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Review of FinFET Technology for Low-Power 5G mmWave Applications

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ABSTRACT: In recent years, FinFET technology has emerged as a critical solution to meet the high-performance and low-power requirements of 5G millimetre-wave (mmWave) applications. This paper provides an extensive review of FinFET advancements, with a particular focus on the Extremely-Low Threshold Voltage (ELVT) FinFET. Developed to address the unique challenges of 5G applications, ELVT FinFETs are optimized for reduced power consumption and enhanced current efficiency through precise doping and process integration techniques. By comparing ELVT FinFETs with their Super-Low Threshold Voltage (SLVT) counterparts, we explore how threshold voltage adjustments influence key performance metrics such as on-state current (IDSAT), effective drive current (IEFF), frequency gain (FT, FMAX), and device reliability. Experimental and simulation data are analysed to highlight the ELVT FinFET's ability to reduce supply voltage requirements by approximately 9% and power consumption by 8%, without sacrificing critical RF parameters like phase noise in circuit-level applications. Additionally, the device's resilience to Bias Temperature Instability (BTI) and Hot Carrier Injection (HCI) stress is evaluated, demonstrating comparable or improved reliability relative to SLVT devices. This comprehensive review further examines ELVT FinFET's suitability for various 5G transceiver components, specifically focusing on Local Oscillator (LO) chain and Transmission Line (TL) driver applications. By synthesizing these insights, this paper positions ELVT FinFET technology as a powerful candidate for energy-efficient, low-power 5G mmWave applications, bridging the gap between scalability demands and performance requirements in next-generation wireless communication networks.

KEYWORDS: 5g mmWave, mmWave applications, FinFet technology, RF & LC oscillators

I.INTRODUCTION

The evolution of wireless communication technologies has led to the rapid development of the fifth-generation (5G) standard, designed to meet the growing demand for high-speed data transfer, low latency, and massive device connectivity. Unlike previous generations, 5G utilizes both sub-6 GHz and millimetre-wave (mmWave) frequency bands, with mmWave offering extraordinary bandwidth potential for data-intensive applications. However, operating in these higher frequency bands poses significant challenges for power efficiency, device scalability, and signal integrity, creating an urgent need for advanced semiconductor technologies that can reliably meet these rigorous demands.

In this context, FinFET (Fin Field-Effect Transistor) technology has gained attention as a scalable solution that supports the high-frequency operation and low-power requirements critical to 5G mmWave devices. FinFETs have a three-dimensional gate structure that enhances electrostatic control over the channel, reducing leakage currents and short-channel effects compared to traditional planar CMOS transistors. By leveraging these structural advantages, FinFETs are particularly suited for RF applications where power efficiency, frequency response, and device reliability are paramount. Recent advancements in FinFET architectures, such as Extremely-Low Threshold Voltage (ELVT) FinFET, have further enhanced the technology's applicability in the realm of 5G by optimizing power performance while maintaining high frequency and reliability standards.

ELVT FinFETs are specifically engineered to achieve lower threshold voltages, enabling them to operate at reduced supply voltages while maintaining or even improving current drive capabilities. Through carefully controlled doping of the channel and halo regions, ELVT FinFETs offer approximately 15% improvement in effective drive current (IEFF)

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compared to their Super-Low Threshold Voltage (SLVT) counterparts, making them well-suited for low-power applications that demand both high efficiency and minimal power dissipation. Moreover, with threshold voltages optimized to around 90mV for NFETs and 70mV for PFETs, ELVT FinFETs are capable of achieving superior on-state current (IDSAT) and operating at near-threshold conditions, thereby addressing the battery-life concerns associated with portable 5G devices.

