SAND2011-2673C

THERMAL STRESSING OF InGaP/GaAs HBTs

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Abstract: InGaP/GaAs HBTs grown by MBE have been thermally stressed at 220-260°C. The stress test was interrupted periodically for electrical characterization and multiple electrical parameters were tracked as a function of the stress time. An Arrhenius analysis was performed for three parameters, two of which usually are associated with defect generation: β (current gain) at low V_{BE}, β at high V_{BE}, and reverse-breakdown of the base-emitter junction. The activation energy for all three parameters was approximately 1.9 eV. These activation energies are comparable to those associated with contact metal degradation, also believed to occur mainly as a result of thermal stress. HBT failure in all cases occurred at the base-emitter junction prior to failure at the base-collector junction, and in many cases prior to any degradation at the base-collector junction.

I. INTRODUCTION

InGaP/GaAs HBTs offer reliability advantages over AlGaAs/GaAs HBTs and are attractive in many RF applications. Nevertheless, a full understanding of reliability in InGaP/GaAs HBTs is lacking due to the complexity and possible interactions of the many possible degradation mechanisms. Storage reliability testing using purely thermal acceleration is useful in those applications that require long lifetime under intermittent operation. Temperature stressing also helps generate insight when both thermal and current-driven acceleration factors are important. Often HBT reliability studies have concluded that thermally dominant degradations in HBTs are mainly associated with high activation energies and metal contact degradation [1]. In this work we report and characterize thermally driven defect degradation mainly associated with the base-emitter diode of an InGaP/GaAs HBT.

II. EXPERIMENTAL

Two different device types were studied, differing substantially in their breakdown voltage. They are illustrated schematically in slide 4. Device 1 is characterized by 180 V breakdown, while device 2 is characterized by 50 V breakdown, in both cases greater than that commonly available in commercial processes. Device 1 utilizes a backside collector Ohmic contact, while device 2 utilizes a conventional front side ohmic contact. The active layers for both devices were grown by molecular beam epitaxy (MBE). The epitaxial material layers, the doping polarities of the epitaxial layers, and the order of their growth are denoted in slide 4. The InGaP composition was chosen for a lattice match to GaAs, as is conventional practice. The InGaAs emitter contact layer does not match the lattice constant of GaAs and is presumed to have relaxed through the formation of point defects in the layer.

The fabrication process for device 2 HBTs is illustrated in slide 5 and is intended to follow industry-standard fabrication procedures. The fabrication process for device 1 HBTs is similar to that for device 2, except that device 2 does not make provision for thin-film resistors, does not use electroplating (nor a metal 2 process), and does not use a BCB dielectric process. Wet chemical etching is used to form device mesas. Conventional GeAuNi metals are used for collector and emitter ohmic contacts, while PtTiPtAu is used for the base ohmic metal contact. Plasma enhanced chemical vapor deposition of SiN is used for device passivation. The emitter size for device 1 HBTs is 15x1700 μm^2, with multiple fingers, and the emitter size for device 2 HBTs is 10x50 μm^2, with a single emitter finger.

The HBTs were individually packaged in HSOT packages and a storage test was conducted by temperature stressing the HBTs at 220°C, 240°C, and 260°C for device 1, and 260°C for device 2. The stressing was interrupted at regular intervals to test the electrical characteristics of the HBTs at 22°C. The stressing was continued until the parameters of interest degraded by > 20% or until either the base-emitter (BE) diode or the base-collector (BC) diode were effectively shorted.

A total of 9 devices were stressed in each group. In the 220°C group, 6 devices were lost due to a current spike from an electrical tester. One temperature group (260°C, device 2) utilized extra parts to evaluate both HSOT and TO-18 packages. No unusual differences were found among either of the package types.

III. RESULTS AND ANALYSIS

A standard interpretation of the electrical characteristics was utilized in order to identify and track "electrical signatures" representing different regions of the HBTs. These interpretations are illustrated in slides 7-8 and briefly summarized here. For the base current of the Gummel plot, low base-emitter electrical bias results in collector current that increases with an ideality factor n=2 and represents recombination current in the base-emitter depletion region. At higher base-emitter bias, the collector current increases with an ideality factor n=1 and represents recombination current in the neutral base region. This simplified interpretation neglects other possible contributions to the n=1 region of the Gummel plot. From the reverse biased BE diode characteristic, we monitor the breakdown voltage and leakage currents attributed to either base-emitter mesa leakage or bulk junction leakage currents. Likewise, the BC breakdown and leakage currents are tracked from the reverse-biased BC diode. The forward-biased BE and BC diodes are tracked to observe changes in resistance at high diode currents. Resistance effects may also be observable in Ic-Vc plots (not shown).

The electrical changes were tracked over time, as illustrated in slide 9 for a device 1 HBT stressed at 260°C. It is observed that the Gummel plot and the reverse BE diode plot show evidence of degradation at well below 1000 hours of stressed time. The Ic-Vc and forward BE diode plots showed degradation at 2500 hours. However, no degradation was observed in either the forward- or reverse-biased BC diodes. The breakdown voltage of the BC diode even increased as a result of this stressing. These results were typical for all device 1 stress tests.

