

# Migration from an AlGaAs to an InGaP Emitter HBT IC Process for Improved Reliability

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**Abstract** – A reliable high performance InGaP emitter HBT process has been developed for RF and microwave instruments. The InGaP process achieves  $F_t$  and  $F_{max}$  values of 65 GHz and 75 GHz, respectively, with  $BV_{ce0} = 8.4$  V and  $\beta = 132$ . The MTTF values of  $>5 \times 10^5$  hours at maximum operating conditions ( $T_j = 150^\circ$  C,  $J_c = 0.6$  mA/ $\mu m^2$ ) are an order of magnitude larger than values measured on both internal and commercially available AlGaAs emitter HBT circuits. The dominant failure mode was beta drift, consistent with other published reports for other InGaP HBTs, but the  $E_a$  of 0.68 eV is much smaller than published values, which suggests that an additional high activation energy mechanism was introduced at the high temperatures used in the published reliability tests.

## I. INTRODUCTION

An InGaP HBT IC process has been developed for use in microwave and communications test instruments (e.g., RF sources, network and spectrum analyzers). The high RF power, high gain per unit area, excellent uniformity of gain and turn-on voltage, large gm, and low 1/f noise make HBT ICs a very attractive technology for such instruments. The large 1  $\mu m$  minimum feature size of our HBTs has allowed high yields to be achieved in complex circuits ( $>3000$  HBTs/circuit) and enables delivery of high functionality per chip for instrument applications.

The original process used an AlGaAs/GaAs HBT device, fabricated using commercial MOCVD epi as well as internally grown MBE epi, where both had C-doped p+GaAs bases and n+InGaAs non-alloyed contacts. The process supported AlGaAs HBTs with  $2 \times 2 \mu m^2$  minimum emitters with  $F_t = 65$  GHz,  $F_{max}(MAG) = 75$  GHz,  $\beta = 50$ ,  $BV_{ce0} = 8.4$  V, and  $R_e = 14 \text{ ohm}$  at the standard operating current of  $J_c = 0.6 \text{ mA}/\mu m^2$ . A cross-section of the HBT device is shown in Fig. 1. The process heavily leveraged our existing FET IC processes for passive components, interconnects, and G-line stepper lithography. The resulting HBT IC process supported 22 ohm/sq Ta<sub>2</sub>N resistors, 0.39 fF/ $\mu m^2$  PECVD silicon nitride MIM capacitors, two levels of TiPtAu interconnect with 10  $\mu m$  contacted pitch, and backside ground vias. Several high performance analog and digital circuits were demonstrated in this HBT process, and excellent

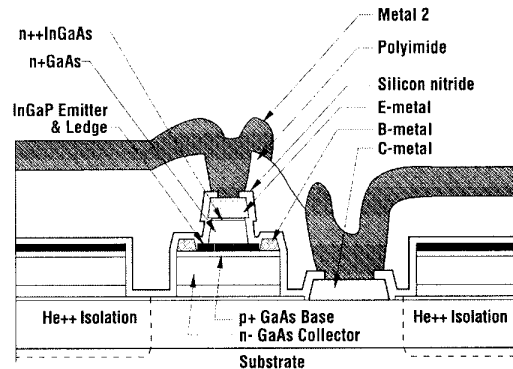


Fig. 1. Cross section of HP's stepper aligned HBT Device. Relevant features for reliability include a non-alloyed n+InGaAs emitter contact, a non-alloyed base contact, alloyed collector contacts, a depleted InGaP passivation ledge, low damage PECVD Si<sub>3</sub>N<sub>4</sub> passivation, and He implant for isolation.

yields were obtained (i.e., typically  $>70\%$  yield for the 1300 HBT yield monitor circuit).

## II. AlGaAs EMITTER RELIABILITY

The main reliability test vehicle in this work was a broadband amplifier (see Fig. 2), but reliability tests were also done on discrete HBTs and divider circuits. The definitions of failure used throughout this work were 1dB decrease in  $S_{21}$  for amplifiers, 1dB decrease in output power for dividers, and 50% decrease in beta for discrete HBTs. Between 16 and 32 circuits were tested for each measured MTTF( $T_j$ ) value, and an MTTF value was recorded only after 50% of circuits had failed (extrapolations from smaller percent failures were not allowed).

