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Cryogenic W-Band SiGe BiCMOS Low-Noise Amplifier

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***Abstract*—In this paper we present the design, modeling, and on-wafer measurement results of an ultra- wideband cryogenically cooled SiGe low-noise amplifier covering at least 71 to 116 GHz. When cryogenically cooled to 20 K and measured on wafer the SiGe amplifier shows 95-116-K noise temperature from 77 to 116 GHz. This means 6 to 7 times improvement in noise temperature compared to room temperature noise. The measured gain is around 20 dB for frequency range of 71 to 116 GHz with unprecedented low power consumption of 2.8 mW. To the best of authors' knowledge, this is the highest frequency cryogenic SiGe low-noise amplifier and lowest noise performance for silicon amplifiers for W-band reported to date.**

***Keywords*—BiCMOS integrated circuits, cryogenics, heterojunction bipolar transistors (HBT), low-noise amplifiers (LNA), MMICs, silicon germanium (SiGe).**

I. Introduction

Applications for cryogenic low-noise amplifiers (LNAs) range from radio astronomy to quantum computing. At millimetre-wave frequencies III-V technologies have dominated the field of cryogenic amplification [1]-[3]. Recently, promising results have been obtained using CMOS and SiGe technologies for cryogenic LNAs operating above 30 GHz. A W-band cryogenic CMOS LNA with 108-155-K noise temperature was reported in [4] and cryogenic operation of a 60-GHz SiGe BiCMOS LNA with an average of 191-K noise temperature was demonstrated in [5]. Although amplifiers based on III-V technologies have better noise figures, the motivation for using silicon based technologies is the possibility to integrate more functions on the same chip. Depending on the application (for example radio astronomy), a hybrid combination of the two technologies could be then used to obtain a high level of integration with a low-noise figure. Provided that the noise figure is low enough and the gain and power consumption reasonable, integrating more functions on the same silicon chip would relax system complexity inside the cryogenic Dewar for a future generation of large receiver arrays with hundreds of elements.

In this paper we report cryogenically cooled SiGe BiCMOS low-noise amplifier for W-band and beyond. To support the results we use a simple pi model for the transistor to model the cryogenic small-signal and noise performance of the W-band SiGe low-noise amplifier.

II. LNA Design and Cryogenic Modeling

The LNA was designed in IHP's 0.13-µm SiGe BiCMOS technology with f_T and f_{max} of 350 GHz and 450 GHz (at room temperature), respectively. The technology has 7 metal layers with two thick top metals including metal-insulator-metal (MIM) capacitors.

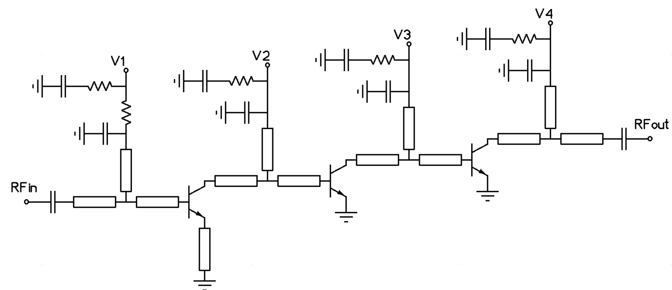


Fig. 1. Simplified schematic of the LNA.

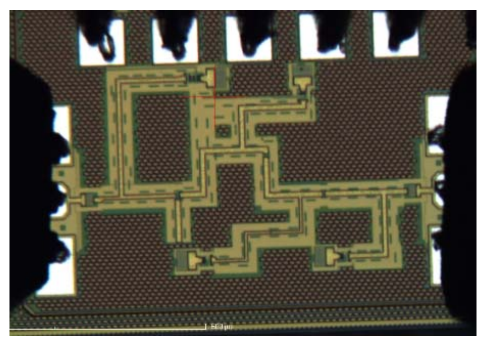
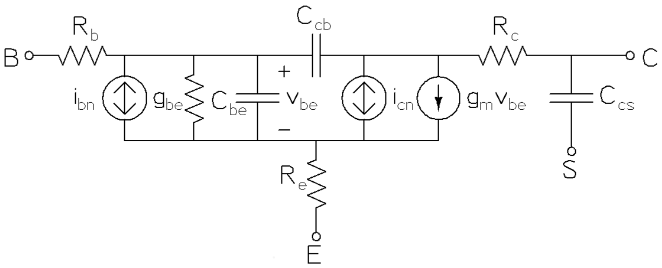


Fig. 2. Micrograph of the SiGe BiCMOS LNA. The chip size is 1000 µm × 700 µm including seal ring.

