

We now show how the type 1 codes of theorem 2 generalise the remaining examples given by Delaney and Farrell.¹ First consider the trivial $k - (v, k, 1)$ design obtained by taking as blocks all the k -subsets of the v points (and hence $b = {}_v C_k$, the binomial coefficient). Then the dual of this design (obtained by reversing the roles of points and blocks) is a PBD(k) with $\lambda(i) = k - i$ and $v_i = {}_k C_{k-i} \cdot {}_{v-k} C_i$; we define two blocks as being i th associates if they have $k - i$ points in common. It should now be clear that the DI code of Delaney and Farrell¹ is simply the type 1 code obtained from this 'trivial' design.

Conclusion: I have shown how the DI codes of Delaney and Farrell¹ may be obtained from more general constructions. Many other DI codes may be obtained from combinatorial designs; the interested reader is referred to Cameron and van Lint.⁵

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SUBMICRON AlGaAs/GaAs HETEROSTRUCTURE BIPOLAR TRANSISTOR WITH HIGH GAIN

Indexing terms: Semiconductor devices and materials, Bipolar devices, Transistors, Epitaxy

We describe the realisation of self-aligned AlGaAs/GaAs heterostructure bipolar transistors with submicron emitter stripe width, current gain of 120 and a maximum operating current density greater than 10^5 A cm^{-2} . The high current gain was achieved by passivating the extrinsic base region with thin AlGaAs.

In recent years there has been interest in using AlGaAs/GaAs heterostructure bipolar transistors (HBTs) for high-speed electronics applications.^{1,2} Because integrated circuits require large numbers of transistors with low power consumption, it is important to scale down lateral device dimensions, thereby minimising the total current (power) associated with device operation. However, scaling emitter stripe widths below $1 \mu\text{m}$ significantly degrades current gain due to efficient minority carrier recombination.^{3,4} It has been reported that proper surface passivation significantly reduces excess base current due to surface recombination in the extrinsic base region. This results in transistors with high current gain.^{5,6} However, these workers did not address device scaling. In this letter we report fabrication of self-aligned submicron AlGaAs/GaAs HBTs with high current gain and ideal lateral scaling.

Fig. 1 shows the device layer structure which was grown by molecular beam epitaxy (MBE) on a $\langle 100 \rangle$ -oriented semi-insulating GaAs substrate. First a 10000 \AA -thick n -type ($1 \times 10^{19} \text{ cm}^{-3}$ Si impurity) GaAs subcollector was grown at a temperature of 580°C , followed by a 1000 \AA -thick $n = 5 \times 10^{18} \text{ cm}^{-3}$ GaAs collector region. The base consists of a 700 \AA -thick p -type ($2 \times 10^{19} \text{ cm}^{-3}$ Be impurity) GaAs layer with a 100 \AA -thick emitter/base doping setback layer. A heavily doped ($n = 1 \times 10^{18} \text{ cm}^{-3}$) $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$ emitter was used. A 3100 \AA -thick GaAs/ $\text{Ga}_{0.85}\text{In}_{0.15}\text{As}$ contact layer

was necessary to facilitate a low-resistance self-aligned ohmic contact. After removal from the growth chamber the material was processed into transistor structures.

| | | | |
|--------------------------------|---|--|------------------------|
| 100 Å | $\text{Ga}_{0.85}\text{In}_{0.15}\text{As}$ | $n > 10^{19} \text{ cm}^{-3}$ | emitter cap |
| 3000 Å | GaAs | $n > 10^{19} \text{ cm}^{-3}$ | |
| 500 Å | $\text{Al}_x\text{Ga}_{1-x}\text{As}$ | $n = 2 \times 10^{18} \text{ cm}^{-3}$ | graded, $0 < x < 0.35$ |
| 500 Å | $\text{Al}_x\text{Ga}_{1-x}\text{As}$ | $n = 1 \times 10^{16} \text{ cm}^{-3}$ | $x = 0.35$ |
| 100 Å | GaAs | undoped | setback |
| 700 Å | GaAs | $p = 2 \times 10^{19} \text{ cm}^{-3}$ | base |
| 1000 Å | GaAs | $n = 5 \times 10^{16} \text{ cm}^{-3}$ | collector |
| 10 000 Å | GaAs | $n = 1 \times 10^{19} \text{ cm}^{-3}$ | subcollector |
| GaAs semi-insulating substrate | | | |

