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Low Temperature Ni-Al Ohmic Contacts to P-TYPE 4H-SiC Using Semi-Salicide Processing

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Abstract. Most semiconductor devices require low-resistance ohmic contact to p-type doped regions. In this work, we present a semi-salicide process that forms low-resistance contacts ($\sim 10^{-4}\ \Omega\ cm^2$) to epitaxially grown p-type ($>5\times10^{18}\ cm^{-3}$) 4H-SiC at temperatures as low as 600 °C using rapid thermal processing (RTP). The first step is to self-align the nickel silicide (Ni_2Si) at 600 °C. The second step is to deposit aluminium on top of the silicide, pattern it and then perform a second annealing step in the range 500 °C to 700 °C.

Introduction

Both bipolar junction transistors (BJTs) and P-channel metal-oxide-semiconductor field-effect transistors (PMOSs) benefit from low-resistance p-type ohmic contacts, as the contact resistance is a parasitic resistance for these devices. It is challenging to form low-resistance contacts to p-type 4H-SiC due to the combination of lack of suitable metal work function (~7 eV), partial Fermi level pinning [1] and technological issues in achieving p-type doping higher than $10^{19}\ cm^{-3}$.

Several different p-type contacts have been proposed and investigated, such as Ni-Al [2-5], Ni-Ti-Al [2, 6-8], Ge-Ti-Al [9], Ti-Al [4, 10, 11], epitaxially grown MAX-phase Ti_3SiC_2 [12], phase segregation annealed co-sputtered Pt-Ti [13] and pure titanium [14]. The necessary annealing temperatures and times vary for different contacts. The contacts typically require annealing temperatures up to 1000 °C to form low-resistance contacts ($\sim 10^{-4}\ \Omega\ cm^2$), with the exceptions of Ge-Ti-Al (600 °C, ultra-high vacuum anneal for 1800 s) [9], titanium (700 °C, surface recrystallization as 3C-SiC after high-dose ion-implantation, contact resistivity higher than $10^{-3}\Omega\ cm^2$) [14], and Ni-Ti-Al (800 °C using rapid thermal processing (RTP), narrow temperature window) [6-8]. Of the cited articles [2-14], all except [12-14] explicitly state that evaporation and lift-off (LO) is used to pattern the contact stack, which is unsuitable for volume production.

In this work, we present a LO free/semi-salicide process for fabricating low-resistance Ni-Al contacts to p-type 4H-SiC. The process employs a first step of nickel salicide (Elahipanah et al. [15]) and a second step of Al sputtering, patterning and RTP (400 °C to 700 °C). The contact resistivity and composition are then measured and discussed.

Experimental

Two 100 mm 4H-SiC (0001) wafers with 4° off-axis cut were used in this experiment. The epitaxy was grown on the Si-face by Norstel [16] and was, from top to bottom, P^+ (0.2 µm, $>5\times10^{18}\ cm^{-3}$) / N^- (0.8 µm, $1\times10^{16}\ cm^{-3}$) / P^+ (1 µm, $5\times10^{18}\ cm^{-3}$) / N^+-substrate. The top P^+-layer was used to form contacts. One wafer was diced into 10 mm × 10 mm pieces for process development, and one wafer was used to demonstrate a wafer-scale process. Transfer length method (TLM) structures of the same dimensions (200 µm width and 100 µm length, separation distances 5, 10, 15, 20 and 25 µm) were fabricated on both pieces and wafer.

The TLM-mesas were etched by magnetically enhanced reactive ion etching (MERIE). Etch damage was removed by sacrificial dry oxidation. The surface was passivated by a deposited oxide, followed by a N_2O-based passivation anneal at 1100 °C. The oxide is opened by MERIE to allow contact formation. The oxide etch uses CF_4/CHF_3/Ar chemistry which etches SiO_2 selectively to SiC. No significant amount of SiC is removed by the etch.