A. Cryogenic Low-Noise Amplifier Design

A three-stage amplifier was designed in a common-emitter configuration and microstrip environment. The simplified schematic and micrograph of the LNA are shown in Fig. 1 and Fig. 2, respectively. T-type matching was chosen for both input, output and interstage matching to obtain low-loss and wideband operation [6][7]. DC-blocking capacitors implemented by metal-insulator-metal (MIM) capacitors are used only at the input and output to avoid potential modeling errors and additional insertion loss. For the two first amplification stages a device size of $A_E=4\times0.07\times0.9\ \mu m^2$ was chosen. Emitter degeneration is used for the input stage to obtain better impedance matching while having optimum noise measure match. The output stage utilizes a larger device ($A_E=6\times0.07\times0.9\ \mu m^2$) for better linearity. Resistor-capacitor (RC) networks are used to ensure out of band stability. Unsalicided polysilicon was used as resistor material because it



Extracted Model Parameters								
R_b	R_c	R_e	g_{be}	C_{be}	C_{cb}	C_{cs}	g_m	τ
8 Ω	8.1 Ω	5.8 Ω	2.6e-5 S	25 fF	6.5 fF	4 fF	68 mS	0.34 pS

Fig. 3. Cryogenic small-signal noise model for a device size of $A_E=4\times0.07\times0.9\ \mu m^2$ with 1 mA of collector current. i_{bn} and i_{cn} represent shot-noise sources for the base and collector, respectively.

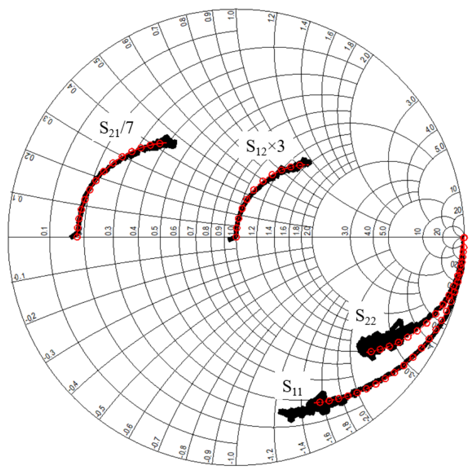


Fig. 4. Measured (solid) and modeled (circles) S-parameters for device size of $A_E=4\times0.07\times0.9\ \mu m^2$ at 20 K with 1 mA of collector current.

was measured to have fairly stable temperature dependence (see also [8]).

B. Cryogenic Transistor Modeling

A simple cryogenic transistor small-signal noise model shown in Fig. 3 was generated based on cryogenic on-wafer dc and RF measurements following the procedures introduced in [9]. It should be noted that this model was not available at the time of the LNA design. However, it will be used to support the measurement results for the LNA.

For RF measurements we used open-short de-embedding [10]. A comparison of the modeled and measured S-parameter data up to 50 GHz shows good agreement as presented in Fig. 4.

III. Measurement Results and Model Comparison

The measured room temperature small-signal gain of the amplifier was higher than 13 dB with better than 9-dB input and output return losses from 68 to 127 GHz. The measured noise figure shown in Fig. 5 was below 6 dB from 75 to 105 GHz.

The amplifier was measured cryogenically on-wafer in a cryogenic probe test station (CPTS) [11][12]. The chuck

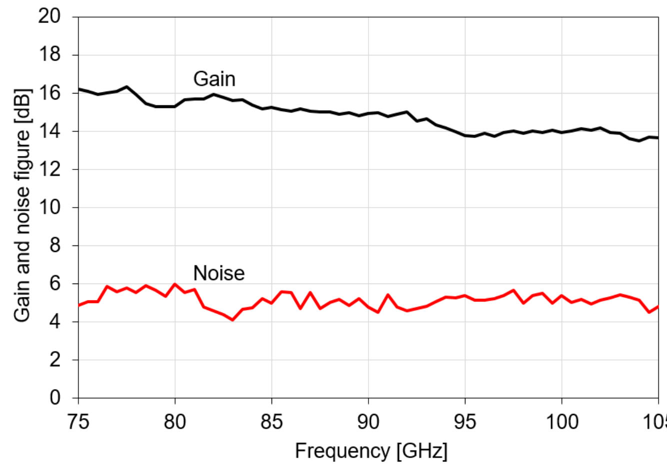


Fig. 5. Measured room temperature gain and noise figure of the LNA. Bias conditions for each stage: [*V1* and *V2*, *I2*] = [0.85 V, 1.67 mA], [*V3*, *I3*] = [0.86 V, 1.65 mA], [*V4*, *I4*] = [0.86 V, 2.6 mA].

