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Title: Novel Gain Materials and Devices Based on III-V-N Compounds

A. ABSTRACT AND KEYWORDS

The proposed COST Action will focus on setting up a network of European researchers active in the field of the novel semiconductor III-N-V gain materials also known as dilute nitrides and indium-rich GaInN. Dilute nitrides, including GaInNAs, GaNP, and GaInNAs-P have emerged from conventional III-V semiconductors by the insertion of nitrogen into the group V sub-lattice, and indium-rich GaInN by the insertion of indium into GaN. These processes have a profound effect on the electronic properties of host materials and allow a wide range of options for band structure engineering, which is expected to lead to novel devices for displays, data storage, transmission, solar cells, photodynamic therapy, surgery, terahertz devices and gas sensors operating in a wavelength range, extending from 0.3 to 3.0 micrometer. The Action covers material growth and characterisation, theory, device modelling and fabrication, as well as device performance and characterisation.

Keywords: Dilute nitrides, GaNAs, GaInNAs, GaInNAs-P, Indium-rich GaInN

B. BACKGROUND

B.1 General background

III-V Semiconductors are indispensable for today’s optoelectronic devices such as semiconductor lasers used in optical communication systems. Likewise, this class of material is dominant in key high frequency electronics components for wireless communication systems.

The miscibility of binary III-Vs and the possibility of stacking such layers of various compositions and doping levels (heterostructures) are crucial for all these applications.

The tailoring of heterostructure properties is limited by the different lattice constants of the binary III-Vs, which limit the range of useful compositions and thereby the range of available band gaps. Thus, on the two most commonly used substrate materials, GaAs and InP, the band edges can be tailored to allow only a limited range of useful wavelengths of a maximum of 1200 nm for GaAs-based and about 2100 nm for InP-based materials. Moreover, the alignment of the band edges, which is very important for the performance of devices, cannot be tailored by the combination of conventional materials at all. These limitations encountered in InP and GaAs based devices can be greatly reduced by incorporating a few percent of nitrogen as a group V element into GaAs or InGaAs, i.e. by creating the so-called "Dilute Nitrides".

The second class of III-V-Nitrides is based on the In1-xGaxN compound. It was recently discovered that InN has a much smaller fundamental energy gap than was believed hitherto. As a consequence the range of wavelengths that can be accessed by alloying this material with Gallium Nitride (GaN) has been significantly extended. Indeed GaInN has the widest range of direct gap of any compound semiconductors ranging from 0.7 eV to 3.2 eV which can be utilised in optoelectronic device applications over a wide range of wavelengths, including numerous key wavelengths for applications in the medical, environmental and communications fields.

Within Europe many research groups are already active in dilute nitrides and scientific excellence has been amply demonstrated. However, with the exception of a few, each group tends to focus on specialist topics within the areas of growth, characterisation, devices and theory and modelling. Over the last few years, informal collaborations have evolved organically, primarily based on supply of materials and devices, and availability of specialist measurement techniques. The current COST Action will enable a more coordinated and focused approach to networking and capacity building activities. As for the indium rich GaInN, it was evident at the recent EMRS-2007 meeting in Strasbourg that only a few fragmented projects have recently begun in Europe. It is the problems of fragmentation and lack of coordination in tackling major research issues or application domains within the existing structure that motivates the proposed COST Action.

B.2 Current state of knowledge

Indium rich GaInN During the last decade there has been intense research activity in indium rich GaInN. The reason for this remarkable interest is primarily due to the potential applications in optoelectronic devices. Until a few years ago, the commonly accepted value for the InN band gap energy was 1.89 eV. The majority of the investigations that reported band gap energies in this range were carried out on samples grown by sputtering technique and were characterised as having a polycrystalline structure. The drastic improvement in the growth techniques, especially in molecular beam epitaxy (MBE) and metalorganic vapour phase epitaxy (MOVPE), has recently led to the availability of very high quality material. Since then a large number of papers from different research groups have been published reporting a value for the band gap between 0.7 and 0.9 eV. As a consequence of the improvement in material quality, the range of optical wavelengths that can be accessed by alloying InN with GaN has been significantly extended. The resultant In1-xGaxN material has the widest range of direct gap of any compound semiconductors extending from 0.7 eV (x =1) to 3.2 eV (x = 0), which can be utilised in various optoelectronic devices over a wavelength range from infrared to ultraviolet, including very many key wavelengths for applications in the data storage, medical (Photo Dynamic Therapy and Surgery), environmental (Solar Cells, Sensors of Obnoxious Gases), security (Terahertz Emitters and Detectors) and communications (Optical Amplifiers, Lasers and Detectors) fields. From a devices point of view, a key commercial target for the In-rich material is high-efficiency low-cost solar cells. In1-xGaxN with $0<x<0.65$ should produce direct band-gaps between 0.7 and 1.9 eV to match the most useful part of the solar spectrum. Efficiencies close to the theoretical limit of 70% could be achieved by use of the whole In1-xGaxN composition range in graded layer cells and/or with quantum well (QW) multilayers; improved radiation hardness over conventional cells for space applications is an additional advantage. A recent press release by Lawrence Berkeley National Laboratory says of In1-xGaxN: "…..It is as if nature designed this material on purpose to match the solar spectrum….. The cost (of solar cells) will be the same order of magnitude as traffic lights. …They will be so efficient and so cheap that it could revolutionise the use of solar power". Furthermore, since the toxicity of materials used in existing solar cells may become a serious concern for large scale deployment and disposal/recycling of these devices, In1-xGaxN also offers the benefit of a safer alternative. While III-Nitrides based solar cells offer the potential of very high conversion efficiencies, there are a number of problems than need to be addressed in order to achieve this goal. The major obstacle is the need for high p-type doping of In1-xGaxN alloys. Up to now direct observation of p-type doping in InN was not achieved, due to electron surface accumulation phenomena as confirmed by High Resolution Energy Loss Spectroscopy (HREELS). However, C-V and Hot Probe Hall measurements reveal that efficient p-type doping may be achieved in the bulk layer. Recognising the potential of In1-xGaxN, significant research programmes have already commenced in the USA and Japan. Although there has been some fragmented work (for example Delight and Rainbow), no comparable European project has yet begun to meet the challenges of this new technology. The realisation of a COST Action will stimulate larger R&D investment programmes with a wide range of applications. There are potentially huge technological and economic benefits if a single material platform can be used for device fabrication and integration over a wide range of operating wavelengths. Dilute nitrides The low loss window of optical fibre has recently been extended to cover 1.3 to 1.7 mm, significantly increasing the potential capacity of optical networks. As a result, optoelectronic devices (such as lasers, detectors, filters and optical amplifiers) operating in this wavelength range dominate photonics research. Many of these devices are enhanced using distributed Bragg reflectors (DBRs) to control the optical field. Typical examples include vertical cavity surface emitting lasers (VCSELs), resonant cavity enhanced (RCE) photodetectors (PDs), RCE- light emitting diodes (LEDs) and vertical cavity semiconductor optical amplifiers (VCSOAs). The device requirements are not met by conventional GaAs or InP based materials, such as InGaAs/GaAs or InGaAsP/InP. Most GaAs-based material systems only allow device operation up to ~1.2 µm, while InP-based systems suffer from poor thermal stability (lowering efficiency) and low refractive index contrast (hindering DBR fabrication). This low index contrast means that many layers are required to achieve high reflectivity InP-based DBRs. Growing thick, uniform stacks without defects is very difficult and introduces the additional problem of high series resistance, which slows device dynamics. These problems can be avoided by fusing AlGaAs/AlAs DBRs to the active layers; however, this complicates fabrication, increasing cost and may result in unreliable devices. Dilute nitrides avoid many of the problems associated with conventional arsenides and phosphides. Incorporating a small percentage of nitrogen into (In)GaAs has a profound effect on its electronic properties. In most III-V materials, substituting an element for one with a smaller atomic radius reduces the lattice constant and increases the bandgap. However, replacing a fraction of arsenic atoms in GaAs with smaller N atoms rapidly reduces the bandgap. In addition to giving access to smaller bandgaps, nitrogen allows band alignment, lattice constant and strain to be tailored, opening up a new dimension of band engineering The quaternary alloy GaInNAs is attractive for a range of devices, offering advantages over conventional narrow gap materials. GaInNAs quantum wells (QWs) can be grown pseudomorphically on GaAs, giving strong carrier confinement (hence thermal stability) and compatibility with GaAs technology, including AlGaAs/AlAs DBRs. A wide range of novel devices could benefit from dilute nitrides. Devices that have already been demonstrated include VCSELs, VCSOAs, RCE-PDs, RCE-LEDs, multi-junction solar cells, modulators and heterojuction bipolar transistors (HBTs). Commercially, the most important devices are for inexpensive optical fibre data transmission at 1300 nm for metro-area links over 10 to 20 km. These links are presently considered to be the bottleneck for large-scale optical communications and constitute a very large share of the market. Rapid progress has already led to the demonstration of high quality 1300 nm dilute nitride laser diodes on GaAs and even 1300 nm VCSELs. Emission from dilute nitride devices has even been pushed above 1500 nm, potentially useful for long haul links. GaNAs/GaInNAs/GaAs tandem solar cells have the potential of harvesting the sun's energy with efficiencies up to 35% and there is much research activity in this area. One major difficulty with dilute nitride growth is maintaining good optical quality as nitrogen is incorporated. This has provoked extensive work to establish the factors affecting optical quality, such as composition, growth and annealing conditions. Techniques, such as photoluminescence (PL), surface photovoltage spectroscopy (SPS), deep level transient spectroscopy, spectral photoconductivity, and scanning transmission electron microscopy (STEM) etc. are commonly used to investigate the presence of structural and compositional fluctuations, impurities and defects. Dilute nitride technology is maturing rapidly and is an excellent candidate to become the driving force for high-frequency electronic devices with an enormous potential for applications in many areas. The Action will seek to assess the fundamental advantages offered by dilute nitrides over rival semiconductors and to quantify the advantages and limitations imposed by the unique band structure and scattering mechanisms that exist in these material systems

