Frontiers of III-V Compounds and Devices

Joachim Würfl[1] and Michael Schlechtweg[2]

[1]Ferdinand-Braun-Institut für Höchstfrequenztechnik,
Gustav-Kirchhoff-Straße 4, 12489 Berlin, Germany, Tel: +49 30 6392 2690
[2] Fraunhofer-Institut für Angewandte Festköperphysik,
Tullastraße 72, 79108 Freiburg, Germany, Tel: +49 761 5159 734

ABSTRACT — **The paper presents an overview on the European status of electronic devices for micro- and mm-wave applications based on III/V compound semiconductors. Both low noise and power devices for applications from a few GHz up to several hundred GHz are considered in terms of specific material and processing technologies and of typical device results. This includes a survey on the actual status of GaAs based HEMT and HBT devices, metamorphic HEMT devices. Furthermore recent results on high speed InP based HEMTs and HBTs are summarized. Regarding power applications the potentials of mature GaAs HBT technologies, power HEMTs and novel GaN technologies are discussed and compared to each other.**

I. INTRODUCTION

III-V semiconductor devices are the enabling constituents for high sophisticated wireless and optoelectronic systems. They comply with the ever growing system demands towards higher power, higher linearity and low noise applications. Low RF noise transistors are the key devices in sophisticated microwave receiver and radar systems. They are mostly based on GaAs based pseudomorphic HEMTS, InP HEMTs or metamorphic HEMTs. For low phase noise oscillators, MMICs based on HBTs show extremely promising features. Regarding power applications GaAs based HBTs for low voltage applications are the enabling devices for the highly efficient microwave amplifiers in mobile handsets. High power HBTs are prone to be implemented for next generation base station and radar systems. Sooner or later these components are facing competition from the emerging GaN based devices because of the superior properties of this new material system. An overview on the microwave power capability of different device families over frequency illustrates the current state of the art (Fig. 1).

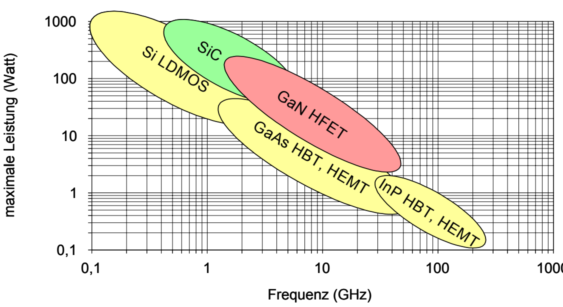


Fig. 1: Maximum expectable power performance of different device families.

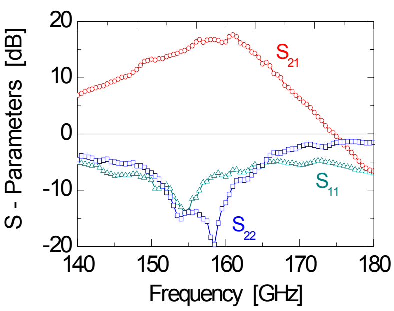
II. LOW NOISE MICROWAVE DEVICES

As far as low-noise and power application in millimeter-wave ICs is concerned, the depletion type HEMT (D-HEMT) is the active device of choice. For mixed-signal circuits, however, enhancement type HEMTs (E-HEMTs) offer the advantage of more compact layouts compared to D-HEMTs, eliminating the need to use complicated level shifting circuitry.

In Europe united monolithic semiconductors (UMS), IEMN in France and Fraunhofer IAF in Germany are working on low noise devices and MMICs for millimeter wave applications. At IAF Fraunhofer both D- and E-MHEMTs are grown on 4-inch semi-insulating GaAs wafers by molecular beam epitaxy (MBE). A linear graded metamorphic $In_xAl_{0.48}Ga_{0.52-x}As$ (x: 0 → 0.52) buffer is grown on the substrate to adapt the lattice constant. The D-MHEMT and E-HEMT devices feature a gate length of 70 and 100 nm, respectively.

