Comparison Between GaN and SiC From the Viewpoint of Vertical Power Devices

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Abstract

Thanks to superior materials properties, GaN has great potential as the next-generation power devices. The author will discuss challenges for GaN vertical devices by referring SiC technologies, which has over 20 years history.

INTRODUCTION

Wide-bandgap (WBG) semiconductors have attracted much attention as materials for the next-generation power devices since they have superior material properties, in particular large breakdown field, compared to silicon (Si). The most advanced WBG semiconductor for power devices is silicon carbide (SiC). SiC has polytypism, which makes high-quality crystal growth very difficult. In 1987, a growth technology called “step-controlled epitaxy” was developed that enables a single-phase (single polytype) growth. Among these polytypes, 4H-SiC has high electron mobility and large energy bandgap. Thus, 4H-SiC is generally used for power device applications. In 1993-1994, 4H-SiC Schottky-barrier diodes (SBDs) were demonstrated that exceed the power performance limit for silicon. In 2001, SiC SBDs were commercialized by SiCED (later, Infineon). Key technologies for SiC SBDs were the development of an edge termination by ion implantation to obtain an ideal breakdown voltage, and a junction barrier Schottky (JBS) structure to suppress the reverse leakage current. SiC SBDs are compatible with Si PiN fast-recovery diodes (FRDs) which are used in switching power supply units. For examples, flat panel displays require high-efficiency power supply units and SiC SBDs are suitably used in these units. The demands of SiC SBDs led to the development of large-diameter high-quality SiC substrates. The size of SiC substrate was 2 inch at the initial stage, and 6 inch SiC substrates are commercially available as of today.

The development of SiC power MOSFETs, on the other hand, took longer than expected due to low channel mobility at the SiO_2/SiC interface and the oxide reliability issues. The channel mobility can be improved by a post-oxidation nitridation process in NO or N_2O ambient. The improved channel mobility is 20-40 cm^2/Vs, which is still much less than its bulk mobility of 1000 cm^2/Vs. By reducing the cell size and the channel length, low-on-resistance SiC vertical power MOSFETs as well as power modules consisting of SiC MOSFETs and SiC SBDs are successfully commercialized.

During the last 5 years, SiC devices were extensively implemented in electronic vehicles and railway trains. These devices and circuits demonstrate significant improvements in the power utilization efficiency. In Japan, for example, SiC-based inverter systems are employed in the latest commuter trains of the Yamanote line (the circle line of Tokyo.)

Gallium nitride (GaN) is another candidate for power devices. AlGaN/GaN HEMTs were originally developed for high-power high-frequency amplifiers. In the last decade, extensive development efforts were carried out on AlGaN/GaN HEMTs grown on Si substrates in hopes to produce cost-effective and high-efficiency power switching devices. Many companies in the U.S., Europe, and Japan have started into mass production. They have a great impact on consumer electronics due to their excellent performance of low on-resistance and high switching speed, which can never be realized simultaneously in Si power devices.

Recently, GaN vertical power devices have attracted great attention for next-generation power devices with large breakdown voltage and high current capability. Required process technologies for GaN vertical power devices are very different from those for lateral AlGaN/GaN HEMTs. Many new technologies should be developed to realize high-performance GaN vertical power devices. In this paper, the author would like to discuss what GaN researchers should do to catch up and compete with advanced SiC power devices.

SUBSTRATE

4H-SiC bulk crystals are grown by the seeded sublimation method (modified Lely method). The growth temperature is around 2200°C. The source material is high-purity SiC powder. Typical growth rate is several hundred μm/h. The temperature control (shape control) of the seed crystal is very important. It becomes difficult with increasing crystal diameter. However, manufacturers manage to overcome this challenge and 6-inch-diameter 4H-SiC substrates are now commercially available. Some of the fabricated substrates are reused as seedling crystals. After many growth runs by selecting good seedling crystal for next growth, the dislocation density is successfully reduced to the order of 10^3 cm^{-2}.

Low resistivity substrates are required for vertical power devices. N-type doping can be done by introducing nitrogen easily. However, heavy doping results in the formation of cubic-phase (3C-SiC) inclusion. The minimum resistivity without the inclusion formation is around 15-20 mΩ cm. To reduce the substrate resistance, a wafer thinning process is generally employed in commercial SiC power devices.

GaN bulk substrates are grown by a hydride vapor phase epitaxy (HVPE) on foreign substrates such as GaAs or sapphire (Al_2O_3) with high growth rate of several hundred μm/h. At the present time, 2, 3, and 4 inch substrates are commercially available. 6-inch-diameter substrates were demonstrated in the R&D level, which showcase the scalability of the HVPE method. Due to the heteroepitaxial growth, the GaN crystal contains threading dislocations of 3×10^6 cm^{-2}. Since current GaN substrates are produced for LDs or LEDs, the resistivity is set at 20 – 50 mΩ·cm to keep good optical transparency. The threading dislocation density seems too large for vertical power devices however. The resistivity should also be reduced. If the optical transparency is not of major concern, GaN substrates with low resistivity (<7 mΩ ·cm) can be grown by the HVPE method.

