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The improvement of low-resistance and high-transmission ohmic contact to *p*-GaN by Zn^+ implantation

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The electrical and optical characteristics of Zn^+ ion-implanted Ni/Au ohmic contacts to *p*-GaN were investigated. After the preparation of Ni/Au electrode on the surface of *p*-GaN, the metal/*p*-GaN contact interface was doped by 35 keV Zn^+ implantation with fluences of 5×10^{15}–$5 \times 10^{16}\ \mathrm{cm}^{-2}$. Subsequent rapid thermal annealing of the implanted samples were carried in air at 200–400 °C for 5 min. Obvious improvements of the electrode contact characteristics were observed, i.e. the decrease of specific contact resistance and the increase of light transmittance. The lowest specific contact resistance of $5.46 \times 10^{-5}\ \Omega\ \mathrm{cm}^2$ was achieved by $1 \times 10^{16}\ \mathrm{cm}^{-2}$ Zn^+ implantation. The transmission enhancement of the electrodes was found as the annealing temperature rises. Together with the morphology and structure analyses of the contacts by scanning and transmission electron microscope, the corresponding mechanism for such an improvement was discussed.

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1. Introduction

Gallium nitride (GaN) is a key material for blue and ultraviolet light emitting devices, high-temperature and high-power microwave devices. Thus the formation of high-quality ohmic contacts to GaN is of great importance. However, there are many difficulties in the realization of low-resistance ohmic contacts to *p*-GaN, the two main obstacles are (i) the difficulty in high concentration doping of *p*-GaN due to the large ionization energy (170 MeV) of Mg dopants and (ii) the lack of appropriate metals with work function higher than that of *p*-GaN (~7.5 eV, sum of band gap of 3.4 eV and electron affinity of 4.1 eV). Therefore improving ohmic contacts to *p*-GaN has become a crucial issue in developing GaN-based devices.

According to tunneling transmission theory of metal/semiconductor contacts, specific contact resistance is mainly determined by Schottky barrier height (SBH) and carrier concentration. Thus reducing SBH and increasing hole concentration can both help to form ohmic contacts to *p*-GaN [1]. So far many efforts have been made to achieve these goals, such as surface treatment by chemical solution and plasma treatment [2,3], different metallization schemes using high work function elements [4,5] and group II elements [6–8], different thermal annealing processes [9,10] and the adoption of a short period superlattice surface capping layer [11,12], etc.

In these attempts, the introduction of *p*-type dopants to the contact interface region is commonly recommended. Ion implantation technology is efficient in achieving this goal, as it is well known that ion implantation has the advantages to introduce impurities with precise control of concentration and distribution [13–16]. In addition, the impact dynamical effects could promote diffusion and interfacial reactions. Recently ohmic contacts on *n*-type layers in GaN/AlGaN/GaN formed by dual-energy Si ion implantation were reported [17]. However, the relevant implantation research result in the study of metal/*p*-GaN contacts has not been reported yet. In this work, the contact interface in conventional chosen contact scheme, i.e. *p*-GaN/Ni/Au, was doped by Zn^+ implantation. The improvement of both specific contact resistance and light transmission is achieved and the possible mechanisms are proposed and discussed.

2. Experimental

The *p*-GaN films used in this study were grown by metal–organic chemical vapor deposition (MOCVD) on sapphire substrate. Mg-doped GaN with a thickness of 0.5 μm was grown on 4 μm undoped GaN layer. Hall measurement showed that the hole concentration in the *p*-GaN films was about $7 \times 10^{17}\ \mathrm{cm}^{-3}$.

To investigate the electrical contact characteristics of electrodes on *p*-GaN, circular-transfer length method (*c*-TLM) patterns were defined on the surface of *p*-GaN by a standard photolithographic technique after an ultrasonically clean with buffered oxide etch (BOE). The inner dot radius was 120 μm and the spacing between the inner and the outer radius was varied from 5 to 30 μm.

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Ni(5 nm)/Au(10 nm) films were deposited on *p*-GaN by electron beam evaporation and were rapid thermal annealed (RTA) in air at 500 °C for 5 min before ion implantation. In order to ensure the dopants distribution mainly centered at the contact interface region, the energy of Zn^+ implantation was set at 35 keV, which was calculated from the simulation by TRIM code [18]. Fig. 1 shows the schematic diagram of Zn^+ implantation. The implantation fluences were set at 5×10^{15}, 1×10^{16}, 2×10^{16} and $5 \times 10^{16}\ cm^{-2}$, respectively.

After RTA treatments of the implanted samples, the current–voltage (*I–V)* characteristics of the contacts were measured by Keithley 4200 semiconductor parameter analyzer. Scanning electron microscopy (SEM) and cross-section transmission electron microscopy (TEM) were used to characterize the morphology and interior structure of the Zn^+ implanted contacts. Based on energy dispersive spectrum (EDS) elemental analyses in TEM, the zinc depth distribution in Zn^+ implanted Au/Ni/*p*-GaN contacts were studied. Fig. 2 shows the depth profiles of Zn, which disclose a relatively high concentration at depth of 15 nm from the surface. As 15 nm is just the depth of contact interface between Ni(5 nm)/Au(10 nm) and *p*-GaN, selective doping of contact interface region is thus effectively achieved by Zn^+ implantation.

