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Improvement of the electrical performance of near UV GaN-based light-emitting diodes using Ni nanodots

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Abstract

We report on the improvement of the electrical characteristics of GaN-based light-emitting diodes (LEDs) fabricated with Ag (1 nm)/indium tin oxide (ITO) (250 nm) p-type contacts by using Ni nanodots. As-deposited Ag/ITO contacts with and without the Ni nanodots give non-linear electrical behaviour. However, annealing the samples at 530–630 °C for 1 min in air results in ohmic behaviour. The reverse leakage current characteristics of near UV LEDs are much improved when the Ni nanodots are used. The output power (at 20 mA) of LEDs fabricated with the Ni nanodots is enhanced by a factor of 1.34 as compared with that of LEDs made without the Ni nanodots.

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III–V nitrides-based light-emitting diodes (LEDs) operating in the green, blue, and UV spectral region have a wide range of applications [1,2]. To maximize the performance of such LEDs, high-quality p-type electrodes having low contact resistivity, good optical properties, and good thermal stability (in particular for high power LED operation) have been developed. Early works were mainly concerned with metal-based multiplayer schemes, such as Ni-, Pd-, Pt-, and Au-based layers [3–9]. These metal-based schemes are semi-transparent and so yield poor optical performance. Recently, transparent conducting oxides (TCOs)-based p-type ohmic contacts having high transparency as well as low contact resistance have been reported [10,11]. For example, Song et al. reported TCOs-based ohmic schemes combined with Ag layers (1–3 nm thick), such as Ag/Sn-doped indium oxide (ITO) [9] and Ag/Sb-doped tin oxide (ATO) [10]. These schemes yielded specific contact resistance in the range of 10^{-4}–10^{-5} Ω cm^2 and transmittance of 88–96% at 460 nm.

It was, however, shown that for p-type ohmic contact schemes containing Ag and Au layers, annealing causes the indiffusion of Ag and Au atoms into the active regions of LEDs through threading dislocations, consequently leading to an increase of reverse leakage current, namely, the degradation of device performance [12,13]. Thus, it is imperative to develop an effective way to minimize reverse leakage current in order to improve the electrical performances of LEDs. Despite its importance, however, studies

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of reducing such leakage problems associated with the indiffusion of Ag or Au have not been extensively performed until now. In this work, to improve the reverse leakage characteristics of LEDs made with Ag/ITO p-type electrodes, we have introduced Ni nanodots between the Ag/ITO contacts and p-GaN. It is shown that the introduction of Ni nanodots effectively improves the electrical behaviours of LEDs as compared with those made with the only Ag/ITO contacts.

Metalorganic chemical vapour deposition was used to grow a 2.0 μm-thick unintentionally doped GaN layer on a (0001) sapphire substrate, on which a 1.0 μm-thick p-GaN:Mg layer ($N_a = 4 \times 10^{17}\,cm^{-3}$) was grown. The GaN layer was ultrasonically degreased using trichloroethylene, acetone, methanol, deionised water (DI), and buffered oxide etch (BOE) for 5 min in each step. Subsequently, a 2 nm-thick Ni layer was deposited on the GaN by electron-beam evaporation (PLS 500 model), which was rapid-thermal-annealed at 500 °C in N_2 ambient for 1 min (AST™). Fig. 1 shows a field-emission scanning electron microscopy image obtained from the Ni-deposited GaN layer after annealing. It is evident that the thin Ni layer was broken into nanodots (6–23 nm in size) and randomly distributed. The density of the nanodots was measured to be about $2 \times 10^{11}\,cm^{-2}$. The GaN layer with the Ni nanodots was ultrasonically degreased using trichloroethylene, acetone, methanol, and deionised water (DI) 5 min in each step, and then pre-treated with buffered oxide etch (BOE) for 1 min and rinsed in DI water [14]. After the BOE treatment, circular patterns were defined by the standard photolithographic technique for measuring specific contact resistance using circular transfer length method (CTLM). The outer dot radius of the CTLM patterns was 75 μm and the spacing between the inner and the outer radii changed from 4 to 25 μm. Ag (1 nm)/ITO (250 nm) films were then deposited by electron-beam evaporation under base pressure of 2×10^{-7} Torr. Some of the samples were subsequently rapid-thermal-annealed at 530 and 630 °C for 1 min in air. Current–voltage (*I*–*V*) characteristics of contacts were performed using a parameter analyzer (HP 4155A). In addition, InGaN/GaN multiple-quantum-well (MQW) LEDs, where the Ni nanodots/Ag (1 nm)/ITO (250 nm), and Ti (30 nm)/Al (500 nm) served as p-type current spreading and n-type contact layers, respectively, were also fabricated and characterized.

