On-Wafer Microwave Measurement Setup for Investigations on HEMT's and High T_c Superconductors at Cryogenic Temperatures Down to 20 K

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***Abstract*—In this paper an on-wafer measurement setup for the microwave characterization of HEMT's and high T_c superconductors at temperatures down to 20 K is presented. Both *S*-parameter and noise measurements, can be performed in the frequency range from 45 MHz to 40 GHz and 2 GHz to 18 GHz, respectively, using standard calibration techniques and commercial microwave probe tips. Microwave measurements on a pseudomorphic FET and an AlGaAs/GaAs HEMT as well as investigations on a superconducting filter are presented to demonstrate the efficiency of the developed system.**

Introduction

At low temperatures the enhanced transport properties of High Electron Mobility Transistors (HEMT's) lead to improved dc and RF characteristics [1], [2]. Therefore these devices are very attractive to realize monolithic microwave integrated circuits (MMIC's) for low temperature operation in satellite communication systems with very high gain and extremely low noise figure. An exact small signal analysis of these devices using a sophisticated on-wafer measurement technique at cryogenic temperature is an indispensable tool for the circuit design.

On-wafer measurement setups to determine the *S*-parameters of HEMT devices at temperatures down to 77 K were presented by several authors [3], [4]. However, for the combination of HEMT devices and high T_c superconductors, investigations at lower temperatures have to be carried out. Hence a microwave on-wafer measurement setup at temperatures from 300 K down to 20 K in the frequency range from 45 MHz up to 40 GHz has been developed and is presented in the first part of this paper.

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The electrical length of the coplanar probe tips exhibits only a small variation with temperature, while the other electrical properties remain unchanged in the whole temperature range. Therefore only a single room temperature calibration has to be carried out, which can be corrected for cryogenic measurements by a simple shift of the reference plane.

The results of microwave measurements on a pseudomorphic FET and for the first time on-wafer noise investigations of an AlGaAs/GaAs HEMT in dependence on temperature are presented in the second part of this paper. The dependencies of the elements of the equivalent circuit are investigated and discussed as well as the effect of temperature on the gain. Finally measurements of a YBaCuO filter are shown in order to demonstrate the efficiency of the developed system even for investigations on superconducting components.

Measurement Setup

The basic construction of the realized low temperature on-wafer measurement setup is shown in Fig. 1. In order to avoid ice formation onto the samples an evacuated chamber is needed. The vacuum of less than 10^{-2} Pa, which is necessary to minimize the thermal conductivity into the vacuum chamber, is provided by a turbo molecular pump in combination with a rough vacuum pump. A closed cycle helium cooled cryostat (CTI Model 21) is used for the cold stage of the measurement setup. Since vibrations of the cryostat could damage the samples and last but not least the probe tips a special arrangement of two copper plates, connected with a high flexible copper cord, is used (Fig. 2).

A conducting silver paste greatly improves the thermal transition between the sample carrier and the device under test (DUT). Additionally, a heat shield is used to reduce the radiation losses. With that a temperature of the DUT as low as 20 K, after a cool-down time of about 1.5 h, is achieved. The temperature is measured using a surface mounted GaAs diode, which detects the temperature on

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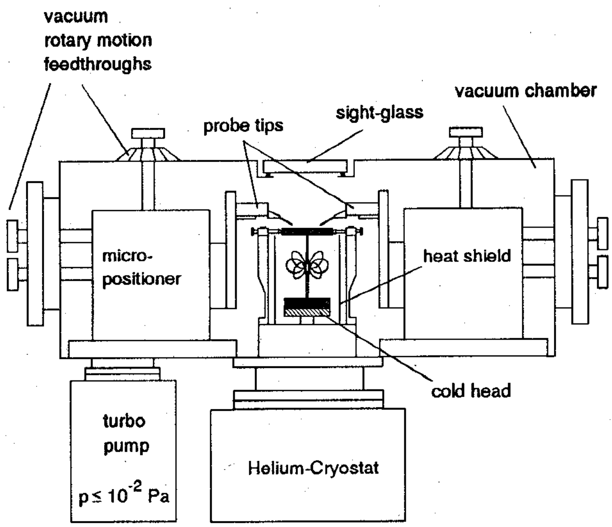

Fig. 1. On-wafer measurement setup for cryogenic mesurements in the millimeter-wave range at temperatures down to 20 K.

