dilute aqueous solutions of KCl and KNO_3. Measurements were made relative to distilled water.

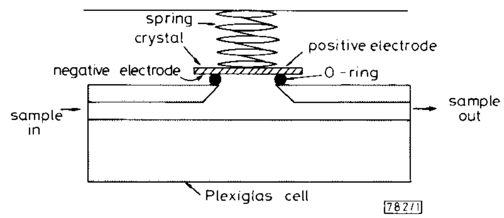

Fig. 1 *Continuous-flow cell*

An instantaneous drop of about 6000 Hz was observed in the oscillation frequency after water came into contact with the quartz surface. Following a slow frequency drift for about 15 min, various concentrations of the solutions were added and mixed into the tank. The measured frequency shifts against conductivity for dilute aqueous solutions at approximately 23°C of KCl and KNO_3 (up to 0·15% by weight) are shown in Fig. 2. The results show good agreement with the theory. The experiments were repeated several times and all the results were within ±5 Hz of each other. To verify that the results were not subject to a 'build-up' effect, a series of experiments were conducted at various midrange points of solution concentration. Also, after flushing the cell with water, the observed frequency was always found to return within approximately 20 Hz of the starting frequency. This drop in the starting frequency could be attributed to a reaction between the solution and the electrode.

The 11 MHz quartz crystal resonator used gave increased sensitivity and represents the highest resonance frequency crystal reported to date for such applications. Various experiments have also shown that the system can be applied to viscous liquids. Whereas the theory serves to explain the trends in the measurements, the repeatability of the experimental results clearly demonstrates that quartz crystal resonator sensors can be used to quantify a solute in a known dilute viscous and/or conductive solution. The reliability and repeatability of the experimental results are mainly due to the unique design of the cell.

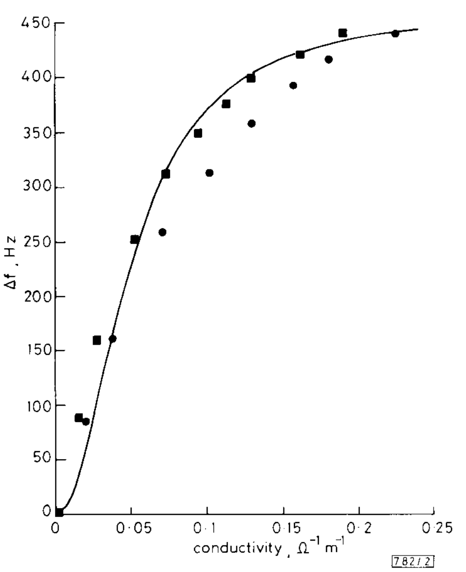

Fig. 2 *Frequency change against conductivity of aqueous solutions of KCl and KNO_3*

Conductivity scale corresponds to 0–0·15% by weight solute, or 0–0·020 mol/litre KCl and 0–0·015 mol/litre KNO_3
—— theory ● KCl ■ KNO_3

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500 mA AlGaAs/GaAs POWER HETEROJUNCTION BIPOLAR TRANSISTOR

Indexing terms: Semiconductor devices and materials, Bipolar devices, Power semiconductor devices

The current–voltage characteristics of 500 mA AlGaAs/GaAs power heterojunction bipolar transistors are reported and the influence of case temperature on current handling capability and current gain are analysed. Current handling capabilities of 400–800 mA/mm per emitter periphery at different case temperatures have been successfully demonstrated using a low-doped GaAs layer as an emitter ballasting resistor to obtain a uniform current distribution over individual emitter fingers. A current gain of 50 at a collector current of 500 mA was realised at room temperature for three elementary devices bonded in parallel, each device comprised ten ($5 \times 25\,\mu m^2$) emitter fingers.

