Cryogenic vacuum high frequency probe station

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Over the past several years, many groups have made cryogenic measurements at microwave frequencies to study Josephson Junctions, GaAs metal–semiconductor field-effect transistors (MESFETs), III–V heterostructure bipolar transistors (HBTs), seminconductor–insulator–semiconductor field-effect transistors (SISFETs), and III–V modulation doped field-effect transistors (MODFETs). In 1976, Liechti and Larrick[1] designed a microwave test fixture which could be immersed in liquid nitrogen. A similar type of setup has been used[2,3,21] to evaluate MODFET performance to 77 K. The most significant difficulties associated with this technique are repeatability and accuracy because the microwave cables are directly cooled subject to changing temperature gradients, and complex deembedding is required of the test fixture. More recently, interest in superconductor technology has also led to the development of cryogenic measurement systems.[4–6] The difficulties associated with all reported apparatus are (1) low frequency operation, below 1 GHz,[4,5] (2) complex deembedding scheme,[6] and (3), specific fixture requirements leading to incompatibility with generic high frequency device structures.[4–6]

More recently, several groups have made cryogenic high frequency measurements utilizing coplanar waveguide probes, which is the most accurate and repeatable technique available to 65 GHz.[7] Measurements have included either immersion of probes in liquid nitrogen[8–10] for measurements on MODFET and HBT structures or a cooled wafer stage with a dry nitrogen vapor curtain, preventing ice formation,[11,12] to measure MODFETs and SISFETs at low temperatures. The problems with immersion of probes in LN_2 are: (1) poor reproducibility, because the probe head and microwave hardware are in contact with varying amounts of liquid nitrogen, (2) short lifetime, because the probes themselves will degrade over time with direct contact of LN_2,[13] and (3) short measurement duration; the measurements must be made in a short period of time to prevent ice formation.[13,14]

Until now the best alternative for immersion in liquid nitrogen has been a cold chuck system with a dry nitrogen vapor curtain and has been tried by at least three groups.[9,11,12] The main disadvantages with this technique are: (1) accuracy, very large thermal gradients exist between microwave hardware and the device under test. Mechanical stress will create significant error in microwave measurements.[12,14] This problem can be alleviated by making calibrations at low temperature, however, measurements must be made within one hour before significant errors are introduced.[12,14] (2) Reliability and the ultimate demise of the system caused by moisture and ice,[9,14] increasing mechanical stress on manipulators requiring extensive calibration of the mechanical apparatus and eventual replacement,[14] and (3) The inability to reach temperatures below 77 K which is necessary for superconductor applications and device physics studies on various transistor structures.

In this paper we report the first use of Cascade coplanar waveguide probes in a vacuum station providing accuracy, reliability (no ice formation or large thermal gradients since the microwave hardware is insulated via vacuum), the potential to achieve temperatures below 77 K by adapting to liquid helium source, frequency capability to 65 GHz, and flexibility to probe both active and passive device structures with a coplanar contact.

The recent progress in compound semiconductor transistors has led to cut-off frequencies above 205 GHz.[15,16] Simulations and theory predict that we can expect ultimate device operation above 300 GHz.[17,18] To improve such device structures we need to gain a better understanding of the underlying device physics. By characterizing state of the art high frequency transistors at cryogenic temperatures, we not only explore the ultimate operation of these devices but also carry out comprehensive studies of the effects of parasitic elements, gate lengths, device structure and materials to determine fundamental transport properties such as effects of the momentum relaxation time. In addition, the recent progress in high T_c superconducting materials has contributed to the need for high frequency measurements at low temperatures. For these reasons we have designed and built a novel cryogenic high frequency vacuum probe station.

To eliminate problems with moisture and ice we mounted the rf probe heads onto X–Y–Z micropositioners located inside a small vacuum chamber. The vacuum also reduces the heat load so that a lower sample temperature can be reached.

