TWO-PORT S-PARAMETER CHARACTERIZATION OF HIGH ELECTRON MOBILITY TRANSISTORS AT MILLIMETER WAVE AND MICROWAVE FREQUENCIES

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ABSTRACT

Although millimeter wave amplifiers and oscillators using high electron mobility transistors (HEMTs) have been reported up to 94 GHz, to date no direct characterization of these devices has been reported. This paper presents the two-port S-parameters of sub-micron gate length HEMTs at W-band (75 to 110 GHz) using a specially constructed six-port network analyzer. In addition, for comparison to the millimeter wave measurements, the HEMTs were characterized at microwave frequencies, at room and cryogenic temperatures.

INTRODUCTION

The high electron mobility transistor (HEMT) has been the pre-eminent device in millimeter wave integrated circuit development, with recent reports of prototype amplifiers operating at 70 GHz (1) and 94 GHz (2). The fabrication of these circuits typically begins with the microwave S-parameter characterization of the transistor for generation of a small-signal equivalent model. This is then extrapolated up to the millimeter wave frequency where the circuit is to be designed. Such methods can be successful only if the frequency extrapolation is not too severe (3). However, above 50 GHz, the transistor model's performance deviates substantially from the actual device's performance and extensive tuning is required to get the circuit to work, if in fact, it will work at all. A better approach would be to measure the transistor directly at the millimeter wave frequency of its intended use. This paper presents the W-band (75-110 GHz) characterization of 0.1 µm gate length AlGaAs/GaAs HEMTs (4), which had gain up to 105 GHz.

Very little has been published on millimeter wave two-port device phasor characterization, due in part, to the lack of reliable millimeter wave network test equipment. In the past few years, some progress has been made to extend the frequency range of microwave network analyzers (5), and recent picosecond optoelectronic time domain measurements have provided GaAs MESFET S-parameters up to 60 GHz (6). An alternate approach to these measurements which uses the six-port network analyzer, has received considerable attention in the past decade because phasor quantities can be obtained by power measurements alone, without sophisticated hardware (7). The HEMT W-band S-parameters that are presented here were measured with a six-port network analyzer that was constructed from WR-10 waveguide components (8).

As a qualitative comparison to the W-band characterization, microwave measurements of the 0.1 µm HEMTs are also presented. In the course of these measurements, microwave S-parameters of 0.25 µm gate length HEMTs were obtained at both room and cryogenic temperatures, and the maximum frequency of oscillation of these devices was found to increase significantly upon cooling.

THE W-BAND SIX-PORT NETWORK ANALYZER

A schematic of the W-band six-port network analyzer implemented for reflection measurements is shown in figure 1; a slight re-configuration of the system allowed for transmission measurements. Power was supplied by a backward wave oscillator that was frequency locked using a frequency counter. W-band thermistors were placed at four of the six ports (labelled P_3 through P_6 in the figure) to provide linear power detection, and power meter readings were directed into a desk top computer via a computer controlled scanner and digital voltmeter. The six-port calibration procedure used four offset short circuits and a matched load for reflection measurements (9), and four phase delays and a total test signal absorber for transmission measurements. Since a single six-port reflectometer was used in this system, it was necessary to rotate the test fixture 180° to obtain both forward and reverse S-parameters.

The reliability of the six-port was evaluated through the use of a number of precision loads. For example, figures 2a and 2b show the reflection coefficient at 90 GHz of a tunable short circuit as the shorting plane was moved over 360°. As can be seen from those figures, the measured reflection coefficient magnitude remained within 1.5% of unity, and the absolute phase error, which is the difference between the measured and calculated phase. remained within 4° of zero. Overall, the system was found to be capable of measuring near unity reflection and transmission coefficients to within 2% of the magnitude and to within 4° of the phase from 75 to 105 GHz. For small reflections and transmissions a maximum error of 12% was found when the return and insertion loss was at 20 dB. Above 105 GHz, the reliability of the six-port calibration standards degraded somewhat, providing a

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high frequency cut-off for these measurements.

