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Memory Effect of Oxide/Oxygen-Incorporated Silicon Carbide/Oxide Sandwiched Structure

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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 increasing 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.
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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 devices, there are essentially two dominant technologies which compete for an ever-expanding world market: (*i*) floating-gate EEPROMs and (*ii*) floating-trap SONOS, historically metal-insulator-SiO_2-Si (MIOS) EEPROMs. To date, 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 an insulator, such as nitride layer, has caught much attention.[4] Among several kinds of MIOS memory devices, silicon nitride, as the charge-trapping insulator in the MIOS structure, is most widely used.[5] Other insulators are investigated 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 SiO_2 to form the interfacial charge-storage centers.[6] Also, to prevent the carriers from injecting into the charge-trapping insulating film from the 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 contribution, a novel 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.

Experimental

Figure 1 shows the device structure in this study. First, a 2 nm thick thermal oxide was grown on p-type (100) 6 in. Si substrate by dry oxidation in an atmospheric pressure chemical vapor deposition (APCVD) furnace as a tunnel oxide layer. Subsequently, a 20 nm SiC:O layer was deposited by high-density plasma chemical vapor deposition (HDP-CVD) on the tunnel oxide as a charge-trapping layer, followed by the deposition of a 20 nm HDP-CVD 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 film was kept at 350°C in a low pressure of 3 mTorr with precursors of SiH_4, CH_4, and O_2 and an inductively coupled plasma (ICP) power of 900 W. The parameters of the deposition of the SiC:O film are listed in Table I. This study was divided into three samples. The deposition of SiC:O with least oxygen content (2 sccm) was defined as sample 1. From sample 1 to sample 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) increased, which improves the uniformity of the thin film.[9] The blocking oxide was deposited at 350°C with the ratio of SiH_4:N_2O = 6 sccm:150 sccm and a 900 W ICP power. Finally, the Al gate electrode was patterned and sintered to form a MOIOS structure.

Results and Discussion

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

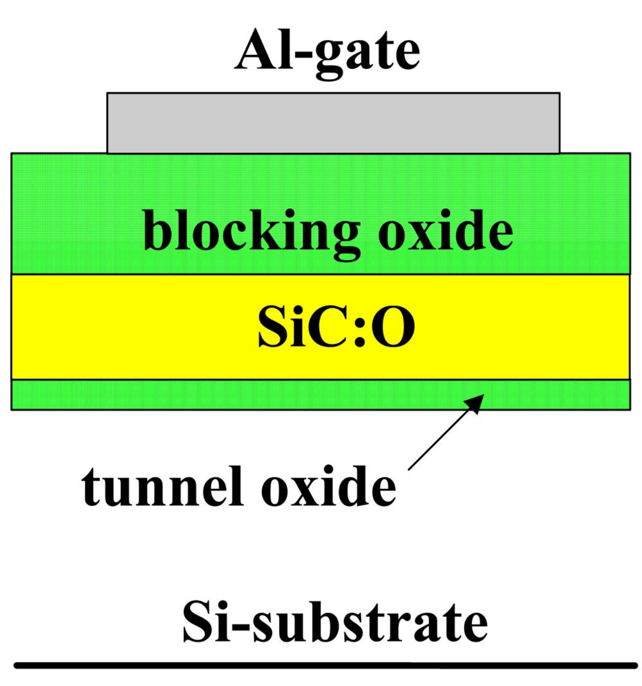

Figure 1. The structure of the MOIOS device shown in this work.

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Table I. The parameters of the deposition of the SiC:O films.

	SiH_4 (sccm)	CH_4 (sccm)	O_2 (sccm)	Refractive index
Sample 1	12	12	2	1.669
Sample 2	12	12	5	1.592
Sample 3	12	12	8	1.483

was performed. Figure 2 shows the capacitance-voltage (C-V) hysteresis in this study for different samples. 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. In Fig. 3 the band diagrams of the "write" and "erase" operation are exhibited. When the MOIOS structure is operated under 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 through tunnel oxide. The different threshold voltages before and after programming can be defined as "1" or "0" for a memory device. The blocking oxide is utilized to prevent the carriers of gate electrode from injecting into the charge-trapping layer by Fowler-Nordheim (F-N) tunneling. HDP-CVD SiC:O is produced in a high-density-plasma chamber with a 900 W ICP power. The radio frequency (rf) ICP power is used to increase the spiral motion of the charged particle. A charged particle gains more energy the more times it moves around the spiral and a high-density plasma is produced.[9] During the deposition of the carbide layer, the simultaneously 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]

