MONOLITHIC INTEGRATION OF METAMORPHIC PIN DIODES AND HFETs FOR HETEROINTEGRATED MMICs

Volker Ziegler, Christoph Gässler, Claus Wölk, Reinhard Deufel, Franz-Josef Berlec, Jürgen Dickmann, *Norbert Käb, *Hermann Schumacher

DaimlerChrysler AG, Research Center Ulm, Wilhelm-Runge-Straße 11, D-89081 Ulm, Germany
Phone: +49 731 505 2299 Fax: +49 731 505 4102
eMail: volker.z.ziegler@daimlerchrysler.com

*Dept. of Electron Devices and Circuits, The University of Ulm,
Albert-Einstein-Allee 45, D-89081 Ulm, Germany

ABSTRACT

This paper presents for the first time the monolithic integration of $In_{0.53}Ga_{0.47}As$ PIN diodes and $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ HFETs on one GaAs substrate. To the best of our knowledge, this is the first approach that these metamorphic devices are heterointegrated on a single GaAs wafer. Special attention was paid to the surface roughness of the layers which was monitored with an atomic force microscope during the processing. Taking advantage of this combined technology, metamorphic PIN diodes and HFETs were processed simultaneously and used to realize different mm-wave circuits on this wafer. The HFETs with a gate-length of 0.12µm demonstrate an extrinsic transconductance of 772mS/mm and cut-off frequencies of f_T = 137GHz and f_{max} = 212GHz. The fabricated SPDT (single-pole double-throw) switch has an insertion loss smaller than 2.5dB and an isolation larger than –21dB from 39GHz to 79GHz and the single-stage amplifier exhibits a gain of 6.5dB at 54GHz.

INTRODUCTION

So far, several integration concepts of different devices have already been demonstrated on GaAs and InP substrates to benefit from the advantages of multifunctional MMIC design [1,2,3] such as: reducing the number of chip interconnections, minimizing testing and assembling efforts, obtaining optimized MMIC performance and thus overall reduce the cost for the modules. For the RF-frontends of mm-wave systems, InP-based LNAs [4] and switches [5] demonstrated superior performance compared to GaAs-based MMICs. However, InP substrates have some major drawbacks compared to GaAs such as smaller size and the brittleness which increase the costs and complicate the production. A very promising solution to use the advantages of both material systems is to grow buffer layers to adjust the lattice constant of the GaAs substrate to the lattice constant of InP for the active device. With this metamorphic approach impressive results from HFET devices and HFET-based MMICs have already been demonstrated [6,7]. The next step which allows the design and fabrication of multifunctional MMICs with optimized performance in a metamorphic technology is the monolithic integration of different metamorphic devices.

In this paper, we present the monolithic integration of a metamorphic PIN diode (MPIN) [8] and a metamorphic HFET (MHFET) on one GaAs substrate. To the best of our knowledge, this is the first time that these two devices are monolithically integrated on one metamorphic wafer. The combined technology is described and the DC and RF performance of the MPIN diode and the MHFET devices are presented. Using these integrated devices two different coplanar MMICs which are widely used in mm-wave T/R modules, a switch and an amplifier, were fabricated on this metamorphic wafer.

TECHNOLOGY FOR METAMORPHIC HETEROINTEGRATION

The layer structure for the integration of the MPIN diode and the MHFET was grown in-house by one single growth step with the MBE system. Starting from the GaAs substrate, the ternary InAlAs buffer layer is grown to adjust the lattice constant to $In_{0.53}Ga_{0.47}As$. After the growth of this buffer layer with a linearly graded indium content, a relaxation level of 94% is achieved at the surface. Continuing the growth, the MHFET layers (all lattice matched to InP) are grown and finally on top of an intermediate InP etch-stop layer, the $In_{0.53}Ga_{0.47}As$ MPIN diode layers are deposited. The height of this combined structure including the buffer layers is about 2.9µm.

The heterointegration technology itself is a merger of the two single device technologies. The first step is the deposition of the ohmic contact metallization for the p^+-layer of the MPIN diode, followed by two mesa etching processes down to the InP etch-stop layer to define the areas for the p^+-, *i*- and n^+-regions. The 500nm thick n^+-region of the MPIN diode consists of the same InGaAs composition as the thin MHFET cap layer and thus, an etch-stop layer between these two layers is crucial for the precise process control. After removing the InP etch-stop layer, the MHFET mesas are defined by one more etch step and TaN thin film resistors are deposited on the wafer. A combined process is then used for evaporating the n^+-ohmic contact layers for the two devices. The 0.12µm T-gates are defined by ebeam lithography and the whole wafer is passivated with silicon nitride. Finally, electroplated gold used for all interconnections and transmission lines completes the process.

