University of Leeds
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ELEC5870M Interim Report

Fabrication of Enhancement Mode pHEMT Devices via Gate Recession

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Abstract

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CHAPTER 1

Introduction

1.1 Context and Motivation

Modern electronic and communication systems impose increasingly demanding requirements on the devices that form their signal paths. Higher carrier frequencies, lower permissible noise levels, stricter linearity constraints and improved power efficiency are now expected. At the device level, these system requirements manifest as targets for cut-off frequency, noise figure, gain and power handling that conventional silicon technologies cannot always achieve.

High-electron-mobility transistors meet many of these system requirements through the use of a carefully engineered heterojunction, which is the interface between two semiconductor materials with different band structures. This band discontinuity causes electrons to collect in a very thin region at the heterojunction, creating a highly mobile sheet of charge carriers known as a two-dimensional electron gas (2DEG). The key advantage of this arrangement is that the 2DEG forms without the need to place donor atoms directly in the conduction path. In contrast to MESFETs, where electrons move through a doped channel, the absence of ionised impurities in a HEMT channel greatly reduces Coulomb scattering [1]. As a result, electrons can move more freely, giving the device high mobility, high transconductance and predictable behaviour at high frequencies. These characteristics allow HEMTs to operate reliably across a broad frequency range, typically from around 1 GHz to beyond 100 GHz [2], making them well suited to low-noise amplifiers, receiver front ends and other high-frequency subsystems.

Within this context, it is necessary to understand how the structure and processing of III–V HEMTs influence their electrical behaviour. Practical device performance is shaped not only by the underlying material system, but also by the fabrication steps used to define the channel, contacts and gate. Engaging directly with these processes provides a clearer view of how device characteristics emerge from both design and implementation. This interim report therefore introduces the key principles that underpin HEMT operation and presents the fabrication and analysis of GaAs-based pseudomorphic III–V HEMT devices produced during the first phase of the project.

1.2 Importance of III–V HEMTs

III–V compound semiconductors play a central role in enabling the performance characteristics associated with HEMT devices. Materials such as GaAs, InP and GaN possess band structures and carrier transport properties that support high-frequency operation, low noise and, in some cases, high power density. [2] Their relatively low effective electron mass and favourable mobility characteristics provide a foundation for transistor behaviour that is difficult to achieve with silicon CMOS or SiGe bipolar processes over the same frequency range. [?]

The heterostructure engineering available within III–V systems allows precise control over carrier confinement, channel composition and interface quality. By separating charge carriers from their parent dopants, these structures sustain mobility values that directly translate into high transconductance and improved gain at microwave frequencies. As a result, III–V HEMTs continue to serve key functions in low-noise receivers, high-frequency amplifiers and specialist instrumentation.

1.3 Current Landscape and Relevance

Although silicon RF technologies have progressed significantly, particularly in CMOS and SiGe BiCMOS platforms, III–V HEMTs remain important in domains where the highest noise performance, highest frequency operation or highest power density are required. Their continued use in satellite communication payloads, microwave backhaul links, scientific instrumentation and radar receivers reflects the practical advantages of III–V material systems in these regimes.

Contemporary research and industry practice continue to refine III–V device structures, epitaxial growth methods and fabrication processes to improve linearity, noise behaviour and frequency response. Even where silicon-based technologies dominate large-volume commercial applications, III–V HEMTs retain a critical role in performance-driven systems that cannot rely solely on silicon.

1.4 Scope and Structure of the Report

This interim report introduces the fundamental operating principles of III–V HEMT devices and describes the fabrication and characterisation work completed during the first phase of the project. The report begins with the physical structure and behaviour of pseudomorphic HEMTs, followed by a summary of the cleanroom fabrication processes used to produce the devices analysed here. Their electrical characteristics are then examined through transfer behaviour, output curves, transconductance and threshold voltage extraction.

The final sections provide a reflection on project management and skills development, before outlining the planned technical work for the second semester.

CHAPTER 2

Technical Background

2.1 Overview of GaAs/AlGaAs High Electron Mobility Transistors

High electron mobility transistors (HEMTs) utilise a semiconductor heterojunction to create a conducting channel with markedly improved electron transport compared with uniformly doped structures. In the GaAs/AlGaAs system employed in this project, the difference in bandgap between the two materials establishes a potential well at their interface. Electrons supplied from the wider-bandgap AlGaAs layer transfer into the narrower-bandgap GaAs, forming a highly mobile sheet of charge known as a two-dimensional electron gas (2DEG). This confined channel supports rapid carrier transport, enabling high transconductance and excellent high-frequency behaviour, as described in standard texts on III–V devices[2, 1].

