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Conference Paper**Author(s):**

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Publication date:

2020-07

Permanent link:

<https://doi.org/10.3929/ethz-b-000430947>

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Originally published in:

Materials Science Forum 1004, <https://doi.org/10.4028/www.scientific.net/msf.1004.559>

4H-SiC Power VDMOSFET Manufacturing Utilizing POCl₃ Post Oxidation Annealing

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Keywords: POCl₃ post oxidation annealing, 4H-SiC power VDMOSFET, device processing, device characterization

Abstract. A novel POCl₃ post-oxidation annealing recipe was developed. The interface trap density (D_{it}) is extracted by the C- Ψ_s method close to conduction band edge. The performance of the POCl₃-treated oxide has been analyzed based on current density-electric field (J-E) measurements. A comprehensive and practical 4H-SiC power VDMOSFET manufacturing traveler has been designed. The power MOSFET fabricated based on this traveler exhibits less than half of the on-resistance and shows improved interface characteristics compared to a similarly designed commercial power MOSFET.

Introduction

The existence of interface traps at the SiC/SiO₂ interface is well investigated. Trapped charge at the interface, which is a function of the trap density and band bending, reduces the mobility due to Coulomb scattering, increasing channel resistance and restricting fast switching. Nitride-based post-oxidation annealing with N₂O or NO is a conventional method widely used in industrial production [1]. As an emerging approach, post-oxidation annealing in POCl₃ was demonstrated resulting in much higher peak mobilities than with nitridation [2-4]. Since the requirements on the precursor gas and furnace are also compatible with a conventional Si device manufacturing line, it has the potential to become a promising alternative for mass production. The purpose of this work is to explore the possibilities of adapting POCl₃ annealing for the fabrication of 4H-SiC power VDMOSFETs.

POCl₃ Annealing Process and MOS Capacitor Characterization

To the best of the authors' knowledge, POCl₃ experiments published with detailed process conditions had the POCl₃ bubbler temperature controlled at 15 °C during the process [2-4]. The annealing in this work is carried out with the bubbler temperature at 20 °C. The annealing atmosphere was a gas mixture with the ratio equal to N₂ carrier gas:O₂:main N₂ of 0.6:1:2.5. Based on the flow, the POCl₃ to total N₂ ratio is 0.007531. The sample used in this work was an n-type 4H-SiC substrate with an 11 μm thick, n-type epitaxial layer ($N_D = 8 \times 10^{15} \text{ cm}^{-3}$) on top. Multiple cleaning solutions including a sulfuric peroxide mixture (SPM), RCA clean, and aqua regia were applied prior to gate oxidation. Starting from here, two types of devices have been fabricated: the first type, called 'full POCl₃', is the usual approach where the entire thermally grown gate oxide is doped with POCl₃. The second kind, here referred to as 'partial POCl₃', was processed with an alternative method described below. The first type of MOS capacitors were oxidized at 1250 °C, yielding an oxide thickness of around 25 nm. The second type received a rapid oxidation at the same temperature, aiming for 6 nm oxide thickness. Then, the samples were annealed in a POCl₃ tube at 1000 °C for 10 min. Another 20 nm oxide using TEOS was deposited by LPCVD on the "partial POCl₃" samples, followed by a densification annealing in N₂. The final oxide thickness of around 49 nm was identical for both MOS

capacitors. Finally, the gate and anode electrodes were formed by a low stress W sputtering. All the post POCl_3 annealing, including densification and gate sintering, were performed at temperatures below 900°C to avoid the redistribution of phosphorus. The MOS capacitors manufactured using the developed POCl_3 post-oxidation annealing recipe were then characterized electrically.

Capacitance-Voltage Analysis

All CV measurements show negligible frequency dispersion for both MOS capacitors as shown in Fig. 1. The comparatively high capacitance of the partial POCl_3 sample in the depletion region suggests a higher interface trap density at its interface.