The surface roughness plays an important role with respect to the performance of the HFET devices as well as to the reliability of the devices and thus great attention should be paid to this parameter. The surface roughness of the top layer of the MPIN diode is quite high and a fairly high level of cross-hatching which is enhanced in one direction can be observed (Fig.1 left part). During the two mesa etching processes of the diodes down to the etch stop layer, this level of cross-hatching is reduced but remnants can still be observed on top of the MHFET layers. It was found that this high level of cross-hatching does not influence the performance of the fabricated MPIN diodes but the functionality of the MHFETs was deteriorated by poor pinch-off characteristics and enhanced gate-leakage currents. But by using optimized mesa etching processes, the excess cross-hatching originating from the MPIN layers can be eliminated (Fig.1 right part). With this modified processes the performance of the devices is drastically improved. During the different etching processes, the surface roughness of the different layers was monitored with the atomic force microscope (AFM). The calculated standard deviations (rms) of the measured surface roughness are depicted in Fig.2. The surface layer of the MPIN diode shows a quite high rms value of 23.7nm but a drastically improvement of the surface roughness can be observed after the etching process which stops on the etch stop layer. This value of 5-6nm is afterwards maintained during the following etching processes and contributes to the impressive results of the heterointegrated MHFETs .

DC AND RF PERFROMANCE OF THE DEVICES

The two different devices MPIN and MHFET were processed simultaneously and the performances were compared with metamorphic and InP-based single-device wafers.

The performance of the MPIN diodes under forward conditions with respect to the *n*-factor and series resistance is comparable to the single InP-based diodes. Examining the reverse bias conditions, one can observe that the MPINs exhibit an improved breakdown voltage and less reverse current at a given reverse bias. For MPIN diodes with a diameter of 10µm, the breakdown voltage is about –18V and the reverse current at a biasing of –5V is 0.17µA. The total on-state resistance is 2.2Ω according to DC measurements and the off-state capacitance is 12fF yielding a cut-off frequency of 6THz. Therefore, the characteristics which are relevant for the MPIN diode as a active switching device do not differ from the ones of the InP-based PIN diodes presented in [5].

The figures 3 and 4 show the DC and RF performance of the heterointegrated MHFETs. The 2x60µm devices demonstrate good output characteristics (Fig.3). The on-resistance is slightly increased, R_{on}=1.24Ωmm, compared to our standard single MHFET with R_{on}=1.15Ωmm. The extrinsic trans-conductance has a peak value of g_m = 772mS/mm at a V_{DS} of 1.8V. The corresponding drain current at this bias point is 429mA/mm. The maximum drain current at V_{GS} = 0.4V is 820mA/mm. Analysing the gate-drain diode yields a breakdown voltage of –4V. The RF performance of the heterointegrated MHFET was measured up to 120GHz and is depicted in Fig.4. Extrapolating with a –20dB/dec. slope results in cut-off frequencies of f_T = 137GHz and f_{max} = 212GHz. For this measurement, the device was biased at a V_{DS} of 1.25V and a drain current of 36.8mA. Comparing these data to our standard single MHFET devices, no significant change in the DC and RF performance can be observed.

METAMORPHIC MMICs ON HETEROINTEGRATED WAFER

Using the above listed metamorphic devices, two different coplanar mm-wave circuits were simulated, fabricated and characterized. The first one is an extremely broadband SPDT switch which has a similar layout as the one previously shown in [8]. This circuit has one MPIN diode in each branch, four DC-blocking capacitors and on-chip DC biasing networks. The switch shows an impressive broadband input matching which is better than –10dB from 37GHz up to 96GHz at all three ports and less than -2.5dB of insertion loss from 40GHz up to 79GHz. The isolation between the ports is better than –21dB for all frequencies up to 120GHz.

The second MMIC on this wafer is a single-stage amplifier with a 2x60µm MHFET, two DC-blocking capacitors and two biasing networks. The input of the amplifier was matched to get a compromise between noise and power matching. S-parameter measurements of the RF-performance up to 120GHz were performed and the results are depicted in Fig.5. The input and output matching is shown in the left part of the figure. The input matching *S11* (thick line) is better than –10dB from 48GHz to 60GHz with a minimum of –16.9dB at 54GHz. Broadband output matching *S22* (thin line) was achieved from 35GHz up to 66GHz with a value of -13.3dB at 54GHz. On the right side of this figure, the small signal gain *S21* and the stability factors k and μ are presented. The measured small signal gain is about 6.5dB at a frequency of 54GHz. Unconditional stability is achieved over the whole measured frequency range as indicated by the stability factors which are larger than 1 from 0.1GHz up to 120GHz.

