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the heating depth to be displayed rather than the profile images presented here.

Microwave interaction with the impedance electrodes was minimal for our experiments, but some effects could be observed at lower RF frequencies and using higher powers.

Some anisotropic effects have been reported,[2] indicating impedance differences for longitudinal muscle, where the current flow is parallel to the tissue fibres, compared with transverse measurements. Our experiments use data relative to a reference condition and, therefore, are not affected by this anisotropy, provided the tissues remain electrically linear.

This letter describes some preliminary *in vitro* and *in vivo* experiments on a promising noninvasive method of thermal imaging during hyperthermia treatment using an impedance imaging method. The system has the advantage over other suggested techniques of being simple to set up using standard ECG electrodes and giving relatively fast data acquisition and image display during microwave or RF heating of a tumour.

However, further detailed study will be necessary to ascertain fully the suitability of this new technique for hyperthermia treatments.

J. CONWAY
M. S. HAWLEY

Department of Medical Physics & Clinical Engineering
Sheffield University & Health Authority
Weston Park Hospital
Whitham Road, Sheffield S10 2SJ, United Kingdom

A. D. SEAGAR
B. H. BROWN
D. C. BARBER

Department of Medical Physics & Clinical Engineering
Sheffield University & Health Authority
Royal Hallamshire Hospital
Glossop Road, Sheffield S10 2JF, United Kingdom

5th August 1985

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GaInAs PIN PHOTODIODES GROWN BY ATMOSPHERIC-PRESSURE MOVPE

Indexing terms: Optoelectronics, Photodiodes, Semiconductor devices and materials, Epitaxy and epitaxial growth

GaInAs/InP PIN photodiodes with low dark currents and capacitances have been successfully fabricated from material grown by atmospheric-pressure MOVPE. Both Zn-diffused and grown-in p^+-n homojunction material have provided yields of over 70% for devices with leakage currents less than 20 nA. This growth technique, therefore, looks particularly appropriate for a reproducible, high-yield and inexpensive method of photodetector production.

Introduction: GaInAs/InP PIN diodes are important components of optical communication systems operating at wavelengths of 1·3–1·55 μm,[1] and are expected to have wide usage in other applications. It is therefore important to have a high-yield, inexpensive and controllable method of producing these devices, in order to have a low-cost, reliable component. Conventionally, liquid phase epitaxy (LPE)[2] and hydride/halide vapour phase epitaxy (VPE)[3,4] growth techniques have been the most popular for producing these devices; however, both these techniques have their drawbacks. In general, the morphology of LPE limits device yield and it is difficult to produce grown-in junctions because of the risk of p^+ contamination of the n^- GaInAs layer. Although VPE has the ability to provide large area slices, we have found the speed of substrate-entry devices is limited because of carrier density grading at the epilayer-substrate interface. This prevents complete depletion under normal bias conditions, and photocarrier generation occurs in undepleted material, giving an undesirable tail at the end of the photoresponse. Other disadvantages of the VPE technique include the high degree of control required over some process parameters, e.g. furnace temperature profiles, and the compositional grading through the epilayer associated with the use of a mixed Ga/In melt.[4]

PIN diodes have also been made by molecular beam epitaxy (MBE),[5] but the slow growth rates and the high cost of the equipment may make this a less attractive technique for the commercial production of these devices. Metallo-organic vapour phase epitaxy (MOVPE), on the other hand, is ideally suited for production because of the fast growth rates possible, high throughput and large-area capabilities, and good layer uniformity. Some devices have been produced by the low-pressure MOVPE technique,[6] but to date no one has reported on the less complicated approach of MOVPE growth at atmospheric pressure. In this letter we report on the growth of low-doped GaInAs for low-leakage, low-capacitance PIN diodes by atmospheric-pressure MOVPE. We also present results on the growth and fabrication of devices which incorporate a grown-in p^+-n homojunction, thereby eliminating the need for a diffusion step, and easing considerably the fabrication process. To our knowledge this is the first report of grown-in junction GaInAs/InP PIN photodiodes by MOVPE, and the technique opens up many possibilities for the integration of detectors with other optoelectronic components.

Experimental: The structures reported in this letter were grown in a conventional horizontal MOVPE reactor operating at atmospheric pressure, using a fast gas switching vent-run arrangement. Trimethylindium (held at 50°C) and trimethylgallium (held at −8°C) provided the group III gas vapours, and 5% arsine or 5% phosphine in H_2 were used as the group V sources. Flow rates were adjusted to give GaInAs epilayers lattice-matched to the InP substrate, with typical double crystal X-ray linewidths in the range 50–100 s^{-1} (FWHM). Normal growth rates were 0·13 μm/min for both GaInAs and InP.

