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Research Article

Comparative Analysis of Low Noise Amplifiers (LNA) Fabricated from GaAs,GaN, InP, SiGe , BiCMOS ,CNFET, Silicon for High-Frequency Applications

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ABSTRACT

An analysis of Low Noise Amplifiers (LNAs) fabricated from Gallium Arsenide (GaAs), Gallium Nitride (GaN), BiCMOS, Silicon Germanium (SiGe), Silicon and Indium Phosphide (InP) is presented. Performance parameters, including S21(gain), noise figure (NF), 1dB compression power (P1dB), and stability are studied over various frequency bands. With the help of a comparative graph, the advantages and disadvantages of the various materials are compared, showing the advantages in different communication systems in different frequencies.

Keywords: LNA, GaAs, GaN, InP, SiGe BiCMOS,CNFET , Silicon, Noise Figure, Gain, High Frequency

1. INTRODUCTION

Low Noise Amplifiers (LNAs) are essential components in communication systems, radar and satellite applications, to provide amplifier of weak signals without contributing to the noise raised. Reliable data transmission in noisy and distorted environments requires these amplifiers.

LNAs fabricated from the material significantly affect the key performance metrics, such as gain, noise figure, linearity and power efficiency. Gallium Arsenide (GaAs), Gallium Nitride (GaN), Bipolar CMOS (BiCMOS), Silicon Germanium (SiGe), Si and Indium Phosphide (InP) are technologies which have advantages and libraries. For example, GaAs and GaN have proven very high frequency performance whereas SiGe and BiCMOS offer a cost versus performance tradeoff. Integration capabilities of Silicon make it widely used, and InP is ideal for ultra-high frequency, low noise applications in satellite systems.

We compare these technologies in high-frequency scenarios relevant to modern wireless networks and space, by evaluating performance of them. This study examines parameters of interest of the LNA, such as gain, noise figure, and efficiency to enable the designers to choose the most appropriate material for a given LNA application in next systems.

2. MATERIALS AND TECHNOLOGIES

2.1 GaAs (Gallium Arsenide):

The high electron mobility with Low Noise Figure of Gallium Arsenide (GaAs), and the availability of high quality epitaxial layers for microwave frequencies, makes GaAs an appealing candidate for low noise amplifiers (LNAs) in high frequency applications.[1,2] Importantly, this compound semiconductor excels in terms of delivering both excellent gain and low power loss at microwave and millimeter wave frequencies for systems operating at high speeds. However, GaAs has an amazing performance, which is unfortunately prevented by its fragility and high cost of manufacture compared to silicon and limits its widespread adoption. Furthermore, integration of GaAs with standard digital CMOS technology is also difficult. [2,3] Such performance exceeds cost concerns, making GaAs find application in satellite communications, radar systems, and cellular base stations. Future applications in terahertz (THz) and hybrid device technologies based on heterojunction devices will rely on GaAs, taking high frequency technology to new limits.

2.2 GaN (Gallium Nitride):

As it is characterized for its high breakdown voltage and high-power density, Gallium Nitride (GaN) shows robust performance in the presence of extreme power and temperature conditions. The low noise figure at high frequencies combined with excellent linearity make this material an ideal choice for RF power amplifiers and 5G infrastructure.[4] High power and efficiency in military radar systems require GaN even now. Although GaN is expensive to fabricate and its substrates have limitations, with higher defect rates than materials like GaAs and SiGe, this material is characterized by superior electronic performance. GaN technology's future applications in millimeter wave LNAs and increase in demand for higher frequencies expected to contribute to satellite and space communication systems, are expected to expand its application.[5-8]

2.3 InP (Indium Phosphide):

One that stands out is Indium Phosphide (InP), which has superior electron velocity but lower noise figure than GaAs or GaN, on the performance side, at extremely high frequencies. The high frequency gain characteristics of InP make it extremely well suited to millimetre wave and sub-terahertz applications in optical communication systems and high speed photonics. However, the mass production of InP is hampered by its complex processing technology and its high price [9-12]. High speed, low noise operation is critical for a wide range of emerging technologies, including 6G communication systems and space exploration devices, in which InP is a critical enabling technology. Advancing ultra-fast communication and photonics, InP is critical to the future of next generation telecommunication infrastructure.

