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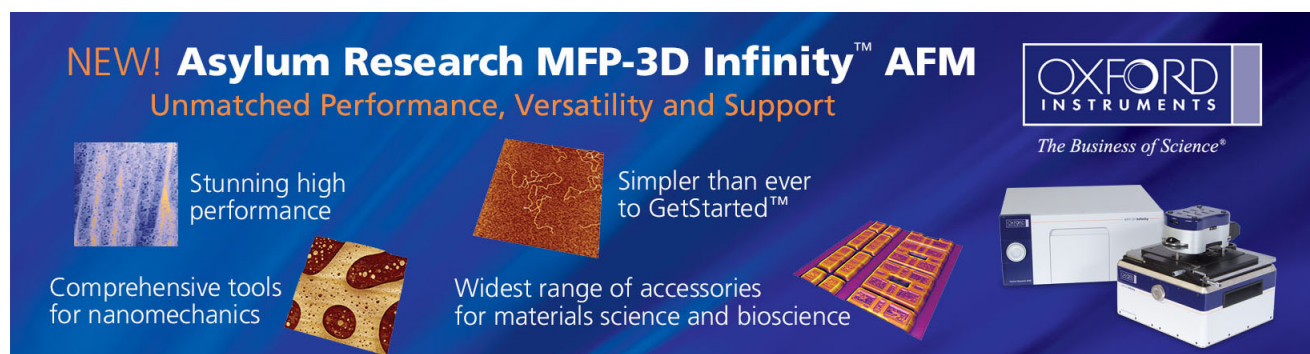
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Memory effect of oxide/SiC:O/oxide sandwiched structures

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The memory effects of the oxide/oxygen-incorporated silicon carbide (SiC:O)/oxide sandwiched structure were investigated. The memory window is decreased with the increase of the oxygen content in the SiC:O film due to the reduction of dangling bonds. A concise model is proposed to explain the reduction of dangling bonds with increasing oxygen content. Also, a higher breakdown voltage is observed with less oxygen content in the SiC:O film, which is attributed to the high barrier height induced by electron trapping in the SiC:O film. © 2004 American Institute of Physics. [DOI: 10.1063/1.1675924]

The Semiconductor Industry Association (SIA) International Technology Roadmap for Semiconductors (ITRS) indicates the challenge, beyond the year 2005, for nonvolatile semiconductor memories is to achieve reliable, low-power, low-voltage performance.¹ In the area of electrically-erasable-programmable-read-only-memory (EEPROM) semiconductor device, there are essentially two dominant technologies which compete for an ever-expanding world market: (1) floating-gate EEPROMs and (2) floating-trap SONOS, historically metal-insulator-SiO₂-Si (MIOS), EEPROMs. To date, the mass produced nonvolatile memory devices are based on the concept of a continuous layer of floating gate.² However, it has faced the difficulties of consecutive scaling down due to the compromise between long-term nonvolatility and high operating speed.³ Recently, the concept of distributed storage of charge by a nitride layer has received much attention.⁴ Among several kinds of MIOS memory devices, silicon nitride, as the charge-trapping insulator in the MIOS structure, is the most widely used.⁵ Other insulators are used to replace the silicon nitride film, such as titanium oxide, tantalum oxide, and aluminum oxide. However, these materials cannot offer sufficient storage centers for the consideration of a large memory window. Therefore, the MIOS device has been made by metal ion implantation (e.g., Au) into SiO₂ to form the interfacial charge-storage centers.⁶ Also, to prevent the carriers from injecting into the charge-trapping insulating film from gate not from the channel, a blocking oxide is regularly used to cap on the insulator film, which forms an oxide/insulator/oxide sandwiched structure.^{7,8} In this study, a metal-oxide-insulator-oxide-silicon (MOIOS) gate stack was investigated. The memory effects of the oxide/SiC:O/oxide sandwiched structure were

demonstrated, which can be utilized as a high-performance MOIOS memory device.

