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GaN/AlN Resonant Tunneling Diode with High Peak-to-Valley Current Ratio Grown by Metal-Organic Vapor Phase Epitaxy

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Abstract

We report a high-quality GaN/AlN resonant tunneling diode (RTD) grown by metal-organic vapor phase epitaxy (MOVPE). A negative differential resistance with a high peak-to-valley current ratio (PVCR) of 28 was obtained by optimizing the device design and growth conditions. This PVCR is much higher than that for a previous GaN/AlN RTD grown by MOVPE, and is also equivalent to the highest PVCR obtained for a device grown by molecular beam epitaxy. Thus, MOVPE growth is also shown to be effective for the fabrication of high-quality GaN/AlN RTDs.

1. Introduction

GaN based devices have recently attracted attention due to their excellent material properties, such as high carrier mobility, wide bandgap, and ability to be grown heteroepitaxially on Si substrates. Therefore, high power electronics devices based on GaN related materials are expected to find many applications [1]. In addition, GaN related materials are promising for quantum effect devices including resonant tunneling diodes (RTDs), because the GaN/$Al_xGa_{1-x}N$ (x=1) heterointerface exhibits a large band offset of 2 eV. Therefore, the current-voltage (I-V) characteristics provide a large negative differential resistance (NDR) and a high peak-to-valley current ratio (PVCR). The application of GaN/$Al_xGa_{1-x}N$ RTDs that have the excellent material properties and large band offset is expected to realize higher performance RTD based devices, such as terahertz oscillator [2] and ultrafast nonvolatile memory [3].

However, it is difficult to fabricate high quality GaN/$Al_xGa_{1-x}N$ RTDs because GaN related materials have inherent polarization and crystal defects. Thus far, various epitaxial growth methods for producing GaN/$Al_xGa_{1-x}N$ RTDs have been investigated, and the resulting NDR in the I-V characteristics was evaluated [4-6]. A NDR with the highest PVCR of 32 was realized for a GaN/$Al_xGa_{1-x}N$ RTD (x=1) with flat heterointerfaces that was grown by molecular beam epitaxy (MBE) [4]. In contrast, the PVCRs of GaN/$Al_xGa_{1-x}N$ RTDs (x=0.2 and 1) grown by metal-organic vapor phase epitaxy (MOVPE) was only 2 or 3, which is less than the value for typical RTDs based on GaAs/AlGaAs and InGaAs/AlAs [5,6]. However, the MOVPE growth technique can realize high productivity, which is very important for practical applications.

In this paper, we report the I-V characteristics of GaN/$Al_xGa_{1-x}N$ RTDs (x=1) grown by MOVPE. The device design and growth conditions are optimized to obtain a high PVCR and demonstrate that MOVPE growth can be effective for the fabrication of high-quality GaN/AlN RTDs.

2. Experiment

The GaN/AlN RTD was grown using a horizontal flow low-pressure MOVPE technique. Trimethlyaluminum and trimethylgallium were used as the metal organic precursors for Al and Ga, respectively. Ammonia and hydrogen/nitrogen mixture were used as the anion source and carrier gas, respectively. Silane was used as the n-type dopant source. The grown structure was shown in Fig. 1(a). Firstly, a u-GaN buffer layer with a thickness of 1 μm was grown on a (0001) sapphire substrate. Low temperature growth at 400 °C was employed to suppress the propagation of crystal defects to the upper RTD region. The RTD structure, n^+-GaN contact layers, and n-GaN electrode layers were then grown on the buffer layer at a high temperature between 1000 and 1100 °C. Appropriate growth rates, growth temperature and III/V ratios were used for each layer. The RTD structure comprised a GaN well layer with a thickness of 2.5 nm, u-AlN barrier layers with a thickness of 2 nm, and u-GaN spacer layers with a thickness of 3 nm. The u-GaN spacer layers were intentionally inserted to avoid disordering of the GaN/AlN heterointerface due to the high Si-doping (1.5×10^{18} cm^{-3}) of the emitter and collector layers. The bottom and top contact layers were more highly doped with Si atoms to reduce the contact resistance with Cr/Au metal [7].

