MICROWAVE CHARACTERIZATION AND COMPARISON OF PERFORMANCE OF $GaAs$ BASED MESFETS, HEMTS AND HBTS OPERATING AT HIGH AMBIENT TEMPERATURES

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Abstract

For the first time microwave measurements at ambient temperatures up to 300^0C have been performed on especially fabricated $GaAs$ MESFETs, $GaAs/AlGaAs$ HEMTs and HBTs, designed for continous operation at ambient temperatures up to 300^0C with high reliability. A technology is presented which allows the realization of MESFET, HEMT and HBT device performance at elevated ambient temperatures. Ohmic and Schottky contacts have been realized with Ni-Ge-Au-Ni-W_5-Si_2-Au and LaB_6-Au, respectively. These results open new possibilities for various applications of such transistors.

1 Introduction

Many applications such as for example high power satellite amplifiers, deep level drilling, intelligent sensors in harsh environment etc., demand highly reliable transistor devices, eventually operating at elevated ambient temperatures up to 300^0C. Furthermore, it has been shown that such devices exhibit much higher reliability of operation in common applications.

Devices based on $GaAs$ and $GaAs$-based semiconductor materials are generally considered to be most appropriate for the operation at elevated ambient temperatures. The maximum operation temperature is determined by the design and technology of the devices and especially of the device contacts.

High-temperature operation of $GaAs$ MESFETs and $GaAs/GaAlAs$ HBTs has been demostrated in Refs.1, 2 and 3. In this contribution we compare the high temperature behavior of the MESFETs, HEMTs and HBTs. For the first time microwave measurements at temperatures up to 300^0C have been accomplished utilizing the above devices.

2 Technology

The stability of the metallizations (ohmic contacts, Schottky contacts and interconnection layers) is the major factor which determines the overall reliability of the device. This means that prolonged operation at high temperatures must not change the physical properties of any metall/semiconductor interface. Therefore only those metallizations are capable to meet the above requirements which do not accidently interact with the $GaAs$ when all fabrication steps have been completed (formation annealing of the ohmic contacts, stabilization annealing of the Schottky contacts) and which are compatible to the overlayer metallization used.

Because of their high electrical conductivity and chemical inertness Au-layers are preferred in any interconnection metallization. Unfortunately, due to the high solid solubility of Ga in gold and the formation of $AuGa$ phases a continous driving force for Au-$GaAs$ interaction is existing. This may lead to severe degradation of both ohmic and Schottky contacts (Ref.4). Therefore any Au, not bonded in a stable intermetallic compound needs to be separated from the $GaAs$ by a suitable diffusion barrier.

For ohmic contacts, a systematic evaluation and optimization has led to a metallization scheme consisting of $Ti/Pt/Au$ for p-type and Ni-Ge-Au-Ni-W_5Si_2-Ti-W_5Si_2-Au for n-type ohmic constacts.

1. n-type ohmic contacts

   The diffusion barrier, separating the top layer from the "active" part of the contact is represented by alternating W and Si layers with a very thin Ti layer in the center of the structure. The Ti is neccessary to effectively reduce the W_5Si_3 formation temperature so that both the formation of the ohmic contact and of the tungsten silicide can be performed in *one annealing step* (Ref.5). The active parts of the contact, responsible for the ohmic behavior, consist of a very thin Ni adhesion layer followed by the Ge dopant, a thin Au layer and a final Ni layer. The layer dimensions assure that any volume of the thin Au layer is completely comsumed during the reaction so that no degradation can take place later on.

2. p-type ohmic contacts

   The p-type ohmic contacts needed for the HBT consisted of $Ti/Pt/Au$ annealed at 500^0C since these exhibited sufficient stability for high temperature operation.

3. Schottky contacts

   The Schottky contact for the MESFET gates have been realized by e-beam evaporation of a LaB_6 diffusion barrier layer followed by a Au top layer (thickness: $100nm$ each layer). Besides the excellent diffusion barrier behavior, LaB_6 is particularly interesting for high temperature applications because it effectively reduces the native $GaAs$ oxide thus forming a good Schottky contact with a relatively large barrier height (up to $0.9eV$) (Ref.6).

In the following the fabrication of the different devices is summarized.