First, a 2-nm-thick thermal oxide was grown on a *p*-type Si substrate by dry oxidation in an atmospheric pressure chemical vapor deposition furnace as a tunnel oxide. Subsequently, a 20 nm SiC:O layer was deposited by high-density plasma chemical vapor deposition (HDPCVD) on the tunnel oxide as a charge-trapping layer, followed by the deposition of a 20 nm HDPCVD silicon dioxide as the blocking oxide. A steam densification at 982 °C was also performed for 180 s to densify the blocking oxide.⁸ The deposition of the SiC:O

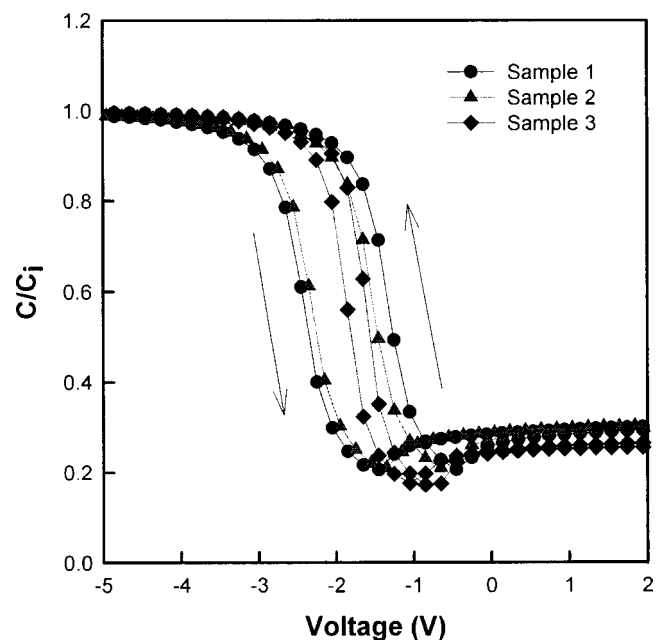


FIG. 1. The $C-V$ hysteresis for different samples under 7 and (-7) V bidirectional voltage sweeping.

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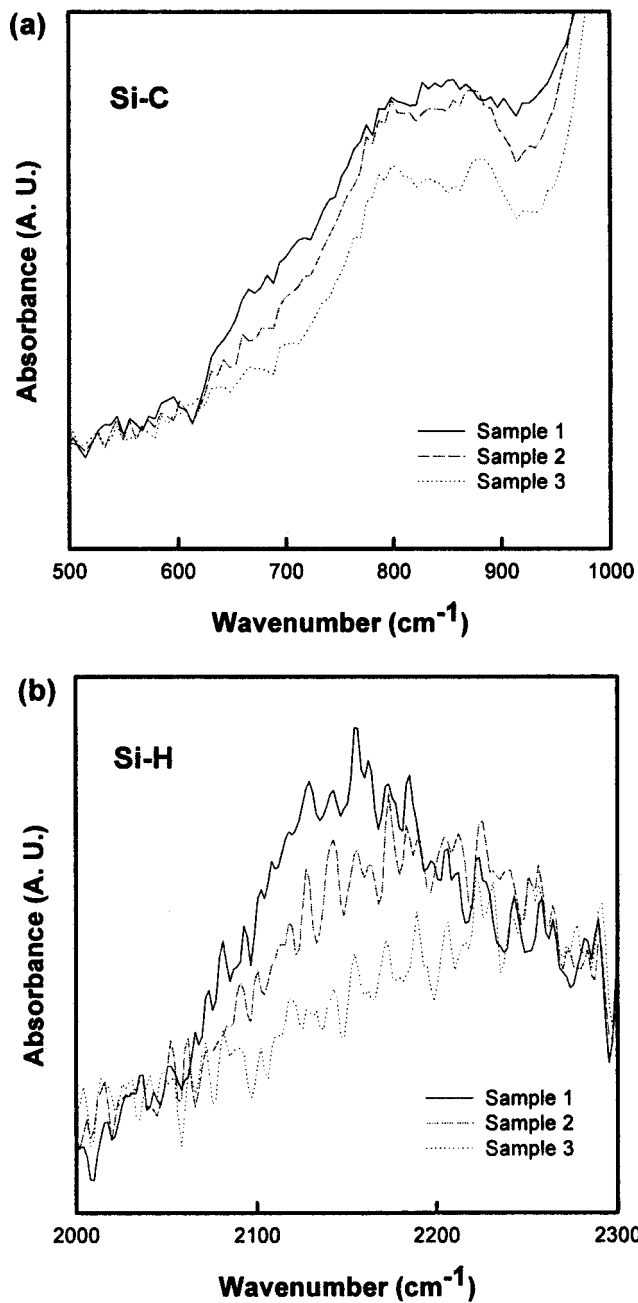


