HBT technology and reliability for satellite applications, within the relatively new APOS project

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1. Abstract

The APOS (Advanced Power Subassemblies project addresses the devices (MMIC or discrete) used in the solid state power amplifiers (SSPA) that drive the transmit active antenna. These are key devices and their electrical and thermal performances have a major impact on both the satellite and the ground terminals. GaAs-based heterostructure bipolar transistor, due to their superior power/linearity performance, could be one of these enabling devices. This aspect will be addressed within the frame of this project through three main objectives :

1. To analyse the reliability of UMS HBT technology and demonstrate it meets the requirements of the commercial satellite markets.
2. To improve the power and thermal performances of HBT by developing a power flip-chip assembly technology using thermal bumps in the active area of the power device.
3. To benchmark the developed power HBT technology by using the power MMIC in a suitable active antenna module.

This project consortium is formed by Alcatel Space, that will co-ordinate the project, United Monolithic Semiconductors (UMS), Thomson-CSF, Institute for Material Research at Limburg University Centrum (IMO-LUC), DESTIN and Institut d'Electronique et de Microélectronique du Nord (IEMN).

2. Main text

Introduction

The GaAs HBT technology is relatively young as compared to the GaAs FET technology . Its development started in the early '80s. Nevertheless, it is already in volume production mainly for RF applications for which it has found several solid openings, benefiting from the booming of the mobile phone market. The world industry leaders are TRW / RFMD and Rockwell in the USA and Sharp in Japan. RFMD, using the foundry facilities of TRW, is claiming that it has manufactured and delivered about 5 millions of HBT per month in 1997, and the forecasts for '98 are 10 millions HBT MMICs per month. To support this exploding production, RFMD has openned in '98 its own 4'' HBT line in Carolina.

Concerning the microwave applications at higher frequencies, the HBT technology has not reached the same level of maturity, albeit impressive performances have been demonstrated especially for power amplifiers (for which record values for output power levels, power-added efficiencies and linearity have been achieved) and for low phase noise oscillator circuits. The performance requirements are more severe; reduced access resistance and parasitic capacitance are necessary, with the consequence that the reliability is more delicate to master. For the HBT microwave applications, and especially for power amplifiers, the industry leaders are T.I. and Northrop Grumann in the USA, but no real production has started and the technology is still in advanced development phase.

In this project, both HBT reliability of United Monolithic Semiconductor and its reduction of thermal impedance through power flip-chip will be addressed.

Consortium description

This project consortium is formed by Alcatel Space, that will co-ordinate the project, United Monolithic Semiconductors (UMS), Thomson-CSF, Institute for Material Research at Limburg University Centrum (IMO-LUC), DESTIN and Institut d'Electronique et de Microélectronique du Nord (IEMN). The project time frame is 30 months with a starting date in October 1998.

Project objectives

The main objective of this project is to introduce HBT technology for satellite (both onboard and ground) applications. This main objective is concurrent with three business and technical objectives. The business objectives are:

- To improve the competitiveness of Alcatel as supplier of advanced telecommunication satellites both for the fast growing Geostationary (GEO) and for the emerging Satellite Personal Communication (S-PCS) and Broadband Multimedia (BMS) markets.
- To confirm UMS as European supplier of reliable, high performance GaAs MMICs and to give it a commercial head start in the satellite markets.
- To help DESTIN market positioning as a supplier of advanced test equipment.

The technical objectives are :

1. To analyse the reliability of UMS HBT technology and demonstrate it meets the requirements of the commercial satellite markets.

2. To improve the power and thermal performances of HBT by developing a power flip-chip assembly technology using thermal bumps in the active area of the power device.
3. To design and manufacture of a power MMIC representative of the BMS application.
4. To demonstrate the performance of the HBT technology by using the power MMIC in a suitable active antenna module.

HBT for space application :

Many satellite systems for the S-PCS and BMS (Skybridge, Teledesic...) will be based on Low Earth Orbit (L.E.O.) satellite constellations in order to minimise the duration of the Transmission between the gateways and the end user, reaching the high interactivity level required for the foreseen applications. The main drawback of L.E.O. constellations is that, in order to maintain fixed Antenna coverage in a terrestrial reference, Antenna have to be continuously re-oriented. It is the reason why these systems are largely based upon Electronically Steerable Active Antennas, which feature better reliability than Mechanical Steerable ones.

Active Antenna concepts for this application make use of small radiating arrays (Approx. 0.5 m of diameter) including about one hundred radiating elements, each one fed by a **Solid State Power Amplifier (SSPA)**. These SSPA's will work in multi-carrier operation mode: namely, each SSPA will amplify several carriers each corresponding to a given spot.

