ICP dry etching ITO to improve the performance of GaN-based LEDs

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Abstract: In order to improve the light efficiency of the conventional GaN-based light-emitting diodes (LEDs), the indium tin oxide (ITO) film is introduced as the current spreading layer and the light anti-reflecting layer on the p-GaN surface. There is a big problem with the ITO thin film's corrosion during the electrode preparation. In this paper, at least, the edge of the ITO film was lateral corroded 3.5 μm width, i.e. 6.43%–1/3 of ITO film's area. An optimized simple process, i.e. inductively couple plasma (ICP), was introduced to solve this problem. The ICP process not only prevented the ITO film from lateral corrosion, but also improved the LED's light intensity and device performance. The edge of the ITO film by ICP dry etching is steep, and the areas of ITO film are whole. Compared with the chip by wet etching, the areas of light emission increase by 6.43% at least and the chip's lop values increase by 45.9% at most.

Key words: ITO; lateral corrosion; dry etching; light extraction efficiency

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1. Introduction

In recent years, GaN-based materials have gained much interest in semiconductor device research and application field because of its direct wide bandgap and excellent optical properties. However, how to improve the GaN-based LED's light extraction efficiency is a technical bottleneck. Current spread layer is an optional way to enhance the light extraction efficiency. Recently, people developed the indium tin oxide (ITO) transparent conductive material which has a penetration rate of more than 90%, very low resistivity ($\leqslant 5 \times 10^{-4}$ $\Omega\cdot$cm^2), and conductivity equivalent to metal[1]. Because of the high penetration rate and high electrical conductivity, ITO thin film has become the best choice for the material of current spreading layer. But along with the well current spreading, another problem of lateral corrosion happens during wet etching. If the ITO is lateral corroded, the surface of p-type GaN cannot be completely covered, and the ITO film could not play an important role as current spreading and anti-reflecting film. In this paper, the mechanism of ITO lateral corrosion was analyzed and an optimization process was introduced to solve this problem. The process could improve LED's performance and also make the LED fabrication process simple.

2. Experiment and analysis

The ITO film consists of a lot of crystalline grains (Fig. 1). The combination between crystalline grains is not very tightly, so that the ITO film can be easily corroded[1]. In addition, the impurity of GaN epitaxial film, equipment, environment and moisture could lead to serious ITO lateral corrosion[2]. We try to avoid the film surface's impurity and moisture in the experiment process. But the etching time is not very easy to control. If the etching time is too short, large area of ITO film will remain on the n-mesa and the sidewall. If the etching time is too long, it will cause excessive ITO corrosion. Once the lateral corrosion occurred, the ITO film would be destroyed[3]. Therefore, wet etching ITO is very difficult to control, and the phenomenon of ITO lateral corrosion is pervasive in the wet etching process.

In this study, GaN epitaxial wafers were all grown on c-face (0001) sapphire (Al_2O_3) substrates through metal organic vapor-phase epitaxy. The layer structure of the GaN epitaxial wafers consisted of a 30 nm thick GaN nucleation layer, a 3 μm thick undoped GaN (3×10^{16} cm^{-3}) layer, five periods of InGaN–GaN MQW as active, and a 1 μm thick Mg doped GaN layer. To obtain a p-type GaN film, postgrowth thermal annealing was performed at 750 ℃ in nitrogen ambient to activate the Mg dopants. The hole concentration of the p-type GaN films, as determined by a Hall measurement, was approx-

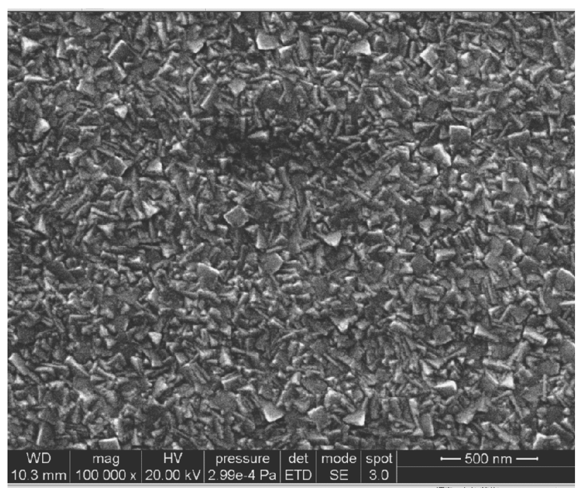

Fig. 1. SEM picture of the surface of ITO film.