To investigate the influence of the oxygen content on the memory window, as shown in Fig. 4, Fourier transform infrared spectroscopy (FTIR) was performed. Figure 5a and b exhibits the bonding types of Si-C and Si-H, respectively.[11] In Fig. 4 and 5, as the oxygen content is increased, the absorbance of Si-O bond is obviously increased and that of both Si-C and Si-H bonds is decreased. We proposed a model to describe the structural formula of the SiC:O film during deposition in Fig. 6. A trap-rich SiC:O film is composed of Si-O, Si-C, C-H, and Si-H bonds, and the dangling bonds, a 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. 6. As the content of oxygen

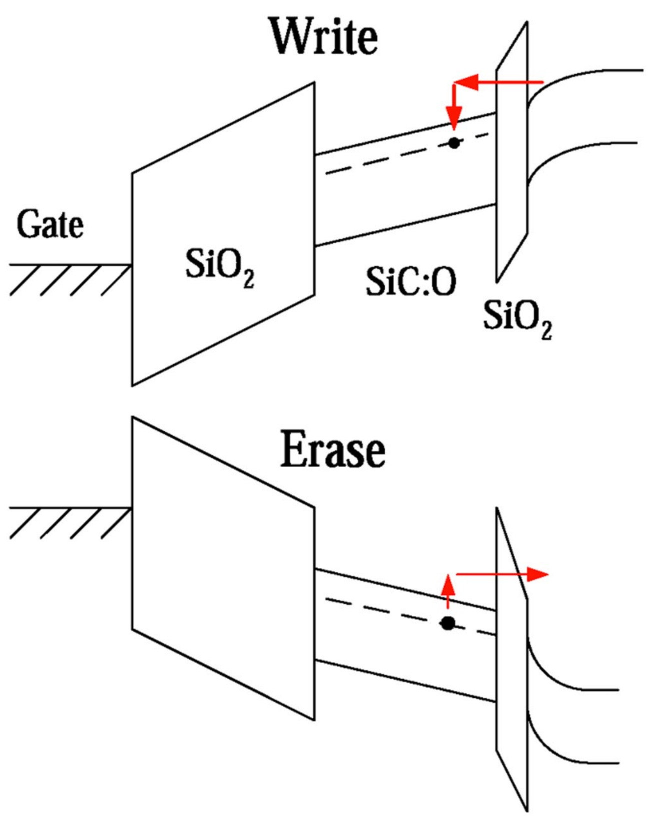

Figure 3. The band diagrams of the "write" and "erase" operation.

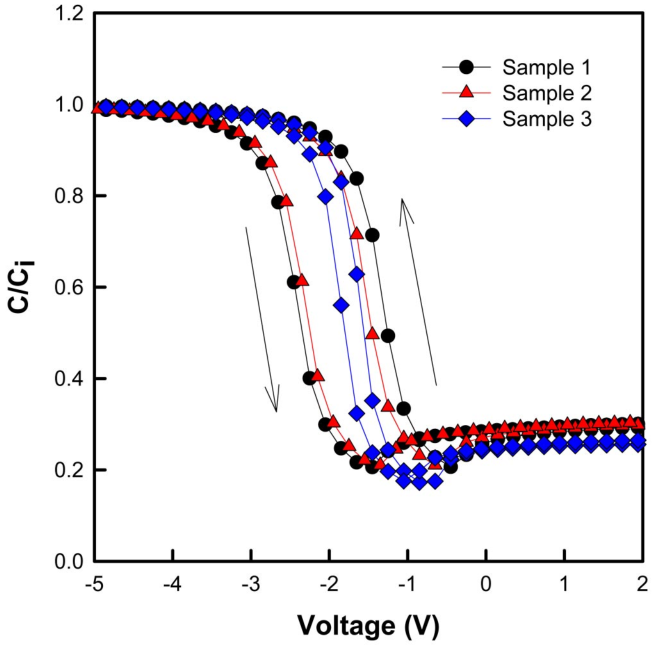

Figure 2. The C-V hysteresis for different samples under 7 and (−7) V bidirectional voltage sweeping.