B.3 Reasons for the Action

Within Europe many research groups are active in dilute nitrides, and scientific excellence has been amply demonstrated so that European leadership in the topic is within reach. However, with the exception of a few of the biggest players, each group tends to focus on specialist topics within the areas of growth, characterisation, devices and theory/modelling. Over the last few years, informal collaborations have evolved organically, primarily based on supply of materials and devices, and availability of specialist measurement techniques and equipment. Within Europe these research groups, mostly members of this Action, are fairly successful in attracting funding from national agencies, but there is as yet little formal collaboration between the groups. It is the problems of fragmentation and lack of resources for tackling major research issues or application domains within the existing structure that motivate this Action. The Action will aim to build collaborative activities and unleash the full European potential in dilute nitrides by exploiting the synergy in the national research activities. Without this collaboration European research in the subject will fall behind that in the USA and Japan where massive coordinated R&D programmes are being deployed.

At this point, a coordinated Networking and Capacity Building activity on the European level in the form of a COST Action is highly desirable for the following reasons:

(i) The sheer number of publications is presently increasing at a rate almost too fast to follow – of course in an uncoordinated way;

(ii) At the same time controversial issues on material properties, theoretical understanding of the band structure and electronic properties, etc. abound;

(iii) The Action could bring researchers from leading research groups together more effectively than any conference can and can do so repeatedly at time intervals determined by the progress of work rather than at given conference rhythms and locations;

(iv) Within the proposed Action the most relevant and urgent questions for research can be identified through discussions; consequently coordinated key actions can be outlined;

(v) Theoretical and experimental work can be coordinated effectively.

(vi) Rapid transfer of basic research to device design, modelling and device fabrication will be possible.

The Action will facilitate efficient sharing and development of expertise and effort that have otherwise been rather fragmented.

B.4 Complementarity with other research programmes

There are several European research projects which are directly related to the current proposal, for example **Rainbow** and **Deligh**t. The members of these are also members of the proposed COST Action. Therefore, it will be possible to have organic links with these projects and organise joint workshops and seminars. The Action will also establish links with any future COST Actions and STREP projects **(Mosel, Nemis, Vertigo and Village)** in areas which may be relevant to its activities for example Medical and Communications Lasers, Terahertz devices, Solar Cells, Sensors etc. The possibility of establishing links and joint activities with directly related European projects and relevant COST Actions will be on the agenda of the very first Management Committee (MC) meeting.

C. OBJECTIVES AND BENEFITS

C.1 Main/primary objectives

The main objective of the Action is to advance novel gain materials based on III-V-N semiconductor compounds including dilute nitrides and indium rich GaInN.

C.2 Secondary objectives

The Action will provide resources for a pan-European effort, so that small laboratories lacking facilities will be able to collaborate with other groups to design, model, realise and characterise novel prototype devices that can be tested in an application context. This Action will therefore also serve to spread the technology know-how in the field to all participating areas in Europe.

The COST Action will bring together experts covering the full technology spectrum of semiconductor technologies and promote an open collaboration between groups already in the field, as well as groups getting into the field. This will lead to faster identification of and solution to problems and possibilities, thus increasing the competitiveness of European electronics and optoelectronics industries.

The expected deliverables of measurable objectives are:

(i) Increased number of European scientific workshops and conferences led by Euro Zone scientists in the field;

(ii) Increase in the collaborative work between the partners of the Action as a result of promotion of short term research visits to initiate the integration of disciplines;

(iii) Increase in dissemination of information and documentation of scientific data and material;

(iv) Increased sharing of materials and devices to promote joint research;

(v) Increase in the number of joint publications within the Action;

(vi) Decrease in the overlap of research in the Euro-zone.

The Action will seek to assess the fundamental advantages offered by these novel gain materials over rival semiconductors. It will also explore the potential offered by the unique band structure and scattering mechanisms that exist in these materials and advance ultra-fast device and systems applications in communications, environmental medical and biological technologies.