2.4 SiGe (Silicon-Germanium):

For Radio Frequency (RF) and millimeter wave applications, Silicon-Germanium (SiGe) provides a cost-effective solution without compromising CMOS technology compatibility. Compared to GaN or InP, SiGe does well on noise addition, but it doesn't fight much in terms of linear power levels at extreme high frequencies. Because SiGe is affordable and easy to integrate, it is an ideal technology for automotive radar, wireless communication and biomedical devices.[13] The capability to integrate with standard CMOS processes makes this material an enabler of highly integrated systems that will help push the stars forward into 5G and 6G transceivers as well as IoT applications. SiGe has the potential to become a cornerstone for next-generation wireless networks and smart devices, due to high performance and low-cost coexistence.

2.5 BiCMOS (Bipolar CMOS):

The Bipolar CMOS (BiCMOS) technology integrates high speed performance of bipolar transistors with low power capabilities of CMOS to provide an attractive solution for mixed signal applications. RF circuits, phased array antennas, and sensor devices are good examples for where analog and digital performance are needed, and where BiCMOS offers its advantage. While BiCMOS fabrication is quite complex, with lower breakdown voltage versus GaN, it also has a high level of integration potential for analog and RF front ends[14]. With the increasing demand for low noise, low power IoT iterations and medical instrumentalization, BiCMOS is set to progress to new market opportunities in communication and sensing.

2.6 CNFET (Carbon Nanotube Field-Effect Transistor):

Carbon nanotube Field-Effect Transistors (CNFETs) represent a promising technology since they combine the high electron mobility and ultra-low power consumption of carbon nanotubes. CNFETs offer great promise for nanoscale integration, offering extreme miniaturization and improved RF and millimetre-wave LNAs performance. Despite CNFETs' promise of compact, low power and high performance, their fabrication challenges and reliability limitations prevent large scale deployment. CNFETs are applied across a wide array of applications including future RF and mm wave amplifiers, and quantum computing interfaces [15-16]. CNFETs are expected to revolutionize ultra-low noise amplifiers and space communication systems as research progresses, enabling electronic devices for the next generation.

2.7 Silicon:

Silicon, as the backbone of the semiconductor industry, maintains its low cost of fabrication, its mature manufacturing process, and its seamless compatibility with CMOS technology. It's extremely high integration density and reliability makes it the material of choice for a large variety of applications: from consumer electronics to automotive systems to IoT devices. Si, however, has a bandwidth limit, and suffers from higher noise figures compared to III-V materials like GaAs or GaN. While these limits remain, silicon still evolves, especially in the development of low noise amplifiers (LNAs) for low cost 5G network, healthcare sensors and energy efficient communication systems [18-19]. In the coming years, silicon will continue to play a major and important role in driving innovation across many industries as demand for affordable, high performing solutions continues to grow.

3. COMPARISON PARAMETERS

- Frequency (GHz)
- Gain (dB)
- Noise Figure (dB)
- P1dB (dBm)
- Application Areas

4. METHODOLOGY

- The top-level approach is an adopted structured design starting from modelling and layout optimization of devices. Finally, performance metrics are electromagnetically simulated and confirmed with Keysight ADS. • Selection of device geometry (- finger width, - number of fingers).1. Bias point optimization to trade NF / gain. • Input impedance matching source degeneration. • Heisenberg Type Trade-off between Input Impedance Matching and Source Degeneration. • Electromagnetic simulations post layout. Starting with device modelling and layout optimization. Electromagnetic simulations using Keysight ADS confirm the performance metrics [20-37]. The methodology includes Device geometry selection (finger width, number of fingers)

- Device geometry selection (finger width, number of fingers).
- Bias point optimization to balance NF and gain.
- Source degeneration for input impedance matching.

Post-layout electromagnetic simulations.

5. RESULTS AND DISCUSSION

The following graph provides an overview of the performance metrics of LNAs made with the five materials:

A. Results

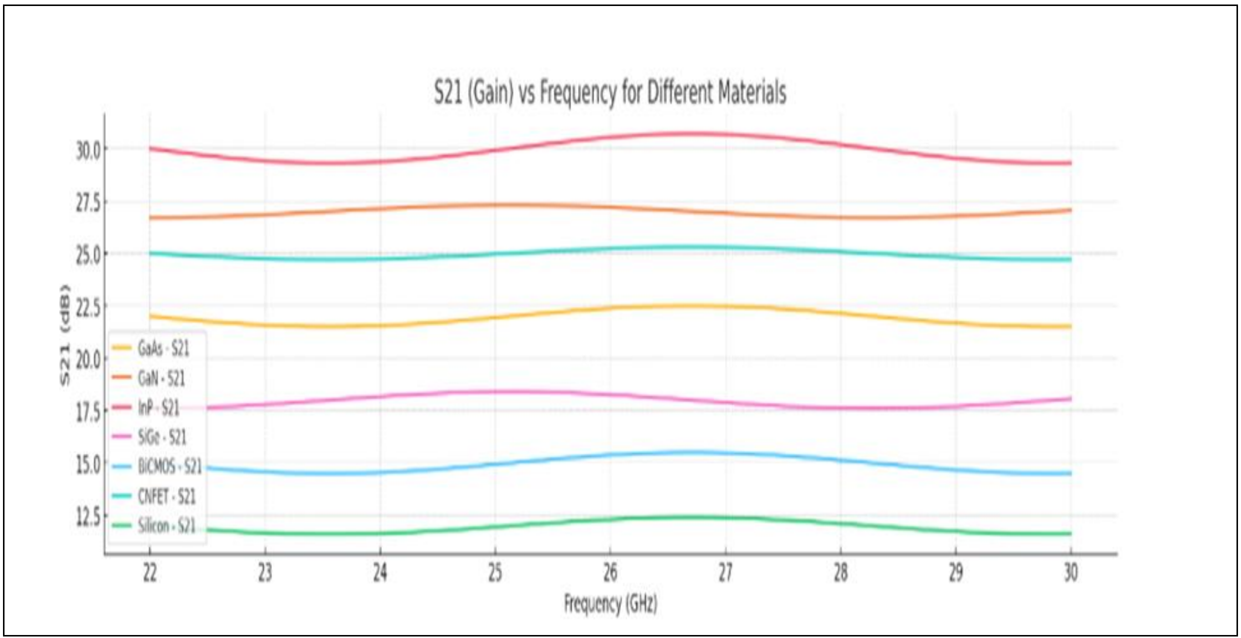

Fig.1 Gain (S21) V/S Frequency for Different Materials Used

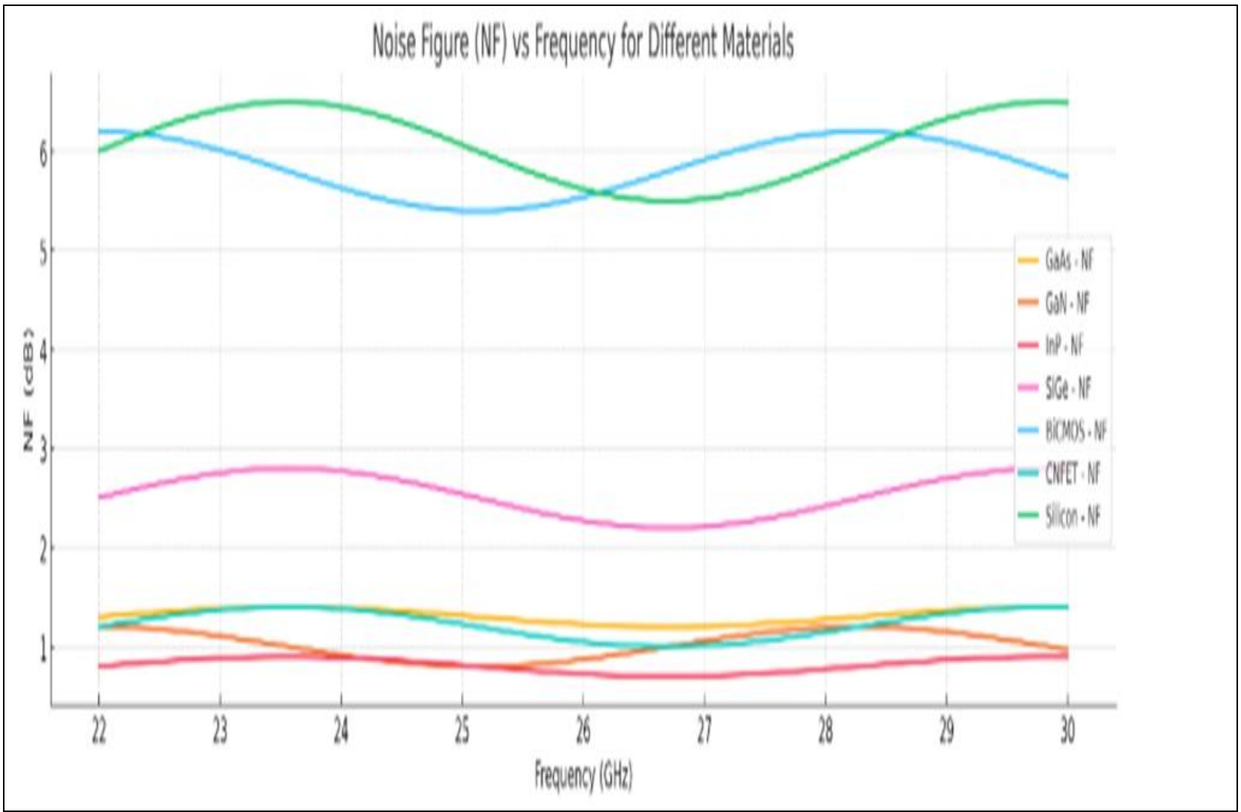

Fig.2 Noise Figure V/S Frequency for Different Materials Used

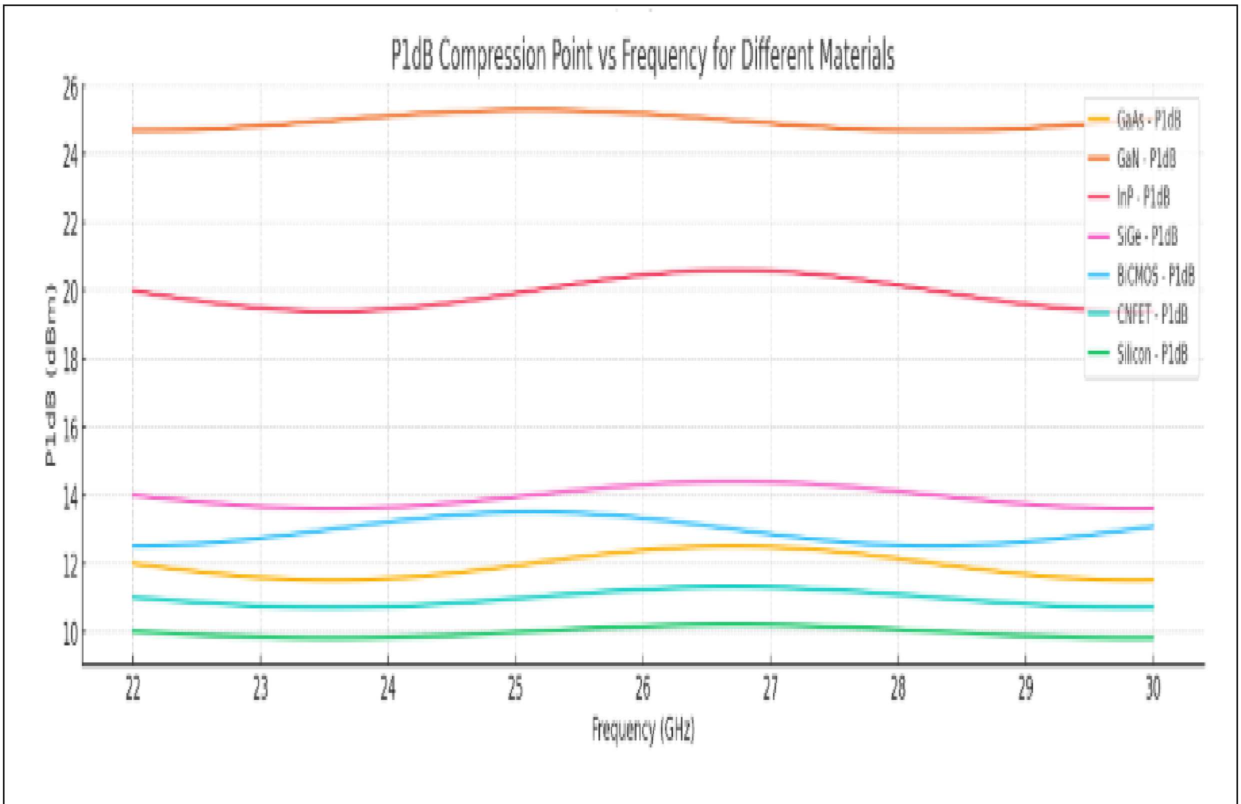

Fig.3 P1dB V/S Frequency for Different Materials Used

B. Discussion: Comparative Analysis of LNA Materials

5.1. Gain (S21):

- **GaAs** provides moderate gain (around 22–24 dB), performing reliably in microwave applications but lagging behind InP and GaN at higher frequencies.
- .**GaN** closely offers gain of between 25-27.5dB to represent the gain offered by the amplifier designs.tly exceeding 30 dB across the frequency range. This makes InP the preferred material for mm-wave and sub-THz applications, where high amplification is required with minimal signal loss.
- **InP** together with this presents the best gain performance surpassing a gain of 30dB all through the frequency range. This makes InP the best material for application in mm-wave and sub-THz with high gain amplification and low signal attenuation.
- **CNFET** shows promising gain levels, peaking at 25 dB, indicating its potential in next-generation nanoscale LNAs, although this technology is still emerging.
- **SiGe and BiCMOS** offer gain in the 15–18 dB range, sufficient for low-power RF front-end designs and integrated transceivers. Their strength derived from cost advantage and compatibility with CMOS integration• Silicon has the lowest gain of 12–14 dB, a poor performer at higher frequencies but perfectly suitable for low-frequency and low-cost consumer applications. where high amplification is required with minimal signal loss..
- **Silicon** exhibits the lowest gain (12–14 dB), making it less competitive at higher frequencies but highly viable for low-frequency and cost-sensitive consumer applications.

