Microwave Technologies for Satellite Systems: an ESA Perspective

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***Abstract* — This paper intends to review the trends in solid-state microwave technologies and their impact on the anticipated performance enhancement expected for space applications.**

I. INTRODUCTION

Microwave technology is essential to most satellites and spacecraft. As a matter of fact, it all started with the first man-made satellite, which had as a "payload", a radio transmitter. Nowadays, microwave technology is critical to all radio frequency (RF) payloads whether for telecom satellites, for navigation (GPS, Galileo) or for space sensors such as radars, radiometers… Furthermore, all radio links from or to any spacecraft, used for data transmission, telemetry and control, rely also on microwaves. In this paper, the term "microwaves" is used in its generic sense i.e. frequencies from few 100 MHz to several tens of gigahertz (millimetre-waves).

The development of most micro/millimetre-wave systems has, for long, been closely related to the progress made in the field of semiconductors. The performance development is primarily dependent on the advancement in material technology as well as innovations in the operating principles of the devices. Semiconductor applications can be classified in three categories. The first two, namely power generation and low noise amplification, are mostly covered by III-V technologies. The last one, which can be labelled as "general purpose" (gain block, switch, mixed function,…), is more open to "new comers", originating from the silicon IC industry, such as SiGe or SOI.

II. POWER AMPLIFICATION

Gallium nitride (GaN) technology is becoming an increasingly interesting candidate for microwave solid-state power amplifiers (SSPA) in the near to medium term. Since GaN is a wide band gap material, devices realised on this compound semiconductor will have inherent high breakdown voltage capability. GaN components can operate at higher bias voltage (typically 40 V, which is almost coinciding with current platform bus voltages, leading to a simplified and cheaper EPC, with better overall efficiency), with very large associated output power per unit gate width (up to 10 times GaAs capabilities). Therefore, very high RF power levels (i.e.100 W at C-band, 40 to 50 W at Ku-band or 20 to 30 W at Ka-band) on a single chip should be possible. Also, due to the relatively high voltage–current ratio of the transistor channel, the devices have higher output impedance, with significant reduction of output matching loss and thus better efficiency. Another advantage of GaN is related to the better thermal resistance as compared to GaAs (1.3 vs. 0.54 W/K.cm), although this improvement may be altered by the properties of the substrate material used to grow the GaN (SiC, Sapphire or Silicon). Finally, GaN is able to withstand much higher junction temperatures than GaAs (500°C vs. 175°C), which should imply good reliability and high power handling capability, especially when grown on SiC. When grown on Sapphire or Silicon, larger wafer sizes allow also significant cost reductions with however, thermal performance degradation. The latter may be acceptable for terrestrial applications such as ground stations and GSM base stations leading to a solid commercial spin-off for safeguarding the technology for the lower quantity market such as space.

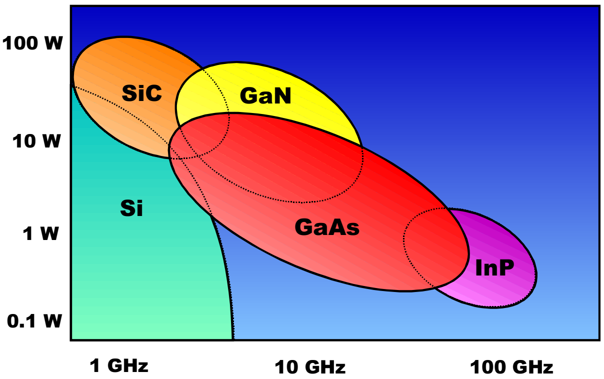

Fig. 1: Current capabilities of RF power solid-state technologies for a single device.

It is anticipated that GaN will represent a breakthrough on active transmit antennas (multiport amplifier based or phased array concepts) for next generation of telecommunication satellite payloads implementing a very high (>100) number of beams. Power amplifiers used in these active transmit antennas will work under multi-carrier conditions, with the associated low efficiency and high heat dissipation. As a consequence a complex and heavy thermal subsystem is required, with large mass and cost increase. GaN, with its excellent power and thermal capabilities will allow very compact and low mass RF front ends from mobile applications (L/S-bands) up to broadband multimedia (Ku/Ka- bands).

GaN technology will certainly play a role in SSPAs for future Ka-band user terminals. GaN, with its very high power density will lead to a ten fold increase of the user terminal EIRP, using similar area chips as currently feasible with GaAs. Alternatively, similar EIRP values as feasible today using GaAs technology could be obtained with a very significant cost reduction on the outdoor unit, due to a drastic reduction on MMIC chip size.