MILLIMETER WAVE CHARACTERIZATION OF 0.1 μm HEMTs

A transition and bias configuration was developed to go from the six-port waveguide to the microstrip environment of the transistor. The W-band test fixture contained a HEMT with the source terminal grounded and with the gate and drain pads ribbon bonded to 50 Ω microstrip line that was fabricated on a 0.005" fused silica substrate. Two five-section Chebyshev ridged waveguide-to-microstrip transformers were designed to couple the microstrip lines to the waveguide of the six-port. The transistor was DC isolated from the test fixture by quarter-wavelength coupled lines, and bias current was supplied through low pass open circuited radial stub filters. A drawing of the test fixture circuit is shown in figure 3. The insertion loss of the test fixture (shown in figure 4) was determined by measuring back-to-back transitions that included the printed circuit bias tees. The return loss of a single transition was found to be an average of 11 dB from 75 to 105 GHz.

The S-parameters of the HEMT were extracted from the test fixture by a two-tier de-embedding process. First, the waveguide-to-microstrip transition was characterized up to the end of the microstrip line by measuring the reflection and transmission coefficients of back-to-back transitions, and the reflection coefficient of a single transition with a microstrip load (10). This information, along with the measured forward and reverse reflection and transmission coefficients of the transistor test fixture, along with the assumption that the test fixture was symmetric, enabled the HEMT S-parameters to be de-embedded. Table 1 presents the two-port S-parameters from 75 to 105 GHz of the best 0.1 μm gate length HEMT measured to date, while figure 5 shows the S_{11} and S_{21} from 75 to 85 GHz in 1 GHz increments. The table and figures reveal the fine structure of the frequency response. Repeated re-assembly and measurement of the test fixture showed that de-embedding errors do not account for these observed resonances. Therefore, these resonances may be attributed to the distributed nature of the bond ribbons and the transistor as the millimeter wavelengths approach the device dimensions. For comparison, the 2 to 26 GHz S-parameters of a 0.1 μm HEMT with the same geometry and similar DC characteristics are affixed to figure 5.

The maximum available gain of this HEMT was calculated from the S-parameters is shown in figure 6 along with the gain calculated from a HEMT small-signal model derived from the microwave characterization. While the extrapolated model predicts a maximum frequency of oscillation, f_{max}, near 140 GHz, it does not account for the measured resonance effects that are present in the high frequency transistor circuit operation. It does, however, give a reasonably accurate projection of the device performance.

CRYOGENIC MICROWAVE CHARACTERIZATION OF 0.25 μm HEMTs

In conjunction with the millimeter wave measurements, cryogenic microwave characterizations were also performed on 0.25 μm gate length HEMTs, that were made using similar material and fabrication technology as the 0.1 μm HEMTs, to determine the extent to which the frequency range could be increased by cooling. A gas helium refrigerator was used to cool the transistors down to 50 K, and the S-parameters were measured from 2 to 18 GHz with an automatic network analyzer. The maximum available gains of a typical HEMT at room temperature and 50 K are shown in figure 7, where the gain is seen to increase from 2 to 4 dB. Small-signal transistor models were derived from the measured S-parameters to determine the projected f_{max}. It was found that for this transistor f_{max} increased from 33 to 45 GHz upon cooling.

CONCLUSION

In conclusion, direct W-band characterization of 0.1 μm gate length HEMTs has been achieved, with the indicated result that substantial gain can be obtained at these frequencies. These measurements also reveal the complex frequency dependence of the S-parameters as the dimension and environment of the transistors become a significant fraction of a wavelength. This detailed information is indispensable for precise design of millimeter wave active circuits. In addition, by cooling the HEMT, it is apparent that the operational frequency can be extended. Further research is being conducted to determine if this same effect can be observed directly at millimeter wave frequencies. As sub-micron device technology advances, the capability to measure both millimeter wave and microwave S-parameters for accurate millimeter wave transistor device and circuit fabrication is essential.

REFERENCES

(1) M. Sholley and A. Nichols, "60 and 70 GHz (HEMT) Amplifiers," *IEEE MTT-S Int. Microwave Symp. Digest*, 1986, pp. 463-465.