The advantages of ELVT FinFETs are not limited to power efficiency. Their robust high-frequency performance, characterized by favourable metrics like cutoff frequency (FT) and maximum oscillation frequency (FMAX), underscores their potential for high-frequency applications. Although ELVT FinFETs exhibit a slight reduction in peak FT and FMAX compared to SLVT FinFETs (approximately 5% and 10%, respectively), their performance at lower bias points remains advantageous, supporting the low-voltage operation typical of wearable and portable devices.
This paper presents an extensive review of ELVT FinFET technology as it applies to 5G mmWave applications. By synthesizing findings from multiple studies, the review examines critical aspects of ELVT FinFET design, including threshold voltage optimization, DC and RF performance metrics, and reliability under operational stress. Comparative analyses are drawn between ELVT and SLVT FinFETs, highlighting how process modifications in ELVT FinFETs, such as channel doping adjustments, impact their performance across a range of metrics. Additionally, this paper explores the practical application of ELVT FinFETs in key components of 5G transceivers, such as Local Oscillator (LO) chains and Transmission Line (TL) drivers, where power efficiency and frequency stability are essential.

II.METHODOLOGIES USED

The methodologies employed in evaluating the performance and reliability of ELVT FinFETs for 5G mmWave applications cover a range of fabrication processes, device-level measurements, simulation techniques, and circuit-level benchmarking. These methodologies are structured to provide an accurate and detailed comparison between ELVT and SLVT FinFETs across critical performance metrics such as threshold voltage, current efficiency.

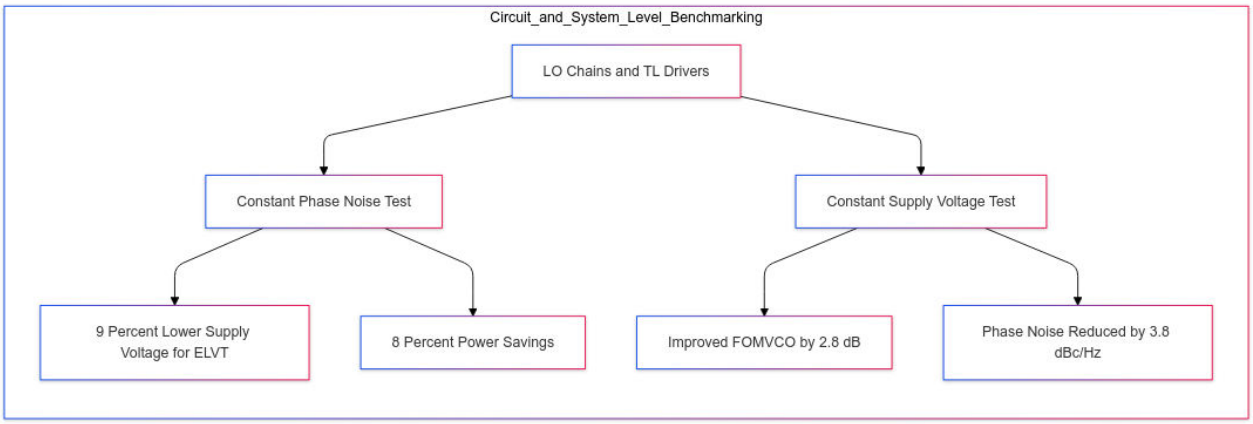

Figure1. Circuit and system level benchmarking

2.1 Device Fabrication and Process Optimization:

ELVT and SLVT FinFETs were fabricated using a 12nm node technology platform, specifically designed to achieve distinct threshold voltages for low-power applications. ELVT FinFETs undergo optimized channel/halo doping adjustments, which reduce the threshold voltage (VTH) by approximately 90mV for NFETs and 70mV for PFETs, as compared to SLVT FinFETs. This process does not require additional masking steps, thus maintaining cost-efficiency. Doping adjustments are carefully controlled to ensure minimal impact on device electrostatics, preventing potential deterioration in the drive current and leakage characteristics. These optimizations allow ELVT FinFETs to achieve high current efficiency at lower voltages, essential for battery-powered 5G devices.
Cross-sectional imaging techniques, such as transmission electron microscopy (TEM), were employed to confirm the structural integrity and profile of the FinFET channels and fins.

