RELIABILITY ANALYSIS OF MICROWAVE GaAs/AlGaAs HBTs WITH BERYLLIUM AND CARBON DOPED BASE.

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ABSTRACT

The reliabilty characteristics of microwave GaAs/AlGaAs Npn Heterojunction Bipolar Transistors (HBTs) with beryllium (Be) and carbon (C) doped base layer has been investigated and compared by means of constant stress lifetest. Three groups of Be doped devices using a newly developed MBE profile exhibit a median-time-to-failure (MTTF) of up to 1.8×10^8 hours at 125°C junction temperature based on the lifetest characteristics of dc current gain, ß. The C doped devices displays a MTTF of 4.2×10^5 hours under the same conditions. An equivalent failure rate of <0.1 FITs and 119 FITs at 10^5 hours were calculated for Be and C doped devices, respectively. Data on HBT stability are essential for microwave circuit applications.

INTRODUCTION

GaAs/AlGaAs Heterojunction Bipolar Transistor (HBT) technology has matured rapidly in recent years and has been demonstrated to have inherent advantages in performance over its silicon counterpart and GaAs MESFET and HEMT technologies [1-3]. One of the next technological issues to focus on is the reliability and stability of HBT technology. Detail reports of Be redistribution during MBE growth [4,5] and during device operation under forward current injection [6-8] shows a serious concern in HBT technology. However, recent advances in MBE growth process have shown that Be redistribution can be controlled to produce well defined and stable Be profile [9].

Presented in this paper is a reliability analysis of various discrete Npn GaAs/AlGaAs HBTs using beryllium (Be) and carbon (C) as the p^+ dopant for the base epitaxial layer. Reliability assessment was based on a constant stress lifetest conducted at three temperatures and using the DC current gain (ß) as the critical device parameter. For this lifetest, a 10% degradation in pre-stress ß at a 1mA collector current was established as the failure criteria. The reported data provides supporting evidence that HBTs can be developed as fundamentally stable structures to be used in monolithic microwave and digital integrated circuit applications. The data presented is the first reported in-depth reliability analysis and comparison of various HBT structures.

DEVICE FABRICATION

The various devices used in this study are 3x10 μm^2 single emitter HBTs fabricated using a common doping profile but grown under various material growth conditions. The epitaxial growth profile for the HBT structure used in this study is shown in Figure 1. Variation in growth condition was mainly focused on the p^+ base layer which includes Be doped base by molecular beam epitaxy (MBE) and C doped base by metal-organic chemical vapor deposition (MOCVD). Other variations include perturbations on the baseline substrate temperature used during Be growth by MBE. Table I summarizes the variation between the four groups of HBTs under study. The difference between the Be/570 and the Be/570,EM+ device is that in the latter device the subsequent emitter layer growth was performed at an elevated substrate temperature. In all three Be groups, the As flux during base layer growth was 3 times higher than the As:Ga flux ratio used during collector growth.

Other device features which was kept consistent among the four groups is the use of silicon as the n-type dopant and a 1200Å wide gap emitter layer of $Al_{0.3}Ga_{0.7}As$ with a 300Å $Al_xGa_{1-x}As$ grading on both sides. AuBe/Pd/Au and AuGe/Ni/Ti/Au metalization were used for alloyed p-type and n-type ohmic contact,

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TABLE I. HBT LIFETEST MATRIX

DEVICE	p+ BASE LAYER GROWTH CONDITIONS				POPULATION SIZE		
	PROCESS	BASE DOPANT	SUBSTRATE TEMPERATURE (°C)	As FLUX	@ 240°C	@ 260°C	@ 280°C
Be/570	MBE	Be	570	x3	16	17	16
Be/570,EM+	MBE	Be	570, EM+	x3	14	14	14
Be/580	MBE	Be	580	x3	13	16	14
Carbon	MOCVD	C	---	---	16	16	16