Another possible application of GaN technology is in the domain of T/R Modules on active arrays for SAR applications. Significant power, thermal and cost improvements will also be induced by the use of GaN on the SSPAs. Furthermore, GaN devices have shown very good low RF noise properties, comparable to GaAs devices. This feature, together with the very high breakdown voltage and high RF overdrive capabilities can allow the suppression of limiters in front of the LNA in T/R modules, with the associated reduction on complexity, cost and noise figure (NF).

GaN technology developments are ongoing in Europe. In the coming years, GaN processes will be available to start breadboarding and development activities on satellite SAR, telecommunication payload and user terminals.

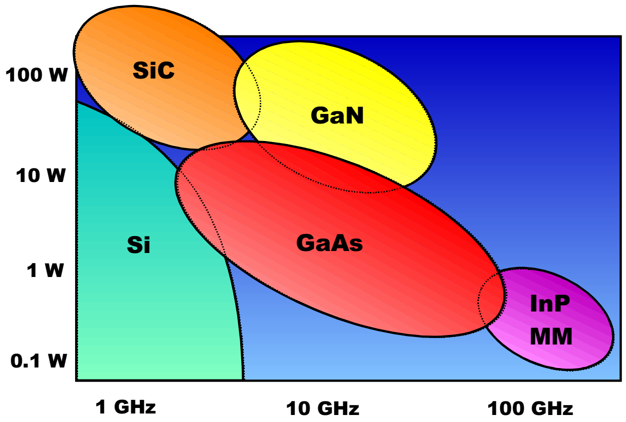

Fig. 2: Foreseen capabilities of RF power solid-state technologies for a single device in medium term.

Silicon carbide (SiC) has even better RF power and thermal properties than GaN up to C-band due to its very high breakdown electric field, high saturated electron velocity and high thermal conductivity. The high thermal conductivity and high allowed junction temperature of SiC together enable power levels that cannot be achieved with any other semiconductor technology. But the commercialisation of the technology is dependent on the wafer quality development, which however, has evolved significantly over the last years. Compared to a GaAs MESFET, a 30-fold power density improvement is foreseen. However, the high operating temperature probably requires new methodologies to be used for proper packaging and for the reliability and quality assessment.

For the same reasons given for GaN technology, SiC will improve the performance, compactness and cost of transmit active antennas for mobile service applications at L and S-band. Also, SiC will allow very high power RF levels (>100 W) for L/S-band HPAs, to be used in mobile payloads supporting contoured beam generation or in navigation applications.

Several players in Europe are involved in SiC technology. Two inches SiC wafers are already available and it is believed that in a few years SiC technology will be mature to start breadboarding and hardware development activities. However, since most of the RF potential applications for SiC, can also be covered by GaN (which can also handle higher frequencies) and/or by low frequency (LF) high power GaAs HBTs, it is not clear that SiC will emerge as a standard process for RF devices.

One of the basic building blocks of the SSPA technology is the GaAs MESFET, which has traditionally been used in a discrete packaged form, from L to C and also X-band today. However, when going to higher frequencies and/or more compact footprint, the trend is to use MESFETs in die format. Although the technology of the discretes is well established, the selection of space qualified European devices is limited. HBT GaAs technology is currently the only technology available in Europe, which has been primarily developed to cover RF high power amplification. However, it was mostly optimised to cover X and Ku-band applications. By optimising the process for lower frequency such as L or S-band, this technology could prove an alternative European solution to current Japanese high power GaAs MESFETs, which are, with their US counterparts, the only high power transistors to be considered for Galileo HPAs.

Due to the fact that the InP technology provides the fastest transistors, the InP HEMT is very well suited for power amplification at frequencies around 100 GHz and above, the GaAs P-HEMT being a better or equal competitor at approximately up to 100 GHz. Power levels of several hundreds of milliwatts are feasible from a single device at W-band today.

III. LOW NOISE AMPLIFICATION

The InP HEMT provides the lowest NF and the highest operating frequency of any three-terminal semiconductor device. Consequently, the InP HEMT technology provides the means for millimetre wave low noise (and also power amplification) at frequencies up to around 100 GHz, and well above in the future.

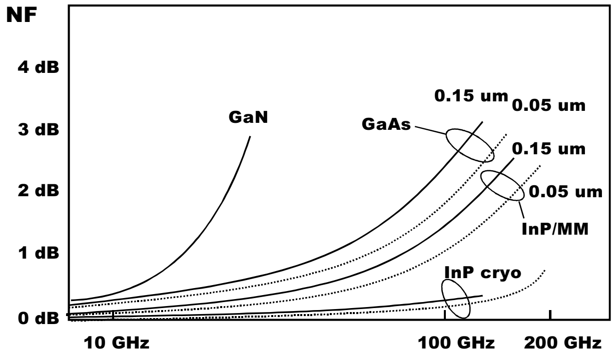

Fig. 3: Capabilities of RF low noise solid-state technologies (solid lines) and expected.