Both processes have composite channels consisting of two $In_xGa_{1-x}As$ layers with x = 53 % and x = 80 % indium concentrations for the D-HEMT process, and x = 53 % and x = 65 % for the E-MHEMT process. These composite channels are used to reduce impact ionization.

Using 70 nm gate technology high cut-off frequencies of f_t=293 GHz and f_{max}=337 GHz have been achieved in DMHEMT technology for 2x30 µm devices. A D-band two-stage cascode type amplifier featuring a gain of 15 dB at 160 GHz (Fig. 2) and a noise figure of 4 dB at 150 GHz evidences the capability of this technology [1].



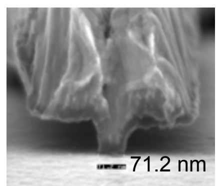


Fig. 2. Left: on wafer measured S-parameters of D-band amplifier MMIC,
Right: TEM cross section of a 70 nm gate.

Heterojunction Bipolar Transistors (HBTs) show much lower 1/f noise levels than field-effect transistors because their current flow is perpendicular to semiconductor interfaces. Thus influences of interface and surface states on the output signal are reduced. Oscillator MMICs based on high speed InP- and GaAs based HBTs ideally match the requirements on low phase noise oscillators for modern communication and radar systems. In Europe especially the Ferdinand-Braun Institut (FBH) is working on this topic. At FBH a high speed GaInP/GaAs HBT process has been developed by systematically reducing the parasitic elements of the active devices as far as possible as shown in Fig. 3. A shallow base finger implantation process and a minimization of the base emitter separation significantly reduces collector-case capacitance and the extrinsic base resistance, respectively. This results in f_t and f_{max} values of 50 and 180 GHz. Using self aligned base technology a f_{max} of 250 GHz was obtained.

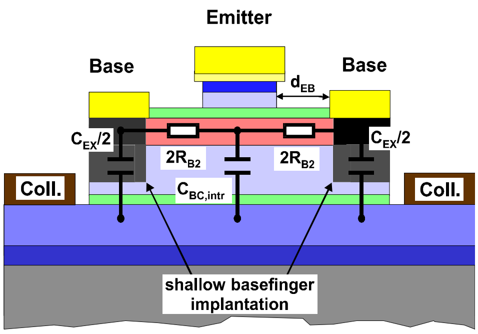


Fig. 3. Schematic cross section of GaInP/GaAs HBT showing the location of critical parasitic elements.

Based on the this technology a single-ended VCO designed as a refection-type oscillator has been demonstrated at FBH [2]. The measured phase noise is around -87 dBc/Hz at 100 kHz and practically independent on tuning voltage. It decreases with 20 dB per decade between 100 kHz and 1 MHz offset frequency to -108 dBc/Hz at 1MHz.

As can be seen from Fig. 4, at 1 MHz offset frequency the VCO exhibits a phase noise level being a record value for GaAs MMIC oscillators in the 30…40 GHz range. It compares well with the SiGe counterparts [3]. In summary, GaInP/GaAs-HBTs combine very good 1/f noise properties with the high frequency potential of GaAs-based MMICs.

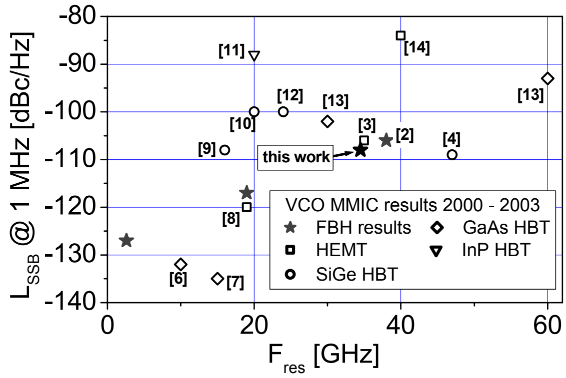


Fig. 4. Phase noise performance of various VCOs published from 2000 until 2003.