The expected deliverables of measurable scientific objectives are:

(i) Growth and characterisation with MBE and metalorganic chemic vapour deposition (m) of dilute nitrides with suppressed recombination centres and optimum conditions for high optical and electrical quality, and of InxGa1-xN layers with minimum defect densities allowing longer diffusion lengths and reduced intrinsic electron densities (n<1.0 x 1019 cm-3);

(ii) Growth and fabrication of III-Nitride Nano-wire structures, fabrication and characterisation of advanced heterostructure designs, modelling and fabrication of basic prototypes. Theory and experimental characterisation to understand growth, band structure, transport and optical properties;

(iii) Demonstration of broad-band optoelectronic devices based on dilute nitrides operating between 1.3 to 1.7

micrometer wavelengths for communications, medical and environmental applications including, tandem solar cells, cavity enhanced photodetectors, broad band vertical cavity surface emitting lasers with single mode operation, electrically pumped broad-band optical amplifiers, sensors, ring lasers high speed pulsed lasers;

(iv) Study of negative effective mass and of compact, low-cost photoconductive and electronic terahertz sources based on the unique band structure of Dilute Nitrides and Indium Rich GaInN and applications in biology and security. (These are of a high risk nature therefore demonstration of these as deliverable objectives is difficult to justify);

(v) Electrical and optical characterisation of the solar cell material to meet the required parameters and study of solar cells for high efficiencies above 50 % (These are of a high risk nature therefore demonstration of these as a deliverable objective is difficult to Justify);

(vi) Theory and advanced modelling of active and passive devices using the experimental data.

C.3 How will the objectives be achieved?

The proposed COST action will bring together more than 30 groups that have made key contributions both experimental and theoretical to the field. These groups will serve as an initial backbone to Action, and by sharing sample material, sample devices and know-how they will ensure a high level of scientific quality from the very beginning.

The specific instruments to achieve the objectives of the Action will include the organisation of scientific research in the form of four closely interacting Working Groups (WGs), and networking and capacity building activities such as short term scientific missions, workshop meetings, training events etc as described in the “Organisation” section.

C.4 Benefits of the Action

The Benefits of the Action can be summarised under four groupings:

Benefits for early career researchers:

The Action will ensure that the early career researchers of both gender are adequately trained in these technologically important materials and that Europe has a strong science base and trained scientists to meet the current and future challenges and competition in the field.

Benefits for the networking partners:

The complexity, novelty and challenges of research in the field require the versatile experimental, theoretical and technological expertise of the partners. At present there is no single national or local group in Europe that is capable of carrying out an extensive project in this field by itself. The material growth technologies, material/device characterisation techniques and the corresponding experimental equipment required for the project are very expensive and it is practically impossible to have all the necessary facilities within a single research group. The Action will enable the maximum level of integration, and spread the excellence in the field across the European research community

Scientific benefits:

The Action focuses on a scientific area that is of high strategic importance for the development of European technological capability. In the short/medium term the development of optoelectronic devices in the 1.3 – 1.65 micro meter window is important for data communications. Looking further ahead there are far-reaching and potentially extremely important applications in many other fields, for example high efficiency tandem solar cells, THz devices for sensing and medicine, optoelectronic integrated circuits (OEICs) for signal processing and defence, and the development of III-V-N materials grown on silicon with the promise of further electronic/photonic integration. From the scientific point of view, new knowledge on this previously unexplored class of highly mismatched semiconductors is also of great value.

Long term benefits to quality of life and environment

The project will contribute to development of novel technologies which are indispensable for improvements in quality of life and the environment. The expected impacts on the photonic components and subsystems are extremely valuable for communications applications. Other key products such as broadband tunable photodetectors can have electro-chemical sensor applications, and high efficiency solar cells are much needed for renewable energy solutions. Finally, apart from technological and economic aspects, the large scale deployment of III-N technologies for example in solar cells will embody the most environmentally friendly class of materials amongst its rivals, since these are arsenic and phosphorus-free compounds.

C.5 Target groups/end users

Early career researchers and graduate students will be the first target group. The Action will enable the members of this target group to further their research careers and employment opportunities in generic and novel semiconductor technologies.

The project will have a significant impact on individual partners, all of which have a strong interest and or have invested significantly in relevant technologies. The academic sector will enhance its research profile and will find new routes for research activities. The industrial partners in the Action will see the technology transfer from the research laboratory to production line.

Another important target group will be the general public. The Action will target the general public by providing access to its dedicated web site where its activities will be displayed and the long term implications and consequences of its research in medical, security and environmental issues will be addressed.

D. SCIENTIFIC PROGRAMME

D.1 Scientific focus

The Action will carry out the following tasks to achieve the objectives described in section C.

Task 1 Growth of dilute nitrides for optimised devices

The action will investigate the growth and characterisation of Dilute Nitrides to push the long wavelength limit as far as possible, and reach an understanding of the intrinsic limitations for the attainable wavelengths in structures within a given design for optimum material quality.

Task 2 Development of indium rich InxGa 1-xN alloys

Previous growth studies of ‘indium-rich’ InGaN alloys have been rather limited compared with InxGa 1-xN

(0.34 d x) alloys which have been developed for visible and UV based light emitting devices. The materials studied have also tended to be limited to growth on sapphire substrates. The aim of this task is to develop MBE growth processes for high quality InxGa 1-xN (x > 0.5) epilayers on both sapphire (0001) and Si (111) substrates and to manipulate their structural, electrical and optical properties within the lifetime of the project. Ultimately this development would enable the growth of Inx Ga1-x N alloys with composition 0<x<1.0 to cover the whole spectrum between 0.3 and 1.7 µm.

Task 3 Understanding band structure, optical and electronic properties of III-N-V compounds

The Action will establish an understanding of the optical quality, non-radiative recombination mechanisms, free carrier refractive index modulation, optical gain, excitonic recombination and exciton trapping, microscopic potential fluctuations, electronic transport parameters and band structure. Optical and electrical parameters determined experimentally will be used in the theoretical studies and advanced modelling of LEDs, lasers, semiconductor optical amplifiers (SOAs), sensors, photodetectors and solar cell structures for gain, efficiency, temperature and spectral dependence and radiation hardness.

Task 4 Growth characterisation and demonstration of novel devices

This task will aim to encompass the full device potential of dilute nitrides (III-N-As, III-N-P and III-N-Sb) and indium rich GaInN semiconductors operating between wavelengths 0.3 µm to 3 µm.

Provisions for the inclusion of new participants and unforeseen activities:

The Tasks listed above are flexible and liable to alterations should new participants and unforeseen activities become available during the implementation.

In order to achieve its objectives the Action will not only set key research areas and establish collaboration between the research groups of the consortium to coordinate research, but it will persistently seek new academic partners and industrial groups to join the consortium. For this reason the Action will actively encourage the entry of new groups through the networking and capacity building, and dissemination activities. The Action will ensure that the “new participants and unforeseen activities” issue is an agenda item in each of the MC meetings.

Human and Technological Resources:

The research groups participating in the Action have well developed national programmes in the key areas of the proposed Action. Therefore, the following core skills and technologies are available from the start to carry out the Tasks listed above.

