AIP Applied Physics Letters

Microstructural evidence on direct contact of Au/Ge/Ni/Au ohmic metals to InGaAs channel in pseudomorphic high electron mobility transistor with undoped cap layer

Jong-Lam Lee, Yi-Tae Kim, and Jeong Yong Lee

Citation: Appl. Phys. Lett. **73**, 1670 (1998); doi: 10.1063/1.122240

View online: http://dx.doi.org/10.1063/1.122240

View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v73/i12

Published by the American Institute of Physics.

APPLIED PHYSICS LETTERS VOLUME 73, NUMBER 12 21 SEPTEMBER 1998

Microstructural evidence on direct contact of Au/Ge/Ni/Au ohmic metals to InGaAs channel in pseudomorphic high electron mobility transistor with undoped cap layer

Jong-Lam Lee[a] and Yi-Tae Kim
Department of Materials Science and Engineering, Pohang University of Science of Technology (POSTECH), Pohang 790-784, Korea

Jeong Yong Lee
Department of Materials Science and Engineering, Korea Advanced Institute of Science and Technology, Taejon 305-701, Korea

(Received 21 May 1998; accepted for publication 17 July 1998)

Microstructural evidence on direct contact of Au/Ge/Ni/Au ohmic metals to a InGaAs channel in AlGaAs/InGaAs pseudomorphic high electron mobility transistor with an undoped GaAs/AlGaAs cap layer was found using transmission electron microscopy, and the results were used to interpret the electrical properties of the contact. The lowest contact resistivity of $3.8\times10^{-6}\ \Omega\,\text{cm}^2$, obtained at 420 °C annealing, is due to the penetration of the interfacial compounds, Au_2Ga and Au_2Al, into the buried InGaAs channel. The direct contact of the compounds to the channel causes the reduction of series resistances between the ohmic compounds and the channel, resulting in the low contact resistivity. *© 1998 American Institute of Physics.* [S0003-6951(98)01138-3]

The Au/Ge/Ni system, widely used as an ohmic contact to AlGaAs/InGaAs pseudomorphic high electron mobility transistors (PHEMTs),[1,2] forms an alloyed AuGe ohmic contact through the alloying reaction of the metals with the substrate at temperatures higher than 400 °C. The reaction produces a AuGa phase and a heavily Ge-doped GaAs layer.[3,4] The heavily Ge-doped GaAs layer formed below the contacts acts as a role in reducing the depletion layer width. Thus, electron tunneling probability at the metal/GaAs interface increases, resulting in the decrease of contact resistivity.

Heavily doped GaAs has been used as a cap layer of the PHEMTs to achieve a good ohmic contact. The heavily doped cap layer, however, degrades the breakdown voltage of the devices.[2,5] Thus, a double recess etching prior to gate metallization is often used to improve the breakdown voltage characteristics. But, the double recess etching increases the processing steps, resulting in the reduction of reproducibility of electrical performance in PHEMTs. If an ohmic contact to a PHEMT with an undoped cap layer is developed, a PHEMT with a high breakdown voltage can be fabricated using a single recess etching. However, no work has yet been conducted on ohmic contacts to the PHEMT with an undoped cap layer.

In the present study, we investigate the microstructure of the Au/Ge/Ni/Au ohmic contact to a PHEMT with an undoped GaAs/AlGaAs cap layer in order to understand the interfacial reactions between the ohmic metals and the substrate during the annealing process. The microstructures in the annealed samples are studied using x-ray and cross-sectional transmission electron microscopy (TEM). The data are used to interpret the electrical properties of the ohmic contacts. From this, we present microstructural evidence on direct contact of Au/Ge/Ni/Au ohmic metals to the InGaAs channel in the AlGaAs/InGaAs PHEMT with the undoped cap layer.

