HERO'S PROJECT AS AN EXAMPLE OF EUROPEAN PROGRAMME ON RF DEVICE IMPROVEMENT

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ABSTRACT

This paper presents the BRITE-EURAM HERO'S project dedicated to the reliability improvement of InGaP/GaAs heterojunction bipolar transistor (HBT) for oscillator and power applications. The key actions are to allow the emergence of a European source of InGaP/GaAs MOCVD material (EPI - UK), to allow a better understanding of the mechanism involved in current gain degradation, to develop new pulsed current aging test, and to evaluate the impact of the device reliability improvement on the performance of X- and Ku Band oscillators and amplifiers.

INTRODUCTION

The HERO'S project is the acronym of "**H**BT **E**pitaxy **R**eliability **O**ptimization and **S**ources". The objective of the project is to allow the emergence of a European source of reliable heterojunction bipolar transistor (HBT). Since the quality of the material is very crucial for obtaining devices with the required reliability, HERO'S project involved partners with complementary expertise from material epitaxy to electronic systems. The objective of the project is to give rise to HBT's for oscillator and power use with reliability as high as 10^6 hours at 30 kA cm^{-2} at junction temperature of 150°C for RF devices working up to 20GHz. This reliability objective complies to the system requirement.

The principle of the project has been settled at the end of 1997 and has been submitted to **BRITE-EURAM** proposal on May 1998. Its contract number is **BRPR-CT98-0789** with A. Lewis as Project Officer. The project has started on October 1998. The project duration is fixed at 30 months.

HERO'S

PARTNERSHIP

The project includes 9 partners from European Academia and Industry. The Table 1 shows the different partners involved in the HERO'S project and their key expertise used in the frame of this project.

PROJECT MANAGEMENT

Thomson-CSF/LCR is the project Coordinator. For project efficiency, the Technische Universität Chemnitz is a major subcontractor and Thomson-CSF Communications (TCC) is an associated partner.
The project is managed using a three Committee structure. The Figure 1 shows the project structure including the participation of the different partners in the different Committees.

- **Steering Committee** : The Steering Committee is formed to solve all the management issues (technical, exploitation, financial, planning, information exchange, supervision). This Steering Committee meets 3 times a year and discusses delivery exchange, publications, intellectual property rights, in accordance with the terms of the contract. Technical meetings between the participants, involving more than one work package, are decided if necessary and called by the Steering Committee. The Table 2 lists the persons involved in the Steering Committee.
- **Technical Committee** : For efficient project operation, the technical tasks have been split into 2 work packages. The task leaders inside these two work packages are playing a key role for project control. These task leaders are members of the technical board of HERO'S project. The Table 3 shows the Technical Committee members.
- **Exploitation Committee :** Industrial partners are reserving specific time for the exploitation of the results. This is quite important to ensure the full use and advertisement of the on-going project. The Table 4 shows the Exploitation Committee and the actions of the different members.

The work is divided in two work packages : one is focused on the material study and the second is focused on the reliability assessment. The work has been distributed within the different partners in the following way (c.f. Table 5).

PROJECT OBJECTIVES

The main HERO'S project objective is to deliver to the European market a commercial source of reliable InGaP/GaAs HBT wafers. If the HBT reliability is improving very rapidly worldwide for mobile phone or instrumentation applications (1-2), i.e. at operation frequency up to 1.8GHz and at medium output power, additional work has to be carried out for applications at higher frequency and higher output power density. This application field is addressed by the HERO'S project. The objective of the project is give to rise to HBT's for oscillator and power use with reliability as high as 10^6 hours at 30 kA cm^{-2} at junction temperature of 150°C for RF devices working up to 20GHz.

The main effort is devoted to optimization of crystal growth conditions (EPI, TH-CSF/LCR), hydrogen effect on HBT reliability (CNRS/LPM, NMRC, TH-CSF/LCR), atomistic simulations (NMRC), advanced material characterization such as photoreflectance or DLTS (NMRC), processing (TH-CSF/LCR, UMS), reliability assessment using long term aging (TH-CSF/LCR) and new pulsed procedures (TUD, TUC). The end-users will assessed the effect of the reliability device improvement by making hybrid 10GHz VCO's (TCC)and 14GHz 0.25W amplifiers (Farran). Those RF circuits will be then used around 40GHz using tripler multipliers. It has to be recalled that the Consortium benefits of the know-how already developed in the frame of the **ESPRIT project 21,375** entitled **GAMMA** in which one objective was the development of InGaP/GaAs HBT presenting satisfactory RF performances .

