Reliability of InP-Based HBT IC Technology for High-Speed, Low-Power Applications

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Abstract

We report on the reliability of an InP-based heterojunction bipolar transistor IC technology for very high-speed and low power applications. We have performed extensive accelerated lifetest experiments under bias and temperature stress and found mean-time-to-failures (MTTF) in excess of 10^7 hours at 125 °C junction temperatures. We have also exposed our devices to a hydrogen ambient, particularly important for integrated circuits in hermetically sealed packages. We did not observe any difference in the characteristics of devices with or without exposure to hydrogen ambient. In addition we have performed extensive lifetest experiments on tantalum-nitride (TaN) thin-film resistors (TFR) used in our IC process. Our TFR reliability performance exceeded the active device reliability, as required in a reliable IC process.

Introduction

InP-based HBT IC technology offers an alternative [1] to the more widely reported GaAlAs/GaAs HBT's for high-performance and low-power integrated circuit applications. This technology offers a heterojunction bipolar transistor with a GaInAs collector and base layers and an AlInAs emitter layer, both lattice matched to semi-insulating InP substrate. If the base-emitter heterojunction is compositionally graded, the transistor exhibits a turn-on voltage, V_{BE}, less than that of the silicon bipolar transistor with nearly ideal base and collector current characteristics. Using this type of HBT we have demonstrated [2] 39.5 GHz performance of integrated circuits operating at a power supply of less than 3.0 V. The unique characteristics of the material system also allows us to scale the transistor dimensions to submicron feature sizes while maintaining acceptable dc and rf characteristics. This is important for reducing IC power consumption. We have previously reported [3] on the reliability performance of InP-based HBT's for low-power operations. This technology also offers [4] very stable dc and RF characteristics over a wide temperature range from cryogenics up to 250 °C. We have also demonstrated [5] the potential of this technology for microwave power amplification when we incorporated an InP layer for the collector material in order to substantially increase the breakdown voltage.

In this paper we will report new lifetest data on HBT's stressed at a bias voltage of 3.0 V and current density of 2.5×10^4 A/cm^2. This bias condition is used for analog and precision integrated circuits such as data acquisition circuits. Furthermore, we report on the effect of hydrogen ambient on these devices which is particularly important for hermetically sealed electronic components. In a hermetically sealed package the part is exposed continuously to an outgassing of H. Thin film resistors (TFR) are the most critical passive component in an IC process. We have collected extensive data on the stability of tantalum nitride TFR's.

Experiments

The HBT devices reported in this work were grown lattice matched on InP substrates by MBE. The epitaxial profile consisted of a GaInAs collector with a thickness of 0.7 µm doped at 5×10^{15} cm^{-3}. The 0.7 µm collector compared with our previously reported 0.3 µm collector exhibits a higher device breakdown voltage suitable for circuits operating at a supply voltage of 5 V. The base thickness was approximately 60 nm doped at 2.5×10^{19} cm^{-3} with beryllium. The AlInAs emitter was 120 nm thick and doped at 8×10^{17} cm^{-3} with Si. The base-emitter (B-E) junction was compositionally graded over a distance of 30 nm. This resulted in a turn-on voltage of 0.656 V at the lifetest bias condition (Vce=3.0 V and Jc=2.5×10^4 A/cm^2). The emitter and collector contact layers were GaInAs doped at 10^{19} cm^{-3} with thicknesses of 0.1 and 0.7 µm, respectively.

Devices were fabricated using a triple-mesa process to access the base and collector and to isolate the device. Non-alloyed Ti/Pt/Au was used for the emitter and base ohmic contacts and AuGe/Ni/Au for the collector contacts. Subsequently, thin-film resistors (TFR) and metal-insulator-metal (MIM) capacitors were fabricated on the substrate. Tantalum nitride (TaN) TFR's were confined within two layers of silicon nitride which enhances the long-term stability of these resistors. The

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device mesa structure and passive components were then planarized by polyimide. Second level of metalization was patterned over the polyimide for interconnection. The Ic-Vce characteristics of a typical HBT are shown in Fig. 1. At peak RF performance, the f_T and f_{max} of this device was 90 and 100 GHz, respectively. The dc current gain was 40. The lifetest was performed at a current density of $2.5x10^4$ A/cm^2 at which point the f_T and f_{max} of the device was 70 and 80 GHz, respectively.