Two different types of structure were grown, as shown schematically in Fig. 1; the first was a completely undoped structure (AQ214) suitable for fabricating Zn-diffused devices and consisted of a 4 μm InP buffer layer followed by a 3·5 μm-thick GaInAs detector layer. The second structure (AQ233) was the grown-in junction type, similar to the above except that, during the growth of the final 1 μm of InGaAs, dimethylzinc (DMZ) was introduced into the reactor cell in order to provide a p^+-n homojunction within the GaInAs. In both cases the structures were grown on nominally (100) oriented Sn-doped ($n \simeq 2 \times 10^{18}$ cm^{-3}) InP substrates at a temperature of 650°C. After growth the slices were characterised by electrochemically profiling through the epitaxial layers. Typically, the doping levels in the undoped GaInAs and InP were less than $n \simeq 5 \times 10^{15}$ cm^{-3} and 3×10^{16} cm^{-3}, respectively, and that of the p^+ GaInAs was approximately $p \simeq 1 \times 10^{19}$ cm^{-3}. The optical quality of the layers was also assessed, by pumping the layers with a 1·06 μm Nd:YAG

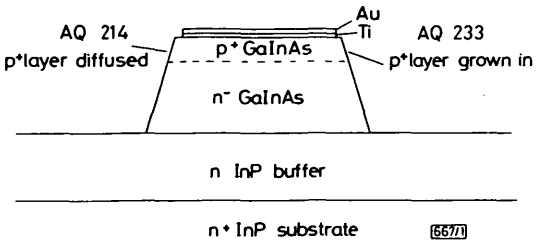


Fig. 1 *Schematic diagram of PIN photodiode structures*

laser and measuring the resultant photoluminescence (PL). Fig. 2 shows a typical PL spectrum at 300 K, together with the spectrum of a VPE slice of similar doping level and thickness. It is clear that the MOVPE slice shows a higher luminescence efficiency, and the lineshape and halfwidth are very close to the theoretical predictions,[7] indicating high-quality material substantially free from nonradiative recombination centres. After assessment, the slices were then processed into mesa devices using techniques described previously.[8]

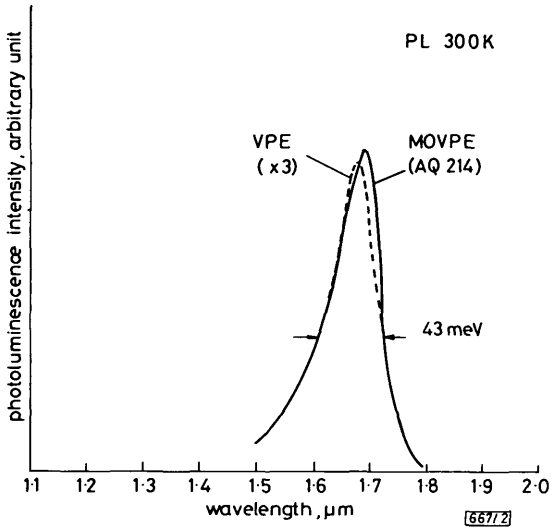


Fig. 2 *Room-temperature photoluminescence spectra of (a) MOVPE slice (AQ214) and (b) VPE slice*

Zn-diffusion into slice AQ214 was carried out in a sealed ampoule using a Zn/Ga/As ternary source for 18 min at 525°C and the *p*-side contact was provided by a titanium-gold bilayer. Substrate thinning (for substrate-entry devices) and metal removal were carried out using mechanical polishing and chemical etching, and an 8:1:1 $H_2O_2:H_2SO_4H_2O$ solution was used at room temperature to etch the mesas through a photoresist mask. This mask consisted of a range of different area devices within a 500 × 500 μm unit cell, which was repeated every 500 μm. A scanning electron micrograph of a typical mesa device, as shown in Fig. 3, demonstrates the smooth and defect-free surface provided by the MOVPE growth process. Measurements on a number of devices similar to this, with areas approximately 80 × 80 μm, indicated that the dark currents were consistently low, and that the capacitance values were small enough for the majority of applications.