1. MBE and MOCVD growth with in-situ monitoring of optical reflectivity and reflection anisotropy spectroscopic ellipsometry facilities

2. Structural characterisation facilities and techniques including X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), atomic force microscopy (AFM), Energy dispersive X-ray spectroscopy (EDX), Energy dispersive X-ray spectroscopy (EELS) and STEM;

3. Optical spectroscopy and electrical characterisation using techniques including absorption, transmission, continuous wave (CW) and transient photoluminescence, photoconductivity, modulated reflectivity, photo induced transient spectroscopy, deep level transient spectroscopy, Hall effect, Photo Hall effect, Superconducting magnets, High speed pulse generators

4. Core skills in theoretical work concerning the many body effects, modelling of devices, scattering mechanisms, electron-phonon effects, materials and gain modelling, small and large signal modulation,

dynamical laser modelling, band structure engineering, calculation of electronic structure and gain characteristics, carrier relaxation and optical properties;

5. Simulation of optoelectronic devices using advanced commercial simulation tools such as SYNOPSYS and CROSS-LIGHT packages;

6. Devices fabrication facilities including micro and nano fabrication wet and dry etching (ion beam and electron beam) facilities, micro-photoluminescence confocal microscopy;

7. Device characterisation and on-chip testing of devices, spectral gain measurements, Sun simulators, Alpha factor - line width measurements, high pressure studies, spectral characterisation of lasers, VCSELs, vertical external cavity surface emitting lasers (VECSELs), semiconductor saturable absorber mirrors (SESAMs), quantum well infra red photodetectors (QWIPs), RCE-PDs, SOAs, VCSOAs, Solar Cells etc.

D.2 Scientific work plan – methods and means

The proposed COST action will achieve its scientific objectives by four scientific themes identified in the WGs. These groups are responsible for carrying out the scientific tasks listed in section D1 as allocated to them.

WG1- Growth and materials development

This activity underpins the other WGs, but also requires inputs from them in order to maximise the impact. Only when all these inputs are in place can the full potential of optimised growth be achieved. The impact of these many collaborative activities will be an understanding of the physical limitations for growth. This will lead to realisation of the concept of “engineered” material for specific device requirements. WG1 will be responsible for Tasks 1 and 2 described in section D1.

The scientific work plan for WG1 activities will include:

1. The growth of materials lattice-matched to GaAs for investigation of thick and strain-free layers (InGaAsN, InGaAsNSb). These are required for many baseline studies such as band structure, electrical properties, or generally where thin layers such as quantum wells are insufficient;

2. The growth of thick layers with well defined, low strain, e.g. to quantify the effect of strain on material properties;

3. The Growth of QWs or other heterostructures of increasingly complex structures with well defined strain in the individual layers: InGaAsN/GaAs, InGaAsN/GaAsN/GaAs, with and without strain compensation by the GaAsN layers;

4. The growth of QWs and other heterostructures with strain-mediating interlayers: GaAsSbN / GaAs and In(Ga)As(N) QWs with InAs- (or more generally InGaAsN-) Quantum Dots embedded in them;

5. Growth of BGaAs, BInGaAs, etc. to study how far B can be used for compensation of compressive strain. If successful, the route given in the steps above will be followed;

6. Growth studies for InP-based (and possibly for others, such as InAs- or GaSb-based) materials will be carried out in an analogous fashion;

7. Control of intrinsic electron density In GaInN. The origin of electrons in InN is only partly understood but work on InN and In rich InGaN is showing progress with reduced electron density as AlN and GaN buffers are utilised. Some low temperature growth techniques have large electron density and have high native density of oxygen that is expected to be donor in InN. The correlation between large dislocation densities and residual strain are yet to be fully evaluated as a potential source of electrons in indium-rich InGaN with low background impurity density;

8. The influence of key parameters in MBE process to grow InN initially and then In-rich InGaN alloys on (0001) sapphire substrates will be investigated. These parameters will principally include the III: V ratio and substrate temperature. The influence of these parameters on polarity, defect structure and electron density will be investigated;

9. The deposition of the In-rich InGaN epilayers to silicon substrates as these could offer potential benefits to the integration of these materials with electronic, optical and optoelectronic devices;

10. The growth of the device structures will require both intentional p- and n-doping of the In-rich InGaN epilayers. To this end the Action will conduct a range of p-doping trails with magnesium over a range of InGaN compositions. The intentional n-doping of the In-rich InGaN epilayers will be investigated using silicon as a dopant. The effect of doping on growth habit will be investigated and the electrical properties of the doped epilayers will be assessed;

11. Growth of GaInN using MOCVD. This is the standard choice for high volume production. The Action will address issues of the MOCVD technology such as the type of precursors used for ensuring efficient nitrogen incorporation, the effects related to In surface segregation, phase separation and relaxation for growth layers with thicknesses in excess of 100 nm.

WG2- Materials and physical characterisation

The objectives here are to achieve a full understanding of the role of nitrogen incorporation on the electronic and optical properties of the dilute nitrides and the Indium incorporation of In-rich GaInN. The scientific work plan for WG2 activities are related to Tasks 1, 2 and 3 as described in section D1.

The scientific work plan for WG2 activities will include:

1. Study of the optical quality of GaInN using spectral techniques that can probe deep into the band gap and hence correlate growth conditions and composition with the mid-gap states, non-radiative centres, dislocations and microscopic potential fluctuations using techniques including absorption, transmission, CW and transient photoluminescence, photoconductivity, modulated reflectivity, photo induced transient spectroscopy, deep level transient spectroscopy;

2. Electrical characterisation of the samples will aim to determine the transport parameters including, carrier density, quantum and transport mobilities, effective mass, energy and momentum relaxation rates, scattering mechanisms etc. These will be correlated with growth and structural parameters;

3. Structural studies: The role of defects and compositional variations in both dilute nitride and GaInN material will be investigated with high resolution via STEM. The atomic structure, chemical composition profiles and interfacial quality will be studied using SEM, TEM and AFM, and these studies will be compared to the absorption spectra and photocurrent studies. EDX and EELS mapping will be performed to cross-sections of samples. The STEM will provide unrivalled capability for quantified mapping of heavier elements such as In, and Ga present at or above ~ 1% levels. This will be particularly useful in developing an understanding of the influence of these elements on the growth process and layer homogeneity.

WG3-Devices

The devices and integration activity is the one of key importance to the industry in the EU zone. Edge emitting and surface emitting lasers for applications in telecommunications and data communications are the main commercial product at present. However, in the future applications in high power high frequency field effect transistors (FETs) and terahertz devices, optical communications, thermo-voltaic cells, electro-chemical environmental sensors and medicine could follow. The work plan for WG3 activities are related to Tasks 3 and 4 in section D1.

