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High Frequency Characteristics of GaAs Vertical JFET Devices Operated in the Bipolar Mode

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The newly developed BSIT/BMFET with heterojunction emitter and first experimental results of high frequency measurements are presented. In comparison with homojunction BMFET an increase in dc current amplification by a factor of 3 could be observed and an f_t of 1.5 GHz and a maximum frequency of oscillation of 1.7 GHz could be measured for the VHF design undertaken. In addition, the transistor has the useful input and output impedances in the usual range of bipolar transistors. The transistor is analysed using a small-signal equivalent circuit.

1. INTRODUCTION

Power applications require transistors to have the capability to withstand high voltages and high current densities together with good thermal coductivity and the possibility to work reliably at elevated temperatures. Bipolar Static Induction Transistors (BSIT) which are also called Bipolar Mode Field Effect Transistors (BMFET) showed good properties for power applications when produced on silicon but poor high frequency characteristics were reported[1]. Far better values for transit frequency and maximum frequency of oscillation were predicted for similar GaAs devices, but a first realisation[2] showed comparable values of the order of 500 MHz for f_t and f_{max}. An analysis of S-parameter measurements indicated that the transit time of electrons through the channel was among the limiting factors for high frequency operation. In order to accelerate electrons in field effect transistors Tomizawa et al. proposed a hot electron launcher at the source side which can be obtained by a heterojunction[3]. A first realisation of this idea was the Vertical Electron Transistor of Mishra et al.[4], but no high frequency data was reported. In our laboratory a BMFET (BSIT) with such a heterojunction at the source was realised and it could be shown that in fact the dc current amplification and the transit frequency f_t could be increased as compared to a homojunction device, although no ballistic transport is possible due to the length of the channel of our design. We intend to discuss which high-frequency effects are due to the heterojunction and which further improvements are possible.

2. FABRICATION

A cross section of the channel region is shown in Fig.1. The low-doped channel, the heterojunction and the graded as well as the GaAs contact layer of the source were produced by MOCVD by Epi Materials, UK. These three layers have a thickness of 100 nm each. Then, zinc doped gate regions were diffused into the material through a mask of PECVD silicon nitride. Diffusion at 620°C in a semi-closed graphite crucible for one hour resulted in a junction depth of 1µm and a doping level of $p=2\cdot10^{19}cm^{-3}$. The gate region surrounds a source finger of 5x100 µm area. The whole device was passivated with PECVD silicon nitride and contact wholes were etched into the passivation layer. NiAuGe contacts were used for the n-doped source and

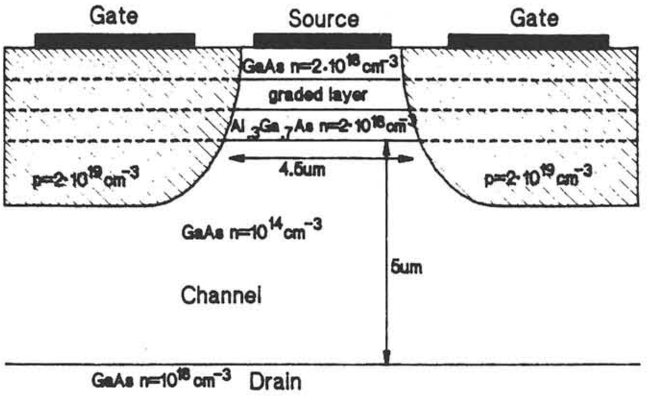

Fig.1 Cross section through the BMFET with heterojunction source

drain and TiPtAu contacts for the p-doped gate. The contacts were annealed simultaneously by rapid thermal annealing at 500°C resulting in contact resistances of the order of magnitude of $10^{-6}\Omega cm^2$. CrAu contact pads for bonding were evaporated onto the fabricated device. The devices were then bonded into a high frequency test fixture and measured using an HP 8510 network analyser.

