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Density and spatial distribution of MERIE-like plasma induced defects in SiO_2

A. Paskaleva[1], **N. Novkovski**[2], **E. Atanassova**[1, *], and **M. Pecovska-Gjorgjevich**[2]

[1] Institute of Solid State Physics, 72 Tzarigradsko Chaussee, 1784 Sofia, Bulgaria
[2] Faculty of Natural Science and Mathematics, Institute of Physics, St. Cyril and Methodius University, 1000 Skopje, Macedonia

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Generation of electrically active defects by Magnetron Enhanced Reactive Ion Etching (MERIE)-like He plasma in thin (12 nm) SiO_2–Si structures is investigated by C–V and I–V techniques. It is found that the plasma creates positive charge near the Si–SiO_2 interface and negative one near the Al–SiO_2 interface, both with significant density ($>10^{12}$ cm^{-2}). The centroid and the density of the negative oxide charge depend strongly on plasma conditions and location of wafers during the plasma exposure. It is established that the negative charge generated behaves as "fixed" oxide charge and cannot be charged or discharged. The trapping properties of the plasma damaged structures are studied by a constant current stress. The density of the trapped charge is generally small and its sign depends on the level of injection current.

1 Introduction

The degradation of oxide and interface parameters of Si–SiO_2 devices by plasma processing steps is one of the major yield and reliability concern**s** facing the development of MOS technologies. Many investigations have been done on the effects of plasma-induced damage on oxide reliability and respectively the study of the damages has progressed tremendously in the recent years [1–13]. The microstructures submitted to each of the plasma processes are more or less damaged, according to the technology used. In a deep submicron scale, however, the requirement for a low level of process-induced damage is a key issue. Therefore, the better understanding of plasma generated electrically active defects (in close relation to the discharge parameters) and the suppression of the source causing their creation is critical for the optimization of the technologies typically used in the production of advanced integrated circuits. The high density plasmas have number of advantages and are without alternative for deep submicroelectronics technology domain. Plasma generated in the presence of magnetic field, however, is highly non-uniform. During these types of plasma processing two major effects play a key role in the reliability degradation: (i) plasma non-uniformity [2, 14] and the associated high electric fields may easily induce an electrical stress in the oxide. The plasma current, which consists of ion and electron fluxes, causes charge build-up on the gate electrode and the accumulated charges change the gate electrode potential and hence the field in the dielectric; (ii) high energy photons, X-rays and plasma particles bombardment may cause breakdown or induce a current flow, which leads to degradation. The SiO_2–Si system is also exposed to ultraviolet radiation from plasma, which

* Corresponding author: e-mail: elenada@issp.bas.bg

can generate electron–hole pairs (hυ > 8.9 eV) and/or electron injection from the silicon into the oxide through the photoelectric effect (4.2 eV < $h\upsilon$ < 8.9 eV). Electron injection induced hole trapping near the gate oxide interface was suggested as a possible mechanism for oxide degradation [15]. The ionizing radiation can induce leakage current in Si–SiO_2 microstructures similar to Stress-Induced Leakage Currents (SILC) [16–18]. SILC and radiation induced leakage current have similar electrical behaviour [17] and the study of plasma-induced leakage currents is extremely important in the perspective of future device scaling down. Early works [2, 14, 15, 19, 20] on plasma processing damage concentrated on the plasma non-uniformity as the major damage mechanism. Despite of the high interest in the interaction mechanisms between the non-homogeneous plasma and the Si–SiO_2 systems and a number of experimental data available, better knowledge of the damage produced by these plasma processes is needed MERIE type plasma, for example, is a technique commonly used for submicron applications owing to its efficient discharge at low pressures. However, MERIE-type plasma has been also identified as one of the processes that can cause damage in the form of interface states and oxide bulk traps. A common opinion is that the non-uniformity of the magnetron plasmas is the major mechanism responsible for the damages. Recently, [5, 8, 12, 13] we have shown that the non-uniformity of the plasma potential in MERIE type reactor, and respectively the electrical charging of the samples, has a strong but not dominating effect on the degradation of Si–SiO_2 structures. Here we will present investigations on the influence of MERIE-like plasma, as a representative of high density plasmas, on the properties of 12 nm thermal SiO_2–Si structures. Plasma-induced changes in the electrical parameters are discussed in close relation with the discharge parameters. As is well known, a variety of electrical techniques have been used to detect and characterize plasma damage. In particular, the plasma defects can be easily reactivated by a subsequent electrical stress and appear as an anomalous oxide trapped charge. For example, a stress is required to illuminate trapped charge. In this work, we utilize a number of electrical techniques to find the density and spatial distribution of plasma-induced damage and to obtain information about the trapping properties of defects.