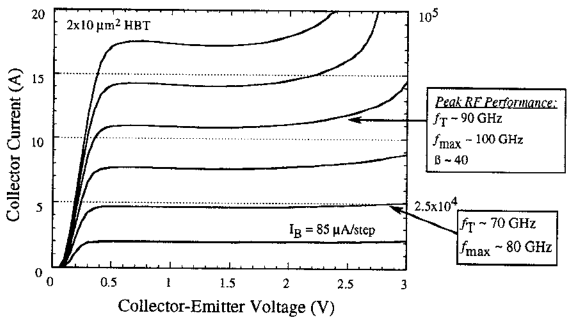

Fig 1. Measured IV characteristic of typical InP-based HBTs. RF performance is also shown at different biases.

To determine the reliability of InP-based HBT devices for IC applications we have performed accelerated lifetest experiments at elevated temperatures ranging from 193°C to 228 °C ambient temperatures. We have stressed two types of devices. The first group was designed for low-voltage, and low-power digital IC applications. These devices consisted a collector thickness of 0.3 µm and exhibited a f_T of 130 to 140 GHz. In our lifetest experiments these devices were stressed at Vce=1.0 V and collector current density, Jc=$7x10^4$ A/cm^2. The second group of devices was biased with Vce=3.0 V and Jc=$2.5x10^4$ A/cm^2 (for analog and precision ADC applications running with a power supply of 5.0 V).

For lifetest purposes, discrete packaged devices were characterized prior to the lifetest as well as periodically throughout the lifetest. The areas of concern in bipolar transistors is generally the stability of junctions, ohmic contacts, and dc current gain. Of particular importance in GaAs-based HBT's is the stability of the base-emitter junction and the dc current gain. In Be-doped GaAs-based HBT's under applied bias, the Be diffuses from the base into the base-emitter junction and leads to instability in the turn-on voltage and dc current gain [6]. In carbon-doped GaAs HBT's the dc current gain and B-E junction degrades due to a strain in the base [7]. Our extensive lifetest data on AlInAs/GaInAs HBT's with graded base-emitter junctions indicate that no such degradation exists in these devices. This is evident from the measurements of base and collector currents as a function of the turn-on voltage taken before and after stress. This is shown in Fig. 2 which is the Gummel plot of base and collector currents before stress, after 96 hours, and after 192 hours of stress at 213°C. This data indicates there is stability in the dc current gain, turn-on voltage, and B-E junction characteristics. In addition the plot also indicates that the contact resistances are unaffected by the bias and thermal stress.

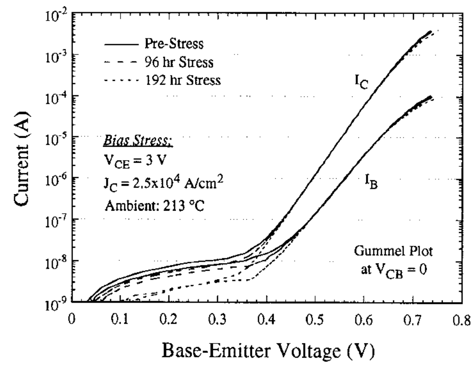

Fig 2. Measured base and collector current characteristics under stress.

Figure 3 is a plot of the base-collector junction characteristics under bias stress which shows a gradual increase in the base-collector (B-C) leakage current under stress. This device was stressed in ambient of 213°C with a bias of 3 V. The rate of increase in the leakage current is dependent on the peak electric field at the B-C junction and the amount of current. Therefore, varying the bias voltage or the thickness of the collector affects the rate of degradation. We have used this leakage increase to set a failure criteria for assessing the useful life of this technology.