After the growth, the device structure was fabricated using photolithography and dry-etching techniques [Fig. 1(b)]. Firstly, the patterned SiO_2 mask was fabricated to make a contact hole in the center of device. ECR dry-etching using Cl_2 gas was then performed to expose the bottom n^+-GaN contact layer. After that, Cr/Au electrodes were formed on the exposed n^+-GaN contact layer and the top n^+-GaN contact layer using liftoff technique. The sizes of the top electrodes were varied between 100×100 μm^2 and 400×400 μm^2 to investigate the dependence of the PVCR on the device size.

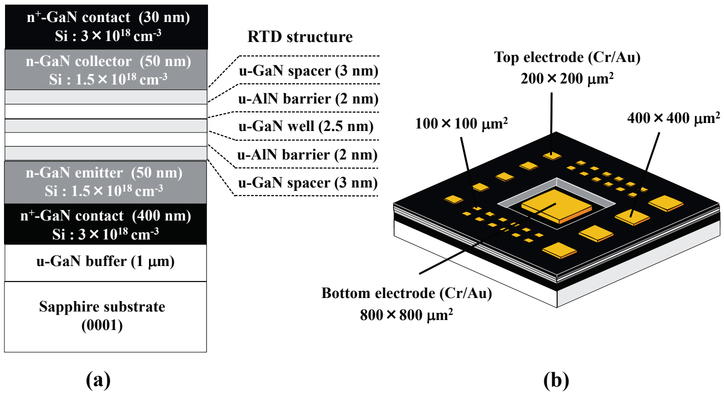

Fig. 1. GaN/AlN RTD grown by MOPVE. (a) Grown and (b) device structures.

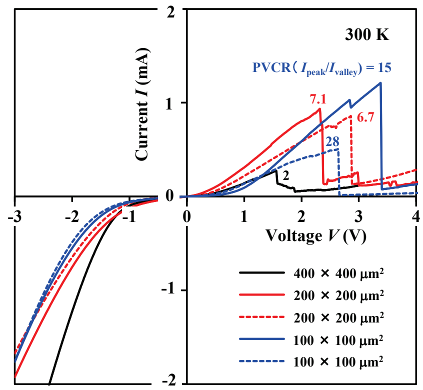

Fig. 2. I-V characteristics for various sized GaN/AlN RTDs.

3. Results

The I-V characteristics of the fabricated GaN/AlN RTDs were measured at room temperature using a probe system and semiconductor parameter analyzer (Agilent, 4156C). Figure 2 shows typical I-V characteristics for GaN/AlN RTD devices with various sizes. Clear NDRs were observed at 300 K for the forward bias side, namely when a positive bias was applied on a top electrode. NDR was not observed for the negative bias side because GaN/AlN RTD device has an asymmetric potential profile due to inherit polarization. On the other hand, the PVCR ($=I_{peak}/I_{valley}$) increases when the size of the top electrode is decreased. The highest PVCR of 28 was obtained for a GaN/AlN RTD device with the smallest size of 100×100 μm^2. This value is much higher than that previously obtained for GaN/Al$_x$Ga$_{1-x}$N RTDs (x=0.2 and 1) grown by MOVPE [5,6], and is almost equivalent to the highest PVCR (=32) obtained for a GaN/AlN RTD grown by MBE [4]. This result shows that MOVPE growth is also effective for producing high-quality GaN/AlN RTDs.

However, the RTD devices fabricated in the present study was not enough to use in the terahertz oscillator and ultrafast nonvolatile memory [2,3]. It is necessary to realize high performance GaN/AlN RTDs with a smaller size and a higher current density. In addition, the small sized pits that originate from crystal defects were observed on the surface of the substrate, and it has been reported that such crystal defects degrade the stability of the I-V characteristics [8]. Therefore, further improvements, such as a reduction of the device size and the amount of crystal defects, are necessary for GaN/AlN RTDs.

4. Summary

A GaN/AlN RTD with a high PVCR of 28 was successfully realized by appropriate device design and growth conditions. This PVCR is much higher than that previously obtained using MOVPE growth. Thus, it was deamonstrated that MOVPE growth can also be effective for the fabrication of high-quality GaN/AlN RTDs. However, further improvements, such as a reduction of the device size and an increase in the current density, are necessary to realize higher performance GaN/AlN RTDs. A reduction in the amount of crystal defects, which can degrade the stability of I-V characteristics, is also important for GaN/AlN RTDs.

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