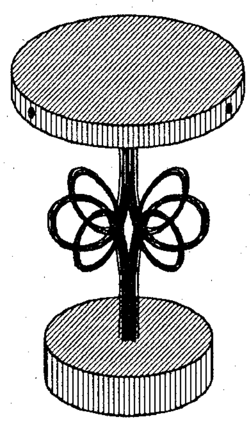

Fig. 2. Arrangement of copper cords and copper plates to keep away vibrations from the samples.

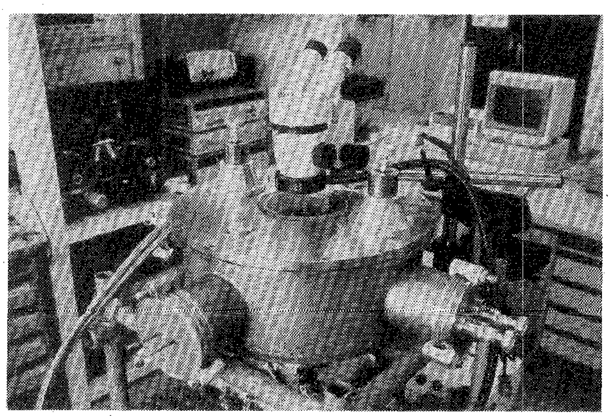

Fig. 3. Photograph of the measurement setup, showing the vacuum chamber with feedthroughs for microwave cables and positioning of the probe tips.

the GaAs surface. An additional Si diode, which is integrated into the upper copper plate determines the temperature of the sample carrier. The known temperature voltage characteristics at a constant current of both diodes are used to exactly control the temperature up to 350 K.

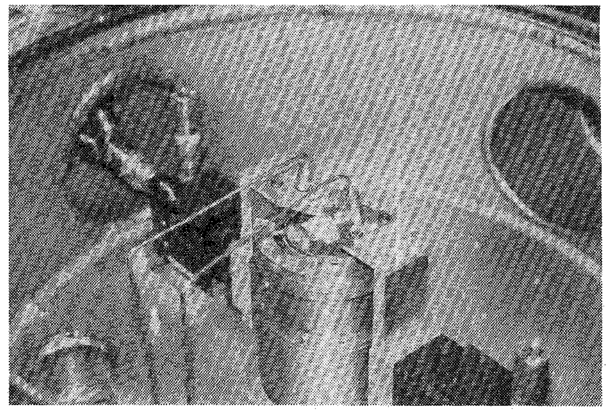

Fig. 4. Detail of the measurement setup, showing the micropositioners with coplanar probe tips and the calibration substrate onto the sample carrier.

Commercial coplanar microwave probe tips are mounted on micropositioners (SUSS PH 150), which are adjustable from outside the vacuum chamber via rotary motion feedthroughs. Microwave semi-rigid cables are soldered into copper pipes which have been soldered first into a seal flange of the vacuum chamber. Some more details of the measurement setup can be determined from the photographs in Figs. 3 and 4.

Calibration of the Measurement Setup

The thermal resistance of the coplanar probe tips is very high due to their ceramic substrate and the small contact pads. For this reason the temperature of the probe tips remain at close to room temperature and only small variations of the reference plane can be expected at cryogenic temperatures.

In order to characterize the phase shift of the probe tips, the reflection coefficient of a short was measured. Fig. 5 shows the phase shift at the reference plane after a standard one port calibration at 300 K in dependence on frequency for different temperatures. A linear increase of the phase shift with frequency can be observed for all temperatures. At 20 K the absolute value of the phase shift is higher than the corresponding value at 250 K, but lower than the value at 100 K. In dependence on temperature the phase shift achieves its highest value at temperatures of about 100 K (cf. Fig. 6).