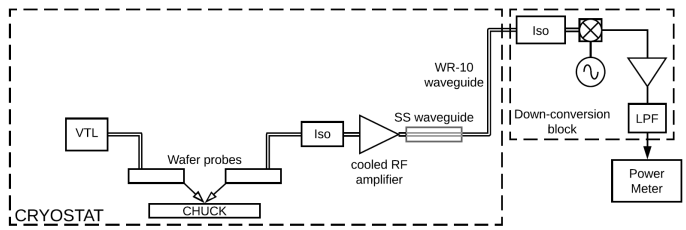


Fig. 6. On-wafer cryogenic (20 K) measurement setup.

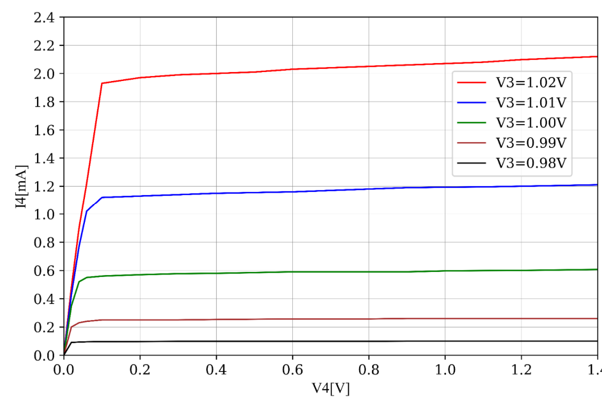


Fig 7. Measured collector current *I4* of the last stage of the amplifier as a function of *V4*.

temperature of the probe station is 19 K. The noise temperature of the LNA was measured using Y-factor method with variable temperature load (VTL). The setup for the noise measurement is shown in Fig. 6. Losses in the input probe are not accounted for since the temperature of the lossy part of the probe is not known. This causes the measured noise temperature to be over-estimated by 10-20%.

The stability of the amplifier was studied in several bias points. A DC sweep was done for the last stage of the amplifier, so, that the first two stages were biased on. As can be seen from Fig. 7 no abrupt changes are seen in the DC curves suggesting stable operation for the transistor and whole amplifier.

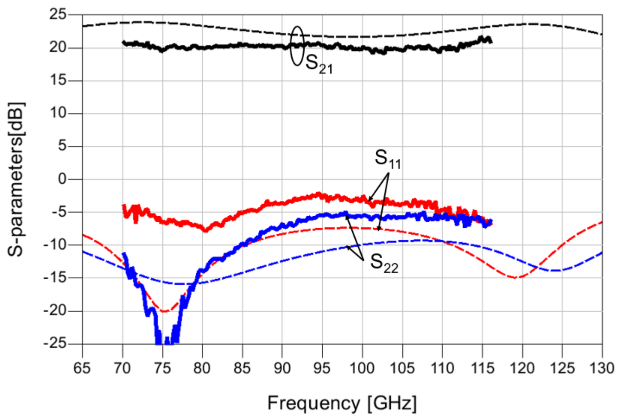


Fig. 8. Measured (solid) and modeled (dashed) cryogenic (20-K) S-parameters of the LNA. Bias conditions for each stage: [*V1* and *V2*, *I2*] = [1 V, 0.78 mA], [*V3*, *I3*] = [1 V, 0.7 mA], [*V4*, *I4*] = [0.9 V, 1.42 mA].

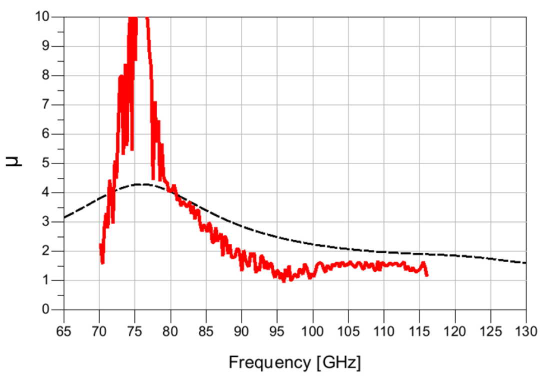


Fig 9. Measured (solid) and modeled (dashed) stability measure $\mu(S)$ for the LNA at 20 K.