(2) P. M. Smith, P. C. Chao, K. H. G. Duh, L. F. Lester, and B. R. Lee, "94 GHz Transistor Amplification Using An HEMT," *Electronics Letters*, Vol. 22, No. 15, July 17, 1986, pp. 780-781.

(3) L. Deardon, G. Miner, and M. Sayed, "Model Extrapolated S-Parameter Design of MM-Wave GaAs Fet Amplifiers," *IEEE MTT-S Int. Microwave Symp. Digest*, 1986, pp 385-388.

(4) K. Nakano, To be published.

(5) Hewlett-Packard Co., "Procedures Explained for Mm-Wave Vector Measurements With the HP 8510A Analyzer," *Microwave System News*, December 1984, pp. 65-90.

(6) D. E. Cooper and S. C. Moss, "Picosecond Optoelectronic Measurement of High Frequency Scattering Parameters of a GaAs FET," *IEEE J. Quantum Electronics*, Vol. QE-22, No. 1, January 1986, pp. 94-100.

(7) M. P. Weidman, "WR-10 Single Six-Port Measurement System," *National Bureau of Standards Press*, NBSIR 81-1650, September 1981.

(8) K. Moeller, To be published.

(9) S. Li and R. G. Bosisio, "Calibration of Multiport Reflectometers by Means of Four Open/Short Circuits," *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-30, No. 7, July 1982, pp. 1085-1089.

(10) E. R. Ehler, "Symmetric Test Fixture Calibration, "*IEEE MTT-S Int. Microwave Symp. Digest*, 1986, pp. 275-278.

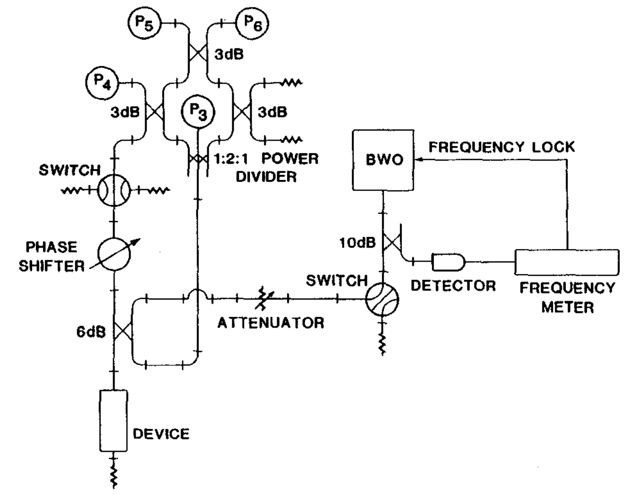

Fig 1. Six-port network analyzer configured for reflection coefficient measurement.

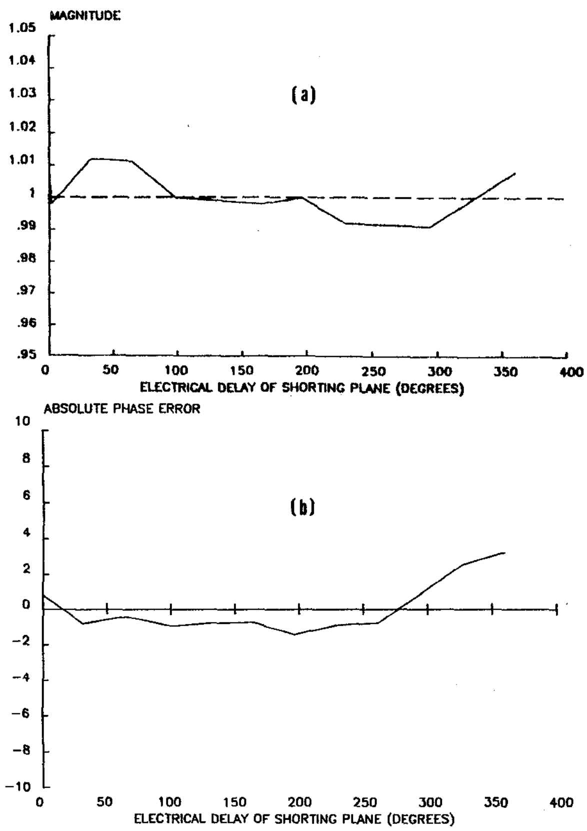

Fig 2. (a) Measured magnitude of the reflection coefficient of a tunable short circuit at 75 GHz. (b) Reflection coefficient phase error of a tunable short circuit at 75 GHz.

