Ultra Low Noise Cryogenic Amplifiers for Radio Astronomy

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***Abstract* — Cryogenic cooling of receivers to reduce their noise temperature is especially important in radio astronomy, as the antenna noise temperature is determined by the cosmic microwave background radiation (2.725 K) modified by the presence of atmosphere. For frequencies up to 120 GHz direct amplification at cryogenic temperatures is typically employed using InP heterostructure field-effect transistors (HFETs) or, more recently, SiGe heterostructure bipolar transistors (HBTs). This article reviews developments in this field and presents the current state-of-the-art. Examples of noise performance of amplifiers using InP HFETs and SiGe HBTs are compared with the model predications. Some gaps in our current understanding of experimental results are emphasized, and some comments on possible future developments are offered.**

***Index Terms* — heterostructure field effect transistors; high electron mobility transistors; SiGe heterostructure bipolar transistors; low noise amplifiers; radio astronomy; radio telescopes.**

I. INTRODUCTION

The first use of cryogenic GaAs FET amplifiers in a large radio astronomy instrument (Very Large Array) dates back to the work of S. Weinreb [1]. Since then several generations of cryogenic amplifiers using different devices have been employed in radio astronomy receivers as described in [2]. It has been long observed that FETs (HFETs) from different wafers manufactured using similar technologies exhibited very different performance at cryogenic temperatures, even if they had very similar room temperature performance. As a result, at any given time HFET devices from a single wafer (or set of wafers manufactured at the same time), exhibiting exceptionally good cryogenic performance were used in the construction of cryogenic amplifiers. The most recent in this series of "radio astronomy golden wafers" are the so-called cryo3 wafers, produced in 1999 by the Northrop Grumman Space Technology (NGST) for the JPL Deep Space Network, which produced tens of thousands of AlInAs/GaInAs/InP HFET chips with 80 nm gate length and different device peripheries. A review of the performance of amplifiers built with these devices for a number of radio astronomy instruments (VLA, Green Bank Telescope, Deep Space Network, CBI, CARMA and others) is given in Section II.

More recently, further improvements in the engineering of artificially structured semi-conductor wafers and aggressive scaling of gate length resulted in InP HFETs exhibiting f_{max} in excess of 1 THz [5]. MMIC amplifiers using these devices produced many records of low noise performance at frequencies of 60 GHz and up. The performance of cryogenic versions of these amplifiers is discussed in Section III.

Although InP HFETs dominate current radio astronomy instrumentation throughout the cm- and mm-wave range, Silicon Germanium HBTs have recently emerged as a competitive low-noise device at cryogenic temperatures, at least below a few GHz. The review of performance of this emerging technology is contained in Section IV. The concluding remarks are offered in Section V.

II. OVERVIEW OF CRYO3 AMPLIFIER PERFORMANCE

The dc properties of the cryo3 InP HFETs, both at room and cryogenic temperatures, were extensively reviewed in [3]. The key observation is that for very low current densities per unit gate width, the transconductance g_m more than doubles upon cooling. This indicates that a device upon cooling preserves very high values of f_t and f_{max} at current densities which are much smaller than those required for optimal room temperature operation. Such a property was observed before in other good cryogenic wafers and it is easily interpretable in terms of the noise model [2]. Typically, the noise temperature of amplifiers built using cryo3 devices is reduced by a factor 10 or more by cooling from 300 K to 15 K. The optimal bias at cryogenic temperatures for these devices typically falls in the range of 25-35 mA/mm for drain currents and 0.7-0.9 V for drain voltages. The optimal cryogenic current bias is about 1/2 or even 1/3 of that at room temperature while the drain voltage remains unchanged [4].