Today, the InP transistors are implemented on bulk InP substrate, which results in relatively high material and processing costs because of the brittleness of InP substrates combined with the limited wafer size. Potential applications are thus limited to those requiring ultimate low noise performance and where the cost is not an issue.

Recent development in epitaxy has lead to the implementation of InGaAs with high In content on a GaAs substrate. This new type of semiconductor substrate is called metamorphic while the HEMT implemented on it, is an M-HEMT. This new approach could result in large savings in substrate and processing costs while still showing potential for equal or nearly equal performance to the InP substrate based HEMT . Transition frequencies of 200 GHz have already been demonstrated. In addition to the use of a less expensive substrate, the MMIC fabrication can take the advantage of the established GaAs MMIC wafer processing. It is expected that the M-HEMT will become a cost-effective replacement for InP at very high frequencies and a performance boosting alternative for GaAs P-HEMT at lower millimetre-wave frequencies. The InP technology still dominates in applications at W-band and above in short to medium term but the M-HEMT technology is foreseen to take its place in the medium to long term.

The InP HEMT applications are found in W-band LNA while usable gain is available at frequencies above 200 GHz. In addition, InP based circuits facilitate lower power operation than equivalent GaAs based circuit while still maintaining similar or slightly better noise performance. This is an advantage in cryogenic applications (The low noise and low-power InP technology is the core of the Planck mission, where the cooled receivers of the Low Frequency Instrument (LFI) exploit it up to 110 GHz). At lower frequencies, low NF is requested in IF amplifiers of sensitive super-heterodyne millimetre-wave receivers. In sub-millimetre-wave super-heterodyne SSB receivers, reasonable side band filtering recalls the use of very high IF frequency (several tens to few hundreds of GHz). InP HEMT and M-HEMT have potential for the lowest NF in these applications, too.

The trend towards shorter HEMT gate-lengths, below 0.1 um, will further improve the performance of both the InP HEMT and M-HEMT technology in the near future (50 nm devices are expected around year 2004). Applications at 200 GHz, and even above, should then be feasible. Several European players are working on the development of the MHEMT and/or InP technology. Important boosters for the industry are the increasing demand on millimetre-wave systems or equivalent such as local to multipoint distribution, wireless LANs, and very high speed digital circuits for terrestrial communications.

Potential space applications in the medium to long term are LNAs up to 200 GHz (a robust replacement of Schottky mixers), very low noise cryogenic amplifiers for science missions, wideband very low noise IF amplifiers in sub-millimetre-wave receivers used for Earth Observation, and state of the art communications systems for deep-space.

Following the industrial orientation towards M-HEMT, it is likely that the M-HEMT technology will be mature before InP, which will remain at laboratory level in Europe. Still, many technological aspects related to M-HEMT need investigations. Attempts shall be made to promote the European M-HEMT MMIC technology for the needs of the future Earth Observation and Science missions in the medium to long term. Although an established European InP HEMT source would be also a very welcome facility for the very top-performing Space Science instruments, it is likely that there is not enough market pull for supporting such an attempt.

IV. GENERAL PURPOSE

SiGe technology is becoming commercially an attractive alternative for GaAs at least up to X-band and possibly up to Ku-band in highly integrated low-cost volume products. The SiGe technology facilitates the implemen-tation of CMOS and HBT devices on a single chip by standard silicon techniques, which in turn, results in a cost reduction by a factor of up to 10 (depending on the volume), compared to a GaAs based equivalent function. A potential application for SiGe could be highly integrated multi-function chip (i.e. variable attenuator + variable phase shifter + gain blocks …) for active array antennas up to at least X-band. SiGe is also an excellent candidate for high performance frequency generation (VCO, PLLs) as described later in this document. However, the rather low volume generally associated with space systems may hinder the access to this technology, which is available mostly from major industrial silicon foundries.

The silicon on insulator (SOI) technology is continuation to the bulk MOSFET technology with improved performance. The key is to fabricate the transistors on top of an insulating SiO_2 layer, which results in lowered parasitics and higher operating frequency, and inherent radiation tolerance. Furthermore, the passive elements can be implemented on high resistivity silicon facilitating low-loss embedding RF circuitry on the chip. The SOI technology facilitates the implementation and low-cost mass production of LNAs, mixers, VCOs, PLLs, and other low-power functions using the standard CMOS processing. As for SiGe, the access to the technology may be difficult given the fairly low volume usually required in space applications..