The scientific work plan for WG3 activities will include:

1. Diode pumped and electrically driven format VCSELs, VECSELs and VCSOAs are closely related to each other, but operate in quite different regimes. VECSELs are generally air-spaced cavity structures, where the cavity length may be anything from ~100 mm (in which case tunability may be achieved by micro electromechanical system (MEMS)-mounting of the external mirror) to tens of cm. These devices are most readily embodied in GaInNAs, for operation in the 1.2 - 1.6 mm range. This covers data and telecom applications, but also interesting regimes for sensing and scientific use;

2. The VECSELs can potentially incorporate saturable absorbers for very high repetition rate (~100 GHz) pulsed and potentially MEMS tunable sources. VECSEL devices in the 2 - 3 mm range for applications in e.g. Free-space optical (FSO) communications are possible using InAsN/InGaAs/InP with AlGaAs metamorphic mirror growth;

3. SESAM structures have demonstrated widespread applicability for self-starting passive mode-locking of (diode-pumped) solid-state lasers, to produce high performance picosecond and femtosecond laser sources for scientific, instrumentation and industrial use. Low loss and high damage threshold requirements demand pseudomorphic growth, and have, until very recently, essentially limited these devices to the 800 - 1100 nm range, but extension beyond this range is urgently required by a host of mode-locking applications. GaNAs/GaAs and GaInNAs/GaAs alloys clearly offer the potential to cover the 1.1 - 1.6 mm range, These sources may be expected to cover ps to fs operation with average powers of 0.1 - 100 Watts at 0.1 – 10 GHz repetition rate, depending upon design and gain media specifics, to impact areas including confocal microscopy for biomedicine, nonlinear optics (including frequency conversion to the visible for projection displays), metrology and materials processing;

4. Modulators and photodiodes, including QWIPs and resonant cavity-enhanced photodiodes (RCE-PDs);

5. Devices based on Indium rich GaInN. The first aim from a devices point of view will be to understand the implications of and exploit the high surface electron densities in hot electron (FET, microwave) and terahertz devices. Given that the band gap of InN is now understood to be close to 0.7 eV, the implication of these findings is that InN may be a candidate for terahertz generation as a photo mixer using 1.55 µm lasers in portable THz systems for spectroscopy and imaging;

6. Study of ballistic transport: Voltage pulses up to 400V with pulse widths of about 1ns and a duty cycle of less than 1.0x10-5 will be launched across the 2D electron gas at the surface of InN the width of which is estimated to be around 300-400 Angstrom, hence generating electric fields up to 12 MV/cm. The aim will be to understand the role of inter-valley-transfer effects and to look for the existence or otherwise of the negative mass effects which will also be studied theoretically.

WG4- Theory and modelling

WG4 will enable device design to be optimised with confidence. This will only be possible with appropriate inputs from the other WGs in the Action. Device and material specifications, and measurements of key parameters will feed into the theory and modelling in order to ensure a close match of theory and practice, and that the models developed are ‘fit for purpose’. The work plan for WG4 will encompass, therefore, all the four Tasks listed section D1.

The scientific work plan for WG4 activities will include

1. Realistic band structures for In-rich InGaN, only now becoming available, will be used to calculate optical gain and spontaneous emission rates in order to aid design of lasers and optical amplifiers. Key parameters such as differential gain, differential index and the line width enhancement factor will be computed as functions of wavelength and carrier concentration for various material compositions and quantum well widths. These studies will lead to optimised designs for VCSELs, SOAs and VCSOAs, as well as conventional edge emitting lasers (EELs) for operation;

2. Recent modelling of terahertz generation in quantum wells has drawn attention to the fundamental advantages offered by InN over rival semiconductors. Theoretical studies will seek to assess the magnitude of these advantages and to quantify the limits on terahertz emission from InN and In-rich InGaN. We plan to demonstrate terahertz surface emission by both optical and electrical excitation.

3. Realistic modelling of InGaN p-i-n photodetectors and uni-traveling-carrier (UTC) photodiodes, intended for both signal photo detection and photonic generation of THz radiation;

4. Calculations of electronic structure and gain characteristics, carrier relaxation, optical properties many body effects, scattering mechanisms, electron-phonon effects, small and large signal modulation, dynamical laser modelling and band structure engineering of dilute nitride structures;

5. Simulation of optoelectronic devices using advanced commercial simulation tools such as SYNOPSYS and CROSS-LIGHT packages.

E. ORGANISATION

E.1 Coordination and organisation

The organisation of the Action conforms to the "Rules and Procedures for implementing COST Actions"

It has been very clear from previous Actions that the underlying aims of COST are best achieved through providing the right platform for scientists and engineers to get together via regular workshops and training schools and by enabling young researchers, to receive training and share resources via short term scientific missions.

The Action will have 5 aspects to the coordination and organisation to realise its aims.

(i) Management: MC chaired by the Action Chairperson will steer and oversee the activities, and ensure that the milestones as defined in section (v) below are accomplished. Chair persons and Vice Chair Persons of the WGs will be elected by, and report to the MC.

The MC will meet twice a year. One member of the MC will report on gender related issues and early career researcher activities. These meeting will follow the WG workshop meetings.

(ii) Action specific web site: A dedicated interactive web site will be established that will contain information about partner groups, research activities, conferences/workshops/symposia, list of potential host groups for short visits/training, forthcoming activities, device/sample exchange. The web site will be maintained by a manager appointed by the MC.

(iii) Coordination of networking and capacity building activities: These activities will be coordinated by the four WGs managed by the chairpersons and comprise the following:

1. Organisation of the various training opportunities such as training schools, short term scientific missions, hands-on training of students and early career scientists at selected centres participating in the Action;

2. Organisation of lecture tours by prominent researchers from the participating countries;

3. Establishment of a “ digital travelling theses library” so that copies of recent PhD and MSc. theses can be borrowed by member groups;

4. Encouragement of the publication of scientific collaboration within the Action in special issues of scientific journals;

5. Organisation of two annual workshops each year with the aim of publishing the proceedings in scientific journals;

6. Fostering links with other relevant EU programmes and industry;

7. Organisation of joint workshops with other COST actions on inter disciplinary areas

(iv) Coordination of meetings and workshops

1. The Action will organise a general kick off meeting to which all partners will be invited and where the work plan and the management structure will be discussed and decided;

2. MC meetings will be held every year where the forthcoming Action activities will be planned and those that have taken place will be reviewed;

3. The main platform to promote the networking and capacity building activities is the organisation of WG Workshop Meetings. These will be organised twice per year for the first three years and once in the fourth year;

4. The Action attaches upmost significance to the training of early career researchers. Therefore, in addition to the short term scientific missions, there will a training school on a specific topic every year and two specific training activities every other year;

5. The action will complete its activities via the organisation of an international conference in the field.

(v) Deliverables and Milestones:

Year	Milestones	Deliverables
1	**3rd. Month**: Kick off meeting organised: MC set up, Work Plan is established **6th. Month** : Interactive web site fully operational. First workshop & MC organised **12th. Month**: Training School, Second Workshop and second MC organised	(i) STSM reports (ii) WGs reports (iii) Annual Report
2	**6th. Month**: First workshop, first MC and first Training Activity organised **12th. Month**: Training School, second Workshop and second MC organised	(i) STSM reports (ii) WGs reports (iii) Annual Report (iv) Publications of Joint Scientific Activities

3	**6th. Month**: First workshop & first MC organised **12th. Month**: Training School, second Workshop and second MC organised	(i) STSM reports (ii) WGs reports (iii) Annual Report (iv) Publications of Joint Scientific Activities
4	**6th. Month**: First workshop & first MC organised **12th. Month**: Training School, second Workshop and second MC organised. International Conference is held	(i) STSM reports (ii) WGs reports (iii) Annual Report (iv) Publications of Joint Scientific Activities (v) Proceedings of International Conference

E.2 Working Groups

The proposed COST action will achieve its scientific objectives via the themes as identified in four WGs.