Unfortunately, careful reliability measurements of discrete AlGaAs HBTs and broadband amplifiers from this process showed low and variable values of MTTF ( $3 \times 10^3$  hrs to  $8 \times 10^4$  hrs) projected at our maximum allowed current density and junction temperature ( $J_c = 0.6 \text{ mA}/\mu m^2$ ,  $T_j = 150^\circ$  C). The only observed failure mode was beta degradation, and the activation energy for the failure was quite low at  $E_a = 0.57 \text{ eV}$  (see Fig. 3). The low MTTF values for these AlGaAs HBTs are

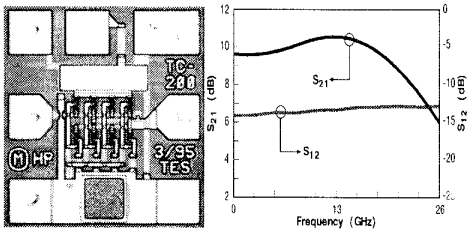


Fig. 2 DC-20GHz amplifier. This 8 transistor Darlington amplifier was the main reliability test vehicle for this work. It has 9.75dB gain, 12dBm power at P-1dB, 15dB return loss, a low 20kHz 1/f noise corner, 6.5dB NF, 5V single supply, and 260mW Pdiss.

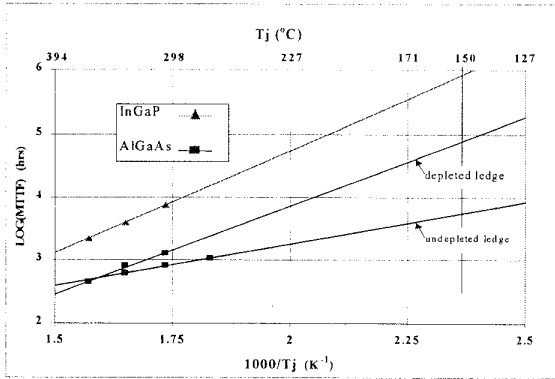


Fig. 3. MTTF vs  $1/T_j$  of AlGaAs HBT and InGaP HBT broadband amplifiers. The projected MTTF at the operating point ( $T_j=150\text{C}$ ,  $J_c=0.6\text{mA}/\mu\text{m}^2$ ) was improved to  $>5 \times 10^5$  hrs for InGaP HBTs compared with  $8 \times 10^4$  hrs for the best AlGaAs HBTs amplifiers. The activation energies are similar for InGaP HBTs (0.68eV) and our standard AlGaAs HBT (0.57eV) with a fully depleted ledge. Epi designs with an undepleted AlGaAs ledge give much lower MTTF of  $\sim 5 \times 10^3$  hrs and a smaller  $E_a$  of  $\sim 0.3\text{eV}$  (see plot).

unacceptable for instruments, and they triggered an extensive HBT reliability improvement effort, both in exploring variations of AlGaAs HBT epi design, and in developing a process for InGaP HBTs and evaluating their reliability.

The AlGaAs HBT reliability improvement effort focussed on variations in emitter design (passivation ledge thickness, AlGaAs doping, and  $X_{Al}$  grading) as well as variations in base design (base thickness, In co-doping, base doping, and  $X_{Al}$  grading). The variations included both internal MBE epi and commercial MOCVD epi. These AlGaAs HBT epi variations and reliability experiments are beyond the scope of the present paper, but none of the experimental AlGaAs designs had MTTF values larger than the  $8 \times 10^4$  hrs exhibited by the standard AlGaAs epi.

Samples of broadband amplifiers and dividers from two commercial AlGaAs HBT suppliers were also

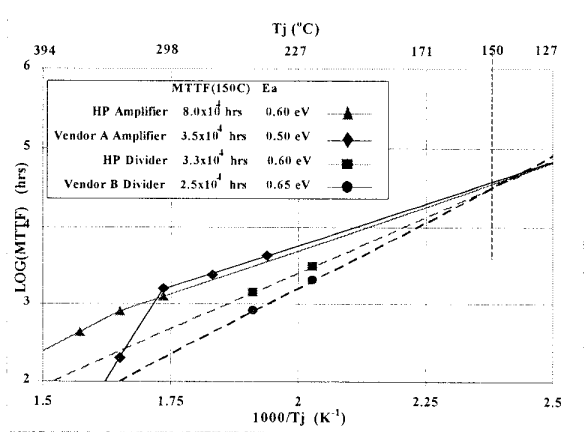


Fig. 4. MTTF vs  $1/T_j$  measured by HP for broadband amps and divider circuits from HP's AlGaAs HBT process and for similar parts purchased from two commercial AlGaAs HBT suppliers. All the HP and commercial circuits, both the amplifiers and dividers, show similarly low projected MTTF values ( $3 \times 10^4$ - $8 \times 10^4$  hrs) at  $T_j=150\text{C}$ , with similarly low activation energies of  $E_a=0.40$ - $0.65\text{eV}$ .