Due to the high number of SSPA per Antenna, power consumption of these SSPA's appears as a major contributor of the power consumption budget at satellite level. In order to minimise the power consumption, SSPA should be operated near their saturation level. Unfortunately, at this level, intermodulation products due to the SSPA non-linear transfer characteristics appear at the output of the SSPA. Consequently, the selection of the SSPA operating point is a compromise between power consumption and linearity.

Linearity performance of SSPA's can be measured by a figure (in dB) that represents the difference between the output power of the amplifier at 1 dB of gain compression and the third order intercept point of the SSPA.

For SSPA's based on MESFET or p-HEMT transistors, which are the two technologies available today, the sate of the art figure is 12 dB. For HBT, it reaches 16 dB or more (for example TRW, T.I.,..) : that means that HBT SSPA's can be driven at a higher compression level than MESFET or p-HEMTs without degradation of the linearity performance or that, for similar output power level and power consumption, they will exhibit better linearity performances.

These improvements will have a drastic impact on future LEO telecommunication systems :

- At satellite level, the reduction of the power consumption (and consequently of the amount of energy that has to be dissipated by the payload) will simplify both the Power Supply and Thermal Control systems, reducing the overall satellite mass and cost. For SKYBRIDGE, where the SSPA's consumption represents 40% of total, a reduction of 10% in the consumption gives 10 kg in mass reduction coming from the thermal control and the power subsystem itself.
- At ground level, an improvement of the linearity of the on-board SSPA's will provide a higher margin on the signal over noise ratio; this will simplify and reduce the cost of the user receiver, which is a key aspect of the success of these future systems.

In addition to the SSPA application, there is another major application for all kinds of Telecommunication Satellites GEO or LEO, where HBT technology could substantially improve the performance of Alcatel products. In the **receiver**, which is at the core of Alcatel industrial business, both the medium power stages found at the output section and the LO (Local Oscillator) can benefit from the HBT superior performance.

Firstly, the **output RF stages of the receiver** (presently based upon MESFET technology) represents up to 20 % of the total power consumption of a receiver, this is due to the high linearity level required, that needs a large development output transistor operated with a high output back-off level. The good linearity performances of the HBT will permit to reduce the size of the output transistor, and consequently the power consumption of the future generation of Alcatel receivers.

Moreover, HBT's have demonstrated attractive performance in term of low frequency noise. HBT device shows low noise level at low frequency range compared to field effect transistors. This is of prime interest for the design of high spectral purity oscillator and could be used for improvement of the phase noise of the **local oscillators included in the receivers**. In addition, HBT Technology should make easier the design of the local oscillator since a single positive bias supply is required to bias circuits (HBT VCO and buffer amplifier).

UMS HBT technology has been designed for frequencies below 20 GHz. This covers 100% of existing commercial and military satellite applications for both GEO satellites and for LEO constellations for mobile communications. It also covers the proposed European broadband system Skybridge. Other broadband systems proposed by American companies use higher frequency bands (Ka) for which current HBT technology cannot be used.

First phase HBT reliability analysis :

Gallium arsenide heterojunction bipolar transistors (HBTs), such as AlGaAs/GaAs or InGaP/GaAs, are the most promising candidates for key devices as used in very high speed communication systems. Recent progress in HBT fabrication technology, together with circuit design technology, has made it possible to produce very-high-speed HBT ICs.

There is however still some concern about the reliability of the devices, which is of critical importance. More in particular, it is of crucial importance to obtain data about the stability of the transistor parameters after a large number of operating hours. Up till now, the reliability of the HBT is subject of much discussion and various researchers have reported a wide range of activation energies for degradation mechanisms as shown in the table 1 below, and corresponding projected lifetimes.

FAILURE MODE	MECHANISM	EA (EV)	CURRENT DEPENDENCE
B-E Leakage	Traps formed in base	0.45	Yes, e-h recombination
V_{be} Shift	Hydrogen in base	0.6	Yes, e-h recombination
DLD	Dislocation propagation	0.1	Yes, e-h recombination
R_{coll} Increase	Ohmic contact degradation	0.8-1.1	No. Thermal effect
B-C Leakage	Base metal spike to collector	1.2-1.8	No. Thermal effect
B-C Short	Contact degradation, local heating melting	0.8-1.8	No/Yes. Thermal degradation then localised I^2R heating
E-B Short	Same as above	0.8-1.8	Same as above

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table 1 : HBT Failure Modes, Mechanisms and Activation Energies

For APOS, the objective in term of reliability for satellite application is listed in the following :

- MTTF=2 x 10^6 hrs T_j = 115°C for a given power application in Ku band

Preliminary reliability results obtained on both InGaP/GaAs and AlGaAs/GaAs are here to confirm that there is a good case for HBT technology to meet the above satellite specifications.