PROJECT ACHIEVEMENTS

Despite the recent start of the HERO'S project at the date of the writing of paper, the project has already obtained major achievements, in both the material and reliability fields.

A. MATERIAL ACHIEVEMENT

EPI has grown samples to allow the Consortium to carry out the studies. Epitaxial structures are either full HBT structures made to realize active devices or test structures to characterize the impact of the growth condition on the material quality. In all the case, the specific layers comply with the HBT specificity, at least for the doping levels, to allow direct feedback to the device needs. The key layers of the device of HBT's have the following characteristics :

- InGaAs/GaAs emitter cap layer : up to 1 x 10^{19} cm^{-3}, 200 nm
- InGaP spacer : 1 x 10^{18} cm^{-3}, 100 nm
- InGaP Emitter integrated ballast resistance : 1 x 10^{17} cm^{-3}, 150 nm
- InGaP Emitter layer : 3 x 10^{17} cm^{-3}, 150 nm
- Base layer : 3 x 10^{19} cm^{-3}, 100 nm
- Collector layer : 1.8 x 10^{16} cm^{-3}, 1 µm
- Subcollector : 2 x 10^{18} cm^{-3}, 800 nm

The Table 6 shows typical average values of key HBT electrical elements of 2 different wafers. The one-sigma dispersion on all the element is below 5%.

The hydrogen contamination has been identified as a major player of current gain device instability (for instance (3)) during the first hours of device operation. CNRS/LPS in collaboration with NMRC is studying the kinetics of hydrogen incorporation and exodiffusion inside HBT structure. The Figure 2 shows an infrared spectroscopy of a HBT structure with 1µm thick base layer. It has been discovered the presence in the base layer of C=H and C_2=H chemical complexes. The latter ones have not been often reported. Annealing has been carried out at 650°C. The Figure 2 shows that the C=H signal disappears after annealing (2630cm^{-1}), while the C_2H signal at 2690cm^{-1} is stable. This leads to the assumption that C_2H complexes are much more stable than the C=H ones which may explains the difficulty to remove hydrogen from the epitaxial layer. In the mean time, NMRC has carried out, for instance, on various thick InGaP layers, photoluminescence study on the hydrogen study. It appears that post-annealing improved drastically the PL signal of the base due to the recovery of the carbon activity by removing hydrogen sample content (Figure 3). On the same hydrogen topic, atomistic force-field simulations have been carried out to understand the impact of the C_2H complexes on the residual stress in the base. The Figure 4 shows the stress of the lattice around these complexes (big gray spheres are carbon atoms, the small white sphere is the complexed hydrogen atom, meshing around represents the Ga and As atoms of lattice). Thanks to all these studies, EPI is optimizing its growth procedure to both suppress as much as possible the hydrogen incorporation and the presence of C_2 complexes. Other atomistic simulations are also currently made to assess also the possibility to decrease the residual stress of the base induced by the small size of the carbon atoms by using Indium co-doping. The Figure 5 shows that for the C doping used in RF HBT, indium concentration in the range of 6% reduces to zero the stress of the base layer.

B. RELIABILITY ASSESSMENT

Since the HBT reliability assessment is a key part of the project, Darmstadt and Chemnitz Technical Universities are developing a pulsed aging method for two basic reasons :

- Short pulses in the range of 100ns will allow to discriminate the current and temperature contribution on the reliability figure. In the case of classical reliability aging test, self-heating of the device can't be avoided.
- High current stresses are achievable which could speed-up drastically the feedback to the device manufacturer by reducing the test duration.

