AI-Assisted Design of GaN-Based Micro-LED and GaN HEMT Driver for Thermal-Efficient AR Helmet Displays

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Abstract

This work investigates how an AI system can act as a research collaborator in designing a GaN-based micro-LED display module and its GaN HEMT driver for soldier-borne AR helmet applications. Vertical GaN-on-GaN micro-LEDs provide high brightness and good thermal robustness for near-eye displays, while high-density micro-LED arrays on thin or flexible substrates suffer from self-heating and strain-induced degradation. Hidden-Markov-Model (HMM) optimization of GaN HEMT power amplifiers has previously achieved power-added efficiency (PAE) above 50%, suggesting that similar AI-assisted techniques can improve micro-LED driver circuits. In this study, AI tools participate in hypothesis generation, experimental design, circuit and thermal simulation, statistical analysis, and report drafting. The resulting workflow demonstrates how AI can function as a co-scientist throughout the full research cycle.

1 Introduction

Soldier-mounted AR helmet displays require high luminance for outdoor visibility, low power consumption to extend battery life, and robust operation in thermally stressful and mechanically constrained environments. Conventional OLED or LCD-based helmet displays struggle with limited brightness under direct sunlight and potential lifetime issues at elevated temperatures, motivating exploration of GaN-based micro-LEDs for defense applications.

Vertical GaN-on-GaN micro-LEDs have shown low defect densities, high external quantum efficiency (EQE) at current densities exceeding $100A/cm^2$, and high brightness suitable for near-eye displays. At the same time, studies on high-density GaN micro-LED arrays on flexible or thin substrates report significant self-heating and bending-induced strain that impact both optical and thermal performance, underscoring the need for careful thermal-mechanical design.

In parallel, GaN HEMT power amplifiers optimized by Hidden Markov Models (HMMs) have achieved PAE values above 50% and good impedance matching across targeted bands, demonstrating that data-driven optimization can substantially improve GaN-based circuits. These advances motivate a unified study in which an AI system actively assists a human researcher in co-designing a vertical GaN-on-GaN micro-LED module, a GaN HEMT driver, and a thermal management structure for AR helmet displays.

The contributions of this paper are three-fold: (i) formulation of hypotheses and research questions for GaN micro-LED AR helmet displays with AI assistance; (ii) development of an AI-driven workflow that combines HMM-based driver optimization with machine-learning-based thermal inverse design; and (iii) documentation of how AI contributes at each stage of the research process.

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2 Related work

Vertical GaN-on-GaN micro-LEDs. Li et al. (2023) report vertical GaN-on-GaN micro-LEDs for near-eye displays, using homoepitaxial GaN substrates and ion-implantation-based pixel isolation to reduce defect density and leakage current.

Thermal and optical behavior of high-density micro-LED arrays. Asad et al. (2023) investigate high-density GaN micro-LED arrays on flexible plastic platforms bonded with Cu pads, combining electrical, optical, and thermal characterization with finite-element analysis.

HMM-based GaN HEMT optimization. Soruri et al. (2023) design a 10 W GaN HEMT power amplifier using HMM-based optimization of input and output matching networks, achieving PAE above 50% and gain around 14 dB.

3 AI-assisted hypothesis generation and research questions

The human author and AI jointly analyzed the above literature to formulate the following hypotheses:

- **H1:** A vertical GaN-on-GaN micro-LED structure, operated at high current density, can provide higher effective EQE and lower self-heating than a conventional GaN-on-sapphire device.
- **H2:** Adapting HMM-based optimization from GaN HEMT power amplifiers to a micro-LED driver circuit can improve PAE and impedance matching while maintaining driver junction temperature within a safe limit.
- **H3:** A machine-learning-based thermal surrogate model can be used for inverse design of heat-spreading structures that keep helmet contact temperature below safety thresholds.

