LOW NOISE DEVICE AND AMPLIFIER CHARACTERIZATION FOR DEEP SPACE COMMUNICATION APPLICATIONS

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Abstract

The significant advances in the development of high electron mobility field-effect transistors (HEMTs) has resulted in cryogenic low-noise amplifiers (LNAs) which rival masers at S- and X-band. Further advances in the characterization and device technology at cryogenic temperatures may eventually supplant maser amplifiers at K_a- band. A systematic cryogenic on-wafer study of advanced FET technology is performed and an empirical model for the cryogenic operation of ion-implanted MESFET technology is presented. Multi-stage HEMT based LNAs have been fabricated and characterized for operation at K_a - band.

Introduction

The overall objective of this work is to characterize the DC, S-parameter, and noise parameter results of advanced MESFET and HEMT devices to develop accurate temperature dependent models for the design of high performance LNAs at K_a-band. A detailed and complete understanding of the cryogenic performance of such structures will eventually allow HEMT based LNAs to replace maser amplifiers for deep space communications. A cryogenic microwave measurement system has served as the main experimental tool for the noise and S-parameter characterization of discrete transistors.

Experimental Technique

In 1976 Liechti and Larrick [1] designed a microwave test fixture which could be immersed in liquid nitrogen. Similar types of setups have been used [2,3,4,5] to evaluate HEMT performance from 300 K to 77 K. More recently, systems have been developed for broadband S-parameter measurements of lattice temperatures to 20K and below [6,7]. To date, it has been difficult for broadband noise parameter measurements in such an environment due to limited success with accurate full two-port calibrations.

The short-open-load-thru (SOLT) and line-reflect-match (LRM) calibration methods are used with an impedance standard substrate (ISS) supplied by Cascade Microtech. From our experience, we find a marginal increase in accuracy with the LRM over the SOLT calibrations at cryogenic temperatures, see Fig. 1. More importantly, we find measurement accuracy is directly correlated to calibration conditions. For S-parameter calibrations several criteria are used to qualify the two-port calibration. The principle for the initial investigation of on-wafer noise measurements at cryogenic temperatures has been to cool only the probe tips and keep the impedance state generator and solid state noise source at room temperature. This configuration does not lend itself to the most accurate single frequency noise measurements, but does provide an accurate and efficient measurement system for broadband S-parameter and noise parameter measurements.

Experimental Device Results

Passivated, conventionally doped pseudomorphic 0.25 x 75 µm gate HEMTs have been studied. At 100% I_{dss} the F_{min} is ~ 1.25 dB, with G_A ~ 15 dB at 18 GHz and 300K. The variation of F_t and F_{max} are shown in Figs. 2 and 3. When the device lattice temperature is reduced from 300K to 16K the peak cutoff frequency increases less than 25%. The variation of F_{min} with temperature is shown in Fig. 4. The F_{min} (@18 GHz) decreases from 1.25 dB at 300K to below 0.25 dB at 16K.

Initial modeling has been carried out on several of the data reported here. From the temperature

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dependent transistor S-parameter measurements accurate small-signal models can be developed using the technique outlined in [8]. The critical elements for the active structure include transconductance (g_m), gate-source capacitance (c_{gs}), feedback capacitance (c_{dg}), and the output conductance (g_{ds}). In general, the rise in g_m results in an appreciable increase in F_t and F_{max}. The increase in g_m can be attributed to the increase in carrier high-field velocity with decreasing temperature. Also, enhanced carrier confinement with reduced lattice temperature reduces gate leakage and allows for more efficient modulation of the channel charge which ultimately increases g_m and reduces g_{ds}.

The pioneering work of Weinreb and Pospieszalski [9,10] has led to the development of HEMT based LNAs which are the lowest noise transistor based circuits produced to date. It has previously been established that GaAs based MESFETs can achieve noise figure values comparable to GaAs based HEMTs at room temperature [11,12,13]. Based upon 0.5 µm GaAs MESET results, it is expected that a properly scaled and designed 0.1 µm MESFET technology may rival the best noise performance of GaAs based HEMT technology, as shown in Fig. 5.

