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InP Microelectronics reaching maturity

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Introduction

While InP and the related (lattice matched) compounds are now well established in long wavelength (1.3 - 1.55 µm) optoelectronics owing to their unmatched light emission properties, these materials are still fighting for a niche in microelectronics. InP and $In_{0.53}Ga_{0.47}As$, with a composition lattice matched to InP, obviously exhibit very attractive electronic transport properties, with respect to Si and GaAs. However the maturity of InP technology has been trailing considerably GaAs development, so that InP microelectronic devices and ICs are still more at the research and development stage than ready for large scale production. This paper is intended to show how the current progress in InP and related materials growth and process technologies now allows to benefit from their intrinsic electronic properties for the fabrication of high performance devices, ICs and OEICs.

Properties of InP and InGaAs

Electronic properties

The attractive transport properties of these two materials have been recognised for a long time. While the electron mobility in InP is somewhat lower than in GaAs (Table 1, [1]), its peak velocity is higher, resulting in shorter transit times in the high field region of transistors; for InGaAs, the low field mobility is larger than in GaAs but although the peak velocity can also be higher, the saturation velocity is slightly less than in GaAs.

	InP	InGaAs	AlInAs
Bandgap (eV)	1.35	0.75	1.45
Mobility (cm2/Vs)	4000	10000	2000
Peak velocity (107cm/s)	2.5	2.5	
Bulk resistivity (Ωxcm)	108	2 103	
Schottky bar. height (eV)	0.4	0.2	0.6-0.8
$\Delta E_{\Gamma L}$ (eV)	0.6	0.55	0.6
Therm. cond. (W/cmK)	0.72	0.05	
ΔE_C (eV)	0.2	0.55	

Table 1: Electronic properties of InP and main related compounds

Worth noting is the fact that the combined velocity vs field characteristic for InP and GaInAs always remains above the one for GaAs (Fig.1). This situation, valid for the static characteristics is also expected to stand under transient regime [2]. What appeared as a most attractive feature of InP (and InGaAs) was the negative differential resistance resulting from the large difference in velocity for electrons travelling in the lower conduction band valleys, with a large energy separation $\Delta E_{\Gamma L}$ of about 0.5 eV. The resulting behaviour, allowing the fabrication of very efficient InP Gunn diodes, is a possible source of problem in transistors [3].

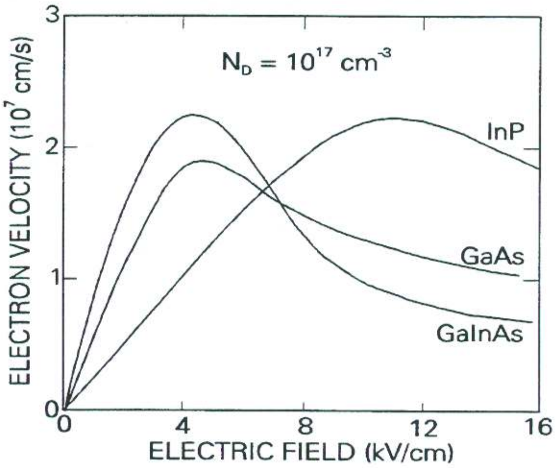

Fig.1: Drift velocity of electrons in InP, GaAs and GaInAs under constant field

Other characteristics of InP and InGaAs are to be considered, with microelectronic devices in mind. For instance the ionization coefficients which mainly govern the high field behaviour: these coefficients are extremely low in InP, lower than in GaAs, favouring high brekdown voltages; on the opposite, ionization coefficients in InGaAs are much higher, due to the lower bandgap (Fig.2). This situation mostly restrain InGaAs to low voltage applications.

Another important property of these compounds is their thermal conductivity, controlling the power a device can dissipate at a given junction temperature: this conductivity is higher for InP than for GaAs although only half of the Si one (Table 1). This is to be contrasted with the InGaAs conductivity which is extremely poor. Fortunately the thickness of InGaAs layers in actual devices is quite small (a few 100 nm at most), and, providing some care is given to the device structure, the prevailing thermal conductivity is usually that of the InP substrate.

