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Schottky diodes of Ni/Au on *n*-GaN grown on sapphire and SiC substrates

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GaN films were grown on sapphire and SiC substrates. The crystal qualities of GaN films were investigated by photoluminescence, atomic force microscopy, and electron-beam-induced current measurements, etc. It was found that the crystal quality of GaN on SiC is better than the one on sapphire. Ni/Au Schottky contacts were formed on the both samples. The electronic characteristics were obtained by current–voltage and capacitance–voltage measurements. Schottky diodes on sapphire substrate show breakdown voltage of −80 V. While for SiC substrate, the strong breakdown was not observed even at −100 V. The reverse leakage current of diodes based on SiC is over three orders of magnitude lower than that of sapphire substrate when the reverse voltage is above 50 V, which is due to the presence of low dislocation density and high thermal conductivity.
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GaN-based wide band gap III–V nitride materials have been intensively studied because of its potentials for high-temperature and high-power electronic device applications.[1–5] As a substrate material for III–V nitride growth, sapphire, and SiC are extensively used.[1–6] However, high dislocation density, which is ascribed to large mismatch in the lattice constants and thermal expansion coefficient of III–V nitrides and sapphire, was found limiting the devices performance. SiC substrate has several advantages over sapphire, such as small lattice mismatch and thermal expansion coefficient mismatch with GaN, high thermal conductivities, etc. Much work about Schottky diodes of GaN grown on sapphire substrate has been reported previously because of its importance in applications of electronic devices.[7,8] However, very few studies have been reported on the Schottky diodes of GaN grown on SiC substrate to our knowledge. In this letter, the crystal quality of GaN films grown on sapphire and SiC substrates was investigated, and the electronic characteristics of Schottky contacts Ni/Au on *n*-GaN were also reported. It was found that the performances of Schottky diodes based on SiC substrate were improved because of high-quality GaN films with low dislocation density.

3.0 μm thick *n*-GaN films were grown on (0001) sapphire and SiC substrates by the horizontal metalorganic chemical vapor deposition at atmospheric pressure, respectively. Trimethylgallium (TMG), trimethylaluminium (TMA), and NH_3 were used as source material, and monosilane diluted in H_2 (10 ppm) was used as the *n*-type dopant. A 30 nm thick GaN low temperature (at 500 °C) buffer layer was used for the GaN film growing on sapphire substrate. For SiC substrate, an 200 nm thick AlN layer was deposited at 1150 °C as the buffer layer before the GaN epilayer was grown. The Hall mobility and carrier concentration of 509 $cm^2/V\,s$, $7\times10^{16}\,cm^{-3}$ (1142 $cm^2/V\,s$, $1.9\times10^{16}\,cm^{-3}$ at 77 K), and 568 $cm^2/V\,s$, $5.5\times10^{16}\,cm^{-3}$ (1469 $cm^2/V\,s$, $1.1\times10^{16}\,cm^{-3}$ at 77 K) were obtained by Hall measurement at room temperature for sapphire and SiC substrates, respectively. The full width at half maximums (FWHM) of x-ray rocking curve is 200 and 150 arcs for sapphire and SiC substrates, respectively. Comparing with reported results, both samples show very high crystal quality.

Photoluminescence (PL) measurements were carried out for the two samples at room temperature. The results are shown in Fig. 1. Both spectra show sharp and strong near-band-edge exciton emission peak with a FWHM of 49 meV and 41 meV for sapphire and SiC substrates, respectively. The "yellow band" modulated by Fabry–Perot interference fringes is observed. The appearance of the interference confirms the smooth surface of the films that also indicates the high crystal quality of both samples. A shift of the band-edge peak between the two samples is also observed in Fig. 1,

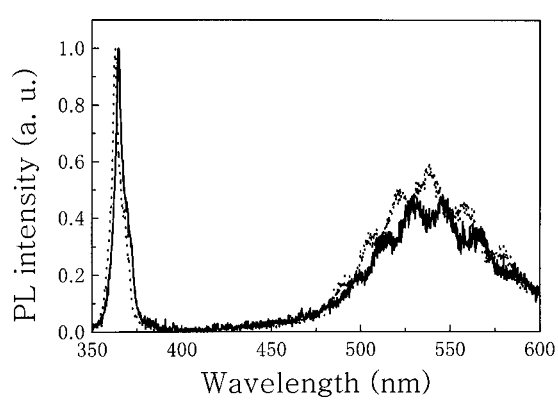

FIG. 1. Room temperature PL spectra of *n*-GaN grown on sapphire (dash line) and SiC substrates (solid line).