LNA Development and Design

In this work a semi-empirical method was utilized to demonstrate four stage K_a- band HEMT LNA operation. The LNA is based on a design developed at the National Radio Astronomy Observatory and utilizes conventional AlGaAs/GaAs HEMT devices [14]. The first two stages use 0.25 x 75 µm HEMTs from General Electric while the third and fourth stages use Fujitsu 0.25 x 100 µm HEMTs (FHR10X). Although the LNA was designed for Fujitsu HEMTs, the temperature dependent noise model for the General Electric HEMT is reasonably close to that achieved with Fujitsu HEMTs.

In Fig. 6 we show the LNA noise and gain response using both GE and Fujitsu HEMTs in a four stage LNA which exhibits a noise temperature of 27°K with an associated gain of 28.4 dB at 32 GHz and a lattice temperature of 25°K. When all four stages have been fabricated with Fujitsu HEMTs the noise temperature increases to 34.6°K and the associated gain falls to 27.8 dB at 32 GHz and lattice temperature of 25°K, as shown in Fig. 7. Both results were in reasonable agreement with noise model predictions [15].

Summary

The continued development of HEMT based LNAs is critical to the future of the Deep Space Network. Systematic studies are necessary to properly select, develop, and design high performance cryogenic LNAs and to develop device technologies, such as ion-implanted MESFETs, for future applications. The feasibility of broadband on-wafer S-parameters and noise parameters measurements is demonstrated, and such a measurement tool should provide important data for LNA development. Presently HEMT LNA development at X-band rivals that of maser technology and future development may replace maser amplifiers at K_a-band.

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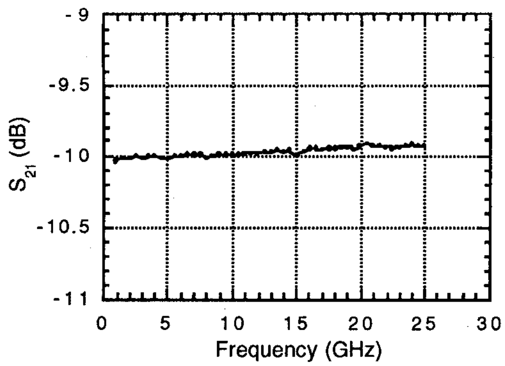

Fig. 1 Transmission through 10dB attenuator at a lattice temperature of 20K using LRM calibration.

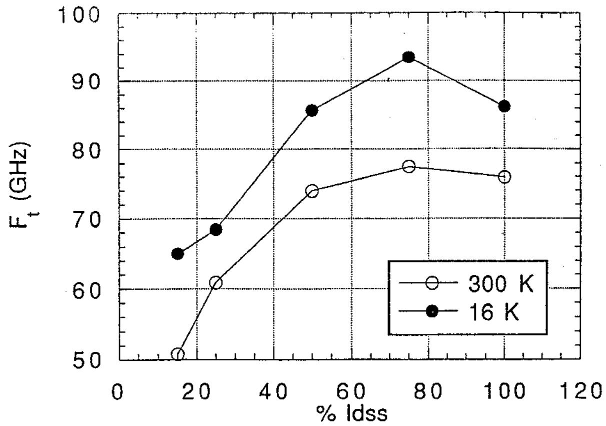

Fig. 3 Variation of F_T with bias at 300K and 16K for Pseudomorphic HEMT.

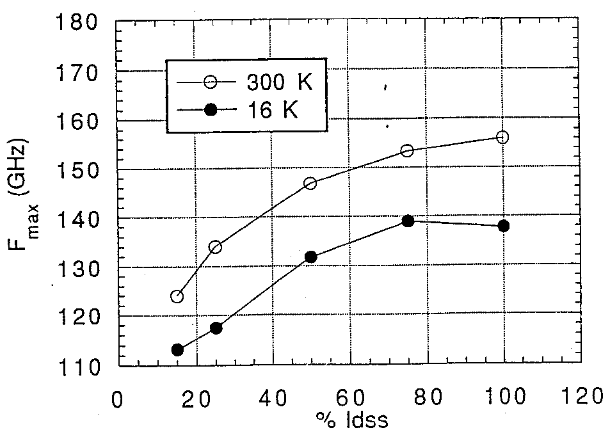

Fig. 2 Variation of F_{max} with bias at 300K and 16K for Pseudomorphic HEMT.