HBT A high temperature n-p-n $GaAlAs/GaAs$ HBT with wide band gap emitter has been fabricated with MOCVD grown epitaxial layers on (100) oriented semi-insulating $GaAs$ substrates. The $AlAs$ mole fraction used in the wide band gap emitter of $0.15\mu m$ thickness was choosen to be 0.45% to achieve a reasonable current gain even at increased ambient temperatures. Compositional gradings of $0.05\mu m$ thickness were introduced at the emitter-base junction and at the interface to the the $GaAs$ cap layer to reduce the $C-E$ offset voltage. A $10nm$ spacer layer was placed between emitter and base because of the high diffusion constant of the Zn used for p doping of the $GaAs$ base layer. The device was structured with wet etched mesas for base and collector by the combination of a selective and non-selective etchants. The $AlGaAs$ layer between emitter and base was reduced only to a thickness of about $60nm$. This layer is completly depleted and reduces efficiently the surface recombination.

The surface was passivated by a $10nm$ thick $UVCVD$ (Ultra Violet CVD) deposited Si_3N_4 layer in order to reduce the surface recombination current at the base emitter interface and to prevent the outdiffusion of As atoms from $GaAs$ surface during alloying and high temperature operating of the HBTs. The UV-deposited Si_3N_4 layer was followed by a $100nm$ thick $PECVD$ (Plasma Enhanced CVD) Si_3N_4 layer. A $Ti/Pt/Au$ layer was evaporated for the bonding pads.

MESFET The MESFETS were fabricated on MOCVD grown $GaAs$ with an active layer doping of $1 \times 10^{17}/cm^3$ and a thickness of $0.4\mu m$. The gate was evaporated into a wet etched recess. The gate length was $1\mu m$ and the gate width $400\mu m$. The mesa was structured using wet etching. For the passivation PECVD of Si_3N_4 was used. The PECVD process has been systematically optimized to give best adhesion and blocking of As outdiffusion (Ref.7).

HEMT For the HEMT devices the same set of masks was used as for the MESFETs. The layers of the MOCVD grown material are as follows: on the semiinsulating $GaAs$-substrate a $1 \mu m$ thick $GaAs$ buffer was grown. After a $8 nm$ thick $AlGaAs$ undoped spacer a Si doped delta-doping with a peak doping of $6 \times 10^{18}/cm^3$ and finally a $30 nm$ $AlGaAs$ layer and a n-$GaAs$ cap of the same thickness has been grown. The other technological steps are the same as for the MESFET.

3 Characterization of MESFETs HEMTs and HBTs at High Ambient Temperatures

The characterization of all devices has been carried out in an especially manufactured test fixture with locally heated transistors, which have been mounted into commercially available $100 mil$ packages. The temperature was controlled by a thermoelement directly at the package surface. DC measurements have been carried out at a number of ambient temperatures starting from 25^0C up to 300^0C. Fig.1 and fig.2 demonstrate the I/V characteristics of the fabricated MESFET and HEMT at room temperature, 200^0C and 300^0C. The comparison of the characteristics at the different temperatures reveals the following effects:

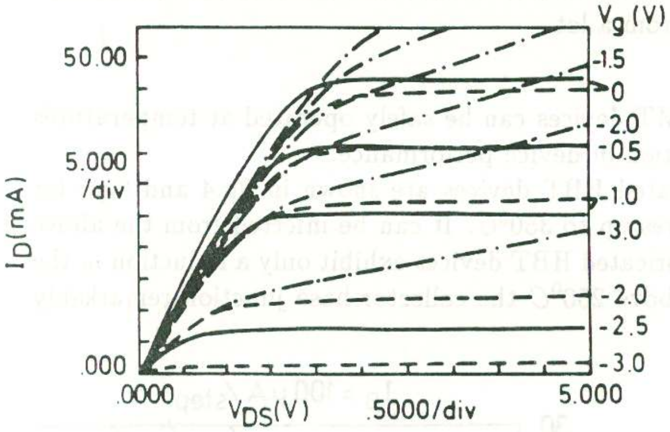

Figure 1: I/V characteristics of the fabricated MESFET devices at room temperature (solid line), 200^0C (dashed line) and 300^0C (dash-dotted line).

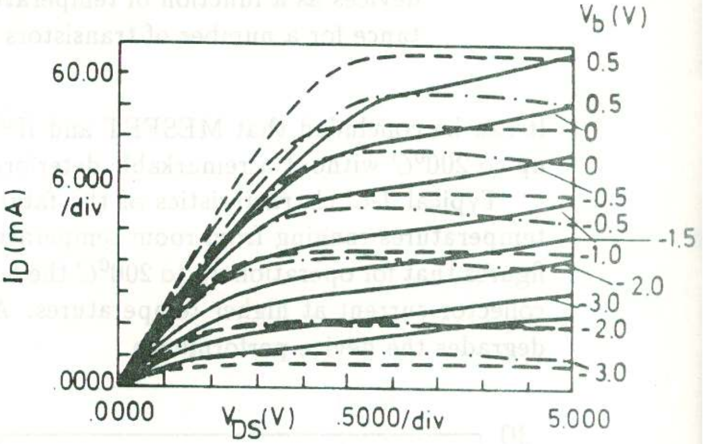

Figure 2: I/V characteristics of the fabricated HEMT devices at room temperature (dashed line), 200^0C (dash-dotted line) and 300^0C (solid line).