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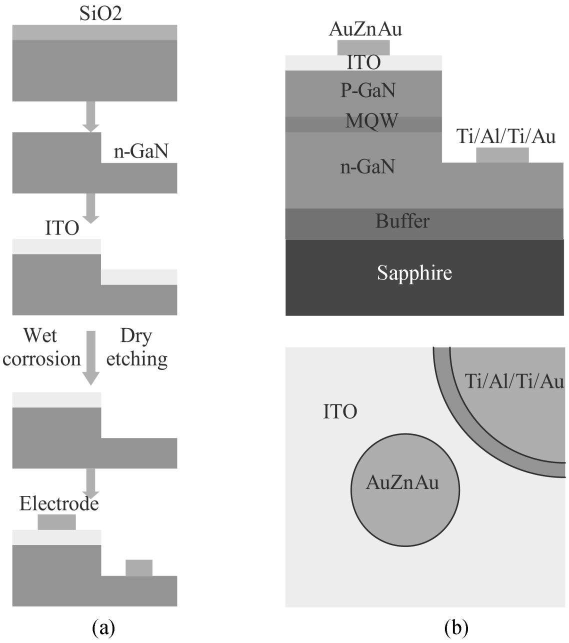


Fig. 2. (a) Process flow and (b) structure of GaN-based LED.

imately 2×10^{17} cm^{-3}.

The process flow chat is shown in Fig. 2(a). Five GaN-based LED epitaxial samples were used for the fabrication of the LED. First, 500 nm SiO_2 was deposited on the surface of GaN by PECVD (plasma enhanced chemical vapor deposition). Second, the mesa graphics was formed by light lithography, then the n-GaN was exposed by ICP etching and the depth etched was 800 nm. Third, all samples were evaporated 250 nm ITO film. Consequently, the ITO film of four samples were wet etched, the ITO film of the last sample was etched by ICP and the depth must be larger than the thickness of ITO films so that all unwanted ITO film was removed. At last, p-electrode and n-electrode were made. The structure of GaN-based LED is shown in Fig. 2(b).

3. Results and discussion

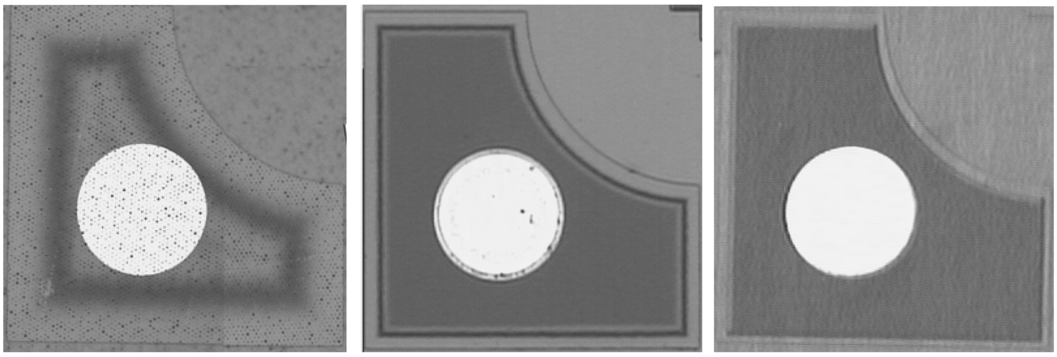
The p-GaN layer is very thin and the current is difficult to spread completely, so an ITO current spread layer plays a very important role in GaN-based LEDs. The influences of the pollution and the water vapor are very important, and a little impurity and water vapor could cause ITO to be lateral corroded (Fig. 3(b)). In severe cases, a majority of ITO was lateral corroded (Fig. 3(a)). In this paper, in order to remove all the unwanted ITO film, 10 nm of the mesa was also etched away, so the ITO and 10 nm of the mesa were etched together. The environment had little influence on the ICP method, so the ITO film's edge was neat and steep (Fig. 3(c)). The factors which influence ITO lateral corrosion were uncertain, and the corroded area was also uncertain. In order to compare test results, three chips were selected. These three chips were respectively the severe lateral corroded, a little corroded and ICP dry etching. We signed the three chips as chip A (lateral corroded), chip B (corrode), chip C (ICP etching). The experiment process of the devices A and B are exactly the same. But the result of devices A and B is uncertain. The wet etching is uneasy to control. The one reason for this is the structure of the ITO film, and another reason is the influence of environment. Usually, four wafers were wet etched, just the best device and the worst device were selected to compare with the ICP dry etching. The device A is the worst device and the device B is the best device. So we introduced the ICP dry etching to solve the problem.