Introduction: In recent years, considerable progress has been realised in the AlGaAs/GaAs heterojunction bipolar transistor (HBT) for microwave and digital applications. As microwave devices, HBTs are useful as amplifiers and low phase noise oscillators. Probably the most salient feature of the HBT for microwave and millimetre wave circuits is its high power amplification capability. CW power densities as high as 2·5 W/mm of the emitter periphery have been demonstrated at 10 GHz, and under pulsed conditions even higher power densities of 5·4 W/mm have been reported.[1–3]

A basic requirement of power HBTs is that the devices have large current gain or high cutoff frequency f_T at high current. It is well known that the current handling capability is dependent on the emitter periphery, base doping and collector doping. From electrical considerations alone, HBTs with sufficiently high base doping are expected to exhibit high current density without emitter crowding and base conductivity modulation effects. In practice, however, the low thermal conductivity of the GaAs material and its negative temperature dependence limit the current handling capability of GaAs-based HBTs.[4]

In this study, the 'intrinsic' current capability of the AlGaAs/GaAs power HBT was investigated; the thermal effects at high current levels were minimised by keeping the device case at low temperatures. The investigated devices incorporated the first use of a lightly doped GaAs layer as an emitter ballasting resistor for achieving uniform current distribution over the emitter fingers. From the resultant uniform current distribution, a current of 500 mA was realised for an *npn* AlGaAs/GaAs power HBT consisting of 3 individual transistors, each with ten ($5 \times 25\,\mu m^2$) emitter fingers. The total emitter periphery was 1·5 mm; the current gain was 50 at room-temperature operation at 500 mA. Meanwhile, current handling capabilities as high as 400–800 mA/mm per emitter periphery were realised in individual devices at case temperatures between 25 and −80°C.

Device structure and fabrication: The AlGaAs/GaAs heterostructure was grown by MBE on a $(100)n^+$GaAs(Si) substrate. The detailed layer structure is schematically illustrated in Fig. 1. Beryllium and silicon were used as the *p* and *n*-type dopants, respectively. The lightly doped ($n = 5 \times 10^{15}\,cm^{-3}$) GaAs layer grown on the $Al_{0.3}Ga_{0.7}As$ emitter is the emitter ballasting resistor. A five-period 15 Å InAs/15 Å GaAs ($n = 5 \times 10^{18}\,cm^{-3}$) strained-layer superlattice followed by an InAs cap layer was employed to facilitate very-low-resistance ohmic contact formation.[5]

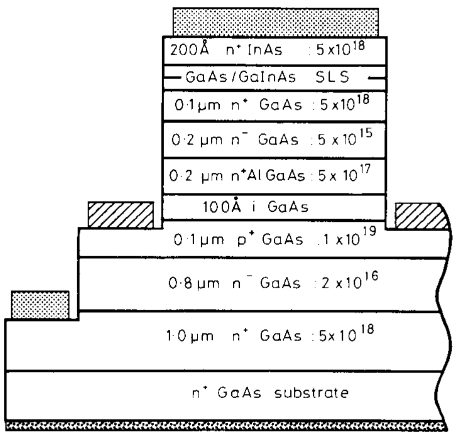

Fig. 1 *Power HBT device structure showing individual emitter finger*

After MBE growth, self-aligned HBTs were fabricated by standard photolithographic and wet chemical etching techniques. The completed device consisted of ten ($5 \times 25\,\mu m^2$) emitter fingers on a ($29 \times 107\,\mu m^2$) base mesa. Ohmic contacts were formed by evaporating AuGe/Ni/Au and AuBe on the *n*-type and *p*-type layers, respectively. Polyimide was used for electrical isolation and Ti/Au was deposited as the overlay metallisation. The substrate was thinned down to 250 µm; an additional 20 µm was chemically etched to obtain a smooth surface, after which palladium plating was performed. Individual devices (500 µm × 500 µm) were cleaved and tested prior to die attaching and wire bonding to a (9 mm × 20 mm) device package. Die attaching was performed at ~420°C using Sn : Au (20% : 80%) pellets. During the device characterisation, case temperatures were determined by a thermocouple mounted directly onto the surface of the device package.

Experimental results and discussion: The room-temperature common-emitter characteristics of the single power HBT displayed significant thermal effects at collector currents around 100 mA, namely decreasing collector current I_C with increasing collector–emitter potential bias V_{CE} at fixed base currents I_B. This thermal behaviour effectively reduces the current gain of the HBT at high V_{CE}.