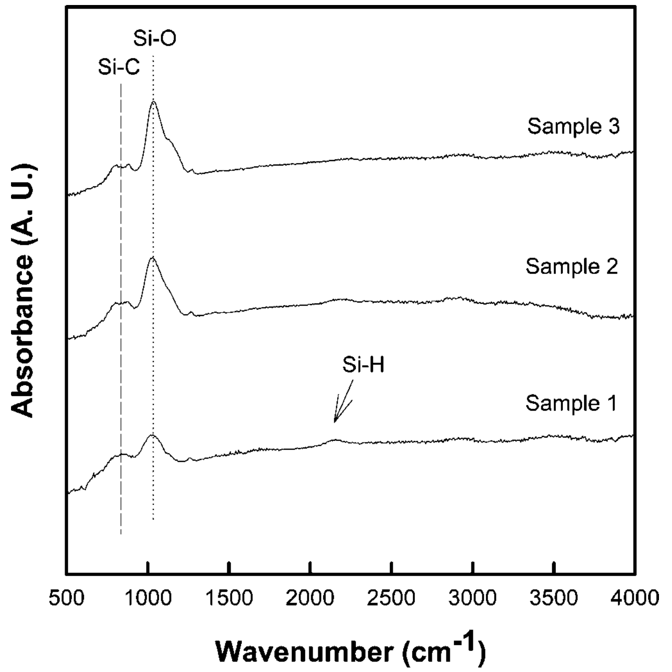

Figure 4. FTIR spectrum of the deposited SiC:O film.

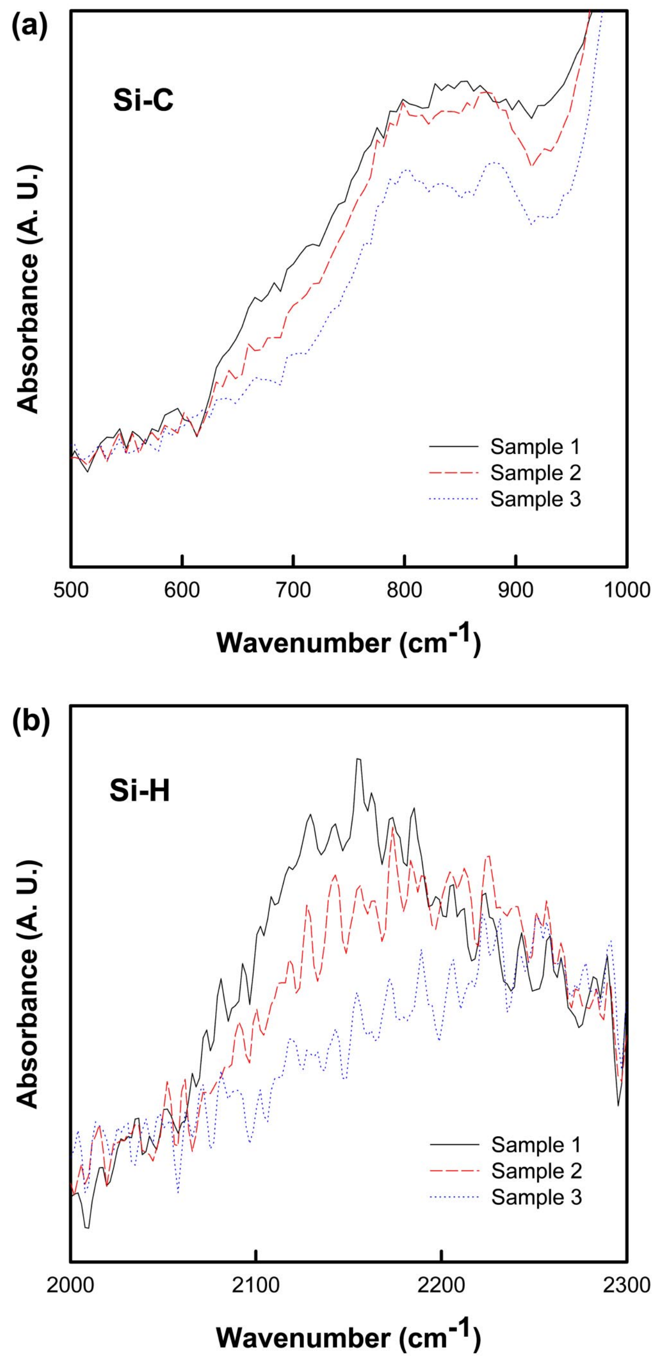

Figure 5. (a) The FTIR absorbance of Si-C bonds and (b) FTIR absorbance of Si-H bonds.

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 decreased. It is inferred that the magnitude of the memory window of the oxide/SiC:O/oxide sandwiched structure is in accordance with the amount of dangling bonds. A smaller memory window is attributed to fewer charge-trapping sites with more oxygen content.

Figure 7 shows the C-V characteristics of the oxide/SiC:O/oxide sandwiched structure. All the samples retain 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. As shown in the band diagram of Fig. 8, when electrons are captured in a charge-trapping layer with rich charge-trapping sites,[12] the conduction band of the charge-trapping layer is lifted, which forms an energy barrier for conductive electrons. If more electrons are trapped in the SiC:O film, a higher barrier is generated, which results in lower leakage current and higher breakdown voltage of the gate-stacked structure. Therefore, the SiC:O film with less oxygen content contributes to a larger memory window and a higher breakdown voltage, demonstrating the reliable characteristics as a candidate for use of future MOIOS nonvolatile memory devices.

