THE CORRELATION BETWEEN MATERIAL PROPERTIES AND HBT RELIABILITY

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ABSTRACT

The impact of the material quality on the reliability of heterojunction bipolar transistors (HBT) is discussed. So far, a clear impact of the material structure is clearly found on the electrical performances of HBT's. The InGaP/GaAs heterostructure shows impressive reliability figure compared to the AlGaAs/GaAs ones. This behavior is strongly related to the surface passivation of the extrinsic base layer. Three main behaviors are believed to have a positive impact on the reliability: higher electron injection, better stability of the InGaP material, better InGaP passivation. Aging tests have been carried out for more than 6,500hr on 100 devices without any catastrophic failure at stress as high as junction temperature of 200°C and collector current of 40kA cm^{-2}. This result confirms the excellent reliability of InGaP/GaAs HBT and enables to use them in high power applications.

INTRODUCTION

GaAs devices are now widely used for microwave applications. Products have finally emerged with a strong market growth due to the emerging wireless market. Amid those devices, MESFET's are now the most used devices thanks to their costs and maturity. However HFET's (generic name of any field effect transistor including at least one heterojunction with any kind of doping management) first developed on 1980 (1) are also quite used thanks to their low high frequency noise, power capability and extremely high f_{max}. HBT's whose development started in the mid '80s (2-3) for microwave applications are now also coming to commercial market.

AlGaAs/GaAs HBT's VERSUS InGaP/GaAs HBT's

III-V HBT's are mostly obtained using AlGaAs/GaAs or InGaP/GaAs heterojunction. The first ones has been mainly used thanks to the easy lattice matching between $Al_xGa_{1-x}As$ and GaAs for almost all the aluminum content. This epitaxial behavior is however embedded by various limitations compared to InGaP material. The table I shows a synthesis of the key material features of these two heterojunctions. Due to a better bandgap matching for the HBT operation, InGaP/GaAs heterostructures require no emitter-base interface grading and also a better electron injection.

The heterojunction materials have also a strong impact on the processing and devices characteristics.

- Etching selectivity has a strong impact on the wafer electrical uniformity. InGaP offers extremely high etching selectivity compared to AlGaAs
- Passivation of InGaP is easier than AlGaAs
- Breakdown voltage is 80% higher for InGaP than AlGaAs

InGaP/GaAs HBT's

The table II shows a typical N-P-N InGaP/GaAs HBT structure. The epitaxial structure includes 12 layers to achieve the appropriated DC and RF performances. The presented structure is suitable to RF applications up-to 20GHz associated with common emitter breakdown voltage above 15V. The base and collector layers have a strong impact on the final performances. The current gain of the device is very sensitive to both the lifetime of minority carriers in the base and to the device passivation, but most of the applications required values ranging from 30 to 150. The device passivation of HBT seems to be mostly realized by leaving on the extrinsic base layer a thin layer of wide bandgap semiconductor to stabilize the base surface.

The device performances and reliability are directly impacted by the epitaxial structure. Table III shows the direct impact of the material on the device reliability as it is understood by the III-V HBT community. This table shows the strong impact of the material control over the electrical performance of the devices and the reliability.

HBT reliability improvement is mainly driven by material and processing studies. As it can be seen in table III, almost all the parameters are strongly coupled.

The set of analysis to be carried out to improve the reliability requires deep material and device characterization such as :

- AFM
- X-Ray diffraction
- SIMS measurement
- Photoluminescence
- TEM
- Fine electrical measurements
- Long term aging

By using all these characterization tools and by using full experiment plan, impressive reliability improvements can be achieved. The current gain is the main weak parameter of HBT devices under thermo-electrical stress, associated with base leakage increase.

EMITTER MESA AND CONTACT

The Figure 1 shows the schematic of an InGaP/GaAs HBT cross-section. The typical emitter size is 2µm for microwave applications.