A block diagram of our system is shown in Fig. 1. The vacuum chamber has a modular design with a removable upper portion which contains ports for: rf probing, rf cables, cryogen lines, thermocouples, sample manipulation, vacuum pump, and dry nitrogen backfill line. Two Cascade Microtech high frequency probes are attached to micromanipulators (Line-Tool Model H) with their motion fed through a custom stainless-steel bellows into the vacuum chamber.[19] To prevent the bellows from collapsing under vacuum, we designed a linear motion manipulator for the X-axis micrometer. A fine threaded shaft is attached to standard micromanipulators with a ball and socket for fine scale manipulation capability. Standard *O*-ring sealed Klamp–flange (KF) vacuum flanges are used to keep vacuum integrity. For dc and rf electrical measurements, semi-rigid high frequency

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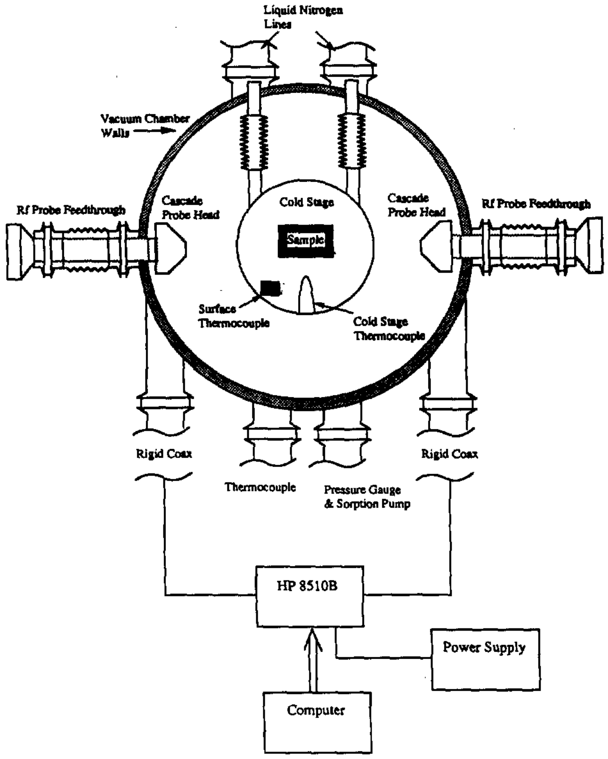

FIG. 1. Block diagram of cryogenic high frequency probe system showing details of the vacuum chamber portion.

coaxial cables are inserted at 90° angles to the probes and are sealed with *O*-ring compression fittings mounted on KF vacuum flanges. The *O*-ring compression seal allows three-dimensional motion of the semirigid cable without deforming the outer wall of the rf cable which could cause signal distortion.

A novel design is used for the cold stage for efficient cooling of the sample. The lower portion consists of a boredout stainless steel cylinder with 1/2 walls. The upper portion oxygen-free high-conductivity consists of an OFHC copper block which has openings for inlet and outlet liquid cryogen and a copper dowel inserted into the stainless steel base. The cryogen is fed into the vacuum chamber through a stainless steel bellows line which is welded to a NW flange. The cold stage fills up with cryogen and then cools the upper block via conduction along the copper dowel. The stage is continuously fed with liquid cryogen to insure an equilibrium surface temperature.

Temperature is monitored with two copper-constantan (type *T*) thermocouples. One thermocouple is attached 1/16 below the surface of the copper block and gives a reading of the stage temperature. The second thermocouple is attached to a GaAs substrate, which has dimensions similar to typical device samples, and is mounted on the surface of the three inch diameter copper block giving a reading empirically related to the sample temperature. We can estimate the change in temperature ΔT from the thermal conductivity k and the dissipated power P_d

$$\Delta T = (L/Ak)P_d. \quad (1)$$

For a GaAs device on a wafer with $P_d = 200$ mW, thickness $L = 0.5$ mm, $A = 1$ cm^2, and using $k = 0.8$ W/cm °C, we obtain $\Delta T = 0.013K$.

When changing samples or performing calibrations at low temperature, sample manipulation under vacuum is occasionally required in order to insure proper probe alignment. The manipulator is constructed from an L-shaped aluminum shaft inserted through an *O*-ring compression seal (Varian 1340) and welded to a NW flange. This sample manipulator behaves like a "wobble stick" providing the capability of probing different samples, e.g., a device wafer and a calibration substrate under vacuum. The chamber pressure is monitored with a Pirani-type gauge (Convectron 275) and the chamber is evacuated with a LN_2 sorption pump.

