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Defect Formation in 18 MeV Electron Irradiated MOS Structures

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Abstract. Defect formation in MOS structures irradiated with 18 MeV electrons has been investigated by high frequency capacitance-voltage (HF C/V) and deep level transient spectroscopy (DLTS) methods. It has been shown that high-energy electron irradiation decreases the oxide capacity as well as the positive charge in the oxide and creates surface states at the Si–SiO_2 interface of the samples. The energy and capture cross section of the radiation-induced traps created by high-energy electron irradiation at the Si–SiO_2 interface of the samples have been determined. The nature of these radiation induced traps has also been discussed. It has also been demonstrated that oxygen surface density at Si–SiO_2 interface depends on the kind of the oxide as well as the electron dose irradiation

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1 Introduction

The influence of high-energy (11–22 MeV) electron irradiation on the interface states of the Si–SiO_2 system has been investigated in our previous work [1-3]. It has been shown that high-energy electrons create a new spectrum of interface states in the silicon band gap. The parameters of the states located at the Si–SiO_2 interface have been estimated by thermally stimulated current method [1]. It has been demonstrated that the primary defects induced in n-type silicon MOS structures by a high-energy electron irradiation are vacancy-oxygen and vacancy-phosphorus defects [1,4]. The effect of MeV electron irradiation on p-Si–SiO_2 structures and n-Si–SiO_2 structures implanted with boron ions has been also studied by deep level transient spectroscopy measurements [2-3]. The formation and annealing of radiation induced defects in silicon transistors with 4 MeV electrons have been studied by F. P. Korshunov *et. al.* [5].

In this paper we report the results of a new experiment, in which n-type Si–SiO_2 samples with oxide thickness of 49 nm are irradiated with 18 MeV electrons for different duration. The samples are measured by HF C/V and DLTS methods after each dose irradiation. It will be shown that the density of the interface states at the Si–SiO_2 interface induced by the high-energy electrons increases with radiation dose increasing. The main parameters of the electron-induced interface traps are determined. The oxide capacity and the positive charge in the oxide of the samples decrease with electron irradiation dose increasing.

2 Experimental Details

The samples studied in the present paper are fabricated on n-type $\langle 100 \rangle$ oriented silicon wafers of 5.4 Ωcm resistivity. Following a standard cleaning procedures, thermal oxidation in dry oxygen is performed at 1000°C to produce 49 nm oxide. After finishing the oxidation the samples are cooled with a rate 1°/s in a nitrogen ambient. The oxide thickness is measured by the ellipsometry method. Then Al gate electrodes are photolitographycally defined. The back side of the silicon wafers is coated with a thin layer of Al (12 nm) to serve as an ohmic contact. After backside metallization, post-metallization annealing of the samples in forming gas at 400°C for 10 min is performed. Then the irradiation with 18 MeV electrons is completed from the gate side of the wafers. The distance between the Microtron window and the sample is 150 mm. The samples are bombarded with electrons for 15, 30 or 60 s and the average current of the electron beam at the samples is about 9 μA. The energy (18 MeV) is high enough for the electrons to penetrate through the whole samples. No bias is applied to the devices during the irradiation. Some of the samples are left to be used as a reference in the comparison of the electrical properties of the initial MOS structures with those of the structures exposed to the electron irradiation. These series are used for investigation of the electro-physical parameter dependence on the electron dose irradiation.

High frequency C/V and DLTS characteristics of the MOS structures are measured in order to determine the parameters of the radiation defects induced by high-energy electron irradiation. The oxide capacity and the oxide charge are defined by C/V characteristics of MOS structures. Different trap centers induced in silicon band gap by high-energy electron irradiation have been identified from the DLTS characteristics. The radiation traps number is directly evident from the peaks number of DLTS spectrum. The energy positions in silicon band gap and capture cross section of each of the traps corresponding to these peaks are evaluated.

3 Results and Discussion

We have chosen the C/V measurements because the significant changes of the C/V curves after electron irradiation are observed. Figure 1 shows typical C/V curves obtained on initial (curve 1) and electron irradiated Si–SiO_2 structures for 15, 60 s (curves 2 and 3) respectively. As can be seen from this figure, high-energy electron irradiation seriously distorts C/V curves of the irradiated MOS samples. After 7200 s irradiation of the samples the C/V characteristics are not measurable. It is obvious that 18 MeV electron irradiation decreases the oxide capacity, positive charge in the oxide as well as the slope of the C/V curves of MOS structure. Our experiment shows that the oxide capacity of the initial MOS sample is equal to the value of $C_{\text{ox}} = 132.68$ pF. The oxide capacity of the samples decreases to $C_{\text{ox}} = 129.77$ pF after 15 s irradiation and it decreases respectively to $C_{\text{ox}} = 113.89$ pF after 60 s irradiation. The decrease of the oxide capacitance can be caused by three reasons. The first possible reason – the induced defects in the oxide by electron irradiation – can change the value of the dielectric constant of the oxide. The second reason is an increase of the oxide thickness and the third reason is a combination of both of them. To check the reason we use ellipsometry technique to measure the oxide thickness of the samples before and after each electron irradiation. Our measurements show that the oxide thickness of the samples increases. The oxide thickness is 49 nm before

