Investigation of Material Removal Mechanisms Involved in ICP Etching of InGaN/GaN

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ABSTRACT

The chemical inertness and high bond strength of GaN material do not permit a simple wet etch process for pattern transfer in fabrication of devices. It has been demonstrated inductively coupled plasma could significantly improve etching process producing a highly anisotropic etch profiles and high etch rate. Etching of InGaN/GaN multiple quantum wells (MQWs) materials was performed using inductively coupled Cl_2/Ar plasmas, and the effects of main process parameters such as gas flow rate, induction rf power, self bias voltage, chamber pressure on the etching mechanisms and their relations to the etch rates and morphologies of InGaN/GaN materials was investigated. InGaN/GaN etch rates increased with the increase of chlorine radical density and ion energy, and a vertical etch profile having an etch rate over 450 nm/min could be obtained at 350 W induction power and –400 V bias voltage. The etch rate of InGaN/GaN MQWs appeared to be more affected by the chemical reaction between Cl radicals and GaN compared to the physical sputtering itself.

Keywords: ICP etching, InGaN/GaN, material removal mechanisms

感應耦合電漿蝕刻 InGaN/GaN 材料移除機制研究

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摘 要

氮化鎵(GaN)材料具有寬能隙，適合應用於 UV/藍/綠光發光二極體、雷射二極體和高功率的電子元件。但由於 GaN 材料具有很強的鍵結力及化學惰性，難以利用傳統的濕蝕刻製作出所需的圖案，而感應耦合電漿蝕刻系統是在目前深蝕刻技術中最廣為被利用的，透過適當的製程參數控制，可以得到光滑的蝕刻側壁、高深寬比、高非等向性、高蝕刻速率及高選擇比等。本研究使用 Cl_2/Ar 感應耦合電漿對 GaN/InGaN 材料進行蝕刻，製程參數如氣體流速、感應耦合電漿功率等對蝕刻機制及其相關的蝕刻率、形貌影響都做了探討。GaN/InGaN 材料的蝕刻速率隨著 Cl 活性離子密度和離子能量的增加而升高，當基板自偏壓–400 V，感應耦合電漿功率為 350 W 時蝕刻速率可達到 450 nm/min，且可得到垂直的蝕刻側壁。InGaN/GaN 材料的蝕刻速率受 Cl 活性離子密度的影響較受單純的離子能量的影響來的顯著。

關鍵詞：感應耦合電漿蝕刻，InGaN/GaN，材料移除機制

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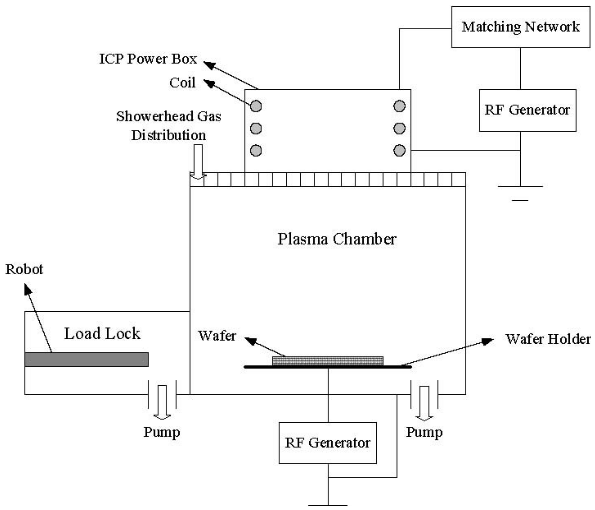
I. INTRODUCTION