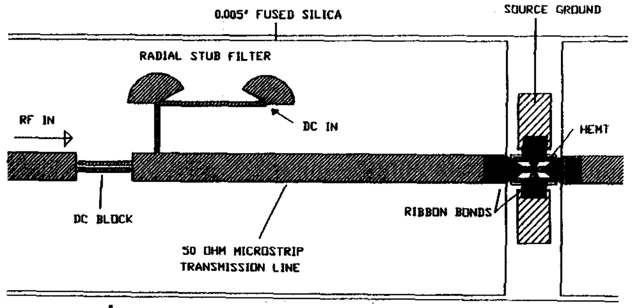

Fig 3. Attachment of a HEMT to the 50 Ω microstrip line and printed circuit bias tees.

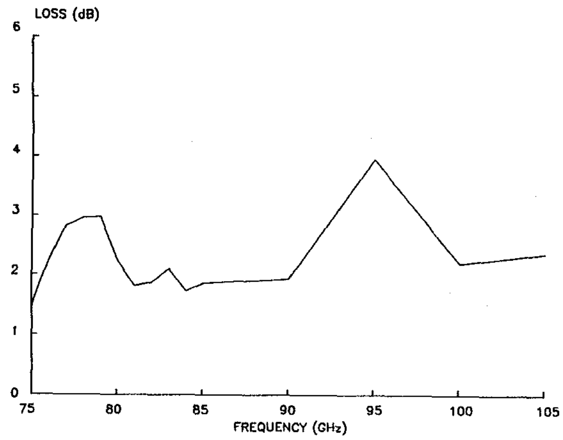

Fig 4. Insertion loss of back-to-back waveguide-to-microstrip transformer/bias tee section.

Freq.	S11		S12		S21		S22	
(GHz)	MAG	PHA	MAG	PHA	MAG	PHA	MAG	PHA
75	0.599	14.4	0.105	-37.6	0.632	-74.2	0.357	67.6
80	0.413	-22.2	0.385	-53.9	1.126	-98.4	0.695	57.9
85	0.635	-13.9	0.327	-48.3	0.578	-93.4	0.533	35.4
90	0.378	-44.4	0.604	-98.7	0.852	-122.2	0.735	20.2
95	0.655	-36.9	0.440	-86.3	0.542	-88.4	0.453	-10.4
100	0.281	-33.3	0.605	-124.0	0.843	-117.3	0.192	0.4
105	0.219	4.1	0.608	-155.3	0.915	-140.9	0.233	44.4

Table 1. S-parameters of a 0.1 μm gate length HEMT measured from 75 to 105 GHz.