A cross-sectional view of the AlGaAs/InGaAs PHEMT used in this work is shown in Fig. 1. A double heterojunction structure with a double-planar-doped layer was grown by molecular beam epitaxy on a semi-insulating GaAs wafer. The undoped InGaAs channel was separated from the two planar-doped layers with undoped AlGaAs spacer layers of 30 Å thickness. The doping layers of the planar-doped layers in undoped AlGaAs were asymmetric. The AlGaAs/InGaAs/AlGaAs active layers were grown on a 1-μm-thick-undoped GaAs buffer layer in which GaAs/AlGaAs superlattices were introduced. The undoped GaAs (300 Å)/AlGaAs (300 Å) layers were used as a cap layer, which plays a role in protecting the active layer from the point defects generated at

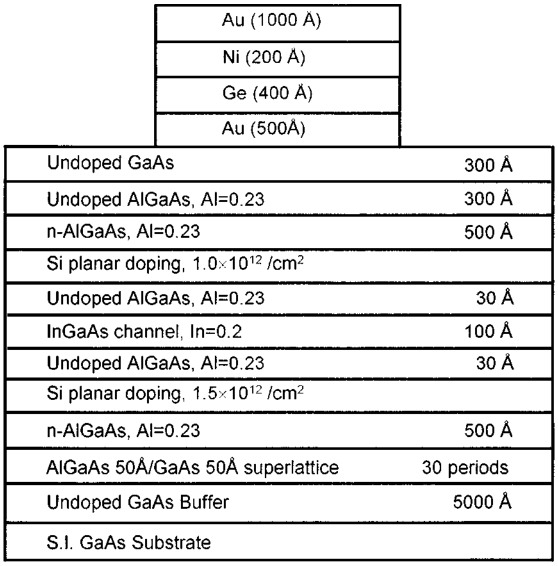

FIG. 1. A schematic cross-sectional view of the PHEMT structure.

---

[a] Electronic mail: jllee@vision.postech.ac.kr

TABLE I. Electrical measurement as a function of annealing temperature for Au/Ge/Ni/Au on a AlGaAs/InGaAs PHEMT.

Annealing temperature (°C)	Contact resistivity (Ω cm^2)
300	Non-ohmic
340	3.5×10^{-3}
380	1.1×10^{-5}
420	3.8×10^{-6}
460	4.0×10^{-6}
500	3.9×10^{-6}
540	4.6×10^{-6}

the subsurface of GaAs, resulting in the improvement of the electrical characteristics.[6] The sheet resistance of the grown PHEMT substrate was measured to be 340 Ω/□.

The ohmic contact resistivity was measured using the transmission line method (TLM). An active region was defined by an etching solution of $H_3PO_4{:}H_2O_2{:}H_2O$, on which TLM test structures were patterned using photoresist. Prior to metal deposition, the native oxide was removed using $HCl{:}H_2O(1{:}1)$ solution, followed by a deionized water rinse and a dry N_2 blow.

A layer structure of Au (500 Å)/Ge (400 Å)/Ni (200 Å)/Au (1000 Å) was deposited in sequence on the PHEMT substrate by an electron-beam evaporator. After evaporation, metal lift-off was performed and the remaining metal on the TLM test structures was annealed in the temperature range of 340–540 °C for 20 s under atmospheric pressure of the forming gas (10% H_2 and 90% N_2) by rapid thermal annealing.

Microstructural analysis of the sample was carried out after annealing using TEM. The samples were examined using a JEOL system (200 kV) equipped with a high-resolution pole piece and ultrathin window x-ray detectors for microdiffusion.

The electrical characteristics of the Au/Ge/Ni/Au contact are summarized in Table I. A U-shaped dependence of contact resistivity on the annealing temperature is obtained. ohmic behavior is observed at 340 °C. However, contact resistivity is too high ($3.5\times10^{-3}\,\Omega\,\mathrm{cm}^2$) to be used as an ohmic contact. The contact resistivity rapidly decreases to $1.1\times10^{-5}\,\Omega\,\mathrm{cm}^2$ at 380 °C. The lowest contact resistivity is $3.8\times10^{-6}\,\Omega\,\mathrm{cm}^2$ at 420 °C. Note that the low contact resistivity obtained with the undoped cap layer is comparable to the previously reported one obtained using a heavily doped GaAs cap layer[3] doped with $1.5\times10^{18}/\mathrm{cm}^3$.The contact resistivity maintains almost the same level up to the annealing temperature of 540 °C.

Figure 2 shows x-ray diffraction (XRD) profiles in the annealed samples, measured with a glancing angle of 1.5°, as a function of annealing temperature. Diffraction peaks corresponding to Au were only observed in the as-deposited state. The intensities of the Ni peaks were too low to be observed. After annealing at 380 °C, the Au peaks significantly decreased and a new peak corresponding to β-AuGa was detected.[7] Thus, the ohmic contact formed at 380 °C is related to the formation of the β-AuGa phase. The β-AuGa was transformed to Au_2Ga at 460 °C. Note that Au_2Al peaks, as well as NiAs peaks, with a low intensity were detected in the sample annealed at 460 °C. Even after the annealing temperature increased to 540 °C, the diffraction pattern was not significantly changed.

