Effect of surface treatment of GaN based light emitting diode wafers on the leakage current of light emitting diode devices*

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(Received 30 April 2009; revised manuscript received 25 May 2009)

To form low-resistance Ohmic contact to p-type GaN, InGaN/GaN multiple quantum well light emitting diode wafers are treated with boiled aqua regia prior to Ni/Au (5 nm/5 nm) film deposition. The surface morphology of wafers and the current–voltage characteristics of fabricated light emitting diode devices are investigated. It is shown that surface treatment with boiled aqua regia could effectively remove oxide from the surface of the p-GaN layer, and reveal defect-pits whose density is almost the same as the screw dislocation density estimated by x-ray rocking curve measurement. It suggests that the metal atoms of the Ni/Au transparent electrode of light emitting diode devices may diffuse into the p-GaN layer along threading dislocation lines and form additional leakage current channels. Therefore, the surface treatment time with boiled aqua regia should not be too long so as to avoid the increase of threading dislocation-induced leakage current and the degradation of electrical properties of light emitting diodes.

Keywords: GaN, light emitting diode, surface treatment, leakage current

PACC: 7360L, 7280E

1. Introduction

GaN based light emitting diodes (LEDs) have been widely used in many areas, such as traffic signals, full-colour displays, backlights in liquid crystal displays, and lighting.[1,2] The various applications demand a higher lighting efficiency and a longer lifetime for LEDs. For this purpose a good Ohmic contact is necessary to achieve low resistance and stable display devices.[3−5] The surface treatment of LED wafers is important for the fabrication of Ni/Au Ohmic contact electrodes. In the present study, we research the effect of surface treatment of GaN based LED wafers with boiled aqua regia on the current–voltage (I–V) characteristics of LED devices fabricated from the treated wafers. Before the deposition of Ni/Au (5 nm/5 nm) film, several LED chips are treated with boiled aqua regia for different lengths of time. Then the changes of surface morphology are measured by atomic force microscopy (AFM). After the electrode is fabricated, I–V characteristics of LED devices fabricated from the wafers are studied. According to a comparison between samples with different aqua regia treatment time lengths, it is found that the surface treatment can effectively remove the oxide from the top of the p-GaN layer thereby improving the Ohmic contact performance.[6] But at the same time the surface treatment also reveals defect-pits which may be related to the termination of threading dislocation (TD) lines on the surface,[7] and can introduce a higher leakage current. The simulation analysis results of the I–V curves of LED devices are consistent with the assumption that the additional leakage current channels are attributed to the diffusion of metal atoms of the Ni/Au electrode into the p-GaN layer during Ni/Au electrode annealing.

2. Experiment

The InGaN/GaN multiple quantum well LED structures were grown on c-plane sapphire substrates by low-pressure metal organic chemical vapour depo-

*Project supported by the National Natural Science Foundation of China (Grant Nos. 60776047, 60836003, 60476021 and 60576003).

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sition (MOCVD). Trimethylgallium, trimethylindium, and ammonia were used as Ga, In, and N precursors, respectively. The LED wafers were composed of a GaN buffer layer, 2 μm thick undoped GaN layer, 2 μm thick Si-doped n-GaN layer, five periods of InGaN (3 nm) / GaN (10 nm) multiple quantum well (MQW) active layers, and a 0.2 μm thick Mg doped p-GaN layer. The typical full width at half maximum (FWHM) of the (0002) high resolution x-ray rocking curve of the GaN layer is 210 arcsec, and the emission wavelength of the LED structure is 425 nm. The coplanar LED diode devices were fabricated by a standard process with a 300×300 μm area. Before the deposition of the Ni/Au (5 nm/5 nm) transparent electrode on the top of the p-GaN surface, the LED wafer was first cut into three samples (which were named samples A, B, and C respectively) and cleaned in acetone and alcohol. Following the cleaning, boiled aqua regia (composed of hydrochloric acid and nitric acid with a ratio of 3:1) was used to perform the chemical treatment of samples A, B, and C for 0 min, 20 min, and 40 min, respectively. A small part of the samples was cut to measure their surface morphology by atomic force microscopy. The other parts of samples A, B, and C were used to fabricate LED devices and investigate their I–V characteristics.