The devices studied and fabricated in this project are based on this GaAs/AlGaAs heterostructure. The epitaxial stack comprises an undoped GaAs channel, an undoped AlGaAs spacer separating the channel from ionised donors, and a silicon-doped AlGaAs barrier which supplies electrons. Above these layers sits a highly doped GaAs cap that enables practical device fabrication, providing a clean, conductive surface for ohmic metallisation and gate definition. A schematic cross-section is provided in Figure 2.1, and the subsequent sections expand on the structure's electronic function and its relevance to device operation.

2.2 The GaAs/AlGaAs Heterostructure

The electronic behaviour of the HEMT derives from its carefully engineered epitaxial heterostructure. The arrangement of the GaAs and AlGaAs layers dictates how electrons are distributed, confined and subsequently modulated by the gate. Only three layers form the active electronic structure responsible for the formation of the high-mobility channel: the undoped GaAs channel, the undoped AlGaAs spacer, and the Si-doped AlGaAs donor layer. These layers determine the depth and population of the two-dimensional electron gas and therefore underpin the device characteristics measured later in the report.

2.2.1 Undoped GaAs Channel

The lowest active layer in the structure is an undoped GaAs region, which serves as the host material for the two-dimensional electron gas. Its absence of intentional doping ensures that electrons do not encounter ionised impurities within the conduction path; this greatly reduces scattering. The uniformity and crystalline quality of this GaAs layer are essential, as the electronic properties of the device depend sensitively on the interface quality at the GaAs/AlGaAs boundary. The thickness of the channel is chosen so that electrons remain tightly confined near the interface without introducing strain or dislocations.

2.2.2 Undoped AlGaAs Spacer

Directly above the GaAs channel lies a thin undoped AlGaAs spacer. Although only a few nanometres thick, its role is critical. The spacer physically separates the conduction channel from the doped barrier layer above it. This separation prevents ionised donor atoms from residing within the channel region, significantly suppressing Coulomb scattering. At the same time, the spacer remains thin enough to maintain strong electrostatic coupling between the donor layer and the channel. The balance between these requirements is central to achieving both high sheet density and high mobility.

2.2.3 Si-Doped AlGaAs Donor Layer

The Si-doped AlGaAs layer provides the electrons that populate the channel. Its larger bandgap, compared with GaAs, places its conduction band edge at a higher energy. Electrons therefore diffuse into the GaAs channel until equilibrium is reached, leaving behind positively charged ionised donors in the AlGaAs. The aluminium composition determines the magnitude of the conduction band offset, while the doping concentration sets the density of available electrons. Together, these parameters determine the depth of the potential well at the interface and the resulting sheet electron density in the two-dimensional electron gas.

2.2.4 Summary of Heterostructure Behaviour

These three layers act together to create a structure in which electrons are supplied by the AlGaAs donor layer, confined within the GaAs channel, and shielded from ionised impurities by the spacer. The resulting elec-

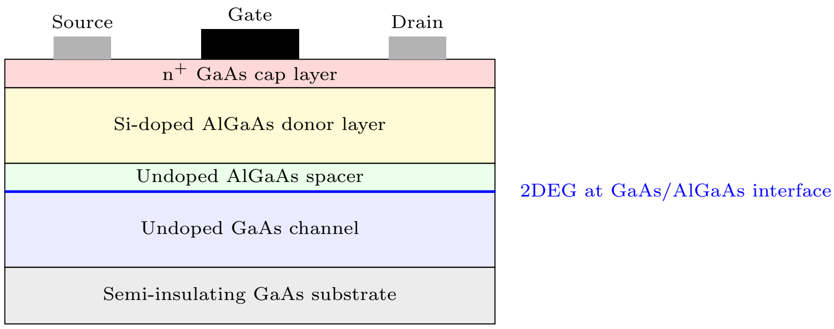

Figure 2.1: GaAs/AlGaAs HEMT cross-section (not to scale). Labels are inset to reduce clutter; the two-dimensional electron gas (2DEG) forms at the GaAs/AlGaAs interface.

tronic environment enables high carrier mobility, strong gate control and the characteristic performance advantages associated with GaAs/AlGaAs HEMTs. This foundation supports the device operation described in the following sections and informs many of the fabrication decisions discussed later in the report.

2.3 Formation and Properties of the Two-Dimensional Electron Gas

Electron transfer from the doped AlGaAs barrier into the undoped GaAs results in the formation of a two-dimensional electron gas at their interface. This occurs because the conduction band in GaAs lies at a lower energy than in AlGaAs; a potential well is therefore formed at the heterojunction. Electrons spill over from the AlGaAs into this well and accumulate in a very thin region close to the interface. The channel thickness is much smaller than in a conventionally doped epilayer, which enhances carrier mobility by reducing the probability of scattering within the conducting layer.

The absence of intentional doping in the GaAs channel eliminates ionised impurity scattering, which is typically one of the dominant mechanisms limiting mobility in standard GaAs transistors[2, 1]. Instead, carriers in the two-dimensional electron gas experience primarily phonon scattering at room temperature and, to a lesser extent, interface roughness. These mechanisms still influence mobility, but their combined effect is significantly weaker than the impurity-driven scattering present in a uniformly doped channel. The resulting electron sheet density is typically high, since the doped AlGaAs layer supplies a substantial reservoir of electrons. This high density, combined with the improved mobility, produces a channel with strong conductivity and excellent transconductance potential.