CONCLUSION

The monolithic integration of a metamorphic PIN diode and a metamorphic HFET was demonstrated for the first time. These two devices with an indium content of 53% were heterointegrated on one GaAs substrate. A comparison of these devices with InP-based and metamorphic single-device wafers indicates no significant difference in DC or RF performance. Using these integrated MPIN diodes and MHFETs, two different MMICs, a SPDT switch and a single-stage amplifier were fabricated and characterized. These results demonstrate that a technology is now available to fabricate metamorphic multifunctional MMICs which combine the advantages of InP-based devices and GaAs substrates.

References:

[1] K.W. Kobayashi, D.C. Streit, D.K. Umemoto, A.K. Oki "A novel monolithic HBT-p-i-n-HEMT integrated circuit with HBT active feedback and p-i-n diode variable gain control" , IEEE Trans. on Microwave Theory and Techniques, Vol.43, No.5, pp. 1004-1009, May 1995

[2] H. Wang, R. Lai, L. Tran, J. Cowles, Y.C. Chen, E.W. Lin, H.H. Liao, M.K. Ke, T. Block, H.C. Yen "A single-chip 94-GHz frequency source using InP-based HEMT-HBT Integration Technology", IEEE MTT-S Digest, pp. 219-222, 1998

[3] V. Ziegler, C. Gässler, C. Wölk, F.-J. Berlec, R. Deufel, M. Berg, J. Dickmann, H. Schumacher, E. Alekseev, D. Pavlidis "InP-based and metamorphic devices for multifunctional MMICs in mm-wave communication systems", Indium Phosphide and Related Materials Conf., pp. 341-344, Williamsburg, Virginia, USA

[4] M. Barsky, R. Lai, Y.L. Kok, M. Sholley, D.C. Streit, T. Block, P.H. Lui, E. Sabin, H. Rogers, V. Medvedev, T. Gaier, L. Samoska "190 GHz InP HEMT MMIC LNA with Dry Etched Backside Vias", 11th Indium Phosphide and Related Materials Conference, pp. 423-425, 1999

[5] V. Ziegler, M. Berg, H. Tobler, C. Wölk, R. Deufel, J. Dickmann, A. Trasser, H. Schumacher, E. Alekseev, D. Pavlidis "InP-based Monolithic Integrated PIN Diode Switches for mm-wave Applications", European Gallium Arsenide and Related III-V Compounds Conference, pp. 127-132, 1998

[6] S. Bollaert, Y. Cordier, V. Hoel, M. Zaknoune, H. Happy, S. Lepilliet, A. Cappy "Metamorphic $In_{0.4}Al_{0.6}As/In_{0.4}Ga_{0.6}As$ HEMTs on GaAs substrate", IEEE Electron Device Letters, Vol. 20, No. 3, pp. 123-125, March, 1999

[7] C.S. Whelan, P.F. Marsh, W.E. Hoke, T.E. Kazior "GaAs metamorphic HEMT (MHEMT): The ideal candidate for high performance, millimeter wave low noise and power applications" GaAs MANTECH, Washington DC, USA, pp. 237-240, 2000

[8] V. Ziegler, R. Deufel, C. Wölk, C. Gässler, J. Dickmann, H. Schumacher "Metamorphic PIN diodes for high isolating and low power consuming mm-wave switching circuits" submitted to IEEE Electronics Letters

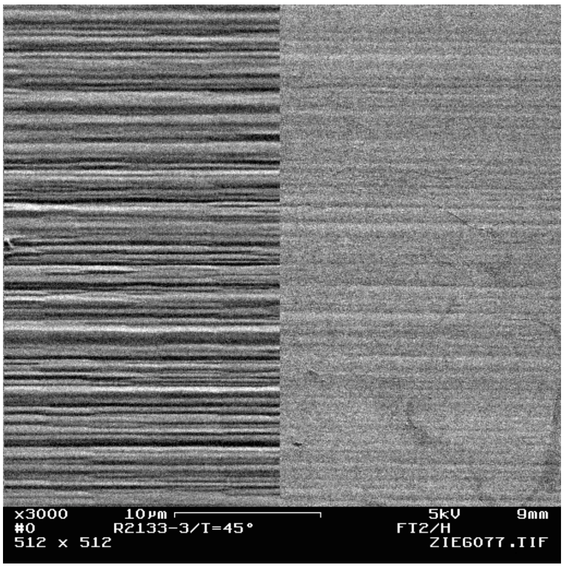

Fig.1: SEM picture of surfaces on top of the layers (left) and on the etch stop layer (right)