- The I/V characteristic of the fabricated MESFET devices do not change significantly up to ambient temperatures of 200^0C.
- The fabricated HEMT devices exhibit larger negative differential output conductance as compared with the MESFET devices. This is probably due to an escape of electrons from the $2-DEG$ channel. This effect is more pronounced at increased temperatures.
- Both devices show clear deterioration of their performance at temperatures near 300^0C. This is mainly due to the increased gate current and a possible increase in the substrate current.

- At room temperature the transconductance of both devices is approximately $80\,mS/mm$ and decreases slightly with increased temperatures as can be inferred from fig.3.

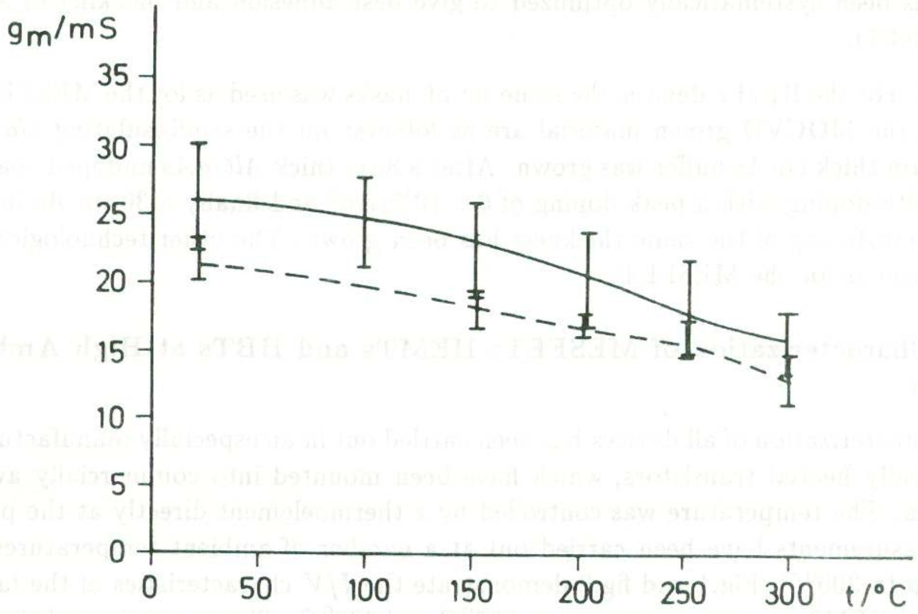

Figure 3: Transconductance g_m of the fabricated MESFET (dashed line) and HEMT (solid line) devices as a function of temperature. The bars indicate the variation in transconductance for a number of transistors from a lot.

It can be concluded that MESFET and HEMT devices can be safely operated at temperatures up to 200^0C without a remarkable deterioration in device performance.

Typical DC characteristics of the fabricated HBT devices are shown in fig.4 and fig.5 for temperatures ranging from room temperatures up to 350^0C. It can be inferred from the above figures that for operation up to 200^0C the fabricated HBT devices exhibit only a reduction in the collector current at higher temperatures. Above 250^0C the collector-base junction remarkably degrades the device performance.

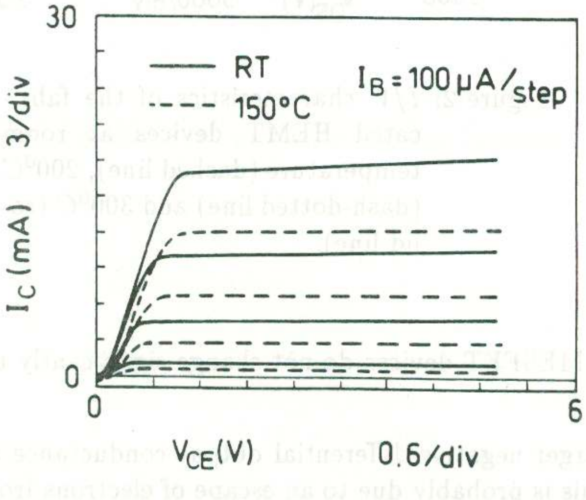

Figure 4: I/V characteristics of the fabricated HBT devices at room temperature and 150^0C.

