INTEGRATED CIRCUITS ON GaAs FOR THE TEMPERATURE RANGE FROM ROOM TEMPERATURE UP TO 300°C

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Abstract

The purpose of this paper is to present a technology for GaAs integrated circuits which allows stable operation in the temperature range from 20°C to 300°C. We shall show by some examples that it is possible to fabricate MESFET-based integrated circuits with small temperature dependence up to 300°C. Long term thermal stress tests demonstrate the excellent reliability of the technology. However, the need for adequate design tools will be shown as well, as more complicated circuits have an unpredictable behaviour at very high temperatures.

Introduction

Due to the growing need of sensing in hot environments like car engines, satellites, or deep level drilling significant research efforts on high temperature integrated circuits have been undertaken in the last years [1-5]. Also, MMIC researchers are interested in a reliable technology for higher temperatures to be able to drive their circuits with a higher power density. In spite of all this very little has been reported on a technology for reliable operation of circuits at high temperatures.

Due to the higher bandgap compared to Si and hence the lower intrinsic carrier density, GaAs is a good semiconductor material for high temperature applications. Compared with other compound semiconductor materials like SiC the technology to produce epitaxial material and to manufacture devices is very mature for GaAs. Still, devices operated for long terms at high temperatures usually fail due to the degradation of ohmic and Schottky contacts or of the semiconductor surface. Our laboratory has been working for some time on these aspects and has achieved significant results [6-9]. A complete technology for reliable MESFETs was published recently [10]. We want to show now that using the same technology integrated circuits can be produced that work reliably at temperatures up to 300°C presenting three tested integrated circuits, namely a differential amplifier, a multivibrator [11] and a NOR-gate. Also, we shall show that models are necessary to predict circuit behaviour at high temperatures and we shall postulate some demands on these models.

Technology

As mentioned above most of the device and circuit failures are due to contact and surface degradation. In the following we want to present briefly the established technology to prevent these failures:

Ohmic contacts to n-GaAs for FETs and diodes:

Conventional ohmic contacts consist of a doping material (Ge) and a well conducting material to which bonding wires can be attached (Au). Interdiffusion between Au and GaAs is the main degrading mechanism of these contacts. To prevent this interdiffusion contacts with a WSi_2 diffusion barrier were developed. The contacts used for the integrated circuits consisted of a 20nm Ge layer, a 10nm Ni layer to enhance the drive-in process of Ge during the subsequent annealing step, a 100nm WSi_2 layer (alloyed out of 9 alternative electron-beam evaporated W and Si layers), and a 50nm Au layer. Rapid thermal annealing with a peak temperature of 640°C produced good ohmic contacts with a resistance of $10^{-5}\Omega cm^{-2}$ into $10^{17}cm^{-3}$ n-doped GaAs.

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Schottky contacts for FET gates and Schottky diodes:

Although TiPtAu Schottky diodes show slight degradation at 300°C [7], this material was chosen to produce integrated circuits for the ease of production and the compatibility with the manufacturing of passive components: Due to the good adhesion of this material to GaAs and to the dielectric silicon nitride it could be used for bonding pads, interconnects and the capacitor plates. Parallel experiments showed that any circuit degradation is not due to this material [10]. Fig.1 shows drain and gate current of a MESFET built using this technology at 300°C before and after a simultaneous electrical and thermal stress of 500 hours duration: no degradation can be seen - the gate current is even decreasing. Nevertheless future IC applications will have LaB_6/Au Schottky contacts, which is still more stable due to the higher barrier [8,9].