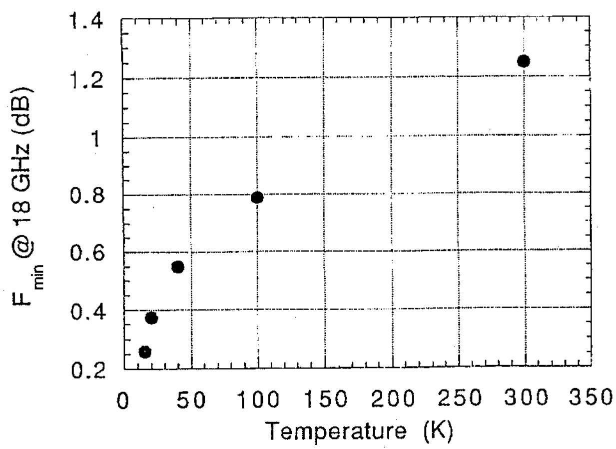

Fig. 4 Plot of F_{min} versus lattice temperature at 100% I_{dss} for Pseudomorphic HEMT.

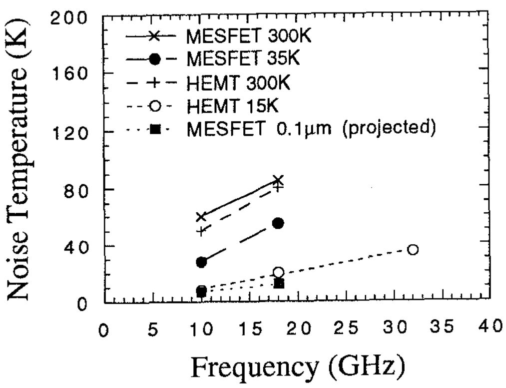

Fig. 5 Plot of minimum Noise temperature versus frequency for GaAs based HEMTs and MESFETs. The measured MESFET results are for 0.5 μm gate length and recent advanced HEMT results. Based upon these results and improvement in F_T it is projected that a 0.1 μm MESFET will rival the state-of-the-art cryogenic HEMT results.

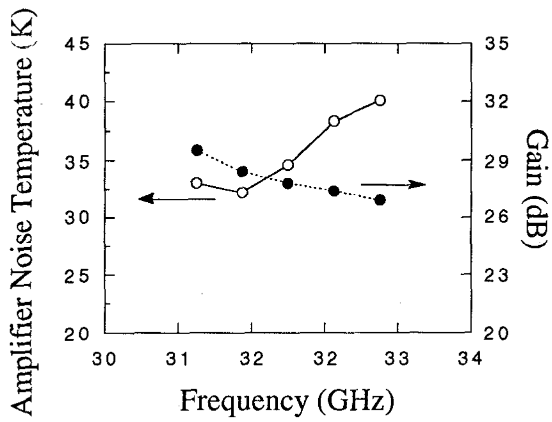

Fig. 7 Plot of noise temperature and gain versus frequency for four stage LNA at 25°K lattice temperature utilizing all Fujitsu HEMTs.

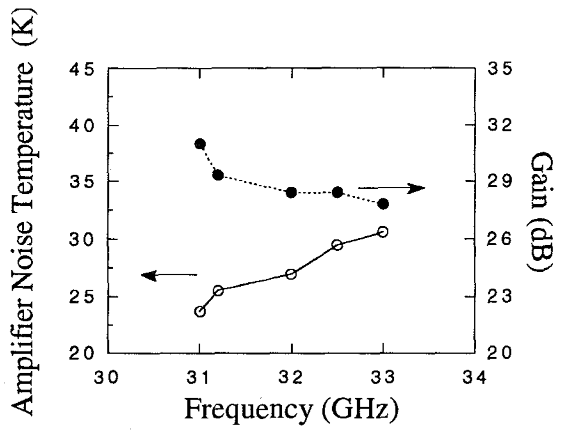

Fig. 6 Plot of noise temperature and gain versus frequency for four stage AlGaAs/GaAs HEMT LNA at 25°K lattice temperature. The first two stages use GE HEMTs while the last two stages utilize Fujitsu HEMTs.