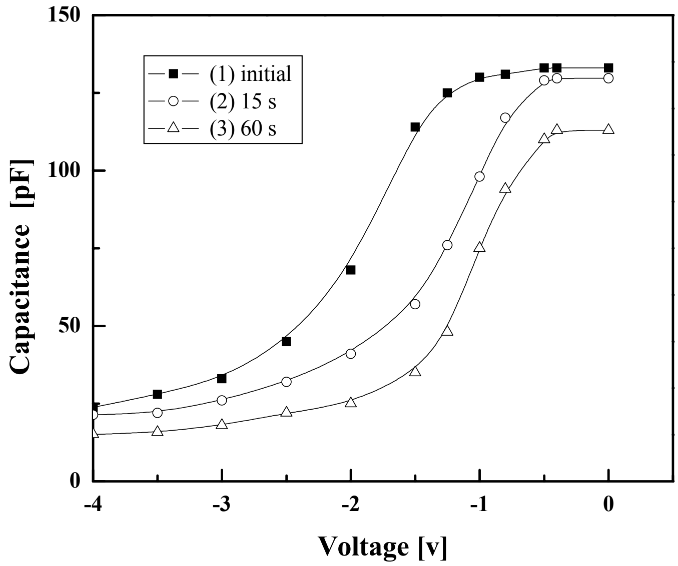

Figure 1. Typical C/V curves obtained on initial (curve 1) and electron irradiated Si–SiO_2 structures for 15 and 60 s (curves 2 and 3), respectively.

irradiation. After irradiation with electrons for 15 or 60 s the oxide thickness increases up to 53 or 64 nm, respectively. We suggest that the oxide thickness increase (in a result of high-energy electron irradiation) may be connected with radiation-stimulated oxidation of the samples.

The C/V curve shift to the positive states of the voltage (curve 2) means that after 15 s electron irradiation the positive charge in the oxide of the initial MOS sample decreases. The positive charge in the bulk oxide can be estimated by the flat-band voltage shift $\Delta V_{\rm fb}$ after irradiation. But the true value of the radiation-induced charge in the oxide should be calculated from the midgap voltage $\Delta V_{\rm mg}$ shift because the charged states at the Si–SiO_2 interface also cause the C/V curve to shift additionally at $V_{\rm fb}$. Assuming that all interface states above E_i are of acceptor type and all below E_i are donor type we can obtain the fixed oxide charge directly from the high frequency C/V curve without using interface state information. The shift in the midgap voltage $\Delta V_{\rm mg}$ is solely due to the change in the fixed oxide charge $\Delta Q_{\rm ox}$, which is given by the expression

$$\Delta Q_{\rm ox} = C_{\rm ox} \Delta V_{\rm mg}/q,$$

where $\Delta V_{\rm mg}$ can be determined in the same way as $\Delta V_{\rm fb}$, $C_{\rm ox}$ is the oxide capacity, and q is the electron charge.

Before irradiation the C/V curve of the initial MOS structure shifts regard the corresponding theoretical C/V curve (without interface states and without charge in the oxide) and $\Delta V_{\rm mg}$ is equal to 3 V. After 15 s irradiation, this shift decreases, and $\Delta V_{\rm mg}$ is equal to 1.75 V (curve 2). After 60 s irradiation the C/V curve shifts more to the positive states of the voltage and $\Delta V_{\rm mg}$ is equal to 1.3 V (as can be seen from Figure 1, curve 3). Secondary electrons resulting from the interaction between the high-energy electrons (higher than 11 MeV) and the Si–SiO_2 structure could be a reason for decreasing of the positive charge in the oxide after irradiation [6].

After electron irradiation the C/V curves are distorted which means that the electron irradiation increases the Si–SiO_2 interface state density. Comparing the C/V curve of the initial sample (curve 1) with those of the irradiated MOS samples (curves 2 and 3) shows that the slope of the C/V curves decreases. It is obvious that curve 1 is steeper than the curves (2 and 3). This means that a set of electrically active centers at the Si–SiO_2 interface is formed as a result of high-energy electron irradiation additionally.