A typical measurement sequence is as follows: (1) load sample and calibration standards; (2) seal system and begin pumping down; (3) after allowing the pressure to equilibrate, typically around 5 mTorr (0.67 Pa), begin cryogen flow, in this case liquid nitrogen, into the copper wafer stage; (4) allow temperature to equilibrate, the minimum temperature is usually reached after 15–20 min; (5) perform electrical calibration, and finally, (6) actual device measurement.

In making the temperature measurements we have found that by changing the chamber pressure, the surface temperature can be controlled from 173 K at 5 mTorr (0.67 Pa) to 110 K at 5 Torr (666.67 Pa) as shown in Fig. 2. The wafer stage temperature is independent of pressure and remains at liquid nitrogen (LN_2) temperatures as expected. We attribute the surface temperature dependence on pressure to the thermal conductivity of the ambient atmosphere in the chamber. We make use of this temperature-pressure relationship to give a convenient variable temperature capability. The chamber pressure is varied by throttling the vacuum pump and backfilling the chamber with dry nitrogen.

The key to accurate microwave measurements is the electrical calibration. We use the short-open-load-through calibration method using the impedance standard substrate (ISS) supplied by Cascade Microtech.[20] Proper electrical calibration is necessary to remove systematic sources of error from the measurement apparatus. After making a full two-part error model correction with 12 error terms, we ver-

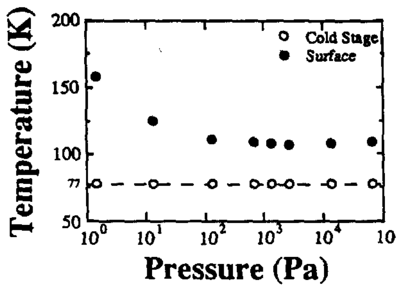

FIG. 2. Dependence of temperature on chamber pressure measured using type *T* thermocouples, mounted on the surface GaAs sample and embedded in a copper cold wafer stage.

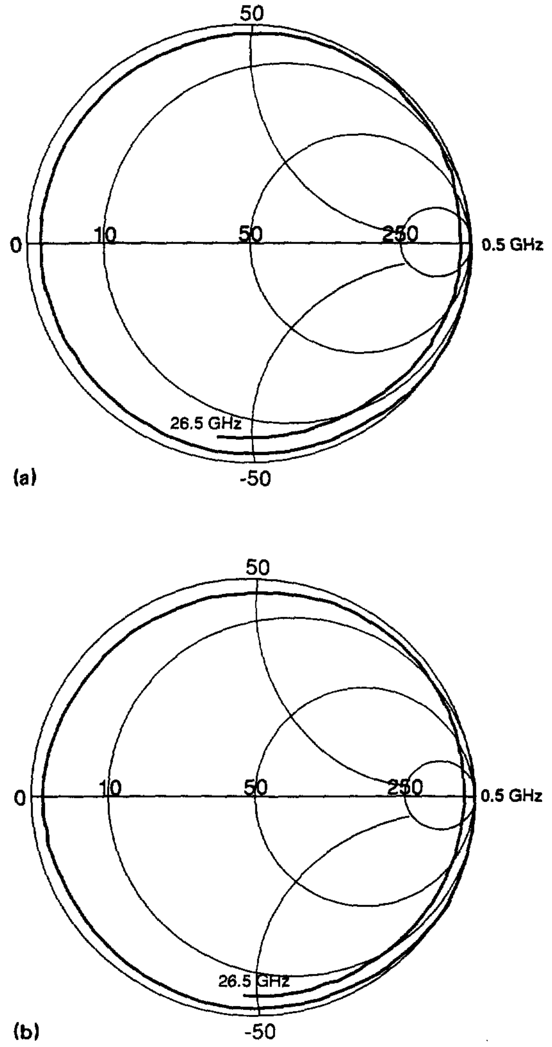

FIG. 3. Reflection coefficient from an open circuit stub shows a concentric spiral which is a signature of a good calibration. (a) 300 K calibration verification on the Smith chart. (b) 110 K calibration verification on the Smith chart showing good calibration at this temperature.

ify the integrity of the calibration by measuring a known standard. We use the technique suggested by Cascade Microtech[20] to verify the calibration procedure by measuring the reflection coefficient from an open circuit 125 mil coplanar transmission line available on the ISS. This method of verification is simple and accurate since we know the magnitude of the reflection coefficient must be less than 1 for a passive transmission line, and we expect a phase shift and slight loss versus frequency, leading to a concentric spiral on the Smith chart. Figures 3(a) and 3(b) show proper calibrations at 300 and 100 K.

