (1000 times lower than for classical type-I laser structures emitting at this wavelength) which is coherent with such a type-II emission.

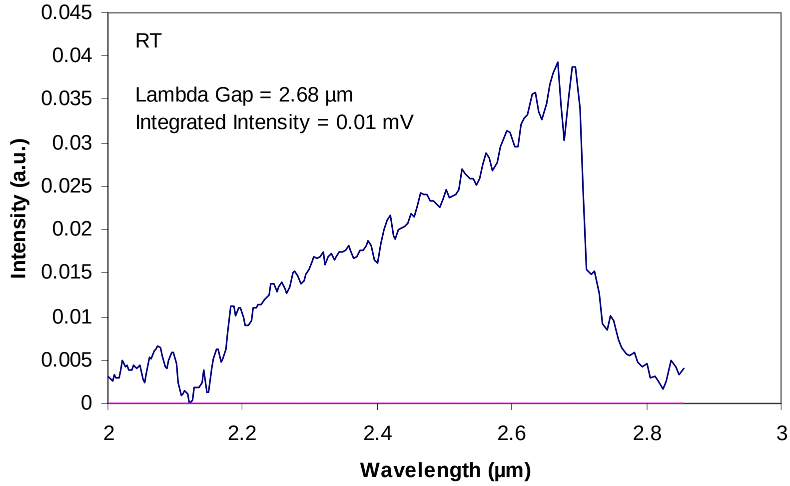

Fig. 16: Photoluminescence spectrum of the sample A82

Several interesting results have been obtained with this structure :

- The laser emission recombinations observed from the previous structures were effectively originating from electron-hole recombinations in the waveguide. The hole confinement in the InGaSb well is not efficient enough and the electrons sweep across the cavity (by tunneling effect) without being stopped and recombine with holes in the waveguide near the p-type cladding layer.
- The observation of a PL emission, at a significantly longer wavelength than the laser emission, demonstrates that holes are effectively quantum confined in the wells and that it is possible to obtain light from radiative recombinations between electrons from the barriers and holes from the InGaSb wells.
- The too short PL emission (about 2.65 µm) compared to the intended one (3.3 µm) proves that a higher indium content in the wells (and thus in the barriers) is necessary to obtain a laser emission between 3 µm and 4 µm.

6.3 Optimized $In_{0.3}Ga_{0.7}AsSb$/ $In_{0.3}Ga_{0.7}Sb$ laser structure

According to the previously described results, it appears that a minimum indium content of 30% is necessary to obtain a HOWL laser emission in the 3 µm to 4 µm wavelength range. Another structure, with the same design than described in the paragraph 6.1, was then fabricated. As in the first structure, the quaternary InGaAsSb alloy was realized using the digital alloy technique. But for this new structure, a particular effort was made in order to improve the well/barrier periodicity control. The DCXRD pattern of this second structure is represented in figure 17. In this case, the DCXRD analysis showed a well/barrier periodicity of 49 nm, closer to the intended value. Laser emission in this device was observed at 2.93 µm in the pulsed regime (200 ns, 5 KHz) up to 243K (figures 18a and 18b).

For this new structure, the wavelength of emission is significantly longer than the wavelength of the first device, suggesting that , in this case, the recombination is taking place between electrons in the barrier layers and holes that are confined in the wells. The shorter (2.93 µm) than calculated emission wavelength (3.3 µm) of this second structure is thought to be due to the shorter than intended (49 nm *vs.* 52 nm) well/barrier periodicity.