III. High Speed Mixed-Signal Devices

Despite the current stagnation in the telecommunication market, recovery is expected within the next time. Presumably, the driving market for next generation high-speed mixed-signal integrated circuits (MIXICs), such as frequency dividers, multiplexers, demultiplexers, clock recovery and modulator drivers, will be metro networks rather than long-haul systems.

The active III/V devices used for MIXICs are both InP-based and metamorphic HEMTs, as well as InP-based HBTs offering high performance with moderate cost for medium scale niche market applications. The maximum operating speed is comparable for both technologies. To date, the fastest ICs reported use HEMT [4] or HBT devices [5]. InP HBTs have the potential for superior performance if high operation speed is combined with high output voltage swing. However, HBT reliability needs further investigation, especially for operation at high current densities. Recently, significant progress has been made especially in Japan and the USA, yielding multiplexers operating above 100 Gbit/s, selectors at 144 Gbit/s, and frequency dividers at 152 GHz [4-5]. In Europe, Alcatel R&I and the Fraunhofer IAF are working on MIXICs for 80 Gbit/s data rate using III/V semiconductors.

Alcatel R&I is using an in-house self-aligned InP DHBT process featuring 180 GHz transit frequency which is presently being transferred to the industrial foundry OMMIC. Various ICs have been realized using this technology, such as DFF, data decision circuit, driver amplifier, frequency doubler [6], and 2:1 selector circuit for 80 Gbit/s yielding a very good quality of the output eye diagram [7]. The 2:1 selector IC (1.4x1.6 mm²) and the related output eye diagram at 80 Gbit/s data rate are depicted in Fig. 5. The output voltage swing is 150 mV, due to the CML architecture of the output buffer.

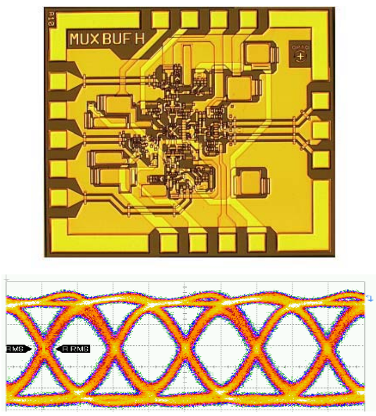


Fig. 5. Chip photograph and Output eye diagram of the 2:1 DHBT selector IC at 80 Gbit/s (Alcatel R&I).

At the Fraunhofer IAF, both metamorphic enhancement HEMT and recently also InP HBT technologies are used to realize 80 Gbit/s MIXICs. HBT-based ICs use self-aligned InP DHBTs with high current gain ($\beta > 50$) and over 200 GHz transit frequency, and have demonstrated 80 Gbit/s selector operation, and VCOs low phase noise operation up to 75 GHz.

A 100 nm gate length enhancement type metamorphic HEMT (E-MHEMT) process on 4-inch GaAs wafers with a transit frequency of 200 GHz is applied for 80 Gbit/s circuits [1]. The devices have composite channels with two $In_xGa_{1-x}As$ layers (x = 53 % and x = 65 %) to reduce impact ionization. The process features gate definition using electron beam lithography, and a three-layer metalization including a 1.2 µm BCB dielectric layer between the first and the second layer for low parasitic capacitance of the interconnects.

Based on this process, static and dynamic 2:1 frequency dividers were realized yielding maximum operating frequencies of 70 GHz at 450 mW power dissipation, and 108 GHz at 360 mW power dissipation, respectively. The static and dynamic dividers comprise 119 and 71 active devices, respectively. The yield for the static frequency divider was of the order of 70 %. The measured sensitivity curves determined at a low input power level below 0 dBm for both ICs are depicted in Fig. 6.