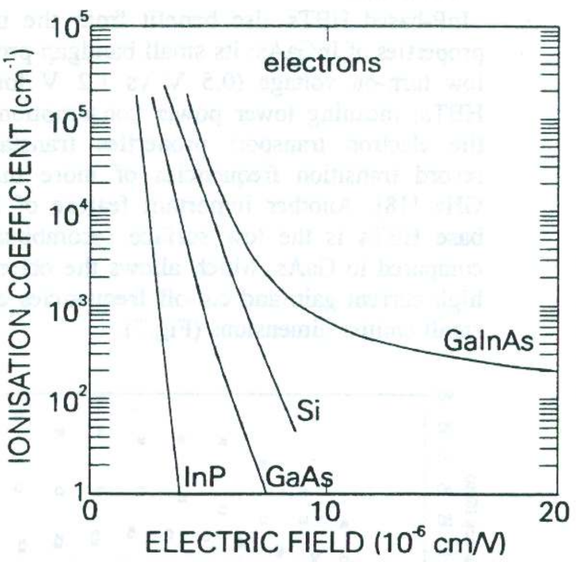

Fig.2: Ionization coefficients of electrons in Si and III-V compounds.

Processing and technological characteristics

When compared to GaAs, InP and its related compounds exhibit specific technological features: first, substrates are smaller (2 and 3") and their SI quality (dislocation density, stability of the semi-insulating behaviour: undoped SI substrates are still a subject of research) has not yet reached the state of development of GaAs substrates; moreover they are more brittle and more difficult to handle, although several pilot lines are presently processing 3" wafers [4].

Another specific characteristic of InP-based materials is their high sensitivity to bombardment by energetic species and to thermal treatments. This implies that great care must be taken during processing; for instance plasma etching or plasma enhanced dielectric deposition usually require operating conditions (low energy, low temperature) which are more stringent than for GaAs processing. The results of an extensive amount of work on soft deposition and etching techniques during recent years are now available, from which reliable processes have been derived.

However the most important aspect of InP microelectronic technology is that the basic structures which made the development of Si and GaAs FET technologies successful, namely the MOS and the Schottky diodes, are not readily available with InP and the related materials. In spite of active research ongoing for almost 2 decades, no MIS technology has been successfully established on InP. In order to benefit from Schottky structures, various schemes have been proposed, including the depleted p+ surface layer [5]. However, the most efficient structure so far has been the semiconductor barrier enhanced Schottky contact, using AlInAs, a wide bandgap material lattice matched to InP (Table 1). Obviously such an approach implies to rely on epitaxy, often considered as an expensive step in III-V process technologies. But epitaxial growth on InP, benefiting from the most advanced techniques like MBE, MOVPE and CBE, offers a wider range of material combinations and ultimately better performances than for GaAs-based devices.

InP-based Transistors

Due to their promising electronic properties, a number of devices have been investigated on InP and InGaAs during the past decades. By the late 80s, only the AlInAs/GaInAs/InP FETs and InP(AlInAs)/InGaAs HBTs families were still actively developed.

AlInAs/GaInAs HFETs

Generally grown by MBE, and benefiting from the development of GaAs HEMT structures (planar doping, pseudomorphic channel,...) these devices take advantage from (a) the high electron mobility in InGaAs, (b) the large conduction band offset between InGaAs and AlInAs (Table 1) to reach higher performances than their GaAs conterparts. This is illustrated by higher cutoff frequencies (Fig.4) and lower noise figures (Fig.3). For instance a record value of fmax = 600 GHz was reported for a 0.15 µm gate length HEMT [6].

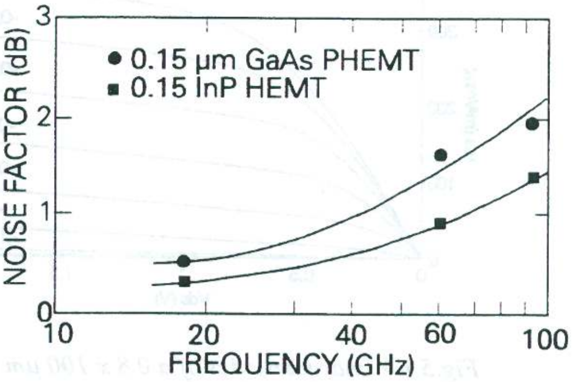

Fig.3: Noise figures of 0.15 µm gate length GaAs and InP HEMTs (from [6])