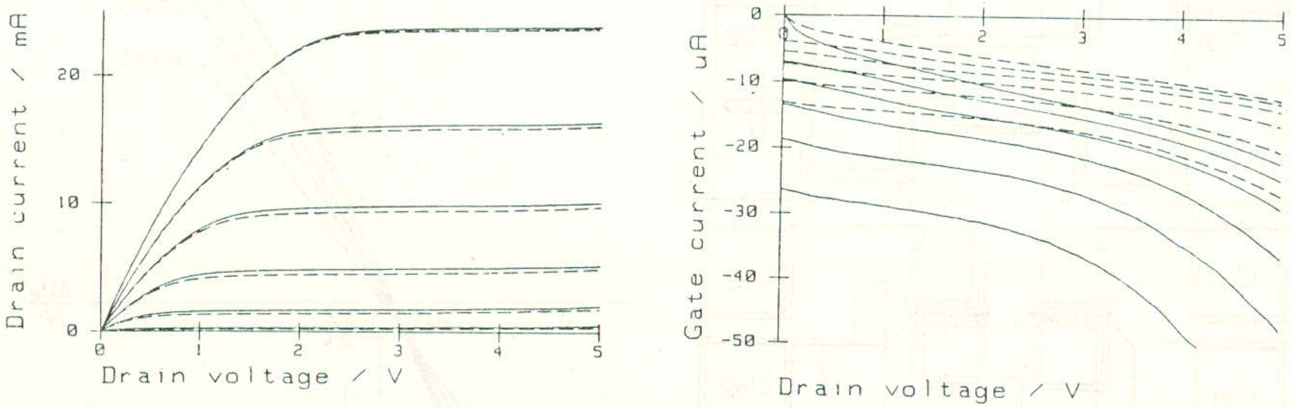

Fig.1 Drain and gate current of a MESFET at 300°C: —— before and --- after 500 hours of thermal and electrical stress

Resistors:

100 nm thick, flash evaporated NiCr showed a fairly temperature independent sheet resistivity of 15-20Ω/■. It turned out to be good to deposit resistors onto a first isolator (Si_xN_y) layer instead of a deposition directly onto GaAs.

Surface passivation and capacitor dielectric:

Plasma enhanced CVD of Si_3N_4 at a substrate temperature of 300°C is well adhering to GaAs and has very few pinholes. Since no surface currents could be measured at room temperature even after several heating and cooling cycles surface oxidation leading to degradation is successfully prevented.

Circuit design and results

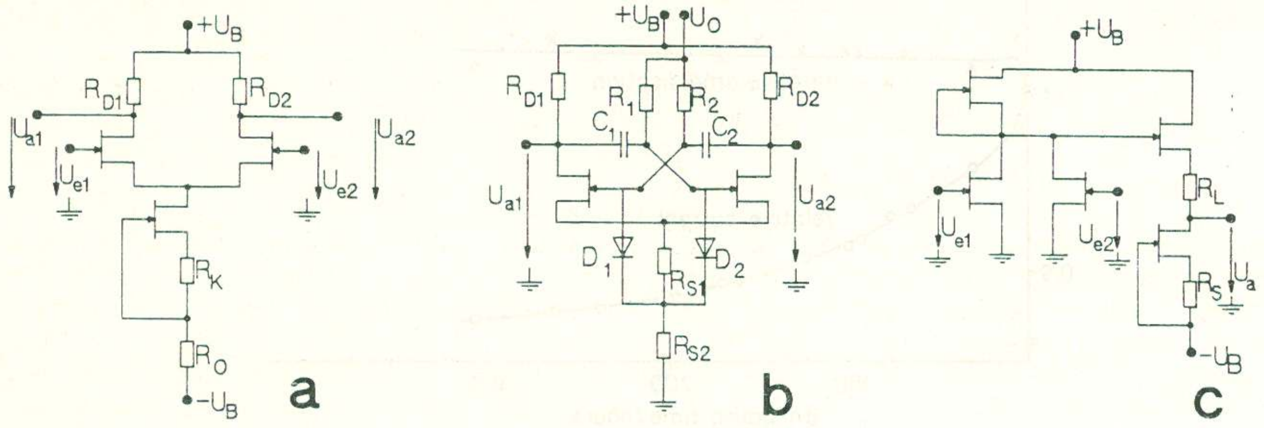

Fig.2 Equivalent circuits of the differential amplifier (a), the multivibrator (b), and the NOR gate (c).