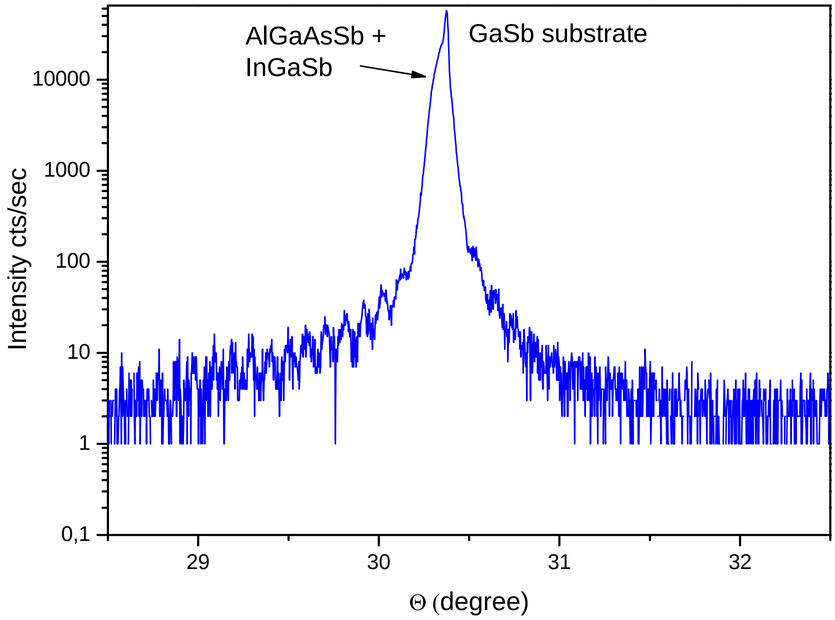

Fig. 17: DCXRD pattern of the $In_{0.3}Ga_{0.7}Sb/In_{0.3}Ga_{0.7}AsSb$ laser structure with optimized well/barrier periodicity. Satellite peaks corresponding to a well/barrier periodicity of 49 nm are visible

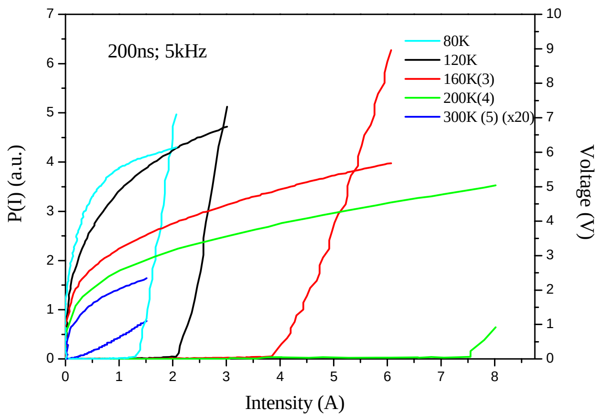

Figure 18a : P(I) and V(I) curves of optimized $In_{0.3}Ga_{0.7}Sb/In_{0.3}Ga_{0.7}AsSb$ laser structure at various temperatures

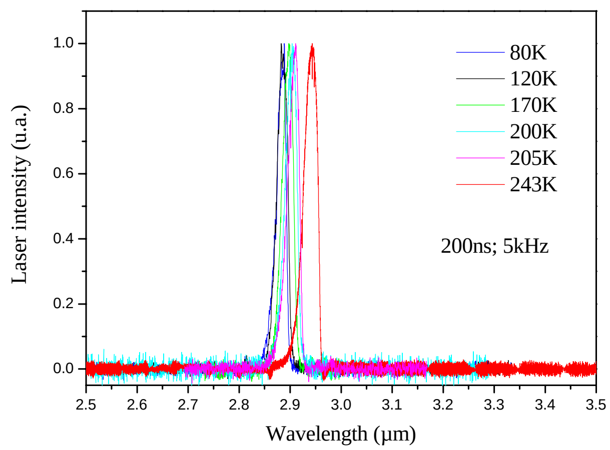

Figure 18b: Laser spectra of $In_{0.3}Ga_{0.7}Sb/In_{0.3}Ga_{0.7}AsSb$ optimized laser structure. A laser operation up to 243K is observed originating from radiative recombinations between electrons from barriers and holes from wells

For this other structure, the $In_{0.3}Ga_{0.7}Sb/In_{0.3}Ga_{0.7}AsSb$ well/barrier periodicity was better controlled than for the sample described in paragraph 6.1. With a thicker well, the hole quantum confinement appears to be more efficient and it was possible to demonstrate laser emission from radiative recombinations between electrons in the barriers and holes in the wells. Moreover, with a similar technological process, diodes with 15 µm-wide mesas, the threshold currents for laser emission near 2.93 µm are higher than those for laser emission near 2.65 µm (about 7.5 A for an emission near 2.93 µm compared to about 1 A for an emission near 2.65 µm at about 200K). Such a result, if considering the weak overlap of electrons and holes wavefunctions in the case of a type-II recombination between electrons in the barriers and holes in the wells, can confirm from another point of view that lasing effect near 2.93 µm was obtained owing to hole quantum confinement in $In_{0.3}Ga_{0.7}Sb$ wells.