For MODFETs, we have investigated the effect of having the calibration temperature being different from the sample temperature during measurement. At a sample temperature of 173 K we see a 20% increase in the frequency response of a InGaAs/AlGaAS MODFET if we use a room temperature calibration rather than the correct 173 K calibration, leading to an erroneous current gain cutoff frequency f_T value if the calibration is performed at the incorrect temperature. We attribute the discrepancy of the room temperature versus low temperature calibration result to the thermal contraction of the microwave hardware inside the chamber. Even though the vacuum has a low thermal conductivity, the rf connectors, cabling, and probe body still experience a drop in temperature, which is even more severe in a nitrogen vapor curtain system.[14] This can cause the apparent cutoff frequency to drift upward during measurement as the rf hardware cools and contracts.[9] We conclude that we must make a calibration at the temperature at which we plan to make active device measurements. We allow the system to equilibrate to a constant temperature before performing the electrical calibration and measurement. For calibrations at the measurement temperature, the measurements in our system have been verified to be stable over at least four hours.

There has been very little work on the frequency performance of compound semiconductor devices at cryogenic temperatures.[1-3,11,21,22] As an example of measurements using the low temperature probe system, in this section we briefly present some promising results on the frequency response of $In_{1-x}Ga_xAs/In_{0.52}Al_{0.48}As$ graded channel pseudomorphic MODFETs having a 0.9 μm gate length. Figures 4(a) and 4(b) show typical dc current–voltage

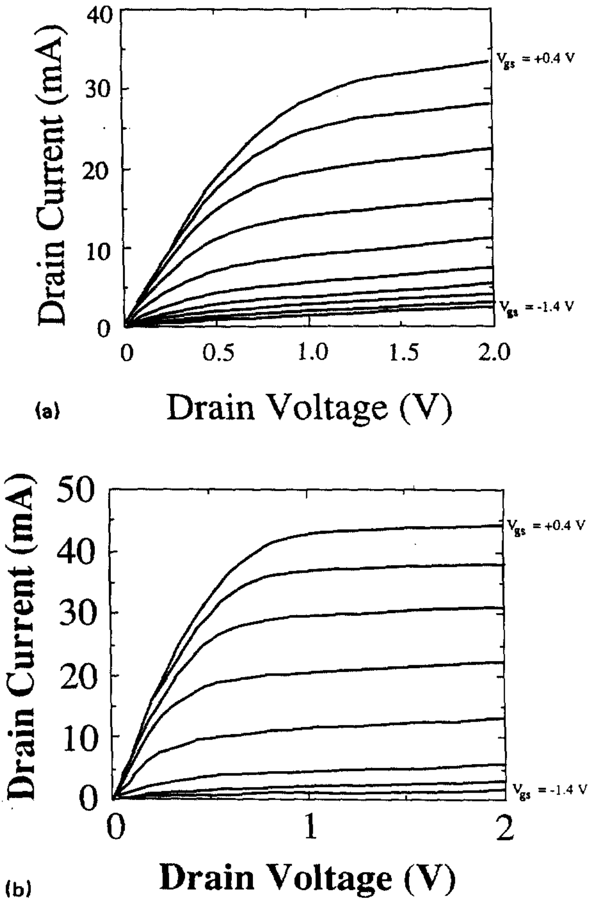

FIG. 4. Typical dc I_{ds}-V_{ds} characteristics of a 0.9×100 μm $In_{1-x}Ga_xAs/In_{0.52}Al_{0.48}As$ graded channel pseudomorphic MODFET. (a) I_{ds}-V_{ds} characteristics at 300 K. The top curve has a gate voltage V_{gs}, $= +0.2$ V, the bottom curve corresponds to $V_{gs} = -1.4$ V, and the step voltage is $\Delta V_{gs} = 0.2$ V. (b) I_{ds}-V_{ds} characteristics at 110 K. The top curve has a gate voltage V_{gs}, $= +0.2$ V, the bottom curve corresponds to $V_{gs} = -1.4$ V, and the step voltage is $\Delta V_{gs} = 0.2$ V.