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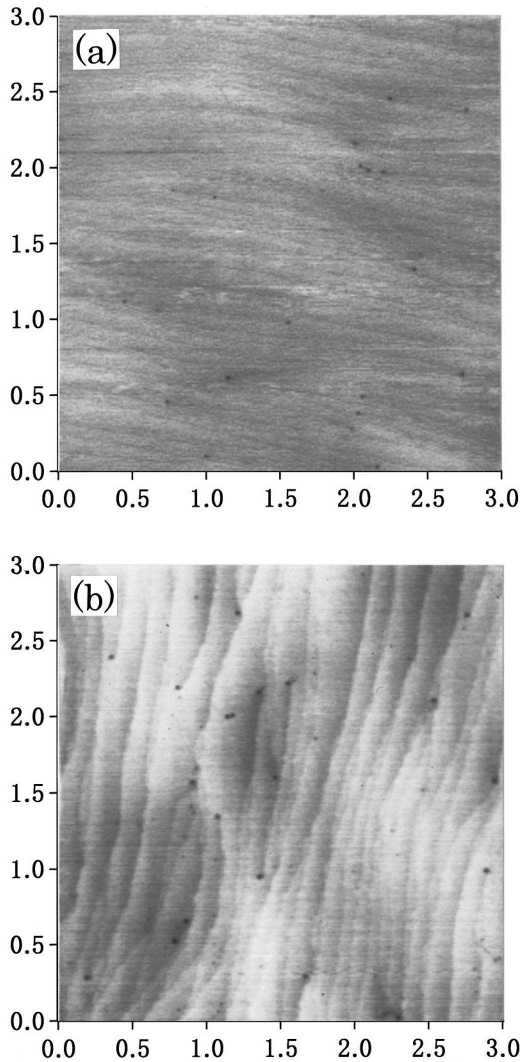

FIG. 2. AFM images of n-GaN surfaces in a $3\times3\ \mu m^2$ area; (a) n-GaN grown on SiC substrate, and (b) n-GaN grown on sapphire.

which is due to the different strains induced by the thermal expansion coefficient mismatch. Atomic force microscopy (AFM) was also performed prior to devices fabrication. AFM images of GaN surfaces are shown in Fig. 2, where [Fig. 2(a)] is for GaN grown on SiC substrate, and [Fig. 2(b)] is for sapphire substrate. The image area is $3\times3\ \mu m^2$. The wavy growth steps and some dislocations are observed clearly in the AFM images. The dislocation density is $6\times10^8\,cm^{-2}$ and $2\times10^8\,cm^{-2}$ for sapphire and SiC substrates, respectively. The low dislocation density on SiC is related to its small mismatch in the lattice constant and thermal expansion coefficient with GaN.

Before metallization, the samples were ultrasonically degreased in acetone and methanol and then the surface oxides were removed in boiling aqua regia for 30 min and rinsed in deionized water. Ohmic contacts of Ti/Al/Ni/Au layers were formed by electron beam evaporation using conventional lift-off technique. Then, the samples were annealed at 700 °C for 30 s in nitrogen ambient in order to obtain ohmic characteristics. Finally, Schottky contacts of Ni/Au were patterned using the photoresist lift-off technique. Prior to the evaporation process, the samples were dipped in $HCl:H_2O$ (1:1) etchant for 1 min to remove possible oxide on the surface.

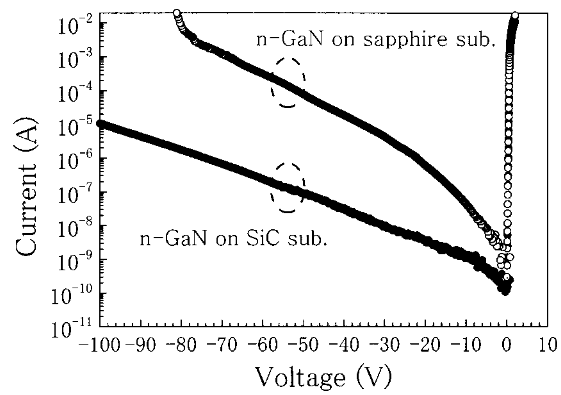

FIG. 3. log(I)–V characteristics of Ni/Au Schottky contacts on n-GaN grown on sapphire and SiC substrates.

The current–voltage (I–V) characteristics of Au/Ni/n-GaN Schottky contact on the two samples were measured at room temperature using HP4145B semiconductor analyzer. The typical semilog I–V characteristics are shown in Fig. 3. The diameter of Schottky contact dot used in our experiment is 200 μm. The barrier heights (Φ_B) and ideality factor (n value) were determined by using the thermionic emission theory.[9] The barrier height and ideality factor of $\Phi_B(I-V)=0.80$ eV, $n=1.17$ for sapphire substrate, and $\Phi_B(I-V)=0.92$ eV, $n=1.13$ for SiC substrate were obtained from the forward I–V characteristics, respectively. The reverse I–V characteristics of the both samples were also shown in Fig. 3. The reverse leakage current of diodes based on SiC is over three orders of magnitude lower than that of sapphire substrate when the reverse voltage is above 50 V. Schottky diodes formed on sapphire substrate show breakdown voltage of −80 V. While for the SiC substrate, the strong breakdown was not observed even at −100 V. This is the result of low dislocation density in GaN film and high thermal conductivity for SiC substrate. Capacitance voltage (C–V) measurements were also performed using HP4845A LCR at a frequency of 1 MHz. The measured $1/C^2$–V plots are shown in Fig. 4 for the two kinds of Schottky diodes. The barrier heights (Φ_B) and carrier concentrations are 0.82 eV, $7\times10^{16}\,cm^{-3}$ for sapphire substrate, and 0.96 eV, $6.5\times10^{16}\,cm^{-3}$ for SiC substrate, respectively. The carrier concentrations values determined from C–V measurements are in good agreement with the value determined from Hall measurement.