This fact is also confirmed by the DLTS measurements. Before electron irradiation no DLTS spectrum is observed. Formation of DLTS spectra is observed after 15 s electron irradiation of MOS samples. The detailed interface state information is taken namely from these DLTS measurements. Figure 2 shows typical DLTS spectra of the electron irradiated MOS samples after 15 s (curve 1) and after 60 s irradiation (curve 2). A little dose electron irradiation (curve 1) creates new DLTS spectrum with four peaks. These four peaks could be associated with

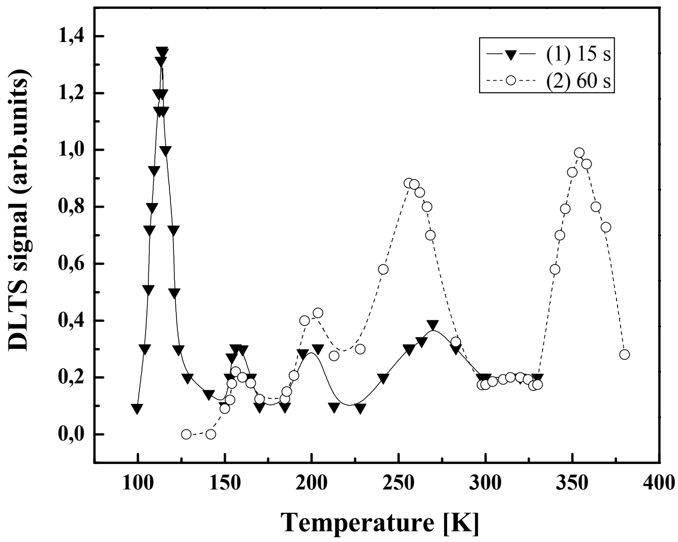

Figure 2. Typical DLTS spectra of the electron irradiated MOS samples after 15 s (curve 1) and 60 s irradiation (curve 2).

four types of the radiation induced traps in the upper half of the silicon band gap (as silicon wafers are n-type). These radiation induced traps are located close to the Si–SiO_2 interface and they strongly depend on the oxide property. The electron irradiation dose increase leads to the reconstruction of the DLTS spectrum: the first peak disappears, the second one weakly decreases, the areas covered by the third and by the fourth peaks increase (weakly and strongly respectively) and a new peak located at the end of the DLTS spectrum appeares. The energy position and capture cross section of these traps corresponding to the peaks are determined from the measurements. The behaviour of DLTS spectra shows that the shallowest level ($E_c$$-0.18$ eV) corresponding to the simplest kind of defects disappears. The concentration of the second kind of defects ($E_c - 0.24$ eV) decreases. The concentration of the last two kinds of defects ($E_c - 0.26$ eV) and $E_c - 0.30$ eV) increases and a new kind of defects corresponding to the deeper traps in silicon band gap ($E_c$$-0, 40$ eV) appears after 60 s of irradiation. The actiavation energy as well as the cross section for the electron capture of the traps created by electron irradiation have been calculated from DLTS characteristics.

These parameters allow to determine the nature of each kind of defects created by high-energy electrons. Table 1 shows the radiation induced trap parameters.

The shallow level $E_c - 0.18$ eV has been attributed to a vacancy trapped by an interstitial oxygen atom or “A” center. The density of these defects decreases with dose increasing of the electron irradiation and it is not observed after 60 s irradiation (curve 2). The concentration of the second kind of defects ($E_c -$

Table 1. Parameters of the radiation defects induced by 18 MeV electrons

Capture cross section	Energy (eV)				
S_n (cm^2)	$E_c-0.18$	$E_c-0.24$	$E_c-0.26$	$E_c-0.30$	$E_c-0.40$
After 15 s irradiation	7.8×10^{-12}	1.8×10^{-13}	2.3×10^{-13}	4.4×10^{-15}	—
After 60 s irradiation	—	1.3×10^{-15}	4.8×10^{-12}	5.9×10^{-14}	8.7×10^{-12}

0.24 eV) decreases also. The levels $E_c-0.24$ eV, and $E_c-0.26$ eV probably are correlated with double acceptor levels of divacancies [5-7]. The third kind of defects corresponding to the E_c–0.30 eV level is still not completely understood, but it can be correlated with higher-order defects [8-10]. The additional high-energy electron irradiation generates new trapping center located deeper on the energy scale in the Si forbidden gap. The activation energy of this last kind of defects introduced by higher dose electron irradiation is estimated as $E_c-0.40$ eV. This electron trapping center is determined as a lattice vacancy trapped at a substitutional phosphorus atom or phosphorus-vacancy pair (P-V), in other words “E” center.