Fig. 1 Schematic diagram of epilayer structure of HBT

Using standard contact photolithography, $1 \mu\text{m}$ -thick NiGeAu emitter strips were defined by evaporation and liftoff. Following a 10 s anneal at 400°C to alloy the emitter contact, the emitter mesa was defined using an $\text{H}_2\text{O}_2 : \text{NH}_4\text{OH}$ (pH adjusted to 7.05) spray etch. The selective etch stops 500 \AA short of the base. Approximately 350 \AA of AlGaAs is then removed using an $\text{H}_3\text{PO}_4 : \text{H}_2\text{O}_2 : \text{H}_2\text{O}$ (10 : 2 : 100) solution. The removal of the AlGaAs was monitored by the photocurrent between two emitter stripes. Self-aligned base contact was achieved with AuBe using the overhang of the emitter ohmic contact as a shadow mask. This resulted in a $0.4 \mu\text{m}$ base to emitter electrode spacing. The heterostructure was then annealed to facilitate the diffusion of the beryllium

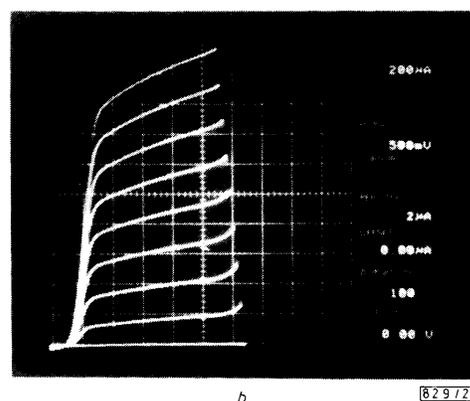
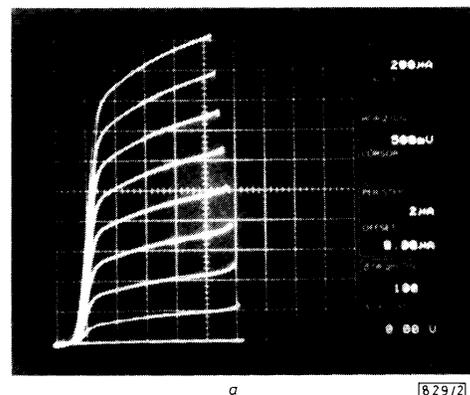


Fig. 2

- a Common-emitter current gain for device with emitter dimension $4 \times 4 \mu\text{m}^2$
- b Common-emitter current gain for device with emitter dimension $0.9 \times 11 \mu\text{m}^2$

through the remaining depleted AlGaAs layer, as previously described by Tiwari *et al.*⁷ The base and collector mesas were then defined by etching in an $\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ (10:2:100) solution. Electrical contact to the subcollector was realised using an alloyed NiGeAu contact. An SiO_2 dielectric layer was then deposited and used as electrical insulation for the final metal contact. The DC electrical characteristics of the completed transistor structures were measured on a curve tracer and an HP4145 parameter analyser.

In Fig. 2a and b we show the results of measuring the common-emitter current gain for two different HBTs. The device in Fig. 2a has emitter dimension $4 \times 4 \mu\text{m}^2$ and shows a current gain of 120 at a collector current of 1.8 mA. As may be seen, the 1000 Å-thick collector shows an emitter-collector breakdown voltage of $V_{CE} \approx 3$ V. The nonideal saturation in the characteristics is due to the Early effect. Fig. 2b shows the current gain characteristics of a device with emitter dimension $0.9 \times 11 \mu\text{m}^2$. Despite the different perimeter/area ratio, the current gain for the two devices is the same. Very large area ($100 \times 100 \mu\text{m}^2$) transistors which are used to monitor processing also show a current gain of 120.