Since the magnitude of the reflection coefficient exhibits negligible variations with temperature, only the reference plane needs to be changed for exact measurements at low temperatures.

The reliability of the room temperature calibration for low temperature measurements is proved using the reflection coefficent of a transmission line on the Cascade LRM calibration substrate. For an open passive transmission line the frequency dependence of the reflection coefficient shows a phase shift, which depends on the length of the line and a magnitude of less than unity with a slight attenuation.

Fig. 7 shows the measured reflection coefficient of the line at room temperature and 20 K in the frequency range

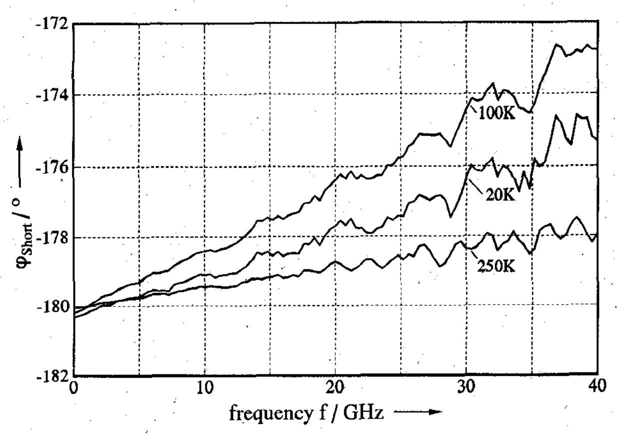

Fig. 5. Phase shift of the probe tips in dependence on frequency for different temperatures, determined by measurements on a short at the reference plane after calibration at room temperature.

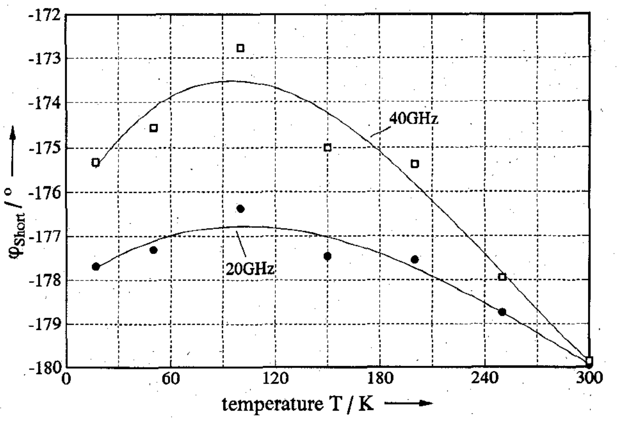

Fig. 6. Phase shift of the probe tips in dependence on temperature for different frequencies determined by measurements on a short at the reference plane after calibration at room temperature.

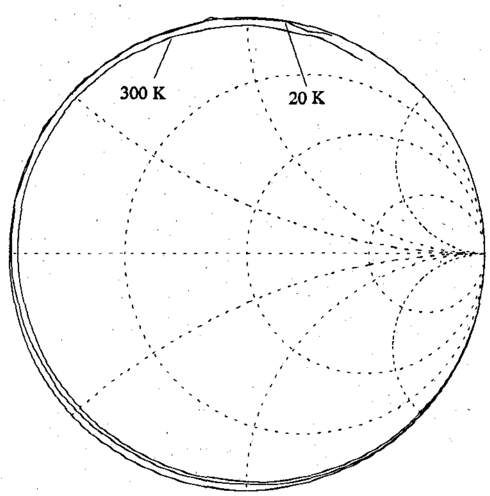

Fig. 7. Reflection coefficient of an open transmission line on the Cascade LRM substrate at 20 K and 300 K using a corrected room temperature calibration for the cryogenic measurement.

from 45 MHz up to 40 GHz. For this measurements a one port calibration was done at 300 K, which has been corrected for the measurement at 20 K. At low temperature a phase shift of only 10° can be observed at 40 GHz. This small phase shift may be explained by the electrical length of the transmission line, which is changed at the cryogenic temperature due to a variation of the effective permittivity and the mechanical length. The magnitude of the reflection coefficient at 20 K is nearly unity in the whole frequency range due to the reduced loss of the line.