Second phase : Power flip-chip development and benchmarking

In space, heat can be evacuated only through conduction. This, coupled with the high power densities to be handled, makes thermal control a major design constraint and is also an important part of the overall mass budget. In SSPA's the power densities under the active parts of GaAs HBT devices is very high (1kW/mm^2) and the standard solution consists of thinning the device down to 50-100 μm in order to reduce the thermal resistance. This is a bad approach that leads to high cost for the final module:

- For a component manufacturer like UMS the thinning and all backside operations take place at the end of the wafer fabrication, and the low yield of this operation has a high impact in cost. Alcatel has approached major European and American GaAs device suppliers and when all backside processing is eliminated they quote a reduction of 25% to 30% in the sale price of their components.
- For a module manufacturer like Alcatel, handling and assembling 50-100μm dice is difficult and manufacturing yields are lower than when using 200-400 μm dice.

In addition flip-chipping the power devices is a much better solution to reducing Rth than thinning. For this to happen thermal bumps have to be placed directly on the emitter fingers, as shown in Figure 1.

The following table 2 shows our simulation results that confirm a reduction of 34%-42% in Rth for the flip-chip with emitter bumps with respect to the same device thinned to 50 μm and wire bonded.

thermal paths	**ΔT [K] for P_T = 7 W**	
	wire bonding (GaAs thickness of 42 μm)	flip chip with emitter bumps (GaAs not thinned)
thermal source to back of AlN substrate	55.5	32
thermal source - AlN - housing	68.8	45.3

table 2 : Power flip-chip vs standard mounting for power applications

This approach is being pursued by most of power MMIC providers: Motorola, TI, Hughes, Lockheed,.... It is the only technical solution that results in a significant reduction in thermal resistance of the high power assemblies.

Technology benchmarking will be done through the development of power module specially designed to incorporate HBT based MMIC. This MMIC will incorporate several features such as CPW design and power bump technology.

Conclusion :

This project will advance European state of the art power MMICs by providing a European source of reliable HBT with power bump technology. It should exhibit that these somewhat new device could go through one of the more demanding industrial application in term of reliability into harsh environment: Space application.

Acknowledgement :

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3. Figure

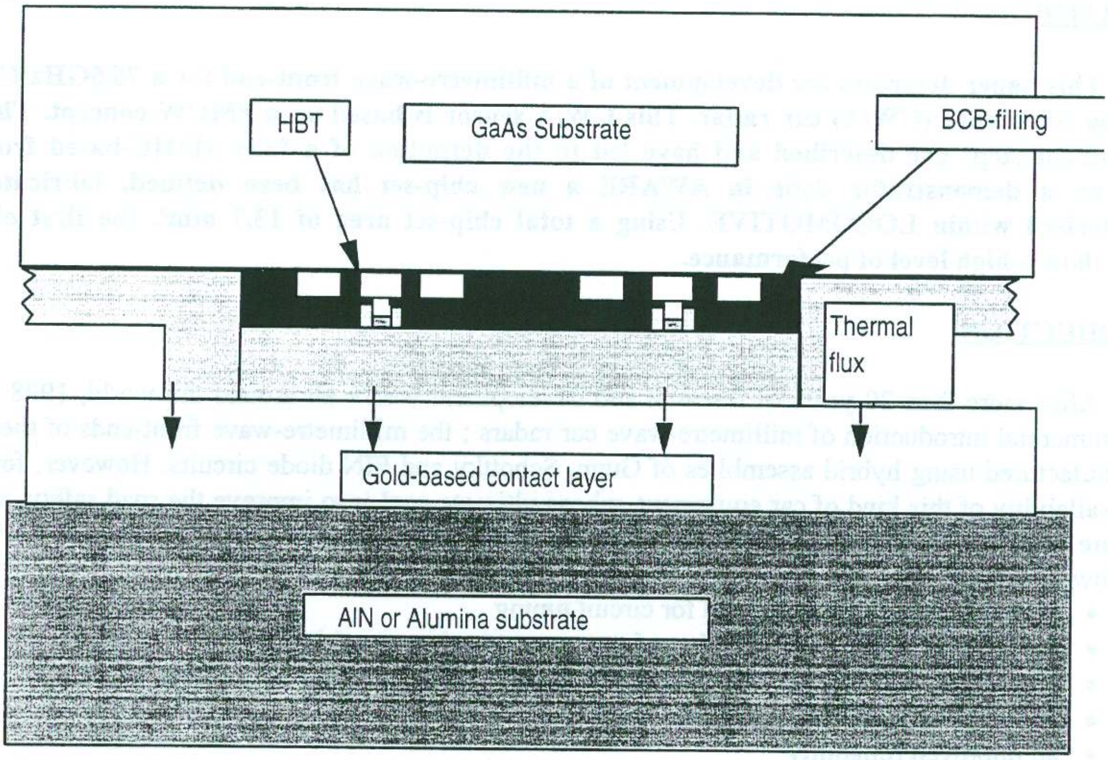

Figure 1: Side view of a FC HBT with power bumps onto its host substrate