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Carrier concentration dependence of Ti/Al/Pt/Au contact resistance on *n*-type ZnO

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Ti/Al/Pt/Au ohmic contacts on *n*-type ZnO with a range of carrier concentrations (7.5×10^{15} – 1.5×10^{20} cm⁻³) show as-deposited specific contact resistances in the range from 3×10^{-4} to 8×10^{-7} Ω cm². Temperature-dependent measurements showed that the dominant transport mechanisms were tunneling in the contacts in the most highly doped films and thermionic emission in the more lightly doped films. After annealing at 200 °C, the lowest specific contact resistance achieved was 2.2×10^{-8} Ω cm². However, the contacts show evidence of reactions between the Ti and the ZnO film even for this low annealing temperature, suggesting that applications requiring good thermal stability will need metallurgy with better thermal stability. © 2004 American Institute of Physics. [DOI: 10.1063/1.1644318]

Currently, bulk and thin-film ZnO are attracting attention for applications to UV light-emitters, varistors, transparent high-power electronics, surface acoustic wave devices, piezoelectric transducers, gas sensing, and as a window material for display and solar cells. It has some advantages relative to GaN because of its availability in bulk, single-crystal form, and its larger exciton binding energy (~60 meV, cf. ~25 meV for GaN).^{1–21} Recent improvements in the quality and control of conductivity in bulk and epitaxial ZnO have increased interest in the use of this material for short-wavelength light emitters and transparent electronics.^{1–14} In addition, ZnO is lattice-matched to InGaN at an In composition of ~22%, raising the possibility that integration of the two materials to provide enhanced functionality may be possible.²² Transparency to visible light provides opportunities to develop transparent electronics, UV optoelectronics, and integrated sensors, all from the same material system. In some respects, the semiconducting properties of ZnO compare favorably to those of the GaN system. ZnO is a direct-bandgap semiconductor, with $E_g = 3.2$ eV. The bandgap of ZnO can be tuned via divalent substitution on the cation site.^{22–24} Cd substitution leads to a reduction in the bandgap to ~3.0 eV. Substituting Mg on the Zn site in epitaxial films can increase the bandgap to approximately 4.0 eV, while still maintaining the wurtzite structure. The electron Hall mobility in ZnO single crystals is on the order of 200 cm² V⁻¹ s⁻¹ at room temperature. While the electron mobility is slightly lower than for GaN, ZnO has a higher saturation velocity.

A key aspect of developing ZnO for these applications is the realization of high-quality ohmic contacts. Past work^{25–37} has demonstrated specific contact resistances from 3×10^{-4} to 9×10^{-7} Ω cm² for a range of metal schemes including nonalloyed In, Pt-Ga, and Ti/Au. A promising contact metallurgy is Ti/Al/Pt/Au,³⁷ which is also commonly used on GaN. In this letter, we report on the carrier concentration

dependence of contact resistance for Ti/Al/Pt/Au ohmic contacts on *p*-doped, *n*-type ZnO thin films. A minimum specific contact resistance in the 10^{-7} to 10^{-8} Ω cm⁻² range was obtained.

The phosphorus-doped ZnO epitaxial films in this study were grown by pulsed-laser deposition (PLD) on single-crystal (0001) Al₂O₃ substrate, using a ZnO:P_{0.02} target and a KrF excimer laser ablation source.³⁸ The laser repetition rate and laser-pulse energy density were 1 Hz and 3 J cm⁻², respectively. The films were grown at 400 °C in an oxygen pressure of 20 mTorr. The samples were annealed in the PLD chamber at temperatures ranging from 425 to 600 °C in O₂ ambient (100 mTorr) for 60 min. The resulting film thickness ranged from 350 to 500 nm. Four-point van der Pauw Hall measurements were performed to obtain the carrier concentration and mobility in the films. The carrier concentrations ranged from 7.5×10^{15} to 1.5×10^{20} cm⁻³, with corresponding mobilities in the range from 16 to 6 cm²/V s.³⁸