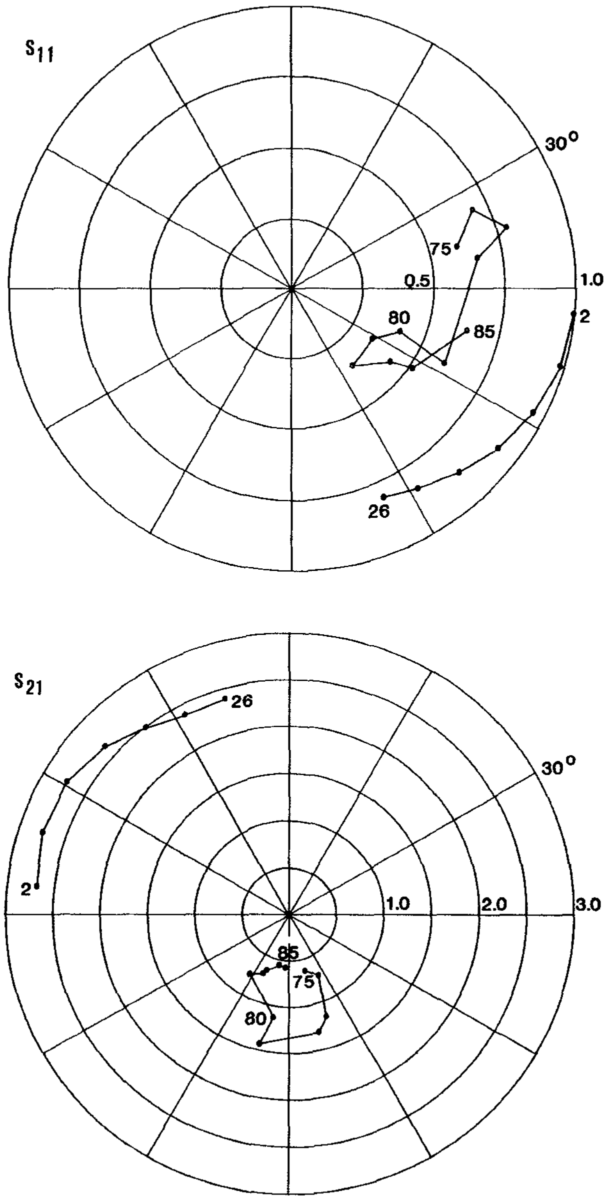

Fig 5. Measured S_{11} and S_{21} of a 0.1 μm gate length HEMT from 75 to 85 GHz, and from 2 to 26 GHz.

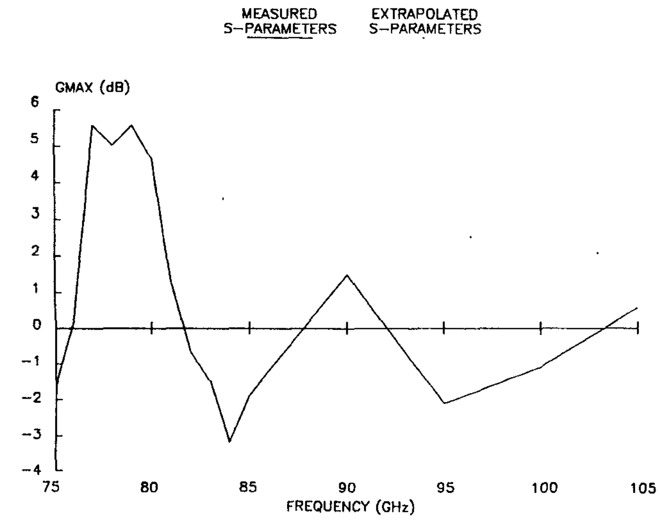

Fig 6. The MAG of the 0.1 μm gate length HEMT calculated from the measured S-parameters and also extrapolated from a microwave model. As the transistor and bond ribbon dimensions become large compared to wavelength, parasitic resonances produce a standing wave pattern in the observed gain.

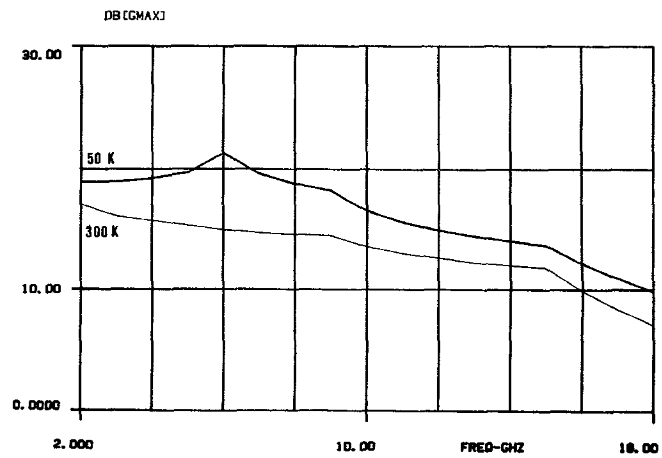

Fig 7. MAG of a 0.25 μm gate length HEMT at 300 K and at 50 K calculated from the measured S-parameters.