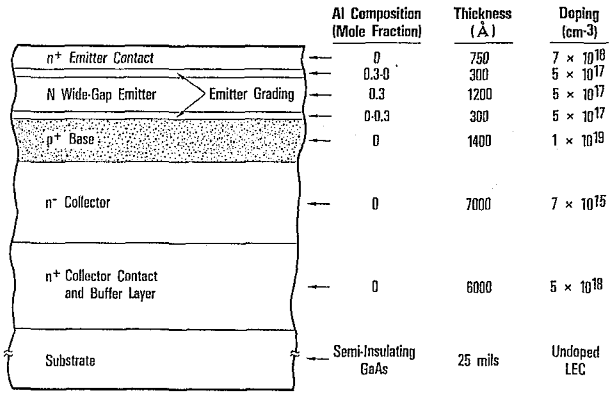

Figure 1. Epitaxial profile of baseline HBT structure where the p+ layer is either Be or C.

respectively. All devices were fabricated using TRW's Self-Aligned Base Ohmic Metal (SABM) baseline process. Details on the SABM fabrication process have been reported earlier [3,9]. After fabrication, the HBTs were mounted on 16 pin DIP packages using conductive silver epoxy and bonded with 0.7 mil gold wire.

EXPERIMENT AND RESULTS

The experiment is a constant stress lifetest at 240, 260 and 280°C ambient temperature. Table I lists the population distribution for each test cell. Not included in Table I are 2-4 control parts (no DC bias) per group and temperature. Over 215 discrete HBTs were subjected to this study. Post epitaxial growth processing is assumed to be identical over the various wafers and not a reliability factor in this study. Electrical testing at 25°C was done periodically to monitor degradation in dc current gain, ß. ß was measured at a 1.0 mA collector current (Ic). The lifetest with periodic electrical testing was continued until greater than 70% of a cell's population failed. During thermal stress all HBTs, excluding control devices, were subjected to a forward bias of Vce=3.0v and Ic=2.0mA (6.67×10^3 A/cm^2). No RF bias was applied during thermal stress. The DC setting is based on nominal operation condition expected in actual applications. The thermal stress and electrical testing were performed under fully automated conditions. In electrical testing, the HBT's forward Gummel characteristics was measured using a HP4145B Semiconductor Parameter Analyzer.

Figure 2 shows typical changes observed during lifetest of a forward biased and an unbiased HBT at 240°C ambient temperature. Figure 2a is a Gummel plot of a forward biased, thermally stressed HBT before thermal stress (t=0 hours) *and after failure (t=550 hours). Figure 2a is an* early lifetest failure showing a 20% degradation in ß after 550 hours. In Figure 2b, at Ic=1mA, no degradation in ß and a minimal shift in Vbe of 7 mV was observed after 1600 hours of unbiased thermal stress. The reduction in base and collector current at low injection levels is due to annealing effects during thermal stress.

For analysis, a 10% degradation in ß or $ß/ß_0<0.9$ was established as the failure criteria. Each cell was sufficiently stressed to extract the median lifetime, t_{50}, of that cell. *Figure 3 is the log-normal plot of cummulative* failure for the Be/570,EM+ device group. For this group, the log standard deviation, σ, of 0.70 was calculated by least square fitting of the log-normal distribution. All experimental data fitted a log-normal distribution and the Arrhenius plot for the four HBT groups is shown in Figure 4. Compensation for an estimated thermal rise of 12°C in junction temperature