The nickel was self-aligned as proposed by Elahipanah et al. [15]. A nominal 10 nm Ni-film was deposited by magnetron sputtering. The sample was in-situ cleaned prior to metal deposition by back-sputtering a nominal 7 nm of SiO_2. The silicidation-step is performed in a RTP system with optical pyrometer at 600 °C for 60 s, N_2 ambient. The unreacted metal was stripped by Piranha (3:1 H_2SO_4 : H_2O_2).

A nominal 90 nm Al-film was deposited by magnetron sputtering on top of the silicide. The thickness was selected to ensure that the Al/Ni ratio exceeds 80 % atomic concentration of aluminium, which has been found to reduce the resistivity and formation of Al_4C_3 becomes favorable [2, 3]. The film was patterned by standard optical lithography and etched by reactive ion etching (RIE) using Cl_2 and BCl_3. The silicide/Al-stack was alloyed using the RTP system. 6 pieces were annealed in the temperature range from 400 °C to 700 °C for 60 s in N_2 to determine the temperature window. The wafer was annealed at 600 °C, which was selected to maximise the temperature margins based on the results from the experiments on pieces. The time dependence for formation was not investigated, due to a pending upgrade of the RTP-system.

The pieces and 5 TLM sets on the wafer were measured after contact formation by directly probing the contacts. The wafer was further processed by SiO_2 deposition, via opening (MERIE and 10 s spraying of diluted HF) and TiW/Al/TiW deposition/patterning. The contact resistivity of the TLM-structures on the wafer was mapped after the metallization.

Results and Discussion

Unlike the conventional Ni-Al contact that requires anneals up to 1000 °C [2-5], the semi-salicide processed contacts only require that the second-step anneal is higher than 500 °C to become ohmic (upper limit not determined). The samples annealed at 400 °C and 450 °C showed rectifying behavior. The contacts became ohmic at around 500 °C, and the resistivity decreased with temperature. It should be noted that the temperature window for ohmic contact formation is wide, which gives good processing margins. For temperatures lower than 650 °C, the aluminium should stay solid – thus solid-state reactions may drive the contact formation. For the conventional Ni-Al contacts, the Ni-Al can form a liquid-phase under equilibrium conditions at 1000 °C. As such, the chemistry may be different for the conventional Ni-Al contacts and these semi-salicide Ni-Al contacts. A hypothesis is that the SiC-Ni-Al net-reaction is more efficient by breaking it up into two efficient steps instead of having one inefficient step. When separated in two steps, the first step is an efficient SiC-Ni reaction, which forms Ni_2Si with carbon precipitates, and the second step is an efficient Ni_2Si-Al step, which forms Al_4C_3 (from the carbon precipitates) and $AlNi_x$. When done in one step, the SiC-Ni-Al reaction may be dominated by the Ni-Al reaction instead of SiC-Ni / SiC-Al, thus making the process inefficient.

The resistance was determined by measuring voltage when sourcing ±1 µA. The leakage current was about 2 nA. All TLM-structures on the wafer measured after metallization show ohmic behavior and can be fitted to the TLM-model (see Fig. 1), although there is a considerable spread in contact resistivity values. As shown in Fig. 2, about 97 % of the dies have a contact resistivity below 10×10^{-4} Ω cm^2. The average wafer contact resistivity and standard deviation are 6×10^{-4} Ω cm^2 and 1.5×10^{-4} Ω cm^2, respectively (degree of non-uniformity is 25 %).

The contacts appear to degrade at some point between contact formation and metallization. The 5 sampled TLM sets gave an average 2×10^{-4} Ω cm^2 (range 0.5×10^{-4} Ω cm^2) before metallization and an average 5×10^{-4} Ω cm^2 (range 2×10^{-4} Ω cm^2) after metallization. It is likely that HF is detrimental for the contacts.

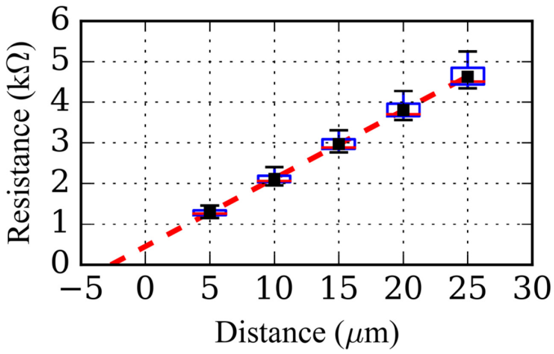

Figure 1. Box plot of TLM-structures on the wafer after metallization. The whiskers represent the range of measured resistance values. The dashed line represent the wafer averaged parameters.

