Low-resistivity Au/Ni Ohmic contacts to Sb-doped p-type ZnO

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Au/Ni contacts were fabricated on Sb-doped p-type ZnO film, which was grown on n-type Si (100) substrate with a thin undoped ZnO buffer layer by molecular beam epitaxy. As-deposited contacts were rectifying while Ohmic behavior was achieved after thermally annealing the contacts in nitrogen environment. Contact resistance was determined by linear transmission line method and it decreased with the increase of annealing temperature. Low specific contact resistivity of $3.0 \times 10^{-4}$ $\Omega \cdot cm^2$ was obtained for sample annealed at 800 °C for 60 s. Secondary ion mass spectroscopy was used to analyze elemental profiles of the contacts before and after annealing. Zn vacancies created by outdiffusion of Zn are believed to couple with activated Sb atoms to increase the surface hole concentration enabling Ohmic contact formation. © 2007 American Institute of Physics. [DOI: 10.1063/1.2750400]

ZnO is a wide band gap semiconductor material that has drawn a lot of attention recently. However, p-type doping is extremely difficult due to the presence of native defects and donors. Active research is currently carried out to explore various suitable p-type dopants for ZnO. Recently, Sb-doped ZnO films grown on Si (100) substrates exhibited reliable and reproducible p-type behavior, where Al/Ti contacts were found to be rectifying with very high contact resistance, as shown by the solid I-V curve in Fig. 1. The current conducted through them is of the order of nanoamperes. Figure 1 also shows the linear I-V characteristics in-....

Transmission line patterns with size of $75 \times 50 \mu m$ and with spacings of 10, 20, 30, and 40 $\mu m$ were fabricated by e-beam evaporation and lift-off. The fabricated patterns are shown as the inset of Fig. 1. Current-voltage (I-V) characteristics of these contacts were measured using 4155C parameter analyzer and Signatone probe station. The point of probing is shown by the arrows on a pair of contacts of the transmission line method (TLM) pattern. As-deposited contacts were found to be rectifying with very high contact resistance, as shown by the solid I-V curve in Fig. 1. The current conducted through them is of the order of nanoamperes. Figure 1 also shows the linear I-V characteristics indicating the establishment of Ohmic conduction for contacts that are annealed at 700 °C (dashed) and 800 °C (dotted). The contact resistance was found to decrease with the increase of annealing temperature, as seen from the increase in the magnitude of current. The total resistance, which includes contact resistance, was calculated from the slopes of I-V curves. A number of TLM patterns were measured and the total resistance with error factor was plotted as a function of the intercontact distance for all the annealed samples.

FIG. 1. (Color online) I-V characteristics of as-deposited contacts (solid line), annealed contacts at 700 °C (dashed line), and annealed at 800 °C (dotted line). The arrows show the point of probing on the schematic of the TLM patterns in the inset.
Figures 2(a)–2(c) show TLM result of the samples which were annealed at 700, 750, and 800 °C for 60 s. The linear characteristic was extrapolated to obtain the contact resistance and transfer length. For example, for the sample annealed at 800 °C, these values are of 168.2 Ω and 2.45 μm, respectively. The specific contact resistivity of about $3.0 \times 10^{-4}$ cm$^2$ was then calculated.

The annealing temperature dependence of specific contact resistivity of samples is shown in Fig. 3. Although Ohmic contacts were established at 700 °C, the specific contact resistivity of the sample was relatively high at about $1.2 \times 10^{-2}$ Ω cm$^2$. The specific contact resistivity decreases noticeably with increasing annealing temperature. The lowest value of $3.0 \times 10^{-4}$ Ω cm$^2$ is obtained for the sample annealed at 800 °C, which is about two orders of magnitude lower than that for 700 °C. As a matter of fact, the values are comparable with the contact resistivities of the Ohmic contacts to phosphorus-doped $p$-type ZnO which are low enough for exploring efficient optoelectronic devices.\textsuperscript{13–15}

To understand possible reason of Ohmic contact formation on Sb-doped $p$-type films, secondary ion mass spectroscopy (SIMS) measurements were carried out to obtain the Zn, O, Au, Ni, and Si elemental profiles of the samples before and after annealing. ZnO layer on Si substrate, thin layer of Ni, and thick layer of Au are clearly identified in Fig. 4(a) for the as-deposited sample. The profiles are distinct without noticeable interdiffusion between metal and ZnO. For the sample annealed at 700 °C, as shown in Fig. 4(b), interdiffusion of ZnO with Ni, and Au can be observed. O at the surface has increased while Au has decreased slightly. This is due to the surface oxidation during thermal annealing. Outdiffusion of Zn is also observed, which may be responsible for the formation of Ohmic contacts. Outdiffusion of Zn cre-
ates Zn vacancies in the ZnO film.\textsuperscript{15} Zn vacancies by themselves produce acceptor levels that are relatively deep. However, these vacancies can couple with activated Sb atoms to form Sb\textsubscript{Zn}+2V\textsubscript{Zn} and produce shallow acceptor levels.\textsuperscript{10,18} This helps us to form low-resistance contacts as the depletion region of the Schottky diode becomes very thin due to strong p-type behavior and holes can tunnel through easily. The sample annealed at 800 °C, as shown in Fig. 4(c), confirms further outdiffusion of Zn, creating more Zn vacancies and hence, better contact resistivity through increased hole concentration.

In summary, Au/Ni Ohmic contacts to Sb-doped p-type ZnO film were achieved by rapid thermal annealing. The lowest specific contact resistivity of 3.0×10^{-4} Ω cm² was obtained for the contacts annealed at 800 °C. The possible reason for the formation of Ohmic contacts involves an original high hole concentration of 1×10^{19} cm⁻³ and the formation of additional Zn vacancies, which couple with activated Sb atoms to increase the local hole concentration. These results suggest that Au/Ni is a very good metal combination to form Ohmic contacts on Sb-doped p-type ZnO for optoelectronic device applications.

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Due to typographical error, the hole concentration in line 35 of the left column and line 17 of the left column of pages 252103-1 and 252103- 3, respectively should read $3 \times 10^{19}$ cm$^{-3}$ instead of $1 \times 10^{19}$ cm$^{-3}$ and resistivity in line 36 of the left column of page 252103-1 should read 0.03 Ω cm instead of 0.3 Ω cm.

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