Main areas of applications are detected in receiving antenna arrays up to Ka-band and in very low-power navigation receivers. As standard silicon production lines can be exploited in the MMIC fabrication, the technology has potential for low-cost and high volumes. Activities shall be started to assess the performance of the technology for integrated RF receiver front-ends by demonstrators.

V. PROSPECTIVE SEMICONDUCTOR TECHNOLOGIES

Up to now, the microwave technologies have been based on Si, GaAs and InP. However, the development in the semiconductor technology has been very fast and new degrees of freedom in implementing material systems, bandgap engineering and epitaxy have been continuously observed. Further developments in these areas could facilitate very high integration degrees with very high performance over the whole range of current applications as well as facilitate many new ones.

GaAs technology has become the workhorse in solid-state microwave circuits to date. However, the main drawbacks of GaAs are the expensive substrate material and manufacturing processes. In order to improve the cost effectiveness of the established GaAs MMIC processes, it would be advantageous to reduce the GaAs chip area by moving the passive functions onto cheaper substrate materials. The use of multilayer (or three-dimensional) structures would allow the passive circuits to be implemented on upper layers and connected using via-holes thus ultimately assigning the GaAs area solely for the active function. Important application field of highly integrated cost-effective GaAs technology is seen in electronically steered low-cost arrays.

InSb (indium antimonide) is a very promising material which has potential for very fast, low-noise, and low-power operation. Based on experiments and theory, it is realistic to expect that InSb could lead to HEMT and HBT devices twice as fast as their InP counterparts.

Solving the problems in the diamond epitaxy would mean a new breakthrough in solid-state power density by an additional factor of 10, when compared to GaN. Development of the ballistic transistor may lead to very fast devices at the terahertz range.

VI. MICRO-MACHINING AND MEMS

Micro-machining is used to realise micro electro-mechanical systems (MEMS). At this moment the main focus in research and development is on the realisation of reliable MEMS switches which are attractive for space use e.g. in switch matrices and redundancy switches. As matter of fact their offer many advantages compared to their semiconductor equivalent (based on PIN diodes or GaAs transistors): very low losses (specially at higher frequencies), negligible consumption (electro-static activation), very high IP3 (passive), … However, the reliability is still an issue (one of the difficulty is to get rid of the “stiction” by which the switch becomes inoperable because the contacts stick together) while the packaging remains expensive since it has to be hermetic to protect the devices form contaminants which enhance the stiction problem.

Next generation telecommunication satellite payloads with a very high number of beams (more than 100) will need the implementation of high order switch matrices for on board channel to beam reconfiguration. In the case of analogue payloads implemented using IF processors, very high order IF switch matrices will be required. The feasibility of such matrices is not obvious using current technologies (i.e. GaAs switches on multi-layer substrates). MEMS technology, together with multi-layer substrates and advanced packaging technologies will allow the implementation of very compact and low cost high order switch matrices. In the same way, large switch matrices are currently required for the implementation of input TWTA redundancy rings. Coaxial technology is currently used. MEMS based switch matrix would allow a extremely compact, reliable and low cost implementation of these input low power redundancy switches.

Micro-machining techniques also offer a solution for manufacturing filters and other waveguide components and housings for high frequencies. Very promising results have been achieved in realising sub-millimetre-wave receivers, especially regarding the ease and cost of manufacturing, and the excellent mechanical tolerances. These efforts are planned to be continued, together with the development of techniques to integrate semiconductor devices to such structures, e.g. by using membranes.

Providing that reliability can be achieved, it is expected that in a few years from now, MEMS devices (inductors, varactors, resonators, filters, …) will find their way to many applications, for microwave functions such as:

- low phase noise voltage controlled oscillators (VCO) with very wide tuning range,
- miniaturised high-Q switchable filter/filterbanks for microwave and below,
- tunable high-Q filters with very high linearity (IP3),
- tunable amplifiers with high linearity,
- resonator based filter and oscillator designs,
- phase shifters.

However, it is the integration potential of MEMS with semiconductor devices like Si and GaAs which may revolutionise the way microwave systems are built, as the integration of entire subsystems on one chip becomes feasible. The integration of above components together with high-speed A/D and D/A converters based on SiGe leads to complete new mixed signal systems on chip (SoC) with unparalleled performance.

VII.CONCLUSION

The performance of many satellite systems depends heavily on microwave solid-state technologies. Any breakthrough in this domain, especially on the power side, as envisaged for GaN, could have a significant impact on those systems. However, in many cases, the exploitation of the full potential of the solid-state technologies leads to some packaging issues (e.g. high temperature operation, large power dissipation, interconnect,…) which have still to be solved.

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