6.4 Current work

As reported in paragraph 3, our MBE system is currently stopped due to a leak in the nitrogen cryopanel of the cells side which will need the whole replacement of this cryopanel. Nevertheless, new optimisations were under investigations. First, we wanted to try to fabricate $In_{0.3}Ga_{0.7}Sb/In_{0.3}Ga_{0.7}AsSb$ MQW structures with InGaAsSb quaternary fabricated by the classical “bulk” technique in order to compare these structures with those previously described with “digital” alloy quaternary. Indeed, since MBE is a non-thermodynamical equilibrium technique and since $In_{0.3}Ga_{0.7}AsSb$ is near the boarder of the miscibility gap, it should be possible to obtain alloys with good crystalline quality even with “bulk” growth method (see also paragraph 5.2). Second, obviously, we wanted to fabricate a third $In_{0.3}Ga_{0.7}Sb/In_{0.3}Ga_{0.7}AsSb$ MQW laser structure with a well/periodicity of 52 nm to verify our modelisation parameters. Finally, we have planned to increase the indium content of the wells (and to adjust the thickness of the wells) to improve the hole confinement, to limit the tunneling effect and to lower the threshold currents.

7. Conclusion

During this work, we have thus demonstrated that InGaSb/InGaAsSb hole multi quantum well active layer is a viable solution to fabricating electrically-injected mid-IR laser diodes. Owing to a 5 $In_{0.3}Ga_{0.7}Sb/In_{0.3}Ga_{0.7}AsSb$ MQW structure fabricated by the digital alloy technique, laser operation at 2.93 µm up to 243K in the pulsed regime (200 ns, 5 KHz) has been demonstrated. Laser threshold current up to 7.5 A at 200K with 15 µm-wide mesas devices has been measured.

The results obtained allowed us to submit an abstract at the next International MBE Conference which be held at Tokyo (Japan) in next September, see annexe of this report. Another paper is currently in redaction.

Research works on this subject are currently stopped due to a severe breakdown of our MBE system, but new experiments are planned to be performed as soon as it will be possible, and this even if the EOARD grant period will be closed. The results will be provided to EOARD in the form of an additional report which will be delivered in the last trimester of 2006.

Annexe : abstract submitted to MBE International, Tokyo (Japan), September 2006

GaInSb/GaInAsSb Hole well laser diodes emitting near 2.93 µm

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Abstract :
Sb-based laser diodes emitting near 2.93 µm up to 243K in the pulsed regime, in which only the holes are quantum confined, are demonstrated. Radiative recombinations originate from InGaSb hole wells embedded in InGaAsSb barriers. Laser structures were fabricated by molecular beam epitaxy on (001) GaSb substrates. The InGaAsSb layers, whose composition is in the miscibility gap, was grown by the digital alloy technique.

Laser sources emitting in the mid-infrared are useful in a number applications such as trace gas detection by laser spectroscopy, infrared countermeasures or free-space telecommunications. It was recently demonstrated that optically-pumped devices with an active zone containing InGaSb hole wells embedded in InGaAsSb barriers provide a novel solution for laser emission between 2 µm and 4 µm[4]. In this paper, we demonstrate lasers that employ similar multi-quantum-well active zones, but which operate under electrical excitation. The structures are grown by molecular beam epitaxy on (001) GaSb:Te substrates. The heterostructure consists of a 100 nm thick Te-doped layer lattice-matched on GaSb with a composition gradually varying from $Al_{0.1}Ga_{0.9}AsSb$ to $Al_{0.9}Ga_{0.1}AsSb$, a Te-doped 1.5 µm thick cladding $Al_{0.9}Ga_{0.1}AsSb$, a first 420 nm thick waveguide of $In_{0.3}Ga_{0.7}As_{0.26}Sb_{0.74}$ followed by a $Ga_{0.7}In_{0.3}Sb/In_{0.3}Ga_{0.7}As_{0.26}Sb_{0.74}$ MQW zone with five InGaSb hole wells. The upper part of the structure is similar to the lower one but with p-type doping (Be). A final 100 nm thick Be-doped GaSb is epitaxied as the contact layer. The first cladding was grown at 510°C. The active region (waveguide + MQW) was grown at 420°C and the second cladding and the top contact layer were grown at 440°C to prevent intermixing in the active region. Because $In_{0.3}Ga_{0.7}As_{0.26}Sb_{0.74}$ is a composition expected to be within the miscibility gap of this alloy system, the digital alloy growth technique[5] was employed to help improve the optical quality of this layer.