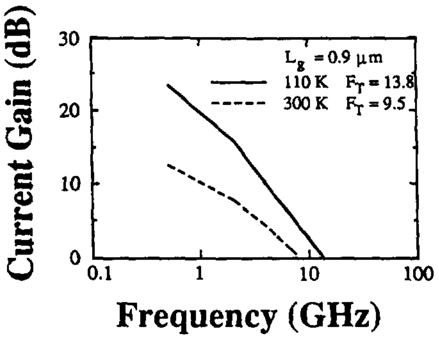

FIG. 5. Current gain (h_{21}) measurements of a 0.9× 100 µm $In_{1-x}Ga_xAs/In_{0.52}Al_{0.48}As$ graded channel pseudomorphic MODFET at 300 K and 110 K. The f_T value increases 45% from 9.5 GHz at 300 K to 13.8 GHz at 110 K.

characteristics of a device having a 0.9 µm gate length and 100 µm gate width at 300 and 110 K, respectively. In Fig. 5 we plot h_{21} versus frequency for 300 K and 110 K. The 110 K measurements were made after calibrating at 110 K and the 300 K measurements were made after calibrating at 300 K. The frequency response of h_{21} follows a −6 dB/octave rolloff and extrapolates to unity gain giving the unity gain cutoff frequency f_T. We can compare the 300 and 110 K data using the first order approximation for $f_T = g_m/2\pi(C_{gs} + C_{dg})$. The 0.9 µm device has a $\Delta f_T = [f_T(300\text{ K}) - f_T(110\text{ K})]/f_T(300\text{ K})$ of 45% while the Δg_m (dc) = 57%. The f_T increases less than the g_m since ($C_{gs} + C_{dg}$) increases by 12% when the device is cooled from 300 to 110 K. We have also calculated the maximum unilateral gain (G_u) which, when extrapolated to unity gain, gives the maximum frequency of oscillation $f_{\max}$. A typical frequency response of G_u is shown in Fig. 6 which was taken on a 0.9 µm gate length device at both 300 and 110 K. In this case, we have measured a 71% increase in $f_{\max}$.

The greater increase with temperature for $f_{\max}$ compared to f_T is partially due to a 25% reduction in the feedback capacitance C_{dg} and may also indicate a temperature dependence of parasitic elements which is under investigation by our group.

These results show the first significant improvement in both f_T and $f_{\max}$ at cryogenic temperatures on MODFET structures. Further study is needed to determine the effects of gate length, material, and channel composition (lattice matched, uniform pseudomorphic, and graded pseudomorphic) at cryogenic temperatures. This information will provide insight into the device physics of the ultimate frequency response of short-gate length devices.

We have demonstrated that reliable and repeatable high frequency measurements can be made at cryogenic temperatures in a vacuum chamber. Internal high frequency probes connect to cable feedthroughs via a custom bellows and manipulator system. Proper sample alignment is maintained with a simple wobble-stick type feedthrough. The temperature of the sample is cooled by LN_2 and varied slightly by changing the vacuum chamber pressure. The lowest temperature we have achieved has been 100 K with LN_2 flowing through the system. Our modular design will allow us to upgrade to a liquid helium cooling system providing a much lower surface temperature. We report significant improvement in 0.9 µm psuedomorphic MODFET frequency performance at 110 K.

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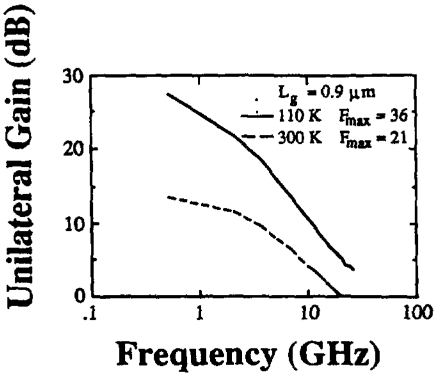

FIG. 6. Unilateral gain (G_u) measurements of a 0.9× 100µm $In_{1-x}Ga_xAs/In_{0.52}Al_{0.48}As$ graded channel pseudomorphic MODFET at 300 and 110 K. The $f_{\max}$ value increases 71% from 21 GHz at 300 K to 36 GHz at 110 K.

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