The measured and modeled cryogenic S-parameters are shown in Fig. 8. The measured gain is 20 dB from 70 to 116 GHz. The measured input and output matching are only 3 dB and 5 dB around 95 to 100 GHz. However, the amplifier shows unconditionally stable operation (μ>1 [13]) for the whole measurement range as presented in Fig. 9.

The measured and modeled noise temperature and gain are shown in Fig 10. A record 95-116-K noise temperature from 77 to 116 GHz was obtained with power consumption of only 2.8 mW.

Taking into account the overestimation of the measured noise there is a fairly good agreement between measured gain and noise compared to modeled results. The simulated gain is somewhat higher which is because the model was generated for a higher collector current. Although the measured and modeled input and output matching have similar shape simulations show better matching across the band.

IV. Conclusion

A cryogenic W-band SiGe low-noise amplifier was demonstrated for the first time. A record 95-116-K noise temperature from 77 to 116 GHz was obtained which means 6 to 7 times improvement in noise temperature compared to the room temperature noise. The results are compared to other recently published W-band cryogenic amplifiers in Table 1.

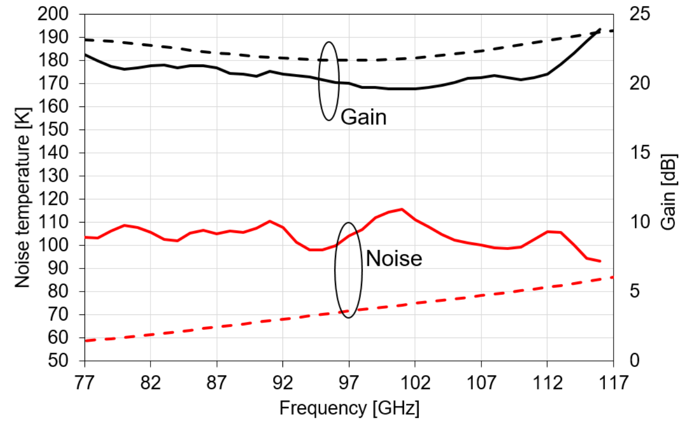


Fig. 10. Measured (solid) and modeled (dashed) cryogenic (20 K) noise and gain of the SiGe BiCMOS LNA. Bias conditions for each stage: [*V1* and *V2*, *I2*] = [1 V, 0.8 mA], [*V3*, *I3*] = [1 V, 0.64 mA], [*V4*, *I4*] = [0.9 V, 1.5 mA]. The measured noise temperature of the LNA has been corrected for post-amplifier noise of 0.5-3 K depending on the frequency. However, based on our previous measurements we have determined that the CPTS noise temperatures are overestimated by about 10-20%. For the LNA noise presented, we do not attempt to correct for this effect.

Table 1. Comparison of W-band Cryogenic Amplifiers.

Ref	Tech.	T_{amb} (K)	Freq. (GHz)	Gain (dB)	T_n (K)	P_{DC} (mW)	Gain/P_{DC} (dB/mW)
[2]	100-nm InP HEMT	16	65-116	21-25	28.4	7	3.3
[3]	35-nm mHEMT	15	70-116	23.2	32.2	17	1.4
[3]	50-nm mHEMT	15	70-116	24.8	32.5	29	0.86
[14]	35-nm InP HEMT	20	68-113	14	25-36	6	2.3
[4]	28-nm SOI CMOS	20	75-115	19-23	108-155	22	0.95
This work	**SiGe BiCMOS**	**20**	**77-116**	**20**	**95-116**	**2.8**	**7.1**

To the best of authors' knowledge these are the lowest noise temperatures reported for any silicon based amplifiers operating around this frequency range. Although the noise performance of the InP and mHEMT amplifiers are better it seems that the noise performance of the SiGe amplifier is low enough for cascading it with a preceding InP amplifier. Because of the outstanding low power consumption of the SiGe amp more functions such as mixers with LO multiplier chains could be integrated on the same silicon chip and assembled inside the cryogenic Dewar without excessive increase in overall power consumption. This would relax the LO distribution enabling more compact receivers for future generation of large receiver arrays with hundreds of elements.

In addition, a simple pi model was used for simulating the cryogenic performance of the LNA. A reasonable modeling accuracy was obtained for supporting the measured results. However, further studies are needed to determine if this simple model can be used for designing a more optimized LNA around 100 GHz or whether a higher order model is required [15] (see also discussion in [16]).

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