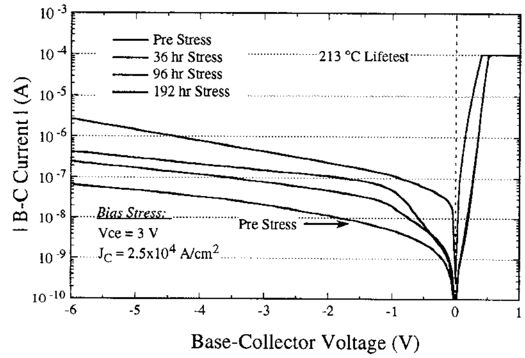

Fig 3. Measured IV Characteristic of InP-based HBT under bias and temperature stress, showing gradual increase in b-c leakage current.

Under normal operating conditions the B-C leakage current is injected from the collector to the base thus canceling the base current and causing the current gain to appear higher. For circuit performance the leakage current must remain small compared to the collector current while the apparent increase in the current gain dose not affect the circuit performance. However, as a conservative failure criterion we required that the leakage current remain less than a fraction of the base current. Applying this criterion to the data taken periodically throughout the lifetest, we can project the useful device life using an Arrhenius plot such as shown in Fig. 4. In this plot, each of the three data points (corresponding to three different ambient temperatures) represents the mean-time-to-failure (MTTF) of a sample device population stressed at Vce=1 V and Jc=7x10^4 A/cm^2. This is our stress condition for low-voltage, low-power applications of the technology. The MTTF for each device population is determined from a plot of logarithm of the time-to-failure of each individual device versus a normal probability scale.

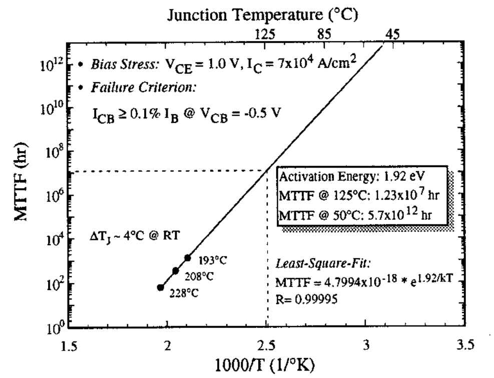

Fig 4. Arrhenius plot of MTTF for devices with 1.0 V bias stress for low-voltage, low-power IC applications.

The Arrhenius plot of the data projects a MTTF of 1.23x10^7 hours at 125°C ambient. The activation energy for the B-C junction degradation mechanism is estimated from the figure to be 1.92 eV.

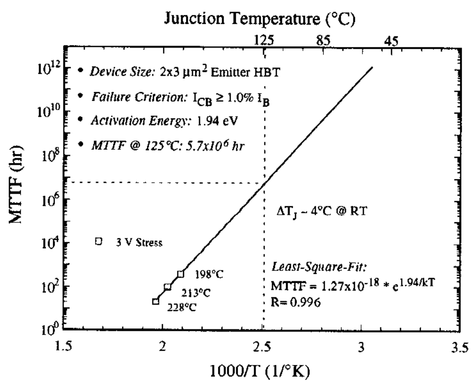

Fig 5. Arrhenius plot of MTTF for devices with 3.0 V bias stress.

Similarly, lifetests were conducted for devices which are biased with Vce=3 V for IC applications requiring a 5.0 V power supply. The Arrhenius plot of Fig. 5 summarizes the results of the three lifetest experiments at ambient temperatures of 198, 213, and 228 °C. At this bias condition, the activation energy was the same as before. The projected MTTF at 125 °C ambient was 5.7x10^6 hours.