It is relatively straightforward to develop a noise model of such "well behaved" cryogenic HFET which can easily be scaled for devices with different gate peripheries if the current density is preserved [2]. A choice of gate periphery is important for an optimal wide band low noise design. Knowledge of the small signal and noise model of a device allows the determination of its minimum noise measure. The noise temperature of a properly designed, low-noise, high-gain, and wide-band amplifier should touch upon the minimum noise measure of the device used at some frequencies within its band. The measured noise temperatures of many different amplifiers built with cryo3 HFETs are plotted in Fig. 1 along with the expected minimum noise measure. Measured noise temperatures of representative amplifiers covering 4-100 GHz frequency range are shown. At each frequency band (but for W-band) the number of amplifiers built with similar performance range from 70 to 140. Significant progress has been made in matching the performance of cryo3 devices in the cm-wave range using longer gate length (130 nm) and by optimizing the device for low temperature, low current operation [14].

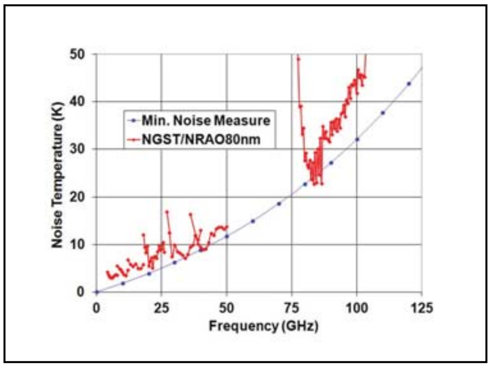

Fig. 1. Comparison between the prediction for the minimum noise measure of cryogenic InP HFET and the typical noise temperatures measured for NRAO cryo3 amplifiers.

III. 35NM GATE LENGTH INP HFET MMICS

While the noise performance up to about 50 GHz has reached the practical limit of 4-5 times the quantum limit using 80nm InP HFET MIC amplifiers (see Fig. 1), further improvements are possible in the 65-120 GHz frequency range. Recently, a new generation of 35nm gate length InP HFETs has been developed by Northrop Grumman Corporation (NGC) to demonstrate transistor amplifiers operating at or near 1 THz [5]. It is a fortunate by-product of this pursuit, developing InP HFETs with shorter gate lengths for higher transconductance and lower parasitics, that these devices also promise lower noise temperatures at relatively lower frequencies, such as 65-120 GHz.

In 2008, W-band MMIC LNAs were first fabricated on a 35nm wafer to evaluate the process for cryogenic noise performance. Samples of a 3-stage MMIC design were packaged in a WR-12 module and measured in a cryogenic test receiver. The 22 K minimum noise was the lowest ever measured in this frequency range [6].

Results from a 2012 35nm wafer run have yielded data for new W-band designs consistent with the initial 2008 measurements, with cryogenic noise temperatures below 30K up to 108 GHz [7]. Additionally, cryogenic measurements of the 2008 design from the 2012 wafer give very similar results, indicating some degree of repeatability of cryogenic noise performance from wafer to wafer, an important criterion in selecting between MMICs and hybrid MICs for new instrumentation development.

Fig. 2 shows a comparison of the best 35nm cryogenic noise performance to date. It is compared to the best W-band Superconductor-Insulator-Superconductor (SIS) mixer receiver [8] in this frequency range as well as to the minimum noise measure for 80nm gate length InP HFETs from Fig. 1. Also shown on Fig. 2 is a minimum noise temperature fit to the best 35nm noise results. While this new generation of 35nm gate length InP HFETs is outperforming the 80nm devices, the improvement is not as great as expected based on simple scaling of the gate length. The reasons for this effect are being explored, including the possibility that current state–of–the-art InP HFETs are approaching the limits of achievable noise performance.

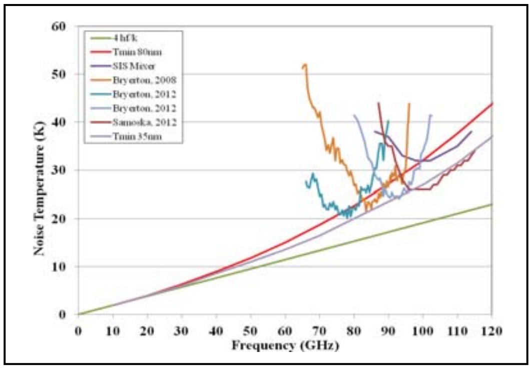

Fig. 2. Summary of the best noise temperatures for 35nm InP HFET MMIC LNAs, with comparison to SIS mixers.