Transmission line method (TLM) patterns, consisting of 100 μm² contact pads and gap spacings varying from 5 to 80 μm, were created by dry etching of mesa and lift-off of e-beam-evaporated metals. The samples were etched in an Unaxis 790 reactor in a CH₄/Ar/H₂ plasma with gas flows of 3, 5, and 8 sccm, respectively, under 5 mTorr pressure, 200 W rf power, and 500 W inductively coupled plasma power for 3 min. The samples were then deposited with Ti (200 Å)/Al (800 Å)/Pt (400 Å)/Au (800 Å) by e-beam evaporation. After metal deposition, the samples were annealed in a Heatpulse 610 T system at 200 °C for 1 min in N₂ ambient. A secondary electron image of the ohmic contact pads on a ZnO mesa is shown in Fig. 1.

The specific contact resistance (ρ_c) was derived from the TLM-based measurements on Agilent 4156C precision semiconductor parameter. The measurement temperature was regulated with a Wentworth Labs Tempchuck TC-100, ranging from 30 to 200 °C. The interdiffusion of the metal layers was examined by Auger electron spectroscopy (AES) on a Physical Electronics 660 scanning Auger microprobe with a

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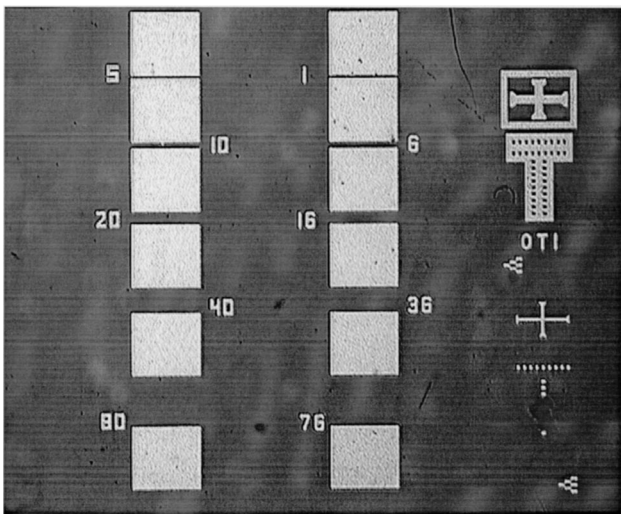


FIG. 1. Scanning electron micrograph of TLM ohmic contact pads on ZnO mesa.

10 keV, 1 μ A beam at 30° from the sample normal. Depth profiling during AES analysis was achieved by sputtering with a 3 keV Ar-ion beam at a current of 2 μ A rastered over a 3 mm² area. The sputter rate for the metals was in the range of 90 to 200 $\text{Å}/\text{min}$.

Figure 2 shows the dependence of specific contact resistance for as-deposited Ti/Al/Pt/Au, and also carrier concentration in the ZnO films on the post-growth annealing temperature. In general, the contact resistance is lower for higher carrier concentrations, with a minimum value for $8 \times 10^{-7} \Omega \text{cm}^2$ at a carrier concentration of $1.5 \times 10^{20} \text{cm}^{-3}$. At this high carrier density, tunneling was found to be the dominant transport mechanism, with the specific contact resistance³⁹ $\rho_c \sim \exp[(2\sqrt{\epsilon_S m^*}/\hbar)(\phi_{Bn}/\sqrt{N_D})]$, where q is the electronic charge, ϕ_{Bn} the barrier height, ϵ_S the ZnO permittivity, m^* the effective mass, \hbar Planck's constant, and N_D the donor density. The strong influence on doping is attributable to the $N_D^{-1/2}$ term. At lower carrier concentrations, temperature-dependent measurements over a fairly limited range (30–200 °C) showed that thermionic emission was the dominant transport mechanism, with the contact resistance³⁹ $\rho_c = (k/qA^*T)\exp(q\phi_{Bn}/kT)$, where k is Boltzmann's constant,