To compete with SiC vertical power devices, low-cost, large-size, low-dislocation-density, and low-resistivity GaN substrates are needed. The epitaxial growth on a foreign substrate is also a limiting factor. One of the promising approaches is a combination of an ammonothermal method and the HVPE. Ammonothermal method (a GaN growth condition under supercritical ammonia) has low growth rate. However, it can achieve strain-free GaN bulk crystal with large substrate size and low dislocation density. By using high-quality crystal as the seed, long period of HVPE growth can be possible, and multiple GaN substrates can be obtained from one ingot.

DRIFT LAYER

The drift layer is the most important part of vertical power devices. The drift layer support applied voltage in the off-state. For kV-class devices, low doping (5×10^{15} cm^{-3}) and thick growth (10-30 μm) are required. An reduction of the background impurity and point defects that form donor or acceptor states in the bandgap is important. In addition, high-speed growth is required to reduce the manufacturing cost.

For SiC, the drift layer is grown by VPE using silane and propane with hydrogen carrier gas. The growth reactor is made by high-purity graphite (some parts are coated by high-purity poly-SiC). Thanks to the simple chemistry, high-purity SiC with background donor concentration of $<1 \times 10^{14}$ cm^{-3}, can be grown by VPE. The growth rate can be 100 μm/h, which is good enough. The deep-level trap concentration is much less than the background donor concentration.

For GaN, currently available growth method for the drift layer is metal-organic vapor phase epitaxy (MOVPE). Because of source material such as metalorganic gallium, carbon incorporation is inevitable. It is known that carbon substituting nitrogen site in GaN (C_N) acts as a deep acceptor. If the donor concentration is less than the concentration of C_N, the layer becomes semi-insulating. Typical carbon concentration in MOVPE-grown GaN is 5×10^{16} cm^{-3}, which limits the controllable range of *n*-type doping. Recently, carbon concentration was reduced by controlling growth condition [1]. The smallest value is $1\text{-}3 \times 10^{15}$ cm^{-3}. The value is small enough for 1kV-class devices but not enough for >3kV-class devices. The growth rate for such low carbon layers is around 1-3 μm/h, and is too low for manufacturing.

High-speed, low-background-impurity growth methods for GaN drift layers are needed. One of the promising methods is the HVPE. Generally HVPE-grown GaN has high residual Si and O concentrations. However, a recently report showed that a well-designed reactor and optimized growth condition could enable high-purity GaN growth with high growth rate (60 μm/h) in HVPE reactors [2].

ION IMPLANTATION

Selective doping by ion implantation is essential for the making of vertical power devices. To fully utilize superior material properties in WBG materials, electric field crowding should be avoided by utilizing a junction termination extension (JTE) structure, which can be formed by ion implantation. Both *n*-type and *p*-type doping in SiC can be made possible by nitrogen and aluminum ion implantation, followed by high temperature annealing at 1650°C. Graphite is a nice capping material for high temperature annealing.

For GaN, there are many reports on *n*-type doping by Si ion implantation. The *p*-type doping was difficult. However, Mg/H co-implantation methods [3] and AlN epi capping layer method [4] are recently proposed. Although further R&D are needed, especially for proper annealing methods for GaN materials, the proof-of-concept work for both *n*-type and *p*-type doping in GaN materials by ion implantation is encouraging.

MOS CHANNEL

As mentioned above, SiC suffers from low channel mobility. The origin has not yet revealed. However, many researchers believe carbon play an important role. Commercial SiC power MOSFETs seem to use the channel mobility of 20-30 cm^2/V-s. The channel resistance is reduced by a proper design in the device geometry.

GaN have great potential from the perspective of the channel mobility. There are some reports on the inversion-channel in GaN MOSFETs. A channel mobility of > 120 cm^2/Vs with normally-off characteristics was demonstrated in lateral GaN MOSFETs [5]. It is clear that SiC devices cannot replace Si power MOSFETs with a blocking voltage 600-900 V due to their low channel mobility. GaN MOSFETs, however have a chance to become a contender in this application space as long as the channel mobility of greater than 300 cm^2/Vs can be achieved.

CONCLUSIONS

As mentioned above, SiC is the most advanced WBG semiconductor for power device applications. There are many things to be developed for GaN vertical power devices. However, GaN have a great potential to provide low-cost substrate and drift layer in the future. Realization of high-performance low-cost WBG power devices have a strong impact to the society.

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ACRONYMS

FRD: Fast Recovery Diode
HVPE: Hydride Vapor Phase Epitaxy
JBS: Junction Barrier Schottky
JTE: Junction Termination Extension
MOVPE: Metal-Organic Vapor Phase Epitaxy
SBD: Schottky Barrier Diode
WBG: Wide BandGap