GaN has a wide band-gap and direct leap which makes it a very suitable material for fabricating UV photo-detector, blue and green LEDs, laser diode and other high power/temperature electronic devices[1-2]. The technique for producing GaN/InGaN hetero-epitaxial layer is rather mature and, as a result, blue light LEDs has successfully improved its efficiency and commercialized. As to the blue light laser diode, smooth side-wall surfaces are critical requirement for laser cavity, on top of the high quality epitaxial-layer, and are normally done by plasma etching. Owing to its high bond strength (8.9eV/atom) and chemical inertness, conventional wet-etching process is no longer suitable for pattern transfer in fabrication of devices and is replaced by plasma etching technique. Amongst the reactive gases such as Cl_2、CH_4/H_2、I_2、Br_2、BCl_3 and SF_6 commonly used in etching III-V compound semiconductors, Cl_2 plasma is most widely used for etching GaN related materials. However, if In is involved in the reaction (etching InGaN quantum well for example), dry etching mechanism gets complex and fine etched surface becomes hard to obtain due to the big gap in meltling points between products of the process namely $GaCl_3$ and $InCl_3$ (201^oC for $GaCl_3$, and 600 ^oC for $InCl_3$)[3-5]. The high density plasma-based etching systems now in use can roughly classify into two categories namely inductively coupled plasma-reactive ion etching (ICP-RIE) and electron cyclotron resonance (ECR) plasma etching system. Being relatively easier to design and to maintain, ICP is widely used for deep etching. However, efforts have to be made to improve its anisotropy, etch rate, surface quality obtained, reduction of induced-damage, aspect ratio, and selectivity. Modification of system design and appropriate selection of process parameters are necessary to advance the process. During the plasma etching process, ions and radicals released from the plasma are responsible for the physical sputtering and chemical etching in removing materials respectively. Proper tuning the weighting of these two effects involved in the etching process can result in good surface finish, high resolution patterns, minimized plasma-induced damage and high quality devices without trading off too much etch rate. In an attempt to further the understanding of fundamental mechanisms and to improve the process, influences of gas composition, chamber pressure, ICP power, bias and RF power on the etching rate and surface integrity were investigated in this study.

II. EXPERIMENTAL SET-UP

A Plasma Therm 770 system was used in this study as plasma machine (Fig. 1a). Sample was mounted on an electrostatic chuck(ESC) where He gas was circulating around sample and chuck to provide proper cooling during plasma etching. An RF powered reactor was employed to generate inductive electrical then magnetic fields so as to induce coupled plasma. Another RF power of 13.56MHz was linked to the ESC to induce dc bias and to further improve the destructive energy of ion bombardment. Cl_2 and Ar were fed in the ICP chamber through flow controllers. The sample was φ2” (0001), c-sapphire substrate on top of which a GaN buffer layer and InGaN/GaN multiple quantum wells were grown (Fig. 1b). Nickel was adopted as etch-mask material and was removed by Piranha(H_2SO_4/H_2O_2) after etching. Etch-depth, surface morphology, microstructure and composition were subsequently measured and analyzed by a stylus profiler(α-Step), SEM, AFM and EDAX respectively.



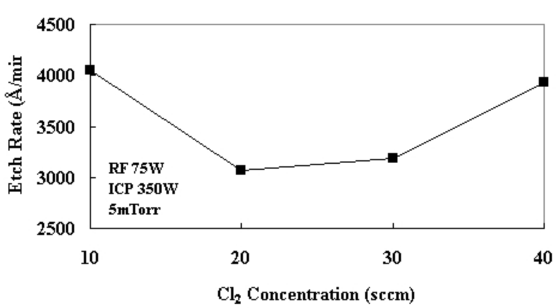
p-GaN	~0.2µm
InGaN (MQW)	~0.1µm
n-GaN	~3µm
GaN buffer layer	~0.02µm
Sapphire substrate	~450µm

(a) (b)

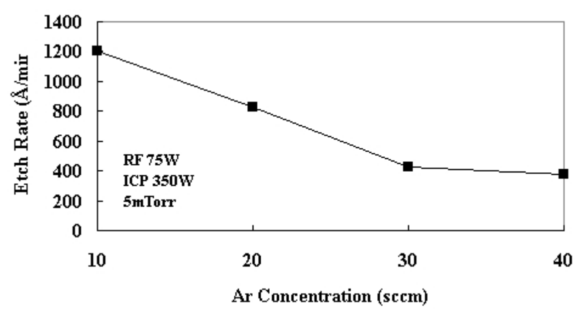
Fig. 1. (a) Schematic diagram of the ICP system (b) the structure of the specimen used in this study.

