Investigation of stressing InP/InGaAs DHBTs under high current density

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Abstract

We report on an InP/InGaAs DHBT technology, allowing high-speed operation with F_t=150 GHz, F_{max} =200 GHz at current densities of J_c=110 kA/cm^2, while maintaining BV_{ceo} >12 V. Moreover, excellent device uniformity and reliability is demonstrated under high current density stress with Time-to-Failure (TTF) > 45 years at T_{junc}=110 °C with $\Delta(\beta/\beta_o) < 20\%$ making this technology suitable for high-speed IC fabrication.

INTRODUCTION :

InP based hetrojunction bipolar transistors (HBTs) are an attractive technology to be used in high-speed (>40Gb/s) class ICs, see for example [1,2]. Consequently, intensive efforts have been devoted to device fabrication for further improvement of F_t and F_{max}. Much progress has been made to improve high-speed device performance. F_t's as high as 340 GHz have been reported at current densities exceeding J_c=800 kA/cm^2 [3]. High J_c and F_t is achieved by decreasing the collector thickness, which in turn will decrease the on-state breakdown voltage BV_{ceo}.

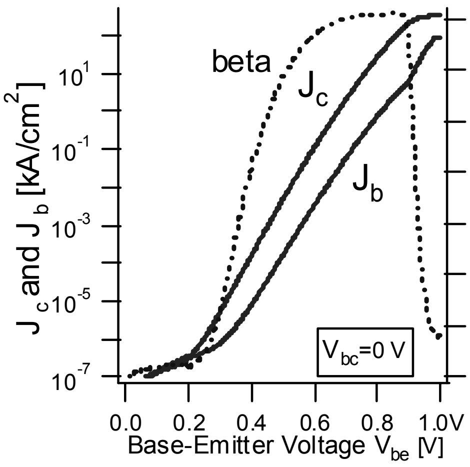

Figure 1 : Gummel plot of the fabricated DHBT's with A_e=1.2 x 7 μm^2 emitter.

For successful implementation in high speed IC's in addition to high F_t and F_{max}, a useful DHBT technology also requires high breakdown voltage BV_{ceo}, and excellent device yield as well as uniformity.

Long-term reliability is a major concern for any technology to be commercially viable. To our knowledge there have been a few reports on device uniformity, degradation and reliability of these type of devices [4,5]. Reliability up to now is mostly done under much lower current density stress as compared to high current density needed for high speed device operation [3,5]. In this paper we willl report on a high-yield, high performance InP/InGaAs DHBT technology with excellent device uniformity and long-term device reliability at high current density stressing.

The InP/InGaAs DHBT's were grown on a 2-inch diameter (100) oriented InP substrate using Metal-Organic Molecular Beam Epitaxy (MOMBE). The base layer thickness is 500Å and activated base doping concentration is as high as 5x10^{19} cm^{-3}. To ensure high breakdown voltages of upto 12 V, a wide band-gap InP collector is used.

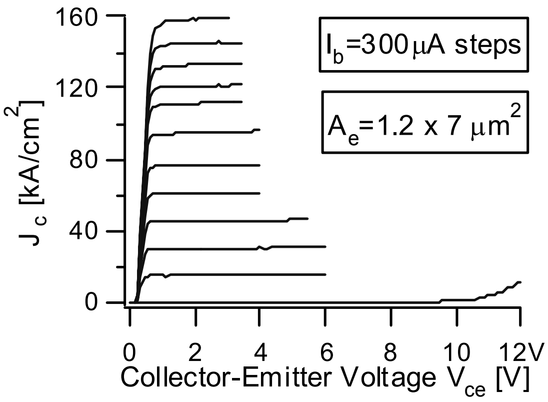

Figure 2 : Common-emitter I-V characteristics. On-state breakdown voltage BV_{ceo}> 12 V.

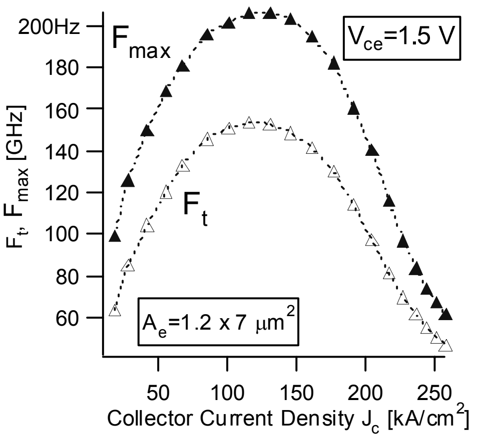

Figure 3 : Measured cut-off frequency F_t and maximum oscillation frequency F_{max} of the fabricated DHBT's.