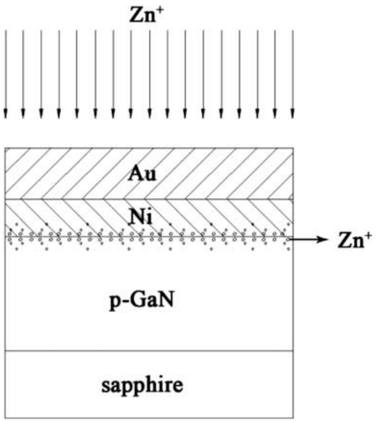

Fig. 1. Schematic diagram of Zn^+ implantation. A 35 keV implanted Zn^+ were distributed mainly around the electrode/*p*-GaN interface.

3. Results and discussion

The implanted samples were RTA in air for 5 min. Linear *I–V* curves, which indicate the formation of ohmic contacts to *p*-GaN, were obtained for the samples RTA at 200 °C, 300 °C and 400 °C, respectively. But for the implanted samples RTA at 500 °C, *I–V* curves became nonlinear, indicating the contacts turned rectifying. For the ohmic contacts to *p*-GaN, implantation fluence plays an important role in the control of specific contact resistance (ρ_c) and light transmittance.

3.1. Influence of implantation fluences

Fig. 3 shows the relation between ρ_c and implantation fluences. All the implanted samples were RTA at 200 °C. There is a sharp decrease of ρ_c when Zn^+ implantation fluence is less than $1 \times 10^{16}\ cm^{-2}$, while a slow increase of ρ_c when the fluence is above $1 \times 10^{16}\ cm^{-2}$. Thus the implantation of Zn^+ is actually able to improve the ohmic contacts but the reduction of ρ_c does not show monotonous relation with the implantation fluence.

As a group II element, Zn introduction to the interface of metal/*p*-GaN could improve the hole concentration near the surface of *p*-GaN layers [19,20]. The incorporation of group II elements to the electrode contacts, e.g. Ni–Zn/Au and Ni–Mg/Au, have been reported and the hole concentration near the contact interface with *p*-GaN are found increased [7,8,21–24]. In the mean time, the former Mg-acceptors near *p*-GaN surface would be further activated due to the dislocation of Mg–H complexes by the hydrogen-storage of Zn–Ni [6]. Besides the conventional increase of hole concentration, the dynamic annealing effect during ion implantation may promote interfacial reactions [25,26] and bring about novel Ni–Zn–Ga–O phase, other than NiO, Ni–Ga–O or Ni–Zn–O phases [8,22,24]. The resulting Ga vacancies (V_{Ga}) in *p*-GaN surface could further increase the hole concentration in the contact area [27], and then enhance the interface tunneling of carriers and decrease the contact resistivity.

However, implantation damage to the contact region by energetic ions bombardment is always inevitable. Although GaN is extremely resistant to ion disordering due to very efficient dynamic annealing processes [28] and the implanted samples are thermal treated by rapid annealing, the implantation damage in the implanted region cannot be fully recovered after high fluence implan-

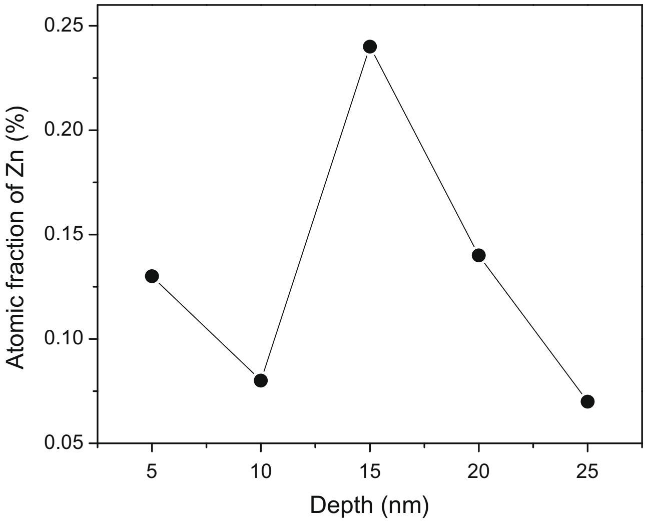

Fig. 2. Zinc depth profiles in Au/Ni contacts on *p*-GaN by 35 keV Zn^+ implantation. The values of Zn atomic fraction are calculated from EDS results.

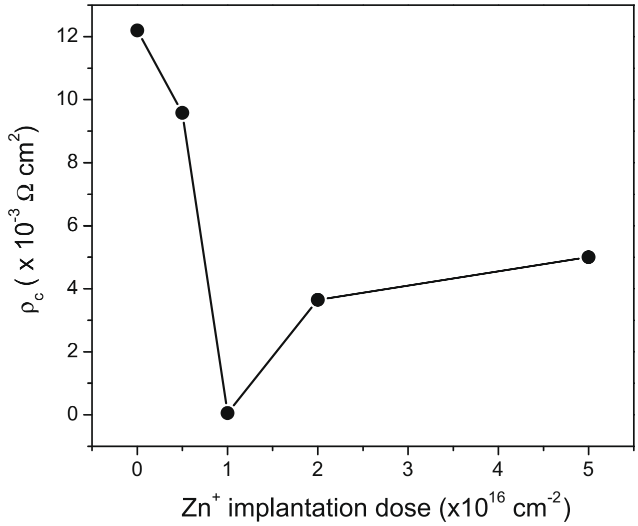

Fig. 3. Specific contact resistivity (ρ_c) as a function of Zn^+ implantation fluence. All the implanted samples are RTA in air for 5 min at 200 °C.

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