RF Low Noise Amplifiers and Filter Design Using High Electron Mobility Transistors To Reduce Cooling Power Consumption

Research Thrust R1 – RF, Microwaves and Millimeter-wave Systems

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Abstract

This report presents the properties of Silicon (Si) and heterojunction materials and compares them in terms of mobility and thermal conductivity. Designs and simulations of two Low-Noise Amplifiers (LNAs) implemented in Silicon (Si) and Gallium Arsenide (GaAs) technologies. They were designed to operate between the L & S bands of the radio frequency (RF) spectrum (1GHz - 2.5GHz). The study aims to compare the performance of the two technologies in terms of noise figure and frequency range. Equations used in the design and simulations, along with schematics for both LNAs are presented and discussed.

Lastly, a programmable Winner Takes All Rank Order filter (WTAROF) is shown as a potential circuit to handle spurious noise.

Problem and Hypothesis

Silicon is the most commonly used semiconductor in electronic device industry. However, Si is an unlikely candidate for RF LNA design due to its low mobility and high thermal noise. Literature shows that heterojunction materials such as InP[1] and GaAs hold promise as the material of choice for LNAs due to their wide bandgap and high electron mobility.

This work proposes the use of heterojunction materials to design an LNA that will have a reduced noise factor with a lower noise figure at higher temperatures when compared to Si.

Designing an LNA will allow for a higher frequency of operation with less thermal noise at the L and S bands when compared to Si.

Objectives

- Design an LNA that operates between the L-band (1GHz – 2GHz) and S-band (2GHz - 4GHz) with the following parameters:
  - Gain: 18.31dB-33.51dB
  - Operating frequency: 1GHz - 2.5GHz
  - Noise Figure: 1dB
- Compare LNA designs each of Si and GaAs in terms of gain and Noise Figure at specific temperature

Challenges

- Redesign programmable level detector circuit for GaAs technology
  - GaAs PMOS Transistors are too noisy
  - GaAs are depletion mode transistors
- Design WTAROF with only NMOS transistors in Si to later redesign for GaAs
- Develop a circuit that can handle spurious noise
  - Programmable level detector circuit
- Modern wireless communication devices cause unwanted interference

Equations Used

$$Z_{in,Si} = s(L_s + L_g) + \frac{1}{sC_{gs}} + \frac{g_m L_s}{C_{gs}} = 8.17 + j117.3$$

$$Z_{in,GaAs} = 6349.2 + j16.4$$

$$L_s = \frac{R_s}{\omega_T}$$

$$\omega 0^2 = \frac{1}{(L_s+L_g)Cgs}$$

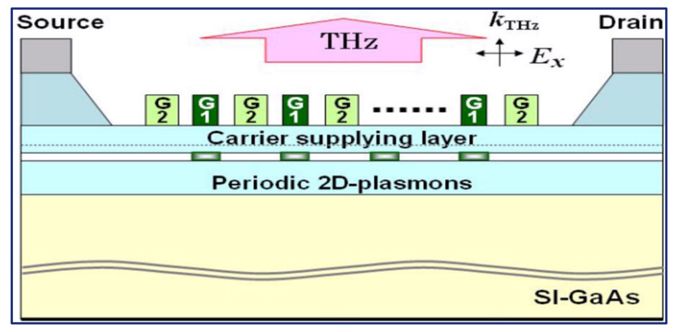
Methodology

A study of several semiconductor materials was done to compare mobility and thermal noise (See Table 1). The equations previously mentioned were used to design LNAs in Si and in GaAs. A comparison of performance was done. A circuit to handle spurious noise, a programmable rank order filter, was designed to sense and filter large magnitude incoming signal. It was simulated in Si. An impedance matching network was designed to couple the antenna with the LNA and to couple the WTAROF.

In this project, the choice of Si as the foundational material for LNA designs is due to its extensive research and widespread use within the electronics industry. After achieving favorable results in S-parameter and noise analysis simulations at room temperature (27°C), the design was transitioned from Si to GaAs. This switch was motivated by GaAs lower noise figure at higher temperatures. Subsequent adjustments were made to optimize the circuit for LNA functionality. After completing S-parameter and noise analysis using the modified GaAs LNA design, the results were compared to the Si circuit.