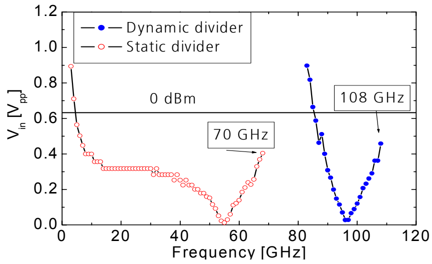


Fig. 6. Measured input sensitivity for the static and dynamic 2:1 frequency divider ICs.

Completely integrated 2:1 multiplexer and 1:2 demultiplexer ICs based on the E-MHEMT process, as well as modules were also developed for 80 Gbit/s data rate. The 2:1 multiplexer IC (chip size 1.25×1.75 mm^2) with a DC power consumption of 1350 mW comprises 297 active elements. The multiplexer IC and the related output eye diagram (vertical scale: 150 mV/div) at 80 Gbit/s are shown in Fig. 7.

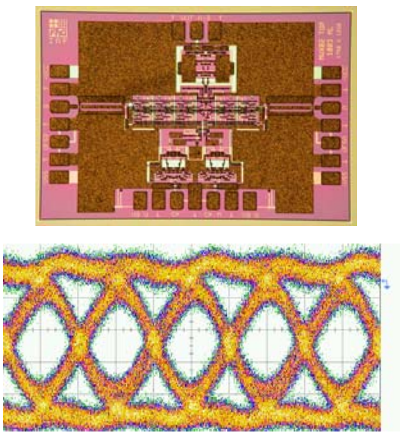


Fig. 7. Chip photograph and output eye diagram of the 2:1 MHEMT multiplexer IC at 80 Gbit/s (IAF).

The demultiplexer IC has a DC power consumption of 750 mW, comprises 285 active elements, and was successfully tested at 80 Gbit/s using the output signal of the 2:1 multiplexer.

IV. High Power Microwave Devices

For microwave power applications up to Ku-band frequencies GaInP/GaAs heterojunction bipolar transistors (HBTs) are well suited. Power applications at higher frequencies are dominated by GaAs- or InP-based HEMT devices. The key advantages of HBTs are their high efficiency, high linearity and high power density. The high output impedance of HBTs, especially when operated at high voltages (around 28V) allows an easy power combining to large power cells.

Significant work on high power HBTs suitable for higher operation voltages has been performed at UMS and at the FBH [8, 9]. For power devices both, the available maximum current as well as efficient heat sinking are of crucial importance. HV-HBT power cells have the capability to deliver high currents at low knee-voltage. Additionally, flip-chip mounting provides a lower thermal resistance (R_{th}) as compared to the conventional substrate thinning and backside mounting [9].

For the HV-HBTs, a proprietary flip-chip soldering process on patterned AlN or diamond submounts has been developed at FBH. A flip-chip soldered HV-HBT chip is shown in Fig. 8. The simulated low thermal impedance (R_{th}) of flip chip soldered devices can only be obtained with high quality homogeneous solder joints as illustrated in Fig. 8 (left). Flip-chip mounting leads to a 40% reduction in R_{th} as compared with the on-wafer situation. An even further improvement by 25% is possible by using diamond submounts (R_{th}~12 K/W) instead of AlN submounts (R_{th}~16 K/W).

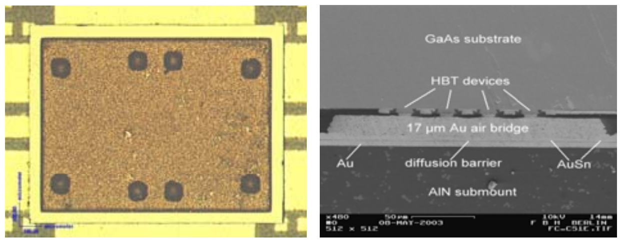


Fig. 8. left: Top view of HV-HBT power cell, flip-chip soldered on AlN submount.
right: Cross-section of flip-chip mounted HV-HBT showing quality of the soldering process (FBH).

