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The growth of heavily Mg-doped GaN thin film on Si substrate by molecular beam epitaxy

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ABSTRACT

This paper reports the growth of p-GaN by molecular beam epitaxy. During growth, reflection high electron energy diffraction displayed streaky pattern. Hall Effect measurement indicated a hole concentration of 3.90×10^{20} cm^{-3}. Scanning electron microscopy and X-ray diffraction measurements revealed that p-GaN has high structural quality. Photoluminescence spectrum showed that band edge emission was found at 354.1 nm, significantly shifted from usual reported value, i.e. 364 nm. The shift was attributed to Burstein–Moss effect. In addition, a broad emission peak at 387.5 nm was also observed which was due to the transition from conduction band edge to Mg acceptor level. Moreover, the presence of 657 cm^{-1} Raman peak also confirmed the heavy Mg-doped characteristic in p-GaN.

1. Introduction

The wide band gap semiconductors of III-nitrides such as GaN, AlN and their alloys, have received considerable attention as ideal materials for optoelectronic and high-temperature/high-power devices due to their unique properties, such as large direct band gap, high breakdown field and high thermal conductivity.

Unintentional doping of GaN has always been an issue in the growth III–V nitrides where in all cases, natural undoped GaN has always been observed to be n-type with the best samples still showing an electron concentration of $n\sim4\times10^{16}$ cm^{-3} [1]. The level of unintentional doping in some cases could be as high as 10^{20} cm^{-3} [2]. Due to this reason, efforts to obtain high p-type doping have always resulted in heavily compensated high resistive films. Therefore, the control of the electrical properties of GaN remains the foremost obstacle hindering the fabrication of high performance device.

Various types of acceptor atoms including Mg and C were tried for p-type doping where the result obtained was compensated high resistive material until Akasaki et al. [3] made the initial breakthrough when they observed that compensated Mg-doped GaN could be converted into conductive p-type material by low-energy electron-beam irradiation (LEEBI). This discovery attracted enormous attention of the III-nitride community and eventually led to the active research activities on p-type GaN studies. However, high hole concentrations in GaN are difficult to achieve due to large binding energy of Mg (150–200 meV). There is less than 1% of Mg acceptors which are typically electronically active at room temperature [4]. Therefore, in order to achieve acceptable hole concentrations, usually, high Mg incorporation far above normal doping densities is used, however this will degrade the crystalline quality of the epilayers consequently the resistivity will be increased. Hence, the development of a reliable high concentrations p-type doping for GaN remains a primary challenge for researchers.

The growth of GaN thin film on silicon substrate has a number of advantages as compared to other substrates including lower cost, excellent wafer quality, and more design flexibility with current silicon electronic circuit system [5]. The heteroepitaxy of GaN on Si can potentially combine the optoelectronic properties of GaN with highly advanced silicon electronic devices. Therefore, the growth and study of GaN epitaxy on Si are of practical importance. P-type GaN on Si was normally grown by using molecular beam epitaxy (MBE) or metalorganic chemical vapor deposition (MOCVD). MBE and MOCVD have been demonstrated and reported to be two of the advanced growth techniques for fabricating III-nitrides compound semiconductors with high crystal quality for device applications. However, MBE offers a number of potential advantages over MOCVD for the growth of III-nitride materials. For instances, more efficient use of source materials, higher accuracy in controlling the epilayers, as well as no requirement for post-growth annealing for the activation of p-type dopant.

It is well known that reflection high-energy electron diffraction (RHEED) intensity oscillation caused by atomic layer by layer growth is useful in providing the epitaxial growth and film thickness information during growth process. Unfortunately, from the literature, the use of RHEED for real-time epitaxial growth monitoring has been rarely reported. In this paper, we present the growth of heavily Mg doped GaN on Si (111) by plasma-assisted molecular beam epitaxy (PAMBE). The structural and optical characteristics of the grown p-GaN were subsequently analyzed by a variety of tools. Apart from post deposition

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physical properties characterizations, we also report in detail the use of RHEED for in-situ epilayer monitoring during growth process.

2. Experimental

2.1. Growth of p-GaN

The epilayer was grown by Veeco GEN II plasma-assisted molecular beam epitaxy (PAMBE) with standard elemental effusion cells consisting of group III materials, Mg-dopant, as well as active nitrogen (produced by Veeco Unibulb radio-frequency plasma source). The nitrogen plasma was operated at 300 W. The Si (111) substrate was cleaned by Radio Corporation of America (RCA) method prior to loading into the load lock chamber and was heated at 200 °C for 2 h. The substrate was subsequently transferred to the growth chamber and again heated at 900 °C for 20 min for removal of surface contaminants.