2 Experimental procedure

100 mm diameter, 50 Ω cm, p-type (100) Si wafers were used as substrates in this study. The wafers were oxidized in dry oxygen at 1173 K (with 60 min post-oxidation annealing in N_2 ambient) to the thickness d_{ox} = 12 nm. Al-gate MOS capacitors with an area 3.8×10^{-4} cm^2 were formed on the wafers by photolithography. The test structures were used to study the effect of helium magnetized plasma on the Si–SiO_2 system. Helium is chosen as a plasma source in order to clarify the role of plasma action apart from the chemical surface reaction and the real etching. The plasma was created in a MERIE-like reactor [21] in which a 13.56 MHz rf discharge was combined with two kinds of magnetic fields. The reactor consists of two coaxial Al cylinders. This reactor geometry is acceptable for a high flux reactive ion etching. Discharge confinement by permanent magnetic fields is combined with an additional variable magnetic field over the plasma bulk. The permanent fields permit low pressure operation (mTorr range) at high densities (>10^{11} cm^{-3}) while the variable field can be used to control the sheath voltage. The system base pressure was approximately 10^{-5} Pa. The He gas pressure was maintained constant by a mass flow controller. The experimental structures were exposed to the plasma influence under the following discharge conditions: total pressure, p = 0.5 Pa; He flow rate –3 sccm; substrate bias voltage –75 V; axial magnetic field, B = 37 G; rf power, P = 1000 W; plasma exposure time, t_e, 5 s and 1 min. Wafers placed on the grounded and on the powered electrode were investigated. The damage in the structures caused by the MERIE plasma was evaluated electrically by capacitance–voltage (C–V), current–voltage (I–V) and constant current stress (CCS) measurements. A PAR 410 and HP 4140B were used to perform the HF C–V and quasistatic C–V and I–V measurements, respectively. Constant current stress measurements were carried out using HP 3245A universal source and HP 3458A multimeter.

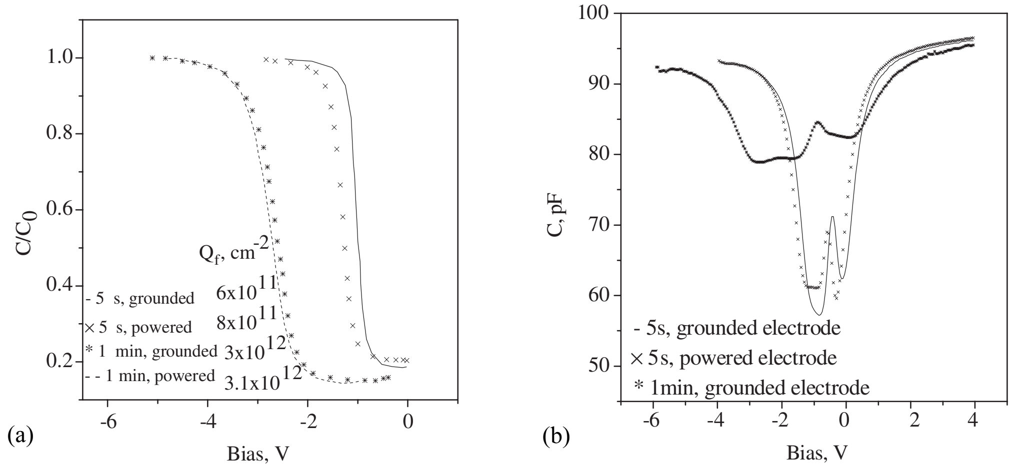

Fig. 1 a) HF C–V curves; b) QS C–V curves of plasma exposed MOS structures, placed on the grounded or powered electrode, respectively for different t_s (C_0 is the capacitance in accumulation.)