In the InGaSb/InGaAsSb MQW system, only holes are confined in the wells. Modeling has shown that 2.4 nm thick wells embedded in 50 nm thick barriers should result in room temperature emission near 3.3 µm. In the first structure grown, double crystal X-ray diffraction (DCXRD) analysis (figure 1a), indicates that the well/barrier periodicity was 42 nm, considerably thinner than the intended 52 nm. In this case, laser emission was observed at 2.65 µm up to 283 K in the pulsed regime (200 ns, 20 KHz) (figure 2), originating from electron-hole recombination directly in the barriers. A second structure, with the same design, was then fabricated. In this case, the DCXRD analysis (figure 1b) showed a well/barrier periodicity of 49 nm, closer to the intended value. Laser emission in this device was observed at 2.93 µm, a significantly longer wavelength than the first device, suggesting that the recombination is taking place between electrons in the barrier layers and holes that are confined in the wells. Lasing was observed in the pulsed regime (200 ns, 5 KHz) up to 243K (figure 3). The shorter than calculated emission wavelength of this second structure is thought to be due to the shorter than intended (49 nm vs. 52 nm) well/barrier periodicity.

We have thus demonstrated that InGaSb/InGaAsSb hole multi quantum well active layer is a viable solution to fabricating electrically-injected mid-IR laser diodes.

This work was supported under an EOARD grant.

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[4] A. P. Ongstad et al., J. Applied Physics, 98, 043108 (2005)
[5] R. Kaspi et al., J. Crystal Growth, 251, 2003, pp. 515-520

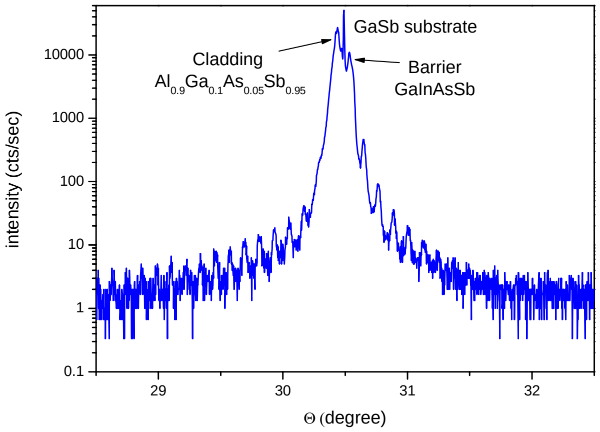

Figure 1a : DCXRD pattern of structure 1. Satellite peaks corresponding to a well/barrier periodicity of 42 nm are visible

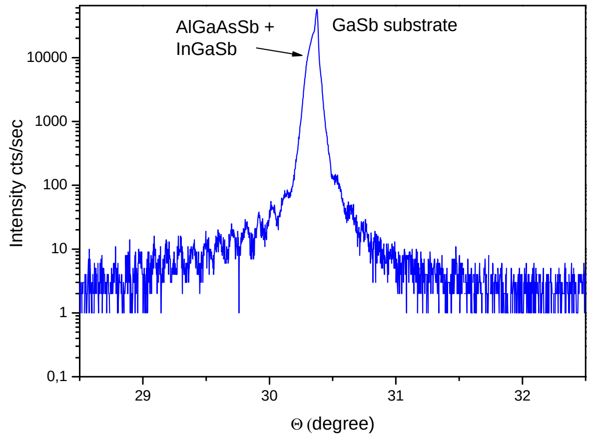

Figure 1a : DCXRD pattern of structure 2. Satellite peaks corresponding to a well/barrier periodicity of 49 nm are visible