III. RESULTS AND DISCUSSION

Shown in Fig.2(a) is the influence of Cl_2 flowrate on the etching rate under the conditions of 75W RF power, 350W ICP power and 5mTorr chamber pressure. Cl_2-plasma etching is dominant with chemical reaction. The etch rate, instead of going straight upward or downward, had a slump at Cl_2 flowrate of 20~30sccm. Based on the works done by Lee et al [2] the product generated by the etching process $InCl_3$ had formed a selvedge layer and limited the etching rate due to its high boiling point.



(a)



(b)

Fig. 2 Effect of (a) Cl_2 (b) Ar flow on etch rate of GaN (75W, RF-power, 350W ICP-power and 5mTorr chamber pressure).

In the case of Ar plasma, being energized/ accelerated by the bias, the bombardment will be capable of inducing bond breaking of Ga-N and performing physical etching by sputtering. However, the etch rate obtained by the physical etching is rather low and it is a major drawback. Shown in Fig.2(b) is the influence of Ar flowrate on the etching rate under the conditions of 75W RF power, 350W ICP power and 5mTorr chamber pressure. The etch rates of Ar-plasma are generally lower than that of Cl_2 plasma and etch-rate decreases as Ar flow rate increases. This means that, without the help from Cl-ion induced chemical reaction, solely depending on physical bond-breaking is not a very effective way for material removal. Further increase the Ar flow rate will not push up the etch rate but can result in more damages on surface. Adding Ar into Cl_2-plasma and making the physical bond-breaking to work with chemical reaction proved to be a better and effective choice for etching GaN.

Since RF-power can induce dc bias, raising the RF-power will result in an increase in induced dc-bias (as shown in Fig.3). The dc-bias can then improve the destructive energy of ion bombardment and improve the etch rate. As shown clearly in Fig.3, the higher the RF-power the higher the dc-bias and etch rate could be obtained. This trend will stretch to a critical point where chemical reaction is saturated and further increase RF-power can only increase the physical sputtering. As a result, the slope upward is slowing down.

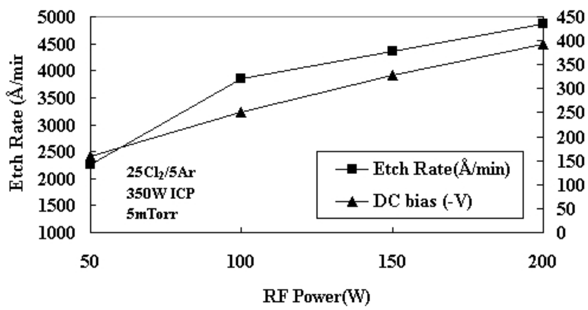


Fig. 3 Higher the RF-power can result in higher the dc-bias and etch rate (Cl_2=25sccm, Ar=5sccm, ICP Power = 350W and chamber pressure=5mTorr).

ICP power is used to dissociate gas molecule and produce plasma, higher ICP-power means more radicals are generated. Shown in Fig.4 is the influence of ICP-power on the etching rate under the conditions of 75W RF power, Cl_2=25sccm, Ar=5sccm and 5mTorr chamber pressure. It demonstrated that the high ICP-power could promote etch rate and, in the same time, suppress self-induced bias. This is in good agreement with the equation (*PRF=IIon x VBias*), where PRF and IIon represent the ion flux induced by RF power and ICP-power respectively, VBias is the self-induced dc-bias. As to the influence of chamber pressure, higher pressure means higher gas concentration, shorter mean-free- path, lower molecular dissociation and lower impact energy.