3 Results and discussion

The high frequency (HF) and quasistatic (QS) C–V curves for different samples are shown in Figs. 1a) and b) respectively. The values of positive oxide charge Q_f derived from the flatband voltage shift of HF C–V curves are also given. The plasma treated samples exhibit a characteristic peak due to radiation induced interface states, which had been investigated in more details in [5, 12]. It is seen that the plasma generates oxide charges with significant density – even in the first 5 s plasma induced oxide charge, ΔQ_f, is $6–8 \times 10^{11}$ cm^{-2}. Q_f for the initial (before plasma treatment) samples is about 10^{10} cm^{-2}. ΔQ_f slightly depends on the wafer position (on the grounded or on the powered electrode) and increases monotonically with t_s. The exposure when the sample is on powered electrode produces more damage in the form of interface traps. This means that the larger sheath voltage at the powered electrode in comparison with the grounded one stimulates interface states formation. The stronger impact on the quality of interface and the density of positive oxide charge, however, is the exposure time. The sample exposed for 1 min at the grounded electrode shows higher Q_f and the QS C–V curve is more distorted implying a higher density of the interface states. Ramp I–V characteristics for dual polarity are shown in Fig. 2. For negative gate biases (Fig. 2a) a well pronounced parallel shift to more negative biases is obtained for the sample exposed 5 s on the powered electrode and for one exposed 1 min on the grounded electrode. No shift is observed for the sample exposed for 5 s on the grounded electrode. As is well known the current flowing through the oxide depends on the cathode field and the relation is given by the Fowler–Nordheim equation. Therefore, any shift of the I–V curves can be connected with the charge build up near the cathode interface which alters the internal oxide field and hence the current. The observed shift to more negative biases implies that the charge generated is negative. It should be noted that the location of the wafers during the exposure influences the I–V shift stronger in comparison with the C–V curves where the duration of exposure is the major impact determining the damage level. This phenomenon suggests that there are plasma generated charges located rather near the Al–SiO_2 interface than Si–SiO_2 interface. 5 s exposure on the powered electrode produces nearly the same I–V shift as 1 min exposure on the grounded one. The plasma exposure does not alter significantly the I–V curves for positive gate polarity (Fig. 2b) – the curves shift slightly in positive direction and the largest shift is for the sample located on the grounded electrode and t_s = 1min. This behaviour confirms our suggestion that the MERIE-type plasma creates negative charge near the Al–SiO_2 interface (hence, this charge does not influence the I–V characteristics for positive polarity). To obtain more information about the density and location of the charge we used the method proposed in [22, 23]. According to this method the density of the charge Q_t and the