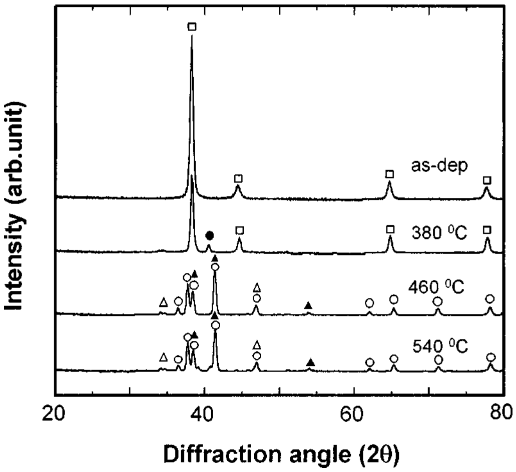

FIG. 2. Change of x-ray diffraction patterns with annealing temperature for Au/Ge/Ni/Au on a PHEMT (□: Au, ●: β-AuGa, ○: Au_2Ga, ▲: Au_2Al, and △: NiAs).

Figure 3(a) is a cross-sectional TEM micrograph image of the sample annealed at 380 °C for 20 s. After annealing, the ohmic metals penetrated deep by 750 Å from the original interface of GaAs with the metallic layers, considering the InGaAs layer was located at 1130 Å far from the surface of the PHEMT. Thus, the ohmic contact was formed on the *n*-type AlGaAs layer. A number of grains with white and dark images were observed in the alloyed region. Comparing the results with those of the XRD, the grains are mainly composed of the β-AuGa phase. At this stage, the contact resistivity decreased to $1.1\times10^{-5}\,\Omega\,\mathrm{cm}^2$. This is deeply related to the formation of β-AuGa because its melting point is 375 °C. Formation of β-AuGa produces Ga vacancies below

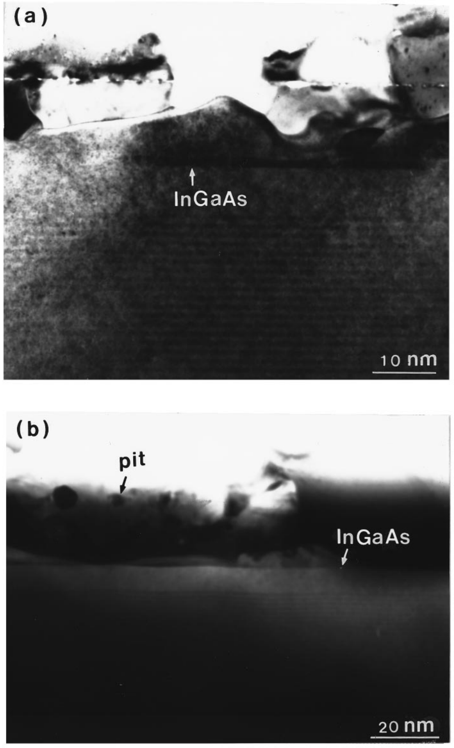

FIG. 3. Cross-sectional TEM micrograph: (a) for the sample annealed at 380 °C and (b) for the sample annealed at 460 °C.

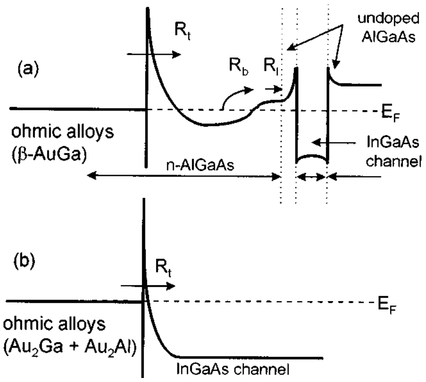

FIG. 4. Energy-band diagrams for the samples annealed (a) at 380 °C and (b) 460 °C.

the contact, which generates free electrons by incorporation of Ge into the Ga vacancies. Thus, the increase of the carrier concentration below the contact makes the contact resistivity reduction. The contact resistivity obtained is lower than the previous result for ohmic contacts to *n*-AlGaAs.[7]

