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主 論 文 の 要 旨

論文題目 **Study on plasma etching of GaN at high temperatures for damageless fabrication of next-generation power devices**
（次世代パワーデバイスにおける窒化ガリウムの低ダメージ加工に向けた高温プラズマエッチングに関する研究）

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論 文 内 容 の 要 旨

GaN has attracted much attention as a promising candidate for next-generation high power devices. To realize normally-off operation in a lateral AlGaN/GaN high electron mobility transistor (HEMT), a precise and damageless etching technology with controllability of several nm-scale in depth is required to fabricate the recess gate structure. This requirement has been approached by the high-temperature Cl_2 plasma etching process.

A stoichiometric surface after the etching of GaN films can be provided by elevating the stage temperature, i.e., the ratio of Ga and N is unity. However, plasma-induced damage (PID) due to irradiations of plasma reactive components such as ion, photon, and radical, has not been completely solved so far. Therefore, the author has focused on the elucidation of the individual effects of ion, photon, and radical on damage formation and then optimized a variety of parameters for controlling the plasma etching processes.

Ions play a key role for physical bombardment damage on GaN lattices, especially for the temperatures below 400 °C. As the stage temperature increased, the evaporation rate of etched products and thermal annealing of lattice damages are positively helpful to suppress such physical damage formation. Photons with shorter wavelength of higher energies than GaN band gap energy (3.4 eV) play a critical role for the scissions of Ga-N bonds and these damage formations are thermally enhanced at 500 °C. Radicals, unlike ions and photons, induce morphologically surface roughness on GaN, owing to preferentially chemical etching of intrinsic crystalline defects, such as a large density of threading dislocations in the GaN films. These effects will be discussed in chapter 3.

Next, the author finds an optimum condition for etching with less damage. The optimum temperature of 400 °C minimizes damage formation and provides a smooth and stoichiometric GaN surface after the etching processes. In chapter 4, results of the optimization of plasma etching at 400 °C for a shallow etching of nearly 7 nm are discussed. On the other hand, the detailed mechanisms of thermally photon-induced damage occurred at 500 °C are analyzed in chapter 5. Notably, this additional photon irradiation is effective for a deep etch of the smooth GaN surface and the mechanisms are also described in chapter 6.

This dissertation is organized as follows; the research backgrounds are written in chapter 1. The plasma processes remained issues of the PID on degradation of device performances such as a current collapse phenomenon and a high leakage current. In physical aspect, the author focuses on the formation of nonstoichiometric surface of GaN after the conventional Cl_2 plasma etching at room temperature (RT). The main cause has been widely considered as the higher vapor pressures of nitrogen-containing by-products than those of Ga-containing residues. To solve this problem, the high-temperature Cl_2 plasma etching is proposed to maintain the surface stoichiometry of GaN films after plasma etching.

In chapter 2, the principals of plasma diagnostic and film analyses are explained. Optical emission spectroscopy (OES) is utilized to diagnose plasma. X-ray photoelectron spectroscopy (XPS) is applied to analyze the surface stoichiometry. Atomic force spectroscopy (AFM) is carried out to observe the surface morphology. Scanning electron microscopy (SEM) is used to observe the etch profiles and estimate the etch depths. Photoluminescence (PL) is applied to investigate the optical properties of GaN films.

In chapter 3, the effects of ions, photons, and radicals on damage formation are discussed. By means of separation from the effects of plasma using the pallet for plasma evaluation (PAPE) method, the author finds that damage formation on GaN was strongly dependent with the stage temperatures. As a result, PID was successfully suppressed by carrying out Cl_2 plasma etching at the optimal temperature of 400 °C. Namely, the etching characteristics in PL, stoichiometric composition, and surface roughness were improved. Consequently, Cl_2 plasma etching at 400 °C resulted optimally in low damage and a stoichiometric and smooth GaN surface.

In chapter 4, dependences of etch time and incident ion energy on PL properties and surface morphologies of GaN films exposed to Cl_2 plasma at 400 °C are systematically discussed. The author describes the temporal behavior of ion induced-damage, which saturated by prolonging etch time and reached constantly within more than 2 min. On the other hand, the GaN surface was continuously roughed with etch time. As a consequence, PID was successfully suppressed by reducing bias voltage, leading to the decrease in incident ion energy, and thus the near-band-edge emission (NBE) intensity as PL properties was increased to 98.8% of the initial value in the optimally plasma etching condition for a remove of 6.8 nm of GaN films.

In chapter 5, the photon-dominated damage formation in Cl_2 plasma etching of GaN at 500 °C is described. The author concludes the thermally enhanced formation of photon-induced damage on GaN. Deep UV photons emitted from Cl_2 plasmas became a critical cause of degradation in both PL properties and surface stoichiometry as PID in GaN films after high-temperature Cl_2 plasma etching. As depended on the stage temperatures above 500 °C, the thermally enhanced formation of photon-induced damage, which originated from Cl_2 plasma emissions with energies higher than GaN band gap energy, degraded PL property of GaN films as a result of the thermally enhanced photon-dissociated Ga-N bonds with a depth of approximately 3.2 nm. The author emphasizes the clarification of the wavelength-dependence of optical emission lines on photon-induced damage formation. Damage formation induced by high energy photons was attributed to Cl_2 plasma emissions at 258 nm and 306 nm. The line at 258 nm favorably formed these damages than those at 306 nm because of its higher photon energy. In order to fabricate highly reliable GaN-based devices, UV emissions during plasma etching processes should be precisely controlled.

In chapter 6, the author expresses an important finding with respect to suppress the roughening of a GaN surface by simultaneous irradiations of photon and radical. After Cl radical exposure, a N-rich chlorination layer was formed on the GaN surface, revealing severe chemical reactions and thereby the surface was roughened. However, this chemical reaction was effectively suppressed in simultaneous irradiations of photon and radical as a result of the photodissociation of both Ga and N chlorides by photons in vacuum ultraviolet (VUV) region and ultraviolet (UV) region at 258 and 306 nm of Cl_2 plasma emission. Therefore, a smooth and damageless surface would be highly expected for a deep etching of GaN by controlling photon irradiations precisely. Namely, in fabrications of a vertical GaN power device using high-temperature Cl_2 plasma etching, a suppression of this severely roughened surface in the deep etching of GaN will be important.

In chapter 7, the author summarizes the investigation about the individual contributions of ion, photon and radical on PID. The damageless etching of GaN films was actually demonstrated by controlling the stage temperature, and bias voltages were proved to be critical in Cl_2 plasma etching of GaN to suppress damage formation. The thermally enhanced photon-induced damage by deep UV photons emitted from Cl_2 plasma is also addressed. The damageless fabrication of GaN power devices opens the novel plasma etching technology with precise control nm-scale in depth.