RF Measurements on a Pseudomorphic HEMT at Cryogenic Temperatures

RF 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-content of 25%, 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 length of about 0.55 μm is fabricated by optical contact lithography and consists of 8 gate-fingers with a total gate-width of 240 μm [5].

Fig. 8 shows the *S*-parameters of the device at T = 20 K and T = 300 K in the frequency range from 45 MHz up to 40 GHz under illumination with a halogen lamp. 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 and constant bias voltages the device exhibits a slightly reduced drain current of about $I_{D,20\,K}$ = 29.3 mA ($I_{D,300\,K}$ = 33 mA).

The characteristics of the *S*-parameters in the dark are strongly differ from the illuminated curves, due to deep traps in the buffer layer and photo induced currents in the channel [6]–[8]. This behavior requires further investigations, which would exceed the aim of this work. Therefore an analysis of the light sensitivity will be given in future work.

The small signal equivalent circuit of the device at 300 K and 20 K has been calculated from hot and cold measurements [9] in a very good agreement. Table I gives a comparison of the most important elements. The increased output capacitance C_d at 20 K leads to a strong phase shift of the output reflection coefficient S_{22}. At low frequencies the magnitude of S_{22} at 20 K is slightly reduced, since the output resistance R_d at this temperature is smaller than its room temperature value. The backward transmission S_{12} at the cryogenic temperature is much smaller, but exhibits a pronounced phase shift due to both, the increased C_d and gate-drain capacitance C_{gd}. At low temperatures in the dark the phase shifts of S_{22} and S_{21} are strongly reduced. Therefore the increased capacitances may be related to traps and photo conductivity as mentioned above.

At 20 K and low frequencies the forward transmission S_{21} is much higher than the corresponding room temperature value and indicates the improved transconductance g_m and the slightly reduced source resistance R_S. By using a sensitivity analysis of the equivalent circuit it can be shown that the large output capacitance is also responsible for the strong variation of the real part of the input reflec-

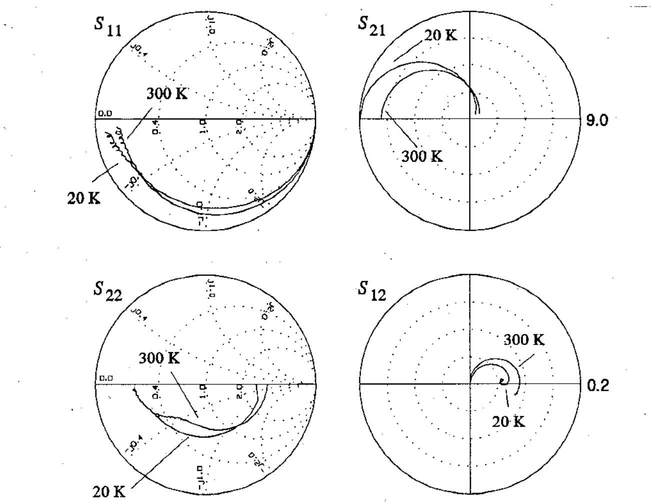

Fig. 8. S-parameters of the pseudomorphic HEMT at 20 K and 300 K in the frequency range from 40 MHz to 40 GHz; V_{DS} = 1.5 V, V_{GS} = −0.2 V; $I_{D,20\,K}$ = 29.3 mA, $I_{D,300\,K}$ = 33 mA.

