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Influence of N_2 flux on the improvement of highly c-oriented GaN films on diamond substrates

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ABSTRACT

High-quality GaN films are deposited on freestanding thick diamond films by electron cyclotron resonance plasma-enhanced metal organic chemical vapour deposition (ECR-PEMOCVD). Trimethyl gallium (TMGa) and N_2 are applied as precursors and different N_2 fluxes are used to achieve high-quality GaN films. The influence of N_2 flux on the properties of GaN films is systematically investigated by X-ray diffraction analysis (XRD), reflection high energy electron diffraction (RHEED), atomic force microscopy (AFM) and Hall effect measurement (HL). The results show that the high-quality GaN films with small surface roughness of 4.5 nm and high c-orientation are successfully achieved at the optimized N_2 flux of 90 sccm. The most significant improvements in morphological, structural, and optical properties of GaN films are obtained by using a proper N_2 flux.

1. Introduction

The increasing interest in digital communication and video systems has heightened the need for higher frequency surface acoustic wave (SAW) devices. Of particular interest is that the SAW devices with operation frequencies higher than 1 GHz will be widely applied in the wireless communication devices. However, the development of SAW devices with operation frequency greater than 2.5 GHz has been greatly limited due to the restrictions in the conventional photolithography process. For SAW devices, the frequency is determined by the equation $f = V/L$, where f, V and L are the centre frequency, the velocity and the wavelength of the SAW, respectively. This equation shows that there are two ways to achieve the higher frequency operation. The first one is to reduce the wavelength L. As the wavelength L is determined by the size of the inter-digital transducer (IDT), this method is greatly limited due to the restrictions in the conventional photolithography process. The other way is to use a substrate with higher sound velocity. Diamond is currently one of the most promising materials as a substrate for SAW devices [1–14] due to its excellent mechanical, thermal, electrical, and chemical properties. Especially diamond has the highest sound velocity and the highest thermal conductivity, which can guarantee a higher frequency operation at a given linewidth resolution of the inter-digital transducer (IDT). However, diamond is not a piezoelectric material so it is necessary to deposit the piezoelectric films on the diamond films for SAW devices. GaN is currently one of the most promising materials for SAW devices due to its high SAW velocity, piezoelectric coupling, chemical stability and excellent thermal properties. By combining the virtue of diamond as substrate and GaN as piezoelectric film, the GaN/diamond structure will offer an attractive means for high frequency SAW devices with sufficient power durability.

At present, SAW devices have been reported based on ZnO/diamond structure deposition by the metal organic chemical vapour deposition (MOCVD) technique [1–14]. However, the performance of GaN/diamond for high frequency SAW devices is expected to be much better than ZnO/diamond. Because the phase velocity of GaN (approx. 5.6 km/s) is higher than that of the ZnO (approx. 2.6 km/s), the GaN/diamond can achieve higher frequencies under the same width of the IDT. In addition, the phase velocity of GaN (approx. 5.6 km/s) is lower than that of diamond (approx. 10 km/s), so GaN/diamond structures are expected to achieve a smaller velocity dispersion for SAW devices. ZnO/diamond/Si layered structures with a diamond layer of 10–100 μm grown by chemical vapour deposition (CVD) technique have also been reported [2–12], but the heat dissipation performance of the structure was considerably degraded due to the poor heat dissipation property of the silicon substrate compared to that of diamond. Methods for improving the power persistence of SAW

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filters have become a hot subject in the field. The GaN/diamond structure can make full use of the high thermal conductivity and sound velocity characteristics of diamond, and the problem of heat dissipation would be solved due to the removing of silicon substrate.

In general, high-quality SAW devices require two key factors: high frequencies and low insertion [15]. For the SAW devices based on GaN/diamond structure, these two properties will be determined by the quality of as-grown GaN films. It is worthwhile to mention here that there have been limited reports on GaN/diamond structures deposited by the metal organic chemical vapour deposition (MOCVD) technique [16], where the orientation and surface smoothness of GaN films were still not good enough for the requirement of SAW devices. Their result further demonstrates that the GaN/diamond structure is feasible for SAW devices.

In order to achieve the SAW devices with higher frequency based on the GaN/diamond structure, GaN films with preferred orientation and smooth surface are expected to be required. In this paper, GaN/diamond films were prepared using an electron cyclotron resonance plasma-enhanced metal organic chemical vapour deposition (ECR-PEMOCVD) system. The N_2 reactivity can be remarkably enhanced by the ECR process, which was necessary for the formation of GaN films at low temperature. The influence of N_2 flux on structural, morphological and electrical properties of GaN films is systematically investigated. The results demonstrate that the GaN films with small surface roughness of 4.5 nm and high c-orientation are successfully achieved at the optimized N_2 flux of 90 sccm, and that these can be used as piezoelectric films for surface acoustic wave (SAW) devices.