Using DC characteristics of MESFETs measured at room temperature and 300°C and supposing no temperature drift of the passive compounds three standard circuits could be dimensioned: a differential amplifier (Fig.2a), a multivibrator (Fig.2b), and a NOR-gate (Fig.2c). No circuit simulation was undertaken. A brief discussion of the results and the problems encountered is the following.

a) Differential amplifier (Fig.3)

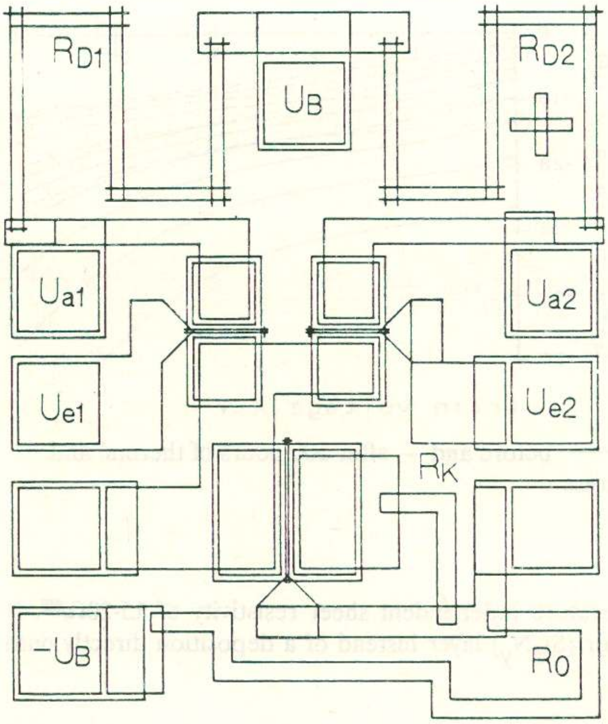

Fig.3 Layout of the differential amplifier

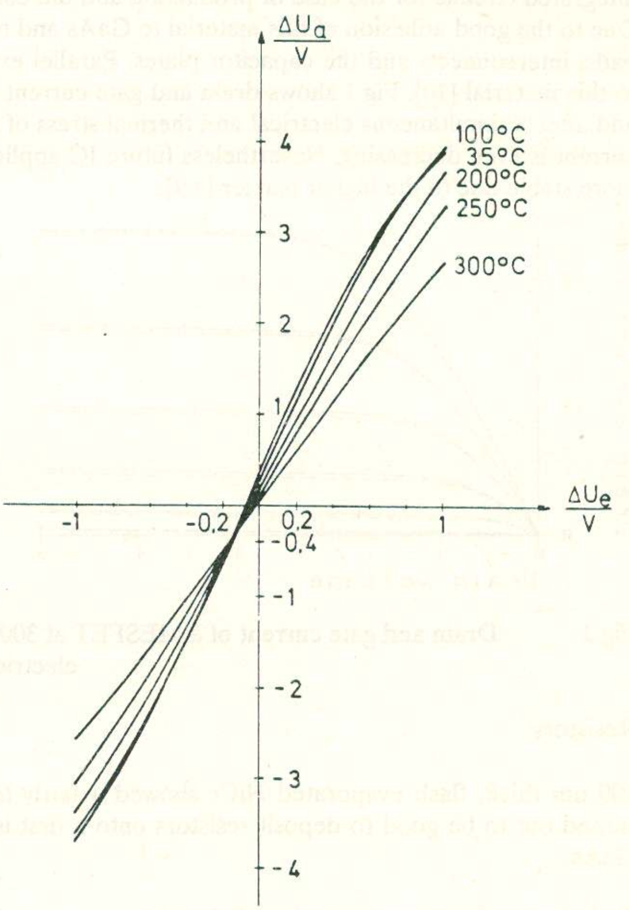

Fig.4 DC amplification at different temperatures

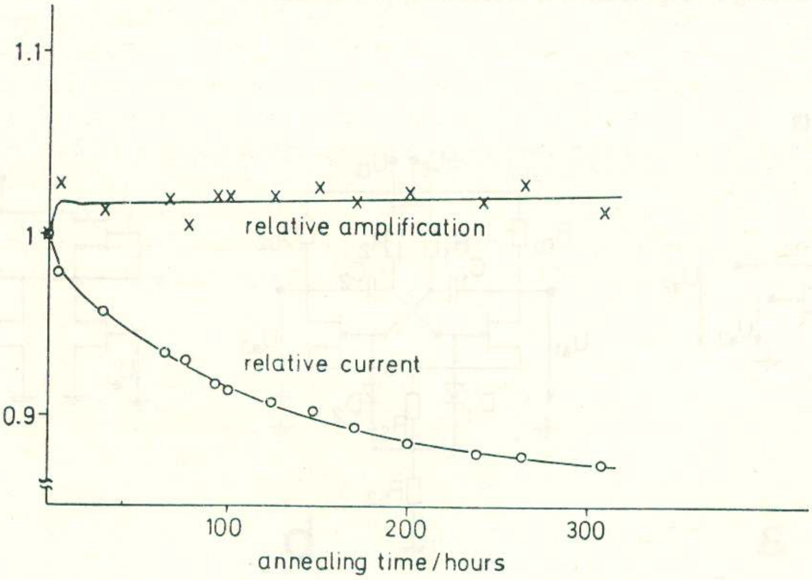

Fig.5 DC amplification of the differential amplifier and current during 300 hours of thermal stress at 300°C

The amplification of a sensor signal near to the sensor, possibly in a hot environment, will reduce noise and thus improve the measurement results. As a first amplifying circuit we realised a simple differential amplifier. Although the NiCr metallisation has an almost temperature independent resistivity the effective resistive load of the amplifier is decreasing with temperature. This leads to a decreasing amplification (Fig.4). The current source, however, showed a perfect temperature compensation. Also, it could be shown that a decrease in current, which took place during a thermal stress at 300°C of 300 hours duration, did not deteriorate the DC amplification (Fig.5). In addition it needs to be mentioned that the circuit worked satifactorily for 100 hours at 400°C.

b) Multivibrator (Fig.6)

