ASPECTS OF RESEARCH AND DEVELOPMENT IN III-V SEMICONDUCTORS IN BRITISH INDUSTRY AND UNIVERSITIES

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A review of R and D activities in III-V semiconductor devices and materials in UK companies and universities where substantial activity exists is given. Much of the industrial work is concentrated in four companies, namely GEC, Plessey, STL and Philips and two goverment establishments, British Telecom and RSRE. Approximately 15 University departments have research activity in the area; a national centre to grow customised epitaxial layers for universities was set up by the UK Science and Engineering Research Council in 1978 at Sheffield University.

Introduction

This lecture will describe some of the current research and development activities in III-V semiconductor materials and devices in U.K. Industry, Goverment Establishments and Universities. In general only one or two projects per establishment can be mentioned and the choice of which to describe has necessarily been subjective.

Much of the U.K. industrial effort is driven by the commitment towards establishing a completely digital optical fibre trunk system by the early 1990's. Recently, a 1.3 μm link between London and Birmingham, a distance of 180 km has been installed; the first operational monomode link will be installed later this year and nearly all trunk systems laid after 1984 will be monomode. Some 30,000 km of fibre system are presently on order with 6,000 km already installed. The first undersea fibre between the U.K. and Europe, 120 km in length, is planned for 1984 and will operate at 280 Mb/s. A transatlantic system is scheduled for 1988.

The device and material research activity needed to support this programme is chiefly centred at British Telecom Research Laboratories (BTRL), Standard Telecommunication Research Laboratories (STL) and the Allen Clark Research Centre, Plessey (ACRC). Monolithic microwave integrated circuits, discrete microwave sources and detectors, GaAs logic, HEMT, MESFET and bipolar transistors are under development at all the above laboratories and also at the Hirst Research Centre of GEC (HRC) and the Royal Signals and Radar Establishment, Malvern (RSRE).

An indigenous supply of alkyl reagents and adducts for MOCVD growth has been obtained by the decision of the company Thomas Swann Ltd. to enter the field, and the establishment of a new company, Epichem Ltd.

Industrial and Government Establishments

(a) BTRL At BTRL, the systems' requirements of trunk networks predicate research on advanced confinement laser structures and here the channel substrate buried heterostructure laser which can be grown in a single growth run has been most widely researched. Good single transverse mode operation up to 10 mW has been achieved with threshold current of a few 10's of mA's.
In order to operate at the attenuation minimum of 1.5 μm, where the dispersion is finite, a number of techniques have been explored to narrow the laser linewidth. Success has been achieved in the very difficult problem of fabricating distributed feedback structures using electron beam lithography to generate the grating profile, and subsequent MOCVD overgrowth which removes the etch-back problems encountered in LPE. Broad contact devices have operated at room temperature with threshold current of ∿100 mA at 0°C where the gain spectrum matches the grating period in these particular wafers.

Receiver technology for longer wavelengths has been based almost exclusively on the PIN-FET module developed between BTRL and Plessey. The rear entry version of this device has a quantum efficiency of 70% without AR coating and a sensitivity with a 0.3 μm gate FET of -46.5 dBm at 140 Mb/s.

On the materials front, two MBE systems are aimed at the production of III-V layers for devices and integrated-optoelectronics operating in the 1.3∿1.6 μm region. The programme includes both AlGaInAs and GaInAsP systems and the constituent binaries and ternaries. A distinctive feature of this work is the successful incorporation of group VI dopants in MBE by using an electro-chemical cell. S in GaAs and GaAlAs and Se in GaAs have been used in this way. A key advantage is the ability to tailor doping profiles to order and it is expected that the technique may be used also with other important matrices, e.g. InGaAsP. The MOCVD work at BTRL has been chiefly concerned with investigating pre-prepared Lewis acid-base adducts for the growth of layers in the InGaAsP system. In particular, by the use of $InMe_3PEt_3$ it has been found possible to grow InP layers with good crystallographic quality and background carrier concentrations down to $2 \times 10^{15} cm^{-3}$. The use of such adducts have considerable advantages over the metal alkyls in terms of safety, ease of preparation and handling, and consequently purity.

(b) ACRC, Plessey The bulk of the III-V optoelectronic research at plessey, Caswell is aimed at providing sources and detectors for optical communication systems. Material growth techniques include LPE (GaAs/GaAlAs, InP/GaInAsP) MOCVD (GaAs/GaAlAs, InP/GaInAsP) and VPE (GaAs/ GaInAs). The source devices include a high radiance surface emitting device which radiates moderate powers into a 50 micron core fibre, is ultra reliable and can be fabricated over < 0.8 to 1.65 micron. The applications include telecomms, military and CATV. A 1.3 micron ELED gives improved coupling to the 50 micron core fibre for telecomms and is now being deployed for 10 km, 140 Mb/s systems. Lasers for monomode include simple stripe devices and buried heterostructure devices for low threshold and high modulation rates. Minimum threshold current is ∿15 mA and a multilayer infil is designed to minimise leakage currents.

