On-Wafer RF Measurement Setup for the Characterization of HEMT's and High T_c Superconductors at Very Low Temperatures Down to 20 K

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Abstract

The possibility of microwave measurements at cryogenic temperatures is very important to investigate the pronounced RF performance of high electron mobility transistors (HEMT) /1,2/. In order to perform an exact small signal analysis of the investigated devices the On-Wafer measurement technique is an indispensable tool. A measurement setup which is cooled by liquid nitrogen has been presented by Laskar et al. /3,4/. However, to investigate the combination of high T_c superconducting materials and HEMT devices lower temperatures have to be achieved. For this reason a microwave On-Wafer measurement setup at temperatures down to 20 K and frequencies up to 40 GHz has been developed. Using this equipment a detailed RF analysis of pseudomorphic HEMT at low temperatures and measurements on a superconducting filter will be presented.

Measurement Setup

The measurements in the temperature range from 20 K to 300 K have been done using the On-Wafer measurement setup shown in Fig. 1. A turbo molecular pump provides a vacuum of less then 10^{-2} Pa which is necessary to avoid ice formation on the samples. In order to avoid vibrations, caused by the helium cooled cryostat, the samples have to be fixed onto a copper block which is separated from the cold head of the cryostat using a flexible copper cable. Commercial microwave probe tips are mounted on micropositioners, which are adjustable from outside the vacuum chamber via vacuum rotary motion feedthroughs. Due to the high thermal resistance of the ceramic probe tips the calibration of the measurement setup can be done at room temperature using standard calibration techniques. The temperature of the samples is exactly controlled using a surface mounted GaAs diode.

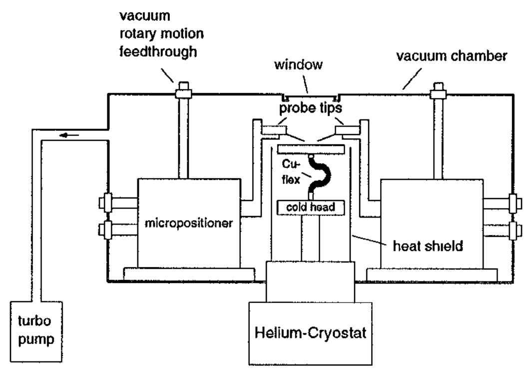

Fig. 1. On-Wafer measurement setup for cryogenic measurements in the millimeter-wave range at temperatures down to 20 K

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Measurements on a pseudomorphic FET

The measurements were performed on an $Al_xGa_{1-x}As/In_yGa_{1-y}As/GaAs$ pseudomorphic HEMT with a 10 nm channel layer and an In-concentration of $y = 0.24$ initially optimized for room temperature operation. A sheet carrier concentration of about $1.8 \cdot 10^{12}$ cm^{-2} at 300 K is provided by a $3 \cdot 10^{18}$ cm^{-3} homogeneously doped AlGaAs layer with an Al-content of 25%. The gate is fabricated by optical contact lithography, consisting of eight 0.55 μm gate-fingers with a total gate-width of 240 μm.

Fig. 2 shows the s-parameters of the device at T = 24 K and T = 300 K in the frequency range from 40 MHz up to 40 GHz. The drain-source voltage and the gate-source voltage are V_{DS} = 1.5 V and V_{GS} = -0.2 V, respectively. At low temperature

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the device exhibits a negligible lower drain current of about $I_{D,20\,K}$ = 29.3 mA ($I_{D,300\,K}$ = 33 mA).