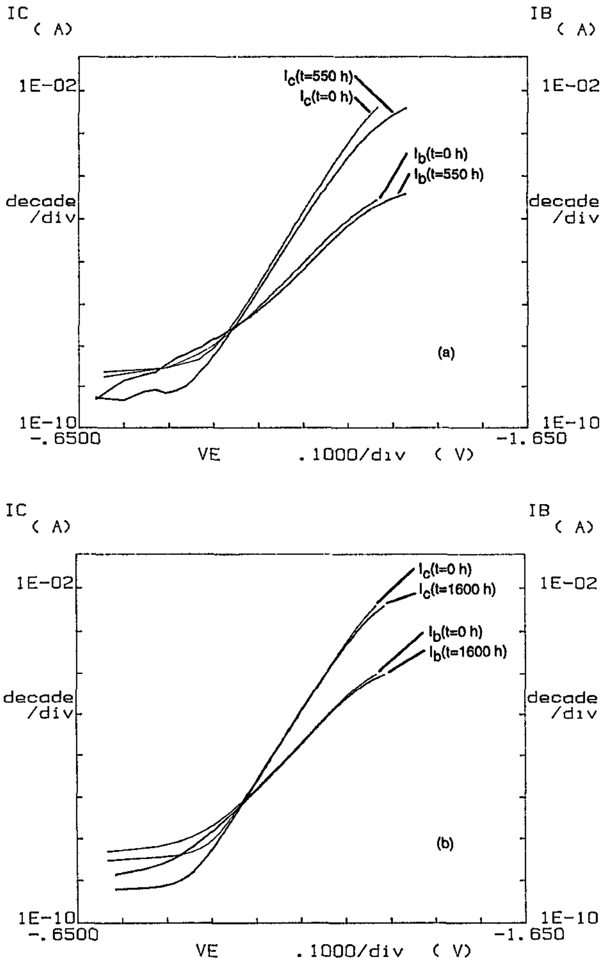

Figure 2. Typical changes in forward Gummel characteristics of (a) forward biased and (b) unbiased Be/570°C, EM+ HBT subjected to 240°C thermal stress.

over ambient temperature has been factored into Figure 4. This 12°C rise is a conservative estimate based on liquid crystal measurements and thermal conductivity, k(T), of GaAs. Table II lists the calculated activation energy (Ea), median-time-to-failure (MTTF) and failure rate. Also listed in Table II is the corresponding log standard deviation defined as $\sigma \approx \ln(t_{50}/t_{16})$ where t_{16} is the time when 16% of a cell's population fails. The Be doped groups display a highly reliable characteristic of less then 0.1 FITs at the end of a 10^5 hour (11.5 year) mission while the C doped group have shown a higher but acceptable failure rate of 119 FITs at 10^5 hours. One FIT is defined as one failure per 10^9 device hours.

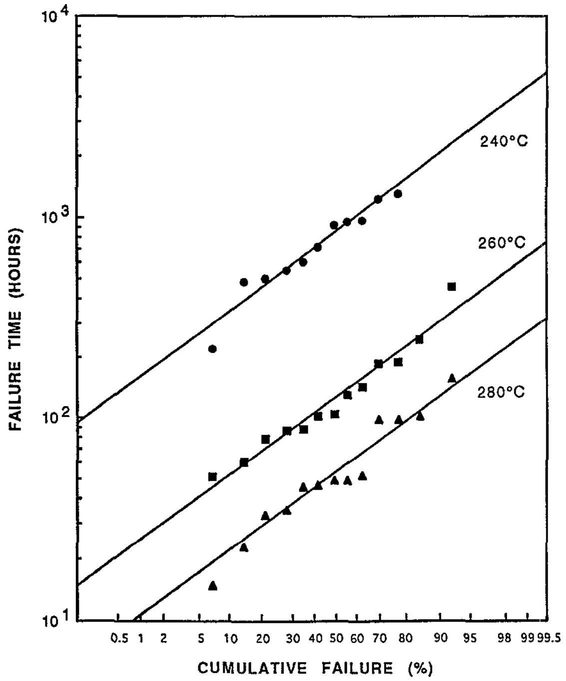

Figure 3. Log-normal plot of Be/570°C, EM+ group. σ = 0.7.