TABLE I
MOST IMPORTANT ELEMENTS OF THE EQUIVALENT CIRCUIT, CALCULATED FROM MEASURED S-PARAMETERS AT T = 300 K AND T = 20 K

	T = 300 K	T = 20 K
R_G/Ω	0.9	0.4
C_{gs}/pF	0.28	0.34
C_{gd}/fF	64	90
g_m/mSmm^{-1}	549	767
R_S/Ω	2.6	2.2
R_d/Ω	134	99
C_d/pF	0.064	0.38

tion coefficient S_{11} at 20 K. As a result of the calculation of the equivalent circuit the gate-resistance R_G drops from about 0.9 Ω at 300 K to about 0.4 Ω at 20 K due to the reduced resistance of the gold metallization. The increased gate-source capacitance C_{gs} at 20 K can be explained by the improved confinement of the electrons in the channel at cryogenic temperatures.

Fig. 9 represents the effect of the temperature on the maximum extrinsic transit frequency f_T, which has been extrapolated from the current gain h_{21} of the device. At each temperature measurements were performed at a large number of different bias points. From these data the maximum value of f_T was chosen. So, the value of about 54 GHz at 20 K demonstrates the improved transport properties of the pseudomorphic FET at low temperatures. The intrinsic f_T, which can be calculated from the elements of the equivalent circuit using (1), increases from about 61 GHz at 300 K to 68 GHz at 20 K. Since the value at 20 K is much closer to the extrinsic value, this indicates the reduced parasitic elements at cryogenic temperatures.

$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})} \tag{1}$$

Even more, the improved transconductance and the reduced parasitic elements of the device at cryogenic temperatures result in a strong increase of the cut-off fre-

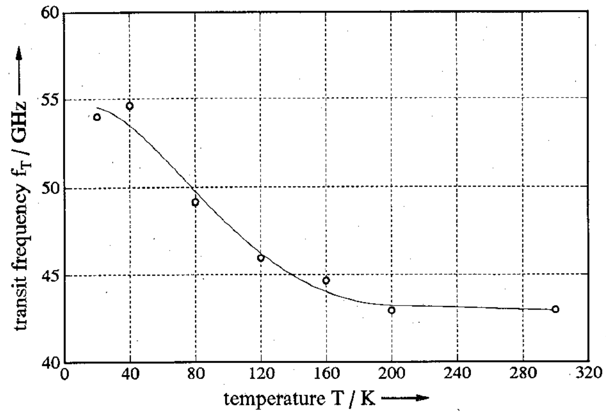

Fig. 9. Maximum of the extrinsic transit frequency f_T in dependence on temperature.

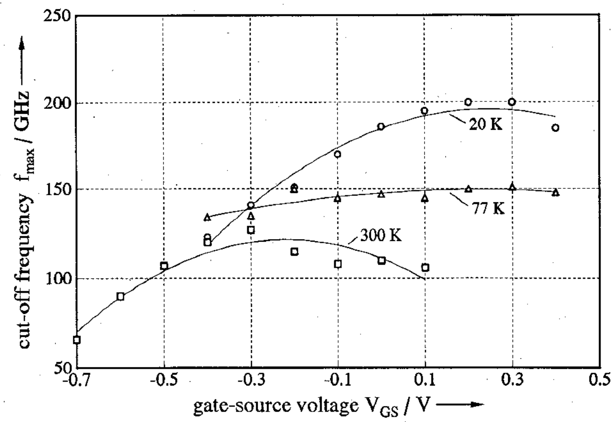

Fig. 10. Cut-off frequency calculated from the unilateral gain U in dependence on gate-source voltage at different temperatures; V_{DS} = 2 V.

quency f_{max}, which is calculated from the unilateral power gain U.

$$U = \frac{|S_{21}/S_{12} - 1|^2}{2k \cdot |S_{21}/S_{12}| - 2 \cdot \mathrm{Re}\,\{S_{21}/S_{12}\}}$$

$$k\text{: stability factor} \tag{2}$$

Although the increase of the transit frequency is only about 25%, the unilateral power gain can be significantly improved at cryogenic temperatures (Fig. 10). In dependence on the gate-source voltage, f_{max} increases from 120 GHz at 300 K up to 195 GHz at 20 K. Even at 77 K a considerable improvement of the cut-off frequency to a value of about 150 GHz is achieved.

