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TITLE: Advanced room temperature mid-infrared antimony-based lasers by MOVPE
“ADMIRAL”

PROJECT CO-ORDINATOR: Epichem Limited (UK)

PARTNERS: AIXTRON Semiconductor Technologies AG (DE)

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University Montpellier II (FR)

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Contents

1. EXECUTIVE SUMMARY

It was the objective of the ADMIRAL project to develop light-emitting diodes and lasers emitting in the mid-infrared (MIR) and consisting of group III-antimonide semiconductors. The devices were bipolar devices aimed at operating in the current injection mode, favorably up or close to room temperature (RT). The largest challenge was the deposition of the layer structures by metalorganic vapor phase epitaxy (MOVPE), a process technology which presently is most widely used for industrial application. In the future it will certainly be the technology for mass production of devices operating in the MIR. The 36 month ADMIRAL project was brought to a conclusion with all deliverables of the work plan submitted in a timely manner: Overall project progress has been measured against four milestones, of which three have been fully completed in a successful manner. The final milestone was 80% achieved however it proved too optimistic a goal to reach RT operation within the time constraints of the project.

The whole spectrum of the steps necessary for the achievement of the project goals was investigated, starting with the development of novel precursors (EPICHEM), continuing with their test including vapor pressure measurements and epitaxy test runs (RWTH). Simultanously layer structures were designed and simulated, which should enable the room temperature operation of LEDs and laser (UM2). Also simultaneously special methods for the evaluation of both grown layer structures and fully processed devices were developed (IP-AVCR). During the course of the project further improvements of the epitaxial equipment were identified and specially manufactured parts were installed and tested (AIXTRON).

As a general result it can be stated that the goals were achieved in such a way that MOVPE grown LEDs, based on an Al-free material system, operate up to RT and at wavelengths from three to four micrometers. MOVPE lasers, based on this system, operate at temperatures up to 135K with low threshold current densities. These devices were not available elsewhere at the start of the project and only one group reports higher operating temperatures using the MOVPE growth technique. The active regions in these devices form the essential part of Al-containing lasers, which are expected to operate at RT due to better confinement properties. Considerable progress was made in the oxygen-free synthesis of group III and Sb precursors resulting in a reduction of background impurities in the epitaxial layers such as carbon and oxygen by orders of magnitude. Only the commercially available As precursor, tertiarybutylarsine now suffers the severe handicap of high oxygen contamination. Despite this, the full set of process parameters for the deposition of Al-containing laser structures is available and only the quality of the overall combined structure has prevented the fabrication of RT operating lasers.

With these results achieved the project ADMIRAL represents the international cutting edge of current R&D in MOVPE grown MIR lasers. ADMIRAL was the first group to obtain MOVPE RT LED’s in the Sb system operating at 3.3micons and considerable improvements of this technology were realised. A major impact on the scientific community was achieved with numerous publications and the hosting of four topical MOVPE conferences by the ADMIRAL participating academic institutions during the course of the project.

2. MAIN RESULTS

2.1 Precursor/equipment technology for improved process performance to allow fabrication of highest quality layers

New aluminum and antimony precursors from Epichem, as well as several standard In and Ga precursors prepared using improved, oxygen free synthesis were tested at RWTH Aachen for suitability in the deposition of various Sb alloys. All sources were characterised by new techniques developed during the project to ensure reproducibility and allow optimisation of the process parameters ready for scale up.

The optimum precursor combination has been determined for each alloy and state of the art layer structures may now be deposited. These precursors will be marketed as a new grade called EpiPure^{TM} and sale into this developing market will make use of the <3ppm detection limits for oxygen species now achievable following investigations during the collaboration.

The MOVPE set-up (i.e. gas blending system as well as the MOVPE reactor) has been especially adapted to grow Al and Sb containing compounds in a collaborative effort by AIXTRON and RWTH Aachen with much improved homogeneity and reproducibility achieved. Increased gas purification has contributed to this result and all modifications will be used to improve AIXTRON MOVPE equipment systems.

Both Epichem and Aixtron have global marketing and distribution networks for their products to ensure the widest user base is reached.

2.2 Laser demonstration: 3.3 µm emission at low temperature from a new semiconductor laser structure

A new diode laser structure, based on III-V antimony compounds, was designed and modeled to achieve maximum efficiency in the desired emission range (3-5µm). Different cladding layers and active region layers were evaluated to achieve the highest potential structure prior to growth trials at RWTH Aachen using MOVPE. Following a series of iterative improvements in the design and deposition techniques laser emission was achieved at low temperature (up to125K) around 3.3 µm with an output power of 31 mW/A/facet.

Increased maximum temperature of operation, more than 240K, is planned by the end of the project to enable component fabrication for applications in gas sensing, chemical process control, and laser medicine. Efficient and compact mid-infrared laser diodes are very useful for gas trace detection and pollution monitoring. An important market is predicted for portable gas analysers using stable mid-infrared laser diodes operating at room temperature or temperatures achievable by Peltier cooling (more than 200 K).

Two companies (Oldham and GDF) are clearly interested by the lasers developed in the ADMIRAL project and wish to use these devices in new gas analysis systems.