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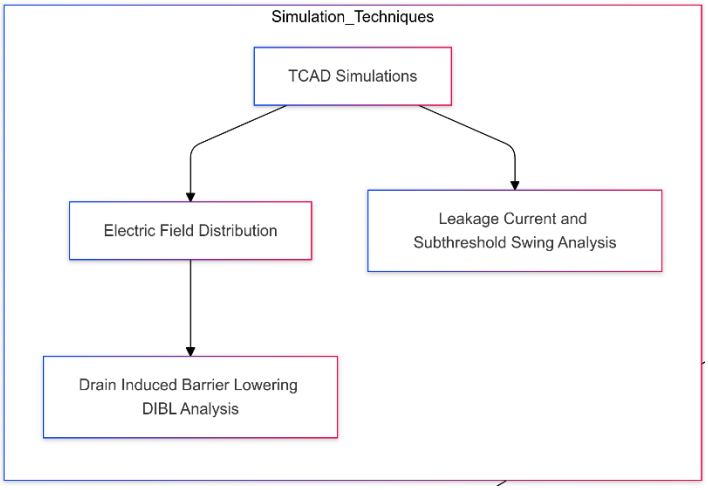

Figure2. Simulation Techniques

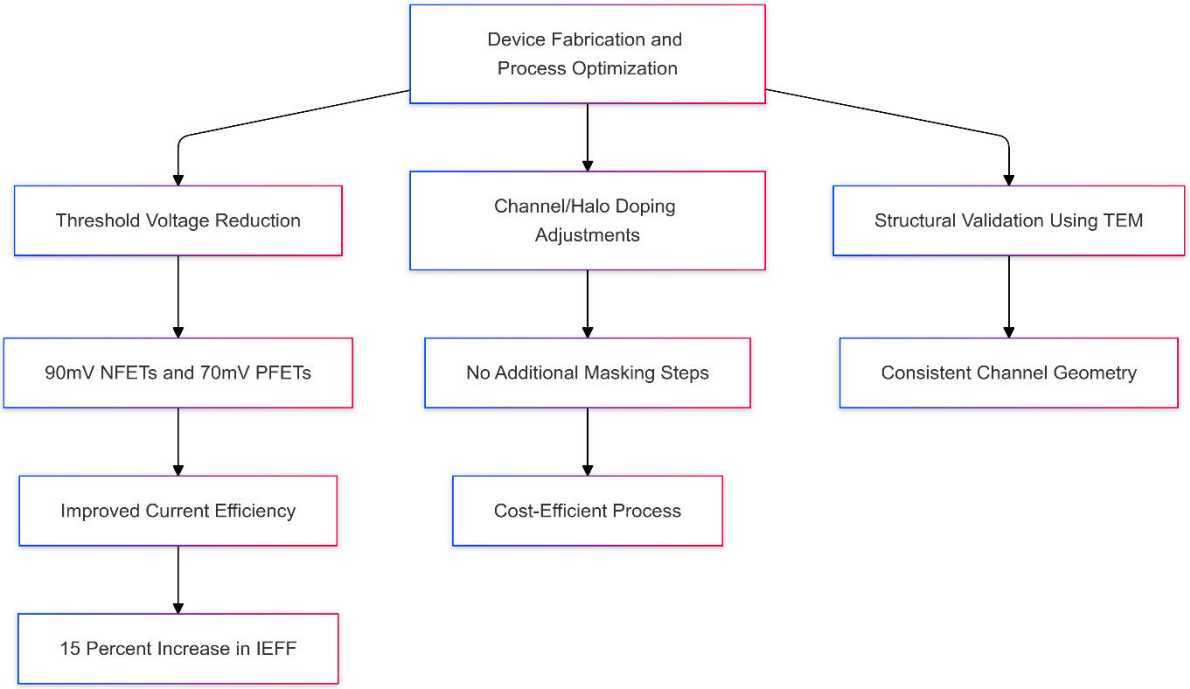

Figure3. Device Fabrication and process optimization

2.2 Performance Metrics and Characterization Techniques:

To accurately assess the DC and RF performance, several key parameters were measured, including the on-state current (IDSAT), effective drive current (IEFF), cutoff frequency (FT), and maximum oscillation frequency (FMAX). IDSAT and IEFF are particularly important for evaluating current efficiency, while FT and FMAX are indicators of a device's frequency response capability.

Output and transfer characteristics were recorded for both ELVT and SLVT devices under a range of biasing conditions to quantify how each device responds to varying voltages. These measurements provide insight into the effect of threshold voltage on the current drive capability and overall efficiency of the devices. FT and FMAX were determined through S-parameter measurements, which were conducted over a frequency range of 1-50 GHz, employing open-short de-embedding techniques to remove pad and interconnect parasitics. This process ensures an accurate representation of intrinsic device performance, isolating the effects of the device structure and threshold adjustments.

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Two scenarios were tested: constant phase noise and constant supply voltage. In the constant phase noise scenario, the supply voltage for both ELVT and SLVT TL drivers was adjusted to achieve an identical phase noise level, revealing that the ELVT-based driver could operate with approximately 9% lower supply voltage and consume 8% less power than the SLVT driver. In the constant supply voltage scenario, the ELVT TL driver exhibited improved VCO figure of merit (FOMVCO) by approximately 2.8dB at 1 MHz offset frequency, demonstrating a reduced phase noise by around 3.8 dBc/Hz relative to SLVT designs. These experiments confirmed the superior power efficiency of ELVT FinFETs at the circuit level, underlining their value for power-sensitive 5G transceiver applications.