Fig. 2 shows *I*–*V* characteristics for the Ag/ITO contacts with the Ni nanodots before and after annealing, measured on the 4 μm-spaced pads. For comparison, the *I*–*V* characteristic of the Ag/ITO contacts annealed at 630 °C is also presented. The contacts with and without the Ni nanodots produce linear *I*–*V* characteristics after rapid-thermal-annealing, indicating the formation of ohmic contacts. It is noted that the contacts with the nanodots show somewhat better electrical behaviours as compared to that without the nanodots. Specific contact resistances were determined from plots of the measured resistances versus the spacing between the inner and outer regions. The method of least squares was used to obtain straight-line plot of the voltage drops versus gap spacings [15]. Measurements showed that the specific contact resistances are 9.18×10^{-5} and $8.46 \times 10^{-5}\,\Omega\,cm^2$ at 530 and 630 °C for 1 min, respectively. For the sample without the nanodots, the specific contact resistance is measured to be $1.69 \times 10^{-4}\,\Omega\,cm^2$. This indicates that the use of Ni nanodots is beneficial to the formation of high-quality ohmic contact on p-type GaN. The exact mechanism why the addition of the Ni nanodots improves the electrical properties is not clear at this moment. However, the improvement may be explained as follows. First, it might be related to the interaction between Ni and GaN during annealing, leading to the removal of a contamination layer on GaN and the uptake of hydrogen from the GaN surface region (causing the dissociation of Mg–H complex and so an increase of hole concentrations), as suggested by Yu and Qiao [16] and Qiao et al. [17]. In addition, the Ni could react with GaN and form either Ni-gallide [5], or Ni–Ga solid-solution [6], resulting in the generation of deep acceptor-like Ga vacancies near the GaN surface region

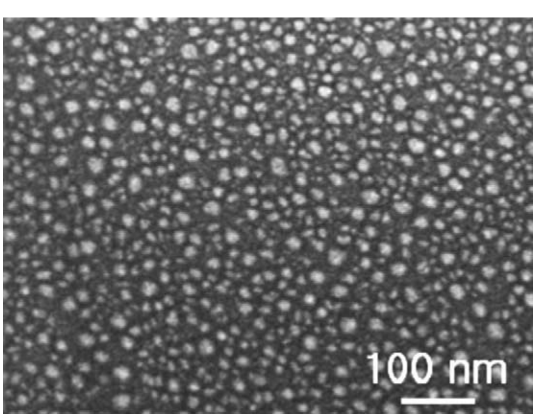

Fig. 1. A field-emission scanning electron microscopy image obtained from the Ni-deposited GaN layer after annealing.

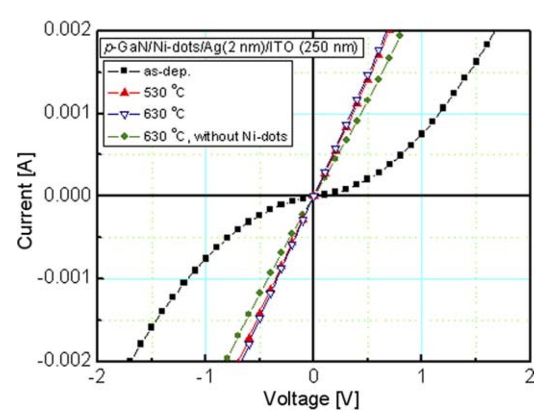

Fig. 2. The *I*–*V* characteristics for the Ag/ITO contacts with the Ni nanodots before and after annealing, measured on the 4 μm-spaced pads. For comparison, the *I*–*V* characteristics of the Ag/ITO contacts annealed at 630 °C is also presented.

underneath the contact and so the reduction of the Schottky barrier height [14,18,19]. It was shown that Ag could react with GaN and form Ag–Ga solid-solution upon annealing, leading to the formation of Ga vacancies near the GaN surface region [20]. Furthermore, it may be related to the formation of inhomogeneous Schottky barriers at the contact/GaN interface. In other words, there are two different nanodots, such as Ni- and Ag-based alloys at the interface region. This could lead to an increase of the electric field at the metal/semiconductor interface [21], which causes a lowering of barrier heights and so the reduction of contact resistivity [11,22–24]. However, detailed mechanisms are presently under investigation.