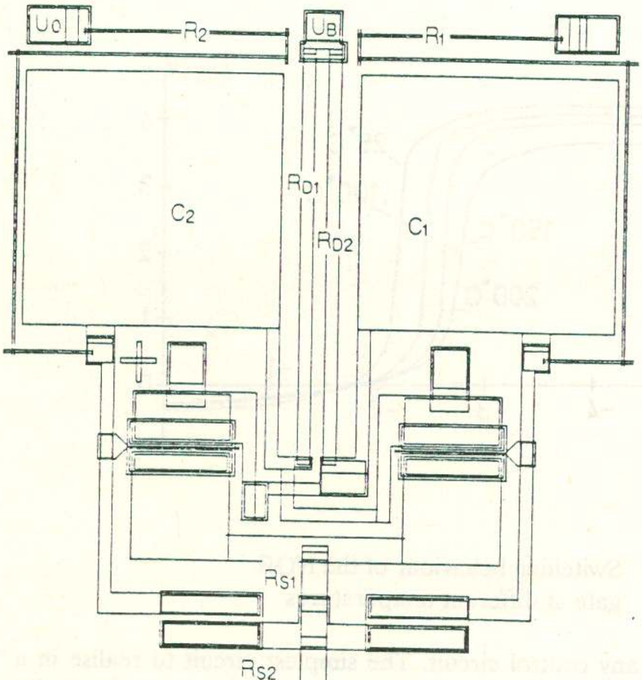

Fig.6 Layout of the multivibrator

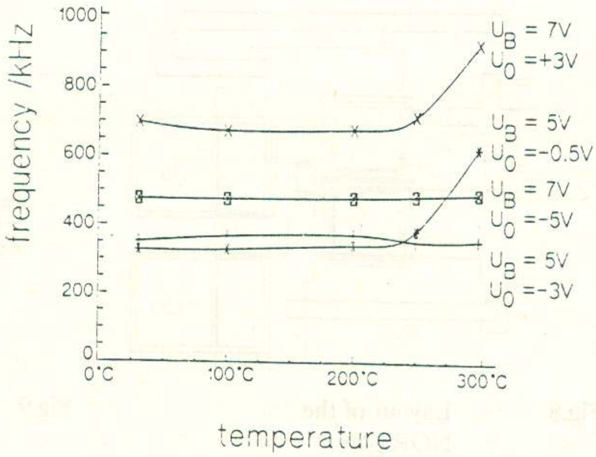

Fig.7 Temperature dependence of the output frequency

The conversion of signals to a frequency encodes the signal and thereby protects it against noise. Higher frequencies are necessary, when the wireless transmission is necessary. A first oscillator was built to check the possibilities. Due to the lack of simulation tools the behaviour of the multivibrator could not be predicted. The influence of the protective Schottky diode could be seen only during the characterisation phase: Since the knee voltage of the diode is decreasing strongly with temperature a strong frequency increase over 200°C is noted, which can be inhibited by a strong reverse bias of the diodes. Thus a temperature stable oscillation is possible (Fig.7). Long term reliability tests at 300°C demonstrated stable operation for 750 hours with virtually no frequency change after a first annealing time of approx. 24 hours. Some reliability problems occured at several tested circuits due to electric discharge at the capacitor edges. There is a need to examine the maximum admissible electrical stress at high temperatures.

c) NOR gate (Fig. 8)

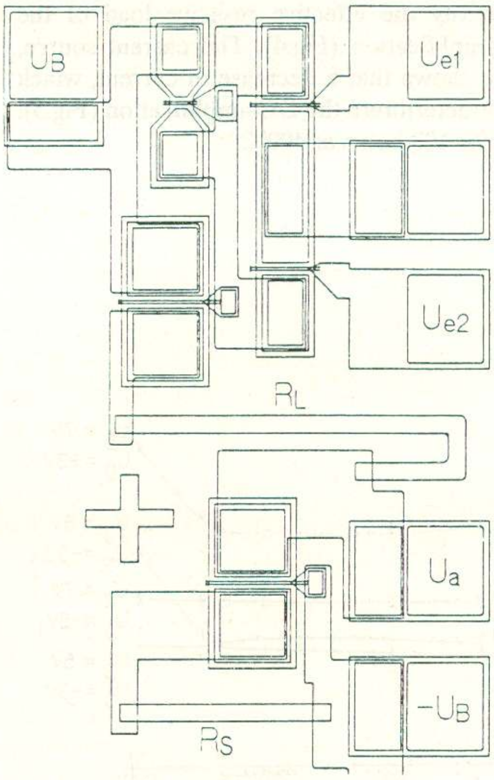

Fig.8 Layout of the NOR gate

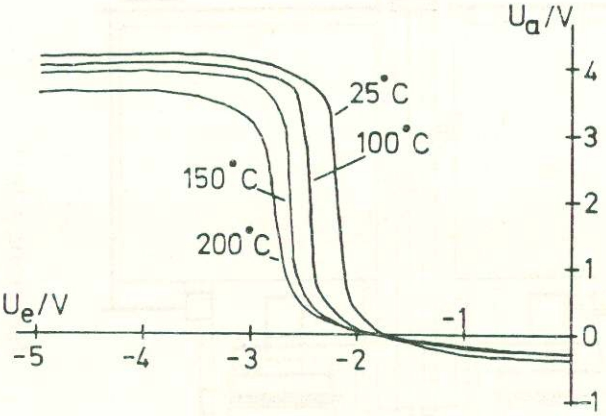

Fig.9 Switching behaviour of the NOR gate at different temperatures

Logic circuits for signal processing are very important in any control circuit. The simplest circuit to realise in a pure n-logic is a NOR gate. Unfortunately several errors occured during the layout, so that the output levels did not correspond to the input levels although the voltage swing was correct. However, we could observe a fairly precise switching between low and high level up to a temperature of 200°C (Fig. 9). At a higher temperature lack of current control caused a lowering of the high level output. Good switching behaviour (delay time 20ns - 60ns and rise time 140nsec independent of temperature) demonstrated the ability of GaAs to produce high temperature logic circuits.