III. RESULTS AND DISCUSSIONS

3.1 Reliability under Bias Temperature Instability (BTI) and Hot Carrier Injection (HCI):
The reliability of ELVT FinFETs was tested through BTI and HCI stress tests. Both tests assessed how ELVT and SLVT devices behaved under prolonged operational conditions, a crucial factor for 5G applications that require stable long-term performance. In BTI tests, which measure degradation due to charge trapping in the gate dielectric, ELVT FinFETs demonstrated similar or improved performance compared to SLVT counterparts. HCI tests, which focus on device degradation caused by high-energy carriers impacting the interface quality, also showed comparable or slightly improved performance for ELVT devices.
These results suggest that ELVT FinFETs, despite the reduction in threshold voltage, maintain robustness under stress, making them reliable for RF applications where thermal and electrical stresses are frequent. This stability is essential for 5G transceivers, where consistent performance and minimal degradation over time are expected (Figure 3).

3.2 DC and RF Performance:
ELVT FinFETs exhibited strong DC performance metrics. For instance, the IDSAT and IEFF values for ELVT devices were consistently higher across various biasing conditions, demonstrating superior current delivery at lower voltages compared to SLVT FinFETs. This enhanced current efficiency is crucial for high-frequency applications, where efficient power management is necessary to support prolonged operation.

In terms of RF performance, ELVT FinFETs maintained favourable metrics, although they exhibited a slight reduction in peak cutoff frequency (FT) and maximum oscillation frequency (FMAX) by approximately 5% and 10%, respectively, compared to SLVT FinFETs. These reductions are attributed to the impact of counter-doping on channel and overlap capacitances. Despite this slight decline in peak values, ELVT FinFETs outperformed SLVT devices at near-threshold bias points, a feature that is beneficial in wearable and low-power IoT applications.

