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Research Article

Effect of low-energy electron irradiation on voltage-capacity curves of Al/SiO_2/Si structure

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Abstract

Charging of dielectric targets by electron irradiation is a well-known phenomenon which should be taken into account in characterization of dielectric materials and coatings with electron microscopy, in electron beam lithography, in development of dielectric coatings for spacecrafts and other fields of science and engineering. Charging kinetics is strongly affected by spatial distribution of electrons and holes formed by irradiation. At the experimental electron beam energy electron penetration depth is smaller than dielectric thickness and this allows identifying the contribution of excess carrier transport to trap formation at the SiO_2/Si interface. Low-energy electron beams have been shown to substantially affect *C*–*V* curve slope, i.e., to form traps at the interface. We have studied the effect of bias applied to the test structure before and after electron beam irradiation. The experiment has shown that bias of either polarity applied to the test MOS structure before low-energy electron beam irradiation practically does not affect the *C*–*V* curves of the test structure. Positive bias applied to the metallization layer during low-energy electron beam irradiation has a strong effect on the *C*–*V* curve pattern while negative bias affects the *C*–*V* curves but slightly. Study of the stability of the changes caused by electron beam irradiation has shown that the *C*–*V* curves of the test structure restore slowly even at room temperature. Application of negative bias decelerated charge relaxation.

Keywords

silicon oxide, low-energy electron beam, MOS structure, *C*–*V* curves

1. Introduction

Charging of dielectric targets by electron irradiation is a well-known phenomenon which should be taken into account in studies of dielectric materials and coatings with electron microscopy, in electron beam lithography, in development of dielectric coatings for spacecrafts and in other fields of science and engineering. Most of the works reported so far dealt with measuring the potential of the charged surface which is mainly determined by the balance between the charge of the primary electrons penetrating into the material and the charge of the emitted secondary electrons [1–9]. It was shown however [10] that charging kinetics is strongly affected by the spatial distribution of the electrons and holes formed by irradiation. This distribution determines the effect of electron beam irradiation on the parameters of the metal–oxide–semiconductor **(MOS)** structures because the charge at the surface is compensated by the charge of the metallic contact.

The aim of this work is to study the effect of electron beam irradiation on the parameters of Al/SiO_2/Si structures. The study included measurements of voltage-capacity curves **(C–V)** that are sensitive to the charge at the SiO_2/Si interface and in the bulk of the SiO_2 film near the SiO_2/Si interface.

2. Experimental

The effect of electron beam irradiation on the parameters of the test MOS structure was studied on boron doped Si substrates of *p*-type conductivity with an impurity concentration of 3×10^{14} cm^{-3} and a SiO_2 dielectric layer thickness of 200 nm. The oxide layer was produced by thermal oxidation of silicon. The diameter of the metallic pads was 1.6 mm, however the actual contact areas could decrease as a result of multiple measurements with a spring probe.

The capacitance-voltage curves were measured with a PAR Model 410 C–V plotter at 1 MHz. The irradiating electron beam parameters were as follows: an acceleration voltage of 2.5 kV, a beam current of within 1 nA and irradiation doses of 10, 20, 25 and 30 µCl/cm^2. The specimens were irradiated in a Jeol-840A electron microscope in TV mode through deposited Al metallization. The specimens were earthed in all the experiments and therefore the charge accumulated in SiO_2 was compensated by the charge at the metallic contact. Under these irradiation conditions the incident electrons did not reach the SiO_2/Si interface because the electron penetration depth into the oxide layer was within 80 nm.

We also studied the effect of bias applied during electron beam irradiation on the charge accumulation. The irradiation parameters were the same as in the previous experiments but positive or negative bias was applied to the metallization for moving the semiconductor surface at the SiO_2/Si interface either to accumulation or to strong inversion, respectively. The bias was produced by a B5-49 DC source.