Detectors based on the 'PIN-FET' concept, give sensitivities better than -45 dBm at 160Mbaud. The combination of low capacitance PIN with GaAs FET in a hybrid assembly minimises noise. Current work includes: PIN-FET for 565 Mb/s; ultra low capacitance PINs (∿ 0.05 pF achieved); III-V APDs.

Integration of opto devices, electronic devices and passive components on single chips are very attractive, both for mass market and for high performance, high frequency circuits. Test chips combining LED, detector, waveguide, resistor on a single GaAs/GaAlAs chip have been demonstrated. Operation as transmitter, receiver, repeater and linearised LED source have also been demonstrated.

Electron beam FET's with 0.3 μm gates have been fabricated which give 7 dBm gain at 29 GHz. A wide range of GaAs monolithic microwave circuits have been realised; integral heat sink InP mm. wave transferred electron devices are actively being developed.

(c) Philip's Research Laboratories (PRL) There is an extensive fundamental programme on aspects of MBE growth at PRL including dopant incorporation, influence of the group V element species, growth dynamics and surface studies. On the device front the first MQW lasers in the visible region in the U.K. have fabricated using GaAs/ GaAlAs for video disc applications. The effective Schottky barrier height of nickel on GaAs has been varied between 0.48eV and 0.96eV using MBE to grow a range of thin heavily doped layers, either n type (silicon or tin doped) to decrease the barrier, or p type (beryllium) to increase it. Bulk unipolar GaAs diodes have been made with p^+ completely depleted barrier region of thickness ∿150Å and excellent agreement has been obtained between predicted and measured barrier heights and ideality factors.

(d) Hirst Research Centre (HRC) VPE, MOCVD, MBE growth of GaAs and ion implantation and annealing studies are undertaken to support a large programme on monolithic microwave I.C's. An ultra wide band (D.C. to 13GHz) distributed amplifier with 7dB gain and well matched over the band, on a chip size 3.0 x 1.5 mm, has been realized; 1μm gate length discrete GaAs MESFETs, produced by ion-implantation in 3 μm thick, $<10^{14} cm^{-3}$ buffer layers have given 7 dB associated gain at 10 GHz, with 1.8 dB noise figure; this is believed to be the lowest noise figure ever reported for 1μm gate length MESFETs.

(e) Standard Telecommunication Laboratories (STL)
The key areas of activity are the development of an ultra reliable 1.3μm laser for single mode submarine and landline applications, high reliability single mode laser package for submarine applications, laser and LED sources for multimode fibre systems and narrow linewidth sources for very long haul submarine systems at 1.55μm wavelength. In the case of the first area mentioned, inverted rib waveguide structures are found to give high power, high temperature, single mode performance, and being a comparatively simple growth process, high yields are obtained. Life tests of several thousand hours at elevated temperatures and output powers have demonstrated good reliability in a range of mounted devices with different solders, contacts and pedestals. A single package including a monitor photodiode and single mode fibre pigtail giving high launching efficiency has been developed.

(f) RSRE, Malvern Structural defects in LEC InP have been studied for some years now and a means of growing defect free Ge doped InP has been described. MOCVD InP has been grown by using $InMe_3$ rather than $InEt_3$ as the indium source. Two variants, a direct reaction with PH_3 and the use of an in-situ adduct of $InMe_3 \cdot PMe_3$ has been investigated. Good morphologies at a growth rate of 3μm/hr, giving $N_D \sim 8 \times 10^{14} \rightarrow 10^{16} cm^{-3}$ with a 77K mobility of 55,000 cm^2/Vs have been obtained. High purity InP grown by the $In\text{-}PCl_3\text{-}H_2$ technique can be obtained by controlling the PCl_3 bubbler temperature. Hall mobilities as high as 130,000 cm^2/Vs at 77 K have been measured and analysis of the Hall data shows that N_A has been reduced to about $3 \times 10^{13} cm^{-3}$.

A programme of work to investigate, procure, fabricate and combine optoelectronic components in all optical fibre links between centrally placed items in a phased array rader and the elements of the antenna structure has recently started.

Universities in the United Kingdom

University effort in III-V semiconductors is spread amongst approximately 15 University Departments of Electronic Engineering or Physics.
In 1978, the U.K. Science and Engineering Research Council set up several University Centres to assist other Universities working in the field of micro-electronic / optoelectronic devices. Silicon processing facilities were set up at the Universities of Southampton and Edinburgh, and the existing ion implantation facilities at the University of Surrey were enlarged. A centre for III-V semiconductors was set up at Sheffield University with a remit to grow epitaxial layers to customer specification and to assist in device fabrication. This laboratory is equipped with four LPE, one MOCVD and one MBE reactor. Some fifteen joint projects are currently underway which range from the growth of five layer double heterostructure laser layers for the University of Bath (Prof. T. Rozzi) to investigate instabilities in twinstripe laser structures, to the growth and fabrication of twin sided GaAs FET structures to allow experiments on the 3D to 2D transition to be observed in thin pinched-down electron channels for the University of Cambridge (Dr. M. Pepper).

