Materials Science Forum
ISSN: 1662-9752, Vol. 1090, pp 101-105
doi:10.4028/p-9v5b6v

Submitted: 2022-08-30
Revised: 2022-12-24
Accepted: 2022-12-28
Online: 2023-05-31

Passivation of Very Fast Near-Interface Traps at the 4H-SiC/SiO$_2$ Interface Using Sodium Enhanced Oxidation

A.M. Vidarsson[1,a*], D. Haasmann[2,3,b], S. Dimitrijev[2,3,c], E.Ö. Sveinbjörnsson[1,4,d]

[1]Science Institute, University of Iceland, 107 Reykjavik, Iceland

[2]Queensland Micro- and Nanotechnology Centre, Griffith University, QLD 4111 Brisbane, Australia

[3]School of Engineering and Built Environment, Griffith University, QLD 4111 Brisbane, Australia

[4]Department of Physics, Chemistry and Biology (IFM), Linköping University, SE-58183 Linköping, Sweden

[a]amv10@hi.is, [b]d.haasmann@griffith.edu.au [c]s.dimitrijev@griffith.edu.au, [d]einars@hi.is

Keywords: Silicon Carbide, MOS Capacitor, Interface Characterization, Interface Traps, Capacitance Voltage, Conductance Spectroscopy

Abstract. The channel carrier mobility in commercially available 4H-SiC MOSFETs with NO annealed gate oxides is still far below the theoretical limit. It has been suggested that the main reason is high density of very fast interface traps, labeled NI, located inside the oxide very close to the SiC conduction band edge. The NI traps are usually not observed at room temperature but can be detected at cryogenic temperatures. In this study we use conductance spectroscopy and high-low CV analysis of MOS-capacitors at cryogenic temperatures to show that the very fast NI traps are practically absent in oxides grown using sodium enhanced oxidation.

Introduction

Silicon carbide (SiC) power devices are now commercially available. However, poor channel carrier mobility has hampered the development and manufacturing of power devices in the 300 – 650 V range where the channel resistance is adversely affecting the power efficiency of these devices. The limiting factor is often attributed to high density of interface defects at the SiC/SiO$_2$ interface [1-4].

The SiC/SiO$_2$ interface contains rather high density of interface traps compared to the Si/SiO$_2$ interface. These interface traps are located at the SiC/SiO$_2$ interface or inside the oxide, 1 – 2 nm from the SiC/SiO$_2$ interface. The most common and successful way to passivate these traps is post-growth annealing in either N$_2$O or pure NO at high temperatures (1150–1350°C). This method is able to reduce the density of interface traps for about an order of magnitude in the energy range 0.1 – 0.5 eV below the SiC conduction band edge [5,6]. However, the peak field-effect mobility is only about 30 – 50 cm^2/Vs in low doped epilayers, which suggest that there still is a high density of traps hampering the mobility, but they are not observed by conventional CV analysis at room temperature [7-8].

Recent studies using conductance spectroscopy at cryogenic temperatures show high density of very fast interface traps with energy levels close to the SiC conduction band edge. These traps have been labelled NI and are observed both in dry thermal oxides and nitrided oxides. Subsequent studies have shown that the NI signal can be explained by direct tunnelling in and out of traps inside the oxide very close to the SiC conduction band edge [6]. These findings are in line with Hall-effect analysis of NO annealed gate oxides, where a high density of near-interface traps aligned with the SiC conduction band edge was detected. These traps were not detected in oxides made by sodium enhanced oxidation, and the Hall electron mobility was about four times higher in sodium enhanced based MOSFETs than in NO annealed MOSFETs [9]. MOS devices based on sodium enhanced oxidation (SEO) are not useful due to mobile sodium, but the field-effect mobility achieved in such MOSFETs is two to three times higher than in nitrided MOSFETs [10,11]. Using conductance spectroscopy and high–low CV at cryogenic temperatures, we demonstrate in this work that the NI trap is practically absent in SEO oxides.