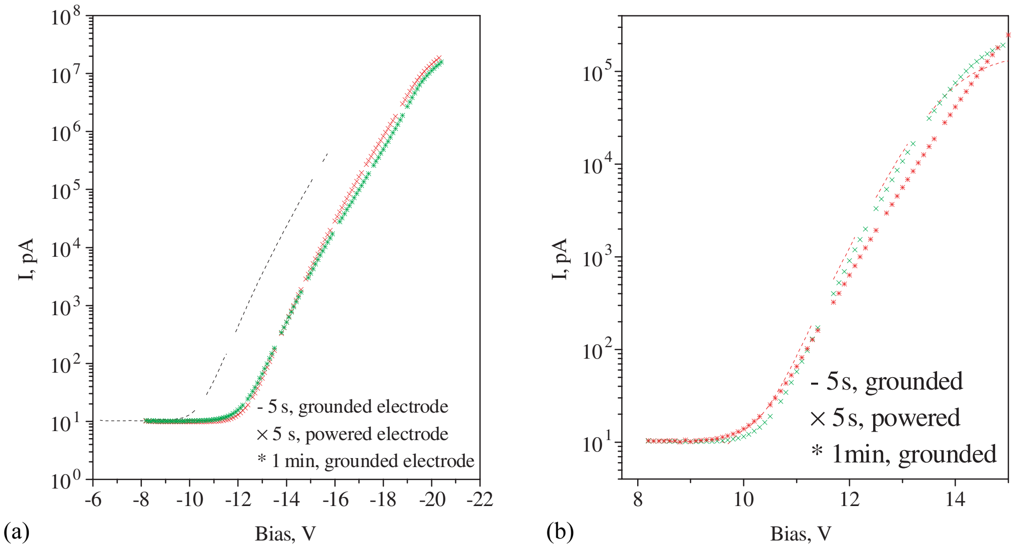

Fig. 2 (online colour at: www.interscience.wiley.com) I–V curves of the plasma exposed structures (the same discharge conditions as indicated in Fig.1) at: a) negative gate biases; b) positive gate biases.

distance d from the substrate of its centroid can be calculated from the shifts of I–V curves using the equations:

$$Q_t = \varepsilon_0 \varepsilon_{ox} [\Delta V(-) - \Delta V(+)]/d_{ox} ,$$

$$d = d_{ox} [1 - \Delta V(-)/\Delta V(+)]^{-1} ,$$

where ε_{ox} is the dielectric constant of SiO_2, and $\Delta V(+)$ and $\Delta V(-)$ are the induced shifts of I–V curves with positive and negative gate bias polarities, respectively. The exposure of the wafers located on the grounded electrode for 5 s does not produce negative charge formation, whereas for the samples exposed for the same time on powered electrode a generation of negative oxide charge $Q_t = 4 \times 10^{12}$ cm^{-2} with a centroid located at a distance 1–2 nm from Al–SiO_2 interface has been found. For $t_e = 1$ min, (sample on the grounded electrode), these values are 6×10^{12} cm^{-2} and 3 nm, respectively. These results imply that the exposure on the powered electrode produces more damage in the form of negative oxide charge located near the Al electrode. The stronger the plasma conditions the higher the density of this charge is and deeper in the oxide it is located. This can be explained taking into consideration the design and the operation principles of the MERIE reactor used [21]. Generally, there are two major sources of plasma damage – radiation damage due to the existence of high energy ions, electrons and Vacuum Ultra Violet (VUV) in the plasma; and electrostatic charging damage caused by plasma non-uniformity. In addition charging damage, for example, is not only process but also design related. As the Al-gate thickness of the samples is 600 nm, the results are not influenced by VUV radiation, (VUV typical of the plasma used cannot penetrate through Al electrode thicker than 300 nm). The sheath voltage at powered electrode in our case is higher than that at grounded one [21]. This can have two different consequences: (i) the higher sheath voltage means higher ion energy hence, more radiation damage. Also, at magnetic field of about 40 G, close to the powered electrode, the ion density increases about twofold [21]; (ii) electron current depends exponentially on the local sheath voltage and it is the most important factor in charging [24]. Therefore, the present experiments cannot distinguish the damage caused by the two sources. Having in mind our previous studies [5, 12] we can conclude that generation of both positive oxide charge and interface states is due to the combined action of plasma radiation and electrostatic charging (electrostatic charging has essential but not dominating effect, i.e. the non-uniformity is only one of the key mechanisms responsible for the damage but it is not dominant factor), and the defect level is defined rather by exposure time than by location of wafers during the plasma action.