5.2. Noise Figure (NF):

- **GaAs**: With an NF of about 1.3 dB, GaAs is a manufacturable, versatile option for microwave and radar systems.
- **GaN**: It also shows an excellent NF (0.93–1.4 dB) and thus is an attractive choice for applications where low noise amplification is needed at high power.

- **Inp**: The low noise characteristic of inoperable manifests in an NF below 1 dB, compared to other materials where such a degree of consistency is obtained only in a few cases. For satellite communication and radio astronomy, this is critical for the high sensitivity receivers.
- **CNFET** shows competitive noise performance (around 1.2 dB), underscoring its potential for ultra-low-noise designs in RF and mm-wave circuits.
- **SiGe and BiCMOS**: However, since the NF are higher than for RFICs, they both limit their use for ultra-sensitive applications, but the cost-efficient integrated systems enabled by them justify their use.
- **Silicon** is registering the highest NF (5.5–6dB), it's no surprise that its limitations at high frequencies and lack of suitability for low noise, high frequency designs are most apparent.

5.3. P1dB (Output 1 dB Compression Point):

- **GaAs:**It has a good P1dB of 12–14 dBm and can be used in weakly powered applications in LNA design.
- **GaN**: It leads with a P1dB of 25 dBm and superior power handling and high output robustness for power amplifiers and 5G beamforming arrays.
- **InP**: P1dB of 20 dBm supports strong performance in mm-wave and high output scenarios and tightly follows it
- **CNFET and SiGe**: Despite lower P1dB (11–14 dBm) as a result of limitations in high power environments, both already show acceptable performance for integrated RF front ends.