The impact of the top InGaAs layer ensuring the emitter ohmic contact is fundamental to device quality and reliability. Those layer has a direct influence on the respect of the emitter size and access resistance. In the specific case of InGaP HBT, the stability of this layer with HCl-based agent is fundamental to avoid emitter stripe undercut and high emitter resistance increase. This phenomenon imposes important material optimization of the InGaAs layer and appears very sensitive to growth process.

The etching behavior of the emitter material sandwich is also quite sensitive on process management. The control of all the thin ledge layer is quite critical both in term of remaining thickness and lateral size. The etching behavior of the InGaP emitter has to be optimized for easy HCl-based etching. Slightly ordered InGaP appears the right choice for device processing and DC performances.

AlGaAs/GaAs HBT's suffer of different limitation during the emitter mesa etching. The lack of satisfactory etching selectivity between AlGaAs and GaAs induces a difficult control of the emitter mesa to stop on the base layer. This imposes in general the use of thin total emitter thickness. Full dry etching process with in situ etching control is quite useful to master the emitter mesa etching.

CURRENT GAIN AND BREAKDOWN VOLTAGE

The current gain is the key parameter of the bipolar devices. The most direct control of the material quality assessment uses the ratio between the current gain b and the base sheet resistance. This ratio should be in the range of 0.25 Ω^{-1} for constant emitter doping level of 3 x 10^{17} cm^{-3}. The impact of the current gain on the breakdown voltage is very strong in the case of common emitter operation (BVceo). The Figure 2 shows the evolution of the common emitter breakdown voltage of GaAs-based HBT as a function of current gain. This experimental curve has been obtained for HBT's with 1µm thick GaAs collector doped at $2x10^{16}$ cm^{-3}.

HBT RELIABILITY

An important HBT project has been settled to improve the reliability of HBT for microwave power applications mainly for X-Band applications. An important research activity has been realized to achieve satisfactory reliability professional applications. The present status is quite encouraging. The Figure 3 shows the current gain evolution of InGaP/GaAs HBT's processed by Thomson-CSF/LCR. The stress condition of the devices is 40kA cm^{-2} at 200°C over 5800hr. The HBT's are $2x30\mu m^2$ monofinger devices. These devices are non-selfaligned and can be used up to C-Band for high power applications with power added efficiency above 50%. The collector current is kept constant using real time feedback loop for each devices. Various stress conditions have been applied on HBT's from 150°C to 200°C and 20 to 60 kA cm^{-2}. The total aging test duration for all the stress condition reaches 450,000 hr and no catastrophic failure has been so far observed. The slow initial current gain decrease is believed to be due to hydrogen contamination of HBT devices.

This reliability result shows the excellent stability of InGaP/GaAs HBT's. Hewlett-Packard (4) has published last year similar results and concluded that AlGaAs reliability figure is ten time worst than InGaP/GaAs one. Sharp and associated partners (Kopin and Urbana University) have also obtained excellent results with the InGaP/GaAs material (5) and also the Fujitsu Laboratories (6). The origin of this strong difference is not yet understood, but may rely on three different material/process factors :

1. The better bandgap matching and higher bandgap of InGaP compared to AlGaAs allow a higher electron injection efficiency, leading to lower amount of electron-hole recombination in the emitter, which could decrease the number of defect creations.
2. The energy to furnish to deplace atoms in the InGaP lattice should be higher than for AlGaAs, which is made with atoms having roughly the same size. In the case of InGaP, the size of indium atoms
3. It is well known that In-based material presents an easier passivation than Al-based compound. This behavior allowed in the late '80 to study the InP MISFET and not the GaAs ones.

CONCLUSION

The HBT reliability is sensitive to material and process quality. The material aspects have a direct impact on the degradation mechanisms and the device electrical performances. HBT reliability improvement relies on strong cross-disciplinary studies. InGaP/GaAs HBT's are now appearing like an excellent solution to achieve high HBT reliability. Thomson-CSF/LCR has demonstrated stable device with lifetime over 5800hr at 40kA cm^{-2} at 200°C. The total aging test reaches 450,000hr without any catastrophic failure for stress conditions ranging from 150°C to 200°C and for collector current density ranging from 20 to 60 kA cm^{-2}.