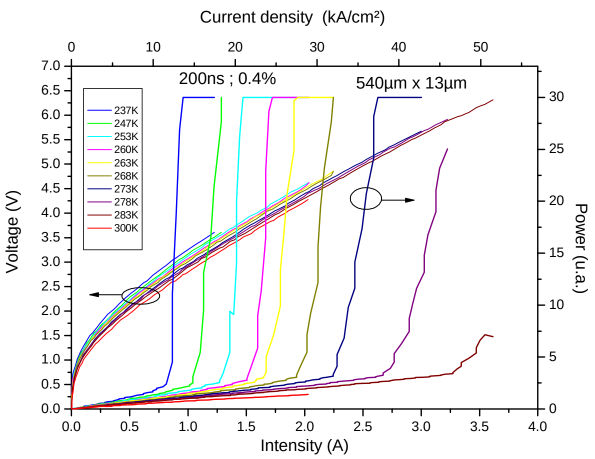

Figure 2a : P(I) and V(I) curves of structure 1 at various temperatures

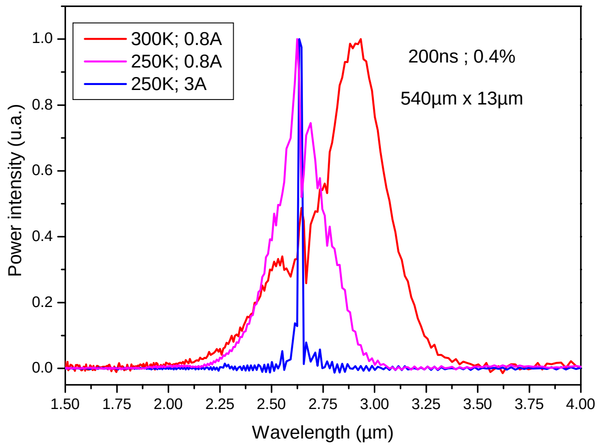

Figure 2b : Electroluminescence of structure 1. Laser emission near 2.65 µm at 250K is obtained

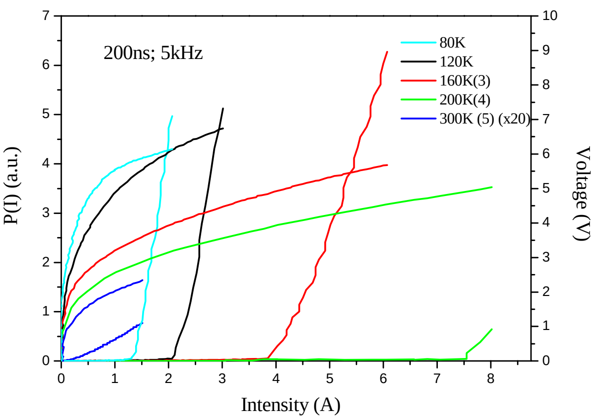

Figure 3a : P(I) and V(I) curves of structure 2 at various temperatures

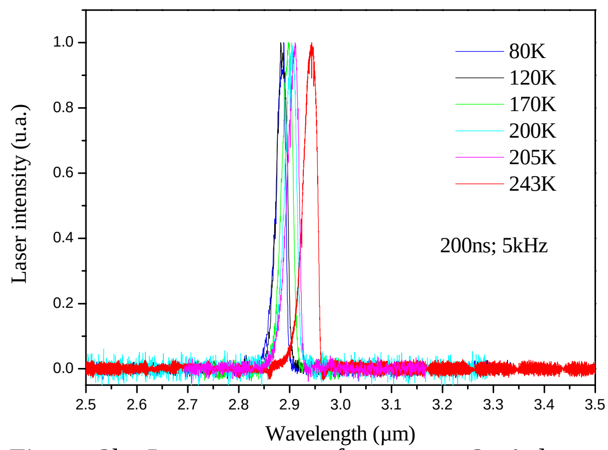

Figure 3b: Laser spectra of structure 2. A laser operation up to 243K is observed originating from radiative recombinations between electrons from barriers and holes from wells