FIG. 2. (a) The FTIR absorbance of Si-C bonds, (b) FTIR absorbance of Si-H bonds.

film was kept at 350 °C in a low pressure of 3 mTorr with precursors of SiH₄ (12 sccm), CH₄ (12 sccm), and O₂ (2–8 sccm) and an inductively coupled plasma (ICP) power of 900 W. This study was divided into three samples. The deposition of SiC:O with least oxygen content (2 sccm) was defined as sample 1. From samples 1 to 3, the content of oxygen was increased with a decreased refractive index. The low pressure of 3 mTorr during deposition makes the path length an electron travels without undergoing a collision with a gas atom (or mean free path) increase, which will improve the uniformity of the thin film.⁹ The blocking oxide was deposited at 350 °C with SiH₄:N₂O=6 sccm:150 sccm and a 900 W ICP power. Finally, the Al gate was patterned and sintered to form a MOIOS structure.

To study memory effects of the oxide/SiC:O/oxide sandwiched structure, a bidirectional voltage sweeping between 7

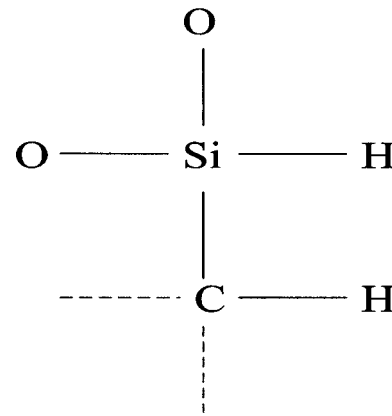


FIG. 3. The structural formula of the proposed model. As the oxygen content is increased, both Si-C and Si-H bonds may be decreased, which renders the decrease of the dangling bonds. The dotted lines indicate the dangling bonds of the C-H bonds which are not well-bound.

and (–7) V was performed. Figure 1 shows the capacitance–voltage (*C–V*) hysteresis in this study for different samples. When the MOIOS structure is operated in positive polarity, the electrons directly tunnel from the Si substrate through the tunnel oxide, and are trapped in the forbidden gap of the SiC:O layer. When the device is negatively operated, the electrons may tunnel back to the Si substrate. The different threshold voltages can be defined as “1” or “0” for a memory device. The blocking oxide is utilized to prevent the carriers of the gate electrode from injecting into the charge-trapping layer by Fowler–Nordheim tunneling. It is clearly observed that as the content of oxygen is increased, the threshold voltage shift (memory window) is decreased from sample 1 to sample 3. The memory window of sample 1 is estimated to be about 1.1 V under 7 V operation. HDPCVD SiC:O is produced in a high-density-plasma chamber with a 900 W ICP power. The rf ICP power is used to increase the spiral motion of the charged particle. A charged particle will gain more energy the more times it moves around the spiral and a high density plasma is, hence, produced.⁹ During the deposition of the carbide layer, the simultaneous slight etching due to the bombardment of the high-density plasma is processed, which forms a densified and trap-rich layer and contributes a larger memory window than other processes to fabricate the SiC:O film.^{9,10} The electrical instability observed during the long time programming is the reduction of the memory window. It is inferred that there are deep trapping centers within the SiC:O film. Once the injecting electrons from the channel are trapped in the deep centers, they are not easy to erase. It is, therefore, an important issue for the operation of the nonvolatile memory devices and the improvements for the reduction of the deep trapping centers need to be taken into account.

