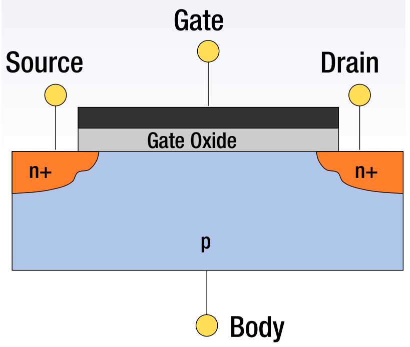
Understanding field scattering in AlGaN/GaN heterostructure field-effect transistors

Field-effect transistors featuring stacked layers of semiconductors are important elements of many electrical devices, especially in wireless communication systems. Through a series of studies, research led by Professor Zhaojun Lin at Shandong University, China, has identified one particular mechanism driving an unavoidable limitation in these devices. By drawing from their new theoretical description of 'polarisation Coulomb field scattering', the team hopes that future AlGaN/GaN heterostructure field-effect transistor designs could overcome these challenges, even as the demand for electrical devices continues to grow.



Field-effect transistors vary the flow of electrical current between a 'source' and a 'drain'.

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Field-effect transistors (FETs) are devices that vary the flow of electrical current between a 'source' and a 'drain' electrode. This flow is controlled using a semiconductor: a material which can act as either a conductor or an insulator, depending on the strength of the electrical field passing across it. By fine-tuning this field, also known as the 'gate voltage', users can alter the semiconductor's conductivity, in turn, varying the flow of the current between the source and drain electrodes, which are placed on top of the semiconductor.

Now featuring a diverse array of different designs, combined with the ability to be readily miniaturised and mass-produced, FETs now play a central role in our everyday lives – forming the building blocks of many modern electronics, computers, and communications devices. Dr Zhaojun Lin at Shandong University in China, with his collaborators, has gained new insights into the next generation: AlGaN/GaN Heterostructure Field-Effect Transistors.

HETEROSTRUCTURE FETS

In one particular FET design, named 'heterostructure' FETs (HFETS), semiconducting components contain two different semiconductors stacked on top of each other – each with different gaps in energy between their insulating and conducting states. At the interface between these materials, this difference creates a '2D gas' of electrons – giving rise to some unique electrical properties.

Altogether, the characteristics of this setup allow HFETs to handle currents which alternate in direction at higher frequencies than would be possible with more conventional FETs, making them particularly well-suited to wireless communication systems.

Today, HFETs are crucial elements of the power amplifiers used in these systems, allowing them to handle dauntingly high volumes of multimedia traffic. Yet as these systems continue to rapidly develop, there are growing concerns that even the latest HFET designs may not keep up for long.

UNEVEN STRAIN DISTRIBUTIONS

Currently, limitations to the HFET's design make the device vulnerable to effects that alter its behaviours in inconvenient and unpredictable ways. Among these is the 'inverse piezoelectric' effect, which causes semiconductor materials to reversibly change shape when electrical fields pass through them.

As a result, the HFET's 'barrier layer' is unavoidably stretched and deformed in non-uniform ways.

While these effects can be ironed out by applying external forces, the process is both time-consuming and power-hungry, and the extra hardware required is difficult to integrate into complex miniaturised circuits.

EXPERIMENTS WITH AlGaN/GaN

To address this problem, Lin's team identified a need to understand precisely how electrical currents are affected by these uneven strain distributions. If a theoretical basis for the effect could be established, they suggested it could pave the way for new HFET structures that account for any irregularities by themselves, without any external influence.

In their study, the researchers considered a common HFET design: featuring a barrier layer composed of aluminium gallium nitride (AlGaN), with a lower layer of gallium nitride (GaN) deposited onto a substrate. On top of the heterostructure, they added the source and drain electrodes; in between, they placed the gate electrode, which is used to apply the electric field across the semiconductor heterostructure.

UNCOVERING PCF SCATTERING

As they passed a current through their HFET, Lin's team identified one particular mechanism as the main culprit for scattering the flow of electrons, named 'polarisation Coulomb field' (PCF) scattering.

In semiconductors, polarisation occurs when separations of the material's positive and negative charges are aligned along a single direction by an external electric field – such as the HFET's gate voltage.

At the AlGaN/GaN interface, non-uniform strain in the barrier layer, triggered by the inverse piezoelectric effect, causes this polarisation to itself become non-uniform. In turn, any electrons interacting with interface regions of differing polarisation will become scattered in different ways, diminishing the HFET's overall performance.