Experimental Details

Samples are grown on 4° off-axis n-epitaxial 4H-SiC layer with net doping of about 1×10^{16} cm^{-3}. The NO oxide is grown by dry oxidation at 1250°C for 60 minutes and subsequent annealing in pure NO for 60 minutes at 1250°C, resulting in a 41 nm thick oxide. The SEO sample was grown in oxygen at 1200°C for 40 minutes using Al_2O_3 carrier boats that are Na contaminated, resulting in a 52 nm thick oxide. Quasi-static measurements were performed using Keithley 6517B electrometer by sweeping the gate voltage, measuring the charge at a rate of 1.67 V/s, and calculating the capacitance as $C = dQ/dV$. High frequency capacitance (1 kHz to 1 MHz) and conductance spectroscopy measurements were performed using Agilent 4980A LCR meter using 10 mV test signal. Quasi-static and high frequency measurements are done at fixed temperatures between 75 K and 300 K by sweeping the voltage from -10 V to 10 V with 50 mV steps. Conductance spectroscopy measurements were performed by cooling the samples to 50 K without applied bias. At 50 K a weak depletion bias is applied, and the sample is heated to 300 K at a fixed ramp rate of 5 K/min while the conductance is monitored. The applied bias is stepped by 250 mV between measurements and is chosen near the location of the flatband voltage of the samples. All measurements are done using a Leybold closed loop helium cryostat that is controlled and monitored using Lakeshore 331 temperature controller.

Results and Discussion

Figure 1 (a) shows the conductance spectra for the NO sample for different gate voltages that correspond to weak depletion. The peak at about 200 K at gate bias of -1V is the NI signal due to the very fast near-interface traps [4-6]. The NI peak shifts to lower temperatures with higher applied voltage and the peak grows rapidly. The peak of the NI results in density of interface traps, Dit, in the range of 2×10^{11}-2×10^{12} $cm^{-2}eV^{-1}$ in the energy range of 0.05 – 0.25 eV. The broad signal at higher temperatures is due to slower interface traps labelled OX that are reduced significantly after nitridation [5]. The peaks at 50 K and 75 K are due to nitrogen donors located at cubic and hexagonal sites as shown in [5]. Figure 1 (b) shows the spectra of the SEO sample. The NI peak is absent while the OX signal is reduced significantly as compared to the NO sample. The detection limit of the NI peak is of the order of 10^{11} $cm^{-2}eV^{-1}$. The small peak at about 140 K is only detected in depletion and is probably due to trace amount of titanium in the SiC epilayer from the growth process. The activation energy (170 meV) and the peak location in temperature agrees with a previous report on Ti [12].