The HERO'S is just starting and the 2 Universities are up-grading their bench to shorten the pulse duration and carry out 1/f and RF noise characterization just after pulsed stress. The Figure 6 shows the device degradation of old HBT generation (6×10^6 A cm^{-2} - 100ns pulse - Ts = room temperature). This figure shows the Gummel plot of the device which exhibit a drastic increase of the base and collector leakage current as expected with this older technology. Work is starting on newer generation devices. The first RF transistors using improved passivated devices have been produced recently by Thomson-CSF/LCR using EPI material. On-wafer stress tests have been realized at high collector current density (80 kA cm^{-2}) and the self-heating of the device reaches 275°C, as measured by electrical and photoluminescence and confirmed by 3-D thermal simulation. The device stability appears quite excellent since tests above 80hrs exhibit for all tested devices no catastrophic failure. The Figure 7 shows the variation of the current gain of a 2x30μm^2 HBT, which is the main parameter to degrade in HBT's, as a function of the time. Only an initial current gain increased is observed which is strongly related to hydrogen contamination. The Figure 8 shows Gummel plots carried out during the on-wafer stress (c.f. Figure 7), and any increase of the current leakage is observed with this new technology. This is a proof of the good quality of EPI material. On the basis of those on-wafer measurements, it is believed that the lifetime of the device at 150°C and 30kA cm^{-2} should be close to the project objective. The Figure 9 shows the associated RF gains of the same devices at 6V - 33kA cm^{-2} (Class-A condition). The available RF of 10dB is relatively lower than previously due to the use of non-self-aligned devices. New batches are currently under process to come back to RF gain higher than 15dB at 10GHz using UMS lithography capabilities.

CONCLUSION

HERO'S project is addressing the problem of HBT reliability. After 6 months, progresses have been obtained in many fields ranging from material to reliability assessment. Present reliability level achieved with EPI material is promising. Longer aging tests are starting to evaluate more precise reliability figure of those devices. End-users are starting to fabricate oscillators and amplifiers to assess the impact of the device reliability on the RF functions.

Acknowledgements

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Partner	**Country**	**Main Expertise in Project**
Thomson-CSF/LCR	F	Epitaxy, processing, physical & electrical characterization, classical aging tests
Epitaxial Product Int.	GB	Material growth by MOCVD
NMRC	Irl	Atomistic simulation, optical and electrical characterization
CNRS/LPS	F	Effect of Hydrogen on HBT reliability study
TU-Darmstadt	G	Automated Reliability test set-up and pulsed aging test
TU-Chemnitz	G	Instrumentation for pulsed aging and electrical modeling of degradation
UMS	G/F	Back-side processing and process validation
TCC	F	10GHz oscillator
Farran technology Ltd	Irl	14GHz 0.25W amplifier

Table 1: Partners involved in the HERO'S project

Organization	Member
Thomson-CSF/LCR	S. L. Delage
Epitaxial Product Int.	S. Bland
NMRC	G. Crean
CNRS/LPS	J. Chevallier
TU-Darmstadt	H. Hartnagel
TU-Chemnitz	V. Krozer
UMS	D. Pons
TCC	L. Collin
Farran technology Ltd	P. Duffy

Table 2 : HERO'S project Steering Committee

Organization	Member	Deputy
Thomson-CSF/LCR	S. L. Delage	S. Cassette
Epitaxial Product Int.	S. Bland	A. Joel
NMRC	M. Murtagh	J. Greer
CNRS/LPS	J. Chevallier	B. Theys
TU-Darmstadt	H. Hartnagel	M. Brandt
TU-Chemnitz	V. Krozer	K. Kraatz
UMS	D. Pons	H. Blanck
TCC	L. Collin	Y. Guillerme
Farran technology Ltd	P. Duffy	B. Lyons

Table 3 : HERO'S project Technical Committee

Organization	Member	Deputy	Contribution to project exploitation
Thomson-CSF/LCR	S. L. Delage	P. Michel	Public disclosure of reliability results
Epitaxial Product Int.	S. Bland	M. Scott	Advertisement to foundry end-users
UMS	D. Pons	G. Delaval	HBT device market analysis
TCC	G. Cachier	R. De Monts	Impact on oscillator source
Farran technology Ltd	P. Duffy	B. Lyons	Impact on millimeter-wave products

Table 4 : HERO'S project Exploitation Committee

Work package & (Leaders)	Task Leader	Task	Other Partner involved
WP1 : HBT material (S. Bland)	S. Bland (EPI)	1.1. Growth of reliable HBT wafers	NMRC
	J. Chevallier (CNRS)	1.2. Understanding of H effect	NMRC, TH-LCR
	M.A. DiForte-Poisson (TH-LCR)	1.3. Improved base compounds	NMRC, EPI
WP2. HBT reliability (S. L. Delage)	S. Cassette (TH-LCR)	2.1. HBT process	UMS
	M. Brandt (TUD)	2.2. Reliability studies	TUC, TH-LCR
	D. Pons (UMS)	2.3. End-user applications	TCC, Farran

