Ohmic Contacts to *n*-type 3C-SiC using Cr/Ni/Au and Ni/Cr/Au metallizations

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Abstract:

The electrical characteristics of Cr/Ni/Au and Ni/Cr/Au contacts to *n*-type 3C-SiC have been examined using a two-contact circular test structure. In Ni/Cr/Au contacts with Ni as contact layer and Cr as intermediate layer, both the modified sheet resistance, R_{sk} , and the specific contact resistance, ρ_c , have decreased continuously with increase in annealing temperature within the range 750-1000 °C. In comparison, the Cr/Ni/Au contacts with Cr as contact layer have exhibited a leveling-off in R_{sk} and increase in ρ_c after annealing at 900 and 1000 °C.

These measurements have been correlated with depth profiles of the interfaces using Auger Electron Spectroscopy (AES). The AES profiles have shown a large-scale interdiffusion of the metal layers in the *n*-type 3C-SiC/Cr/Ni/Au structure after annealing at 750-1000°C. In comparison, the *n*-type 3C-SiC/Ni/Cr/Au contacts have shown only a limited interdiffusion of the metals (Ni: Au) with the intermediate layer of Cr acting as a diffusion barrier for these metals.

Keywords

Silicon carbide, ohmic contact, electrical properties, AES

1. Introduction:

The wide band-gap semiconductor SiC has shown attractive properties in devices operating at high temperature and high power. In particular, the 3C polytype of SiC has shown the unique ability for growth of epitaxial layers on Si substrates [1]. La Via has recently reviewed the parameters controlling the quality of epitaxial 3C-SiC grown by chemical vapor deposition (CVD) on Si (100, 011 or 111) in terms of the minimization of stacking fault density [1]. In the fabrication of devices using 3C-SiC, a critical requirement has been the formation of ohmic contacts with a low specific contact resistance, ρ_c , at the metal/SiC interface. Although various metallization systems have been examined as ohmic contacts to *n*-type SiC, the most widely used metal has been Ni [2-4]. Low values of ρ_c have been reported in ohmic contacts of Ni/*n*-type SiC after annealing at 900-1000 °C [2-4]. These properties have been variously attributed to the formation of Ni₂Si phase and accumulation of graphitic carbon at the interface [2-4], the generation of carbon vacancies near to the interface [2,3] and to the recrystallization of Ni₂Si after annealing at ≥ 900 °C with lowering of the barrier height [5]. But annealing at 900-1000 °C has also been accompanied by a roughening of the surface morphology and the formation of interfacial voids. The carbon clusters and voids have acted as regions of mechanical weakness at the Ni/*n*-type SiC junction during bonding. As an alternative to Ni, the use of a contact layer of NiCr alloy (50 nm) has resulted in a thinner (~10 nm) layer of carbon during the reaction but with equivalent electrical characteristics [6]. The presence of Cr in the contact layer has also reduced the extent of interdiffusion between Ni and the capping layer of Au during annealing [6]. Cr and NiCr alloy have been reported as relatively inefficient as a catalyst in the formation of graphite during annealing [7]. The carbide Cr₃C₂ has exhibited a relatively low tendency to decompose to form graphite compared with Ni [7].

In this paper, we have systematically examined for the first time the role of Cr in both the Au/Ni/Cr and Au/Cr/Ni contact systems to *n*-type 3C-SiC as a function of annealing temperature. The use of these structures has enabled a comparison of the effect of Cr as either the intermediate or the contact layer on the specific contact resistance, ρ_c , the modified sheet resistance, R_{sk} , and elemental depth profile of the contacts. The parameter known as the modified sheet resistance, R_{sk} has been used in the modelling of ohmic contacts to define the region of alloying/reaction in the semiconductor immediately below the metallization as distinct from the sheet resistance, R_{sh} of the semiconductor layer outside of the contact region. R_{sk} was incorporated by Reeves in both the linear transmission line model (TLM) [8] and circular transmission line model (CTLM) [9]. All voltage drop beneath the contact in the horizontal direction was attributed to current flow within R_{sk} while voltage drop perpendicular to the plane of the contact was due to ρ_c [10]. R_{sk} has been reported by several investigators as significantly lower than R_{sh} in metal/ GaAs interfaces after a reaction or alloying (see Table 1 in ref [10]). Other studies of R_{sk} have included Ni/Ge/Au contacts to *n*-type GaAs [10], Pd, Ni or Zn contacts to *n*-type In_{0.47}Ga_{0.53}As [11] and In metal on *n*-type Hg_xCd_{1-x}Te [12]. The magnitude of R_{sk} has been shown to depend on the extent of the interfacial reaction as influenced the annealing temperature and the structural layers used in the metallization [10-12].

