A self-aligned Nickel (Ni) silicide process (Salicide) for n-type ohmic contacts on 4H-SiC is demonstrated and electrically verified in a wafer-scale device process. The key point is to anneal the contacts in two steps. The process is successfully employed on wafer-level and a contact resistivity below $5 \times 10^{-6} \ \Omega \cdot \text{cm}^2$ is achieved. The influence of the proposed process on the oxide quality is investigated and no significant effect is observed. The proposed self-aligned technology eliminates the undesirable effects of the lift-off process. Moreover, it is simple, fast, and manufacturable at wafer-scale which saves time and cost.

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results and Discussion

The proposed self-aligned process is based on two annealing steps. The formation of Ni-silicide \((\text{Ni}_x\text{Si}_y)\) compounds is an important factor to form a low-resistive electrical contact between Ni and 4H-SiC.\(^{16-21}\) The silicide phase at the Ni/4H-SiC interface changes at different annealing temperature. To find the optimum temperature range of the FSA, the formation of \(\text{Ni}_x\text{Si}_y\) silicide at different temperatures is investigated by XRD. Fig. 2 presents the XRD spectra of the Ni silicide contacts after the FSA at different temperatures. A 4H-SiC reference and an as-deposited Ni sample are also added as references in which a peak of single-crystalline 4H-SiC and poly-crystalline Ni are visible. A phase transformation of Ni-silicide is obvious for different annealing temperatures. This interaction between Ni and Si is the key point in this self-aligned process that allows the following wet removal of the unreacted Ni and the consequent SSA. \(\text{Ni}_3\text{Si}_{12}\) at below 600 \(^\circ\)C and \(\text{Ni}_2\text{Si}\) for higher temperatures are the main phases while no trace of Ni is observed after the FSA and removal of unreacted Ni. The SSA at 950 \(^\circ\)C is necessary to produces low-resistive ohmic contacts.\(^{16-20}\) The silicide formation starts at 550 \(^\circ\)C and its phase transformation continues at higher temperatures. The intensity of the \(\text{Ni}_2\text{Si}\) peak is dramatically increased at above 700 \(^\circ\)C. The contact surface became rougher at higher annealing temperatures. Due to presence of Ni atoms, different phases of \(\text{Ni}_x\text{Si}_y\) could be formed due to diffusion and reaction of these atoms. The silicide starts to agglomerate when the temperature increases and the silicide islands become visible. The AFM images of the samples after FSA and wet removal step and after the SSA at 950 \(^\circ\)C compared with the as-deposited Ni are shown in Fig. 3. The annealing process influences the surface morphology of the samples which is attributed to the reaction of Ni and Si and the phase transformation of Ni-silicide. The short annealing time in RTA and the thickness of Ni film could affect the formation of the silicide and its morphology.\(^{21}\) The formation of silicide in larger areas is much more uniform than in the smaller openings. This might be attributed to the immediate expansion of the Ni layer surrounded by oxide sidewalls during the RTA process. The annealing process affects the quality of oxide which could be a passivation layer of BJTs,\(^{3,4}\) gate oxide of MOSFETS,\(^{11,12}\) side-wall oxide of JFETs and trench devices,\(^{13}\) etc. Fig. 4 illustrates the scanning electron microscopy (SEM) image of the Ni-contacts formed by the lift-off process and the double-step annealing salicide process. The contact with lift-off has metal residues and jagged edges whereas the one with the silicide process has smooth metal edges and clean oxide surface.

Fig. 5 presents the \(I-V\) electrical characteristic of the Ni contacts after the FSA from 450 to 950 \(^\circ\)C. The typical Schottky behavior of the
The SEM images of Ni n-contacts on 4H-SiC formed by (bottom) lift-off and (top) salicide process. The proposed Ni-salicide technology results in a smoother metal edge and cleaner oxide surface.

Figure 5. The I-V characteristic of the Ni contacts (a) after the FSA at different temperatures and removal of unreacted Ni and (b) after the SSA at 950 °C. All samples with FSA > 500 °C become ohmic after the SSA at 950 °C. The transfer length ($L_T$) is extracted for each sample.

contacts at lower annealing temperatures gradually changes to ohmic behavior at higher annealing temperatures. All samples with FSA > 500 °C become ohmic after the SSA at 950 °C. However, the lower annealing temperature of Ni/SiO$_2$ saves the oxide quality. The FSA range between 550 to 700 °C results in low-resistive ohmic behavior after the SSA at 950 °C. It is also found that the annealing time between 45–90 seconds is sufficient for the FSA and SSA steps. Hence, the proposed two-step self-aligned process benefits from a wide process window for the annealing temperature and time which makes it a reliable contact technology. The influence of the proposed process on the oxide quality is optically and electrically investigated and no significant effect is observed.

The TLM plots with different FSA temperatures and SSA at 950 °C are shown in Fig. 6. To fairly measure the contact characteristics, the total resistance of different samples is calculated by differentiation of the I-V curves for different distances of TLM pads. All samples with FSA > 500 °C show $\rho_C$ below $1 \times 10^{-5}$ Ω cm$^2$ whereas the samples with the FSA in the range of 550 to 700 °C show $\rho_C$ below $5 \times 10^{-6}$ Ω cm$^2$ which is comparable to that of the conventional single-step annealing at 950 °C. It should be noted that the difference between contact resistances is mainly attributed to the doping variation of the samples. As mentioned earlier, the $\rho_C$ decreases for higher annealing temperatures of FSA. The wafer mapping of the measured contact resistivity is shown in Fig. 7. Among the 112 measured dies with TLM structures, above 50% has a contact resistivity below $5 \times 10^{-6}$ Ω cm$^2$ and more than 80% has a contact resistivity below $6 \times 10^{-6}$ Ω cm$^2$. A high uniformity for the contact resistivity is achieved.

Conclusions

A self-aligned Nickel (Ni) silicide process (Salicide) for n-type ohmic contacts on 4H-SiC is demonstrated and electrically verified on wafer-scale and a high uniformity for the contact resistivity is achieved. To avoid the undesirable effect of the high temperature annealing of Ni/SiO$_2$, the annealing is performed in two steps. A first step annealing (FSA) at low temperature is performed to form one phase of Ni$_x$Si$_y$ and the unreacted Ni on SiO$_2$ is removed by Piranha. The second step annealing (SSA) at 950 °C to form the low-resistance n-type ohmic contacts is then performed. It is found that the FSA range at 550–700 °C with the duration of 45–90 seconds results in a contact resistivity below $5 \times 10^{-6}$ Ω cm$^2$ which is comparable to the conventional silicide formation at 950 °C. The proposed self-aligned process at lower annealing temperatures gradually changes to ohmic behavior at higher annealing temperatures. All samples with FSA > 500 °C become ohmic after the SSA at 950 °C. However, the lower annealing temperature of Ni/SiO$_2$ saves the oxide quality. The FSA range between 550 to 700 °C results in low-resistive ohmic behavior after the SSA at 950 °C. It is also found that the annealing time between 45–90 seconds is sufficient for the FSA and SSA steps. Hence, the proposed two-step self-aligned process benefits from a wide process window for the annealing temperature and time which makes it a reliable contact technology. The influence of the proposed process on the oxide quality is optically and electrically investigated and no significant effect is observed.

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process eliminates the undesirable effects of the high temperature annealing of Ni/SiO$_2$ and lift-off process. Moreover, it is simple, fast, and manufacturable at wafer-scale which saves time and cost.

References