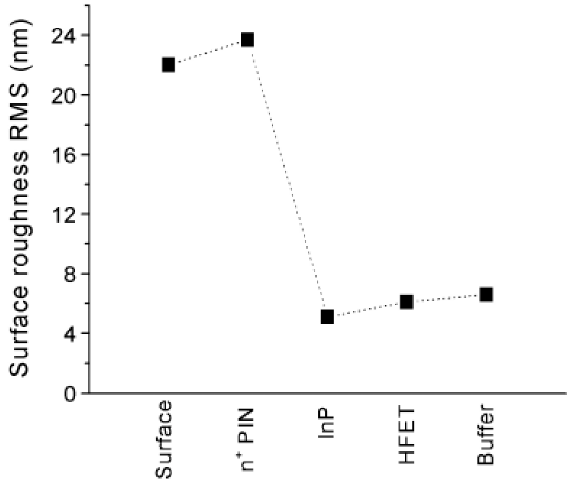

Fig. 2: Surface roughness of different layers after various etching processes

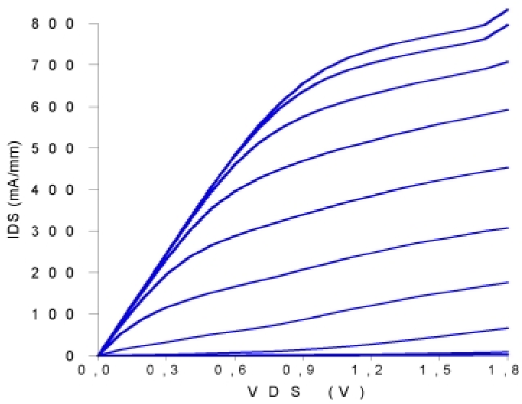

Fig. 3: Output characteristics of the 2x60µm heterointegrated MHFET

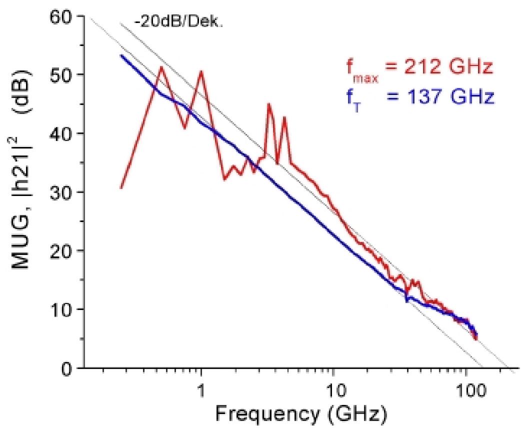

Fig. 4: Measured s-parameters of the 2x60µm heterointegrated MHFET

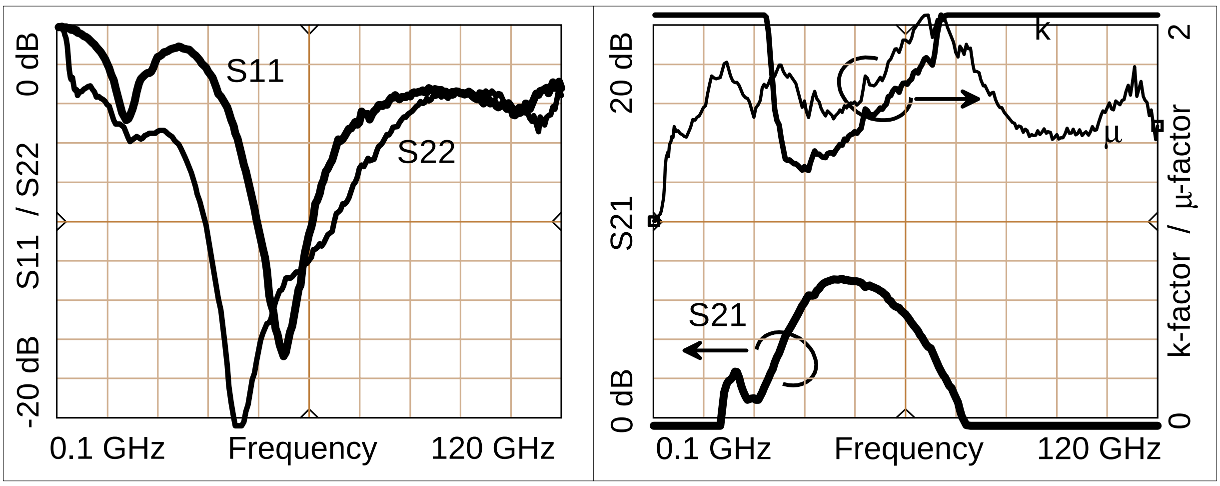

Fig. 5: Measured s-parameters of the single-stage amplifier