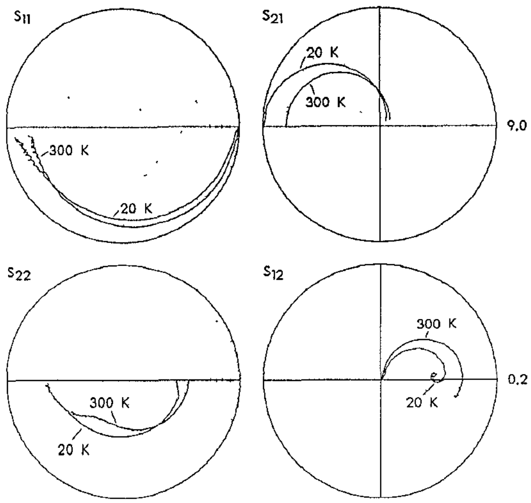

Fig. 2. s-parameters of the investigated HEMT at 20 K and 300 K in the frequency range from 40 MHz to 40 GHz; V_{DS} = 1.5 V, V_{GS} = -0.2 V; $I_{D,20\,K}$ = 29.3 mA, $I_{D,300\,K}$ = 33 mA

As can be seen from the input reflection coefficient s_{11} the input circuit of the device degenerates at the cryogenic temperature since the real part of the input impedance changes with frequency. However, an improved gate-resistance R_G can be observed, which drops to nearly zero at 20 K.

The output reflection coefficient s_{22} exhibits a strong variation with temperature. At low temperature a large phase shift due to an increased output capacitance can be observed. The output resistance decreases slightly from about 148 Ω at room temperature to about 118 Ω at 20 K.

At lower frequencies the forward transmission s_{21} at 20 K is much higher than the corresponding room temperature value and indicates an improved transconductance g_m. Against that the backward transmission s_{12} is much smaller but exhibits a pronounced phase shift at cryogenic temperatures.

Tab. 1 gives a comparison of the most important elements of the equivalent circuit calculated from the measured s-parameters at 20 K and 300 K.

	T = 300 K	T = 20 K
R_G / Ω	1.5	0.1
C_{gs} / pF	0.31	0.43
C_{gd} / fF	64	89
g_m / mSmm^{-1}	475	745
R_S / Ω	1.7	1.3
R_d / Ω	148	118
C_d / pF	0.094	0.27

Tab. 1. Elements of the equivalent circuit, calculated from measured s-parameters at T = 300 K and T = 20 K

Fig. 3 represents the effect of temperature on the extrinsic transit frequency f_T which can be extrapolated from the current gain h_{21}.

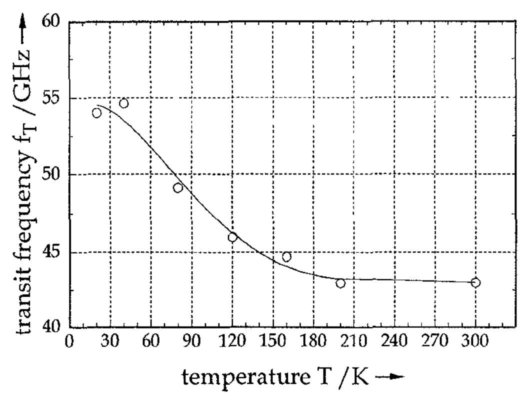

Fig. 3. Maximum of the extrinsic transit frequency f_T in dependence on temperature

From this the transit frequency at cryogenic temperatures can be determined to f_T = 54 GHz, which indicates the improved transport properties of the pseudomorphic FET.

However, the reduced parasitic elements of the device lead to a strongly increased unilateral gain GU at low temperature. In dependence on the gate-source voltage the cut-off frequency f_{max} of GU increases up to 195 GHz at 20 K

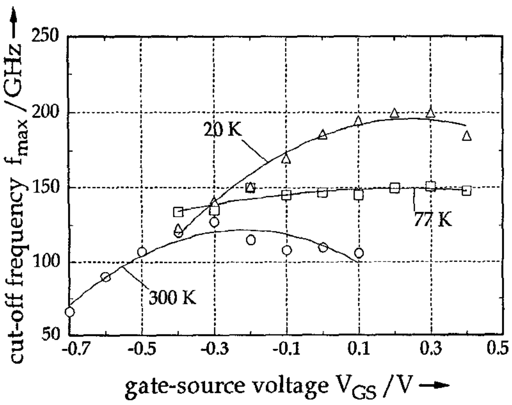

Fig. 4. Cut-off frequency of the unilateral gain *GU* in dependence on gate-source voltage at different temperatures (V_{DS} = 2V)

Hence the unilateral power gain can be extremly improved at cryogenic temperatures, although the increase of the transit frequency is of about 25%, only. Even at 77 K a considerable improvement of the cut-off frequency to a value of about 150 GHz can be achieved.