purchased, and their reliability was compared with that of similar broadband amplifiers and dividers fabricated in the HP process using standard AlGaAs HBT epi design. This was done to benchmark the HP process against the commercial AlGaAs HBT technologies, and in the hope of finding an existence proof of an acceptable MTTF for AlGaAs HBTs. All these amplifiers and dividers were stressed at elevated temperature and otherwise biased at their standard rated operating conditions. Unfortunately, both the HP and the commercial AlGaAs HBT circuits all had similarly low projected MTTF( $T_j=150\text{C}$ ) values, and they all showed similarly low values of activation energy  $E_a$  (see Fig. 4). Interestingly, both the HP and the commercial amplifiers show a "kink" in their MTTF versus  $1/T_j$  data (see solid lines in Fig. 4), with a significantly larger activation energy for the two highest temperatures tested. This suggests another higher  $E_a$  degradation mechanism was turned on at the two highest temperatures. Erroneously large projected MTTF values at the normal use temperature would be obtained if only these high temperature data were used in the reliability analysis.

### III. InGaP EMITTER PROCESS

Motivated by reports of improved reliability for InGaP HBTs [1,2], and by the unacceptable reliability of our AlGaAs HBTs, development of an InGaP HBT process was started. The emitter layers in our standard AlGaAs HBT epi design were simply replaced by an n-InGaP layer, and the  $\text{SiCl}_4$  based RIEs used at emitter mesa, base etch, and trench etch were modified

to stop on or etch through InGaP instead of AlGaAs. The new InGaP HBT IC performance and process steps were almost identical to the existing AlGaAs HBT IC process, except beta increased from 50 to 132.

The InGaP HBT epi was grown by KOPIN in a high rotation speed MOCVD reactor. Source materials were trimethylgallium, trimethylindium, tertiarybutylphosphine, and 100% arsine, and the n-type dopants were Si and Te. Carbon doping of the base layer was obtained by adjusting the V/III ratio, and without use of any dopant gases. The InGaP emitter layer was grown lattice matched to GaAs with a 300 K energy gap of 1.87-1.88 eV. Beta at  $J_c=1\text{ kA/cm}^2$  was  $110\pm 10$  in  $75\times 75\mu\text{m}^2$  large area HBTs, the ratio of beta to base sheet rho typically exceeded  $0.4\ \text{ohm}^{-1}$  indicating a high quality base layer. The emitter-base turn-on voltage was reproducibly  $V_{be}=1.09\pm 0.01\text{ V}$  at  $J_c=1.7\text{ A/cm}^2$ .

#### IV. InGaP EMITTER RELIABILITY

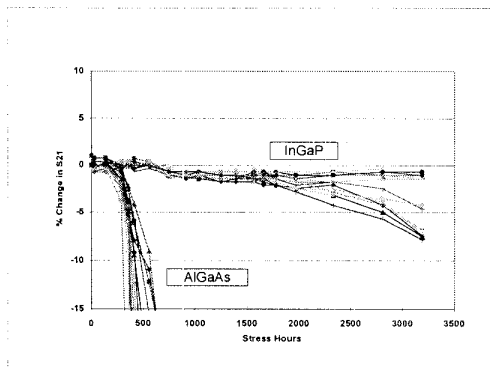


Fig. 5. Gain versus time for broadband amplifiers fabricated from HP's InGaP HBT process compared with our best AlGaAs HBT wafer. The junction temperature was  $T_j=363\text{ C}$ , the collector current was our standard  $J_c=0.6\text{ mA}/\mu\text{m}^2$ . The AlGaAs ICs reached MTTF in only 450hrs, but the InGaP ICs had no failures at 3500hrs (i.e.,  $\text{MTTF}(T_j=363\text{ C})$  is  $\sim 10\times$  larger for InGaP than AlGaAs).