> *Currently, limitations to the HFET's design make devices vulnerable to effects that alter their behaviours in inconvenient and unpredictable ways.*

ESTABLISHING THEORY

Over a series of studies dating back to 2014, Lin and his colleagues have developed a robust theoretical model of PCF scattering for the first time, which clearly establishes its relationship with the HFET's non-uniform strain distribution.

Building on this initial work, the researchers have also explored how this effect varied as they altered the component and size of the material and device structures. They discovered that the unwanted influence of PCF scattering could be diminished by optimising the material and device structures.

FURTHER TESTS

In addition, Lin's team measured the influence of PCF scattering on an effect through which small changes in the HFET's gate voltage can result in large changes in the amount of current flowing from source to drain: measured by a value named the 'transconductance.' Just as before, the researchers' experiments conclusively demonstrated how the HFET's transconductance is affected by PCF scattering.

Through further tests, the researchers examined the influence of PCF scattering on the device linearity of AlGasN/GaN HFETs. The single-tone power of the AlGaN/GaN HFETs with different gate widths and gate lengths was measured. A distinct improvement in device linearity was observed in the device with a larger gate width and a longer gate length. The analysis of the variation of the parasitic source access resistance showed that, as the gate bias is increased, the PCF scattering can offset the increased polar optical phonon scattering, improving the device linearity.

The next generation of field-effect transistors could have wide-ranging applications.

Their theoretical framework could reliably explain the improved device linearity of AlGaN/GaN HFETs.

IMPROVING HFET DESIGNS

Having passed each of these stringent tests with flying colours, Lin and his colleagues now hope that their PCF theory will provide an important next step towards a new generation of HFET designs – that overcome the limitations of their predecessors.

> ***Computing and communication continue to advance at a breakneck pace, placing an ever-higher demand on the requirements of electrical devices.***

By drawing from their theoretical framework, the team proposes that researchers in future studies may be able to conceive suitable modifications to existing HFET designs – particularly to the size and shape of their gate electrodes – which can better account for PCF scattering, without any need for inconvenient external interventions to their operation.

KEEPING PACE WITH NEW TECHNOLOGY

The team's discoveries come at a critical time. As the capabilities of computing and communication continue to advance at a breakneck pace, they are placing an ever-higher demand on the requirements of electrical devices – which often come with daunting technical challenges.

With their robust new theoretical basis for describing PCF scattering, the researchers' work could ensure that future HFET designs can be miniaturised even further, while still enhancing their performance as manufacturing techniques continue to improve.

For wireless communication systems, in particular, enhancing the performance of power amplifiers composed of HFET-based circuits will enable high numbers of users to transmit fast, clear signals from around the world, all using the same system.

This could not only be crucial for everyday commercial applications – such as sending and receiving the internet and phone signals generated by billions of global users; it could also underlie the operation of systems ranging from radar and satellite imaging – for applications ranging from national defence, to monitoring the atmosphere, oceans, and ecosystems of our changing planet.

Reliable wireless signals may even lead to new medical breakthroughs, which could ultimately save many lives: ranging from clearer, more accurate medical images to smart, implantable prosthetics, which can transmit continual streams of data about patients' bodies while being instructed to perform important biological tasks.

Beyond the reach of present-day technology, the theory may also one day be used to transmit microwave signals deep into space – which could help power future spacecraft sent to explore the most distant regions of our solar system.

Behind the Research

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Research Objectives

To investigate the effect of polarisation Coulomb field scattering on improving the performance of AlGaN/GaN heterostructure field-effect transistors.

Detail

Bio

Dr Zhaojun Lin is a professor in the School of Microelectronics at Shandong University in Jinan, China. His current research interests include the device physics and characteristics of GaN electronic devices.

Funding

National Natural Science Foundation of China (Grant Nos. 11974210 and 11574182)

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Personal Response

What advantages do AlGaN/GaN HFETs have over other types of HFET?

" AlGaN/GaN HFETs have increasingly gained wider acceptance as a technology that demonstrates numerous strengths for applications in power electronics, radio-frequency, and more recently in the areas of digital and ultra-high and ultra-low temperature electronics. Due to its unique material attributes, including wide bandgap and excellent transport parameters, GaN can meet the high temperature, high frequency, and high power demands of various industrial applications including deep well drilling, automobiles, and aerospace. At the same time, AlGaN/GaN HFETs can operate in very low temperature environments that are relevant for superconducting and quantum computing applications. "