Nonuniform increase of the junction temperature induces current crowding at isolated locations in the active device area resulting in premature device burn-out. The purpose of the n^-GaAs layer in the emitter (Fig. 1) is to act as an emitter ballasting resistor, to limit any undesired increase in current at individual emitter fingers. These ballasting resistors have identical values for all the emitter fingers owing to the superior uniformity of MBE growth. In contrast, the contact resistances are strongly dependent upon the fabrication and can exhibit wide variability. A very low contact resistance is therefore crucial in removing variations in the values of total resistances in series with individual emitter fingers.

Since a large emitter resistance reduces the power gain whereas small emitter resistances result in nonuniform current distribution, the value of the emitter resistor must obviously be optimised. In this study, the ballasting resistor layer in series with each ($5 \times 25\,\mu m^2$) emitter finger has a resistance of 17 Ω. The devices with ten such emitter fingers were demonstrated to withstand total collector currents of 300 mA and over 350 mA ($V_{CE} = 2.5$ V) for case temperatures of 25 and −23°C, respectively. Collector currents as high as 400 mA were demonstrated on individual devices at −80°C. Current gain against collector current density curves for a single device with ten emitter fingers are presented in Fig. 2 for different case temperatures.

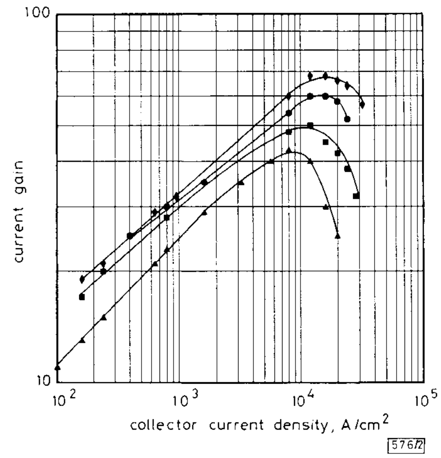

Fig. 2 *Current gain against collector current density for case temperatures of 25°C (▲), −23°C (■), −42°C (●) and −80°C (◆)*

Conventionally, the maximum collector current for bipolar transistors is defined as the current at which the current gain drops to one-half of the maximum current gain, i.e. $h_{FE} = h_{FE_{max}}/2$ at $I_C = I_{C_{max}}$. The current handling capability is the ratio of the maximum collector current to the total emitter periphery. For single devices with total emitter peripheries of 0·5 mm, we have demonstrated current handling capabilities of 400–800 mA/mm per emitter periphery for the individual power HBTs at case temperatures from 25 to −80°C (see also Fig. 2; total emitter area is $1.25 \times 10^{-5}\,cm^2$). When the thermal effects are removed by means of lowering the case temperature, determining $I_{C_{max}}$ becomes difficult because the collector current values are very high, resulting in local heating around the junction, metallisation, and wire bonds. This heating can result in device failure with further increase in the bias after the onset of current gain reduction. The current handling figures presented here, therefore, reflect minimum values for low temperatures.

To demonstrate further the power combining feasibility with HBTs, three devices were packaged in parallel. Fig. 3 shows the I_C/V_{CE} characteristics of this three-transistor device at case temperatures of (*a*) 25°C and (*b*) −170°C. At room temperature (Fig. 3*a*) a negative slope in I_C is observed for $I_C > 300$ mA and the current gain starts decreasing for $I_C > 500$ mA. The current value $I_C \approx 200$ mA at maximum gain for the individual transistor suggests uniform current distribution for the three-transistor device. When the device case is kept at low temperatures, i.e. the temperature effects are reduced, the current handling capability is enhanced resulting in total collector currents as high as 700 mA.