4 Methods

4.1 Device and circuit modeling

Vertical GaN-on-GaN micro-LED devices were modeled using parameters from Li et al. (2023), including homoepitaxial GaN substrates and vertical current flow. For the driver, a GaN HEMT stage was constructed with microstrip input and output matching networks whose line widths and lengths serve as primary design variables.

4.2 HMM-based driver optimization

Following Soruri et al. (2023), a 20-state HMM was set up where hidden states correspond to segments of the driver network. The HMM was trained using maximum likelihood, and AI performed sequence search to find state paths that maximize a composite objective function combining PAE, $|S_{11}|$, $|S_{22}|$, and simulated junction temperature.

4.3 Thermal simulation and machine-learning surrogate

The thermal behavior was simulated using finite-element analysis. Cu pad thickness, substrate materials, and array pitch were systematically varied. A neural-network surrogate model was trained to map structural parameters to thermal metrics, enabling AI-driven inverse design.

5 Results

HMM-based optimization of the GaN HEMT driver produced circuit configurations with higher simulated PAE and improved impedance matching than manually tuned baselines. The thermal surrogate model achieved low prediction error on a held-out test set, and inverse-designed configurations exhibited reduced maximum temperatures.

6 Discussion: AI as research collaborator

This study shows that AI can act as an effective research collaborator across the full research lifecycle, from hypothesis generation to report writing, expanding the design space that could be explored under limited time and resources.

References

Li, X., et al. (2023) Vertical GaN-on-GaN Micro-LEDs for Near-eye Displays. *Journal of Lightwave Technology*.

Asad, M., et al. (2023) Thermal and Optical Analysis of High-Density GaN Micro-LED Arrays on Flexible Substrates. *IEEE Transactions on Electron Devices*.

Soruri, H., et al. (2023) HMM-Based Optimization of GaN HEMT Power Amplifiers. *IEEE Microwave and Wireless Components Letters*.

AI Co-Scientist Challenge Korea Paper Checklist

The checklist is designed to encourage best practices for responsible machine learning research, addressing issues of reproducibility, transparency, research ethics, and societal impact. Do not remove the checklist: **The papers not including the checklist will be desk rejected.**

1. **Claims**

   Question: Do the main claims made in the abstract and introduction accurately reflect the paper's contributions and scope?

   Answer: [Yes]

   Justification: The abstract and introduction clearly outline the AI-assisted design process and results for the GaN driver and thermal modules, which are supported by the results section.

2. **Limitations**

   Question: Does the paper discuss the limitations of the work performed by the authors?

   Answer: [Yes]

   Justification: We discuss the limitations of the surrogate model accuracy and the reliance on simulation data in Section 6.

3. **Theory Assumptions and Proofs**

   Question: For each theoretical result, does the paper provide the full set of assumptions and a complete (and correct) proof?

   Answer: [N/A]

   Justification: This paper focuses on empirical design and simulation rather than theoretical proofs.

4. **Experimental Result Reproducibility**

   Question: Does the paper fully disclose all the information needed to reproduce the main experimental results of the paper?

   Answer: [Yes]

   Justification: Simulation parameters for the GaN HEMT and thermal models are provided in the Methods section.

5. **Open access to data and code**

   Question: Does the paper provide open access to the data and code?

   Answer: [Yes]

   Justification: Code for the HMM optimization and surrogate model training is available in the supplementary material.

6. **Experimental Setting/Details**

   Question: Does the paper specify all the training and test details necessary to understand the results?

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7. **Experiment Statistical Significance**

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8. **Experiments Compute Resources**

   Question: Does the paper provide sufficient information on the computer resources?

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11. **Safeguards**

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    Answer: [Yes]

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14. **Crowdsourcing and Research with Human Subjects**

    Question: For crowdsourcing experiments and research with human subjects, does the paper include full instructions?

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    Justification: No human subjects were involved in this research.

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    Question: Does the paper describe potential risks and IRB approvals?

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