The intensive decreasing of trap density of the vacancy-oxygen complexes possibly is due to the secondary electrons. These secondary electrons could play a role in the disappearing of the first peak of DLTS spectrum (curve 1). On the other hand, higher dose electron irradiation is expected to create defects, which are responsible for the new (last) peak observed in DLTS spectrum (of curve 2). This spectrum also shows that after 60 s electron irradiation the density of all levels (expect the $E_c-0.18$ eV and $E_c-0.24$ eV) increases with electron irradiation dose increasing. The intensive increasing of trap density of the complexes corresponding to the deeper levels in silicon band gap is due to the bigger possibility of interstitial atoms and vacancies creation with radiation dose increase [11]. The dominant density of the defects created by higher dose electron irradiation is the density of vacancy-phosphorus (E-center) complexes. This level is associated with defects connected with doped phosphorus impurities (n-type Si). Moreover, as Si–SiO_2 interface itself is a source of defects and the process of radiation induced defect formation as a result of bigger dose electron irradiation is most active for the vacancy-phosphorus complexes. In this case (n-type Si) the behavior of the defect formation after high-energy electron irradiation is to a certain extent opposite to that of the defect formation in p-type Si where the deepest trap in Si band disappears after 15 s irradiation and four new shallower levels are formed [3]. It can be noted that the behavior of interface states introduced by high-energy electron irradiation at Si–SiO_2 interface of MOS structures depends not only on the radiation dose but it also depends on the type of silicon wafer of the irradiated sample.

Such an effect may be connected with oxide film additional growth under high-energy electron flow. This fact is in good agreement with the results of the work [12]. Taking into account that irradiation was performed in the vacuum one may suppose that oxygen atoms which are necessary for silicon oxidation diffuse from silicon substrate [13].

4 Conclusions

It summary, our results show that the high-energy electron irradiation creates several types of radiation induced interface states at the Si–SiO_2interface of MOS structures. The oxide capacity and the positive charge in the oxide of the MOS samples decrease with electron irradiation dose increasing. It has been shown that when n-type MOS structures are irradiated with low dose electrons, the mainly created defects at the Si–SiO_2 interface are associated with vacancy-oxygen (A-center). When electron irradiation dose increases vacancy-phosphorus (E-center) complexes are mostly formed.

References

[1] S. Kaschieva (1994) *Nucl. Instrum. Methods B* **93** 274.

[2] S. Kaschieva, K. Stefanov, D. Karpuzov (1998) *Appl. Phys. A* **66** 561.

[3] K. Stefanov, S. Kaschieva, D. Karpuzov (1998) *Vacuum* **51** 235.

[4] H.J. Stein, F.L. Vook (1968) *Radiation Effects in Semiconductors* (Ed. by F.L. Vook, Plenum press, New York) 115.

[5] F.P. Korshunov, Yu.V. Bogatyrev, S.B. Lastovsky, V.I. Kulgachev, L.P. Anufriev, I.I. Rubstevich, N.F. Golubev (2003) *Vacuum* **70** 197.

[6] V. Vavilov, N.A. Uhin (1969) *Radiation effects in semiconductors* (Atomizdat, Moskwa).

[7] V.P. Merkevich, O. Andersen, I.F. Medvedeva, J.H. Evans-Freeman, L.I. Murin, L. Dobaczewski, A.R. Peaker (2001) *Physica B*, **308**.

[8] A.F. Saunders, G.T. Wright (1970) *Electron. Lett*. **6** 207.

[9] A.J. de Castro, M. Fernandez, J.L. Sacedon, J.V. Auguita (1992) *Appl. Phys. Lett*. **61** 684.

[10] K. Shinoda, E. Ohta (1992) *Appl. Phys. Lett*. **61** 2691.

[11] S. Nigam, J. Kim, F. Ren, G.Y. Chung, M.F. MacMillan, R. Dwivde, T.N. Fogarty, R. Wilkins, K.K. Allums, C.R. Abernathy, S.J. Pearton, J.R. Williams (2002) *Appl. Phys. Lett.* **81** 2385.

[12] E. Kurmaev, S. Shamin, V. Galakhov, M. Kirilova, T. Kurennykh, V. Viykhodets, S. Kaschieva (1997) *J. Phys. Condens. Matter* **9** 6969.

[13] S. Kaschieva, S.N. Dmitriev (2002) *Vacuum* **69** 87.