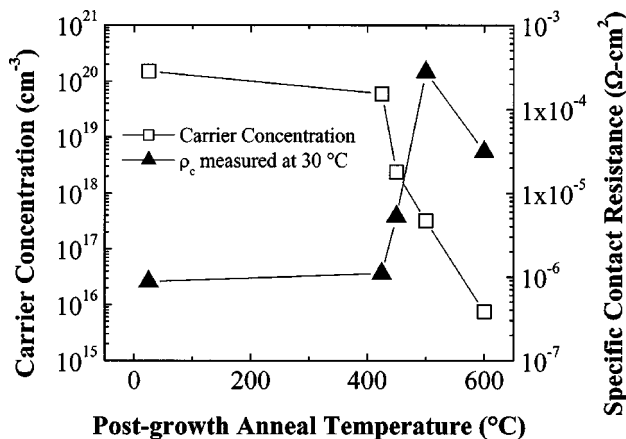


FIG. 2. Carrier concentration of epi-ZnO and specific contact resistance of as-deposited ohmic contacts measured at 30 °C versus post-growth anneal temperature.

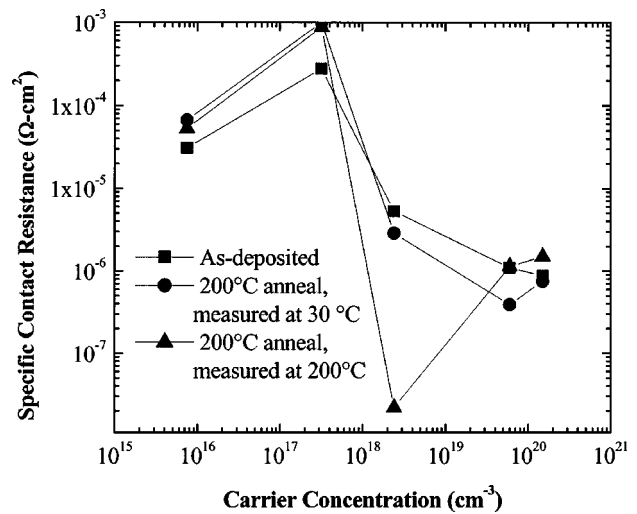


FIG. 3. Specific contact resistance versus measurement temperature of as-deposited ohmic contact measured at 30 °C, and after annealing at 200 °C, 1 min measured at 30 and 200 °C.

A^* the Richardson constant, and T the measurement temperature. Figure 3 shows a summary of the contact resistance data as a function of carrier concentration, for different anneal conditions and measurement temperatures. The lowest contact resistances obtained in the annealed samples, $3.9 \times 10^{-7} \Omega \text{cm}^2$ and $2.2 \times 10^{-8} \Omega \text{cm}^2$, were obtained in samples with carrier concentrations of $6.0 \times 10^{19} \text{cm}^{-3}$ measured at 30 °C and $2.4 \times 10^{18} \text{cm}^{-3}$ measured at 200 °C, respectively.

Finally, Fig. 4 shows AES depth profiles of the Ti/Al/Pt/Au contact after annealing at 200 °C. The initially sharp interfaces between the different metals are degraded by reactions occurring, especially between the Ti and the ZnO to form Ti-O phases^{29,30} and between the Pt and Al. We found that anneals at 600 °C almost completely intermixed the contact metallurgy. Low thermal stability of both ohmic and Schottky contacts on ZnO appears to be a significant problem in this materials system,⁴⁰ and clearly there is a need to investigate refractory metals with better thermal properties if applications such as high-temperature electronics or lasers operating at high current densities are to be realized.