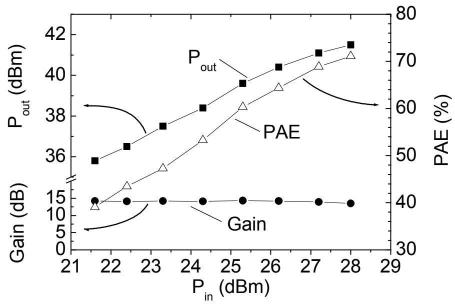


Fig. 9. Load-pull measurement of HV-HBT power cell flip-chip mounted on diamond and packaged in a test fixture (emitter area of 4000 µm^2) (FBH).

Fig. 9 shows the performance of a diamond-mounted power cell. An output power of 14.1 W, a power-added efficiency of 71% and high gain of 13.5 dB are obtained.

GaN based power devices bear the potential of further boosting the power capability being achievable with GaAs devices. Theoretically at least an order of magnitude should be possible since GaN HFETs allow for a far higher operation voltage as compared to GaAs devices. High power microwave devices with bias voltages of 100 V and an output power of 250W are already demonstrated [10]. Besides high power levels, GaN based power devices are expected to operate at high efficiency and also show linearity data complying with the requirements of next generation mobile communication systems.

Therefore all over the world intensive research on GaN-power devices is pursued. In Europe the major players are Tiger in France, QinetiQ in UK as well as Fraunhofer IAF and FBH in Germany [11]. The key towards high power GaN devices is the successful control of the power dispersion effect at high frequencies. The dispersion effect is generally associated with traps or charges at the surface or in the buffer. It can be reduced or even made completely ineffective by various means, such as careful epitaxial layer design in combination with high quality epitaxy and suitable surface passivation. Fig. 10 illustrates the effect and shows how dispersion can be significantly reduced by using SiN_x device passivation.

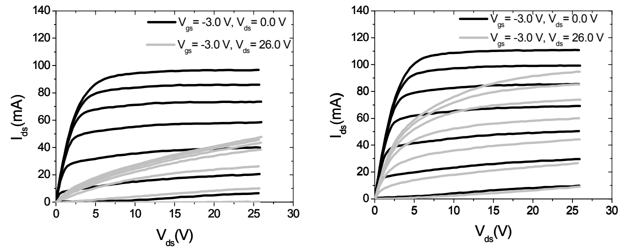


Fig. 10. Pulsed measurements of GaN-HFETs highlighting gate lag effect (V_{GS} =-3V; V_{DS} = 0V) and drain lag effect (V_{GS}=-3V; V_{DS}=26 V) as well as recovery of gate and drain lag after passivation. Left: without passivation, Right: after SiN_x-passivation.

Nearly dispersion free GaN devices deliver high output power levels, high power density and high PAE as shown in Fig. 11 for an X-band device fabricated at FBH.

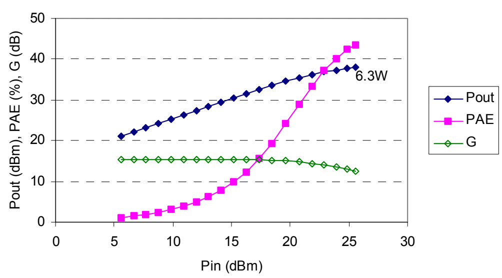


Fig. 11. Load-Pull measurement on GaN HFET power cell (12x125 µm) operated at 8 GHz at a V_{DS}= 26 V.

VI. Conclusions

Today a great variety of III/V-devices on different substrate materials is available to match the demands for future communications and other systems. In the research labs low noise amplifiers and digital circuits for frequencies by far exceeding 100 GHz are feasible and ready for system implementation. Regarding power applications below Ku-band GaAs based HBTs are the dominant devices whereas for higher frequencies power PHEMTs are the matter of choice. GaN power devices are emerging very rapidly and bear the potential for very high power levels, high linearity and high efficiency.