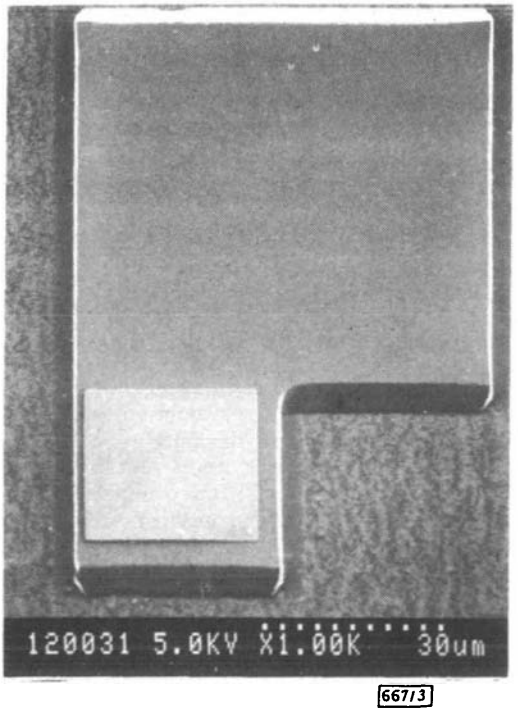


Fig. 3 *Scanning electron micrograph of 80 × 80 μm mesa PIN photodiode*

Device results: Initially, only small areas (a few mm^2) have been processed, the remainder of the slices having been used for material characterisation in order to correlate with device performance. After rejecting damaged devices near the edge of the slices, 26 devices from AQ214 (diffused) and 192 devices from AQ233 (grown-in junction) were available for measurement. For both slices, 70% of the devices had dark currents less than 20 nA at −10 V at room temperature, with the lowest measured dark current being 2 nA at −10 V, corresponding to a leakage current density of 3×10^{-5} A/cm^2. Fig. 4 shows the dark current values at −5 and −10 V for both diffused and grown-in junction devices, and it is noticeable that the grown-in junction devices shows a much larger increase in dark current between −5 and −10 V than do the diffused devices. This, we believe, is caused by the depletion region punching through the GaInAs/InP buffer heterointerface of the grown-in junction devices, which had a thinner n^- GaInAs absorbing region than the diffused devices. With a thicker n^- GaInAs region, the grown-in junction devices would therefore be expected to provide significantly lower leakage currents at −10 V. Nevertheless, it was still particularly encouraging to find that >70% of these devices had leakage currents below 20 nA, similar to the diffused junction devices. For both types of device, the performance compares well with that of devices made from VPE and LPE material in these laboratories.[8]

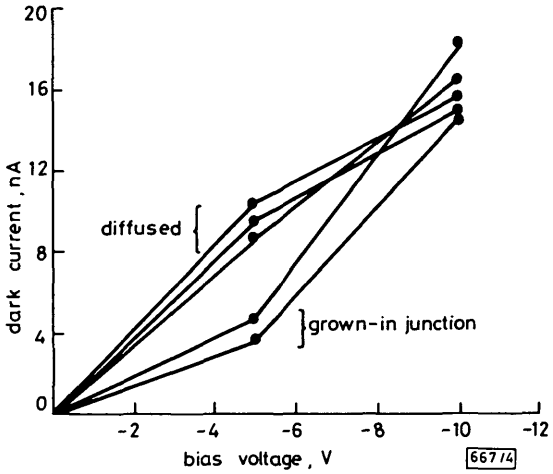


Fig. 4 *Dark leakage currents at −5 and −10 V bias, for both diffused and grown-in junction devices*

The capacitance at zero bias for devices from both slices was 1·1 pF. This is lower than expected for an abrupt *pn* junction with a doping level of 5×10^{15} cm^{-3}, and *C/V* plots revealed that the *n*-GaInAs layer had been compensated near the junction. At −10 V, the capacitance of devices from the diffused slice were about 0·28 pF, while devices from the slice with a grown-in junction were about 0·47 pF. This was because during growth the zinc had diffused, resulting in a thinner n^- region in the final device. Thus the capacitance was limited by depletion to the InP buffer layer ($N_d \simeq 2 \times 10^{16}$ cm^{-3}) at a voltage less than −10 V, as discussed above. Growing thicker n^- layers, thinner p^+ layers or changing the *p* dopant will eliminate this problem.

Conclusion: We have shown that atmospheric-pressure MOVPE is a viable materials growth technique for providing low-leakage GaInAs PIN photodiodes. Devices with both Zn-diffused layers and grown-in junctions have been fabricated, and the yield of low dark current devices is good. The numerous advantages of atmospheric-pressure MOVPE, combined with the simpler fabrication technology associated with grown-in junction devices, provides a very useful route for the reproducible manufacture of such components.

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A. W. NELSON
S. WONG
S. RITCHIE
S. K. SARGOOD

British Telecom Research Laboratories
Martlesham Heath
Ipswich, Suffolk IP5 7RE, United Kingdom

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HIGH-POWER SUPERLUMINESCENT DIODE WITH REDUCED COHERENCE LENGTH

Indexing terms: Light-emitting diodes, Light sources

In work with superluminescent diodes, a significant new device structure has been developed that produces a spectral bandwidth of 160 Å at a power of 10 mW CW at room temperature. This spectrum has a Fabry–Perot modulation depth of less than 25%. These results point to a coherence length of about 45 μm, making this light source very useful for fibre-optic gyroscope applications.