WG1- Growth and Materials Development

WG2- Material and Physical Characterisation

WG3- Devices

WG4- Theory and Modelling

Each WG will have a chair person and vice chair person who are selected by, and report to the MC. They will coordinate the networking and capacity building activities and stimulate short term mission activities and will also contribute to the annual reports via reporting on activities within their WGs. In order to maximise the impact of the COST Action all four WGs will ensure very close collaboration with each other. Only when an abundance of cross-fertilisation of ideas between the WGs is in place, will the full potential of the Action will be realised.

E.3 Liaison and interaction with other research programmes

The interactions with other COST Actions and other European and International programmes will be maintained throughout the duration of the programme. These will be achieved via:

1. Fostering links with other relevant EU programmes;

2. Organisation of joint workshops and seminars with other COST actions on inter disciplinary areas;

3. Organisation of annual WG meetings adjacent to the activities (conferences / meetings) of the other

relevant Actions;

4. Organisation of an International conference in collaboration with other Actions and Programmes.

E.4 Gender balance and involvement of early-stage researchers

This COST Action will respect an appropriate gender balance in all its activities and the MC will place this as a standard item on all its MC agendas. The Action will also be committed to considerably involve early-stage researchers. This item will also be placed as a standard item on all MC agendas.

Men and women will have equal opportunities in all the activities (including management, spreading excellence, research, networking and scientific integration) of this COST Action.

All the members of the Action support fully that:

(i) Women’s participation in research must be encouraged both as active participants and within the evaluation, consultation and implementation processes;

(ii) Research must address equally women’s and men’s needs;

(iii) Research must be carried out to enhance the inter-gender understanding and to contribute gender issues in general.

This COST Action supports the following EU policy and action plan

"The European policy of equal opportunities between women and men is enshrined in the Treaty on European Union. Articles 2 and 3 establish equality between women and men as a specific task of the Community, as well as a horizontal objective affecting all Community tasks"

This COST Action is committed to the following:

(i) Specific measures will be taken to increase the number of women working in the project and to bring them into key positions in the project;

(ii) The Action will appoint a member of the MC to take responsibility for gender issues and the involvement of early stage researchers. This will be made an agenda item at a MC meeting when useful or necessary;

(iii) Female participants will be encouraged to be on the MC and lead the WGs;

(iv) Affirmative action will be taken to enable young researchers of both gender to attend workshops and training schools.

F. TIMETABLE

The Action will proceed over four years. Below is given a tentative timetable of the Action. Due to the nature of COST collaboration, the specific topics of work may be shifted with time in order to react to specific needs identified by the Action.

Activity	Year1	Year 2	Year 3	Year 4
WP1	Networking and	capacity building	activities and	research
WP2	Networking and	capacity building	activities and	research
WP3	Networking and	capacity building	activities and	research
WP4	Networking and	capacity building	activities and	research
Other Activities	(i) Kick off meeting (ii) Establish work plan (iii) set up web site (iv) Organise two workshop meetings (v) Organise one training school on specific themes	(i) Organise two workshop meetings (ii) Organise one training school on specific themes (iii) Organise one training activity	(i) Organise two workshop meetings of WGs (ii) Organise one training school on specific themes	(i) Organise one large meeting of WGs as final workshop (ii) Organise one training activity (iii) Organise one training school on specific themes (iv) Organise one international conference
Management Committee	2 MC meetings	2 MC meetings	2 MC meetings	2 MC meetings
Deliverables	Annual Report	Annual Report	Annual Report	Conference proceedings & Final Report

G. ECONOMIC DIMENSION

The following COST countries have actively participated in the preparation of the Action or otherwise indicated their interest: CZ, FI, FR, DE, GR, IT, IE, LT, PL, PT, RO, ES, SE, CH, TR, GB. On the basis of national estimates, the economic dimension of the activities to be carried out under the Action has been estimated at 28 Million € for the total duration of the Action. This estimate is valid under the assumption that all the countries mentioned above but no other countries will participate in the Action. Any departure from this will change the total cost accordingly.

The following COST countries have actively participated in the preparation of the Action or otherwise indicated their interest:, Czech Republic, Finland, France, Germany, Greece, Italy, Ireland, Lithuania, Poland, Portugal, Romania, Spain, Sweden, Switzerland, Turkey and United Kingdom. On the basis of national estimates provided by the representatives of these countries, the economic dimension of the activities to be carried out under the Action has been estimated, in 2008 prices, at roughly 28 million Euros. This estimate is valid provided that only the countries mentioned above will participate. If other countries are involved the total cost is will change accordingly.

H. DISSEMINATION PLAN

H.1 Who?

H1 who

There is expected to be a strong representation and involvement of many countries and research groups active in this area. It is anticipated that as well as dissemination within this COST Action, the following three broad interest groups will be targeted;

1. Academia, research institutes and semiconductor industry (manufacturers and service providers);

2. Other COST Actions, early career researchers and other researchers working in the field, and potential graduate students;

3. General public, standards bodies, government agencies, European-level policy makers, regional planners and policy makers.

H.2 What?

To maximise the dissemination of the results and progress of this Action four distinct routes will be taken as identified below.

1. A dedicated interactive web site will be set up with two levels of access:

(i) Publicly accessible level

This will contain information about the management structure, contact points and activities of the Action including conferences, workshops, symposia, training schools, training events (both within the network and worldwide), list of potential host groups for technical visits and training. Links to publications and articles in scientific and technical journals, proceedings, job opportunities, project opportunities, PhD and MSc studentships will also be available

(ii) Password-protected level

This will be solely for members of this COST Action and contain information about MC meetings, scientific reports, non technical interim and annual reports, STSM reports, device/sample exchange, financial reports, working papers, guidelines and manuals.

(A web site manager will be appointed by and will report to the MC)

2. An email network will be established for the whole Action and for the WGs

3. Scheduled meetings will be established for the Action. Sub-meetings will be held for WGs in the form of workshops. Seminars and conferences will be organised by the MC.

4. Training schools and training events will be organised, as well as lectures by leading scientists and engineers from both academia and industry.

H.3 How?