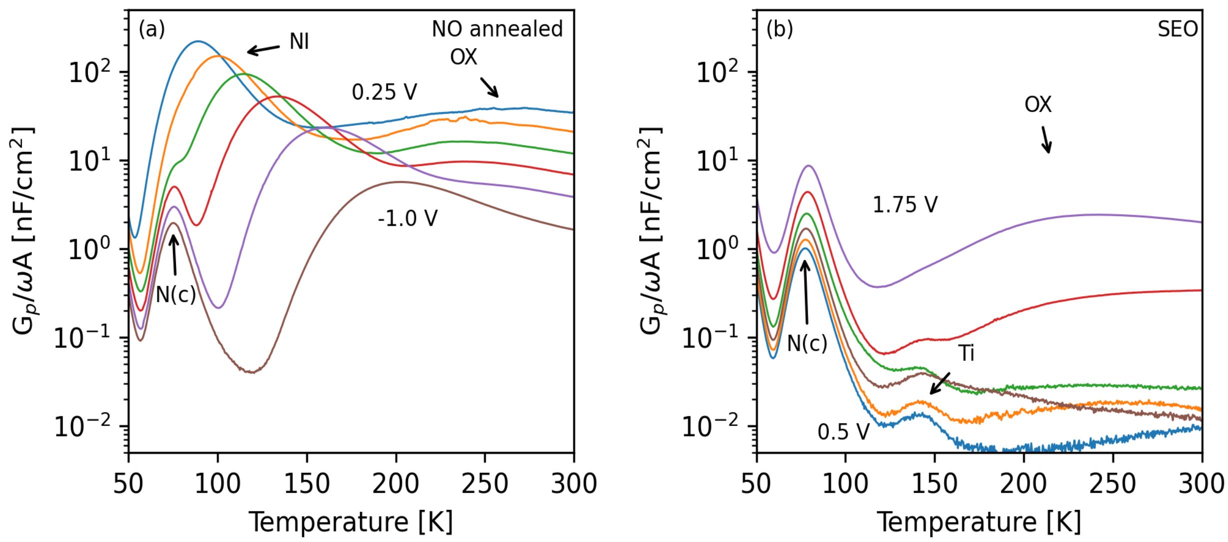

Figure 1. Conductance spectra of NO-annealed (a) and SEO (b) samples at 100 kHz at different applied voltages.

Figure 2 shows the quasi static and high frequency capacitance spectra at several temperatures. Figure 2 (a) shows the NO annealed sample at 300 K, where the small frequency dispersion between the quasi static and the high frequency curves in weak depletion is due to OX traps. After cooling down to 200 K (Fig. 2 (b)), a very small frequency dispersion becomes visible as well in the higher frequency spectra. At 125 K (Fig 2 (c)), this dispersion at high frequencies is further enhanced and grows even larger when the sample is cooled to 75 K (Fig 2 (d)). This dispersion is attributed to NI traps, which also give rise to the knee observed at 75 K. This knee appears at similar surface potential as the NI peak is observed in conductance spectroscopy [13]. The dispersion in weak depletion at 75 K is assigned to the nitrogen donors located at cubic sites that can also be observed in Fig. 1 as a conductance peak around 75 K.