2.3 Demonstration of RT operation of MOVPE grown MIR LEDs

Room temperature electroluminescence (EL) was resolved from $InAs/InAs_{0.94}Sb_{0.06}$ MQW-LEDs (emission wavelength of 3.3 µm) related to InAs near-bandgap transitions. The incorporation of phosphorous in the active layers was found to improve high temperature performance of the devices.

InAs(P)/InAsSb and InAsPSb/InAsSb PIN heterostructures were processed into 270 µm diameter surface light-emitting diodes. Specific contact resistances as low as $2x10^{-5}$? cm^2 on the n-doped InPSb layers were achieved and forward current-voltage (I/V) characteristics closely followed exponential behaviour (Turn-on voltage of 0.1 V at I = 1 mA, T = 290 K). The I/V characteristics of InAsPSb/InAsSb/InAsP "W" LED and laser structures at 300 K indicated lower leakage currents (for lower voltages) for mesa etched top cladding compared with unetched samples. Reduction of leakage currents was achieved throughout the project.

Strong room temperature EL was measured at 3.9 µm on LEDs with "W"-design of the active region. The intensities at high temperature were higher than on InAsPSb/InAsSb MQW-LEDs, therefore the "W"-active region is more promising for room temperature operation of lasers containing similar active regions. This confirms photoluminescence (PL) data for various structures with high intensity and small FWHM observed.

As an example the applicability of the devices fabricated the detection of carbon dioxide at room temperature was demonstrated.

2.4 Characterisation techniques-improved analysis technologies to investigate Sb containing compounds and to evaluate MOVPE epitaxial layers

Throughout the ADMIRAL project lifetime, the partners have put much effort into improving diagnostic methods and analysis technologies to provide reliable accurate results with respect to the final information about deposited layer structures and devices. Several analytical techniques were deployed to investigate electrical, optical, structural and topographic properties. Insights into the various characterisation data has been a key factor in the continuous improvement of MOVPE processes and device performance.

All these techniques will be exploited during future research projects oriented towards the investigation of modern low dimensional structures for basic research as well as for device application in optoelectronics and ultra high frequency electronics. Most of these activities have been used also in the process of PhD studies of several PhD candidates and will be used by several universities even in the future.

3. ACTIVITIES AND ACHIEVEMENTS OF THE PARTNERS

3.1 Epichem

Significant improvement in precursor production and analysis technologies have been made by Epichem during the project which have been highlighted by the ability of the growth team to deposit structures capable of lasing. The reduction of contaminant levels has been progressed throughout the project and has been monitored by a similar reduction in the detection limits of optimised analytical techniques. Improvement in analytical capabilities and sensitivities for impurities in organometallic compounds has been achieved and has allowed the demonstration of reduced oxygen contamination levels in the latest batches (<1ppm). All tasks identified in the project work plan relating to precursors have been successfully completed and the information gained has proved invaluable to achieving state of the art production processes for the optimum compounds. These materials can now be manufactured in a reliable fashion to high quality in volumes suitable to service the current and future markets.

3.2 AIXTRON

AIXTRON AG's main task as a MOCVD systems producer focused on the adaptation and improvement of the MOCVD equipment at RWTH Aachen for the growth of the novel Sb-based material system. The main challenges in the growth of the material and its heterostructures had to be identified and an optimized MOCVD kit, including reactor and gas mixing cabinet as well as necessary purification methods of the precursor materials used, had to be developed. With respect to uniformity of the material deposition on the wafer a rotating susceptor and the incorporation of the rotation mechanism into the existing system's gas and electrical circuitry had to be provided.

Thus, AIXTRON AG has advanced its knowledge in the field of design of reactor chambers and susceptors for the production of Sb-based materials. The constant exchange of information between the growth team at RWTH Aachen, and the characterization and processing teams has lead to a profound understanding of all the issues involved in the growth of Sb-based materials and has helped in understanding the advances made in reactor and gas-mixing system design. A special focus was set on the evaluation of inpurity incorporation into the material and main strategies to avoid such contamination. Processes and system designs are now available for marketing of MOCVD systems capable of growing Sb-based heterostructures for a wide field of applications. The thorough understanding of the influences of reactor chamber design on the grown layers enables us to up-scale the reactor design to multiwafer-type reactors especially interesting for customers in the future thermo-photovoltaic field.

3.3 RWTH Aachen

The first task to be undertaken by RWTH Aachen was the test of several novel precursors for the deposition of both Al-free and Al-containing layers. The problems to be overcome were twofold:

1. the layers had to be grown at temperatures which are below the relatively low melting point of the group III antimonides,
2. the background impurities (especially carbon from the precursors and oxygen from either the precursors, the substrate preparation, the carrier gases or the equipment itself.