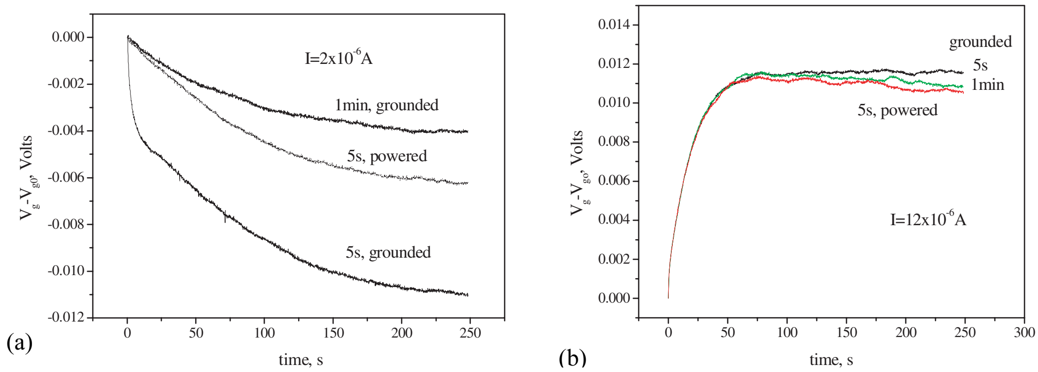

Fig. 3 (online colour at: www.interscience.wiley.com) Evolution of gate voltage under constant current stress for the plasma treated samples: a) $I = 2 \times 10^{-6}$ A; b) $I = 12 \times 10^{-6}$ A

The evolution of the gate voltage under constant current stress is shown in Fig. 3 for two levels of injection currents (injection is performed from the gate). It is seen that at the lower current (~5×10^{-3} A/cm^2) a positive charge is trapped in the oxide whereas at the higher one (~30×10^{-3} A/cm^2) a negative charge build up is observed. These results suggest that at lower injection level detrapping of electrons is more probable unlike the case at higher level where trapping of electrons dominates. It has to be noted that the trapping of positive charge (detrapping of electrons) is stronger in the sample on the grounded electrode after 5 s plasma treatment (Fig. 3a). Figure 3b reveals that the negative charge trapping at higher injection current depends slightly on the plasma conditions. If we try to correlate the data from the I–V and CCS measurements it emerges that the detrapping of electrons is most pronounced in the samples exhibiting less negative charge build-up. This result is somehow strange as it is reasonable to think that the samples with more negative trapped charge should show higher rate of electron detrapping. As is seen, the change of the gate voltage in both cases (Figs. 3a, b), however, is small ($\Delta V_g < 0.012$ V), i.e. the amount of the charge trapped or detrapped under CCS is small ($<2 \times 10^{10}$ cm^{-2}). As the I–V characteristics show that the MERIE plasma creates negative charge with significant density ($>10^{12}$ cm^{-2}) one can conclude that this charge cannot be detrapped or neutralized under CCS. Therefore, we suggest that it is located energetically deep in the SiO_2 bandgap. For all the samples the hysteresis of the C–V curves, when sweeping the voltage from accumulation to inversion and back, is negligible.

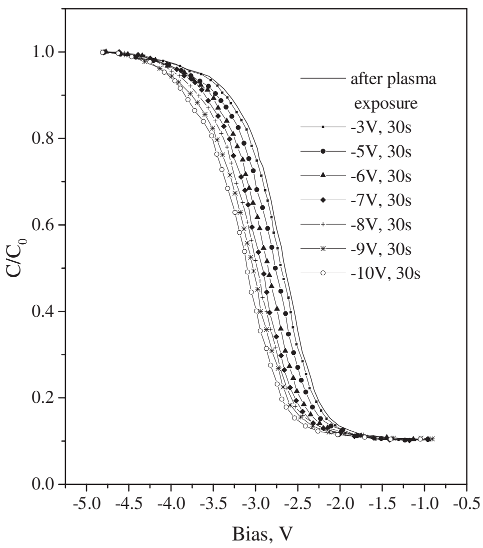

Fig. 4 The shift of the C–V curve of plasma exposed sample (1 min, grounded electrode), under stressing with various negative gate biases.