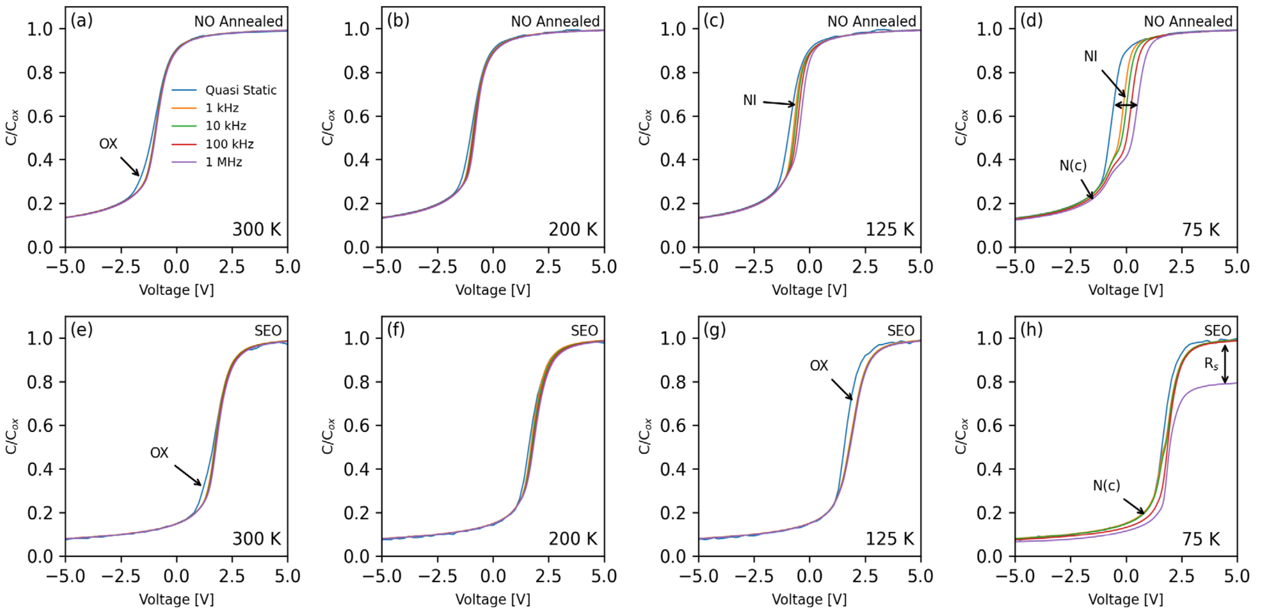

Figure 2. Capacitance spectra of NO-annealed (a-d) and SEO (e-h) samples at 300, 200, 125 and 75 K using quasi-static and high-frequency measurements.

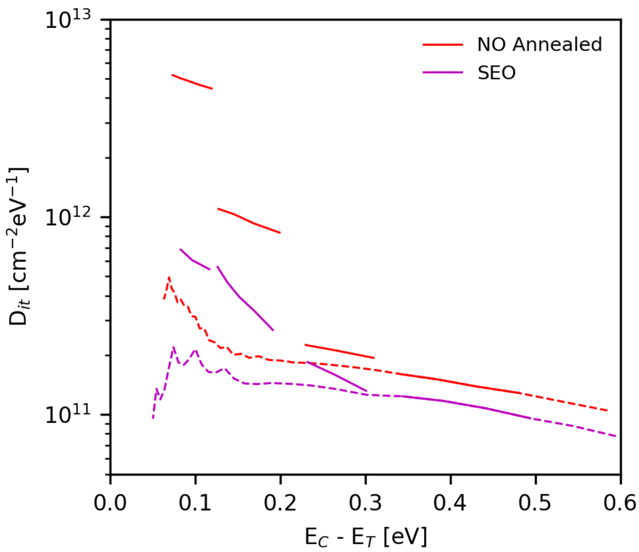

Figure 3. (left) Density of interface traps extracted from CV data in Figure 2, by combining capacitance data at all four temperatures (solid lines). Dashed lines show D_{it} when using only data at 300 K.

Figure 2 (e) shows the SEO sample at 300 K. Similar to the NO sample, a small frequency dispersion in weak depletion between the quasi-static curve and the high frequency curves is observed due to slow OX traps. After cooling down to 200 K (Fig 2. (f)), a small frequency dispersion in the high frequency curves is observed as in the NO sample. However, at 125 K (Fig 2. (g)), there is a negligible dispersion in the high frequency while the quasi-static curve deviates from the rest due to slow OX traps that are only able to follow the quasi-static signal. At 75 K (Fig 2. (h)), a dispersion in depletion due to the nitrogen donors is visible as in the NO sample. However, the high frequency dispersion that is observed in the NO sample and attributed to the NI trap is not visible in the SEO sample. This interpretation agrees with the absence of NI in the conductance analysis in Figure 1 (b). The 1 MHz curve is strongly affected by high series resistance in the sample at this temperature resulting in lower accumulation capacitance.

Figure 3 shows the density of interface traps (D_{it}) extracted from the CV data in Fig. 2. The SEO sample has lower D_{it} throughout the energy range. The dashed lines are extended data from the 300 K data. This illustrates that using only 300 K measurements will underestimate the D_{it} closer to the conduction band edge in both samples. In the case of the NO annealed sample, the underestimate is about an order of magnitude.

The mechanism of the sodium oxidation enhancement is still unknown as well as the origin of the sodium passivation mechanism. What is known is that the sodium accumulates at the SiC/oxide interface and at the oxide/metal interface, and thus is not equally distributed throughout the oxide [11]. Removing the sodium from the SiC/oxide interface can be done either using bias + etching, by applying negative bias to the MOS capacitor to move mobile sodium ions from the SiC/oxide interface to the metal/oxide interface and etch few nm off the top layer, or by annealing in Ar/H_2 ambient and then etch few nm off the top layer. This does not significantly impact the inversion channel mobility which remains about 100 cm^2/Vs but creates a deep interface trap within the SiC bandgap [14].