Table 5 : HERO'S Work packages and Tasks

Device	Emitter size (µm²)	Base Sheet Resistance (Ω per square)	β_F (@50kAcm^{-2})	Re (Ω)	Rc (Ω)	BVceo (V)	Bvcbo (V)
SA23	2x30	254.8	58.7	9.5	9.64	18.7	26.92
Jumbo	100x100	/	49.47	/	11.18	18.72	28.03
SA23	2x30	244.7	60.41	10.2	9.83	17.98	23.59
Jumbo	100x100	/	46.38	/	10.56	18.9	27.7

Table 6 : Main electrical parameters obtained with EPI material

Figure 1 : Management structure of HERO'S project

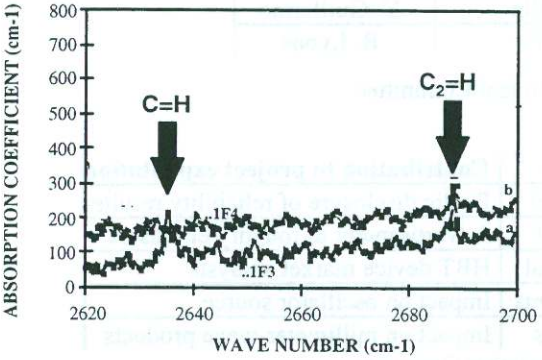


Figure 2 : Infrared (FTIR) spectroscopy of HBT structure before (E3) and after 650°C -30mn annealing

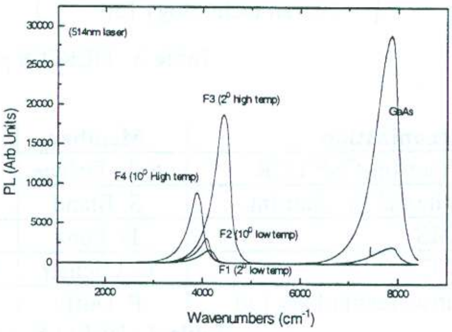


Figure 3 : Photoluminescence spectra of undoped InGaP samples, F1, F2, F3 (various substrate orientation, F4 High Temperature annealing).

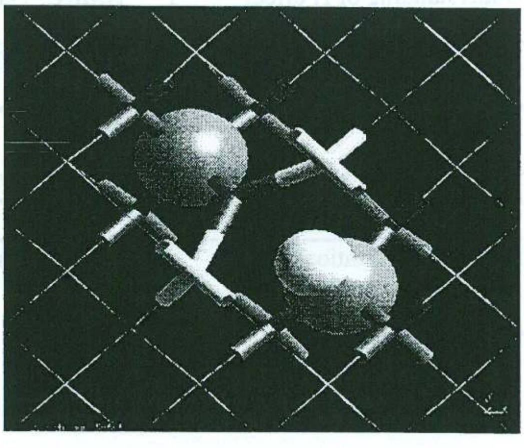


Figure 4 : Geometry of the C2H defect (CAs)2-H complex

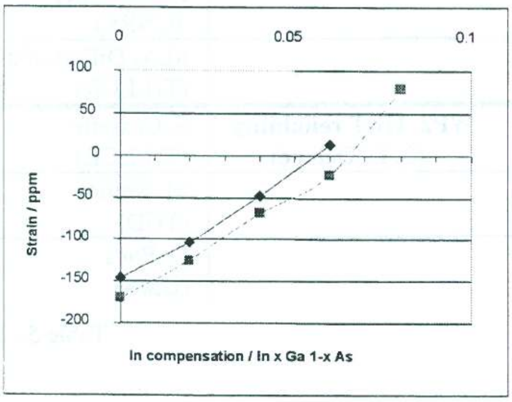


Figure 5 : Impact of indium base co-doping on residual stress (C = 4x10^{19} cm^{-3}). Square : H-free layer, Diamond: Base layer with C-H complexes.