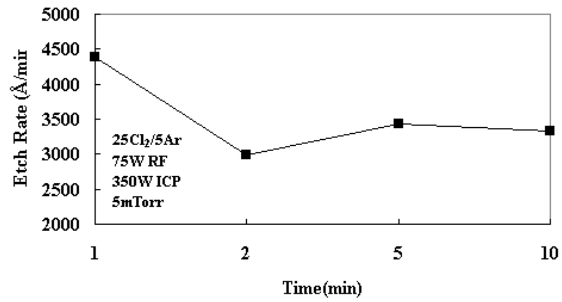


Fig. 4 Influence of ICP-power on the etch rate and dc-bias (75W RF power, Cl_2=25sccm, Ar=5sccm and 5mTorr chamber pressure).

The increase in chamber pressure resulted in, as shown in Fig. 5, a decrease in corresponding etch rate. It was also found in this study that, having all etching parameters fixed, the etch rate got lower with time (as shown in Fig. 6).

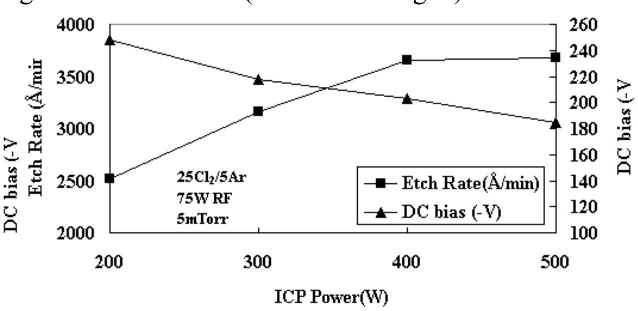


Fig. 5 Influence of chamber pressure on etch rate (75W RF power, 350W ICP power, Cl_2=25sccm, Ar=5sccm and 5mTorr) chamber pressure).

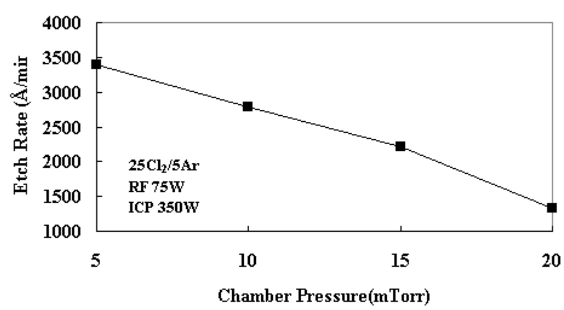


Fig. 6 Etch rate plotted against time (75W RF power, 350W ICP power, Cl_2=25sccm, Ar=5sccm and 5mTorr chamber pressure).

The possible reasons for this is that it gets harder for radical to get into and for the etch products to come out of a deep trench. An ideal dry etching process is to effectively remove material and achieve a feature with good dimension accuracy and surface/sde-wall with good surface finish. However, as shown rather clearly in Fig. 7, fine etch-marks (on the side-wall), residual pillars, mounds and etch pits (Fig.8) are commonly observed on the etched GaN sample if there are any contamination during the pre-process preparation or process parameters are not optimized. It is also found in this study that defects such as residual pillars and etch pits can be significantly minimized by adding gases such as BCl_3, H_2 or CH_4 (Fig.9).

