Device Technology Based on New III-N Heterostructures

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Abstract

III-nitride electron devices are attracting considerable attention for wireless communication equipments and power electronics systems. This paper describes some of the future technological challenges to further improve high frequency power performance of nitride-based heterojunction FETs. Also described are new applications which may be exploited by the development of millimeter-wave power transistors based on new III-nitride heterostructures, including AlInN/InGaN and AlInN/InN.

INTRODUCTION

III-nitride field-effect transistors (FETs) are attracting considerable attention owing to their inherent advantages, such as high breakdown characteristics and high output-power driving capability [1,2]. In addition, one can construct a variety of heterojunctions composed of binary, ternary and quaternary III-nitride materials, providing great freedom in choosing device structures for desired device operation.

Practical use of nitride-based transistors has partly started in microwave power systems. However, there still remain a number of problems to be solved, including manufacturing, reliability and cost of materials. Looking at the present status of device performance on the basis of research and development, III-nitride heterojunction FETs have demonstrated outstanding advantages in high-voltage, high-frequency and high output-power performance. In particular, with rapid advancement in epitaxial growth technology after 2000, state-of-the-art performance in microwave power and power switching applications has been repeatedly renewed year by year.

In 2004, Wu et al. achieved an output power density of 32.2W/mm at 4GHz with an AlGaN/GaN HEMT chip with a gate width (*W*g) of 246μm operated at 120V [3]. Okamoto et al. reported a highest one-chip output power of 230W at 2GHz with an AlGaN/GaN HEMT chip with *W*g=48mm operated at 53V [4]. In 2007, Mitani et al. reported first demonstration of 1kW microwave (pulsed) power operation at 3.2GHz using a packaged circuit with 4 chips of HEMT biased at 80V [5]. In millimeter-wave applications, Murase et al. achieved a highest one-chip output power of 20.7W at 26GHz with a recessed-gate HEMT with *W*g=6.3mm operated at 25V [6]. Higashiwaki et al. reported a highest current gain cutoff frequency of 190GHz with a very thin (6nm) $Al_{0.4}Ga_{0.6}N$ barrier layer and with a gate length (*L*g) of 60nm [7]. These data are summarized in Table I.

TABLE I
SUMMARY OF STATE-OF-THE-ART DATA

Item	Data	Affiliation	Reference
Power Density	32.2W/mm	Cree	[3]
RF Power (CW)	230W	FED	[4]
RF Power (pulsed)	1000W	Eudyna	[5]
mm-wave Power	20W @26GHz	NEC	[6]
Cutoff Freq. f_T	190 GHz	NICT	[7]
Breakdown Voltage	10400 V	Panasonic	[8]

In this paper, we describe some of the challenging issues that are believed to be important from the viewpoint of device performance improvement using new III-nitride heterostructures. Also discussed are the future perspectives of new applications using millimeter-wave GaN-based power transistors.

NEW HETEROSTRUCTURES

Figure 1 shows calculated results of the relationship between the electron drift velocity and the applied electric field for AlN, GaN and InN. The low-field mobility values, estimated from the gradient of velocity vs field relationship, are 1880, 810 and 310cm^2/Vs for InN, GaN and AlN, respectively. InN shows the highest mobility among those three materials. Each drift velocity shows a gradual decrease in the high-field region after reaching its peak value. The peak velocities are 4.2x10^7, 2.8x10^7, and 2.0x10^{7}cm/s for InN, GaN and AlN, respectively. InN shows the highest peak drift velocity, indicating that InN is highly promising as a channel material for ultra-high speed and/or extremely high frequency applications. However, InN has a smallest bandgap (about 0.7eV) and largest lattice constant among the three binary materials, suggesting that any attractive heterojunctions cannot be constructed under strict lattice matching conditions. It is thus proposed a novel unique heterostructure, which utilizes GaN as a substrate material, AlInN (lattice-matched to GaN) as a barrier material and InN as a channel material. Figure 2 shows the device structure. The InN channel layer must be thin enough so as not to induce any detrimental crystal defects due to lattice mismatching. If crystal defect formation is inevitably serious, the channel material of InN can be replaced by in-rich InGaN, as shown in Fig.2(b).