IV. SILICON GERMANIUM HBTS

In addition to very competitive noise performance, SiGe HBTs have a number of practical advantages. First, due to the large current gain of the individual devices, moderate resistive feedback may be used to improve broadband impedance match without degrading noise performance. In contrast, HFET devices large enough to provide near 50 real part of the optimal source impedance at cm-wave frequencies, have historically been unusable at cryogenic temperatures due to intrinsic instabilities that have not been fully understood. In practice, this has necessitated the use of smaller gate periphery devices with isolators or balanced amplifiers, either of which inevitably adds passive loss and thus thermal noise to the system.

Further, unlike depletion-mode HFETs, the HBTs may be optimally biased from a single-polarity supply, simplifying the bias and control circuitry. HBTs are also not expected to suffer from $1/f$ gain fluctuations as severely as the HFETs, which is advantageous in total-power observations on non-interferometric telescopes. Finally, the very high device yield and compatibility with Silicon BiCMOS processes, for which there is significant

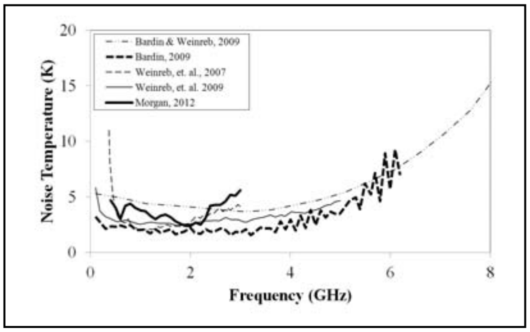

Fig. 3. Summary of the best equivalent noise temperatures reported in recent years for cryogenic SiGe amplifiers.

commercial infrastructure and investment, have led many groups to pursue larger scales of integration on-chip.

Pioneering work in the application of cooled SiGe HBTs to radio astronomy was conducted by researchers at Caltech [9]-[12]. This work has shown that the device is well characterized for the intended application by a simple equivalent circuit with two uncorrelated shot noise sources associated with the base and collector dc currents, plus the thermal noise of the resistive elements (most importantly the base resistance). Thus, knowledge of the small-signal equivalent circuit and some rudimentary dc measurements at cryogenic temperatures are sufficient to determine the four noise parameters and produce an optimized amplifier design. Their measurements further showed that the current gain, , may increase by up to a factor of 20, and g_m by a factor of more than 3 upon cooling, leading to dramatic improvements in noise temperature.

At the NRAO, where most of the world's current active radio astronomy amplifiers have been built using InP HFETs, SiGe devices are now being explored as an alternative in the next generation cm-wave receivers. They have been used successfully in experimental prototypes such as the Phased-Array Feed (PAF) built in collaboration with Brigham Young University [13]. Though not yet competitive with conventional focal plane arrays, this instrument, utilizing cooled SiGe HBTs, is widely recognized as the best-performing PAF built to date. They are also being used in conjunction with a novel orthomode transducer topology which has the potential to realize lower system noise temperatures than have previously been achieved at any frequency using a coherent receiver. Critical to this concept is the minimization of passive input losses, which requires the amplifier not only to achieve state of the art active noise performance, but also to present a good impedance match to the OMT without the use of an isolator or quadrature hybrid. SiGe HBTs are ideally suited for these requirements.

A summary of the best equivalent noise temperatures achieved to date using cooled SiGe HBT technology is shown in Fig. 3. Although the results obtained by different test facilities are known to differ by up to a few Kelvin, the curves shown in this plot were selected as those believed to be most consistent with one another for comparison. This underscores the inherent difficulty in making precise measurements at this level, and the attention to detail that is required to achieve the very high level of sensitivity now demanded for radio astronomy instrumentation.

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