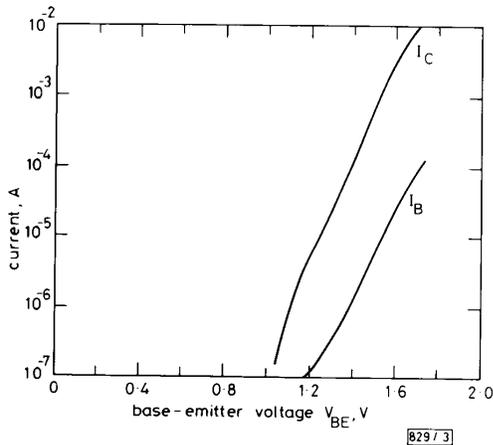


Fig. 3 Transfer characteristics for collector current I_C and base current I_B as function of base-emitter voltage V_{BE} for device used in Fig. 2b

In Fig. 3 we show the transistor transfer characteristics for collector current I_C and base current I_B as a function of base-emitter voltage V_{BE} for the device used in Fig. 2b. The ideality factor n is greater than 2 for both the collector and base current, indicating that tunnelling in the heavily doped emitter dominates current injection. Nevertheless, the fact that I_C and I_B are parallel over a large range of emitter junction bias indicates that all surface recombination adjacent to the emitter stripe has been suppressed. As may be seen in Fig. 3, a current in excess of 10 mA, corresponding to a current density greater than 10^5 A cm^{-2} , can pass through the emitter of dimension $0.9 \times 11 \mu\text{m}^2$.

In conclusion, we have fabricated self-aligned AlGaAs/GaAs HBTs with submicron emitter dimension and current gain of 120.

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GRIN-SCH AlGaInAs/InP QUANTUM-WELL LASERS EMITTING AT 1300 nm

Indexing terms: Semiconductor lasers, Quantum optics

Buried-ridge GRIN-SCH quantum-well lasers operating at $1.3 \mu\text{m}$ with an AlGaInAs continuously graded separate-confinement region and with AlGaInAs quantum wells have been demonstrated with CW threshold currents of 65 mA.

Introduction: Quantum-well lasers in the $1.3\text{--}1.55 \mu\text{m}$ range are important for use in optical transmission systems owing to their higher gain-slope and reduced linewidth enhancement factor, which gives the possibility of improved high-frequency response and narrow linewidth in DFB lasers.^{1,2} To date, devices have been reported using a modified quantum-well structure (see Reference 3 and references therein) or a stepped index profile,⁴ which is intended to approach a true GRIN-SCH structure. We report for the first time in the $1.3\text{--}1.5 \mu\text{m}$ range a true continuously graded structure using AlGaInAs both for the graded regions and for the multiple quantum well active region.

Device design: A number of design issues are raised in arriving at an optimal device specification, and these have been addressed theoretically using a Lorentz broadened model,⁵ which includes both Auger recombination (AR) and intervalence-band absorption (IVBA). Both of these nonradiative loss mechanisms are believed to be important in long-wavelength lasers. Operation at $1.3 \mu\text{m}$ could be achieved, in principle, either by increasing the aluminium content in the wells, or reducing the well width to $\sim 25\text{--}30 \text{ \AA}$ for GaInAs/InP. In long-wavelength materials this latter option is unattractive because of an increased AR and IVBA component in the threshold current which arises from the high carrier densities.

Here, the first option has been adopted with well widths at 100 \AA sufficiently narrow to ensure essentially single sub-band pair operation. Simulations predict threshold currents in the range $750\text{--}1500 \text{ A/cm}^2$ for 3-5 well systems. The long-wavelength GRIN-SCH differs from the GaAs/AlGaAs case, where single-well structures are often preferred despite the relatively poor optical confinement, again because of the large contribution from nonradiative loss at high carrier densities at long wavelength. In MQW GaInAs/InP lasers preferential hole capture and nonequilibrium have been shown to be important.⁶ In our design a number of factors are expected to remove this problem. First, most of the band offset will lie in the conduction band edge; secondly, 5-well structures have been investigated; and finally, the outer GRIN-SCH confinement acts to improve carrier capture in addition to improving the optical overlap.