Figure 3(b) shows the TEM micrograph of the sample annealed at 460 °C. The grain size increased in comparison with that in the sample annealed at 380 °C, indicating that the grain growth proceeded with the elevation of the annealing temperature. A number of pits were observed in the large grains. In addition, the ohmic alloys partly penetrated into the InGaAs channel. This directly evidences that the ohmic junction was formed at the InGaAs layer, resulting in the further decrease of the contact resistivity to $3.8 \times 10^{-6}\,\Omega\,\mathrm{cm}^2$. Considering the XRD results in Fig. 2, the large grains are mainly composed of Au_2Ga and Au_2Al phases, and the pits originate from NiAs. Figures 2 and 3 indicate that the good ohmic contacts obtained at temperatures of 420–500 °C originate from the penetration of the interfacial compounds, Au_2Ga and Au_2Al, into the buried InGaAs channel.

Energy-band diagrams for the samples annealed at 380 and 460 °C are, respectively, displayed in Figs. 4(a) and 4(b), based on the TEM observations in Fig. 3. For the annealed PHEMT at 380 °C, the ohmic metals penetrate into the *n*-type AlGaAs and produce the AuGa in the alloyed region. Thus, there are three resistance sources produced between the ohmic metals and the InGaAs channel; the resistance for electron tunneling through the Schottky barrier (R_t), the resistance by a high–low barrier (R_b), and the sheet resistance in the *n*-AlGaAs layer (R_1), as shown in Fig. 4(a). For the annealed PHEMT at 460 °C, ohmic alloys, Au_2Ga and Au_2Al, penetrate into the InGaAs channel, containing the high concentration of electrons. The direct contact to InGaAs eliminates the R_1 as well as the R_b, and also reduces the barrier height because the band gap of InGaAs is much lower than that of AlGaAs. Thus, the band bending at the junction interface occurs toward the parallel direction with the InGaAs channel, and the consequential energy-band diagram in Fig. 4(b) can be drawn. Therefore, the total series resistance between the ohmic metals and InGaAs channel decreases, resulting in the further decrease of contact resistivity.

In conclusion, the electrical properties of the Au/Ge/Ni/Au ohmic contact to the AlGaAs/InGaAs PHEMT with an undoped GaAs/AlGaAs cap were interpreted using the microstructural observations by cross-sectional TEM and x-ray measurements. The lowest contact resistivity of $3.8 \times 10^{-6}\,\Omega\,\mathrm{cm}^2$ obtained at 420 °C is low enough to be used as the ohmic contact to the PHEMT with a 600-Å-thick-undoped cap layer. The microstructural observations showed that the good ohmic contact obtained is due to the formation of the interfacial compounds, Au_2Al and Au_2Ga, which penetrated into the buried InGaAs channel. The direct contact of the ohmic metals to the InGaAs channel caused the decrease of the total series resistance between the ohmic metals and InGaAs channel, resulting in low contact resistivity.

This work was financially supported by the Ministry of Information and Communication under Grant No. 98-133.

[1] Y.-L. Lai, E. Y. Chang, C.-Y. Chang, T. K. Chen, T. H. Liu, S. P. Wang, T. H. Chen, and C. T. Lee, IEEE Electron Device Lett. **17**, 229 (1996).
[2] J.-L. Lee, H. M. Yoo, and G. Y. Lee, Electron. Lett. **33**, 1909 (1997).
[3] Y. C. Shih, M. Murakami, E. L. Wilkie, and A. C. Callerari, J. Appl. Phys. **62**, 582 (1987).
[4] J. S. Kwak, H. N. Kim, H. K. Baik, J.-L. Lee, H. Kim, H. M. Park, and S. K. Noh, Appl. Phys. Lett. **67**, 2465 (1995).
[5] J.-L. Lee, J. K. Mun, H. Kim, J. J. Lee, and H. M. Park, IEEE Trans. Electron Devices **43**, 519 (1996).
[6] J.-L. Lee, D. Kim, S. J. Maeng, H. H. Park, J. Y. Kang, and Y. T. Lee, J. Appl. Phys. **73**, 3539 (1993).
[7] L. R. Zheng, S. A. Wilson, D. J. Lawrence, S. I. Rudolph, S. Chen, and G. Braunstein, Appl. Phys. Lett. **54**, 877 (1992).