Fig. 3 shows the current characteristics of LEDs fabricated with the Ag/ITO p-contact layers with and without Ni nanodots, which were annealed at 630 °C. The forward *I*–*V* characteristics of the LEDs with the Ni nanodots give somewhat better than that of LEDs without the Ni nanodots, as shown in the inset of Fig. 3. It is, however, shown that there is a significant difference in the reverse current characteristics of the LEDs with and without the Ni nanodots. Measurements show that the typical reverse current of the LEDs is 5.64×10^{-5} and 1.48×10^{-4} A at the reverse voltage of -10 V for the p-type contacts with and without the Ni nanodots, respectively. The result shows that the reverse leakage current of LEDs can be considerably reduced by introducing the Ni nanodots. The improved leakage characteristics could be related to the presence of Ni nanodots, which hampers the indiffusion of Ag into threading dislocations by blocking such dislocations and/or hindering the surface diffusion of Ag.

Fig. 4 shows the current–light output power of LEDs made with the Ag/ITO contact layers with and without the Ni nanodots. It is shown that the LED with the Ni nanodots yields higher output power than that without the Ni nanodots. For example, the output power (at 20 mA) of the LED with the Ni nanodots was improved

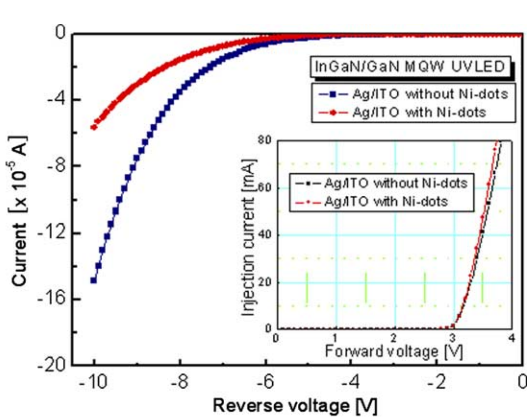

Fig. 3. The reverse current characteristics of LEDs fabricated with the Ag/ITO p-contact layers with and without Ni nanodots, which were annealed at 630 °C. The forward *I*–*V* characteristics of the LEDs are shown in the inset.

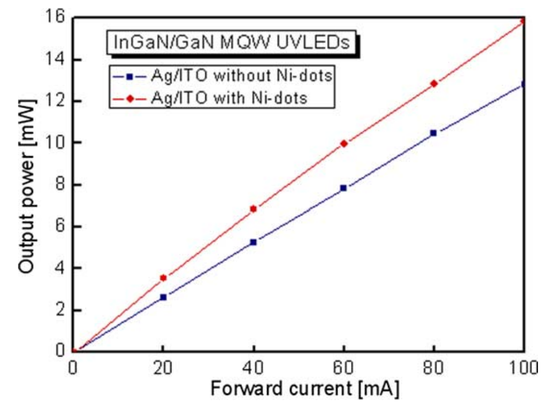

Fig. 4. The current–light output power of LEDs made with the Ag/ITO contact layers with and without the Ni nanodots.

by a factor of 1.34 as compared with that of the LED without the nanodots.

To summarize, we have investigated the effect of the Ni nanodots on the electrical performance of LEDs made with Ag/ITO p-type contacts. It was shown that the use of the Ni nanodots is fairly effective in improving reverse current leakage characteristics. Consequently, LEDs made using the Ag/ITO contacts combined with the Ni nanodots produced higher light output as compared with ones with the only Ag/ITO contacts. The result indicates that the insertion of the Ni nanodots could be a promising process for the fabrication of high-performance high-brightness GaN-based LEDs.

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