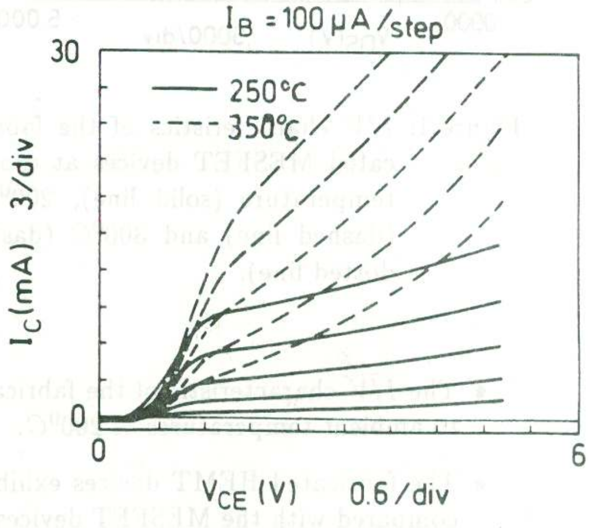

Figure 5: I/V characteristics of the fabricated HBT devices at 250^0C and 350^0C.

The *DC* characteristics the fabricated HBT devices were stable after a number of temperature cycles and after storage tests for $24h$ at 250^0C. The achieved small-signal current gain h_{FE} reaches values between 40 and 100 with the according emitter areas of $7 \times 40\ \mu m^2$, $13 \times 50\ \mu m^2$ and $18 \times 50\ \mu m^2$

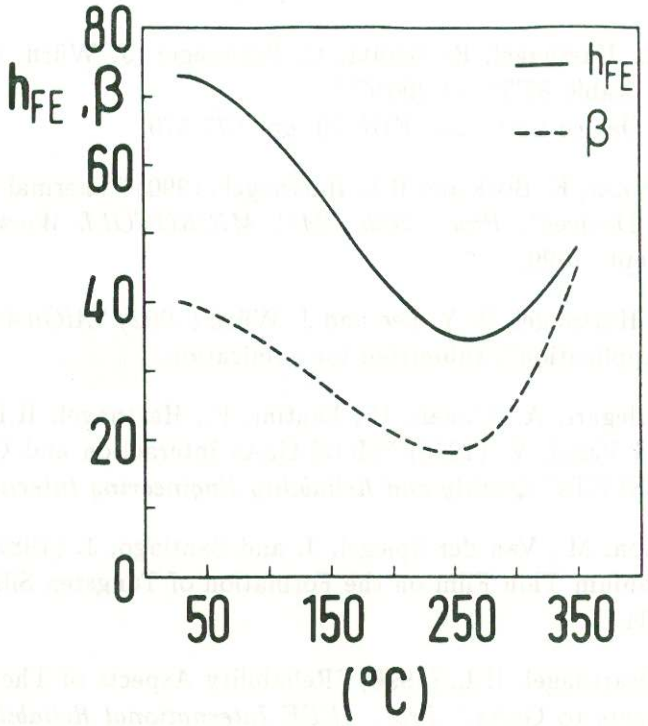

Figure 6: Small signal current gain h_{FE} and the current gain β of the fabricated HBT devices as a function of temperature.

The reduction in h_{FE} and β can be attributed to a higher hole injection from the base into the emitter at increasing temperatures. At very high temperatures (above 250^0C) the current gain increases due to an additional leakage of holes from the collector into the emitter.

RF measurements on the above devices will be shown during the presentation of the paper at the conference.

First results of the *RF* measurements show that only the S_{21} parameter in MESFET devices exhibits a remarkable variation with increased temperatures. Other elements remain nearly unchanged with temperature up to 300^0C.

4 Conclusions

Successful design and fabrication of MESFETs, HEMTs and HBTs for operation at high ambient temperatures has been presented. *DC* characterisation at elevated temperatures up to 350^0C has been demonstrated. It could be shown that the proposed devices can be reliably operated at ambient temperatures up to 300^0C with little deterioration in device performance for temperatures up to 200^0C. The realization is based on a modified GaAs technology especially developed to meet the requirements of devices continuously operating at high temperatures. Lifetime tests demonstrated the stability of the contacts even at 400°C.

The temperature dependence of the I/V characterisitic of all devices is mainly governed by the Schottky contact and the heterojunction. In the case of MESFET and HEMT devices, the deterioration in device performance is essentially due to an increased gate current whereas HBT devices are limited by the hole current across the base-emitter heterojunction.

Acknowledgements

This work has been performed at the Institut für Hochfrequenztechnik of the Technical University of Darmstadt - FRG. We kindly acknowledge the financial support from the Deutsche Forschungsgemeinschaft (DFG, SFB 241).

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