Reliability tests were done on broadband amplifiers and discrete HBTs fabricated in the new InGaP HBT process to compare their reliability with AlGaAs HBTs. The InGaP HBTs had much larger MTTF values than even the best AlGaAs HBTs, as shown in the drift plots in Fig. 5. Beta degradation was again the only observed failure mode (see Fig 6). The MTTF versus  $1/T_j$  for these InGaP HBT amplifiers are plotted in Figs. 3 and 7. This data shows a projected MTTF of  $>5\times 10^5$  hours at  $T_j=150\text{ C}$ , and an activation energy  $E_a$  of 0.68eV. This MTTF value is a 10X improvement over our standard AlGaAs HBT, and is acceptable for instrument applications.

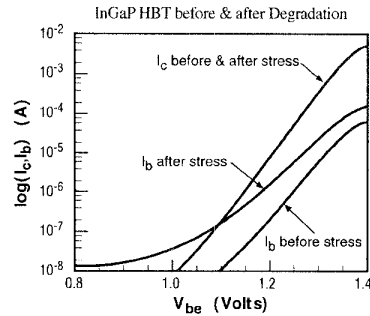


Fig. 6. Gummel plots measured at  $T_a=25\text{ C}$  for a  $3\times 3\mu\text{m}^2$  emitter InGaP HBT before and after stress at  $J_c=0.6\text{ mA}/\mu\text{m}^2$ ,  $V_{ce}=5\text{ V}$ , and  $T_j=333\text{ C}$ . A large  $n=2$  component appeared in the base current  $I_b$  after 1200 hrs of stress. There was almost no change in collector current  $I_c(V_{be})$ , so the beta degradation was entirely caused by the increasing  $I_b$ . This beta degradation is qualitatively similar to that of our AlGaAs HBTs, and to that reported elsewhere for both AlGaAs and InGaP HBTs (c.f., ref 1, 2).

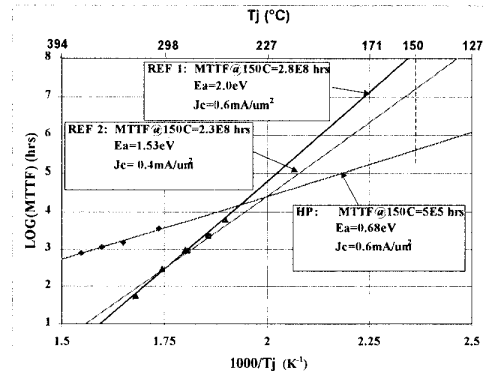


Fig. 7. MTTF versus  $1/T_j$  for HP's InGaP HBT broadband amplifiers compared with published data for InGaP HBTs from refs [1,2]. The activation energy (0.65eV) observed in the HP InGaP HBTs is much smaller than in ref. 1 (2.0eV) and in ref. 2 (1.76eV) which implies a different mechanism is dominating the beta degradation in [1,2], at least at the temperatures used for the reliability testing.

The  $E_a$  value of 0.68eV observed for our InGaP HBT is almost the same as for our AlGaAs HBT. This is quite different from published reliability data, where the  $E_a$  was much larger in InGaP HBTs than in AlGaAs HBTs (2.0eV vs. 0.6eV in ref. 1, and 1.53eV vs. 0.7eV in ref. 2). The published data for discrete InGaP HBTs from refs[1,2] is also plotted in Fig. 7. The fact that  $E_a$  reported in refs [1,2] for InGaP HBTs is much larger than in the present work suggests that a different mechanism is controlling the beta degradation in refs[1,2], at least at the temperatures used in the reliability tests. Note that the published MTTF data from refs [1, 2] all lie below the HP 0.68eV line in Fig. 7. This suggests that a similar low  $E_a$  mechanism could be present in the InGaP HBTs in refs[1,2]. However, reliability test times greater than  $10^4$  hrs at temperatures  $T_j$  below 230C would be