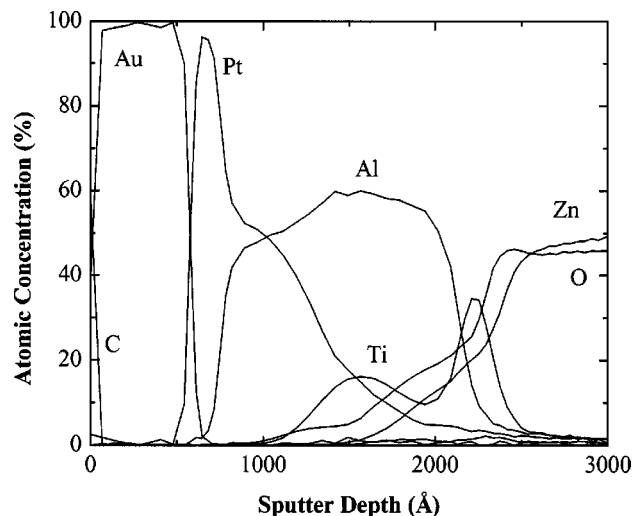


FIG. 4. AES depth profiles of Ti/Al/Pt/Au ohmic contacts to ZnO after annealing at 200 °C.

In summary, specific contact resistances in the range of 10^{-7} to 10^{-8} Ω cm² were obtained for Ti/Al/Pt/Au contacts on heavily *n*-type ZnO thin films, even in the as-deposited state. However, the contacts show significant changes in morphology even for low-temperature (200 °C) anneals, and this suggests that more thermally stable contact schemes should be investigated.

