A Cryogenically-Cooled Wide-Band HEMT MMIC Low-Noise Amplifier

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***Abstract*— A balanced single-stage wide-band HEMT MMIC low-noise amplifier (LNA) was designed, fabricated, cooled to a temperature of 19 K, and evaluated from 8–18 GHz. The MMIC LNA performed without damage at all test temperatures. The amplifier gain flatness over the 8–18-GHz frequency band was maintained at both room and cryogenic temperature, indicating that the broad-band design topology is relatively insensitive to operation temperature. Gain increased an average of 2 dB, while the noise temperature exhibited as much as an eightfold reduction from 160 K to 20 K at 19 K operation temperature. This is the first result on performance of a cryogenically-cooled HEMT MMIC LNA.**

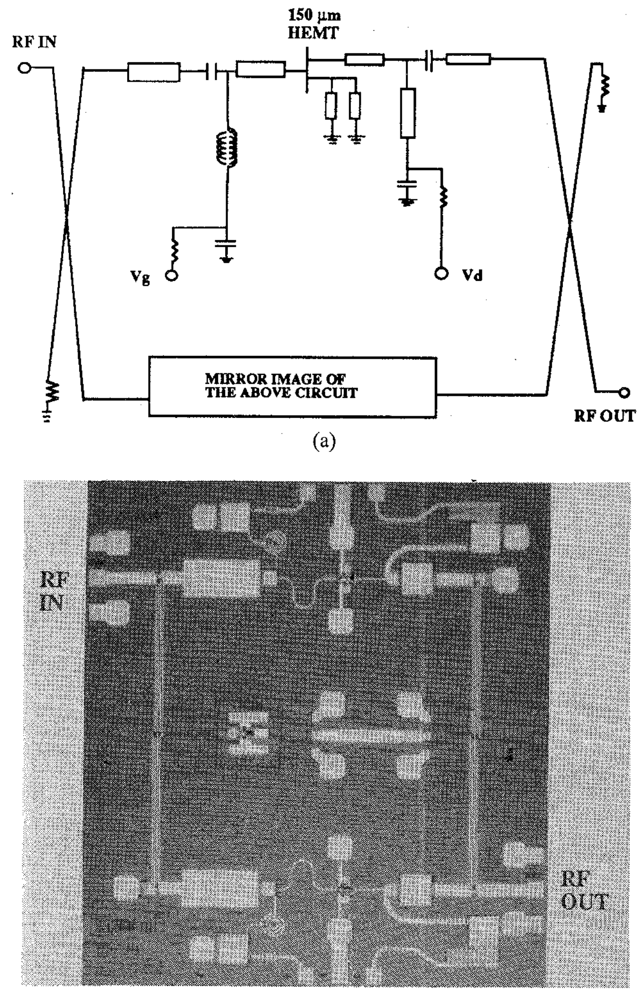

Fig. 1. (a) Circuit schematic and (b) microphotograph of a 8–18-GHz LNA. Chip size is 2.76 mm × 3 mm.

I. Introduction

The low-noise amplifier (LNA) is one of the most critical components in receivers of the modern communication systems. The high electron mobility transistor (HEMT) has been utilized widely for LNA designs due to its inherently low-noise characteristics. The advanced fabrication technology has made low-cost HEMT MMIC LNA's feasible. Cryogenic LNA's with minimal noise are critical in many applications such as satellite receiving systems, radio astronomy, and remote sensing, where maximum sensitivity is the major requirement. The noise from an LNA can be greatly reduced when the operating temperature is lowered. While cryogenically cooled hybrid HEMT LNA's and a MESFET MMIC distributed amplifier have been reported [1], [2], we present for the first time the performance of a wide-band (8–18 GHz) HEMT MMIC LNA cryogenically cooled to a temperature of 19 K.

II. MMIC Design and Fabrication

An 8–18-GHz single-stage MMIC LNA using *T*-gate InGaAs pseudomorphic HEMT (PHEMT) technology designed for room-temperature operation has been evaluated at cryogenic temperatures. A HEMT equivalent circuit model that employs correlated noise current source at the drain and gate has been developed to fit the measured room-temperature noise parameters and *S*-parameters. This device model has allowed us to achieve good agreement between simulated and measured LNA performance at room temperature [3]. The balanced topology incorporating 3-dB Lange couplers at the input and output ports is suitable for high-performance octave band designs. It provides design flexibility in achieving optimum noise match and broad-band gain flatness without degrading VSWR. The circuit schematic and microphotograph with chip size of 2.76 mm × 3 mm are shown in Fig. 1. The input noise matching network employs a three-section impedance transformer for broad-band device noise matching. Series inductive feedback in the source is used to improve the broad-band input noise match as well as the stability. The active devices are two 0.2-μm gate-length, four-finger 150-μm gate-width HEMT's.