In hermetically sealed packages, hydrogen outgasses continuously from the package and has been shown to degrade HEMTs [8] and GaAs/AlGaAs HBT's [9]. In the case of GaAs HBT's the H_2 interacts with the base dopant and causes instability in the dc current gain. The degradation is rapid and can take place in a few hundred hours even at low ambient temperatures. We have exposed our devices to a 4% H_2 ambient for a stress period of over 300 hours at 200 °C. During this test dc bias was also continuously applied to the devices under stress (Vce=3 V, Jc=2.5x10^4 A/cm^2). Figure 6 shows the comparison of dc current gain of devices with and without exposure to the 4% H_2 ambient. The data was taken periodically at room temperature. We did not observe any effect specifically due to exposure to hydrogen in these devices.

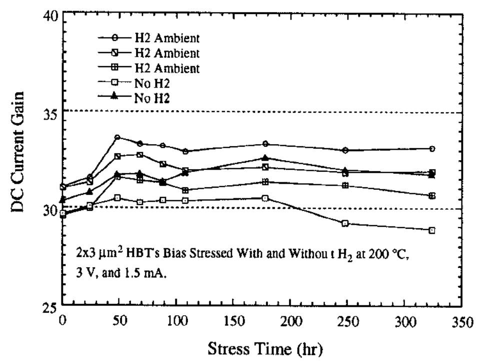

Fig 6. DC current gain of HBT's bias stressed with and without exposure to hydrogen.

Thin-film resistors are the most critical passive component in integrated circuit processes. In our IC process we fabricate TFRs by patterning a film of 80 nm thick sputtered TaN. The film which is deposited on a layer of silicon nitride provides a sheet resistance of 50 Ω/sq. We have done extensive lifetests on our TaN resistors under bias and temperature stress. Figure 7 shows the relative change in the resistance of our typical 100 Ω resistors biased with two different current densities at a 213 °C ambient. We require that the MTTF of resistors with a 2% change (as the failure criteria) exceed the MTTF of our active devices. The MTTF of resistors stressed at two different temperatures is extracted in Fig. 8 from a lognormal plot of time-to-failures for a 2% change in the resistance. The data indicates that the resistor reliability exceeds our requirements.

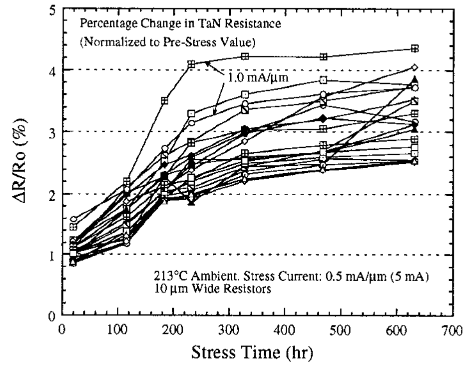

Fig 7. Relative change in the resistance of 100 Ω TaN thin-film resistors bias stressed at two different bias currents.

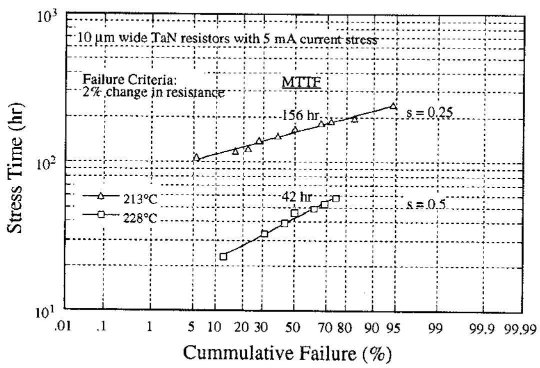

Fig 8. Mean-time-to-failure of TaN thin-film resistors stressed at 213 and 228°C ambient with applied current.

Conclusions

We have conducted a systematic and extensive characterization of an HBT IC technology with millimeter wave performance. Our GaInAs/AlInAs HBT's are free from base dopant related instabilities observed in GaAs-based HBT's. The devices are also insensitive to hydrogen which is appropriate for applications requiring hermetically sealed packaging. Tantalum-nitride thin-film resistors in our IC process exhibited mean-time-to-failures exceeding that of active devices. Our reliability results indicate that this technology has tremendous potential for high-performance, low-power applications with stringent reliability performance requirements.

Acknowledgments

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