Conclusion

It has been shown with several prototype examples that circuits for the use at high temperatures can be integrated on GaAs and that these circuits can be operated reliably at temperatures up to 400°C.
For future developments some main rules have to be kept in mind:

a) the metallurgy of all contacts must be stable at high temperatures, no interaction with GaAs should occur,
b) the passivation of the surface must be well adhering and free of pin holes,
c) active loads are better than passive loads to eliminate the effects of leakage currents,
d) special layout rules have to be observed to prevent failure due to electric discharge,
e) diodes are not useful for level shifting.

The main problems still to be solved are:

a) reliable models to simulate circuits over a wide temperature range do not exist,
b) there is no knowledge about the maximum admissible electrical stress at high temperatures,
c) there is little knowledge about the high frequency behaviour of active and passive components at high temperatures.

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References

[1] J.D.Beasom, R.B.Patterson, "Process characteristics and design methods for a 300^{o}C quad operational amplifier", *IEEE Trans. Industrial Electronics*, vol. IE-29, no.2, 1982, pp.112-117

[2] F.H.Doerbeck, W.M.Duncan, M.V.McLevige, H.Yuan, "Fabrication and high-temperature characteristics of ion-implanted GaAs bipolar transistors and ring-oscillators", *IEEE Trans. Industrial Electronics*, vol. IE-29, no.2, 1982, pp.136-139

[3] E.Pettenpaul, W.Heidenreich, J.Huber, W.Flossmann, "A high-temperature sensor based on monolithic GaAs Hall IC", Proc. GaAs IC Symp., Monterey, CA, USA, Nov.12-14 1985, pp.169-172

[4] T.R.Lepkowski, G.Shade, S.P.Kwok, M.Feng, L.E.Dickens, D.L.Laude, B.Schoendube, "A GaAs integrated Hall sensor/amplifier", *IEEE Electron Device Lett.*, vol.EDL-7, no.4, 1986,pp.222-224

[5] K.Itakura, D.Ueda, M.Hagio, M.Kazumara, "GaAs integrated Hall sensor with temperature stabilised characteristics up to 300°C", *Electronics Lett.*, vol.25, no.22, 1989, pp.1493-94

[6] J.Würfl, A.G.Nassibian, H.L.Hartnagel, R.Langfeld, C.Maurer, "Electron beam annealed Ge-WSi-Au and Ge-Ni-WSi-Au high temperature stable ohmic contacts on n-GaAs", *Int.J.Electronics,* vol.66, no.2, 1989, pp.213-225

[7] J.Würfl, H.L.Hartnagel, "Thermal stability and degradation mechanisms of Ti-Pt-Au, Ti-W-Au and WSi2-Ti-Pt-Au Schottky contacts on GaAs" Proc. 4th Int.Conf.Prevention, Detection and Failure Analysis, Bordeaux/France, April 25-28 1989, pp.133-138

[8] J.Würfl, J.K.Singh, H.L.Hartnagel, "Reliable, high temperature stable Schottky contacts to GaAs based on LaB$_6$ diffusion barriers", Proc. ESSDERC, Berlin/Germany, Sept. 11-14 1989, pp.165-168

[9] J.Würfl, J.K.Singh, H.L.Hartnagel, "Reliability aspects of thermally stable LaB$_6$-Au contacts to GaAs", presented at the Reliability Physics Symp., New Orleans, March 26-29 1990

[10] K.Fricke, H.L.Hartnagel, R.Schütz, G.Schweeger, J.Würfl, "A new GaAs technology for stable FETs at 300°C", *IEEE Electron. Dev. Lett.*, vol.EDL-10, no.12, Dec.1989, pp.577-579