DEVICE TECHNOLOGY :

Figs. 1 and 2 depict the common-emitter IV and Gummel plot of a typical A_e=1.2 x 7 µm^2 device. From Fig 2 it can be seen that BV_{ceo}>12V. The microwave performance was characterized by on-wafer S-parameter measurements from DC up to 50 GHz.
Fig 3 shows the cut-off frequency F_t and maximum oscillation frequency F_{max} as a function of collector current density J_c at V_{ce}=1.5 V. To examine device uniformity, 180 transistors (A_e=1.6 x 3.4 µm^2) distributed evenly on a wafer have been measured (see Fig 4). The tight distribution of the collector current at V_{be}=0.8 V (I_c=1.4 mA, σ=0.1 mA) indicates good device uniformity with this technology is obtained [4]. Device chains of 1000 devices show device yield to be > 99.99%.

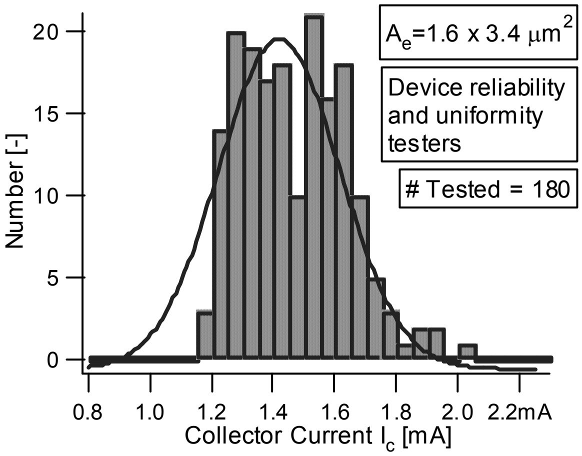

Figure 4 : Collector current distribution of the A_e=1.6 x 3.4 µm^2 reliability and uniformity testers.

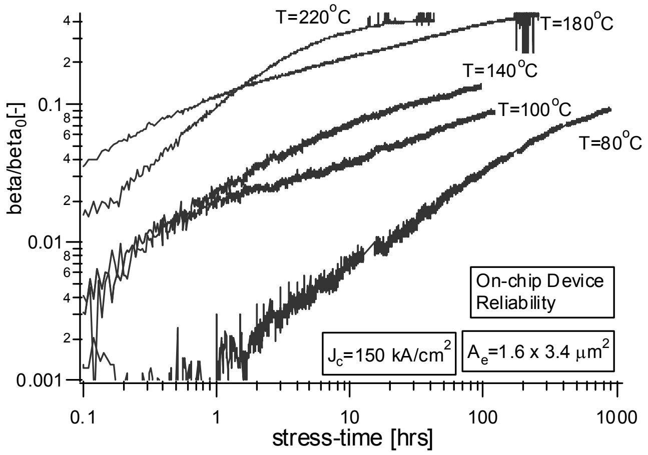

Figure 5 : DC common emitter current gain β degradation at different ambient temperatures T_{amb}.

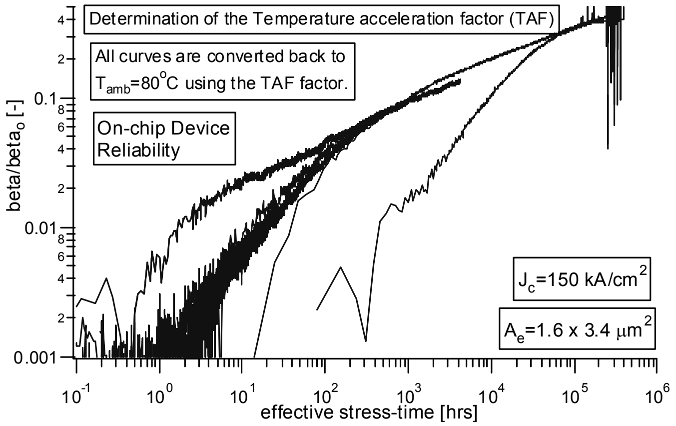

Figure 6 : Effective β degradation at T_{amb}=80°C, assuming an Arrhenius type of function for the Temperature Acceleration Factor (TAF).

DEVICE DEGRADATION :

Device degradation was studied by monitoring the on-chip degradation of the common emitter current gain β at different ambient temperatures T_{amb} under bias conditions of J_c=150 kA/cm^2 and V_{ce}=1.5 V for A_e=1.6 x 3.4 µm^2 devices. For improved device reliability carbon doping was used as the base dopant and the extrinsic emitter-base junction was passivated with an undoped latch layer. Fig 5 depicts the measured relative β degradation as a function of stress time. To establish an activation energy, all degradation curves were converted back to T_{amb}=80°C so they match each other, assuming an Arrhenius type of function for the Temperature Acceleration Factor (TAF), see Fig 6.