Acknowledgement

The authors are gratefully appreciating the support from Dr. Jean Godin from Alcatel R&I in France.

This review article was performed in the context of the network TARGET– "Top Amplifier Research Groups in a European Team" and supported by the Information Society Technologies Programme of the EU under contract IST-1-507893-NOE, www.target-org.net.

References

[1] M. Schlechtweg, A. Leuther, A. Tessmann, C. Schwörer, H. Massler, W. Reinert, M. Lang, U. Nowotny, O. Kappeler, M. Walther, R. Lösch, "Millimeter-wave and mixed-signal integrated circuits based on advanced metamorphic HEMT technology" Proc. IPRM 2004, pp. 609-614.

[2] J. Hilsenbeck, F. Brunner, F. Lenk, J. Würfl, "Fabrication and Electrical Performance of Oscillators in GaInP/GaAs-HBT MMIC Technology up to 40 GHz", Inst. Phys. Conf. Ser. No. 174, Section 4, pp., 239 – 242, 2003.

[3] H. Li et al., "Millimeter-Wave VCOs With Wide Tuning Range and Low Phase Noise, Fully Integrated in a SiGe Bipolar Production Technology", IEEE Journal of Solid-State Circuits, Vol. 38, No. 2, 2003, pp. 184-191.

[4] T. Suzuki, Y. Nakasha, T. Takahashi, K. Makiyama, T. Hirose, M. Takikawa, "144-Gbit/s selector and 100-Gbit/s 4:1 multiplexer using InP HEMTs", IEEE MTT-S Tech. Digest, June 2004, pp. 117-120.

[5] Z. Griffith, M. Dahlström, M. Seo, M. J. W. Rodwell, M. Urteaga, R. Pierson, P. Rowell, B. Brar, S. Lee, N. Nguyen, C. Nguyen, "Ultrahigh frequency static dividers in a narrow mesa InGaAs/InP DHBT technology", Proc. Intern Conf. IPRM, May 2004, pp. 663-666.

[6] V. Puyal, A. Konczykowska, P. Nouet, S. Bernard, S. Blayac, F. Jorge, M. Riet and J. Godin, "A DC-100 GHz Frequency Doubler in InP DHBT Technology", IEEE MTT-S Tech. Digest, June 2004, pp.167-170

[7] A. Konczykowska, S. Blayac, F. Jorge, M. Riet, V. Puyal, and J. Godin, "Design and measurement of very high bitrate digital ICs fabricated in InP technology", IEEE MTT-S Tech. Digest, June 2003, pp. 1177-1180.

[8] P. Kurpas, A. Maaßdorf, W. Doser, W. Köhler, P. Heymann, B. Janke, F. Schnieder, H. Blanck, P. Ausxemery, D. Pons, W. Heinrich, J. Würfl, "Power GaInP/GaAs HBTs for High Voltage Operation", 2003, GaAs MANTECH, Scottsdale, USA, Digest pp. 99 – 102.

[9] P. Kurpas, A. Maaßdorf, W. Doser, P. Heymann, B. Janke, F. Schnieder, H. Blanck, P. Auxemery, D. Pons, W. Heinrich, J. Würfl, "10 W GaInP/GaAs Power HBTs for Base Station Applications", 2002 IEDM Technical Digest, pp. 681 - 684.

[10] T. Kikkawa, T. Maniwa, H. Hayashi, M. Kanamura, S. Yokokawa, M. Nishi, N. Adachi, M. Yokoyama, Y. Tateno, K. Joshin, "An over 200-W output power GaN HEMT push-pull amplifier with high reliability", 2004 IEEE MTT-S Digest, pp. 1347-1350.

[11] R. Lossy, N. Chaturvedi, P. Heymann, K. Köhler, S. Müller, J. Würfl, "AlGaN/GaN HEMTs on Silicon Carbide Substrates for Microwave Power Operation", GaAs Mantech 2003, USA, Conf. Digest, pp. 327-330.