From Fig. 3, we can see that the surface of device A is destroyed and there are many impurities on the surface of the wafer. The impurity has a very important influence on the lateral corrosion. Besides impurity, there are two main explanations. In the process of wet etching, there are some leftover corrosives on the surface of the ITO film. The ITO corrosive leaves over the gap of graphics after light lithography. The agua regia which was used as the ITO corrosive has very strong electrolytic conductivity. When we test the device, the leftover electrolyte transmits current and engenders electric leakage and the series resistance, so it destroyed the ITO film[4]. Guo *et al*.[5] reported another explanation. They thought a lot of GaO_x and carbon was on the surface of the GaN wafer.The aguia regia could clean the oxidation layer on the surface of GaN wafer, so in the process of wet etching, the ITO corrosive can etch the oxidation layer between the ITO film and the p-GaN to make the ITO film peel[5].

From Fig. 4, the ITO film of chip A was severely lateral corroded, and the area of lateral corroded ITO film didn't calculate exactly. We just estimated that 1/3 areas of ITO film was lateral corroded. The ITO film of chip B was least lateral corroded. 3.5 μm width edge of ITO film was lateral corroded and 6.43% of ITO film's areas was lateral corroded. Meanwhile, the edge of chip C by ICP dry etching was very neat and steep.

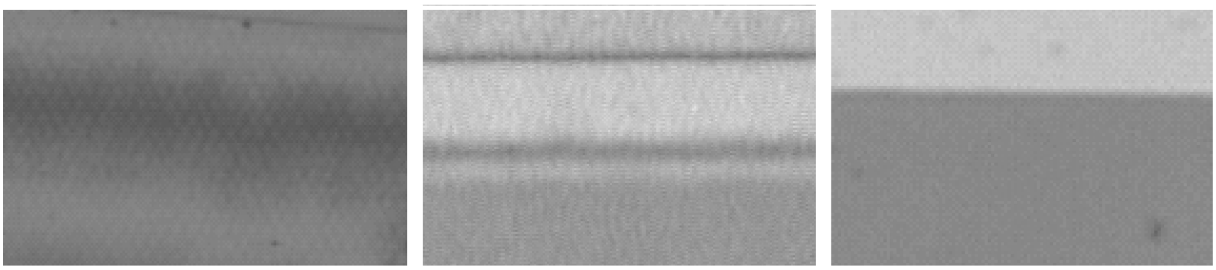
Figure 5(a) shows the current–voltage (I–V) characteristics of the chip A (lateral corroded), chip B (corroded) and chip C (ICP etching). The chip C (ICP etching) exhibited a very good p–n junction behavior (low resistant contact). At a driving current of 20 mA, the forward voltages were about 3.4 V. The chip B (corroded) showed nearly voltage with chip C voltage (ICP etching), while the characteristics of chip A (lateral corroded) were very bad. In the process of the chip fabrication, the ICP dry etch technology was used. The ITO and the mesa can be etched together. After ITO was etched, the mesa was continued to be etched to make all unwanted ITO corroded away. In this way, the phenomenon of short-circuit was avoided. Figure 5(b) shows the LOP (light output power)–current (L–I) characteristics. The chip C (ICP etching) enhanced about 45.9% in light output power. We know that the ITO film was lateral corroded, and then the area of light emission was small, so light intensity decreased.