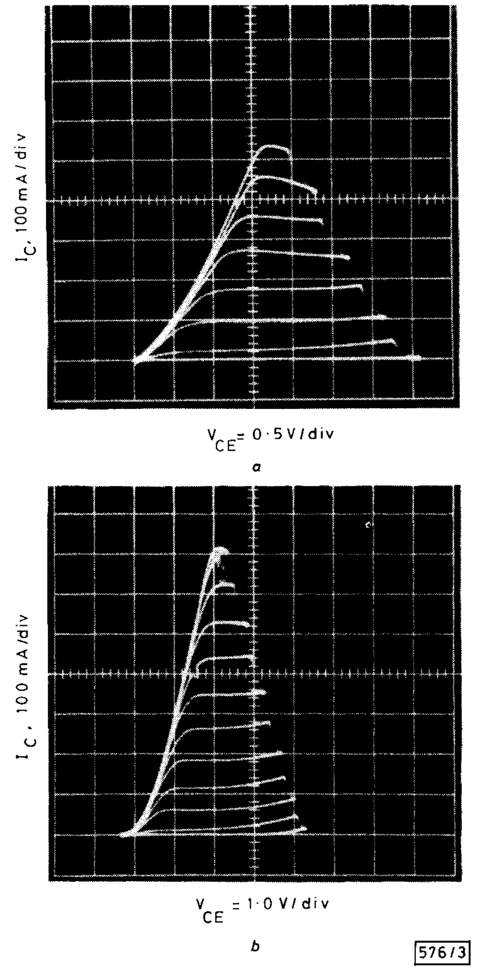

Fig. 3 *Common-emitter characteristics of three power HBTs bonded in parallel for case temperatures*

a At room temperature ($I_B = 2$ mA/step)
b At -170°C ($I_B = 1$ mA/step)

Conclusions: A 500 mA power AlGaAs/GaAs HBT has been realised using emitter ballasting resistors. We have demonstrated that thermal effects limit the current handling capability of GaAs HBTs, even at low operating temperatures. This thermal behaviour suggests that the high thermal resistance of the GaAs material is a crucial limitation of GaAs-based HBTs. In this study, a current handling capability as high as 800 mA/mm per emitter periphery for GaAs HBTs was also demonstrated.

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RELIABLE 1·5 μm BURIED HETEROSTRUCTURE, SEPARATE CONFINEMENT, MULTIPLE QUANTUM WELL (BH-SC-MQW) LASERS ENTIRELY GROWN BY METALORGANIC VAPOUR-PHASE EPITAXY (MOVPE)

Indexing terms: Semiconductor lasers, Epitaxy, Quantum optics, Semiconductor growth

We report the first reliable BH-SC-MQW semiconductor lasers in the GaInAsP quaternary system grown entirely by MOVPE. Threshold currents were as low as 10 mA with differential efficiencies of 0·18 mW/mA per facet at 20°C for 250 μm-long devices. A characteristic temperature of 49 K was measured for a 300 μm-long laser. Initial reliability data suggest these lasers should have lifetimes comparable to standard BH lasers.

Introduction: There is currently much interest in fabricating MQW lasers since, theoretically, they have operating parameters superior to those of bulk active layer lasers. These include lower threshold current density,[1] higher characteristic temperature T_0,[2] higher resonant frequency, higher signal-to-noise ratio[3] and a more stable longitudinal mode.[4] If these benefits are realised, MQW lasers will become the components used in future optical fibre telecommunications systems.

In this letter, we report on reliable BH-SC-MQW semiconductor lasers grown entirely by atmospheric pressure MOVPE in the GaInAsP quaternary system, emitting in the 1·55 μm optical fibre low-loss window. The initial reliability data presented are the only reported for BH-MQW lasers and are comparable to those of standard BH lasers.

Device fabrication: These buried heterostructure lasers were fabricated using three stages of atmospheric MOVPE.[5] Each stage was carried out in a horizontal reactor operating at atmospheric pressure using the metal alkyls TMIn and TMGa.TEP as the group III sources and arsine and phosphine as the group V precursors. DMZn and H_2S provided the *p* and *n*-type dopants, respectively, and all growth steps were carried out at 650°C. In the first stage an SC-MQW structure is formed on a planar *n*-type InP substrate. The active region of the laser is undoped and consists of eight 90 Å GaInAs wells separated by seven 150 Å GaInAsP ($\lambda_g = 1{\cdot}3$ μm) barriers. The separate confinement layers consist of 250 Å-thick doped GaInAsP ($\lambda_g = 1{\cdot}3$ μm) on either side of the quantum well region. The structure is shown schematically in Fig. 1. A mesa was formed using a silica mask and a non-selective etch used to give an active layer width of about 1 μm. Coherent blocking layers were selectively grown around the mesa. After removal of the dielectric layer, *p*-InP and *p*-GaInAs contact layers were successively grown.