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	Bandgap (eV)	ΔEc (eV)	ΔEv (eV)	Traps	Mismatch
$Al_{.3}Ga_{.7}As$	1.78	.24	.15	DX-Center	~0
$In_{.49}Ga_{.51}P$	1.89	.17	.31	No	$<10^{-3}$

Table I : Main material characteristic of AlGaAs and InGaP

Material Compound	thickness	Doping level or equivalent
$GaIn_{50}$ As Cap (with grading)	≈ 100 nm	≈ 1.10^{19} cm^{-3}
GaAs Cap	160 nm	≈ 2.10^{18} cm^{-3}
GaInP Contact	100 nm	1.10^{18} cm^{-3}
GaInP emitter	150 nm	3.10^{17} cm^{-3}
GaAs etch-stop	10 nm	3.10^{17} cm^{-3}
GaInP ledge	20 nm	3.10^{17} cm^{-3}
GaAs p+ base	100 nm	≈ 200 Ω per square
GaAs collector	1000 nm	$1,8.10^{16}$ cm^{-3}
GaAs n+ sub-collector	100 nm	1.10^{18} cm^{-3}
GaInP n+	25 nm	1.10^{18} cm^{-3}
GaAs n+ sub-collector	800 nm	2.10^{18} cm^{-3} and below 12 ohms per square
(100) GaAs Substrate	650µm	Semi-insulating