2. Experimental Details

An epitaxial layer of *n*-type 3C-SiC was grown on a wafer of *p*-type Si (100) of resistivity, $\rho = 15\text{-}25 \text{ } \Omega\cdot\text{cm}$ by low-pressure chemical vapor deposition (LPCVD) in a hot wall reactor [13]. The film of 3C-SiC was 520 nm in thickness with a resistivity, $\rho = 0.001 \text{ } \Omega\cdot\text{cm}$ and a doping level of $N_D = 1 \times 10^{19} \text{ cm}^{-3}$. The wafer of 15 cm diameter was diced into square pieces of 1 x 1 cm using a diamond saw. The individual pieces of wafer were dipped in 10% HF for 15 s to remove any native oxide prior to the deposition of metal layers.

Sequential layers of either Ni (20 nm)/ Cr (50 nm)/ Au (50 nm) or Cr (20 nm)/ Ni (50 nm)/ Au (50 nm) were deposited by e-beam onto the surface of the *n*-type 3C-SiC at 1×10^{-7} Torr. The configuration of a 20 nm thickness contact layer and a 50 nm thick intermediate layer was selected as giving a carbon layer with optimum uniformity of thickness [14]. A two-contact circular test structure [15] as illustrated in Fig. 1 was fabricated by the lithographic process of “lift-off”. A single layer of positive AZ1512 resist with thickness of $\sim 1 \mu\text{m}$ was used for the lift-off without a chlorobenzene soak. A single layer of positive resist has typically formed an overcut profile with a +ve slope rather than an undercut profile [16]. In this case, the measurements of the dimensions of each of the individual circular contact patterns by optical microscopy or SEM have provided the actual dimensions of the metal contact to the semiconductor. A significant advantage of the two-contact circular test structure has been the removal of the middle ring contact from the standard three-contact CTLM resulting in much simpler equations for determining ρ_c . The test structure comprised three pairs of circular dot contacts with different radii (r_{01} , r_{02} and r_{03}) of the central dot with ratios of $x = r_{02}/r_{01} = 1.5$ and $y = r_{03}/r_{01} = 3.5$. In the outer ring contact for the three pairs, the inner and outer dimensions of r_1 and r'_1 were constant. The total resistance, R_{T1} , R_{T2} and R_{T3} between each pair of contacts comprised the sum of the contact resistance of the central dot, R_{C0} , the resistance of the semiconductor ring, R_P and the contact resistance of the outer electrode, R_{C1}

$$R_{T1} = R_{C01} + R_{P1} + R_{C1} \quad (1)$$

$$R_{T2} = R_{C02} + R_{P2} + R_{C1} \quad (2)$$

$$R_{T3} = R_{C03} + R_{P3} + R_{C1} \quad (3)$$

Then, from measurements of R_{T1} , R_{T2} and R_{T3} between each of the pairs

$$R_{T1} - R_{T2} = (R_{C01} - R_{C02}) + (R_{P1} - R_{P2}) \quad (2)$$

$$R_{T1} - R_{T3} = (R_{C01} - R_{C03}) + (R_{P1} - R_{P3}) \quad (3)$$

eliminating R_{CI} . As defined by Reeves for CTLM patterns [9], the analytical equations for R_{COI} and R_{PI} were

$$R_{COI} = \frac{R_{sk}}{2\pi} \left(\frac{I_0(\alpha r_{OI})}{\alpha r_{OI} I_1(\alpha r_{OI})} \right) \quad (4)$$

$$R_{PI} = \frac{R_{sh}}{2\pi} \left(\ln \frac{r_I}{r_{OI}} \right) \quad (5)$$

in which I_0 and I_1 were the zero and first-order modified Bessel functions of the first kind, respectively. The parameter, α , was the inverse of transfer length, L_t in the linear transmission line model for ohmic contacts where α was defined as