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- ¹D. C. Look, *Mater. Sci. Eng., B* **80**, 383 (2001).
- ²P. Zu, Z. K. Tang, G. K. L. Wong, M. Kawasaki, A. Ohtomo, K. Koinuma, and Y. Sagawa, *Solid State Commun.* **103**, 459 (1997).
- ³D. M. Bagnall, Y. R. Chen, Z. Zhu, T. Yao, S. Koyama, M. Y. Shen, and T. Goto, *Appl. Phys. Lett.* **70**, 2230 (1997).
- ⁴M. Wraback, H. Shen, S. Liang, C. R. Gorla, and Y. Lu, *Appl. Phys. Lett.* **74**, 507 (1999).
- ⁵J.-M. Lee, K.-K. Kim, S.-J. Park, and W.-K. Choi, *Appl. Phys. Lett.* **78**, 3842 (2001).
- ⁶J. E. Nause, III-V's Review **12**, 28 (1999).
- ⁷Y. Chen, D. Bagnell, and T. Yao, *Mater. Sci. Eng., B* **75**, 190 (2000).
- ⁸D. C. Look, D. C. Reynolds, J. W. Hemsky, R. L. Jones, and J. R. Sizelove, *Appl. Phys. Lett.* **75**, 811 (1999).
- ⁹D. C. Look, J. W. Hemsky, and J. R. Sizelove, *Phys. Rev. Lett.* **82**, 2552 (1999).
- ¹⁰F. D. Auret, S. A. Goodman, M. Hayes, M. J. Legodi, H. A. van Laarhoven, and D. C. Look, *Appl. Phys. Lett.* **80**, 956 (2002).
- ¹¹S. O. Kucheyev, J. E. Bradley, J. S. Williams, C. Jagerdish, and M. V. Swain, *Appl. Phys. Lett.* **80**, 956 (2002).
- ¹²D. C. Reynolds, D. C. Look, and B. Jogai, *Solid State Commun.* **99**, 873 (1996).
- ¹³M. Wraback, H. Shen, S. Liang, C. R. Gorla, and Y. Lu, *Appl. Phys. Lett.* **74**, 507 (1999).
- ¹⁴T. Aoki, D. C. Look, and Y. Hatanaka, *Appl. Phys. Lett.* **76**, 3257 (2000).
- ¹⁵C. C. Chang and Y. E. Chen, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **44**, 624 (1997).
- ¹⁶P. M. Verghese and D. R. Clarke, *J. Appl. Phys.* **87**, 4430 (2000).
- ¹⁷C. R. Gorla, N. W. Emanetoglu, S. Liang, W. E. Mayo, Y. Lu, M. Wraback, and H. Shen, *J. Appl. Phys.* **85**, 2595 (1999).
- ¹⁸H. Ohta, K. Kawamura, M. Orita, M. Hirano, N. Sarukura, and H. Hosono, *Appl. Phys. Lett.* **77**, 475 (2000).
- ¹⁹M. Joseph, H. Tabata, and T. Kawai, *Jpn. J. Appl. Phys.* **38**, L1205 (1999).
- ²⁰S. Krishnamoorthy, A. A. Iliadis, A. Inumpudi, S. Choopun, R. D. Vispute, and T. Venkatesan, *Solid-State Electron.* **46**, 1631 (2002).
- ²¹Y. Li, G. S. Tompa, S. Liang, C. Gorla, C. Lu, and J. Doyle, *J. Vac. Sci. Technol. A* **15**, 1663 (1997).
- ²²H. Ohta, K. Kawamura, M. Orita, M. Hirano, N. Sarukura, and H. Hosono, *Appl. Phys. Lett.* **77**, 475 (2000).
- ²³W. E. Carlos, E. R. Glaser, and D. C. Look, *Physica B* **308–310**, 976 (2001).
- ²⁴D. C. Look, J. W. Hemsky, and J. R. Sizelove, *Phys. Rev. Lett.* **82**, 2552 (1999).
- ²⁵H. Ohta, K. Kawamura, M. Orita, M. Hirano, N. Sarukura, and H. Hosono, *Appl. Phys. Lett.* **77**, 475 (2000).
- ²⁶J.-M. Lee, K.-K. Kim, S.-J. Park, and W.-K. Choi, *Appl. Phys. Lett.* **78**, 3842 (2001).
- ²⁷A. A. Iliadis, R. D. Vispute, T. Venkatesan, and K. A. Jones, *Thin Solid Films* **420–421**, 478 (2002).
- ²⁸A. Inumpudi, A. A. Iliadis, S. Krishnamoorthy, S. Choopun, R. D. Vispute, and T. Venkatesan, *Solid-State Electron.* **46**, 1665 (2002).
- ²⁹H.-K. Kim, S.-H. Han, T.-Y. Seong, and W.-K. Choi, *Appl. Phys. Lett.* **77**, 1647 (2000).
- ³⁰H.-K. Kim, S.-H. Han, T.-Y. Seong, and W.-K. Choi, *J. Electrochem. Soc.* **148**, G114 (2001).
- ³¹J.-M. Lee, K.-K. Kim, S.-J. Park, and W.-K. Choi, *Appl. Phys. Lett.* **78**, 3842 (2001).
- ³²H. Sheng, N. W. Emanetoglu, S. Muthukumar, S. Feng, and Y. Lu, *J. Electron. Mater.* **31**, 811 (2002).
- ³³H. Sheng, N. W. Emanetoglu, S. Muthukumar, B. V. Yakshinskiy, S. Feng, and Y. Lu, *J. Electron. Mater.* **32**, 935 (2003).
- ³⁴H.-K. Kim, K.-K. Kim, S.-J. Park, T.-Y. Seong, and I. Adesida, *J. Appl. Phys.* **94**, 4225 (2003).
- ³⁵H.-K. Kim, I. Adesida, K.-K. Kim, and T.-Y. Seong, *J. Electrochem. Soc.* (in press).
- ³⁶S. Y. Kim, H. W. Jang, J. K. Kim, C. M. Jeon, W. I. Park, G. C. Yi, and J.-L. Lee, *J. Electron. Mater.* **31**, 868 (2002).
- ³⁷K. Ip, K. H. Baik, Y. W. Heo, D. P. Norton, S. J. Pearton, J. R. LaRoche, B. Luo, F. Ren, and J. M. Zavada, *J. Vac. Sci. Technol. B* (to be published).
- ³⁸Y. W. Heo, S. J. Park, K. Ip, S. J. Pearton, and D. P. Norton, *Appl. Phys. Lett.* **83**, 1128 (2003).
- ³⁹S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1981).
- ⁴⁰A. Y. Polyakov, N. B. Smirnov, E. A. Kozhukara, V. I. Vdovin, K. Ip, Y. W. Heo, D. P. Norton, and S. J. Pearton, *Appl. Phys. Lett.* **83**, 1575 (2003).