From the test results, the chips by the ICP etching increased about 45.9% than the chips by the conventional wet etching. The ITO current spreading layer of the chip A (lateral corroded) was lateral corroded. The current was very different to spread to the whole active region which was below the corroded ITO film. There was no or very little current in that part of active region. In this case, the light extraction efficiency was very low. We observed the chip A (lateral corroded) under the microscope, and find there was no light in the region where the ITO film was corroded. At the same time, we didn't make ITO film on a chip, and found there was light only around the electrode. So solving the problem of lateral corrosion had a very important effect to improve the light extraction efficiency.



(a) Latcral corroded (b) Corroded (c) ICP ctching

Fig. 3. Overlook surface structures of LED chips by (a, b) wet etching and (c) ICP dry etching ITO.



(a) Lateral corroded (b) Corroded (c) ICP etching

Fig. 4. Edge picture of chips A, B and C.

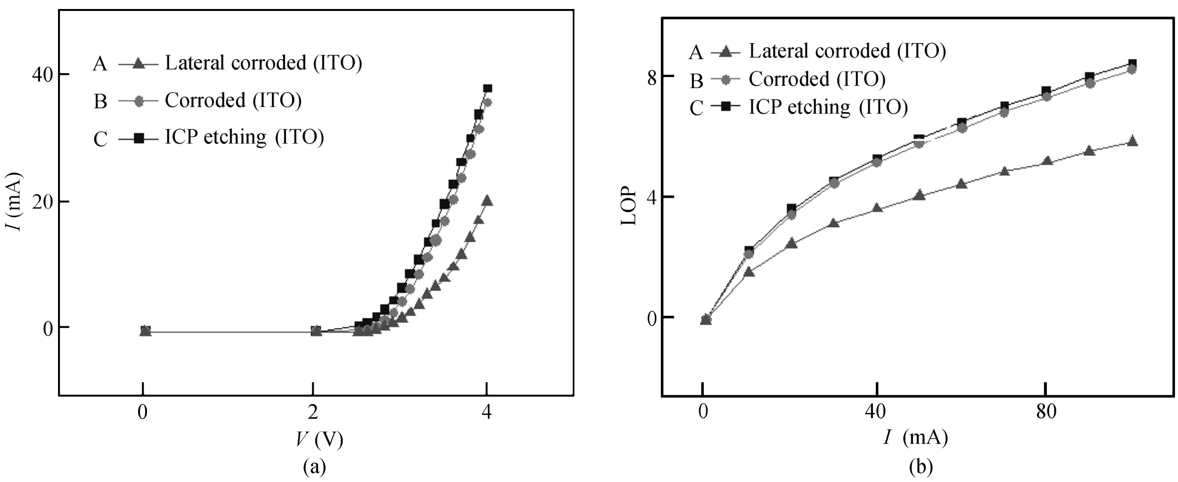


Fig. 5. Characteristics of LED chips by wet and ICP dry etching ITO. (a) $I-V$ characteristic. (b) $L-I$ characteristic.

4. Summary

The ITO film consisted of a lot of crystalline grains, so it was very easy for the ITO film to be lateral corroded. In addition, the surface of GaN epitaxial wafer was also influenced by the environmental pollution which made ITO easy to be lateral corroded. Therefore, dry etching as a simple process was introduced. The simple process not only prevented the ITO film from lateral corrosion, but also improved the LED's light extraction efficiency and device performance. In the least case, ITO film was corroded 1/3 of areas. In the best case, the edge of ITO film was lateral corroded 3.5 μm width, 6.43% of ITO film's areas was lateral corroded. We compared the value of lop and found that the improved process chip's lop values increased about 45.9% than conventional chip's lop value at most.

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