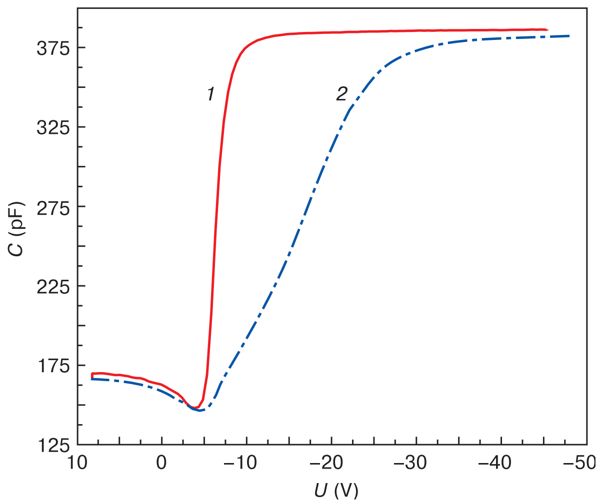

Figure 1. C–V curves of test MOS structure (*1*) before and (*2*) after irradiation. Acceleration voltage is of 2.5 keV, beam current of 1 nA and irradiation dose of 15 µCl/cm^2.

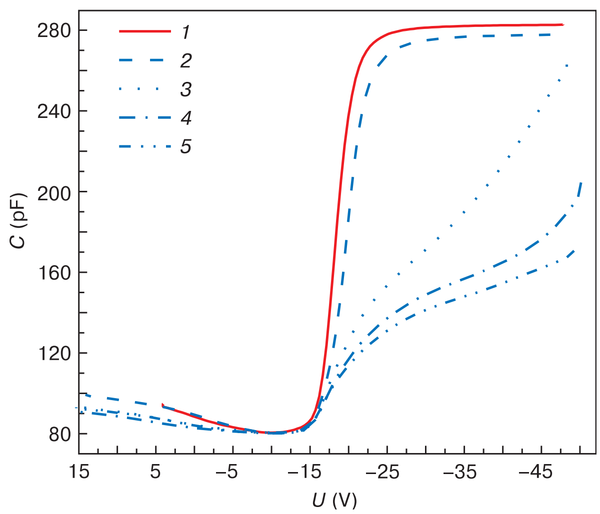

Figure 2. C–V curve variation for different irradiation doses: (*1*) before irradiation and (*2*–*5*) irradiation with doses of 10, 20, 25 and 30 µCl.

3. Results and discussion

Figure 1 shows typical C–V curves before and after electron beam irradiation. Comparison with a calculated ideal curve showed that the C–V curve of the non-irradiated structure is already shifted towards negative voltages but the curve slope is close to that of the ideal one. This shift of the C–V curve can be accounted for by the combined effect of two components. One component is the difference in the work functions of the metal and the dielectric which is about –1 V. However since the shift of the initial C–V curve of the test structure is far greater than –1 V the main contribution to the C–V curve shift must come from the other component, i.e., the built-in positive charge in the bulk of the SiO_2 dielectric layer. Low-energy electron irradiation changes the slope of C–V curve but does not cause any substantial shift towards negative voltages. The change of the C–V curve slope is usually accounted for by the formation of traps at the Si/SiO_2 interface [11, 12]. However at the electron beam parameters used in this work, primary electrons do not reach the Si/SiO_2 interface and therefore trap formation at the Si/SiO_2 interface can only be accounted for by charge transport in the oxide layer bulk and/or carrier exchange with the silicon substrate.