Trisdimethylaminoantimony (TDMASb) was found to be suitable for the deposition of Al-free layers (e.g. InSb with mobilities of 50,000 cm²/Vs at 300K was grown). But serious pre-reactions with triteriarybutylaluminum (TTBAl) occured, while the commercially available triethylantimony (TESb) was a suitable combination with TTBAl. However the quality of the commercially available precursors (e.g. tertiarybutylarsine) was irreproducible and the background impurity concentrations, especially oxygen, often too high to allow high quality Al(Ga)AsSb to be grown at the end of the project. Also, the oxygen background in the MOVPE system prevented the deposition of high purity Al(Ga)AsSb. This is the main reason why Al-containing laser devices were not available at the end of the project. Doping experiments were performed for the ternary and quaternary compounds and carrier concentrations high enough for use in contact layers were obtained. However the full sets of process parameters (including vapor pressure data for novel precursors where not yet available from the literature) for the low pressure MOVPE deposition of InSb, InAs, InAsSb, InAsPSb, InPSb, GaAsSb, AlAsSb and AlGaAsSb were established and delivered to AIXTRON for further use in equipment design.
With these data various laser structures were grown according to designs performed at UM2. The „W“ structure with type-II band alignments proved to be the most promising one with respect to the reduction of Auger recombination and room temperature operation, while MQW structures showed less promising results both theoretically and experimentally. One „W“structure finally selected consisted of the InAsPSb/InAsSb/InAsP/InAsSb/InAsPSb „W“ repeated up to five times and InAsPSb/InPSb guiding and cladding layers. A severe problem was the phase separation of the InPSb at defects in the substrate. Due to the low growth temperatures and the wide miscibility gap of InPSb this materials is very sensitive to decomposition especially at defects. Through the use of strained superlattices as buffers the defect densities could be reduced to values of about 2/mm² on substrates which contained around 8 defects per mm². These heterostructures were processed into LED and laser devices. The LEDs successfully showed room temperature operation in the wavelength regime 3-5 micrometers. As an example the CO_2 absorption at 4.2 micrometers was clearly detected. Broad area and ridge type laser made from the same heterostructures showed very sharp single mode laser lines with maximum operation temperatures of 135 K under pulse operation and with threshold currents as low as 120 A/cm². Such low values were not published at the beginning of the project and are still competitive with results obtained by other groups which also use the MOVPE growth technology.
Due to the relatively low band gap of InPSb it was not possible to extend the laser operation up to room temperature. For this goal the introduction of AlAsSb/AlGaAsSb cladding and guiding layers was necessary. Due to the problems mentioned earlier with the growth of the Al containing compounds Al-containing „W“-type lasers could not be realized before the end of the project. Very recent results on QW structures containing Al-free layers as active layers and Al-containing cladding and guiding

layers showed electroluminescence, thus indicating the validity of the designs chosen in this project.

3.4 University Montpellier II

UM2 was charged with the design of new antimony-based laser structures able to operate at room temperature in the mid-infrared spectral region (3-5 µm), the fabrication and primary characterisation of laser devices from wafers grown by metal organic vapour phase deposition (MOVPE) in Aachen and wafers grown by molecular beam epitaxy (MBE) at UM2.

1- laser structures : the design of laser structures and the simulation of laser diodes were made in collaboration with the *Faculté des Sciences d'Avignon (F).* Three quantum well laser structures based on InAs substrates employing antimonide compounds were proposed :

1- an aluminium-free laser structure with InAsP/InAsP/InAsPSb multi-quantum wells as light emitting region sandwiched between two confinement layers of $InP_{0.69}Sb_{0.31}$ material[1]

2- an aluminium-containing structure with InAsSb/InAs/InAlAsSb multi-quantum wells as light emitting region and two higher band gap lower refractive index $AlAs_{0.16}Sb_{0.84}$ material as confinement layers.

3- an optimised aluminium-containing structure having the same active region as design n°1, but employing $AlAs_{0.16}Sb_{0.84}$ material at the place of Al-free $InP_{0.69}Sb_{0.31}$ alloy (Fig.1).

contact layer	GaSb	p^+
cladding layer	$AlAs_{0.16}Sb_{0.84}$	p
waveguide layer	InAsPSb	
"W" type-II QWs	InAsSb/InAsP/InAsPSb	
waveguide layer	InAsPSb	
cladding layer	$AlAs_{0.16}Sb_{0.84}$	n
buffer layer	InAs	n
substrate	InAs (S)	n

Fig.1 ***: the optimised "W" laser structure based on n-type InAs substrate***

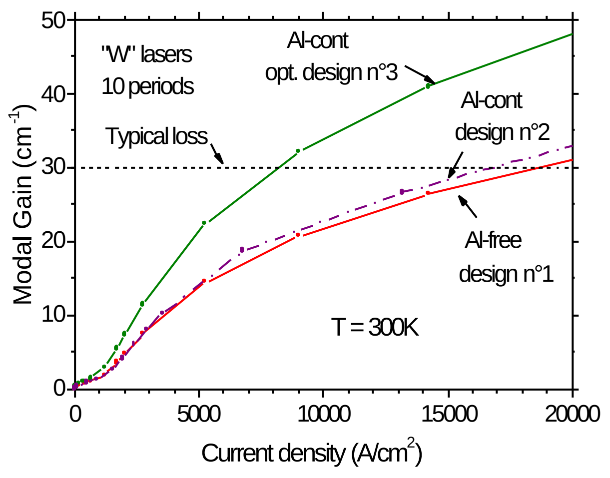

Fig.2 ***: modal gain G versus injected current density for the three different "W" laser diodes . Lasing occurs when G is superior to the total losses.***

The three designed structures have type-II indirect radiative transitions between the InAsSb wells and the InAs(P) barriers, and a conduction band with a "W" shape ensuring a strong overlap of the electron and hole wavefunctions as well as a two-dimensional state density of carriers. These "W" laser diodes theoretically operate at

[1] P. Christol et al., *IEE Proc.-Optoelectron*. 147 (2000) 181-187

room temperature near 3.5 µm with a threshold current density of typically 18 kA/cm^2 (design n°1), 16 kA/cm^2 (design n°2), and 8 kA/cm^2 (optimised design n°3).