To investigate the influence of the content of oxygen on the memory window, Fourier transform infrared spectroscopy (FTIR) was performed. In the investigation of the components of our proposed SiC:O films as a storage element, the FTIR spectrum in the following shows the main bonding types of the SiC:O films are Si–C, Si–O, Si–H, and C–H bonds. Also, the moisture absorption near 3500 cm^{–1} in the FTIR spectrum is not observed even if we left the sample in the cleanroom for 24 h. Figures 2(a) and 2(b) exhibit the

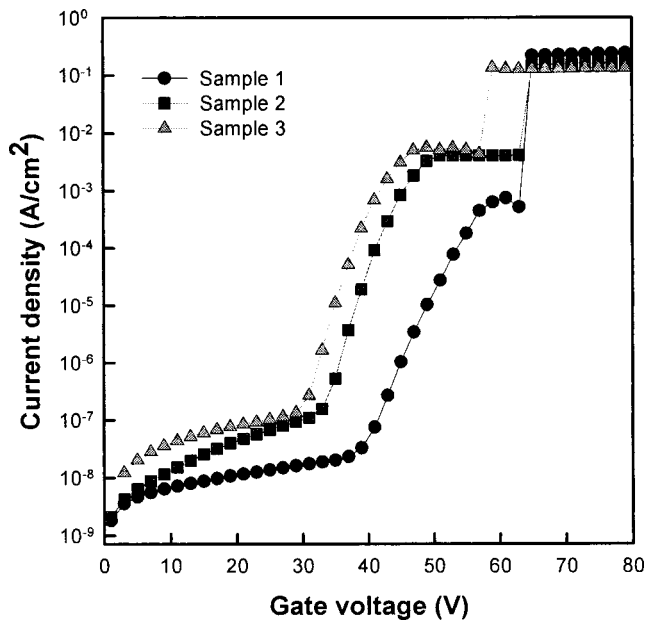


FIG. 4. The leakage current characteristics of the sandwiched structure. The breakdown voltage is increased with the decrease of oxygen content.

bonding types of Si–C and Si–H, respectively.¹¹ As the content of oxygen is increased, the absorbance of Si–O bond is obviously increased (not shown) and that of both Si–C and Si–H bonds is decreased. We propose a model to describe the structural formula of the SiC:O film during deposition in Fig. 3. A trap-rich SiC:O film is composed of Si–O, Si–C, C–H, and Si–H bonds, and the dangling bonds, charge-trapping site, are attributed to the weak Si–H bonds which are easily broken and the C–H bonds which are not well bound as the dotted line shown in Fig. 3. As the content of oxygen is increased, Si–H bonds may be easily broken by oxygen and the oxygen atoms bind with the Si dangling bonds to form the strong Si–O bonds. Also, the increased oxygen reacts with part of the Si–C and C–H bonds to form the volatile CO compound, which makes the dangling bonds decrease. It is inferred that the memory window of the oxide/SiC:O/oxide sandwiched structure is in accordance with the amount of dangling bonds. Smaller memory window is attributed to less charge-trapping sites with more oxygen content.

Figure 4 shows the current–voltage characteristics of the oxide/SiC:O/oxide sandwiched structure. All the samples re-

main good leakage characteristics at the high voltage of 30 V. For sample 1, the breakdown voltage is up to 40 V. Also, it is clearly observed that the breakdown voltage is decreased with the increased content of oxygen. When electrons are captured in a charge-trapping layer with rich charge-trapping sites, the conduction band of the charge-trapping layer will be lifted, which forms a barrier for electrons. If more electrons are trapped in the SiC:O film, a higher barrier height is generated, which results in lower leakage current and higher breakdown voltage of the gate-stacked structure. Therefore, the SiC:O film with less content of oxygen contributes a larger memory window and a higher breakdown voltage.

In conclusion, we have demonstrated the memory effects of an oxide/SiC:O/oxide sandwiched structure for a MOIOS memory device. The memory window of the memory device is decreased with higher oxygen content of the SiC:O film due to the reduction of dangling bonds. A model is proposed to explain the impact of oxygen on the structural formula. Also, a higher breakdown voltage is observed with less oxygen content of the carbide film, which is attributed to the higher barrier height induced by more electron trapping in the SiC:O film.

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