Then we studied the effect of irradiation dose on the C–V curves of the test structure. The results are shown in Fig. 2. The lower maximum capacitance of the structure in this experiment is accounted for by the smaller metallic contact area. It can be seen that an increase in the irradiation dose reduces the slope of the C–V curve while the voltage shift in the inversion region practically does not depend on irradiation. Bulk charge in dielectric films is usually determined from voltage shift for flat zones in comparison with the calculated ideal curve [13] and a change in the curve slope indicates the formation of surface states. Then however a negligible shift of the C–V

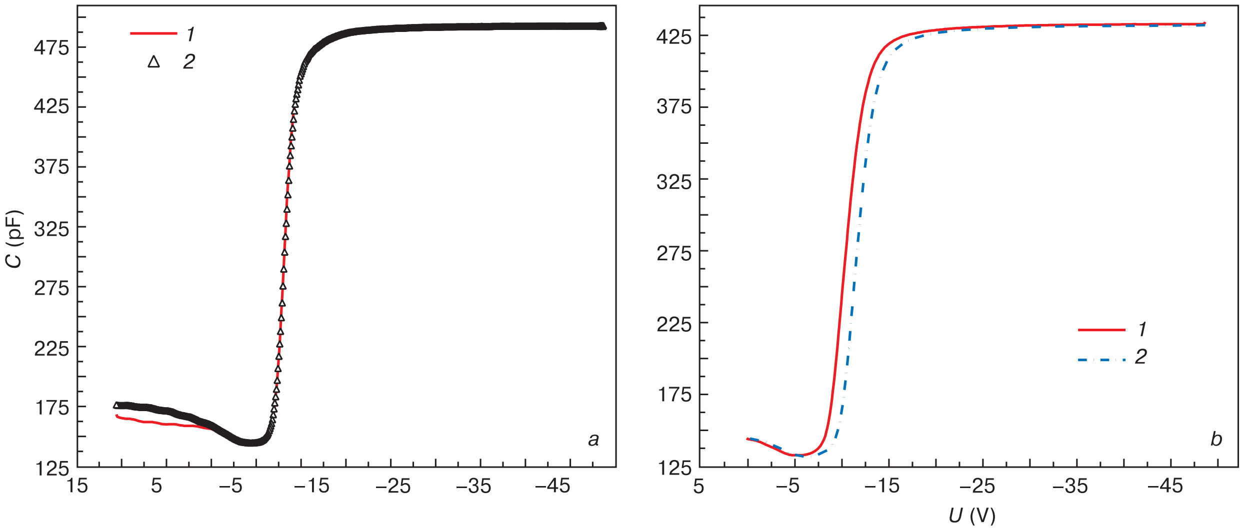

Figure 3. Variation *of C–V* curves of test MOS structure before electron beam irradiation for application of different bias to metallization (*a*) +40 V (inversion), (*b*) –40 V (accumulation), (*1*) before biasing and (*2*) after biasing for 15 min.

curve in the inversion region suggests that the effect of volume charge exactly compensates the effect of surface states. It is more plausible to assume that low-energy electron beam irradiation only slightly changes the bulk charge in the SiO_2 film whereas the density of states at the Si/SiO_2 interface increases with an increase in the irradiation dose.

To verify the assumption of carrier exchange between the oxide and the silicon substrate we studied the effect of bias applied to the metal contact on charge accumulation during irradiation and subsequent charge relaxation. We first verified the effect of bias applied to the initial MOS structure at room temperature. Figure 3 shows results of this experiment for bias voltages of –40 V and +40 V. It can be seen from Fig. 3*a* that positive bias does not affect the built-in charge in the dielectric. Negative bias slightly shifts the curve towards negative voltages without changing the curve slope (Fig. 3*b*). This shift indicates an increase in the positive charge in the bulk of the oxide layer and/or its shift toward the interface. Since negative bias application impedes the shift of the positive charge toward the interface the most probable cause of the *C–V* curve shift is hole injection from silicon to SiO_2.