Summary

We conclude that the fast near interface traps NI detected in nitrided oxides with interface state density D_{it} in the 10^{11} - 10^{12} $cm^{-2}eV^{-1}$ range are not observed in SEO oxides. Based on the detection limit the NI trap density is at least two orders of magnitudes lower in SEO oxides than in NO annealed oxides. The findings are in line with Hall-effect analysis of NO annealed gate oxides, where a high density of near-interface traps aligned with the SiC conduction band edge was detected while such traps were absent in SEO oxides [9]. Based on these observations we conclude that the NI traps are presumably limiting the channel carrier mobility in NO annealed devices.

Acknowledgement

A. M. Vidarsson and E. Ö. Sveinbjörnsson were supported by the Icelandic Centre for Research (Rannis) and the University of Iceland Research Fund. Parts of this work were performed at the Queensland node of the Australian National Fabrication Facility (ANFF), a company established under the National Collaboration Research Infrastructure Strategy to provide nanofabrication and microfabrication facilities to Australia’s researchers.

References

[1] V. Afanasev, M. Bassler, G. Pensl and M. Schulz, Physica Status Solidi (a) 162, 321-337 (1997)

[2] J.M. Knaup, P. Deák, Th. Frauenheim, A. Gali, Z. Hajnal and W.J. Choyke Phys. Rev. B 72, 115323 (2005)

[3] S. Wang, M. Di Ventra, S.G. Kim and S.T. Pantelides Phys. Rev. Lett. 86, 5946 (2001)

[4] H. Yoshioka, T. Nakamura and T. Kimoto, J. Appl. Phys. 112, 024520 (2012)

[5] H. Yoshioka, T. Nakamura and T. Kimoto, J. Appl. Phys. 115, 014502 (2014)

[6] J.R. Nicholls, A.M. Vidarsson, D. Haasmann, E.Ö. Sveinbjörnsson and S. Dimitrijev, IEEE Trans. on Electr. Dev. Vol. 67, (9) 3722 - 3728 (2020)

[7] G. Y. Chung, C. C. Tin, J. R. Williams, K. McDonald, R. K. Chanana, Robert A. Weller, S. T. Pantelides, Leonard C. Feldman, O. W. Holland, M. K. Das and JohnW. Palmour, IEEE Electr. Dev. Lett. Vol. 22, (4) 176-178 (2001)

[8] R. Schörner, P. Friedrichs, D. Peters, D. Stephani, S. Dimitrijev and P. Jamet, Appl. Phys. Lett. Vol. 80, (22) 4253-4255 (2002)

[9] V. Tilak, K. Matocha, G. Dunne, F. Allerstam, and E. Ö. Sveinbjörnsson, IEEE Trans. Electr. Dev. 56, 162–169 (2009)

[10] G. Gudjónsson, H.Ö. Ólafsson, F. Allerstam, P.-Å. Nilsson and E.Ö. Sveinbjörnsson, IEEE Electr. Dev. Lett. Vol. 26, (2) 96 – 98 (2005)

[11] F. Allerstam, H. Ö. Ólafsson, G. Gudjónsson, D. Dochev, and E. Ö. Sveinbjörnsson, J. of Appl. Phys. Vol 101, (12) 124502 (2007)

[12] T. Dalibor, G. Pensl, N. Nordell and A. Schöner, Phys. Rev. B 55, (20) 13618-13624 (1997)

[13] A.M. Vidarsson, J.R. Nicholls, D. Haasmann, S. Dimitrijev and E.Ö. Sveinbjörnsson, J. of Appl. Phys. Vol 131, (21) 215702 (2022)

[14] P.G. Hermannsson, F. Allerstam, S. Hauksson and E.Ö. Sveinbjörnsson, Material Science Forum Vol. 740-742, 749-752 (2013)