The characteristics of the two-dimensional electron gas therefore underpin the performance of GaAs/AlGaAs HEMTs and explain their widespread use in high-frequency and low-noise applications. In the context of this project, they also provide the link between the epitaxial design and the measured drain current, threshold and transconductance obtained from the fabricated devices.

2.4 Practical Device Layers: n$^+$ GaAs Cap and Schottky Gate Interface

Above the active heterostructure sits a highly doped GaAs cap layer. This cap is central to achieving reliable ohmic contacts, as its heavy doping allows metal alloys such as AuGe/Ni/Au to penetrate and form a low-resistance connection to the underlying two-dimensional electron gas during the annealing process. The cap also defines the surface on which lithography is performed, providing a uniform, conductive layer that facilitates consistent gate formation across the wafer.

The gate electrode forms a Schottky contact with the underlying material. When a gate metal such as Ti/Au is deposited onto the GaAs or AlGaAs surface, a rectifying junction is created. This junction is responsible for controlling the depletion region within the AlGaAs barrier; by adjusting the gate–source voltage, the electric field in the barrier is modified, which in turn changes the electron density at the heterointerface. The Schottky barrier therefore replaces the oxide–semiconductor interface used in MOSFETs, and its behaviour directly determines the degree of control the gate has over the channel.

These layers do not contribute to the formation of the two-dimensional electron gas itself, but they make the device physically realisable. Their thickness, doping level and processing quality influence the final device characteristics, particularly contact resistance and the efficiency with which the gate can modulate the channel.

2.5 Operation of the GaAs/AlGaAs HEMT

The operation of the GaAs/AlGaAs HEMT relies on the ability of the gate electrode to modulate the electron density within the two-dimensional electron gas. By applying a voltage to the Schottky gate, the depletion region in the AlGaAs barrier can be expanded or contracted. When the gate potential becomes sufficiently negative relative to the source, this depletion region approaches the channel and begins to reduce the available sheet charge. As the electron density beneath the gate falls, the drain current correspondingly decreases.

In the output characteristics, the device behaves resistively at low drain–source voltages, where the two-dimensional electron gas is uniformly populated along the channel. As the drain voltage increases, the potential near the drain end of the gate reduces the local electron density, leading to pinch-off and the onset of current saturation. This transition marks the point at which an increase in electric field no longer produces a proportional increase in carrier velocity, as velocity saturation in GaAs becomes significant.

The gate voltage also strongly influences the transconductance, as the relationship between the applied bias and the resulting change in sheet charge is highly sensitive. Changes in electron density translate directly into changes in conductivity, and therefore into changes in drain current. The high mobility of the two-dimensional electron gas and the relatively small distance between the gate and the conducting channel enable strong electrostatic control, giving the HEMT its characteristic high transconductance and excellent amplification capability.

2.6 Summary

The GaAs/AlGaAs HEMT achieves its performance through a carefully engineered heterostructure in which electrons donated from a doped AlGaAs layer populate an undoped GaAs channel, forming a high-mobility two-dimensional electron gas. A thin AlGaAs spacer separates the channel from the donors, suppressing impurity scattering while maintaining strong electrostatic coupling. A highly doped GaAs cap and a Schottky gate interface make the structure practically usable, enabling low-resistance ohmic contacts and effective gate control of the channel.

Together, these features yield a transistor with high carrier mobility, strong gate modulation and favourable current–voltage characteristics. This technical background provides the basis for understanding the fabrication sequence and electrical measurements presented in the subsequent chapters of this report.

CHAPTER 3

Fabrication of Depletion-Mode pHEMT Devices

3.1 Overview of the Fabrication Workflow

3.2 Mesa Definition

3.3 Ohmic Contact Formation

3.4 Gate Metallisation

3.5 Final Device Completion and Inspection

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3.7 Key Technical Lessons Learned

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Electrical Characterisation and Critical Analysis

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Exploration of Enhancement-Mode HEMT Devices

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5.2 Mechanisms for Achieving Enhancement Mode

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5.6 Logic Motivation and Stretch Goal

CHAPTER 6

Reflection and Project Management

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6.2 Challenges and Adaptations

6.3 Skills Developed

6.4 Lessons for Semester Two

CHAPTER 7

Semester Two Plan

7.1 Gantt Chart

7.2 Planned Technical Deliverables

7.3 Risk Mitigation Strategy

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[1] F. Ali and A. K. Gupta, *HEMTs and HBTs: Devices, Fabrication and Circuits*. Artech House Microwave Library, 1991.

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APPENDIX A

Additional Figures

APPENDIX B

Code and Process Flow