$$\alpha^2 = \frac{R_{sk}}{\rho_c} \quad (6)$$

The electrical measurements were performed with probes mounted on a micromanipulator. The probes consisted of Micromanipulator Model 7H with a point radius of 1 μm and Be-Cu construction. The fine tip and Be-Cu composition were chosen to minimize or eliminate any damage to the thin film structure during probing. A second series of unpatterned samples was prepared using the same two configurations of metal layers of Ni (20 nm)/ Cr (50 nm)/ Au (50 nm) or Cr (20 nm)/ Ni (50 nm)/ Au (50 nm). These samples were used for the examination of the surface morphology and depth profiling of the contact layers using a PHI 710 Scanning Auger Nanoprobe. In the AES analysis, a Fast Auger Profile was used with a 2keV Ar^+ beam, which was 2 x 2 mm in dimension. The Rapid Thermal Anneal (RTA) of both patterned and planar samples was performed at a temperature of 750, 900 or 1000 $^{\circ}\text{C}$ for 2 min in a flow of pure N_2 .

Fig. 1. A two-contact circular test structure in which the radius of the central dot increased as r_{01} , r_{02} and r_{03} . The inner and outer radii of the outer ring contact, r_1 and r'_1 were constant.

3. Results and Discussion

3.1 Electrical measurements

Fig. 2 (a) and (b) show current-voltage (I - V) plots which were typical for the as-deposited contacts of Cr/Ni/Au and Ni/Cr/Au, respectively. For both types of contact, the I - V plots have shown ohmic characteristics. Fig. 2 (a) and (b) have also shown that both types of metal contacts exhibited a significant reduction in resistance after annealing at 1000 °C. Figs. 3 and 4 show plots of modified sheet resistance, R_{sk} , and specific contact resistance, ρ_c , for both contact types as a function of the annealing temperature. The individual points in Figs. 3 and 4 have represented an average value of 10 measurements with each of the determinations performed on a separate pattern.

In Fig. 3, the value of R_{sh} which was measured from the two-contact test patterns was in the range of 19-21 Ω/sq for annealing temperatures up to 1000 °C. This result was in agreement with resistivity measurements performed on the film of n-type 3C-SiC in which the value of R_{sh} was calculated at 19.2 Ω/sq from $\rho = 0.001 \Omega\cdot\text{cm}$ and a thickness of 520 nm.

Fig. 2. Current-voltage characteristics of a) Cr/Ni/Au and b) Ni/Cr/Au contacts to *n*-type 3C-SiC both as-deposited and annealed at 1000 °C.

Fig. 3. R_{sk} and R_{sh} versus anneal temperature for Cr/Ni/Au and Ni/Cr/Au contacts to *n*-type 3C-SiC.

Fig. 4. Specific contact resistance, ρ_c , versus anneal temperature for Cr/Ni/Au and Ni/Cr/Au contacts to *n*-type 3C-SiC.

The measurements of R_{sk} for the as-deposited Cr/Ni/Au and Ni/Cr/Au contacts to *n*-type 3C-SiC as shown in Fig. 3 were $R_{sk} = 21 \text{ } \Omega/\text{sq}$ and $22 \text{ } \Omega/\text{sq}$, respectively. For these as-deposited contacts, $R_{sk} \approx R_{sh}$ which coincided with the abrupt interfaces in Fig. 5(a) and Fig. 6(a). The annealing of the Cr/Ni/Au contacts at 750-1000 °C in Fig. 3 has shown a decrease in R_{sk} to $R_{sk} \sim 15 \text{ } \Omega/\text{sq}$. In comparison, for the as-deposited Ni/Cr/Au contacts, the mean value of R_{sk} decreased to $4.4 \text{ } \Omega/\text{sq}$ after annealing at 900°C with a reduction to $2.5 \text{ } \Omega/\text{sq}$ after annealing at a temperature of 1000 °C. In Fig. 4, the measurements of ρ_c for the as-deposited contacts were similar at $1.67 \times 10^{-4} \text{ } \Omega/\text{cm}^2$ and $1.3 \times 10^{-4} \text{ } \Omega/\text{cm}^2$ for the Cr/Ni/Au and Ni/Cr/Au contacts. Fig. 4 shows that for Cr/Ni/Au contacts, the value of ρ_c decreased to $2 \times 10^{-5} \text{ } \Omega/\text{cm}^2$ after annealing at 750 °C and then increased slightly at higher temperatures (900-1000 °C). In comparison, after annealing of the Ni/Cr/Au contacts, the value of ρ_c decreased with rise in annealing temperature to 900-1000 °C. A minimum value of $\rho_c = 1.0 \times 10^{-5} \text{ } \Omega.\text{cm}^2$ was measured in Ni/Cr/Au contacts after annealing at 900°C and 1000 °C.