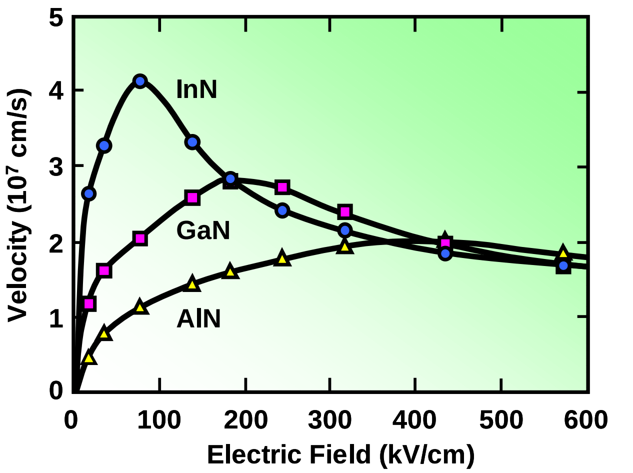

Fig.1 Drift velocity vs electric field for InN, GaN and AlN. Calculation is based on Monte Carlo algorithm.

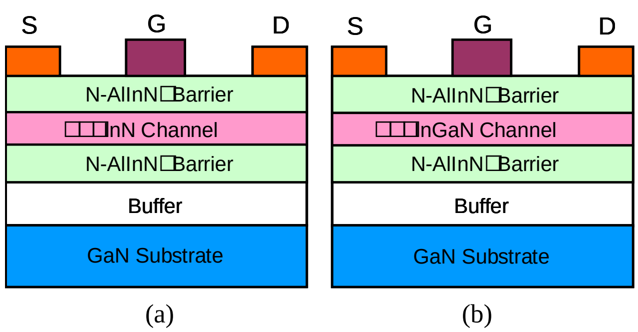

Fig.2 Proposed double-heterojunction FET structures with (a) InN channel and (b) InGaN channel.

Figure 3 shows ensemble Monte Carlo simulation results, where the current gain cutoff frequency is plotted as a function of the gate length for an AlInN/InN/AlInN double-heterojunction FET. By employing InN as a channel material, a current gain cutoff frequency of more than 1THz is predicted with a gate length of shorter than 50nm [9]. If high-quality InN is difficult to grow on an AlInN barrier layer, InGaN with high In composition may be used as an alternative to InN. By reducing the gate length down to 10nm, a current gain cutoff frequency of 1THz is expected using an InGaN channel layer with an In composition of more than 50% [9].

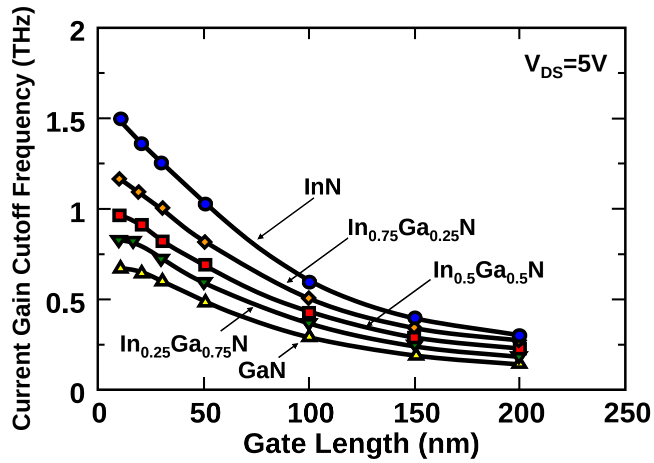

Fig.3 Current gain cutoff frequency as a function of gate length for AlInN/InN/AlInN and AlInN/InGaN/AlInN double-heterojunction FETs.

In the conventional c-plane growth of nitride semiconductors, it is well-known that an internal strong electric field is generated along the growth direction owing to the strong polarization effects. Therefore, when a double-heterojunction is grown on a c-plane substrate, the polarization effects promote electron accumulation at one heterojunction while they act as interference in electron accumulation at the other heterojunction. Because of these reasons, high channel electron densities have not been successfully demonstrated using nitride-based double-heterojunctions. This problem can be solved by choosing the crystallographic orientation of a substrate along nonpolar direction, such as a-plane and m-plane (see Fig.4). Future advanced nitride-based heterojunction devices having both high current drive capability and high-frequency high-gain

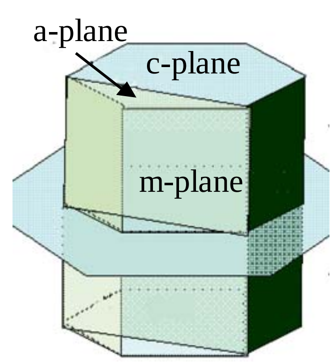

Fig.4 Polar and non-polar planes of Wurtzite crystallographic structure.

performance might be created by developing a nonpolar GaN substrate as well as growing high-quality epitaxial layers on a nonpolar substrate.

NEW APPLICATIONS

So far, various possibilities of nitride semiconductor transistors have been described. In the following, we will discuss new applications of those new transistors and their impact on the society.