At the University of Surrey (Prof. K. G. Stephens, Dr. B. J. Sealy), ion-implantation into InP and InGaAs are currently being investigated. Multiply scanned electron beam annealing of Se^+ ions implanted in the dose range 5×10^{12} to $3.6 \times 10^{14} cm^{-2}$ has led to activation ranging from 9% to 36% respectively with corresponding mobilities of 1400 and 760 cm^2/Vs. High dose, 300 keV room temperature implants of Se and Sn in undoped semi-insulating GaAs have been pulse annealed at 1000°C using AlN as the encapsulant, giving 18% activation and improved surface quality over the use of CVD Si_3N_4 layers. In the Physics Department at Surrey (Dr. A. R. Adams) versatile equipment to perform electrical and optical measurements on semiconductors, over a range of temperatures and pressures, both uniaxial and hydrostatic, has been used for a range of experiments on alloy semiconductors. More recently the influence of pressure on the temperature sensitivity of InGaAsP lasers has been studied. The temperature sensitivity parameter T_o increases from about 65K at atmospheric pressure to 115K at 7kbar. This result supports the intervalence band absorption mechanism as being responsible for T_o rather than Auger recombination.

At Chelsea College, University of London, (Dr. G. Swanson) the switching behaviour of plasma alumina - n GaAs IG FETs between quasi normally-off and deep depletion modes is being studied.

Amongst the main advantages claimed for these devices are: - the possibility of D.C. coupling, large noise margins and the exploitation of surface states with well defined energies at the semiconductor-insulator interface.

Professor G. G. Roberts, at the University of Durham, has a large programme on Langmuir-Blodgett films. The incorporation of these films in a range of MIS structures has been studied. In one example, the electroluminescence efficiency of an MIS device formed by a multi-monolayer film on n type GaP is found to increase with increasing film thickness up to a maximum of 9 monolayers, and then decreases. The use of L-B films to increase the barrier height on InGaAs is also being studied.

The measurements of deep levels in III-V semiconductors, particularly their role in determining recombination in indirect gap materials, has been a main-line research activity at the University of Manchester Institute of Science and Technology (Dr. A. R. Peaker). The work has been extended to study deep states in the GaAs layers of GaAs/$Ga_{.71}Al_{.29}As$, n-n heterostructures grown by MOCVD where it has been shown that the high concentrations of deep electron states in the GaAlAs grown by this method carry over into the subsequently grown GaAs. In the same Department, Dr. K. Singer is investigating planar doped barrier switches, and GaAs/GaAlAs HEMT and heterojunction bipolar transistors realised by MBE growth. The growth of long wavelength antimonide containing compounds and alloys, also by MBE has just started.

Photoluminescence spectra of InP and the InGaAsP alloys has been studied in detail at the University of Nottingham (Dr. L. Eaves). It has been shown, for example, that the photoluminescence linewidth can be used for a simple and rapid determination of the impurity concentration for n and p type samples whose total impurity concentrations lie in the range $10^{16}cm^{-3} < N_D+N_A < 10^{19}cm^{-3}$.

Dr. B. K. Ridley at the University of Essex is engaged in a study of the electron-phonon interaction in quasi-two-dimentional semiconductor quantum well structures. For pure polar mode scattering, negative differential mobility is predicted, whereas for deformation potential scattering, a runaway field exists. Two dimensional electron gas heterojunction superlattices in the GaInAs/AlInAs and InGaAs/InP systems are being studied at the University of Oxford. In the latter system, for example, evidence for a long range phonon interaction is observed, with the field of the InP phonons extending into the InGaAs to couple to the electrons bound in the quantum states.

At the University of Glasgow, the design of a special Knudsen source for MBE growth consisting of two independently heated ovens to produce dimeric group V species from tetramers has been undertaken. The effectiveness of the source in generating the dimers of P, As and Sb from their tetramers has been demonstrated. Also at Glasgow, Prof. C. D. W. Wilkinson has been able to demonstrate low loss waveguides by ion beam etching of GaAs grown on GaAlAs layers. In this group, the fabrication of 200 Å gate width GaAs FETs has been investigated as well. The gate lines were delineated by E beam exposure at 50 keV with an 80 Å spot size. In order to prevent back scattering of the primary writing electrons the active GaAs layer had to be in the form of a 500 Å thick membrane. Techniques for selective etching of such thin membranes using an alternating GaAs/$Ga_{.4}Al_{.6}As$ structure grown by MOCVD on (100) GaAs substrates have been developed.

As well as providing many of the layers required for the experiments described in this section, the University of Sheffield also has its own in-house research programme. One project is concerned with studying selective growth of InGaAsP on structured (111)B InP substrates by LPE. The dissimilar growth rates of the various compositions on the different crystallographic faces of the structured substrate has been used to realise planar floating base InP/InGaAs heterojunction optical phototransistors of very small area ($< 100(\mu m)^2$).