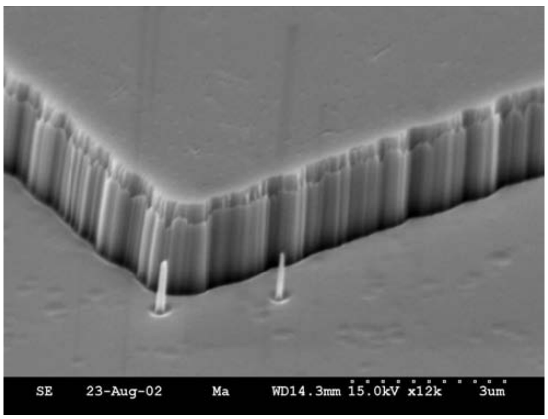
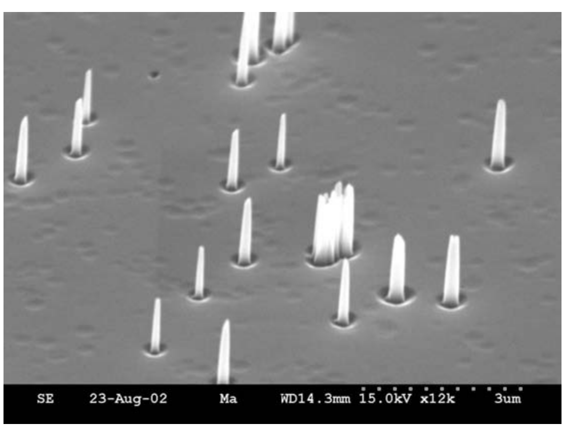
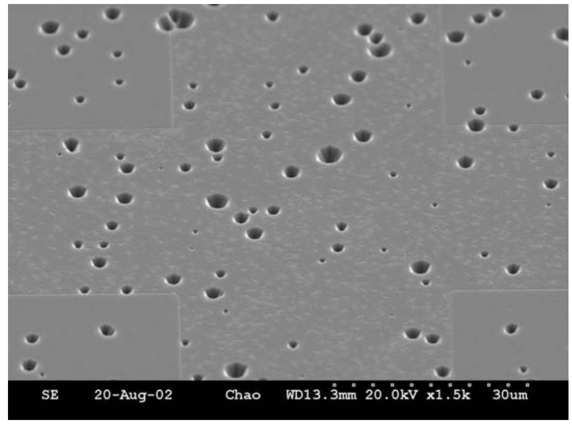


Fig. 7 SEM micrograph of GaN surface after ICP etching (75W RF power, 350W ICP power, Cl_2=25sccm, Ar=5sccm and 5mTorr chamber pressure).



(a)



(b)

Fig. 8 (a) residual pillars and (b) etch pit of GaN surface after ICP etching (200W RF power, 350W ICP power, Cl_2=25sccm, Ar=5sccm and 5mTorr chamber pressure).

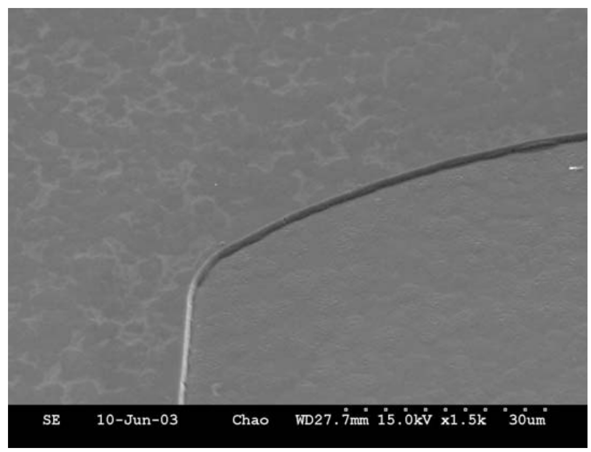


Fig.9 GaN surface after ICP etching (8 sccm CH_4, 10%BCl_3/90%Cl_2, Pressure=2 mTorr，450W ICP power, 150W RF power).

IV. CONCLUSIONS

1). Adding Ar into Cl_2-plasma and making the physical bond-breaking to work with chemical reaction proved to be a better and effective choice for etching GaN. 2). higher RF-power means higher dc-bias and, generally speaking, higher etch rate can be obtained 3). high ICP-power can promote etch rate 4). increase in chamber pressure will result in a decrease in etch rate.

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