A Cryogenic GaAs HBT Microwave Amplifier and its Application to a Superconductor Digital IC

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ABSTRACT

This paper benchmarks the first microwave GaAs HBT amplifier results at 4.2° Kelvin. The amplifier nominal gain is 6 dB and is measured from 130 MHz to 10 GHz at fixture temperatures of 295 K, 77 K, and 4.2 K. The maximum gain variation over temperature was found to be about 2 dB. Maximum gain occured at temperatures around 50-85 K, whereas at 4.2 K, the gain seemed to drop slightly from that at RT. Only slight RF evidence of carrier freeze-out was observed at a fixture temperature of 4.2 K, although, HBT junction temperatures are estimated to be around 25-30 K. Finally, this chip was integrated as a buffer amplifier with an HTS superconductor digital logic gate and has shown functionality up to 320 MHz.

Introduction

Previous studies of cryogenic HBTs have shown dc operation as low as 4.2 K for both GaAs and InP HBT devices [1],[2],[3]. These studies were based on the idea of developing low power dissipation, high speed, and high density bipolar integrated circuits using HBTs. In these studies carrier freeze-out and diffusion transport degradation at low temperatures were major concerns and the study of the HBT's dc beta temperature dependence was emphasized. A technique for improving the dc beta of HBTs at cryogenic temperatures includes the use of a built-in drift field in the base. This is obtained by compositionally grading the material in the base region. At low temperatures where carrier diffusion becomes inhibited, the carriers are swept through the base region by the built-in field. Other techniques for improving the cryogenic operation of HBTs involve grading the doping in the base[4]. While dc beta is important for achieving healthy device operation, no previous reference was made on HBT RF/microwave circuit performance at cryogenic temperatures.

This paper reports on the microwave performance of a GaAs HBT amplifier at cryogenic temperatures. The HBT devices were fabricated using GaAs material with a uniform base composition. These results show successful operation of an HBT direct-coupled amplifier at 4.2 K and frequencies up to 10 GHz. In addition, this amplifier was integrated with an HTS superconductor logic gate which has shown performance up to 320 MHz.

GaAs HBT Device Technology

The technology used is a GaAs 2- and 3-μm self-aligned base ohmic metal HBT process. Fig. 1 illustrates the HBT molecular beam epitaxial profile. The HBT devices feature an MBE structure which consists of a 1400Å base with a uniform doping of 1e19 cm^{-3} and a 7000Å collector with a doping of 7e15 cm^{-3}. The base material composition is uniform AlGaAs. The specific wafers which were

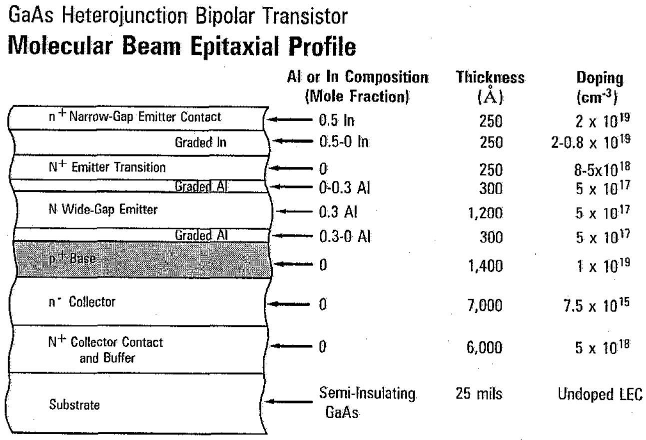

Fig. 1 HBT MBE device profile.

measured yielded dc betas of 40 at room temperature for a current density of 20 kA/cm^2. The F_t's and F_{max}'s were typically 25 GHz and 40 GHz, respectively. This process uses a device nitride passivation for device protection. The wafer is 4 mils thick with back-side vias for good ac grounding and thermal conductivity.

HBT dc performance at cryogenic temperatures has been measured both in AlGaAs/GaAs and InAlAs/InGaAs materials [1],[2],[3]. Specifically, dc measurements at 4.2 K have been obtained for compositionally graded and uniform base devices. For the uniform base composition which is the structure reported in this paper, the current gain is dependent on temperature and may be expressed as:

$$\beta = (2\mu kT\ tau)/(qW^2)\ [1],\ [2]$$

this is based on diffusion limited operation where μ is the electron mobility in the base, tau is the electron life-time, and W is the base thickness. Since the base is heavily doped, the minority carrier electron mobility is weakly temperature dependent. The temperature T and tau are the remaining temperature influences in the equation. Fig 2 illustrates the measured dc beta dependence on temperature from 35 K to 295 K at a current density of 13 kA/cm^2. As the temperature drops from 295 K to about 100 K, the beta steadily increases. This occurs because the minority carrier lifetime, tau, increases more than the temperature decreases due to a reduction of recombination in the bulk base material at lower temperatures. As the temperature further decreases below 100 K, the decrease in

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temperature T begins to overide the effects of the reduction in recombination. Thus, the beta begins to fall-off rapidly as illustrated in fig. 2.