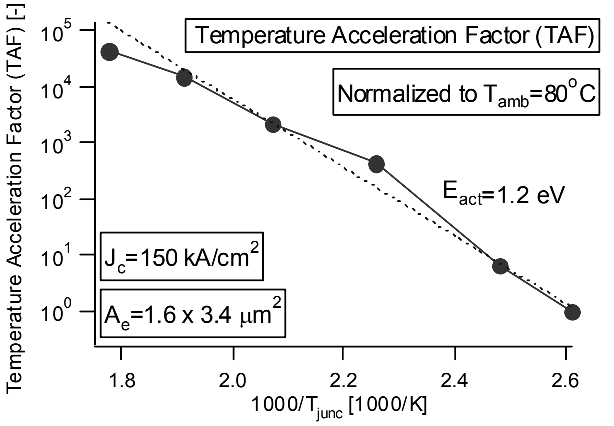

Figure 7 : Temperature Acceleration Factor (TAF), normalized at T_{amb}=80°C.

Fig 7 displays the used TAF normalized at T_{amb}=80°C versus inverse junction temperature T_{junc}. An activation energy E_{act} of 1.2 eV is derived from this figure. It should be noted that E_{act} is determined over a large range of stress temperatures, as compared to [5], providing a check for low activation energy degradation and failures at low temperatures.

Figs. 8 and 9 show the influence of collector current density J_c on the β degradation at a fixed ambient temperature of T_{amb}=140°C. It can be observed from Fig 8 that β degradation increases considerably with increased current density (factor 4.5x is observed going from J_c=145 to 190 kA/cm^2), resulting in a Current Acceleration Factor (CAF) of η=4, see Fig 9. This indicates that the collector current density is an important parameter in determining the long-term device reliability of ultra-high speed InP HBTs operating at high collector current density's J_c.

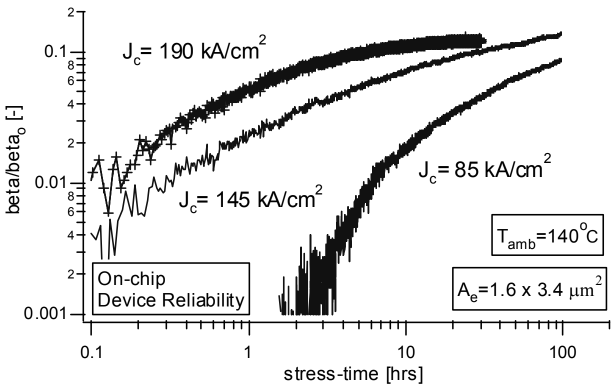

Figure 8 : DC common emitter current gain β degradation at different collector current density's J_c at a fixed ambient temperature of T_{amb}=140°C.

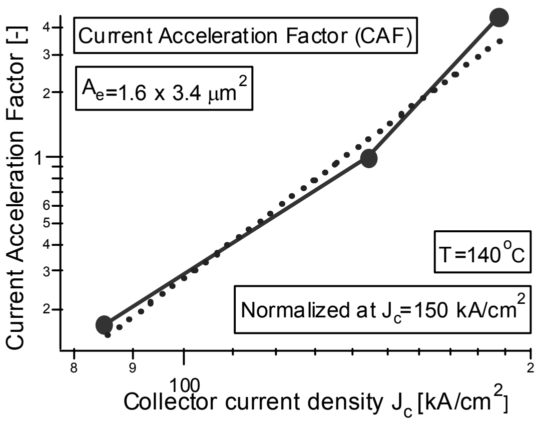

Figure 9 : Current Acceleration Factor (CAF), normalized at J_c=150 kA/cm^2.

The Gummel plot of a typical device before and after 1000 hrs stress at T_{amb}=80°C is shown in Fig 10. It can be seen that β degradation is mainly due to an increase in base current, indicating that the decrease in common emitter current gain β is mainly caused by the degradation of the emitter-base junction.

This is confirmed by Fig 11, showing the Temperature Acceleration Factor (TAF) of β degradation for a device with and without the undoped base-emitter latch layer. Negligible shift in turn-on voltage V_{be} is observed in Fig 10, which is most likely due to C-doped base used in our devices as compared to Be-doped InP HBT devices [5].

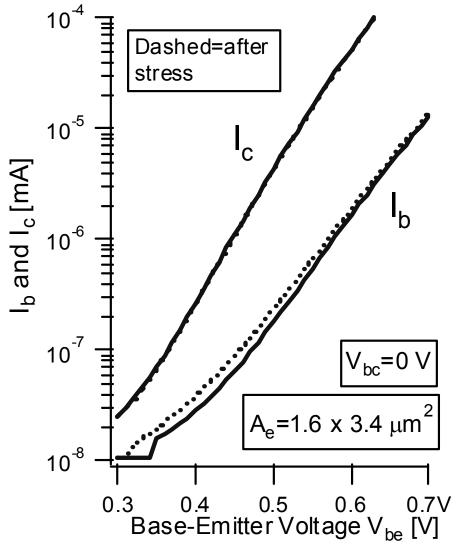

Figure 10 : Gummel plot of a typical device before and after 1000 hrs stress at T_{amb}=80°C.