The following four selected routes will contribute to dissemination activities:

1. The website will be a vital point for dissemination by providing information about the Action, including the management structure and contact points as well as its activities including conferences, workshops, symposia, training schools, training, publications and articles in scientific and technical journals, proceedings, job opportunities, project opportunities, PhD and MSc studentships, access to scientific, interim and annual reports, case study and STSM reports, device/sample exchange, financial reports, working papers, guidelines and manuals;

2. Mailing lists for the committees and members of WGs will allow coordination and information exchange at each level;

3. Workshops, seminars and conferences organised by the MC will also be key dissemination points to other research groups and to industry players. Particular attention will be paid to the organisation of such events in conjunction with other international activities to enable dissemination to broader audiences;

4. Training schools, training events as well as lectures given by leading scientists and engineers from both academia and industry, will enable dissemination primarily to young researchers and PhD students. The progress of the Action as well the results of its evaluation will feed in to updating the dissemination plan during the course of the Action.

Therefore, there will be a continuous monitoring of the dissemination routes by checking the following indicators:

(i) Increased number of European scientific workshops and conferences in the field led by scientists in the Action;

(ii) Increase in the collaborative work and joint publications between the partners of the network;

(iii) Increase in distribution of information and documentation of scientific data and material via the dedicated

WEB site;

(iv) Increased number of available PhD and MSc. projects in the field;

(v) Increased number of STSMs and participants to training schools, workshops and training events.

Part II – Additional Information NOT PART OF THE MoU

Maximum 10 pages
General remark: The main purpose of the second part of the proposal is to facilitate the assessment of the proposal and the nomination of National Representatives to the Management Committee (MC). This part will not be element of the MoU. To some extent, however, the information contained in it may also be useful, when the Action starts and a detailed work programme is being planned. Note that part A (List of Experts) is mandatory as the information given here is important for the later nominations to the MC.
The structure of the Additional Information is not standardised and you are at liberty to structure it in any logical way.

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B. ADDITIONAL INFORMATION

1. History of the proposal

This COST Action was inspired by the WG1 activities of the COST 288 action where the interest in novel gain materials and devices was very high and often dominated the overall activities of the Action.

Also, during the international conference on Superlattices Nanostructures and Nanodevices (ICSNN-2006), held in Istanbul in 2006, and the EMRS symposium in Strasbourg in 2007 it was clear that there was a growing community of researchers in the field in Europe and it was necessary to set up a dedicated network of researchers within the European area. The preliminary networking activities in the field proved that a COST Action dedicated to these technologically important compounds would be the natural choice for the networking needs.

After consultations within the research community and discussions at various COST workshops and symposia the preliminary proposal was prepared in collaboration with research groups who were either participants to the COST 288 action or members of other European research programmes. The coordinators of the action were involved in COST 288 as chair of the action and WG1 chairs and the seeds of collaboration were sown there. This will enable the action to really hit the ground running. Indeed the interaction format between growers, characterisers and modellers has already been established in COST 288 and this will save time.

2. Further remarks

The proposed Action attaches most importance to gender equality issues and capacity building activities via training of early stage researchers.

The proposed Action is committed

(i) To increase the number of women working in the project and to bring them into key positions in the project;

(ii) To appoint a member of the MC to take responsibility for gender issues and the involvement of early stage researchers;

(iii) To encouraged female participants to be on the MC and lead the WGs;

(iv) To take affirmative action to enable young researchers of both gender to attend workshops and summer schools;

(v) To implement training activities and summer schools as well as STSMs specifically for the early stage researchers.

The Action is committed to spread excellence across Europe by taking affirmative action to enable the active participation of research groups from a wide geographical distribution within Europe. Indeed the initial proposal was prepared with contributions from sixteen different COST countries.

The monitoring and evaluation of the progress and achievements of the objectives will be maintained via the annual Monitoring Progress Reports prepared by the Management Committee.

Quantitative evaluation will be maintained via monitoring the following indicators:

(i) The number of scientific workshops and conferences in the field led by scientists in the Action;

(ii) The increase in the collaborative work and joint publications between the partners of the network;

(iii) The increase in distribution of information and documentation of scientific data and material via the dedicated WEB site;

(iv) The increased number of available PhD and MSc projects in the field;

(v) The increased number of STSMs and participants to summer schools, workshops and training events.

The Action has already a number of committed industrial partners who will be instrumental in maintaining the link between the Action and industry. In the event of exploitable results the Action will set up an Advisory Board to deal with the intellectual property rights issues.

3. Recent Activities by the applicant relevant to the Action

3.1 Conference, workshop and symposia organisation and other activities in Fields related to the Action

2003-08 COST 288: Chairman of WG 1

2008 Organisation Committee COST 288 Training School "Nanoscale & Ultrafast Photonics" San Michele, Calabria, Italy

2007 Co-Chair, EMRS Symposium F: Novel Gain Materials and Devices Based on III-N-V Compounds, Strasbourg, France

2006 Symposium organizer, COST 288 "Novel Gain Materials and Devices", Vilnius, Lithuania

2006 Symposium organizer, COST 288 Workshop "Novel Gain Materials and Devices", Nottingham

2006 Chairman, "International Conference on Superlattices, Nano-Structures and Nano-Devices" (ICSNN-2006) International Conference, Istanbul

2005 Symposium organizer, COST 288 Workshop "Novel Gain materials and Devices", St. Andrews, Scotland

2004 Symposium organizer COST 288 Workshop "Dilute Nitrides and Quantum Dots", Rome

2004 Co-chair of the symposium on "Dilute nitride and related mismatched semiconductor alloys", EMRS International Conference, Strasbourg, France

2003 Symposium organizer, COST 288 Workshop "Novel Gain materials and Devices"

2002 Director of the International Research Workshop on "Physics and Technology of Dilute Nitrides for Optical Communications", Istanbul, Turkey

3.2 Editorial of special issue journals in fields related to the Action

1. Special Issue Editor IEE Proceedings: Optoelectronics 2003, Volume 150(1) "Physics and Technology of Dilute Nitrides for Optical Communications"

2. Special Issue Editor Journal of Physics: Condensed Matter, 2004, "Dilute Nitrides"

3. Co-Editor of Special Issue IEE: Optoelectronics "Dilute Nitride and Related Mismatched Semiconductor Alloys" Eoin P. O"Reilly, Naci Balkan, Irina Buyanova, Xavier Marie and Henning Riechert, Volume 151, No 5, 2004

4. Chief Co-Editor of Physica Status Solidi(a) 204 No 2 467-546 and PSS(c) Volume 4 No 2 229-688 (2007) "Proceedings of Int Conference on Superlattices Nanostructures and Nanodevices", N. Balkan, A. Erol, M.J. Adams, M.C. Arikan and A.J. Vickers

3.3 Publications by the Applicant relevant to the Action

1. "The effect of In/N ratio on the Lasing Threshold in GaInAsN/GaAs Quantum Well Lasers" R. Potter, S. Mazzucato, N. Balkan, M. J. Adams, P. R. Chalker, T. B. Joyce and T.J Bullough, Superlattices and Microstructures Volume 29, pp. 169-186 (2001)

2. "Determination of in-plane effective mass and quantum life-time of 2D electrons in modulation doped InGaAs/InAlAs heterojunctions from the quantum oscillations in Hall resistance" E. Tiras, M. Cankurtaran, H. Celik and N. Balkan, Physica Status Solidi Volume 186, No 1, pp. 123-134 (2001)

3. "Interaction Strength between the highly localised Nitrogen states and the extended semiconductor matrix states in GaInNAs" R. J. Potter, N. Balkan, X. Marie, H. Carrere, E. Bedel and G.