An improved interface quality of the “partial- POCl_3 ” sample is further indicated by a lower D_{it} values, which were extracted by the $C-\Psi_s$ method [5] (Fig. 2). If a significantly high-interface-trap density remained at the interface, a small derivation of the surface potential ($\Delta\phi_s$) causes a large the amount of interface traps charged or discharged (ΔQ_{it}). The equivalent interface state capacitance $C_{it} = \Delta Q_{it} / \Delta\phi_s$ will therefore increase. The total bulk capacitance in the semiconductor, which is equal to C_{it} connecting in parallel with the depletion capacitance (C_{dep}), $C_{s,tot} = C_{it} + C_{dep}$, will rise accordingly. Therefore, the measured capacitance in the range below flatband voltage of the partial POCl_3 MOS capacitor is larger than the value of full POCl_3 MOS capacitor. As $C_{s,tot}$ is connected in series with the gate dielectric capacitance (C_{ox}), the total capacitance (C_{tot}) is $\frac{1}{C_{tot}} = \frac{1}{C_{s,tot}} + \frac{1}{C_{ox}}$.

Approximating the real part of the dielectric constants of partial and full POCl_3 oxide are identical, namely, the equivalent oxide thickness (EOT) is the same. As seen from the CV analysis (Fig. 1), C_{ox} starts to play a dominant role in deciding total capacitance at the more negative voltage in partial POCl_3 MOS capacitors compared to the one in full POCl_3 samples. Therefore, the flatband voltage of partial POCl_3 is more negative than for the full POCl_3 MOS capacitor. Accordingly, the negative shift of the flatband voltage is assumed being caused rather by traps than the positive charge induced by phosphorus. [6] The dispersion of capacitance under quasi-static and high frequency measurement of full POCl_3 MOS capacitor may result from more traps induced by POCl_3 annealing in oxide as it probably responses with quasi-static bias but cannot follow the high frequency.

Figure 1. C-V curves of the partial POCl_3 and Full POCl_3 MOS capacitors at 100 kHz, 1MHz and in a quasi-static configuration.

Figure 2. D_{it} extracted using the $C-\Psi_s$ method.

Current-Voltage Analysis

To capture the permanent breakdown of the oxide, two kinds of capacitors with the same diameter of $600\ \mu\text{m}$ were stressed under current density-electric field (J-E) measurements. The partial POCl_3 MOS capacitor had an almost two orders of magnitude lower leakage current at medium electric field

than the full POCl_3 sample. Comparing to the leakage current of the partial POCl_3 capacitor due to the Fowler–Nordheim tunneling, the higher leakage current of the full POCl_3 capacitor may originate from more electron trapping in the gate oxide, which is also verified by bias temperature stress (BTS) measurement [3]. The leakage current for both samples was lower than $9 \mu\text{A}/\text{cm}^2$ until an abrupt breakdown at around $9.34 \text{ MV}/\text{cm}$ occurred.

Figure 3. Current density- electric field measurement of the partial POCl_3 and full POCl_3 MOS capacitor.

Power VDMOSFET Frontend Manufacturing Process

In order to see the effect of POCl_3 annealing on the electron mobility, power VDMOSFETs with test structures were fabricated. The ion implantation sequence was p^+ , Junction Termination Extension (JTE), guard ring, p well, and n^+ source. The implantation profile of the p well was a retrograded profile with the junction depth at around $1.1 \mu\text{m}$ as simulated by an in-house program based on Pearson IV [7]. The total p well implantation dose was $2.4 \times 10^{14} \text{ cm}^{-2}$. The sample was annealed at 1650°C with the surface covered by a carbon cap. Another sacrificial thermal oxidation at 1100°C for 1 hr was applied after carbon cap stripping in order to improve the cleanliness of the surface and to reduce defects in the SiC bulk.