These results were consistent with the few published studies on Ni contacts to *n*-type 3C-SiC. Review papers on ohmic contacts to *n*-type SiC by Roccoforte [3] and Wang [4] have shown that nearly all previous papers have used either the 4H or 6H polytypes. However, Ni contacts on highly doped ($N_D = 1 \times 10^{19} \text{ cm}^{-3}$) *n*-type 3C-SiC has given a similar measured value of $\rho_c = 2 \times 10^{-5} \Omega \cdot \text{cm}^2$ to the present study after annealing at 950 °C and 1050 °C [17]. Ni/Ti contacts formed on 3C-SiC after the implantation of N or P ions and annealing at 1350 °C have given values of $\rho_c = 8 \times 10^{-6} \Omega \cdot \text{cm}^2$ and $2 \times 10^{-5} \Omega \cdot \text{cm}^2$, respectively [18]. In comparison, Ni contacts to *n*-type 3C-SiC with a moderate doping level of $N_D \sim 1 \times 10^{17} \text{ cm}^{-3}$ have been reported by Spera [19] with a value of ρ_c of $3.7 \times 10^{-3} \Omega \cdot \text{cm}^2$. The measurements of ρ_c in the present study were also in agreement with calculations of the contact resistance of ohmic contacts to *n*-type 4H-SiC annealed at 950-1050 °C using thermionic emission and thermionic field emission models and with experimental data [5]. Contact resistances of $2 \times 10^{-3} \Omega \cdot \text{cm}^2$ at $N_D = 1 \times 10^{17} \text{ cm}^{-3}$ and $1 \times 10^{-5} \Omega \cdot \text{cm}^2$ at $N_D = 1 \times 10^{19} \text{ cm}^{-3}$ were calculated in the model assuming a barrier height of 0.35 eV [5].

3.2 Surface Characterization

Auger depth profiles for Cr/Ni/Au and Ni/Cr/Au contacts on *n*-type 3C-SiC both as-deposited and after annealing have been presented in Figs. 5 and 6. In Fig. 5(a), the profiles for the as-deposited Cr/Ni/Au contacts have shown a relatively sharp interface between the layers of Au, Ni and Cr with little signs of intermixing. On annealing of the structure at 750 °C [Fig. 5(b)], the profiles have shown a substantial widening of the Ni, Au and Cr peaks indicating an interdiffusion of these metals. Fig. 5(d) shows that after annealing at 1000 °C, all of the metals (Au, Ni and Cr) had become interdiffused within the junction region. Also evident after 750 °C anneal in Fig. 5(b) was the presence of Si and C within the contact layers of metal.

Fig. 5. AES depth profiles of Cr/Ni/Au contacts to *n*-type 3C-SiC a) as-deposited and after annealing at b) 750 °C, c) 900 °C and d) 1000 °C.

In samples annealed at 900 °C in Fig. 5(c), the near flat profiles of Au, Ni and Cr within the contact region have demonstrated a significant increase in the extent of inward diffusion. Concentrations of C and Si were also evident in the contact region with the C signal increasing strongly in the near-surface region immediately adjacent to the surface. Fig. 6 shows typical Auger depth profiles for the Ni/Cr/Au contacts. In Fig. 6(a), the as-deposited contacts have displayed well-defined peaks for each of the metals. After annealing at 750 °C, Fig. 6(b) shows the continued presence of peaks for Au, Ni and Cr although reduced in height. An increased concentration of C was evident at the location of the original Ni layer within the structure. In Fig. 6(c), the Au, Cr and Ni peaks were still evident after annealing at 900 °C. Again, a strong peak in carbon was present in Fig. 6(c) close to the location of Ni. When annealed at 1000 °C, Fig. 6(d) shows that the peaks for the three metals were still present but with Ni and Cr detected within the SiC.

Fig. 6. AES depth profiles of Ni/Cr/Au contacts to *n*-type 3C-SiC a) as-deposited and after annealing at b) 750 °C, c) 900 °C and d) 1000 °C.

This inward diffusion of Ni and Cr was accompanied by an outward diffusion of C and Si. Another feature of Fig. 6 (d) was the high concentration of Si and C immediately adjacent to the surface. The AES profiles in Fig. 6(b-d) have shown that the interfacial reaction in the Ni/Cr/Au contacts was accompanied by an enrichment in C at the Ni/3C-SiC interface.