3. MEASUREMENT RESULTS

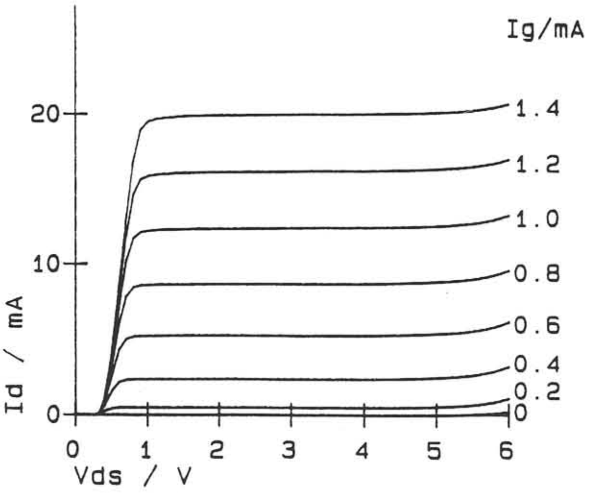

Fig.2 DC characteristics of the BMFET with heterojunction source

The one-finger device shows dc characteristics of a bipolar transistor with no current conduction when no current is injected into the gate (normally-off BMFET) and a maximum current density in the source region of $6kA/cm^2$. In contrast to usual bipolar transistors the current amplification decreases with increasing drain current. This effect as well as the thermal behaviour are discussed elsewhere[5]. The heterojunction BMFET thus has lower on-resistance and higher maximum current density than a GaAs power SIT proposed in 1987[6], but due to the short channel length of 5µm a lower breakdown voltage (6V) which is due to impact ionisation.