The electron-beam-induced current (EBIC) images of

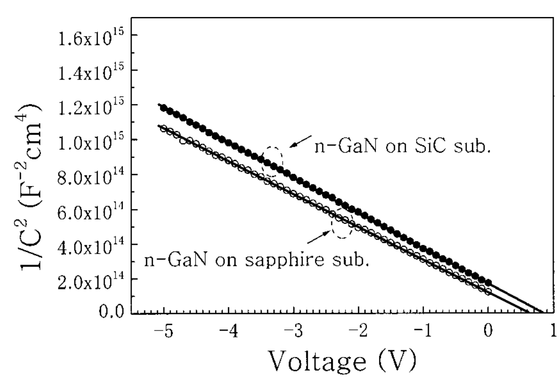

FIG. 4. C–V characteristics of Ni/Au Schottky contacts on n-GaN grown on sapphire and SiC substrates.

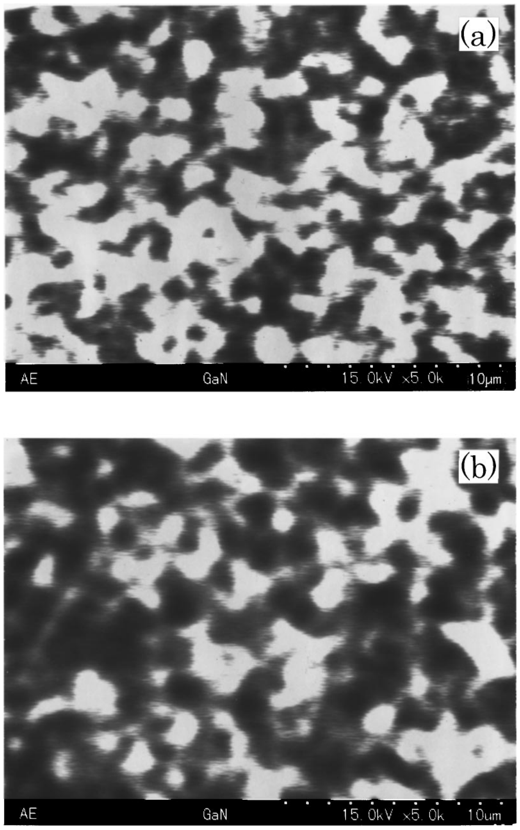

FIG. 5. EBIC images of Schottky diodes; (a) n-GaN grown on SiC substrate, and (b) n-GaN grown on sapphire.

the two kinds of Schottky diodes were shown in Fig. 5, where [Fig. 5(a)] is for GaN grown on SiC substrate, and [Fig. 5(b)] is for sapphire substrate. The accelerating voltage of 15 kV and the magnification of 5 k were used. The EBIC images look like a granular structure with bright and dark grains. The dark EBIC regions reveal the nonradiative recombination and trapping probably associated with high dislocation density, resulting in fully depleted minority carrier. The strains are almost completely relaxed by generation of misfit dislocation during the growth at high temperature since the thickness of GaN layer is thicker than the critical thickness. The dark grain density is about $3\times10^7\,\mathrm{cm}^{-2}$ for SiC substrate, and $9\times10\,\mathrm{cm}^{-2}$ for sapphire substrate. This value is almost one order of magnitude less than the AFM result because the dark grain in EBIC should correspond to the region with high dislocation density. Small dark grain density for SiC substrate is the result of its small lattice mismatch and thermal expansion coefficient mismatch with GaN. The high breakdown voltage and the low reverse leakage current for Schottky diodes on SiC substrate should be ascribed to the presence of low dislocation density and high thermal conductivity.

In conclusion, Ni/Au Schottky contacts were formed on n-GaN grown on sapphire and SiC substrates. The electronic characteristics of Schottky diodes were investigated by $I-V$ and $C-V$ measurements. Compared with sapphire substrate, the performances of Schottky diodes formed on SiC substrates were improved. The reverse leakage current of diodes based on SiC is over three orders of magnitude lower than that of sapphire substrate when the reverse voltage is above 50 V. The strong breakdown was not observed even at -100 V. The high breakdown voltage and low reverse leakage current for Schottky diodes on a SiC substrate are related to the low dislocation density and high thermal conductivity.

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