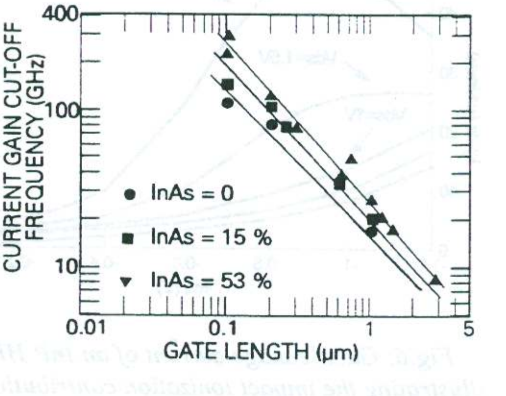

Fig.4: Current gain cut-off frequencies vs gate length of InP HEMTs (from [7])

With respect to their GaAs counterparts, specific characteristics of AlInAs/GaInAs HEMTs have to be noticed, which prevented for some time the fabrication of high performance circuits: because of the low bandgap of the channel, the breakdown voltage is quite low . Actually several reasons explain this behaviour: tunnel assisted leakage current at the Schottky contact and in the channel, but also excess leakage at the mesa edges, where the gate is in contact with the channel layer, and impact ionization in the channel. Much progress in the structure design and in processing has resulted in improved behaviour of InP HEMTs: hole barrier in the wide bandgap [8,9] (Fig.6), air-bridge type gate contact [10], double-recessed structure [11], depleted cap-layer [12] and even planar technology [13], quantum well and quaternary or composite channel [10,14]. Even though all problems are not fully understood and solved yet (kink in the I-V characteristics [15,16], both static and dynamic characteristics of InP HEMTs are now quite adequate for circuit fabrication (Fig.5), as well as their threshold voltage homogeneity (a few 10s mV) and reproducibility, thanks to selective etching processes and etch stop layers [9,17].

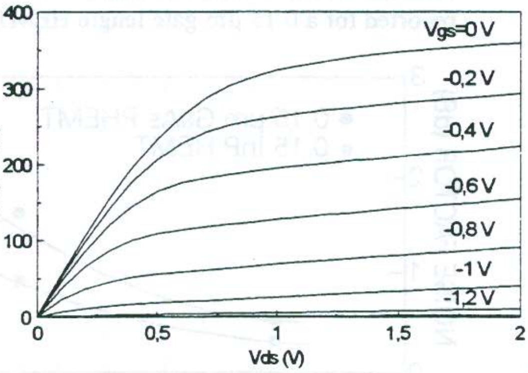

Fig.5 I-V characteristics of a 0.8 x 100 µm HEMT (from [9])

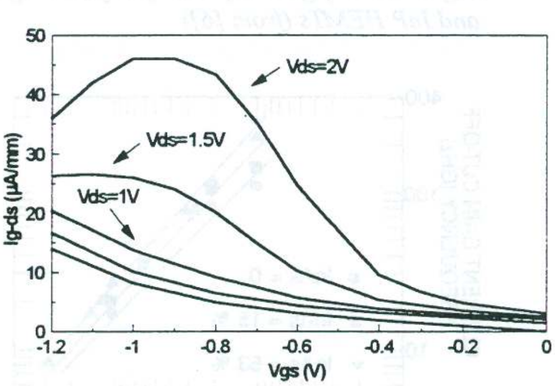

Fig.6: Gate leakage current of an InP HEMT illustrating the impact ionization contribution (bell shaped) superimposed to the usual gate leakage (from [9])

InP HBTs

InP-based HBTs also benefit from the intrinsic properties of InGaAs: its small bandgap provides a low turn-on voltage (0.5 V vs 1.2 V for GaAs HBTs) meaning lower power consumption, while the electron transport properties translate into record transition frequencies of more than 220 GHz [18]. Another important feature of InGaAs base HBTs is the low surface recombination as compared to GaAs, which allows the obtention of high current gain and cut-off frequencies even for small emitter dimensions (Fig.7).