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4. "Compositional Variation in as Grown GaInAsN/GaAs Quantum Well Structures" P. R. Chalker, H. Davock, S. Thomas, T. B. Joyce, T. J.Bullough, R. Potter and N. Balkan, Journal of Crystal Growth Volume 233 (1,2), pp 1-4 (2001)

5. "Electron Energy and Momentum Loss Rates in 2-D GaN" N. Balkan, M. C. Arikan, S. Gokden, V. Tilak, R. J. Shealy and W. Schaff, Journal of Physics: Condensed Matter Volume 14 (13), 3457-3468 (2002)

6. "Hot Electron Capture and Power Loss in 2D GaN" S. Mazzucato, M. C. Arikan, N. Balkan, B. K. Ridley, R. J. Shealy, B. Schaff, Physica B Volume 314 No 1-4, 55-58 (2002)

7. "Photo induced transient spectroscopy and In-plane photovoltage in GaInAsN/GaAs Quantum Wells" S Mazzucato, A Erol, A Teke, M C Arikan, R J Potter, N Balkan, X Marie, A Boland-Thoms, H Carrere, E Bedel, G Lacoste, A Arnoult and C Fontaine, Physica E Volume 17, 250-251 (2003)

8. "Band structure and optical gain in GaInAsN quantum wells" H Carrere, A Arnoult, X Marie, T Amand, E Bedel-Pereira, R J Potter and N Balkan, Physica E Volume 17, 245-246 (2003)

9. "Comparison of theoretical models for interband transitions in dilute nitrides and experimental measurement" R J Potter, D Alexandropoulos, A Erol, S Mazzucato, N Balkan, M J Adams, X Marie, H Carrere, A Arnoult, E Bedel, G Lacoste and C Fontaine, Physica E Volume 17 (1-4), 245-246 (2003)

10. "S-shape behaviour of the temperature dependent energy gap in dilute nitrides" S Mazzucato, R J Potter, A Erol, N Balkan, P R Chalker, T B Joyce, T J Bullough, X Marie, H Carrere, A Arnoult, E Bedel, G Lacoste and C Fontaine. Physica E Volume 17, 242-244 (2003)

11. "Time Resolved PL Study of GaInAsN Quantum Wells" R J Potter, N Balkan, X Marie, H Carrere and C Fontaine, IEE: Proc: Optoelectronics Volume 150(1), 75-77 (2003)

12. "Physics and Technology of Dilute Nitrides for Optical Communications" IEE Proc: Optoelectronics Volume 150(1), 1 (2003)

13. “Experimental and Theoretical Investigations of the Temperature Dependent Operation of GaInAsP/InP VCSELs” C J Hepburn, D Ramoo, R Sceats, Boland-Thoms, N Balkan, M J Adams, A J Dann, S D Perrin, I Read, J Reed, P Cannard, MA Fisher, DJ Elton, & MJ Harlow, Superlattices and Microstructures Volume 32 (2/3), 103-116 (2002)

14. “In-plane photovoltage and Photoluminescence Studies in Sequentially grown GaInAsN and GaInAs quantum wells” S Mazzucato, N Balkan, A Teke, A Erol, R J Potter, M C Arikan, X Marie, C Fontaine, H Carrere, E Bedel, G Lacoste, Journal of Applied Physics Volume 93 (5): 2440-2448 (2003)

15. “Optical Properties of GaInAsN QWs”, S Mazzucato, A Erol, R J Potter, N Balkan, P R Chalker, S Thomas, T B Joyce, T J Bullough, Solid State Electron Volume 47, 483-487 (2003)

16. “Medium Energy Ion Scattering studies of as-grown and anneled GaInNAs/GaAs Quantum Wells” with SL White, S Thomas, TB Joyce, TJ Bullough PR Chalker,T CQ Noakes, S Mazzucato and N Balkan, Solid State Electron Volume 47, 425-429 (2003)

17. “The effect of nitrogen fraction upon the temperature dependence of GaNAs/GaAs quantum well emission” R J Potter, N Balkan, H Carrère, A Arnoult, E Bedel, X Marie, Applied Physics Letters Volume 82, 3400-3402 (2003)

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19. "Momentum relaxation of Electrons in n-type 3D GaN" D Zanato, S Gokden, N Balkan, B K Ridley and W J Schaff, Superlattices and Microstructures 34(1-2), 77-85 (2003)

20. "Spectral Photoconductivity and In-Plane Photovoltage studies of as grown and annealed GaInNAs/GaAs and GaInAs/GaAs QW Structures" A Erol, N Akcay, M C Arikan, S Mazzucato and N Balkan, Semiconductor Science and Technology Volume 19, 1-6 (2004)

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22. "Optical Properties of GaInNAs and GaNAs QWs" R J Potter and N Balkan, Journal of Physics: Condensed Matter, Volume 16, 3387-3412 (2004)

23. "The Physics and Technology of Dilute Nitrides" N Balkan, Journal of Physics: Condensed Matter, Volume 16, Preface (2004)

24. "Hot Electron Cooling Rates via the Emission of LO Phonons in InN" D Zanato, N Balkan, B K Ridley, G Hill and W J Schaff, Semiconductor Science and Technology Volume 19(8), 1024-1028 (2004)

25. "The effect of interface roughness scattering on low field mobility of 2D electron gas in GaN/AlGaN heterostructures" Physica E Volume 24, 249-256 (2004)

26. "The effect of scattering mechanisms on the low field mobility in GaN/A1GaN heterostructures" S Gokden, A Ilgaz, N Balkan and S Mazzucato, Physica E Volume 25(1) 86-92 (2004)

27. "Effect of fast thermal annealing on the optical Spectroscopy in MBE and CBE grown GaInNAs/GaAs QWs: Blue shift versus red shift" N Balkan, S Mazzucato, A Erol, C J Hepburn, R J Potter, A Boland-Thoms, A J Vickers, P R Chalker, T B Joyce and T J Bullough, IEE Proc: Optoelectronics Volume 151, 284-289 (2004)

28. "Dilute Nitride and Related Mismatched Semiconductor Alloys" E P O"Reilly, N Balkan, I Buyanova, X Marie and H Reichert, IEE Proc: Optoelectronics Volume 151, 245-246 (2004)

29. "In Plane Photovoltage Measurements in MBE grown InN" E Tiras, D Zanato, S Mazzucato, N Balkan and W J Schaff, Superlattices and Microstructures Vol 36, 473-485 (2004)

30. "Energy and Momentum Relaxation of Electrons in Bulk and 2D GaN" D Zanato, N Balkan, W J Schaff and G Hill, Superlattices and Microstructures Vol 36, 455-463 (2004)

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