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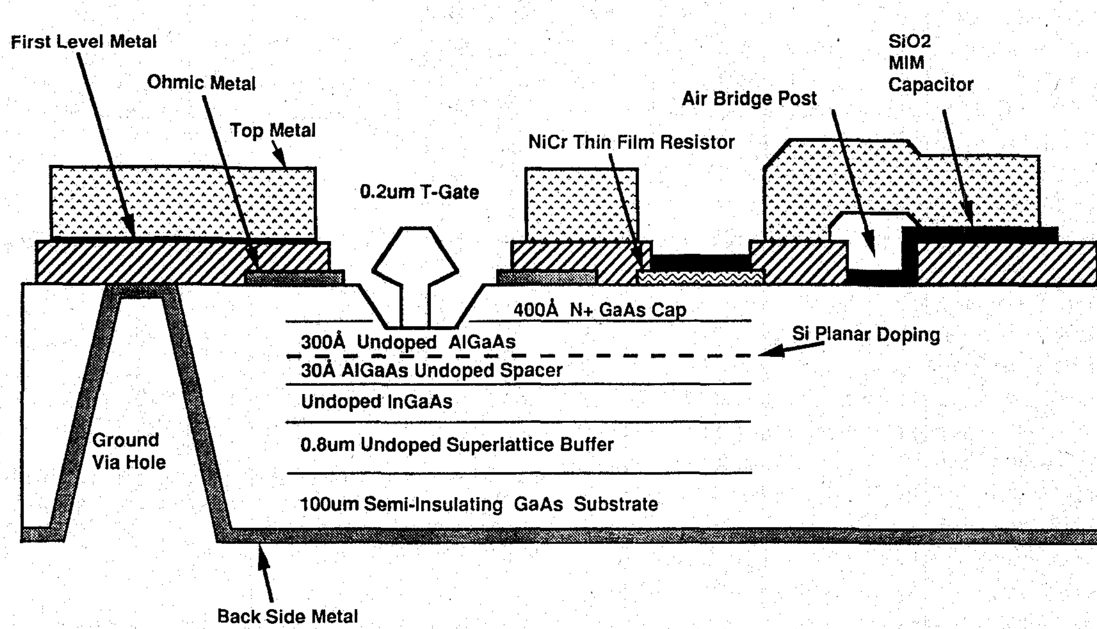

Fig. 2. Cross-section of the InGaAs pseudomorphic HEMT MMIC process.

The MMIC amplifier was fabricated on a 3-inch GaAs substrate with the active layers grown in a Varian Generation II MBE system. A cross-section of the PHEMT MMIC process is shown in Fig. 2. The grown device layer structure consisted of a 0.8-μm undoped GaAs/AlGaAs superlattice buffer, an undoped InGaAs channel, a 30Å AlGaAs undoped spacer, a planar-doped monolayer of silicon, a 300Å undoped AlGaAs layer, and a 400Å n+ GaAs layer for the cap to reduce the ohmic contact resistance. A AuGe alloy was formed for source and drain metallization using rapid thermal annealing to achieve ohmic contact resistance of less than 0.15 Ω-mm. The 0.2 μm *T*-gate was delineated by electron-beam lithography. First-level interconnect metal (FIC) was evaporated and lifted off before the dielectric (4000Å SiO_2) was deposited. MIM capacitors were formed between the FIC and the evaporated top metal. The wafer thickness was thinned to 4 mil. The MMIC fabrication was completed after the ground via holes were etched and the backside was Au-plated.

III. Test And Results

Automatic on-wafer *S*-parameter and noise figure measurements are performed at room temperature for circuit functionality and selection. The MMIC LNA's are then diced and mounted on the center block of a test fixture made of Kovar. Both the MMIC circuit and alumina substrate are mounted on the test fixture using silver epoxy, and cured for 60 minutes at 125 C. A 0.7-mil-diameter gold bonding wire is used to connect the MMIC to the 50 Ω transmission line on the 10-mil-thick alumina substrate. The dc bias wire is bonded to the designated bias pad on the MMIC through a shunt chip capacitor of 50 pF to insure an unconditionally stable cryogenic operation. The *K*-connectors are installed at input and output blocks of the test fixture. The measured back-to-back insertion loss of the test fixture is less than 0.5 dB up to 20 GHz.