Material Property	Si	GaAs	InP
Bandgap (eV)	1.12	1.42	1.35
Electron Mobility (cm^2/V-s)	1500	8000	5400
Hole Mobility (cm^2/V-s)	500	400	200
Thermal Conductivity ($W/cm^{-1}L^{-1}$)	1.56	0.46	0.68

Table 1: *Material Properties Comparison of Silicon(Si), Gallium Arsenide (GaAs), and Indium Phosphide (InP).*



Results

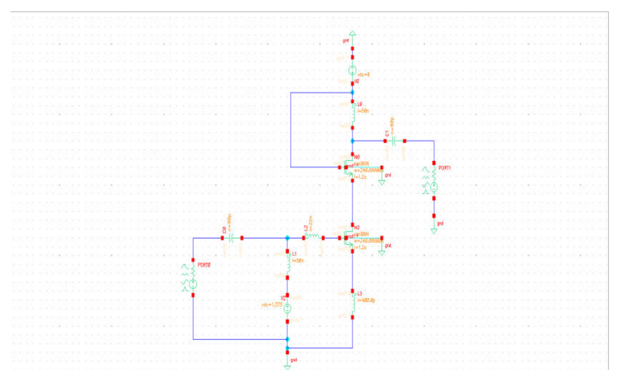


Figure 1: *LNA Design for Si in Cadence using the SNIM optimization technique*

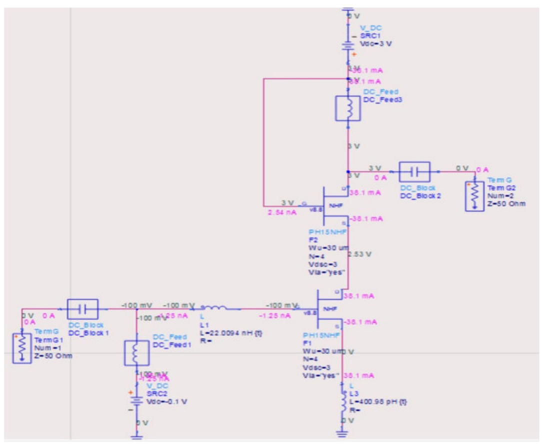


Figure 4: *LNA Design for GaAs in ADS*

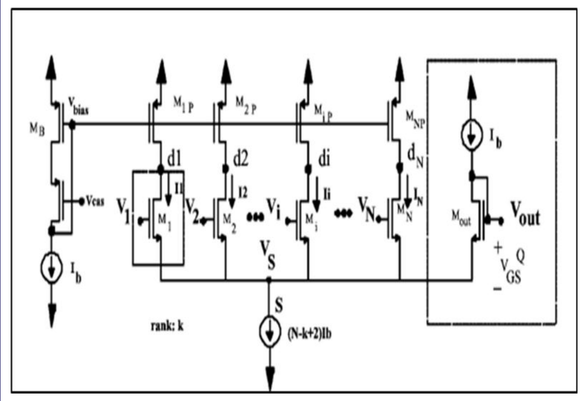


Figure 7: *Schematic circuit of the Programmable Rank Order Filter*

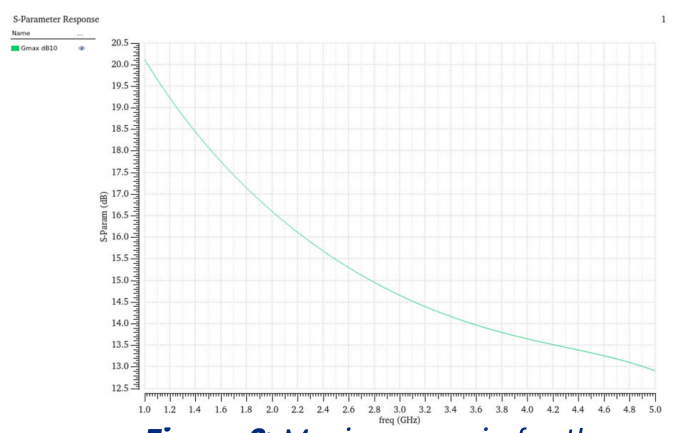


Figure 2: *Maximum gain for the LNA vs Frequency*

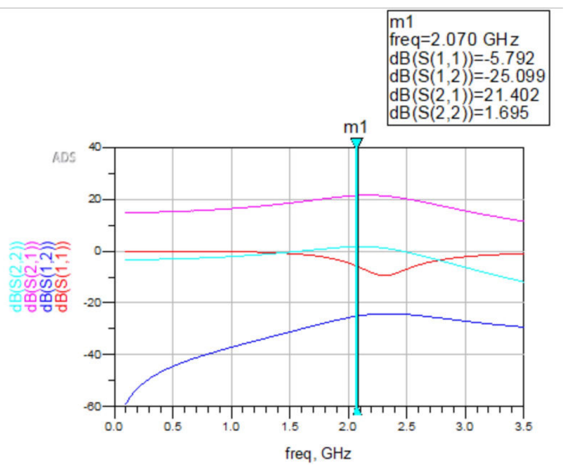


Figure 5: *S Parameters for LNA*

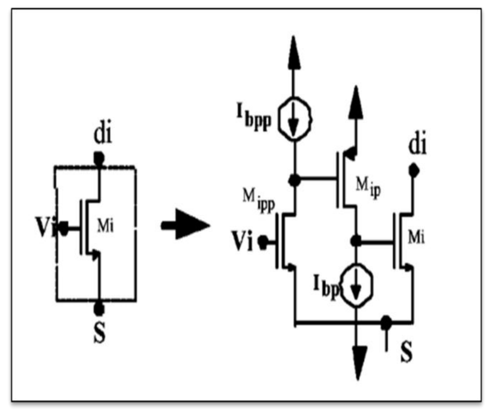


Figure 8: *Replacement of input transistors for supertransistors*

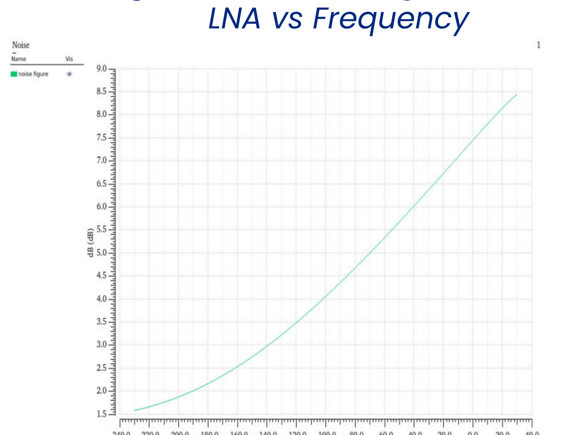


Figure 3: *Noise figure vs Temperature (f=1.7GHz)*

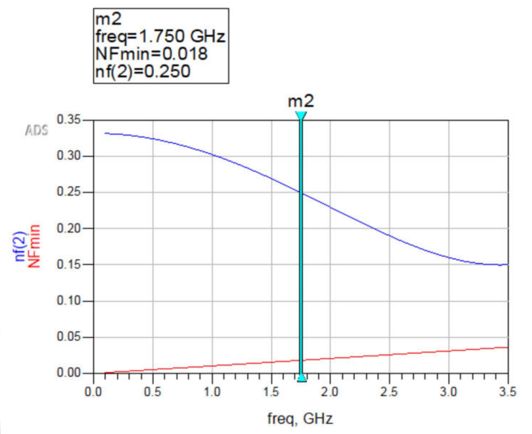


Figure 6: *Noise figure for LNA in GaAs*

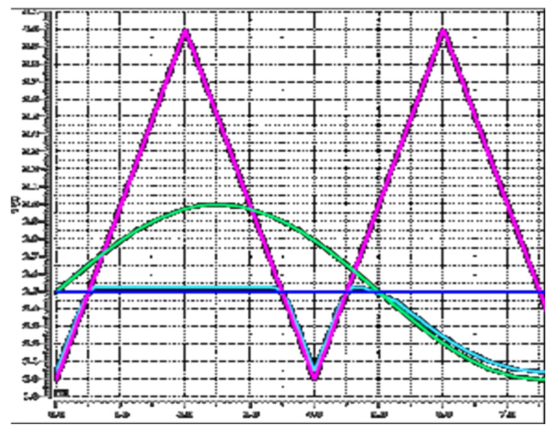


Figure 9: *WTAROF following the lowest order*

LNA Results	*Si*	*GaAs*
Gain	18dB	16.1dB – 21.5B
Operating frequency	1GHz-2.1GHz	1GHz – 2.5GHz
F (Noise Factor)	1.65	1.05
NF (Noise Figure)	2.2dB	**0.25dB**

Table 2: *Comparison of LNA Simulation Results for Silicon (Si), and Gallium Arsenide (GaAs)*

Conclusions

Simulations of a cascoded SNIM in Si (0.6um) and in GaAs (0.15um) shows a degraded performance for Si at the L and S bands. Si simulations presents a higher noise figure than GaAs when compared at the same temperature (27°C). GaAs LNA shows a more stable gain for the frequency range. These preliminary results support the use of HEMTs to reduce cost in cooling when operating sensors for radio astronomy. These results can be extrapolated for higher frequencies.

Spurious noise ideally could be handle by a slope detector and a nulling amplifier. However, the WTAROF circuit shows potential in decreasing saturation downtime.. Thus a WTAROF with LNA could avoid excising at the backend portion of signal detection.

References

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Acknowledgements

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