NOISE MEASUREMENTS ON A AlGaAs/GaAs HEMT

The noise measurement setup consists of an ATN NP5 noise figure system, a HP 8970 noise figure meter and a HP 8971 down converter. In order to place the input matching network of the NP5 very close to the device under test it is installed into the evacuated chamber (cf. Fig. 4). Since the temperature of the electronic tuner is kept constant by its internal heater and the probe tips remain at close to room temperature no additional temperature

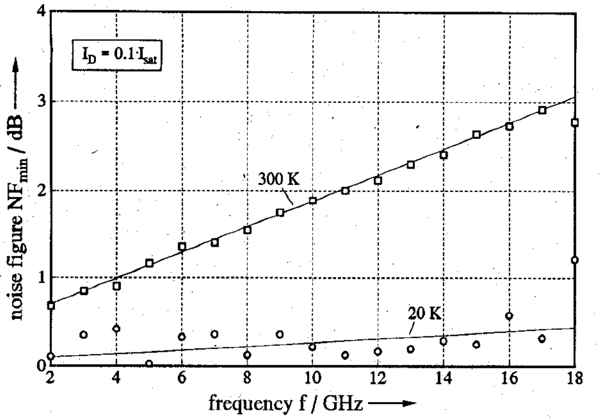

Fig. 11. Minimum noise figure NF_{min} in dependence on frequency at $T = 20$ K and $T = 300$ K; $I_D = 0.1 \cdot I_{sat}$.

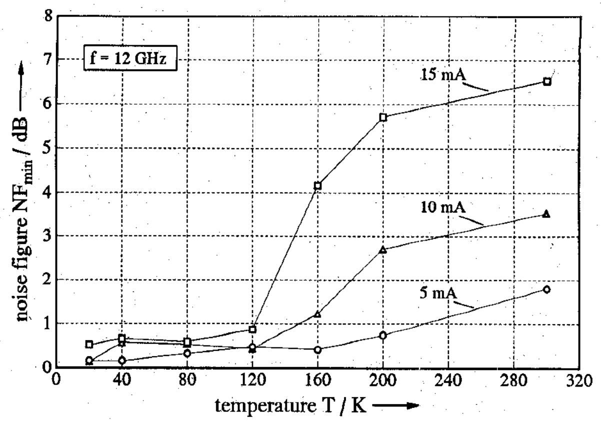

Fig. 13. Minimum noise figure NF_{min} in dependence on temperature for $I_D = 5$, 10 and 15 mA; $f = 12$ GHz; $V_{DS} = 2$ V.

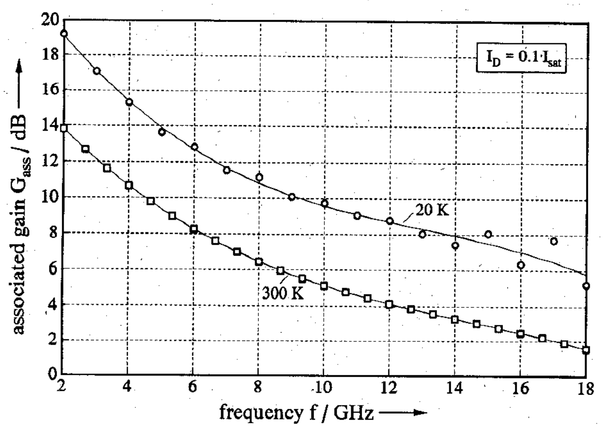

Fig. 12. Associated gain G_{ass} in dependence on frequency at $T = 20$ K and $T = 300$ K; $I_D = 0.1 \cdot I_{sat}$.

measurement of the tuner is needed. The noise source and the output matching network of the NP5 system are located outside the vacuum chamber. As well as the calibration of the network analyzer the calibration of the noise measurement system can be done at room temperature, which has been verified by measuring a transmission line on the calibration substrate.