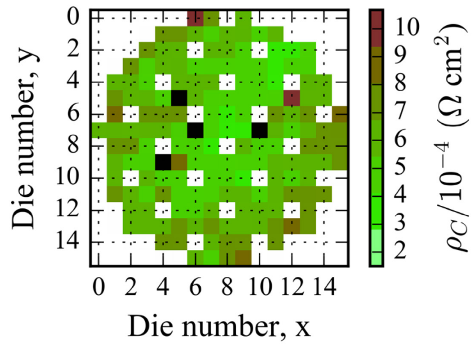

Figure 2. Wafer map of contact resistivity. White squares represent the absence of measurement (either outside of wafer or an excluded die), black squares are dies with resistivity $>10^{-3}$ Ω cm^2. 24 dies were part of another experiment and were excluded.

The contacts were studied structurally by scanning electron microscopy and transmission electron microscopy (SEM and TEM). Fig. 3 is a SEM image of a TLM contact from the wafer. The contact does not cover the contact hole, as was drawn in the lithography. The contact appears to densify during the alloying. The contact surface is non-uniform and composed of two distinct types of regions (appears as dark or bright areas). Fig. 4 is a TEM image from a TLM contact on one of the pieces. Energy-dispersive x-ray spectroscopy (EDS) and electron energy loss spectroscopy (EELS) identifies the contact as being composed of Al_4C_3, $AlNi_x$ and AlO_x.

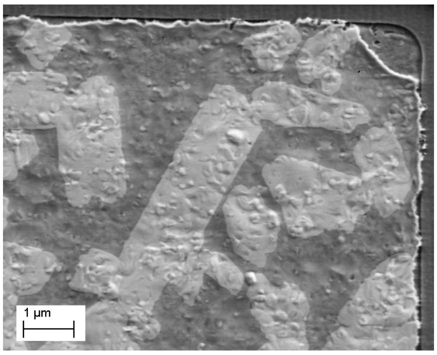

Figure 3. SEM image of the corner of a contact (wafer), after contact formation. Two types of regions are identified (dark/bright), indicating a non-uniform contact. EDS identifies that the bright areas contain more Ni than the dark areas.

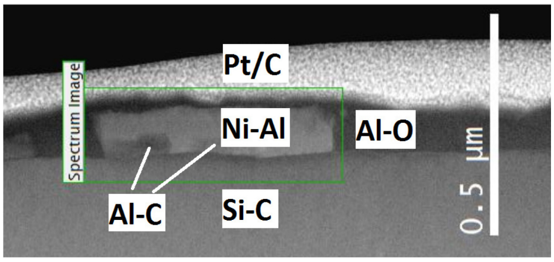

Figure 4. TEM image of a contact (piece). Spectrum analysis by EDS and EELS identifies Ni-Al, Al-C and Al-O. EDS and EELS only identify the composition, not phase. The Al_4C_3-phase is assumed based on previous results [2, 3].

Summary

In this work, we have presented a low-temperature Ni-Al ohmic contact process to p-type 4H-SiC. The Ni is self-aligned, followed by alloying the silicide with Al. The temperature window for ohmic contact formation of the second anneal step is wide, 500 °C – 700 °C. The process was demonstrated on wafer-scale, with 166 measured TLM structures. The average wafer contact resistivity and standard deviation are 6×10^{-4} Ω cm^2 and 1.5×10^{-4} Ω cm^2, respectively. The contact resistivity degrades on exposure to diluted HF. The contacts are structurally composed of $AlNi_x$ and Al_4C_3, and have a patchy texture. The proposed contact process offers flexibility (compatible with both evaporation/LO and sputtering/etching), low thermal budget (RTP at 600 °C) and decent contact resistivity (~10^{-4} Ω cm^2).

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