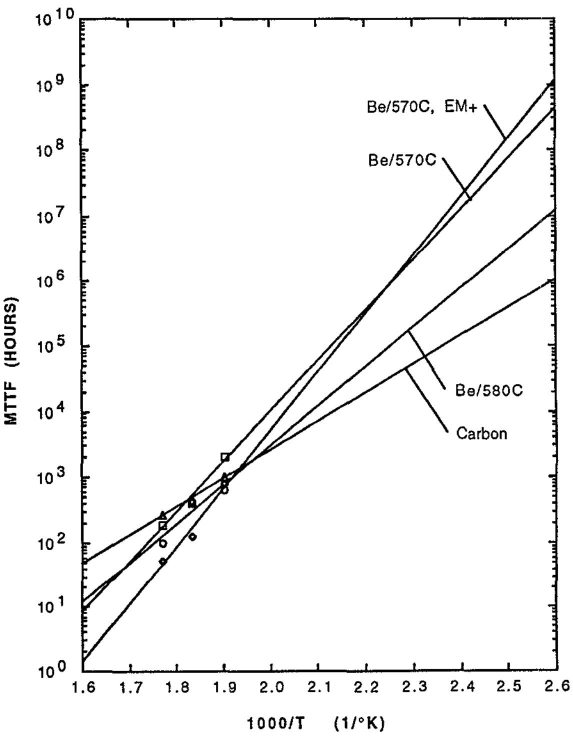

Figure 4. Arrhenius plot displaying median life as a function of inverse junction temperature. A 12°C junction temperature rise have been factored into this plot.

TABLE II. HBT LIFETEST RESULTS

DEVICE	Ea (eV)	MTTF (hrs) @ 125°C	σ	FAILURE RATE (FITs)
Be/570	1.53	$8.4x10^7$	0.75	<0.1
Be/570,EM+	1.77	$1.8x10^8$	0.70	<0.1
Be/580	1.19	$3.3x10^6$	0.61	<0.1
Carbon	0.86	$4.2x10^5$	0.61	119

DISCUSSION

For the Be doped HBT structure, the dominant failure mechanism is the diffusion of positively charged interstitial beryllium (Be^+) from the base to graded base-emitter AlGaAs layer during forward bias operation [8-10]. As a result of Be^+ redistribution, a potential spike in the conduction band of the base-emitter region is formed which reduces electron injection and therefore reduces ß [11]. The validity of this failure mechanism is further supported by the negligible change observed in ß of thermally stressed but unbiased control devices as shown in Figure 2b. Low substrate growth temperature and high As:Ga flux ratio during MBE growth of Be is believed to suppress Be^+ formation which results in a reliable Be doped HBT structure [9]. Also, Nakajima et al. [7] provides data that lower Be doping concentration improves device stability. This study provides results that while the Be redistribution process is not completely eliminated it can be controlled and minimized to produce highly stable Be HBT structures.

The failure mechanism is believed to be the same for all three Be groups. The difference in Ea and σ shown in Table II are due to Be growth conditions. The different MBE growth condition establishes an initial state in the bulk base and base-emitter junction which then governs the degradation rate in ß during forward current injection.

For the C doped structure, the median lifetime was the highest among all four groups at 260°C and 280°C and second highest at 240°C however, its low activation energy projects a MTTF at 125°C that is lowest among the four HBT groups (see Figure 4). The failure mechanism in the C doped structure have not been investigated in this study.

SUMMARY

The reliability assessment of four HBT device groups have been presented with all groups showing acceptable to excellent performance based on the lifetest characteristics of ß. Based on the Be/570, EM+ data, a MTTF of $1.8x10^8$ hours at 125°C junction temperature is projected with corresponding $\sigma=0.7$ and Ea=1.77 eV. This corresponds to a failure rate of less than 0.1 FITs for a 10^5 hour (11.5 year) mission. The other two Be groups also displays a failure rate of less than 0.1 FITs at 10^5 hours. C doped devices were measured at a respectable failure rate of 119 FITs.

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