3. Results and discussion

After the surface treatment, AFM was used to measure the surface morphologies of samples A, B, and C respectively. The AFM surface scanning images of samples A and C are shown in Figs. 1(a) and 1(b) respectively. It is found that many defect-pits appear on the surface of sample C after 40 min aqua regia treatment, while no defect-pits are observed for sample A which was not treated. A few defect-pits are also observed in sample B which was treated by aqua regia for 20 min. The density of defect-pits of sample C is about $3\times10^8/\mathrm{cm}^2$, which is close to the dislocation density D ($\approx3.5\times10^8/\mathrm{cm}^2$) estimated from the FWHM of the x-ray rocking curve[8]

$$D \approx \beta_\alpha^2/(4.36\cdot b^2), \tag{1}$$

where β_α is the FWHM value and b is the length of the Burgers vector. It implies that the pits are the termination of TD lines on the surface.[9,10]

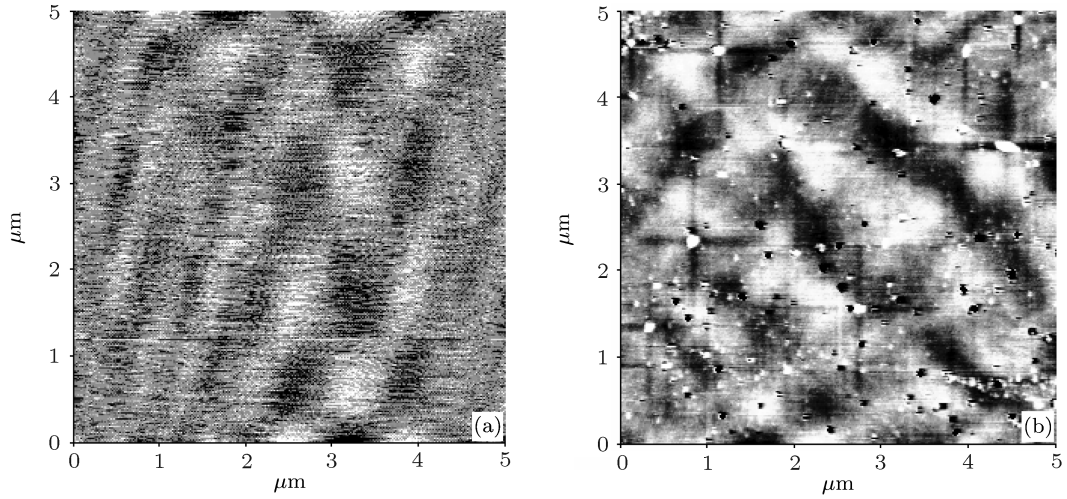


Fig. 1. (a) AFM image of sample A which is untreated in aqua regia. (b) AFM image of sample C which is treated in aqua regia for 40 min.

Figure 2 shows I–V characteristics of LED devices fabricated from the three samples A, B, and C in a logarithm scale of the current I. It is obvious that the sample A without aqua regia treatment displays the lowest leakage current while its working voltage under a current of 20 mA is as high as 4.2 V. Samples B and C have the same working voltage of about 3.3 V with a 20 mA injection current. Sample C, which is

treated with aqua regia for 40 min, suffers a much higher leakage current than sample A, while sample B at both reverse bias and forward bias has almost the same leakage current value as sample A. A combination of the phenomena shown in Figs. 1 and 2 reveals that the boiled aqua regia treatment can effectively remove the oxide from the p-GaN surface of the samples, thus improving the Ohmic contact performance between the p-contact electrode and the p-GaN layer, thereby reducing the forward voltage drop of LED devices. However, due to the presence of defect-pits, the metal atoms of the transparent electrode may diffuse into the p-GaN layer more easily during the annealing process of Ni/Au film,[11] so the leakage current of diodes along the TD pipes terminated at defect-pits is enhanced.[11,12] However, if the surface treatment time is not too long, the increase of leakage current of the LED is very small and can be nearly neglected as shown in the case of sample B.

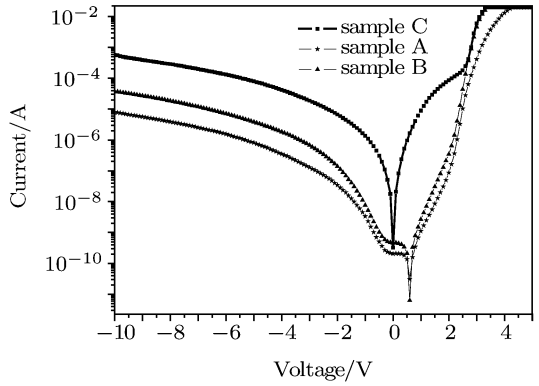


Fig. 2. I–V characteristics of samples A, B and C in the logarithm scale.

In order to check the validity of the above conclusions, we use the circuit model shown in Fig. 3 to simulate the obtained I–V curves in Fig. 2.

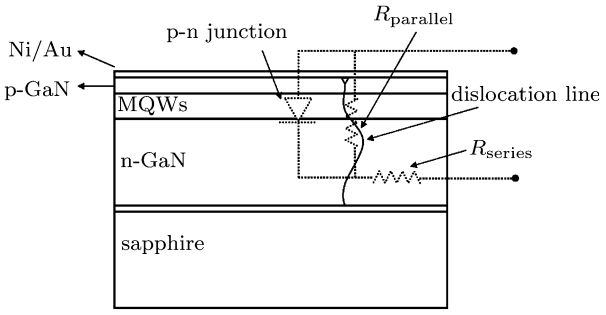


Fig. 3. Schematic model for LED structure with dislocation line; in the inset the dash line represents the circuit model for an LED device.