2- MOVPE laser diodes : the laser structures grown by MOVPE in *RWTH Aachen* are Al-free and approach the design n°1. The grown structures exhibited elliptic defects (typically 5 x 15 µm^2) resulting from a two-phase local decomposition in the n-type InPSb confinement layer. Nevertheless multi-quantum wells in the active region could be grown with good structural quality (Fig.3). Laser emission was obtained at low temperatures (~100K) at wavelengths around 3.1µm and 3.3µm, depending the thickness of the InAsSb quantum wells (5 or 10 nm) (Fig.4). Best results were obtained from asymmetrical devices having n-InAsPSb and p-InPSb cladding layers, because for this kind of structure the elliptic defect density was lower (~ 4/mm^2). The diodes emitted at 3.3 µm with output power of 30 mW/facet/A and threshold current density of 120 A/cm^2. They could operate pulsed up to 130K, and in continuous wave regime (CW) up to 90K, with a characteristic temperature T_0 = 35K[2].

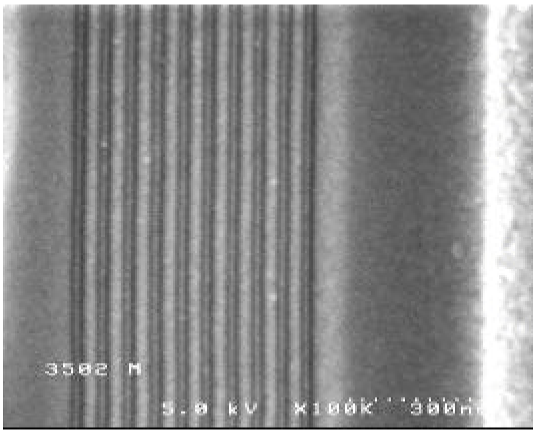

Fig.3 ***: SEM picture of the "W" InAsSb / InAsP / InAsSb / InAsPSb active region***

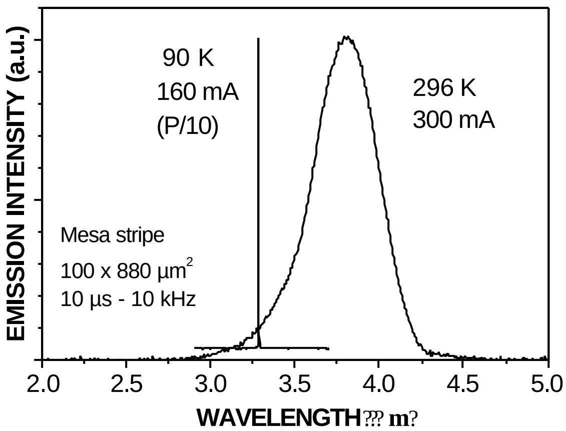

Fig.4 ***: Emission spectra at 90K and 296K of a "W" MOVPE aluminium-free laser diode***

3- MBE laser diodes : laser structures having the design n°2 were grown by MBE in *UM2*. Growth problems appeared for quaternary InAlAsSb inducing bulk defects, and it was difficult to obtain lattice-matched epilayers. Laser emission was obtained nevertheless in the wavelength range 2.9-3.1 µm up to 155K in pulsed regime, and CW at 80K with a good power efficiency of 62.5 mW/A/facet[3]. Simplified "W" structures using InAs at the place of InAlAsSb were grown with higher structural quality. They furnished laser diodes with excellent performances[4] : emitted wavelength ~ 3.5 µm, threshold current density of 150 A/cm^2, output power of 50 mW/A/facet, and characteristic temperature T_0 = 30-35 K. The MBE laser devices could operate in continuous wave regime up to 130K (Fig.5), and in pulsed regime up to 220K. This temperature is sufficiently high to be reached by Peltier cooling.

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[2] A. Joullié et al., *Appl. Phys. Lett.* 76 (2000) 2499-2501
[3] A. Wilk et al., *J. Crystal Growth*, (Proc. 11th Int. Conf. on MBE, Beijing, Sept. 2000
[4] A. Wilk et al., *Appl. Phys. Lett.* 77 (2000) 2298-2300

4- Mid-infrared LEDs : a lot of Al-free structures were grown by MOVPE with, in their active region, InAsSb/InAsPSb type-I multi-quantum wells (radiative transitions occur inside each InAsSb well). The devices did not lase, but they emitted a strong electroluminescence (EL) up to room temperature. At 300K the output power is of the µW order (20 µW for a current I = 50 mA), with a power efficiency of 0.04%. The EL emission peak is around 4 µm, allowing the CO_2 detection with a small injection current (30 mA), as shown in Fig.6.