Thermal stressing of device 2 HBTs was similar to device 1 HBTs, as illustrated in slide 10. Degradation initiated in the low V_{BE} region of the Gummel plot and in the reverse-biased BE diode. However, degradation was also observed in both forward- and reverse-biased BC diodes at later times. In all cases, however, the HBTs reached a condition with a shorted BE diode and a still functioning, though degraded, BC diode.

An Arrhenius analysis was attempted for each type of degradation. Because the device 2 experiment is still ongoing with temperatures other than 260°C, the Arrhenius analysis for device 1 is reported here and only includes three parameters associated with the BE diode: reverse breakdown, β (current gain) at low V_{BE}, and β at high V_{BE}.

The time evolution of reverse BE breakdown and its distribution for device 1 are plotted in slide 11. After a period of parameter stability, the onset of degradation is followed by rapid degradation. This pattern is commonly observed in HBTs by other investigators for β degradation in active stressing of both InGaP/GaAs and AlGaAs/GaAs HBTs. In the 220°C temperature group, the breakdown voltage does not yet exceed 20% degradation. The distributions for the other two temperature groups were best fit using a Weibull distribution with a shape parameter of 2.4. Characteristic failure times (t63.2%) of 6020 at 1240 h were extracted at 240°C and 260°C, respectively. The activation energy for reverse BE breakdown is 1.9 eV.

A similar device 1 analysis was carried out for β at low V_{BE}, and β at high V_{BE}, representing the BE depletion region and the neutral base region, in slides 12-13. For β at high V_{BE}, the Weibull shape parameter and activation energy are substantially the same as for the BE diode reverse breakdown. For β at low V_{BE}, the Weibull fit is not as good as for the other two parameters, possibly due to the limited sample size in the lowest temperature group, and possibly due to factors unique to the n=2 region of the Gummel plot. The Weibull shape parameter is 3.1 and the activation energy is 1.9 eV.

The evolution of the same three parameters for device 2 at 260°C is shown in slide 14. Although the degradation times are shorter than for device 1 HBTs, the pattern of degradation is similar.

An Arrhenius plot is shown in slide 15. The three upper lines represent the device 1 parameters with nearly identical activation energies. The lower line for device 2 assumes an activation energy of 1.9 eV (yet to be verified). It is seen that the device 2 HBTs have a larger exponential pre-factor that leads to a significantly greater degradation. Yet, it may not raise a concern for extrapolation to lower temperatures of interest. For an assumed storage requirement at 70°C, the median time to failure extrapolates to > 10^{12} h. At the mil spec temperature of 125°C, MTTF extrapolates to > $3x10^8$ h.

IV. Discussion

For all experiments reported in this study, the initial degradation observed comes from either the n=2 region of the base current in the Gummel plot or the reverse-biased BE diode breakdown voltage (changes in the reverse-biased BC diode plot of slide 10 are more of a burn-in effect than a degradation). The former degradation is clearly related to defect generation and is quite often observed in HBT reliability studies that combine thermal and current-injection stressing.

We also tentatively associate defect generation as a likely cause for changes in the reverse BE breakdown voltage, though more work is needed to prove this assertion. The BE breakdown voltage is not sharp enough to be associated with avalanche, as is the case for BC breakdown. Defect-mediated leakage appears to be a more likely cause for the reverse BE current characteristic, and defect generation is a likely cause for the time evolution of the leakage since defect generation in the BE depletion region has already been positively identified from the n=2 region of the Gummel plot.

Thermal degradation of collector and base Ohmic contacts have been previously observed with activation energies of 1.94 eV and 1.8 eV, respectively in one study [2] and a collector Ohmic contact degradation activation energy of 1.5 eV in another study [3]. Our results clearly illustrate that in InGaP/GaAs HBTs, thermally generated crystalline defects in specific regions of the HBT can predominate relative to metal contact degradation, assuming that the latter is not indirectly related to the former. Activation energies for the different types of defect buildup are of comparable magnitude to those for ohmic metal degradation. In order to manifest themselves, crystalline defects do not require charge injection.

This work raises a number of questions that will require further investigation to answer adequately. First, we note that most reliability studies are carried out with MOCVD (metal-organic chemical vapor deposition) as the growth method. One can ask to what extent the relative lack of hydrogen in the base of MBE material affects the degradation characteristics observed. Second, the possibility of decoupling thermal and current-injection effects should be explored with HBTs utilizing a similar epitaxial material and fabrication process as a suitable control. This can help answer questions regarding the magnitude of the enhancement of degradation in recombination-enhanced defect reactions.

V. Conclusion

An Arrhenius analysis of thermally stressed InGaP/GaAs HBTs was performed for three parameters, which we associate with defect generation: β at low V_{BE}, β at high V_{BE}, and reverse-breakdown of the base-emitter junction. The activation energy for all three parameters was approximately 1.9 eV. These activation energies are comparable to those associated with contact metal degradation, also believed to occur mainly as a result of thermal stress. HBT failure in all cases occurred at the base-emitter junction prior to failure at the base-collector junction, and in many cases prior to any degradation at the base-collector junction.

Acknowledgement

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

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