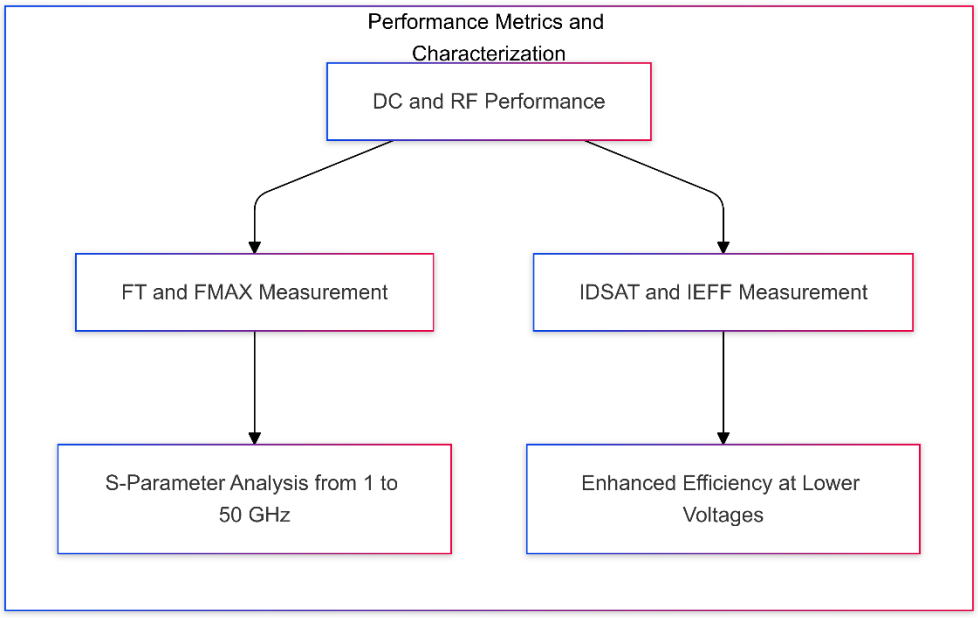

Figure4. Performance metrics and characterization

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3.3 Threshold Voltage and Current Efficiency:

The threshold voltage (VTH) reduction achieved in ELVT FinFETs was significant, with NFETs and PFETs displaying VTH reductions of approximately 90mV and 70mV, respectively. This reduction enabled the ELVT devices to deliver enhanced current efficiency, with an increase in effective drive current (IEFF) of about 15% compared to SLVT FinFETs. Lower threshold voltages are beneficial for reducing overall power consumption, as they allow ELVT FinFETs to operate at reduced supply voltages while achieving comparable or improved on-state current (IDSAT) levels relative to SLVT devices. This boost in current efficiency is particularly advantageous in low-power applications such as portable 5G devices, where battery life and energy consumption are critical factors.

Table1. Comparison of all the proposed methodologies

Parameter	ELVT FinFET	SLVT FinFET	Comparison/Impact
Threshold Voltage (VTH)	NFET: ~90mV; PFET: ~70mV	Higher than ELVT	ELVT achieves lower VTH, enabling reduced supply voltage and improved power efficiency.
Effective Drive Current (IEFF)	15% higher	Baseline	ELVT delivers superior current efficiency, crucial for battery-powered 5G devices.
On-State Current (IDSAT)	Higher across all biasing conditions	Baseline	Enhanced current delivery at lower voltages supports energy-efficient designs.
Cutoff Frequency (FT)	~5% lower than SLVT	Baseline	Slight reduction due to doping but sufficient for low-voltage applications.
Maximum Oscillation Frequency (FMAX)	~10% lower than SLVT	Baseline	Marginal trade-off in high-frequency performance offset by power efficiency gains.
Power Consumption	~8% lower in TL drivers	Baseline	ELVT consumes less power, ideal for wearable and portable 5G applications.
Supply Voltage Requirement	~9% lower in LO chain applications	Baseline	Reduced supply voltage improves energy efficiency without sacrificing performance.
Phase Noise (LO Chain)	~3.8 dBc/Hz reduction	Baseline	ELVT exhibits better phase noise performance, critical for RF stability.
FOMVCO (TL Driver)	~2.8 dB improvement	Baseline	Improved figure of merit confirms ELVT's suitability for high-frequency applications.
Reliability under BTI	Comparable or slightly better	Baseline	ELVT demonstrates robust reliability under prolonged stress conditions.
Reliability under HCI	Comparable or slightly better	Baseline	ELVT maintains stable performance under high-energy carrier impacts.