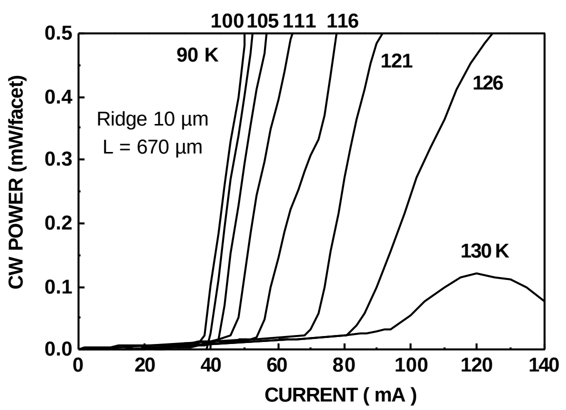

Fig.5 ***: CW output power vs current for a "W" MBE laser diode, at several temperatures***

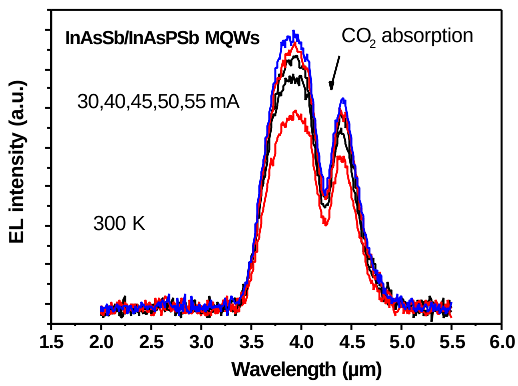

Fig.6 ***: Room temperature electroluminescence spectrum of $InAs_{0.91}Sb_{0.09}$ / $InAs_{0.56}P_{0.30}Sb_{0.14}$ MQW structure for different current injections, showing the CO_2 absorption at 4.25 µm.***

5- Conclusion : three sorts of devices have been processed by UM2 in the frame of the ADMIRAL project :

1- *MOVPE laser diodes*, aluminium-free, which could operate near 3.3 µm, pulsed up to 135K, and CW up to 90K.

2- *MBE laser diodes*, aluminium-containing, which could operate near 3.5 µm, pulsed up to 220K, and CW up to 130K.

3- *Light Emitting Devices*, grown by MOVPE, operating at room temperature near 4 µm with output power of the µW order, allowing the CO_2 detection.

A strong increase of the maximum temperature of operation of laser diodes is expected by improving the structural quality of the epitaxial wafers, and by growing laser structures having the proposed design n°3 which uses "W" InAsSb/InAsP/InAsPSb quantum wells in the active region and symmetrical $AlAs_{0.16}Sb_{0.84}$ confinement layers.

3.5 Institute of Physics of the Czech Academy of Sciences

IP AVCR´s main task was to provide a wide range of characterisation techniques, relevant to all the necessary stages of laser structure preparation and optimisation in order to support and in important areas to extend the range and precission of techniques currently available at the cooperating technological partners. Samples for evaluation were supplied by the technological partners and the resuts of required measurements were immediately supplied back to the sample provider together with critical evaluation of the result and its importance. The great advantage was in the fact that IP AVCR is also running its own technological research dealing with similar mid infrared semiconductor epitaxial structures and materials, so the understanding of the problems and cooperation was very smooth.

Main improvements:
In the course of the project we have extended the the spectral range of our characterisation techniques. All the optical measurement techniques are presently available at least up to 5.5?m including photoluminescence, which was the most often reqired type of measurement, electroluminescence, optical power, photoconductivity as well as absorption. measurements (some are available even up to 16?m). Aso the temperature range of most techniques had to be extended towards helium temperatures with 2K as the standard lower temperature limit.

Electrical measurements:
These temperatures are available not only for most optical techniques but also for trasport measurements, including I-V and C-V measurements Hall effect and conductivity measurements. These measurements were performed mainly on layers and structures intended for laser structure preparation but certain measurements were performed also on ready made devices. For mounting the laser diodes IP AVCR has supplied coaxial holders of the RCA type for high frequency use and convenient handling.
Some of the techniques made available were not required like the measurement under high hydrostatic pressure, DLTS measurements, differential I-V characteristic measurements and bevelled angle profiling.

Optical measurements:
Most requirements for optical measurements were for low temperature photo and electro luminescence measurements and the interpretation of the emission peaks and assigning them to specific optical transitions. Raman spectra measurements have brought some rough estimates about the type of InAs/GaSb interface and composition of extremely thin layers.

Structural measurements:
High resolution X-ray diffraction measurements were provided with a high power rotation anode X-ray source on a four crystal difractometer with an uptodate analytical software. The results obtained were compared with similar results obtained at both technological laboratories and after finding out that all partners have similar quality of their X-ray diffraction fascilities,

this type of evaluation has been mainly provided by On the other hand X-ray microanalytical techniques have shown to be very useful and important especially after reliable composition measurements were obtained even for very thin epitaxial layers with the limiting thickness being less than 400nm for the most frequent layer compositions InAsSbP and AlAsSb. For the later composition even the problem of GaSb capping layer had to be solved in order that reliable compositional data can be obtained also for layers with the necessary capping layer.