The investigated $Al_{0.35}Ga_{0.65}As/GaAs$ HEMT consists of a 35 nm $2 \cdot 10^{18}$ cm^{-3} doped AlGaAs layer on a 500 nm GaAs buffer. By using a 5 nm spacer between the dopant layer and the channel, the device was optimized for low temperature operation. A T-gate structure with a gate width of 300 μm, a gate length of about 1.1 μm and a drain-source spacing of 4 μm was chosen to demonstrate the strong influence of the parasitic resistances on the noise behavior.

Fig. 11 shows the minimum noise figure NF_{min} of the device at 300 K and 20 K in dependence on frequency. Since the saturation current I_{sat} and the threshold voltage V_T are strongly dependent on the temperature, due to the drastically improved transport properties, the drain current was kept constant to a value of $0.1 \cdot I_{sat}$ ($I_{sat, 300K} = 40$ mA, $I_{sat, 20K} = 55$ mA), which is commonly used for minimum noise operation [10]. The drain-source voltage was 2 V for all measurements. At room temperature the noise figure is strongly dependent on frequency and rises to about 3 dB at 18 GHz, whereas at low temperatures the minimum noise figure is nearly constant in the investigated frequency range. The associated gain G_{ass} is about 5 dB higher at 20 K (cf. Fig. 12), which is caused by the reduced parasitic resistances. In this manner their thermal noise contribution is negligible at cryogenic temperatures. Thus the remaining noise mechanisms are related to the intrinsic FET, only. As can be seen in Fig. 13 for temperatures below 120 K the drain current has no effect on the noise behavior, while at room temperature a strong dependence on the drain current is observed, which may be related to the DX center in the AlGaAs dopant layer [7], [11].

Measurements on a Superconducting Filter

For this investigation a coplanar interdigitated bandpass filter was fabricated from a high T_c superconducting YBaCuO film on a $LaAlO_3$ substrate using laser ablation [12]. The patterning was performed by standard photolithography and wet etching with EDTA. Au contact pads were evaporated onto the YBaCuO film with a thin chromium interlayer to increase the adhesion of the gold layer.

Fig. 14 shows the layout of the realized filter [13]. The coupling of the six $\lambda/4$ lines results in a bandpass filter characteristic with a calculated center frequency and bandwidth of about 6.5 GHz and 1 GHz, respectively.

In order to demonstrate the high dynamic range of the measurement setup, which is up to 70 dB at the reference plane, the effect of temperature on the $\lambda/2$ resonance of the filter has been investigated.

The measured transmission of the filter around the $\lambda/2$ resonance is in a good agreement to the calculated values (cf. Fig. 15), but strongly dependent on frequency and temperature. At a frequency of about 9 GHz a highest attenuation of -56 dB is measured at a temperature close to the critical temperature. The unexpected decrease of this peak at lower temperatures is supposed to be caused by the Cr layer, forming a Schottky contact to the YBaCuO layer.

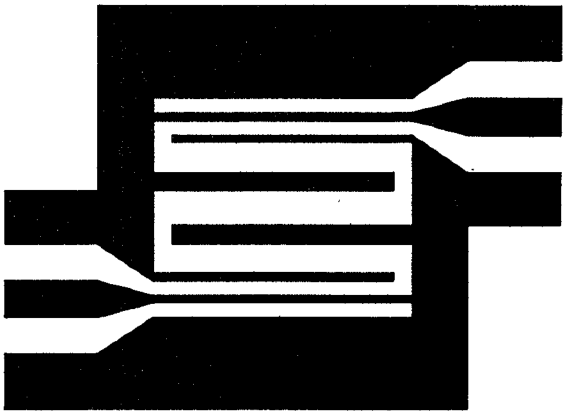

Fig. 14. Layout of the interdigitated bandpass filter, made from a superconducting YBaCuO layer on a $LaAlO_3$ substrate.