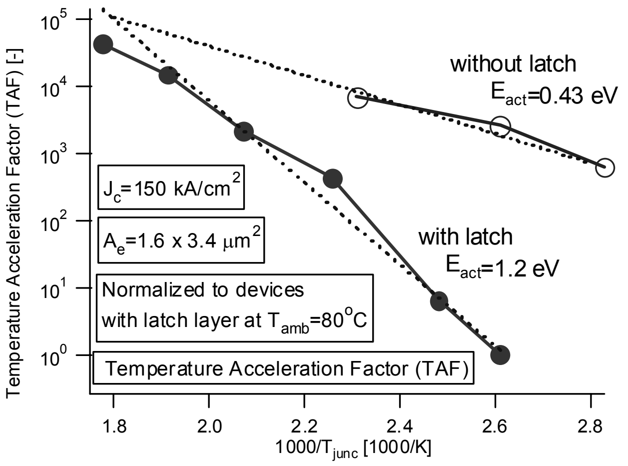

Figure 11 : Temperature Acceleration Factor (TAF) of a typical device with and without an undoped base-emitter latch layer.

DEVICE RELIABILITY :

For device reliability measurements 11 devices, distributed randomly across the wafer, were packaged and stressed at T_{amb}=140°C under high collector current density operation bias conditions for 1000 hrs. No burn-in was applied. Fig 12 displays the relative beta degradation as a function of stress time. It can be seen that the β degradation is uniform and no device failed after 1000 hrs. Also beta degradation is less than 20% (β/β_o > 0.8). Based on an activation energy of E_{act}=1.2 eV derived earlier, this results in a Time-To-Failure > 45 years at T_{amb}=80°C/T_{junc}=110 °C. This is sufficient for any advanced technology (typical product life of 15 years) to be utilized for high speed IC's in optical communication systems.

CONCLUSIONS :

In summary, we investigated the long-term device reliability of our InP/InGaAs DHBT's under high collector current stressing. Excellent device uniformity and reliability is demonstrated with Time-to-Failure (TTF) > 45 years and $\Delta(\beta/\beta_o)$ < 20% at T_{junc}=110 °C and J_c=110 kA/cm^2. Furthermore, our InP/InGaAs DHBT technology, allows high-speed device operation with F_t=150 GHz, F_{max} =200 GHz at current densities of J_c=110 kA/cm^2, while maintaining BV_{ceo}>12 V.

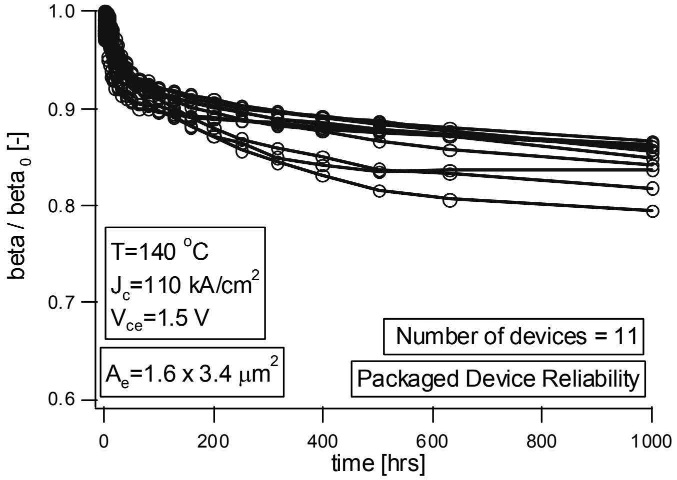

Figure 12 : Packaged device reliability of 11 devices at an oven temperature of T=140°C.

REFERENCES :

[1] Y.K. Chen et al., "Semiconductor Technologies for High-Speed Optical Networking," IEDM 2001, pp. 15.1.1-15.1.3.

[2] Y. Baeyens et al., "InP D-HBT IC's for 40Gb/s and higher bit-rate lightwave tranceivers" GaAs IC 2001, pp. 125-128.

[3] M. Ida et al., "InP/InGaAs DHBT with 341-GHz ft at high current density of over 800 kA/cm^2", IEDM 2001, pp. 35.4.1-35.4.4.

[4] Y. Yang et al., "High-Performance and High-Uniformity InP/InGaAs/InP DHBT", GaAs IC 2002, pp. 269-272.

[5] K. Kiziloglu et al, "Reliability and Failure Criteria for AlInAs/GaInAs/InP HBTs", IRPS, 2000, pp. 294-297.