Superluminescent diodes (SLDs) are currently considered as one of the optimum light sources for fibre-optic gyroscopes.[1–3] The short coherence length of SLDs significantly reduces the Rayleigh backscattered noise, while in contrast to ordinary light-emitting diodes, SLDs provide higher power and a relatively narrower emission pattern for ease in fibre-optic coupling. This letter reports on a high-power SLD based on the twin-channel laser (TCL) structure on a *p*-type substrate with current blocking layers.[4] The SLD is fabricated from the TCL structure by applying antireflection coatings (Si_3N_4) on one facet and a thin dielectric (Si_3N_4) followed by a metal reflector on the other facet.

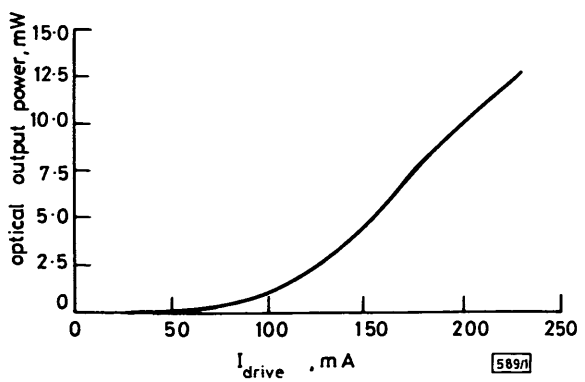


Fig. 1 *Optical output power against CW drive current for 0·83 μm SLD*

Fig. 1 shows the optical power/drive current characteristic for this SLD. The maximum CW output power is 12·5 mW at 230 mA. This represents the highest CW output power for an SLD reported to date.[3–7] The threshold current is ~100 mA, corresponding to the expected values of 1·5–2·0 times the average threshold current of 50 to 70 mA for completed TCLs made from the same wafer.

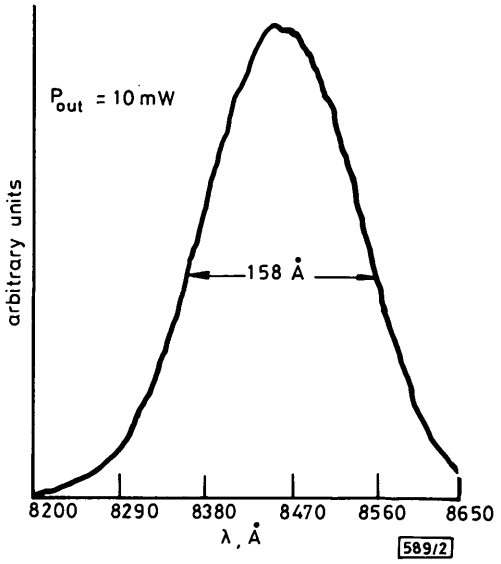


Fig. 2 *Spectral distribution of SLD*

The spectrum of this SLD for an output power of 10 mW CW is depicted in Fig. 2. As shown, the spectral bandwidth is 158 Å and is the widest bandwidth for this power level reported to date.[3–7] Using a coherence length relationship defined for a Gaussian profile to be $l_c = 0{\cdot}22(\lambda^2/\Delta\lambda)$ and taking $\lambda \sim 8450$ Å, the coherence length for our device is calculated to be ~45 μm. Furthermore, the depth of modulation of the Fabry–Perot modes is less than 25%.

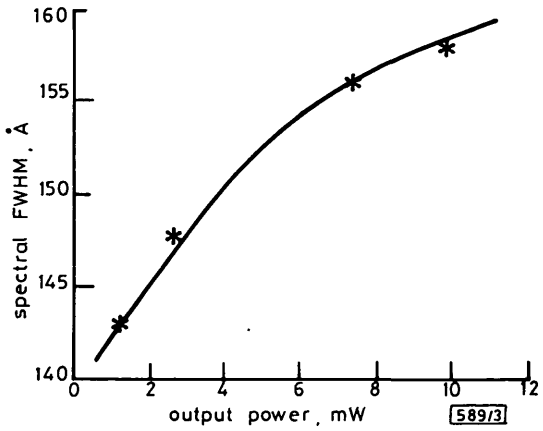


Fig. 3 *Spectral FWHM as a function of output power*

Fig. 3 shows a plot of the spectral bandwidth against optical output power for this SLD. It is evident that the bandwidth increases with an increase in the output power. We speculate that this is caused by heating effects, and thus use of thermoelectric coolers may be required in a completely packaged device. The current I at constant output power can be approximately[6] written as $I(T) = I_0 \exp(T/T_2)$. T_2 for this device is measured to be ~193 K, 156 K and 70 K for 1 mW, 3 mW and 10 mW light output, respectively. Heating effects are more fully described in Fig. 4, which shows the output power against temperature for several constant drive currents. These measurements were made after the device was mounted on a thermoelectric cooler. As can be seen in Fig. 4, a maximum power of 16 mW was reached at 12°C with a drive current of 300 mA.