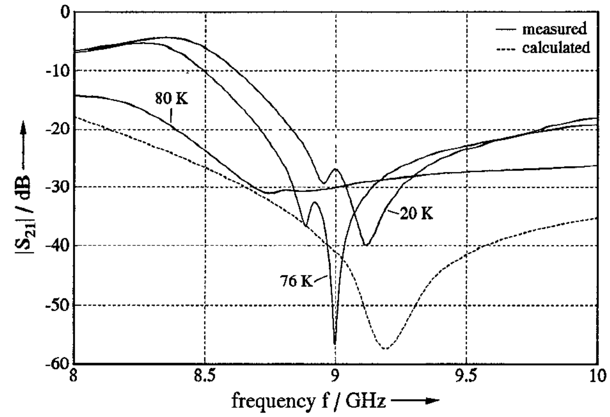

Fig. 15. Magnitude of the transmission S_{21} of the superconducting filter in dependence on frequency at different temperatures.

With decreasing the temperature a frequency shift to higher values is observed due to inhomogenities in the YBaCuO layer and a slightly reduced permittivity of the substrate [14].

Conclusions

A cryogenic on-wafer measurement setup with high dynamic range for the characterization of semiconductor devices and superconductor components 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 noise measurements on an AlGaAs/GaAs HEMT have been carried out as well as investigations on a superconducting filter and demonstrate the efficiency of the developed system.

Though the investigated pseudomorphic HEMT is not optimized for low temperature operation, the device exhibits an improved microwave performance at low temperatures. While the extrinsic 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.

At low temperatures the investigated AlGaAs/GaAs HEMT exhibits a very small noise figure compared to the room temperature values. Since the influence of the parasitic resistances is negligible at low temperatures only the noise contribution of the intrinsic FET is determined.

The effect of temperature on a superconducting bandpass filter, made from a YBaCuO layer on a $LaAlO_3$ substrate was investigated. The strong dependence on temperature and frequency of the $\lambda/2$ resonance of the filter shows the high dynamic range of the measurement setup.

Acknowledgment

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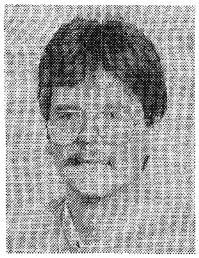

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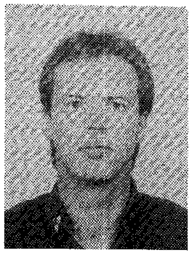

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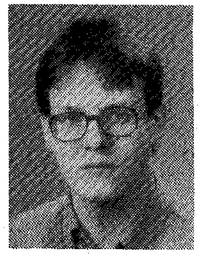
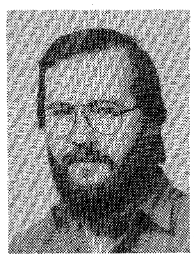
Franz-Josef Tegude, photo and biography not available at the time of publication.

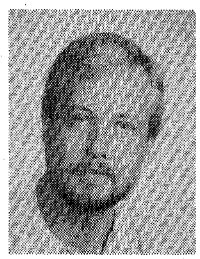


Michael Bode was born in Bad Nauheim, Germany, on March 1964. He received his diploma in physics in 1990 from RWTH Aachen. He is currently working on his Ph.D. thesis at the Inst. of Thin Film and Ion Technology, Research Center Jülich. His research focusses on Josephson junctions of high T_c superconductors.



Jürgen Schubert was born in Cologne, Germany, on October 1958. He received the degree in physics in April 1986 and the Ph.D. degree in physics in December 1989 both from the University of Cologne, Germany.

He is currently leader of the laser ablation group of the Institut für Schicht- und Ionentechnik, Forschungszentrum Jülich. His research focuses in preparing thin films of high-T_c-superconductors and correlated oxide-materials. He is currently exploring electrical field effect in ultrathin films of YBCO.



Willi Zander was born in Jülich, Germany, on May 1952. He is a member of the technical staff in the Laser Ablation Laboratory of Institut für Schicht- und Ionentechnik, Forschungszentrum Jülich. He is responsible for development of laser ablation systems. He is involved in preparing YBCO-films for Josephson devices and developed several methods of patterning films.