These results have shown that both R_{sk} and ρ_c were significantly lower for the annealed Ni/Cr/Au contacts with than in the annealed Cr/Ni/Au contacts. As previously reported, the interfacial region in Ni /SiC contacts after annealing in the range 750-1000 °C has been characterized by the formation of Ni_2Si [2-4] or $NiSi$ [20] and uniformly distributed elemental carbon [14]. In addition, the recrystallization of Ni_2Si at >900 C to form δ - Ni_2Si grains has been associated with a reduction in Schottky barrier height and a transition to

ohmic behaviour [5]. A reduction in the barrier height of Ni/SiC contacts with increase in annealing temperature from 600 to 950 °C was also reported by Ferrero [21] and Calcagno [22]. Ferrero has attributed the decrease in barrier height to the formation of carbon vacancies which acted as donors for electrons [21] while Calcagno has proposed the formation of an inhomogeneous barrier [22]. Each of these processes was enhanced by an increase in annealing temperature. More generally, an increase in anneal temperature has significantly widened the interfacial region of the Ni/Cr/Au contacts by the inward diffusion of Ni and Cr and an outward diffusion of C and Si as evident in the AES depth profiles in Fig. 6. The width of the interfacial region has increased by a factor of ~2 and ~2.5 after annealing at 750 - 1000 °C. The decrease in R_{sk} and ρ_c with increase in annealing temperature in Ni/Cr/Au contacts was consistent with a broadening of the interfacial region by inward diffusion and an increasing formation of reaction products.

In Cr/Ni/Au contacts, the results in Figs. 3 and 4 have indicated that a minor rise in R_{sk} and ρ_c after annealing at 900 °C and 1000 °C coinciding with a leveling-off in the local sheet resistance of the reaction products. The product, Cr_3C_2 has been identified in reactions between Cr and SiC [6] with virtually no tendency of Cr to form a silicide. The metal Cr has been identified as less efficient as a catalyst in the graphitization process with SiC in comparison with Ni [6]. An extensive broadening of the width of the Cr/Ni/Au contacts was also evident in Fig. 5.

In addition, the AES profiles in Fig. 6(b-d) for Ni/Cr/Au contacts have shown a significantly reduced interdiffusion of the Ni and Au layers than in Fig. 5(b-d) for Cr/Ni/Au contacts. These profiles have indicated that the intermediate Cr layer in Ni/Cr/Au contacts has acted as an effective barrier to both the interdiffusion of the metal layers and outward diffusion of the Si and C.

In relation to leakage current in a Si substrate compared with a conducting overlayer, the levels of current eventually tend to a steady state value which has been shown as inversely proportional to their respective sheet resistances [23]. Hence in the 3C-SiC/Si, since R_{sk} was $< 20 \Omega/\text{sq}$ and R_{sh} of the Si was $20 \Omega/\text{cm} / 500 \mu\text{m}$ or $400 \Omega/\text{sq}$, then R_{sh} for the Si layer is $\sim 400 \Omega/\text{sq}$ or at least 20 times higher than R_{sk} . Thus, the current in the Si was 1/20th or less than in the SiC layer. This calculation has ignored the ρ_c that exists between the SiC and Si which further reduced the current in the Si and also introduced a transfer length between the two layers. It has also ignored the reduction in R_{sk} with annealing temperature, which further reduced the current in the Si substrate.

4. Conclusions

For Ni/Cr/Au contacts to *n*-type 3C-SiC, the modified sheet resistance, R_{sk} and specific contact resistance, ρ_c , decreased continuously with increase in anneal temperature to 900-1000 °C. In comparison, in Cr/Ni/Au contacts to *n*-type 3C-SiC both R_{sk} and ρ_c had decreased at an anneal temperature of 750 °C. At higher anneal temperatures in Cr/Ni/Au contacts, the magnitude of R_{sk} had leveled-off with an increase in ρ_c . This trend has demonstrated that with Ni as the contact layer, a region of lower modified sheet resistance was formed by reaction with *n*-SiC than with Cr as the interfacial layer. The *n*-type 3C-SiC/Ni/Cr/Au contacts have shown significantly lower inward diffusion of the metal layers and outward diffusion of Si and C than in *n*-type 3C-SiC/Cr/Ni/Au contacts. An intermediate layer of Cr in the contact structure has acted as an effective barrier which confined the diffusion of Au and Ni in *n*-SiC/Ni contacts.

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5. References

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