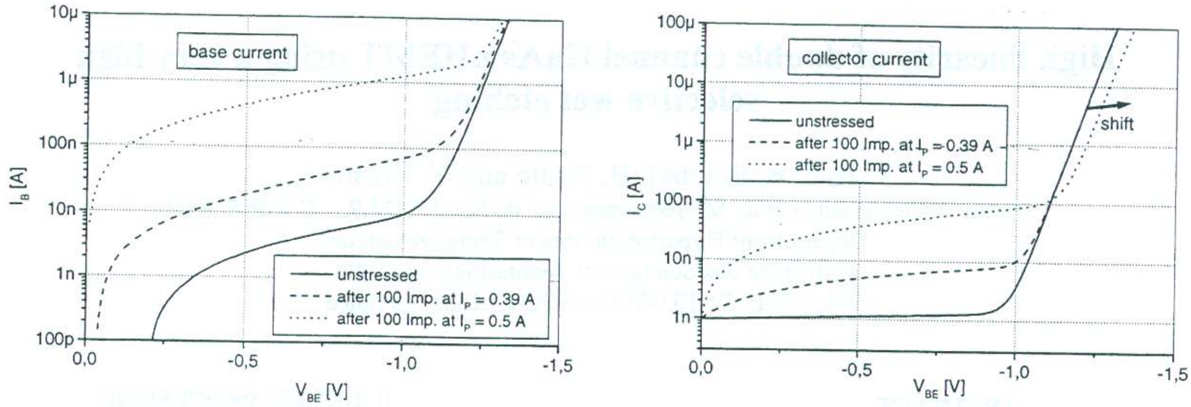
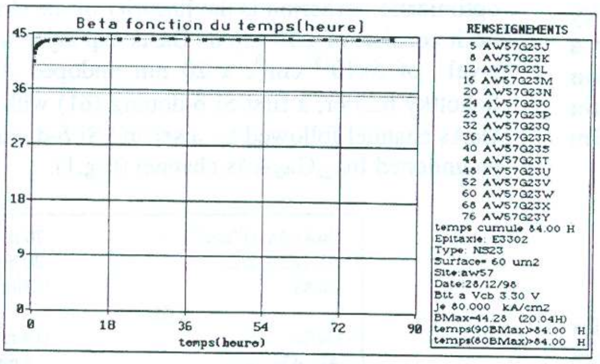


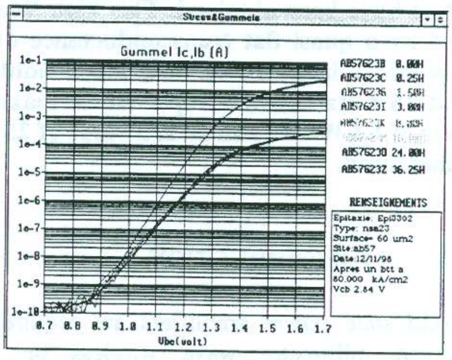
Figure 6 : Degradation of Gummel plot of 2x30 µm² HBT during C-E stress.



RENSEIGNEMENTS
5 AW57G23J
8 AW57G23K
12 AW57G23L
16 AW57G23M
20 AW57G23N
24 AW57G23O
28 AW57G23P
32 AW57G23Q
36 AW57G23R
40 AW57G23S
44 AW57G23T
48 AW57G23U
52 AW57G23V
60 AW57G23W
68 AW57G23X
76 AW57G23Y
temps cumule 84.00 H
Epitaxie: E3302
Type: NS23
Surface= 60 um2
Site:aw57
Date:28/12/98
Btt a Vcb 3.30 V
je 80.000 kA/cm2
BMax=44.28 (20.04H)
temps(90BMax)>84.00 H
temps(80BMax)>84.00 H

Figure 7 : Current gain evolution versus time

(Jc = 80kAcm^{-2}, Pd = 250mW, Tj = 275°C)



RENSEIGNEMENTS
Epitaxie: Epi3302
Type: nsa23
Surface= 60 um2
Site:ab57
Date:12/11/98
Apres un btt a
80.000 kA/cm2
Vcb 2.84 V

Figure 8 : Gummel plots of a stressed HBT at different periods of the stress

(c.f. Figure 7)

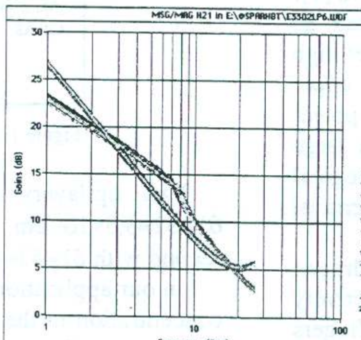


Figure 9 : RF gain (H_{21}, MSG/MAG) of 2x30µm² HBT's)