Measurements on a superconducting filter

In order to demonstrate the applicability of the developed equipment for investigations on high T_C devices a superconducting YBCO-filter on a $LaAlO_3$ substrate was measured. The layout of the filter consists of a coplanar waveguide and is shown in Fig. 5.

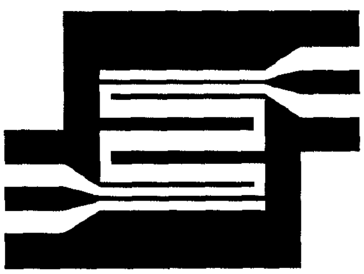

Fig. 5. Coplanar layout of the investigated superconducting YBCO-filter on a $LaAlO_3$ substrate

In dependence on frequency and temperature the transmission coefficient s_{21} exhibits a strong variation (cf. Fig. 6.)

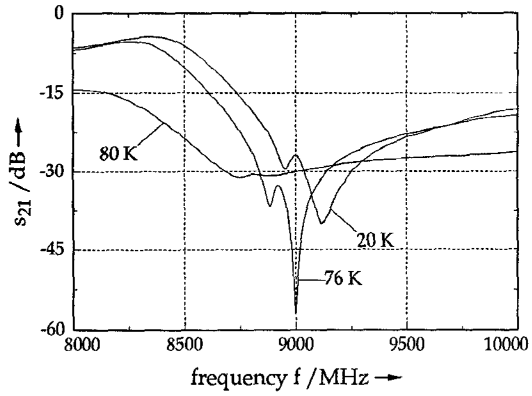

Fig. 6. Transmission s_{21} of the investigated filter in dependence on frequency at different temperatures

The *Q*-factor of the filter achieves its highest value around the critical temperature of 77 K. A maximum value of $Q \approx 3000$ can be observed at $T = 76$ K. However, at lower temperatures the quality factor drops to a value of $Q \approx 100$.

Furthermore the center frequency of the filter shifts from about 9.1 GHz at 20 K to 8.75 GHz at 80 K (cf. Fig. 7.) due to the shift of the kinetic inductance in the YBCO layer.

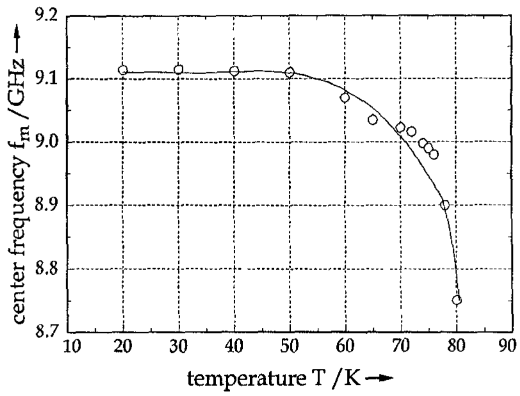

Fig. 7. Shift of the center frequency of the superconducting filter in dependence on temperature

Conclusions

A cryogenic On-Wafer measurement setup for the characterization of semiconductor devices and superconducting materials has been introduced which allows an exact small signal analysis of the investigated devices at temperatures down to 20 K in the frequency range up to 40 GHz. Measurements on a pseudomorphic HEMT with a gate-length of 0.55 μm and on a superconducting filter have been carried out and show the applicability of the developed system.

Though the investigated HEMT is not optimized for low temperature operation the device exhibits an improved microwave performance at low temperatures. While the transit frequency of the transistor increases from about 43 GHz at room temperature to 54 GHz at 20 K the cut-off frequency of the unilateral gain rises from 120 GHz up to 195 GHz.

The filter characteristic of the high T_c superconductor, represented by the Q-factor and the center frequency was found to be strongly dependent on temperature. However, near the critical temperature the Q-factor increases from about $Q \approx 100$ at 20 K to about $Q \approx 3000$ at 76 K.

In order to develop MMIC´s including superconducting layers and to investigate their low temperature operation the developed equipment is an indispensable tool.

Acknowledgement

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