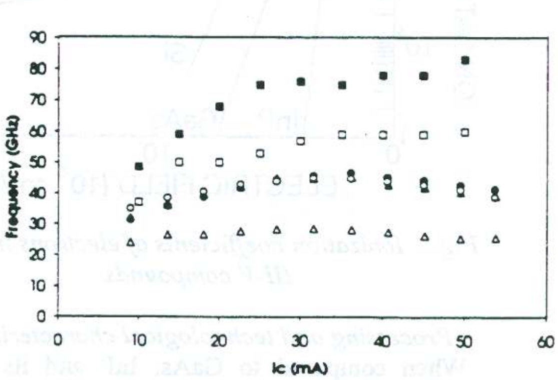

Fig.7: Comparison of ft and fmax (open symbols) for InP (square) and GaAs HBTs with 6 x 15 µm2 emitter (in the case of GaAs HBTs, both a conventional mesa structure (triangle) and a GaInP passivated structure (circle) are considered) [19,20]

In recent years, a large amount of work has been devoted to the definition of the vertical structure of the device; taking into account the numerous possibilities offered by the epitaxial growth techniques (both AlInAs and InP are used for the emitter, while collector can use InGaAs as well); in particular the base-collector junction design has received much interest: besides bulk InGaAs collector, often characterized by low breakdown voltage or moderate transit time, composite collectors have been developed to improve the breakdown behaviour, but also the transit time [21]. These devices are also facing another problem, which impacts fmax: the lower base doping level than achieved in GaAs together with the lower hole mobility of InGaAs tends to result in larger base resistance than for GaAs HBTs, while the difficulty in turning the extrinsic collector insulating through ion implantation makes the base-collector capacitance slightly larger than in GaAs HBTs. Nevertheless, extremely promising results have been reported with ft and fmax larger than 220 GHz simultaneously [18].

InP-based ICs

The promising characteristics of InP electronic devices have been translated into attractive analog and digital circuit performances, for both HEMT and HBT technologies [22].

HEMT ICs

As GaAs PHEMTs made considerale progress, they can now be used throughout the mmwave bands up to 100 GHz, restricting the frequency range of interest for InP HEMTs to even higher frequencies [23]. However, their lower noise and higher fmax makes InP HEMTs to perform better in the lower frequency range (from about 50 GHz), wether in low noise amplifier or even in power amplifier applications [24] for which InP devices offer higher power added efficiency and higher gain [25]. A few industrial laboratories (mainly Hughes, Lockeed-Martin, TRW, Daimler) are presently actively investigating the potential of InP HEMTs in mmwave applications.

High speed digital ICs suitable for very high bit rate are also investigated using InP HEMTs [26]. In particular NTT recently demonstrated a full set of circuits and modules operating at 40 Gbit/s [27]; these are presently the fastest digital circuits ever fabricated and used in actual system demonstrators.

HBT ICs

Bipolar transistors have always shown attractive 1/f noise properties, and InP HBTs appear to offer the best performance among III-V HBTs [28]. A real interest exists for InP HBTs mixer and VCOs applications, which is just being investigated [29]. The high thermal conductivity of InP together with their low offset voltage makes InP HBTs attractive as power transistors in particular in low voltage (wireless) applications.

However, the main field of expansion of the HBT technology might be in digital circuits, where their high drive capability and low threshold voltage dispersion are key factors. Very impressive demonstrations have been achieved by Hughes, with the first 40 GHz frequency divider in 1992 [30], and more recently a 15-bit accumulator including 1500 HBTs [31].

InP OEICs

InP optoelectronics and microelecrtonics are benefiting from the same technological developments, and the use of the same substrate naturally allows the fabrication of circuits incorporating both electronic and optoelectronic devices. An illustrative exemple is given by photoreceiver arrays in which the base-collector junction of the HBT is used as a photodiode, providing state of the art performance at no extra cost as compared to conventional HBT ICs processing [32]. Receiver OEICs are presently the most popular circuits being investigated [33], with performances usually quite similar to hybrid circuits, and attractive compactness. As for transmitter OEICs, their fabrication is still impeded by the rather complex structure of lasers and the lack of epitaxial layer compatibility with electronic devices.

Conclusion

As a new player in microelectronics, the InP technology is looking for markets; performances are there and the technology is now eraching maturity, but which company is willing to pay for the neccessary developments required to bring InP substrates quality and dimension to the level of GaAs ones, so that InP wafers could be processed in the same line ? Some promising results have been reported on metamorphic InP HEMTs grown on GaAs substrates [34] which is a first answer. However, it is from an increasing demand in communications (carried by optical fibre and microwave) and other markets like car avoidance systems, pollution monitoring, that an InP microelectronic technology can develop, as a complement to GaAs.

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