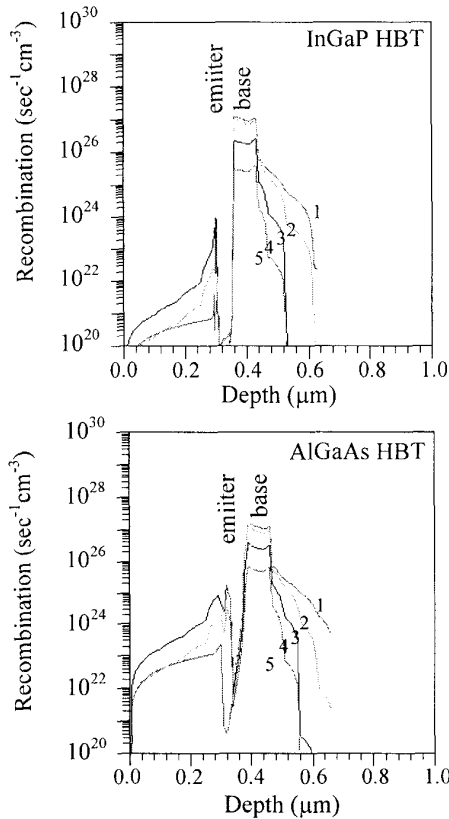


Fig. 8. Recombination versus depth for an AlGaAs HBT (top) and an InGaP HBT (bot) simulated in vertical slices (1-5) through a 2um emitter device with slices spaced from the center of the emitter (1) to the base end of the passivation ledge (5). The recombination rate is  $\sim 1000X$  smaller in the InGaP emitter than in the AlGaAs emitter, because the hole barrier is larger in the InGaP/GaAs heterojunction (see Fig. 9). This smaller recombination offers a possible explanation for the superior reliability of the InGaP HBT.

needed to verify the absence of this low  $E_a$  mechanism.

The observed beta degradation is consistent with a model proposed in ref. 1, where recombination in the AlGaAs or InGaP emitter generates defects, some of which then form recombination centers elsewhere in the emitter-base junction, and thereby contribute additional  $n=2$  base current. Two-dimensional physical models predict that the recombination rate in the InGaP emitter should be  $\sim 1000X$  smaller than in the graded AlGaAs emitter (see Fig. 8), primarily due to the larger hole barrier at the InGaP/GaAs heterojunction (see Fig. 9). The smaller InGaP emitter recombination offers a possible explanation for the superior reliability of InGaP HBTs. If  $E_a$  is interpreted as the formation energy for some recombination center, then the similar  $E_a$  values for InGaP HBTs and AlGaAs HBTs suggests that beta

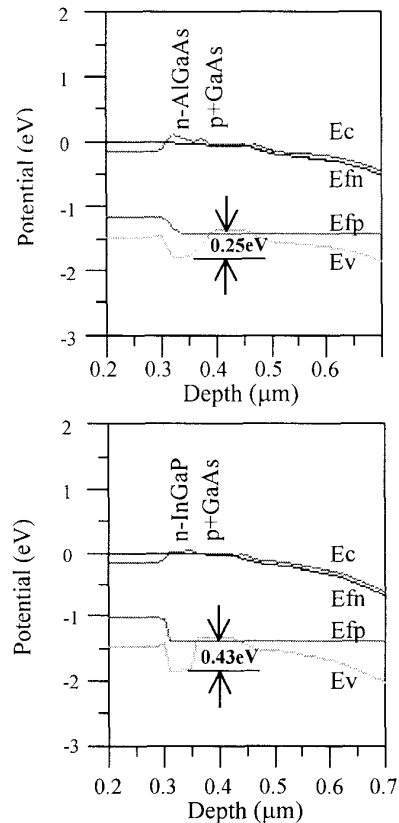


Fig. 9. Band structures versus depth for our AlGaAs HBT (top) and InGaP HBT (bot) operating at  $J_c=0.6mA/\mu m^2$  and  $V_{bc}=0V$  (simulated with Dawn Technology's SIMC). Here  $E_{fp}$  is the hole quasi-Fermi level and  $E_v$  is the valence band energy. The hole barrier  $E_{fp}-E_v$  in the InGaP emitter is 0.43eV, but it is only 0.25 eV in the AlGaAs emitter. This  $\sim 7kT$  larger hole barrier makes the np product  $\sim 1000X$  smaller in the InGaP emitter than in the AlGaAs emitter, and suppresses emitter recombination.

degradation in both device types may be caused by formation of the **same** recombination center (i.e., in the p+GaAs base, common to both device types).

## V. CONCLUSION

In summary, based on  $1.5 \times 10^7$  circuit-hours of HBT reliability test data, we have compared the reliability of AlGaAs HBT and InGaP HBT circuits. We have demonstrated MTTF values of  $> 5 \times 10^5$  hrs for InGaP HBT amplifiers, which is a 10X improvement compared with our best AlGaAs HBT amplifiers. The improved MTTF motivated a complete migration from AlGaAs to InGaP HBT processing, and has allowed the InGaP HBT IC process to be released for use in HP instruments.

- 1) O. Ueda, et. al., Solid State Elect, Vol. 41, No. 10, 1997, p. 1605.
- 2) C. Beaulieu, et. al., JEDEC 1996 GaAs REL Workshop, p. 11.