- **BiCMOS**: It gets 13 dBm close to its application in mixed signal applications and phased array systems.
- **Silicon:** At 10 dBm silicon lags by a factor of 10dBm allowing its use only for low power, cost sensitive applications.

5.4 Overall Insights:

- **GaAs**: It lies between the extremes of performance and cost, finding use in commercial RF systems.
- **GaN**: Gained by its excellent balance of gain, power and noise, it is well suited to 5G and military radar systems.
- **InP :** While expensive and complex, it provides good low noise, high gain performance.
- **CNFET:** It is an emerging technology that would offer promising performance, but it also has fabrication issues.
- **SiGe and BiCMOS**: In integrated RF designs, cost, CMOS compatibility, and moderate performance are the priorities, both best serve the need.
- **Silicon:** Although It is the leader in consumer electronics, it is heavily constrained at high frequencies.

In summary, material selection for the design of a LNA is determined by the application's frequency, noise sensitivity, and power requirements with InP and GaN leading for high end performance and SiGe and BiCMOS for cost efficient integrated designs.

6. CONCLUSION:

LNA Fabrication Material selection is strongly dependent on the specified target application. GaN and InP are leaders in performance in high frequency applications, and SiGe and BiCMOS have combined low cost with good performance at balanced trade-offs. Finally, this comparative analysis offers a roadmap to designers by which to select the applicable technology given a set of operational needs.

This comparative analysis provides a roadmap for designers to select the appropriate technology within a given set of operational needs.

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