In the microwave frequency range, GaN devices extend their application area mainly because of their high drain bias capability (>50V) and possible high-temperature operation up to 200-300ºC. It is no exaggeration to say that almost all microwave transmitter amplifiers would be replaced by high-efficiency and cooling-less nitride power transistors. In the quasi-millimeter-wave frequencies up to 30GHz, the superiority of high-voltage nitride transistors will be more positively recognized to open up new applications, such as high-speed wireless internet access and satellite communication systems. Since nitride semiconductors do not include toxic elements, such as arsenic and phosphorus, the society will more favorably accept those new compound semiconductors from the environmental safety and sustainability point of view [10].

Compared to the microwave frequency range, millimeter-wave frequencies beyond 60GHz are the frequency range where one can make the best use of the advantage of nitride semiconductor transistors. One of the well-known millimeter-wave application systems is the car collision warning or avoidance radar system at 76-77GHz. The currently required distance of observation is not more than 200m, which results in a very small output power of typically less than 10mW. The present car radar system may be acceptable when it is regarded as just an auxiliary security system, but there is a detrimental risk of power shortage when one encounters fierce rain or snow. Once the system recognizes hazardous situations, it would be a reasonable and favorable selection to increase the output power of the radar system though we may have to change public regulation rule to some extent. Thus, the next-generation car radar system might be something which regards driving safety as most important in case of any emergency.

In general, it is not so easy to achieve high output power performance at millimeter-wave frequencies of more than 60GHz. This is primarily due to the reduced breakdown voltage of the device by scaling down the critical dimension of transistors for ensuring higher gain. Bias voltages applied to millimeter-wave power GaAs-based FETs are typically less than 5V, Therefore, the maximum output power has been limited around 100mW at frequencies over 60GHz. In the meanwhile, GaN-based FETs can be operated with a bias voltage of more than 20V, even when the gate length is scaled down into a nano-meter range. This indicates that a GaN-based millimeter-wave power FET can deliver an order of magnitude larger output power density than that obtained by conventional GaAs devices. Figure 5 shows the expected output power as a function of frequency. More than 1W output power at 100GHz would be delivered from a GaN-based amplifier properly designed for high gain and high voltage operation. With higher output power densities in a power amplifier, one can drastically eliminate the peripheral circuits, such as a power combiner/divider circuit, giving rise to a twofold advantage of overall high efficiency as well as small size and low cost.

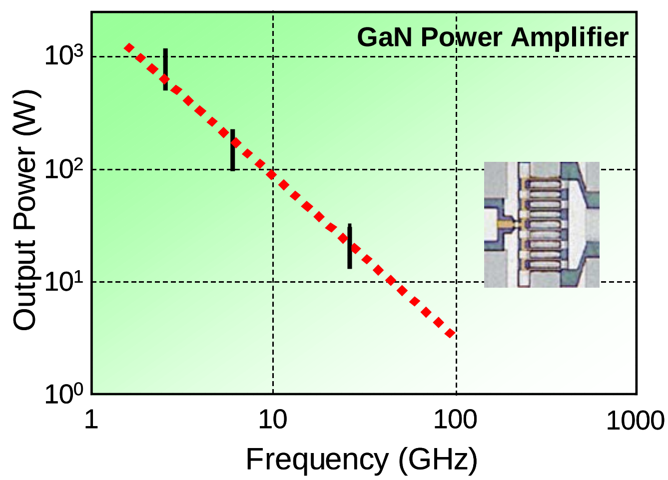

Fig.5 Output power vs frequency of GaN-based power amplifier.

Possible new applications of 60GHz and beyond frequency bands include millimeter-wave surveillance systems for home and public security. The advantages of using millimeter-wave frequencies include 1) effective operation under heavy rain, mist and snow, 2) clear detection of metals, and 3) concealing of antenna and system by paper or cloth. To realize these new millimeter-wave systems, the most important component will be a power amplifier and nitride-based millimeter-wave FETs will provide higher output power performance with excellent efficiency, much smaller chip-size and less complicated circuit dimensions.

CONCLUSIONS

State-of-the-art performance and future perspectives of III-nitride high-power transistors have been described. Simulation results indicated that an InN or In-rich InGaN channel FET is extremely promising for THz frequency operation. Novel III-nitride heterostructures, such as AlInN/InN/AlInN and AlInN/InGaN/AlInN fabricated on non-polar substrates, will provide additional freedom in designing a new device structure that ensures both high current drive capability and high-frequency performance. It was predicted that millimeter-wave high-power transistors operated at over 60GHz became more important to realize safe and sustainable society in the future.

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ACRONYMS

FET: Field Effect Transistor