Other activities:

In the course of the work we have extended our activities also in the direction of epitaxial growth using our MOVPE AIXTRON 200 macine. We have mainly studied problems of growth of Sb based materials in order to understand better to the problems of our technological partner, using the same technology. We have also grown GaAsSb/InAsSb quantum well epitaxial structures lattice matched to InAs and emitting in the range of wavelengths round 3.2?m at 90K.

4. EXPLOITATION OF RESULTS AND OTHER FOLLOW - UP

As described in detail in the Technological Exploitation Plan (TIP) the exploitation potential of the ADMIRAL project is great despite the fact that the MOVPE grown structures did not qualify for room temperature operation of laser diodes. The industrial partners Epichem and AIXTRON both are launching new products and services stemming from the project , i.e. improved precursors and new MOVPE kits respectively. AIXTRON AG’s main target for exploitation of the achieved results is the marketing of its systems for the new family of semiconductors. Their application for lasers and detectors will be an important field for this new type of low bandgap semiconductor. In addition to the devices subject to this research project the new Sb material system will be marketable for the use in thermo-photovoltaic devices for the efficient conversion of IR radiation and heat into electrical power. For this use large areas of wafers will have to be deposited. Thus, as a follow-up action the adaptation of the processes and the system requirements to AIXTRON’s family of Planetary Reactors? will be paramount for future work at AIXTRON AG. This will include the up-scaling of the gas-purification methods as well as the adaptations of the reactor chamber for multiwafer reactors. Epichem’s main target is to ensure that the precursor production capacities required for the MOVPE reactors AIXTRON market can be met whilst retaining the ultra high precursor purities demanded.

The academic partners plan to pursue further research building on the progress achieved and in the case of UM2 several French companies in the gas detection business have expressed interest in the project results. The gas detection applications of MOVPE grown MIR lasers include a mass market for cheap detection systems for green house gas emissions in the earth’s atmosphere suggesting a European added value in terms of EU policy toward sustainable development and improved quality of life for the citizen.

5. EUROPEAN DIMENSION

5.1. Community added value and contribution to EU policies

5.1.1 European dimension of the problem

To date, important industrial research is being carried out in the USA on the fabrication of Sb-based mid-infrared lasers, because it is predicted that these lasers could operate at room temperature, which is a key aspect for the achievement of low-cost gas monitoring systems. Due to military considerations during the cold war, open research on Sb-containing materials was restricted in Europe. Thus the US gained a considerable lead. The ADMIRAL project therefore directly addresses a vital scientific technological development which will strengthen European competence. Since Sb-containing materials are of key importance for civil applications such as environmental and medical fields, it is critical that Europe retains competitiveness in this area. This holds true not only for the key components such as lasers, but also for the systems which depend on the availability of such components. The successful completion of the ADMIRAL project will provide the starting materials, equipment, process technology, and devices necessary for the realisation of this goal.

In light of these strategic considerations, the ADMIRAL project is contributing to solve problems at a European level foremost by attempting a scientific breakthrough in mid-infrared laser technology that would find application in the monitoring of greenhouse gas emissions by portable, low cost gas monitoring systems with high sensitivity, high selectivity and high speed. The ongoing build up of greenhouse gases in the atmosphere responsible for global warming is a growing concern of European policy and will be a leading issue of public and political attention around the world in the 21st century. The rapid climatic changes that are predicted to occur within the next hundred years due to global warming will adversely affect hydrological patterns, sea- level, incidence of catastrophic weather events, and human health world wide without regard to national borders. In order to deal with these difficult issues in respect to safeguarding ecological sustainability, policy makers need the help of the best possible scientific data, forecasts and control systems. It is the vision of the ADMIRAL consortium that in the future up-to-date emission data of all types of greenhouse gases will be collected through gas detection devices ubiquitously installed, covering all regions throughout Europe. Another example of the use of such gas detection devices utilising Sb-based mid infrared lasers would be the in-situ monitoring of exhaust gas from automobile combustion engines to provide input for the control of the fuel burning process in order to minimise pollution. In the future all automobiles may be equipped with such a control system which would be a responsible measure toward reducing the $C0_2$ pollution caused by automobiles.

5.1.2 Contribution to S&T co-operation at international level

From the perspective of subsidiarity, the research and development agenda of the project ADMIRAL can only be pursued with an international consortium, as the required high level of expertise is today not available in any one country. The project is very demanding from the point of highly sophisticated MOVPE layer and structure growth, MOVPE equipment optimisation, special high purity new precursor availability, deep physical understanding and detailed diagnostic techniques, and laser device construction and fabrication. The consortium combines some of the best available European institutions for this joint project. For example, UM2 (F) is the top European specialist for III-V mid infrared lasers, and RWTH Achen (DE) is the top European specialist for MOVPE OF Sb-containing materials. IP-AVCR (CZ), as a leading academic institution working in the field of mid-IR lasers for more than a decade, has unique diagnostic and interpretation expertise. Moreover, the industrial partners, Epichem (UK) and AIXTRON (DE) are world leaders in their respective fields of precursor and MOVPE equipment manufacturing. Clearly it is impossible to combine such a high caliber, multidisciplinary consortium with a strong link to manufacturing techniques in one national effort in one country. Thereby, new European transnational cooperative S&T relationships are built in an important and strategic technological field and crucial skills and resources are pooled to achieve the desired results.