The shift of C–V curves when stressed at small positive biases (4–6 V) is also negligible. These results imply that no charge exchange between slow states and Si bands occur, i.e. the short-time (≤ 1 min) exposure to MERIE-type plasma does not generate acceptor like slow states. The evolution of C–V curves under relatively low negative biases (less than the bias at which FN injection starts) is shown in Fig. 4. The sample was stressed at a certain voltage for 30 s and after that the HF C–V curve was measured. The C–V measurement took not more than 10 s and one can suppose that during this period the charge distribution was not affected. The figure shows continuous build-up of positive charge. Generally speaking the amount of the generated charge is relatively small. After 1 min stress at –3 V it is $\sim 3 \times 10^{10}$ cm^{-2}. Another 1 min at –5 V creates $Q_f \sim 6 \times 10^{10}$ cm^{-2}. The overall amount of charge created after different stresses at (–3 to –10 V) is $\sim 3 \times 10^{11}$ cm^{-2}. As there is no FN injection at these fields (Fig. 2a) we suppose that the positive charge is due rather to trapping/detrapping of charges than to generation of traps by the stress. A confirmation of this suggestion is the fact that another 30 s stress at the given bias does not create additional shift of C–V curve. There are two possibilities for the trapping/detrapping of carriers and the resultant positive charge formation: (i) detrapping of electrons from the traps in SiO_2 into the oxide conduction band; (ii) as the structure is in accumulation the trapping of holes from the Si valence band in the near interface region is also probable. If this is the case the trapped holes should be easily detrapped under relatively low positive gate biases. To check for this we applied voltages of 6–9 V to the structure. The results showed that only a fraction ($\sim 1 \times 10^{11}$ cm^{-2}) of the positive charge is neutralized. This allows us to conclude that the first process considered dominates. Half ($\sim 1.5 \times 10^{11}$ cm^{-2}) of the generated positive charge is neutralized under +10 V, (1 min). As this is the voltage at which FN tunneling begins (Fig. 2b) it means that the charge annihilated is located in the bulk of the oxide rather than in the near interface region (tunneling distance from Si). It should be noticed that as in the case of CCS, there are not indications for a significant trapping/detrapping in the oxide. This can be considered as another confirmation of our suggestion that negative charge created by MERIE-like plasma cannot be neutralized (it cannot change its charge state).

4 Conclusion

Complex investigation by various electrical techniques (QS and HF C–V measurements, I–V and constant current stress measurements) has been performed to study the charges created by MERIE-like He plasma, (traps density, location in the oxide and trapping properties). From the results obtained we can conclude that plasma exposure creates damage in the form of interface states, positive oxide charge near SiO_2/Si interface and negative charge near Al/SiO_2 interface. Different dependencies on plasma conditions have been established for these types of damage. Exposure on the powered electrode creates a slightly higher density of positive charge and interface states compared to that on the grounded electrode. The plasma exposure time is the stronger impact defining the level of positive charge and the interface states, (very rapid increase of the plasma induced oxide charges up to $6–8 \times 10^{11}$ cm^{-2} is detected in the first 5 s plasma action). The density of the negative charge and its centroid, however, are strongly influenced by the wafer position during exposure: 5 s exposure on the powered electrode generates nearly the same amount of negative charge ($\sim 6 \times 10^{12}$ cm^{-2}) as 1 min exposure on grounded one. This means that the nature of plasma-induced defects in MOS capacitor depends on the wafer position – the plasma stimulates the generation of negative oxide charge when the wafer is on the powered electrode. The results imply that the stronger the plasma conditions the higher the density of this charge is and deeper in the oxide it is located. The experiments performed show that its charge state can not been changed under the constant current stress, i.e. it is located deep in the SiO_2 band gap.

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