Cryogenic HBT Microwave Amplifier

A schematic of the HBT amplifier is shown in fig. 3. The amplifier is a Darlington feedback configuration with resistive dc feedback for self-biasing. This amplifier is known for its wide bandwidth capability and compact size. Transistors Q_1 and Q_2 are 2 x 10 μm^2 quad-emitter devices operating at a current density of 20 kA/cm^2. Each transistor dissipates 64 mW of power which translates into a junction temperature increase of about 25 K, This design also incorporates shunt and series feedback through resistor R_F and R_{EE}, respectively. These are adjusted for gain and bandwidth. These resistors in combination with R_L, R_b, and R_{bias}, provide negative dc feedback which regulates and stabilizes the dc bias. The amplifier topology has an inherent bias regulation which can tolerate fluctuations in the dc beta of the HBTs over temperature. The fabricated chip is shown in fig. 4 and measures 1x1 mm^2.

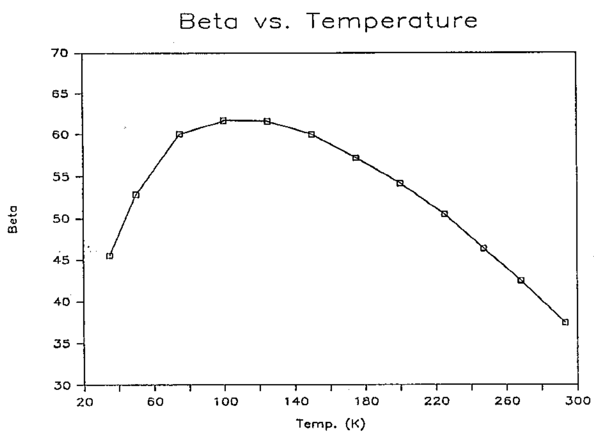

Fig. 2 Beta as a fucntion of temperature for a 3 x 10 μm^2 single emitter transistor at a J_C = 13 kA/cm^2.

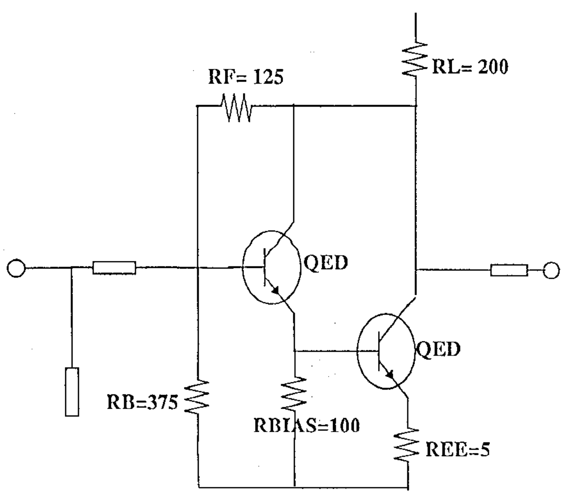

Fig. 3 Schematic of the HBT cryogenic microwave amplifier.

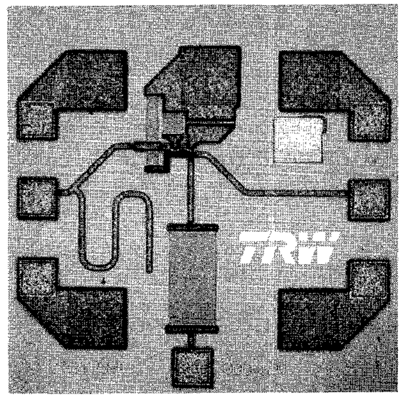

Fig. 4 Photograph of the HBT MMIC amplifier. Chip size is 1.0 x 1.0 mm^2.

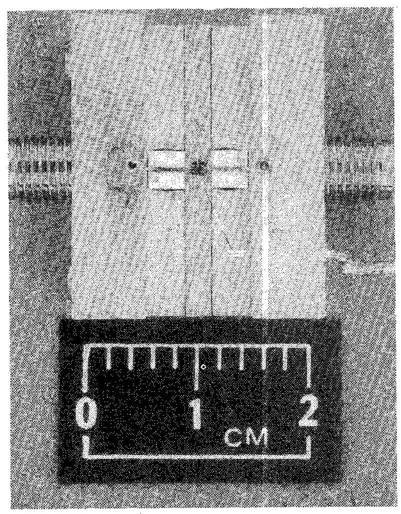

Fig. 5 Hybrid fixture containing the HBT amplifier.