Subsequently, the field oxide was patterned. The samples were loaded into an oxidation furnace immediately after the pre-oxidation clean to prevent the formation of the native oxide. The oxidation temperature was 1250°C . The annealing in POCl_3 was then performed according to the previously described “partial POCl_3 ” process. The equivalent oxide thickness (EOT) is controlled to reach around 43 nm . The final oxide thickness was determined by ellipsometry measurements. Tungsten was chosen as the gate electrode in this work since it is a refractory metal and frequently used as the gate material in the high- k process. Finally, a 200 nm thick low-stress tungsten was sputtered as the gate electrode and patterned by the lithography and an RIE etch with high W/SiO_2 selectivity.

Power VDMOSFET Backend Manufacturing Process

The inter-layer dielectric (ILD) was deposited by ALD (SiO_x) and PECVD (TEOS). ALD SiO_x is required since it provides better conformal shape and prevents the formation of voids. The oxide was then etched for the contact slot opening by using a high selectivity SiO_x/SiC RIE process. Ni was evaporated on both sides of the native-oxide-free face of the chip. The source/drain metal silicide was formed simultaneously by annealing at 950°C for 1.5 min. The unreacted Ni was then removed using heated Ni etchant. The final source and drain metallization was sputtered by PVD. The source metal

on the front side was Al, while the drain metal on the backside was Ni/Ag. The source Al metal and metallic oxide were etched by ICP. For the final passivation layer, SiO_x was used.

Power MOSFET Characterization

For the mobility extraction, lateral NMOSFETs, fabricated on the same die as the power VDMOSFET, were used and a peak effective mobility of 70 cm²V⁻¹s⁻¹ was measured as shown in Fig. 4. The channel length of the analyzed device was 10 μm and the width was 200 μm.

Fig. 5 presents I_d-V_g curves of the power VD-NMOSFETs. The active area is approximated to 5.4 mm². The threshold voltage is 2.5 V, extrapolated from the subthreshold exponential region.

Figure 4. Mobility extraction from the transfer characterization of the test low voltage lateral MOSFET with $L = 10 \mu\text{m}$ and $W = 200 \mu\text{m}$.

Figure 5. Transfer I_d - V_g characterization of the power MOSFET.

Figure 6. Output I_d - V_d characterization of the power MOSFET, extracted from a pulsed measurement.

The source Al metal layer of the measured power MOSFET is only about 800 nm thick. Such thin metal layer is unfavorable for the current spreading. Moreover, during the I_d-V_d large current measurement, the probing needles were badly connected to the source metal. Therefore, the Al source layer was burnt out after several measurements due to the current crowding. However, the MOSFET was still functioning with reduced output current after a local Al melting as shown in Fig. 7.

The C-V curves of the power VD-NMOSFETs, which are plotted in Fig. 8, are similar to the commercial device [8]. In comparison, the peak-like shape in C_{rss} and C_{oss} at low V_{ds} observed in Ref. [8], is not present here. One explanation of this could be that the near surface JFET region is modified with higher n-type doping in [8] such that the equivalent dopant concentration varies with the

depletion depth developing below the gate overlay at the JFET area. Excess doping reduces the parasitic JFET resistance and lowers the quasi saturation effect during on-state. No JFET implantation step was performed for the devices shown here.

Figure 7. Output I_d - V_d characterization of the power MOSFET after the Al source metal was molten.

Figure 8. Capacitance voltage (C-V) characterization of the power MOSFET. The junction temperature is 25 °C, the V_{AC} is 30 mV, the frequency is 1 MHz.

Summary

In this work, a full 4H-SiC power MOSFET process based on a novel POCl_3 post oxidation annealing recipe has been developed. The interface trap density was effectively decreased by annealing. The oxide formed with this method shows good reliability and could therefore be used as gate oxide in power VDMOSFET manufacturing. The characterization of the fabricated power VDMOSFET proves the significant drop of the specific on-resistance and comparable CV properties as measured for a similar commercial power VDMOSFET.

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