5.1.3 Contribution to policy design or implementations

One of the most difficult challenges facing European societies at the beginning of the 21st century is the question of how to respond to the threat of global atmospheric warming due to the build-up of green house gases (GHGs) caused by pollution through human activities. Many GHGs occur naturally but human activities are adding gases to the natural mix at an unprecedented rate; the most important ones being carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_20), hydroflourocarbons (HFCs), perflourocarbons (PFCs), chloroflourocarbons (CFCs)and sulfur hexaflouride (SF_6). It is scientifically documented that the earth's climate is warming at a faster rate than ever before recorded. In the last 100 years the atmosphere has warmed up by about half a degree Celsius. If the earth continues to warm as climate models have predicted, the temperature of the earth surface may be 2 – 3 °C warmer by 2100 than it is today. This rapid change in temperature would be harmful to many ecosystem, and many species of plants and animals. Climate change will affect rainfall patterns, sea level, probability of catastrophic weather events, such as draughts, floods, and storms, and last but not least affect human health and quality of life.

In the past, EU member states were going their own national ways in making (or abstaining from) relevant legislation. European action had largely indirect effects, e.g. R&E funding support for environmentally friendly and energy efficient technologies (JOULE /THERMIE), promotion of renewable energy sources (ALTENER I) and energy efficiency (SAVE I & II). Some energy efficiency related directives introducing European labels and standards were implemented but really effective instruments such as a European wide energy/ CO2 tax was not realised (pertinent Commission proposal so far ignored by the council). June 1993 a monitoring mechanism for GHG emissions by the member states was introduced. Also, some voluntary agreements to limit GHG emissions with industry were concluded (e.g. car industry). In 1992 at the UN Conference on Environment and Development in Rio, Europe signed (and later ratified) the United Nations Framework Convention on Climate Change (UNFCCC). Under this convention the European Union has committed itself to return GHG emissions, not controlled by the Montreal protocol, to 1990 levels by 2000. Five years later, in 1997 at the Third Conference of Parties (COP3) Europe signed the

Kyoto protocol and committed itself to reducing its emissions of the six main GHGs by 8% during the period 2008 – 2012 in comparison with their levels in 1990. In June 1998 a system of burden sharing between the member states was agreed upon regarding the Kyoto targets. Further, in April 1999 the GHG emission monitoring system was amended by the Council.

Right now European policy regarding GHGs is at crossroads. Under the responsibility of the new Commissioner for Environment Ms. Margot Wallström preparations are under way for the 6th Environmental Action Programme to be launched in autumn this year based on a critical evaluation of the preceding programme. As stated by Ms. Margot Wallström on many occasions progress in the area of climate change will be high priority during her term in office[5]. Hence, giving new impetus to this effort on this issue the European Commission established in March 2000 the European Climate Change Programme (ECCP) starting a multi-stakeholder consultative process (including member states, experts, industry, and green NGOs) and setting up a number of working groups to develop policy proposals. Concurrently a Green Paper has been issued on a EU-wide emissions trading scheme in preparation for the flexible mechanisms foreseen by the Kyoto protocol[6]. A reinforcement of policy actions was announced in order to set Europe back on track for meeting her international commitments- in particular the targets of the Kyoto protocol[7].

Unfortunately, statistics point out that not enough progress has been made toward these targets. May 29 this year the EEA broke the news that total European GHG emissions have fallen 2% from 1990 to 1998[8]. However, this slight decrease was mainly due to positive trends in Germany (economic restructuring of the former East Germany) and UK (fuel switching from coal to natural gas) while in most of other member states the reverse applies. Thus, the European Commission is aware that without a reinforcement of current policy measures, the "business as usual scenario" is likely to end up more in the range of a increase between 6 and 8%, instead of a reduction of 8% compared to 1990 levels. The same failure is predicted by baseline emissions projections for an enlarged EU (EU25) which take into account the GHG emissions reduction potential of the 10 Central and Eastern European entry candidates. A failure of Europe to improve her performance would amount to an embarrassment In the international diplomatic arena where the EU has taken on a leadership role in searching for a political compromise on the terms of the Kyoto protocol as to expedite the ratification process. Whereas in the USA the Clinton administration has been in an extended political deadlock with the republican majority legislature on the issue, the EU is currently preparing for ratification of the Kyoto protocol, which it wishes to see enter into force and to become binding international law by 2002 (in time for the RIO+10 conference).