The following equations are employed in the analysis,[13]

$$V = I \cdot R_{\rm series} + (I - I_{\rm junction})R_{\rm parallel}, \quad (2)$$

$$I_{\rm junction} = I_0[\exp(q(V - I \cdot R_{\rm series})/nkT) - 1], \quad (3)$$

where $I_{\rm junction}$ is the current flow across the p-n junction, I_0 is the saturation current, n is the ideality factor of the diode, q is the unit charge, k is the Boltzmann constant, T is the absolute temperature, I is the total injection current, $R_{\rm parallel}$ is the parallel resistance mainly attributed to the TD lines, and $R_{\rm series}$ is the series resistance. We replot the I–V curves of Fig. 2 in the linear scale as shown in Fig. 4(a), in which the fitted values of series resistance of samples A, B, and C are 43 Ω, 24 Ω, and 24 Ω, respectively.

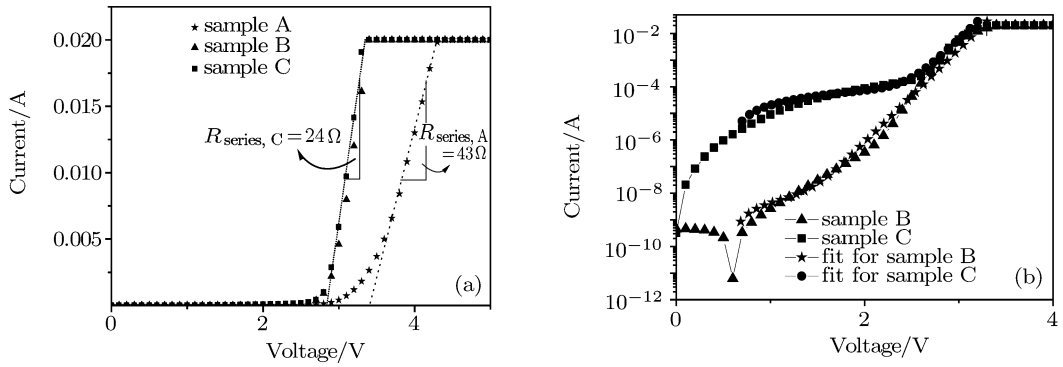


Fig. 4. (a) I–V curves of samples A, B and C under forward bias voltage in the linear scale. (b) Simulated and experimental I–V curves of samples B and C under forward bias voltage.

From Eqs. (2) and (3), the following expression can be obtained:

$$I = \frac{V}{R_{\rm series} + R_{\rm parallel}} + \frac{I_0 \cdot R_{\rm parallel}}{R_{\rm series} + R_{\rm parallel}} \exp\left(\frac{q(V - I \cdot R_{\rm series})}{nkT}\right) - \frac{I_0 \cdot R_{\rm parallel}}{R_{\rm series} + R_{\rm parallel}} \quad (4)$$

Figure 4 (b) shows the calculated curves of samples B and C according to expression (4) with the fitted parameter values of n, I_0, $R_{\rm series}$, and $R_{\rm parallel}$ as listed in Table 1.

Table 1. Fitted parameter values of n, I_0, $R_{\rm series}$, and $R_{\rm parallel}$ of samples A, B and C respectively.

sample	n	I_0/A	$R_{\rm series}/\Omega$	$R_{\rm parallel}/\Omega$
A	5	10^{-11}	43	2×10^{8}
B	4.8	10^{-11}	24	1×10^{8}
C	5	5×10^{-11}	24	2×10^{4}

It can be seen that the fitted parameters of n and I_0 are almost the same for the three samples, but the value of $R_{\rm series}$ for sample A nearly doubles those for samples B and C, and the value of $R_{\rm parallel}$ for sample C which suffered a 40 min-long aqua regia treatment is 4 orders less than that of samples A and B. The simulation results of $R_{\rm series}$ and $R_{\rm parallel}$ give a strong support to the above-mentioned analysis that the aqua regia treatment can effectively remove the oxide from the p-GaN surface, and meanwhile it may produce additional leakage current channels since the metal diffusion along TD lines will take place more easily. In fact, Hsu *et al.*[11] have found that the metal atoms of the Ni/Au electrode can easily diffuse into the p-GaN layer through dislocation pipes under high temperature annealing.

4. Conclusion

The effects of boiled aqua regia treatment on the electrical properties of InGaN/GaN LEDs are investigated. According to the results of AFM images and I–V characteristics of samples with different surface treatment times, we find that aqua regia treatment can effectively remove the oxide from the p-GaN surface and also reveal defect-pits at the terminated points of TDs on the p-GaN surface. An appropriate aqua regia treatment can achieve a low specific resistance of p-ohmic contact, but too long an aqua regia treatment time will bring on a high leakage current and thus degrade the electric performances of LED devices.

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