The growth of p-GaN could be divided into three steps. First, the surface of the substrate was cleaned by exposing it to Ga flux at 850 °C. This step was particularly important for Si substrate, since the Ga flux aided in the removal of SiO_2 by transforming it to Ga_2O_3 before the deposition of AlN buffer layer could take place [6]. Evidence for such transformation was provided in RHEED studies. Fig. 1 shows the schematic of the evolution of the Ga flush on Si (111) with different corresponding RHEED patterns. In the initial stage, the Si substrate surface showed a clear 7×7 surface reconstruction at high temperature, shown in Fig. 1(a). This result was similar to that reported by Hellman et al. [7]. When a few monolayers of Ga were deposited on the Si, the RHEED pattern became streaky and the Kikuchi lines disappeared, as depicted in Fig. 1(b). Fig. 1(c) shows the RHEED intensity just after closing the Ga shutter. A typical Si (111) 7×7 surface reconstruction pattern appeared along with the presence of prominent Kikuchi lines. Since the RHEED intensity increased, this verified the desorptions of the native oxide and indicating a clean Si (111) surface [8,9].

The Ga cleaning process was repeated a few times until the RHEED intensity remained constant. This process could remove impurities such as hydrocarbons and oxides, and in addition, improve the surface periodicity. This is similar to the effects of O_2 or H_2/Ar plasma cleaning. The Ga cleaning has an advantage where it requires no additional plasma source.

The second step involved the deposition of AlN buffer epitaxy at 840 °C for 15 min. Prior to the growth of buffer layer, Al was deposited on the substrate. This step suppressed the formation of Si_xN_y at the Al/Si interface [6] and would result in a two dimensional (2-D) growth of GaN. Fig. 2 shows the observed RHEED patterns for the growth of AlN buffer layer on Si (111). The RHEED patterns became dim when a few monolayers of Al (from high flux Al) were deposited on the substrate. This dim pattern indicated excess aluminum was on the surface of the growing film. For AlN growth under high Al flux, the weakly reconstructed RHEED pattern indicated that the surface morphology has a 2-D component, as shown in Fig. 2(b). After the growth of AlN buffer layer, RHEED displayed a sharp and clear streaky pattern, indicative of good surface morphology as revealed in Fig. 2(c).

The final growth step took place at 840 °C. The film was doped p-type by varying the Mg-cell temperature ranging from 360 °C–380 °C. During the growth of p-GaN (Fig. 2(d)), the streaky RHEED pattern was sharpened compared to Fig. 2(c), suggesting improvement in the crystalline quality of the main layer relative to the AlN buffer layer. The absence of spotty RHEED patterns throughout the entire growth

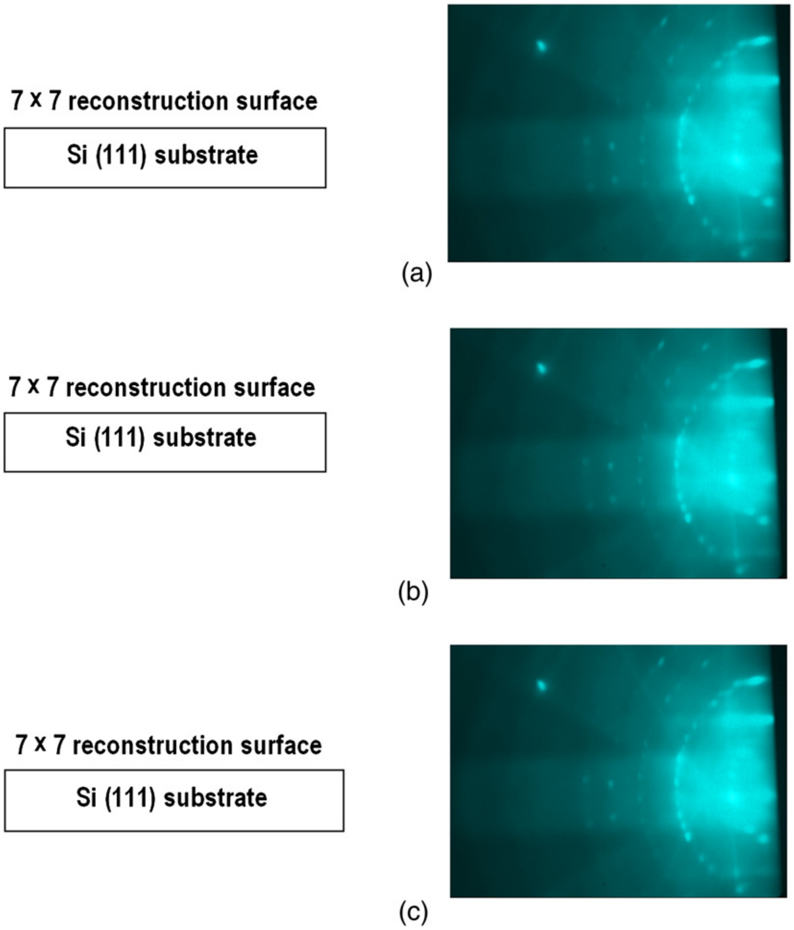

Fig. 1. RHEED patterns and corresponding schematic illustration for the Ga cleaning process on Si substrate.