The test-fixtured amplifier is then placed in a vacuum dewar, and covered by a radiation shield. A temperature sensor is also installed on the test fixture. The dewar is cooled by a CTI 1020 closed-cycle helium refrigerator. Without a heat load, the amplifier mounting plate can be cooled down to 12 K. The thermal isolation at the input and output is preserved by 0.141-inch-diameter stainless steel semirigid coaxial cables. Hermetically-sealed OSM feedthrough adapters are installed in the walls of the dewar to provide a vacuum seal for the semirigid coaxial cables. A calibrated HP 346C noise source and HP 8970B noise figure meter are used for gain and noise figure measurement.

Due to the loss of the matched attenuator consisting of semirigid coaxial cable and test fixture transition, the measured noise temperature (Tm) of the test-fixtured amplifier can be expressed as

$$\mathrm{Tm} = (\mathrm{L} - 1)\mathrm{Tx} + \mathrm{TampL} \qquad (1)$$

where L is the loss factor, Tx is the physical temperature of the matched attenuator, and Tamp is the noise temperature of the MMIC LNA. Since accurate on-wafer measurement has been performed prior to chip dicing, the measured noise temperature of the test-fixtured amplifier at room temperature (297 K) can be used to calculate the room-temperature loss factor at each frequency of interest using (1). The attenuation loss can be further verified by comparing the measured amplifier gain to the MMIC LNA gain of the on-wafer measurement. The resultant attenuation loss is 0.5 dB at 8 GHz and 0.6 dB at 18 GHz. The test fixture without MMIC LNA is placed in the vacuum dewar and cryogenically cooled to 19 K in order to calibrate the gain and noise temperature of the test setup from 8–18 GHz. It is found that the cryogenic attenuation loss is reduced approximately by one half, while the average effective physical temperature of the coaxial cables is 165 K.

The drain current was set to 13 mA for the optimum room-temperature performance, and reset by gate voltage adjustment to 9 mA for the optimum cryogenic noise performance. The drain voltage was kept at 2.6 volts. No illumination was used in any of the tests when lowering the dewar temperature. Fig. 3 shows the noise temperature and gain of the MMIC LNA at 19 K operation temperature over the 8–18-GHz frequency band with a 0.5 GHz increment. The data is corrected from the test fixture up to the MMIC chip. For comparison, the room-temperature on-wafer performance is included in the same figure. The amplifier gain flatness over the frequency band was maintained at both room and cryogenic temperature, indicating that the broad-band design topology is relatively insensitive to operation temperature. Gain increased an average of 2 dB at 19 K. The lowest noise temperature was less than 160 K at room temperature between 10 and 11 GHz, and reduced to less than 20 K at temperature of 19 K, exhibiting an eightfold reduction in noise temperature. It should be noted that the cryogenic noise temperature data shown in Fig. 3 has an uncertainty of ±15 K, which is determined by the accuracy of the HP 346C and HP 8970B measurement system. However, the cryogenic measurement accuracy can be improved by inserting a cooled attenuator in front of the test unit.

The MMIC LNA consists of two HEMT's, two Lange couplers, ten via holes, eight thin-film resistors, eight MIM capacitors, and two spiral inductors. In addition to these active and passive devices, a number of air bridges are used for connections and crossovers. The thermal cycling did not crack or collapse any of these structures. The measured results were repeatable after the dewar was warmed back to room temperature, indicating that the MMIC LNA was not damaged during cryogenic operation.

IV. Conclusion

A wide-band HEMT MMIC LNA has been evaluated at an ambient temperature of 19 K for the first time. A 2-dB increase in gain and reduction of noise temperature to 20 K was achieved. No chip damage was observed during cryogenic operation, verifying the thermal rigidity of the MMIC chip.

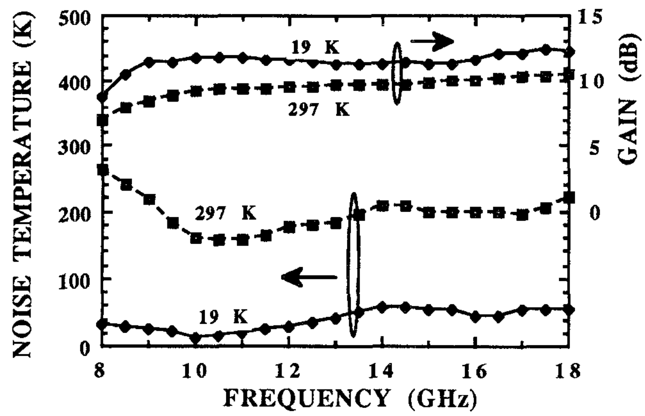

Fig. 3. Measured noise temperature and gain of a 8–18 GHz MMIC LNA at 19 K and room temperature. The room-temperature data is from on-wafer measurement, while the cryogenic data is corrected from the test fixture up to the MMIC chip.

These unique features make MMIC LNA's ideal for cryogenic receiver systems.

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