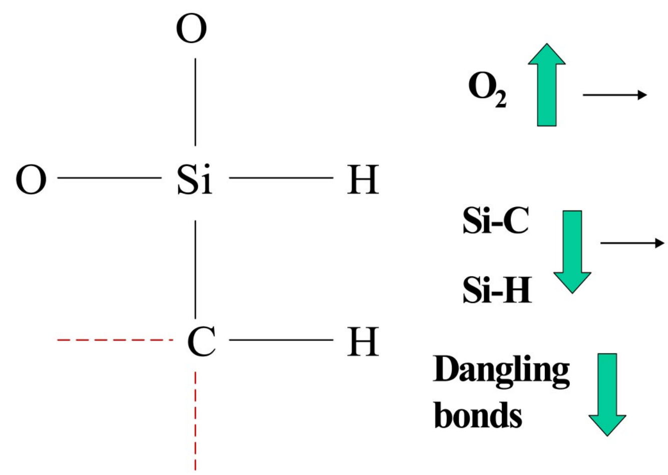

Figure 6. The structural formula of the proposed model. As the oxygen content is increased, both Si-C and Si-H bonds may be decreased, which renders the decrease of the dangling bonds. The dotted lines indicate the dangling bonds of the C-H bonds which are not well-bound.

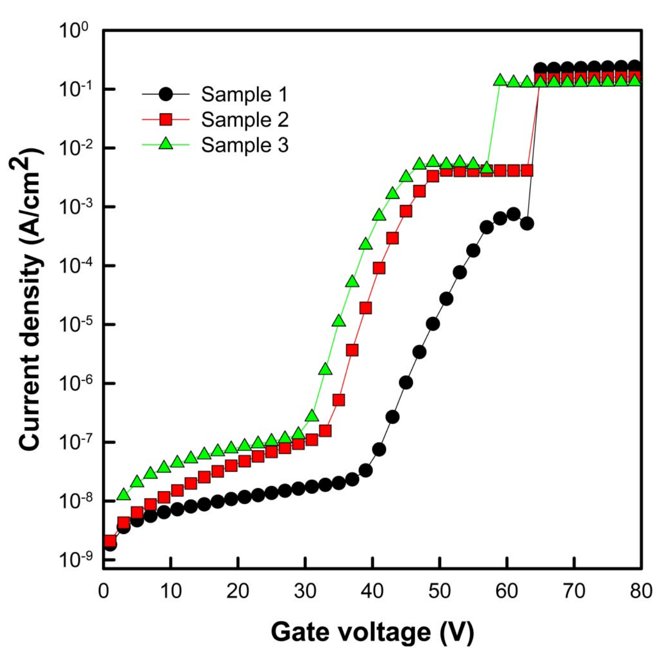

Figure 7. The leakage current characteristics of the sandwiched structure. The breakdown voltage is increased with the decrease of oxygen content.

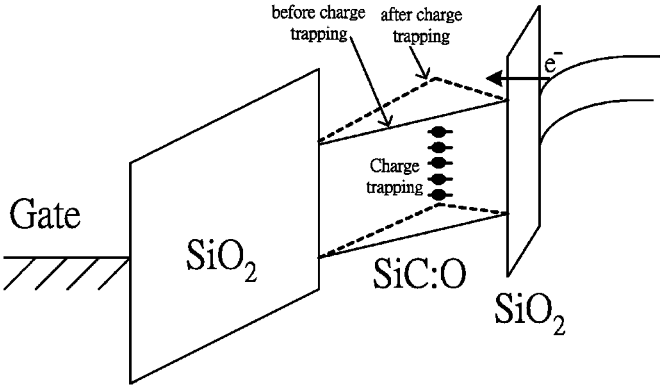

Figure 8. The band diagram shows that when the electrons are captured in a charge-trapping layer with rich charge-trapping sites, the conduction band of the charge-trapping layer is lifted, which forms an energy barrier for conductive electrons.

Conclusion

In this contribution, we have demonstrated the memory effects of an oxide/oxygen-incorporated silicon carbide/oxide sandwiched structure for a novel MOIOS nonvolatile 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 a higher energy barrier induced by more electron trapping in the SiC:O film. Afterward, further investigation about the reliability, such as endurance and retention characteristics, of the MOIOS memory device needs to be taken into account in the future.

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