Table II : Typical InGaP/GaAs HBT

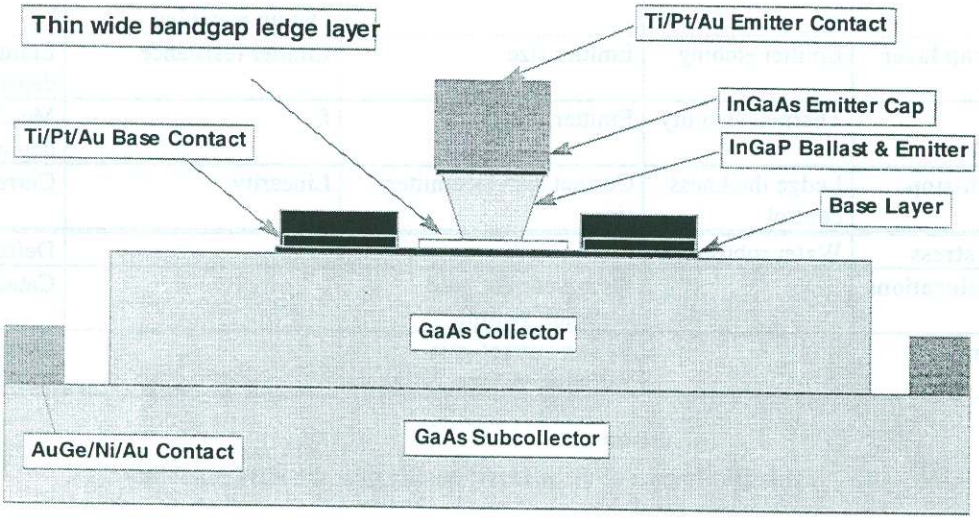

Figure 1 : Typical InGaP/GaAs HBT Cross-section

Parameters	**Processing**	**Electrical Parameter**	**Electrical Impact**	**Reliability Aspects**
Base Sheet Resistance		Current Gain	Power added efficiency	Carbon precipitates, Hole recombination into the emitter
		Base resistance Ohmic contact resistance	RF gain, Early voltage, Power added efficiency, Low 1/f noise	
Base thickness		Transit time (f_t)	RF gain	Carbon precipitates, Strain due to carbon
Emitter doping level		Current gain	Power added efficiency	Hole recombination in the emitter
Total emitter thickness	Emitter mesa etching	Emitter resistance	RF gain Thermal runaway	
Emitter material	Emitter mesa etching	Emitter size Base contact	Emitter resistance (f_{max}) Base resistance (f_{max})	Emitter current density
	Bandgap	Electron injection	Current gain	
Collector doping level		Base-Collector capacitance Kirk effect	f_{max} f_t and Output power	
Collector thickness	Base-collector mesa etching	Base-Collector capacitance	f_{max}	
Subcollector sheet resistance		Collector resistance	f_t Power added efficiency Output matching	
InGaAs cap layer	Emitter etching	Emitter size	Emitter resistance	Emitter current density
	Thermal stability	Emitter resistance	f_t	Metallurgical degradation
GaAs etch-stop	Ledge thickness control	Current gain vs emitter size	Linearity	Current gain stability
Residual stress	Wafer robustness			Defect migration
Native dislocations		Strong current gain variation vs time		Catastrophic failure
Hydrogen		Strong current gain variation vs time		Current gain instability

Table III : Impact of the material quality over the HBT reliability

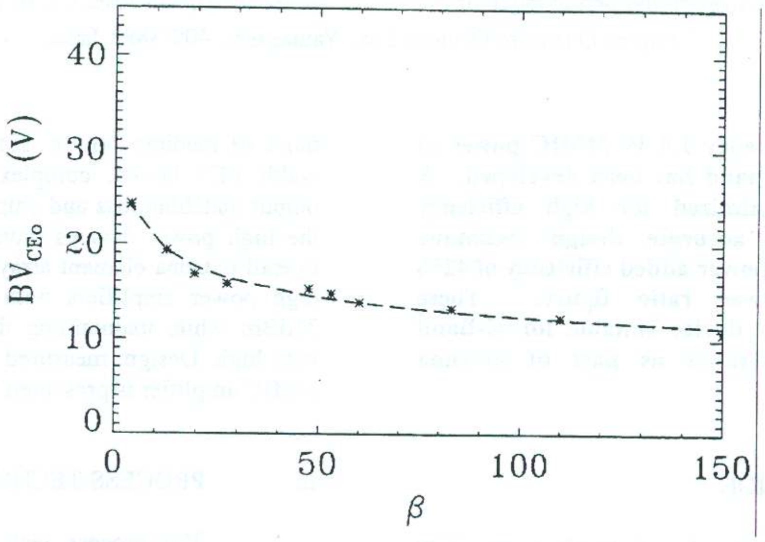

Figure 2 : Impact of current gain on HBT breakdown voltage (BVceo)

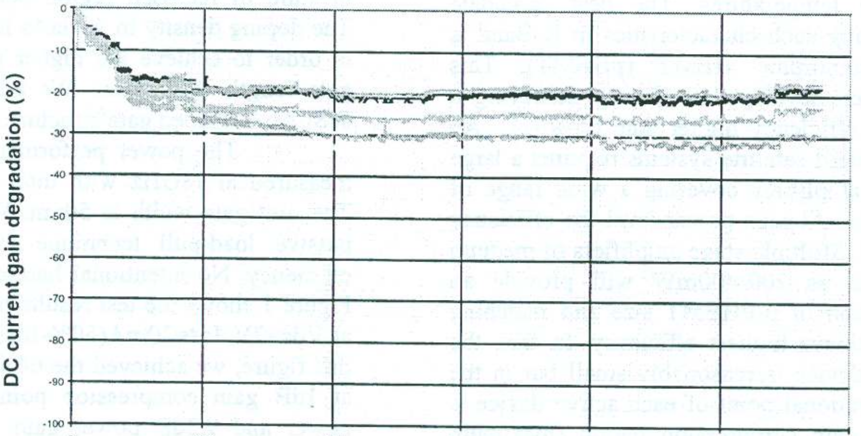

Figure 3 : Current gain evolution versus time of InGaP/GaAs HBT

(40kA cm^{-2}, 200°C)