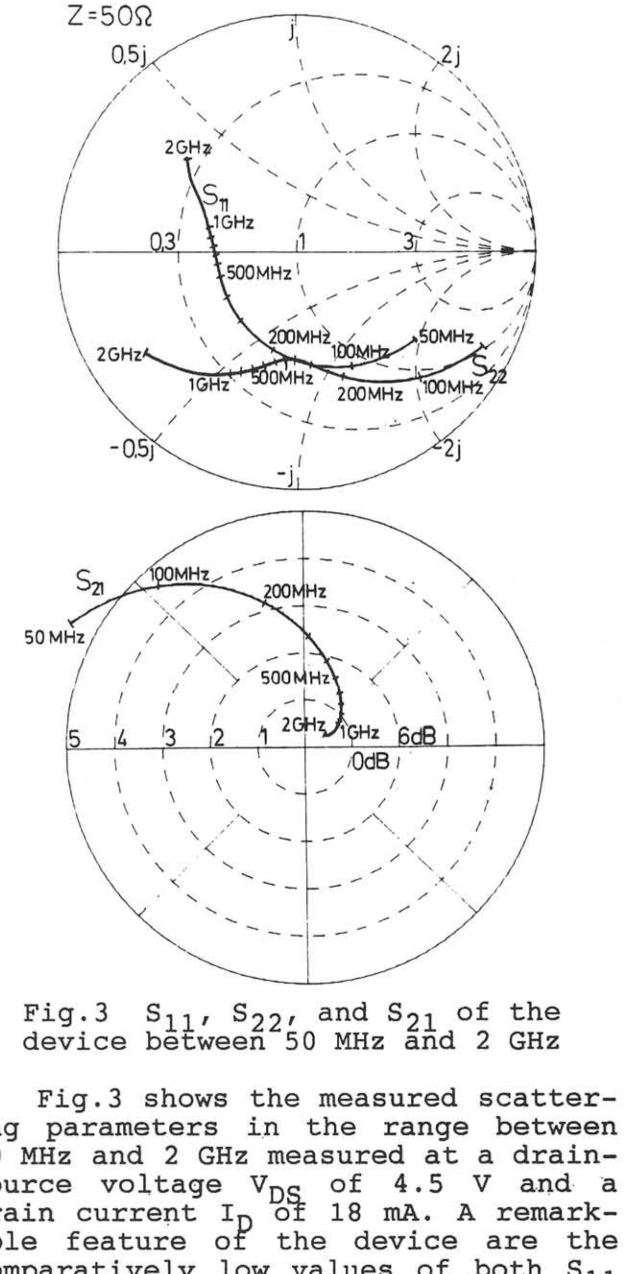

Fig.3 S_{11}, S_{22}, and S_{21} of the device between 50 MHz and 2 GHz

Fig.3 shows the measured scattering parameters in the range between 50 MHz and 2 GHz measured at a drain-source voltage V_{DS} of 4.5 V and a drain current I_D of 18 mA. A remarkable feature of the device are the comparatively low values of both S_{11} and S_{22}, which enable easy matching to high frequency circuits.

The scattering parameters are almost independent of V_{DS}. On the other hand, particularly $|S_{21}|$ depends on the drain current: At 50 MHz $|S_{21}|$ increases with I_D, at 250 MHz it remains constant when I_D changes and at higher frequencies a decrease with increasing drain current can be observed. The reason of this can be the lifetime of excess holes in the channel as discussed below.

The small-signal current amplification h_{21} and the maximum available gain can be calculated and an extrapolation of these values to 0dB allow one to estimate an f_t of 1.5 GHz and a maximum frequency of oscillation f_{max} of 1.7 GHz.

4. DISCUSSION

Although the small-signal equivalent circuit of a bipolar transistor shown in Fig.4 is a simplification of the actual situation the optimisation of the values of the circuit elements given in this figure leads to an acceptable fitting of calculated and measured scattering parameters.

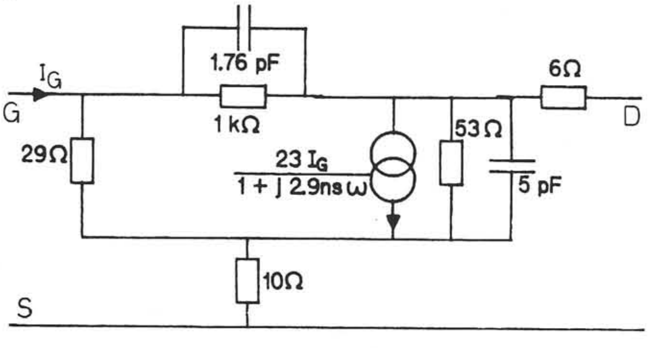

Fig.4 Simplified small signal equivalent circuit of the BMFET with heterojunction source

We can note very low series resistances at all contacts and no capacitive coupling between gate and source. On the other hand we see strong conductive coupling between gate and drain and a remarkably high time constant of the current source.

Comparing the heterojunction device with a homojunction BMFET, this time constant is reduced by 25%, whereas the amplification factor is increased from 15 to 23. This increase in low frequency amplification is mainly due to the fact that the heterojunction reduces the hole leakage from gate to source. The decrease in the time constant can be attributed to the higher kinetic energy of electrons entering the channel from the wide-bandgap source.

However, the conductive coupling between gate and drain and the time constant of the current source need to be decreased to obtain better values of f_t and f_{max}.

Such improvements can be obtained by an improved sequence of the epitaxial layers in the channel as proposed by Kim et al.[7], a decreased area of the gate or by means of an additional implanted isolation layer between gate and drain. When it is possible to produce a wide-bandgap gate by selective epitaxy, leakage from drain to gate can be reduced significantly. By proper bandgap engineering it might be possible to accelerate holes between the gate and the channel area, because the lifetime of holes in the channel might be an important factor limiting the operating frequency.

5. CONCLUSIONS

We have presented the high-frequency characteristics of the first realised heterojunction BMFET on GaAs, indicating the improvements compared to homojunction devices. First measurements gave a transit frequency f_t of 1.5 GHz and a maximum frequency of oscillation f_{max} of 1.7 GHz. The limiting factors are strong conductive backcoupling, the transit time electrons need to cross the channel and the minority carrier lifetime in the channel. By design optimisation all these limits can be pushed to higher frequencies so that high power operation of the device at the usual microwave frequencies will be possible.

6. REFERENCES

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