2. Experiments

The GaN films were prepared on diamond substrates using an electron cyclotron resonance plasma-enhanced metal organic chemical vapour deposition (ECR-PEMOCVD) system. In this experiment, freestanding thick diamond films with thicknesses of about 0.5–0.8 mm were used as substrates, which were prepared using a direct-current glow discharge PCVD. The growth surfaces of the freestanding diamond films were found to be too rough to be used as the substrates for GaN deposition, so we used the smooth nucleation surfaces of diamond films as the growth surfaces for the GaN films. First of all, the nucleation surfaces of diamond films are polished mechanically to meet the requirements of depositing GaN films. Secondly, the diamond substrates are immersed in a 3:1 mixture of sulphuric acid and phosphoric acid for 24 h at room temperature in order to remove a thin layer of metal carbide which forms as a result of the long time taken for diamond deposition at high temperature. Finally, the substrates are cleaned ultrasonically with toluene, acetone, ethanol and deionized water sequentially, dried with N_2 and then introduced into the PEMOCVD reaction chamber. The details of the freestanding diamond substrate treatment can be found elsewhere [17]. Trimethyl gallium (TMGa) and N_2 were used as the source of Ga and N, respectively. The temperature of the TMGa was kept at −14.1 °C using a semiconductor well. The N_2 reactivity can be remarkably enhanced by the ECR process, i.e., there are many more particles of reactive nitrogen over the substrate as a result of this ECR enhancement, which was necessary for the formation of GaN films under the low temperature. A buffer layer was first deposited on the substrate at room temperature for 30 min with TMGa flux of 0.5 sccm and N_2 flux of 80 sccm. This buffer layer was expected to alleviate the lattice and thermal mismatches between diamond substrate and GaN film, and also was used to supply nucleation centres with the same crystallographic orientation as the substrate and to promote the crystalline quality of GaN [18–20]. In addition, the higher N_2 flux was used to provide an N-rich atmosphere. Subsequently, the GaN film was grown at 400 °C for 180 min with the TMGa flux controlled at 0.5 sccm by mass flow controllers. To investigate the effect of N_2 flux on the structure and property of the as-grown film, the N_2 flux was varied in the range of 80–120 sccm. Finally, the temperature was reduced slowly to room temperature in order to reduce the thermal stress induced during cooling. The thickness of the GaN buffer layer and the final high-quality GaN films were roughly determined to be 110 nm and 800 nm, respectively.

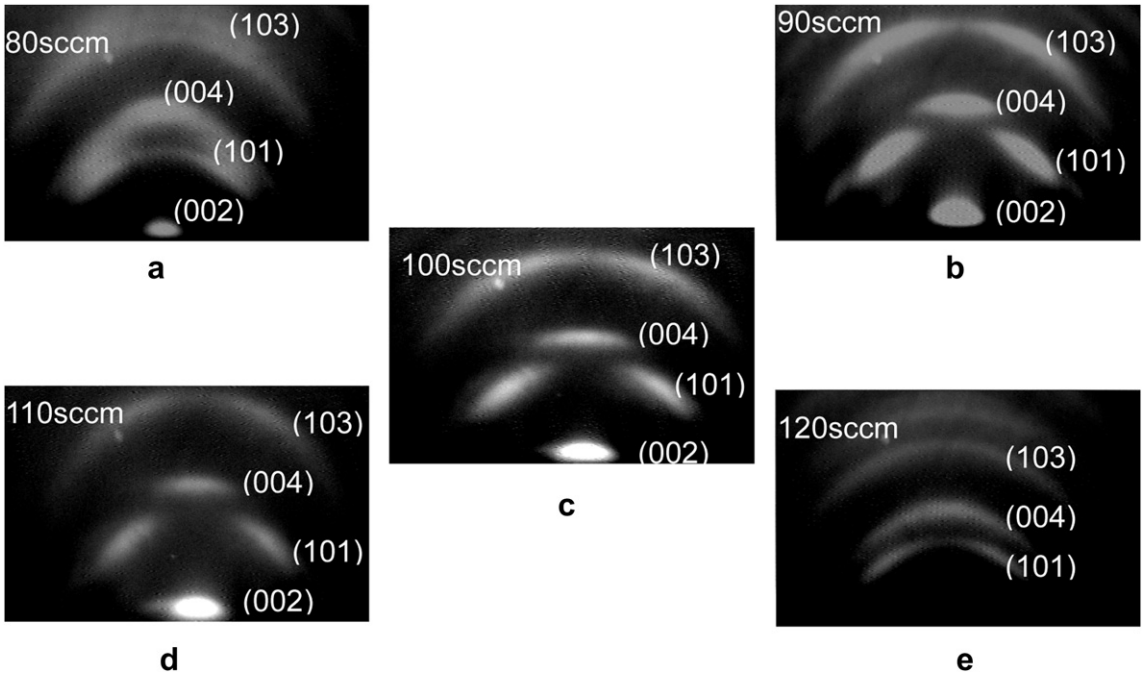

Fig. 1. The RHEED images of the GaN films deposited at the N_2 flux of 80 sccm (a), 90 sccm (b), 100 sccm (c), 110 sccm (d), and 120 sccm (e), respectively.