The HBT amplifier chip was mounted in a hybrid fixture illustrated in fig. 5. The fixture has 50 Ω microstrip lines made from 15 mil alumina substrates. The chip was placed in the hybrid by a non-electrical-conducting laquer which could withstand gross temperature changes and has good thermal conductivity. The ground of the chip was realized by four 3 mil ribbon bond wires to the fixture ground. The amplifier was submerged in a dewar containing liquid hellium. The temperature was monitored by a sensitive thermal coupler which was attached to the fixture. Various temperatures were achieved by submerging the fixture down into the dewer at various depths. S-parameter of the amplifier were measured from 130 MHz to 10 GHz. The calibration plane of reference was up to the fixture connectors.

The amplifier was measured at room temperature, 77 K and 4.2 K. Fig. 6 shows the gain response for these temperatures. Maximum variations in gain between room temperature and 4.2 K were about 1 dB at a frequency of 7 GHz. At a temperature of 77 K, the gain was higher than that at RT or 4.2 K by 2 dB. The amplifier gain at 4.2 K also shows a more pronounced roll-off. It appears that

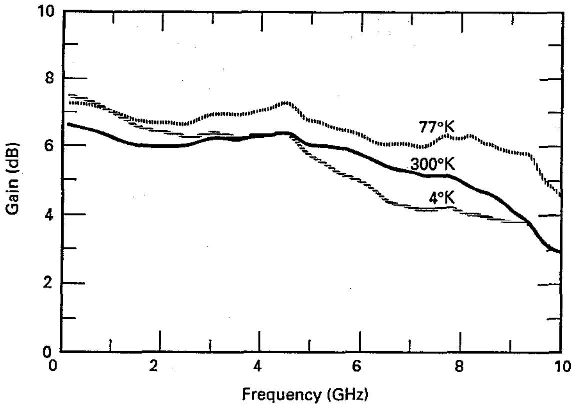

Fig. 6 Gain response at 300°, 77°, and 4.2°K.

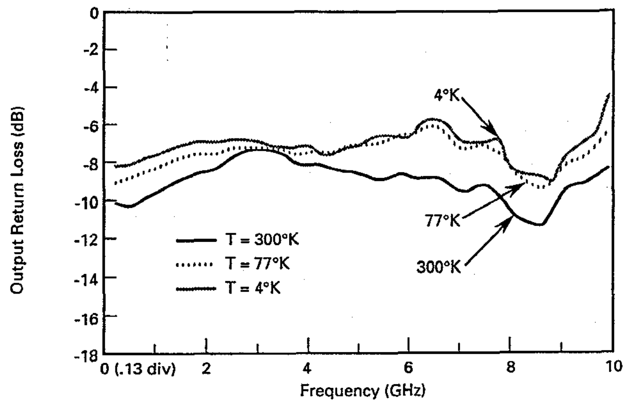

Fig. 8 Output return-loss at 300°, 77°, and 4.2°K.

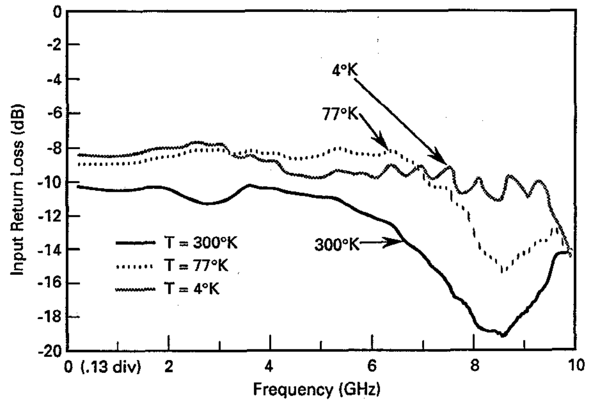

Fig. 7 Input return-loss at 300°, 77°, and 4.2°K.

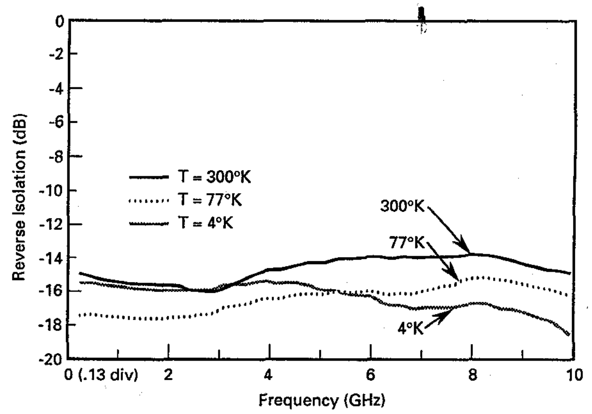

Fig. 9 Reverse Isolation at 300°, 77°, and 4.2°K.

the nominal gain peaked somewhere around 77 K and degraded as the temperature approached 4.2 K. This parallels the HBT transistor dc beta characteristics and can be explained by the same diffusion transport mechanism. The dc current draw through the amplifier is constant through the full temperature range due to the self-bias network. Figs. 7 and 8 show the input and output return-loss performance over temperature. Unlike the gain response, the return-losses show a monotonic degradation with decreasing temperature. Both return-losses were a reasonable 8-10 dB. On the average, the return-losses changed by about 2-3 dB. The reverse isolation characteristics shown in fig 9, indicate a maximum variation of 4 dB with an average isolation of 16 dB. Both return-loss and isolation showed no significant changes over the temperature range between 300 K and 4.2 K.