In this context, the ADMIRAL project is potentially contributing to the design and implementation of European environmental action toward the reduction of green house gases. The ADMIRAL consortium is attempting a scientific breakthrough in mid-infrared laser fabrication technology that would find application in the monitoring of greenhouse gas emissions by way of portable, low cost gas monitoring systems

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[5] Speech by European Commissioner for Environment Ms. Margot Wallström „The Future of European Environmental Policy: the Way Towards Sustainable Development, Berlin, 10 February 2000

[6] COM(2000)87 Green Paper on Greenhouse Gas Emissions Trading Within the European Union, 08 March, 2000

[7] COM (2000)88 Communication from the Commission to the Council and European Parliament „EU Policies and Measures to Reduce Greenhouse Gas Emissions: Towards a European Climate Change Programme", 08 March 2000

[8] European Environment Agency, „European Community Greenhouse Gas Inventory 1990 – 1998", May 2000

with high sensitivity, high selectivity and high speed. In order to deal with these difficult issues in respect to safeguarding ecological sustainability, policy makers need the help of the best possible scientific data, forecasts and control systems. It is the vision of the ADMIRAL consortium that in the future up-to-date emission data of all types of greenhouse gases will be collected through gas detection devices ubiquitously installed, covering all regions throughout Europe. Another example of the use of such gas detection devices utilising Sb-based mid infrared lasers would be the in-situ monitoring of exhaust gas from automobile combustion engines to provide input for the control of the fuel burning process in order to minimise pollution. In the future all automobiles may be equipped with such a control system which would be a responsible measure toward reducing the $C0_2$ pollution caused by automobiles

5.2. Contribution to Community social objectives

5.2.1 Improving the quality of life in the Community

ADMIRAL project has made important scientific contributions towards the fabrication by MOVPE technology of RT MIR lasers having application in green house gas monitoring and control systems. Insofar as these system may in the future be an essential tool to inform European public and private decision makers in their effort to reduce green house gas emissions world-wide, the quality of life of the EU citizens may be directly affected. The political objective must be to avert the danger of rapid global warming and climate change in the next century which can have severe health implications especially for the elderly and the young by causing respiratory distress (heat causes high levels of ground level ozone) and cardiac failures as well as increased incidence of infectious diseases.

Moreover, the MIR laser developed through ADMIRAL has several applications in the medical field, which potentially improves the quality of life in the community. The use of MIR lasers in medicine will enable/improve non invasive diagnostics and therapy, thereby reducing stress to patients, as well as lowering the cost of treatment. Moreover the availability of a portable mid-infrared laser operating at room temperature will improve the safety of roads. Such portable systems can be used for detecting of CO_2 in the blood of truck and bus drivers, which would greatly increase safety on the road by providing measures for reducing the numbers of dangerously tired drivers.

5.2.2 Provision of incentives for monitoring and creating jobs

As is evident from the point of the anticipated high demand applications in environmental gas monitoring and medical diagnostics, the availability for the first time of AMIRAL MIR diode lasers operating at room temperature fabricated with the MOVPE technology implies an enormous exploitation/business potential with considerable direct and indirect job creation effects. At present MIR lasers operate only at cryogenic temperatures limiting applications and market potential. The presently available MIR lasers, made of lead salt, cost $ 2000 a piece, a price too high for consumer applications. Therefore, the market for MIR laser can at present be considered only a niche market with a world wide volume of only approximately $ 0.3 million in 1997. The anticipated scientific breakthrough of ADMIRAL to achieve Sb-based room temperature MIR laser diodes will allow exploitation of a projected market by 2001 of $ 1.5 billion for systems using efficient and compact infrared lasers. If the project is successful, the industrial partners Epichem and AIXTRON, as well as system manufacturers and sellers, will need to hire more workers to keep up with the anticipated demand.

5.2.3 Supporting sustainable development

The concept of sustainable development refers to a form of economic growth which satisfies society's needs in terms of well-being in the short, medium, and –above all-long terms. It is founded on the assumption that development must meet today's needs without jeopardising the prospects of future generations. In practical terms, it means creating conditions for long term economic development with due respect for the environment. The treaty of Amsterdam, 1997, wrote an explicit reference to sustainable development into the recitals of the EU treaty. The 5th community action programme on the environment "Towards Sustainability" established the principles of a European strategy of voluntary action for the period 1992-2000 and marked the beginning of a horizontal community approach, which would take into account all causes of pollution.

The ADMIRAL project brought to a successful conclusion clearly has European added value in the field of environmental policy toward sustainable growth by making tangible contributions in the design and implementation of policy measures that would drastically reduce the amount of greenhouse gases released into the atmosphere. Due to the increasing awareness of the environmental and health risks from greenhouse gases and the corresponding increase in the stringency of EU environmental regulations, the demand for simple, cheap, and lightweight systems of atmospheric gas monitoring in the mid-infrared region is rising.
Monitoring systems for the mid-infrared region employing Sb-containing lasers developed in ADMIRAL could easily be combined with other omnipresent devices (e.g. traffic lights) to provide a dense network for a comprehensive region. With such systems, greenhouse gas emissions can be controlled and reduced.
Such devices can also be used for the monitoring of the exhaust gas from combustion engines to provide input for the control of the fuel burning process in order to minimise air pollution.
In the sphere of precursor synthesis, Epichem will develop handling technologies for raw materials, products, and waste residues throughout the project, leading to reduction in emissions of toxic vapours to the atmosphere during precursor production.