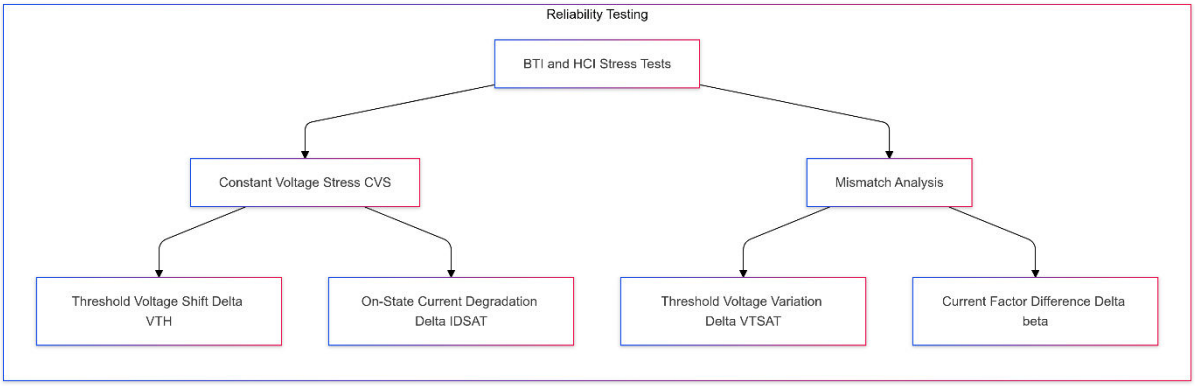

Figure5. Reliability Testing

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IV.CONCLUSION

The rapid expansion of 5G mmWave applications and the demand for high-speed, high-frequency communications have underscored the necessity for energy-efficient and reliable semiconductor technologies. In response to these requirements, ELVT FinFET technology, based on a 12nm node platform, represents a significant advancement in the design of low-power RF transistors. This paper has reviewed ELVT FinFET in-depth, assessing its superior performance in threshold voltage control, current efficiency, and RF metrics relative to SLVT FinFETs. The comparative analysis illustrates that through targeted channel/halo doping modifications, ELVT FinFET achieves lower threshold voltages, resulting in approximately 15% higher IEFF, while maintaining competitive reliability standards across BTI and HCI tests. Importantly, ELVT FinFET devices maintain high performance even under near-threshold voltage conditions, making them exceptionally well-suited for battery-powered 5G applications where power efficiency is paramount.

At the circuit level, the use of ELVT FinFET in LO chains and TL drivers reveals that power consumption can be significantly reduced—by approximately 8%—while maintaining equivalent or improved phase noise levels. This reduction is achieved without additional mask steps or substantial cost increases, underscoring ELVT's value proposition for cost-effective 5G integration. Furthermore, with demonstrated resilience against device degradation and robust performance across DC/RF benchmarks, ELVT FinFET offers a scalable, reliable solution for the diverse needs of 5G transceivers.

In summary, the integration of ELVT FinFET technology into 5G systems aligns well with the goals of modern RF design, providing high efficiency, minimized power loss, and durability under operational stresses. While the current advancements in ELVT FinFET establish it as a superior alternative to SLVT FinFET for low-power applications, ongoing research into further reducing gate resistance and optimizing frequency response will expand its applicability. Looking forward, ELVT FinFET technology is poised to drive significant innovations in energy-efficient 5G transceivers, supporting the development of robust, low-power, high-performance wireless communication systems that meet the rigorous demands of next-generation technology.

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