The self-regulating bias network was very convenient in keeping the bias current constant throughout the temperature range. The total current at RT was 43.8 mA and at 4.2 K it was 41.6 mA. This is less than 5% change in current. With a more complicated biasing scheme, a temperature dependent current bias could be designed which increases the current with decreasing temperature to compensate for the drop in gain.

HBT-Superconductor Digital Demonstration

HBT technology is ideal for buffer circuit applications for high speed digital ICs because of their low phase noise, high frequency bandwidths, and high output drive characteristics. Low phase noise and 1/f corner frequency is important for maintaining high clock rate digital signals with sharp clock edges. HBTs have the advantage of having a lower 1/f noise corner frequency compared to other cryogenic technologies such as HEMT. The noise corner for InP HBTs is in the KHz range while the corner frequency for typical HEMT devices is in the hundreds of MHz. But until recently, HBTs have not demonstrated ICs working at cryogenic temperatures which precluded their use in these types of applications. The HBT amplifier described in this paper demonstrates the feasibility of using HBT ICs in cryogenic digital applications. In addition, HBT MBE material growth technology can offer techniques to improve device performance at cryogenic temperatures[1],[2],[3],[4]. Thus, HBT technology can provide a good match for superconductor digital applications.

The direct-coupled HBT amplifier described in this paper was use to enhance the performance of a superconductive logic gate at high clock rates. A logic gate made from high temperature superconductor Y-Ba-Cu-O is being developed for sub-GHz clock rate operation. The gate operates with 100 μV output signal levels. Fig. 10 shows a block diagram of the BER measurement system for the HTS logic gate.

Because of the low level output of the superconductor logic gate (100 μV), the digital signal is subject to noise pick-up. This noise is predominantly electro-magnetic coupling from other signal sources in the circuit's proximity. A low noise direct-coupled microwave bandwidth pre-amplifier is required to amplify the 100 μV signal level and improve the noise immunity (signal to noise ratio) of the superconductor digital IC. Placing the pre-amplifier close to the gate improves pick-up immunity and overall noise figure.

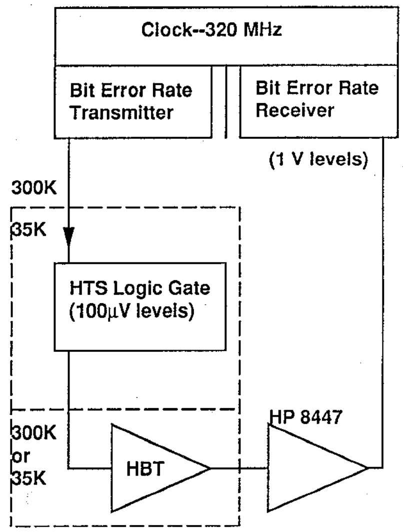

Fig. 10 Block diagram of the BER measurement system. An RT HBT amplifier is integrated with an HTS superconductor inverter gate at 35°K.

The HBT amplifier at RT has been used as the pre-amplifier with good results. The measured pseudo-random digital input and output waveforms are shown in fig. 11. Using a cooled HBT pre-amplifier and integrating it in a hybrid with the superconductor logic gate is planned in a future bench-top demonstration.

Conclusion

Cryogenic GaAs HBT microwave amplifier performance has been demonstrated down to 4.2 K. These results benchmark the first microwave results of an HBT amplifier at cryogenic temperatures. A nominal gain of 6 dB and bandwidth up to 10 GHz has been obtained. Also, integration of this amplifier with an HTS superconductor logic gate has been demonstrated with clock rates as high as 320 MHz.

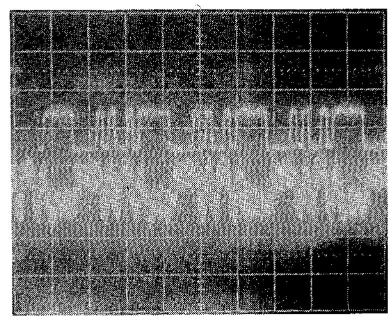

Fig. 11 Pseudo-random 320 MHz digital word input and inverted output signals.

Acknowledgment

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