Study of the effect of bias applied to metallization on charge accumulation during electron beam irradiation revealed the following regularities. The effect of irradiation is smaller if a negative bias is applied to the metal contact (the electric field in the dielectric attracts holes to the metal contact pad) than for a positive bias (the electric field in the dielectric repels holes to the Si/SiO_2 interface). Figure 4 shows *C–V* curves of the same metal contact to which bias was applied during irradiation (the irradiation dose was 20 μCl/cm^2). It can be seen from Fig. 4 that application of a positive bias of 10 V to the metallization not only changes the *C–V* curve slope but also shifts the curve towards negative voltages. One can therefore conclude that charge is accumulated not only at the Si/SiO_2 interface but also in the dielectric bulk.

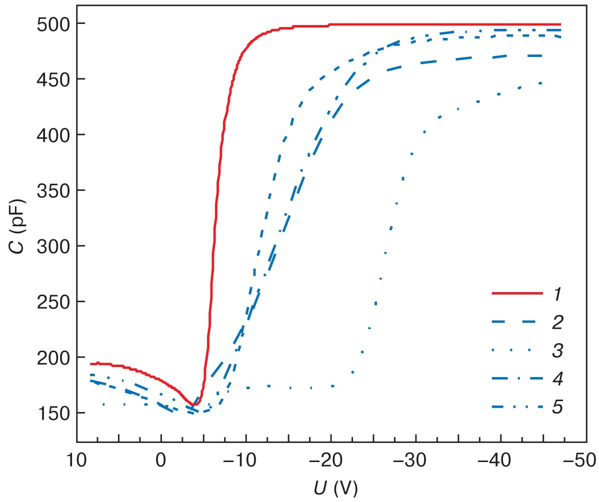

Figure 4. Variation *of C–V* curves of test MOS structure (*1*) before irradiation and (*2*–*5*) after irradiation with different bias: (*2*) +10 V, (*3*) 0, (*4*) –10 V and (*5*) –20 V. Irradiation dose: 20 μCl/cm^2.

As noted above the depth of electron/hole pair generation for the electron beam energy used in this experiment is within one half of the SiO_2 film thickness. Moreover it was shown earlier [14, 15] that the hole free path in SiO_2 is a few tens of nanometers. It should be also noted that the built-in electric field in the unirradiated specimen generated by the positive charge in the oxide layer suppresses hole transport toward the Si/SiO_2 interface and stimulates electron drift toward the interface. The contribution of the charges near the metal contact to this field is screened and hence the main contribution to the field comes from the positive charge at the Si/SiO_2 interface. Our experimental results show that irradiation of the structure at a zero bias increases the positive charge in the oxide layer. The electric field inside the dielectric should impede nonequilibrium hole transport toward the interface and stimulate electron transport toward the interface. Thus our experimental results suggest that the formation of surface states at the Si/SiO_2 interface due to low-energy electron irradiation of the structure is stimulated by nonequilibrium electrons reaching the interface. This however does not agree with the common opinion [11, 12] that nonequilibrium electrons leave rapidly the specimen or recombine inside it and the formation of surface states and bulk charge involve non-recombined nonequilibrium holes. Noteworthy, our study of the effect of electric field application during irradiation shows that nonequilibrium holes can also stimulate the formation of surface states (Fig. 4) although in this case the process can be stimulated by electron injection from silicon which is known to cause MOS structure device degradation [16–19].

It was also of interest to study the stability of the irradiation induced charge. The study showed that *C–V* curve recovery occurs even at room temperature, though very slowly. Charge relaxation was found to obey a logarithmic law

$$\Delta V = \Delta V_0 - A\ln(t/t_0),$$

where ΔV_0 is the bias applied after electron beam irradiation measured at 0.8–0.9 of the capacity in the enriched region, t is the annealing time, A is the coefficient equal to 0.1–1 V and t_0 is the normalization constant equal to approx. 150 s. According to earlier works [20, 21] the logarithmic dependence can be accounted for by electron tunneling from the silicon substrate to the SiO_2 layer and compensation of the positive charge accumulated as a result of electron beam irradiation. To confirm this assumption we studied the effect of bias applied to the metallic electrode on the relaxation of the charge accumulated after irradiation. The study showed that the accumulated charge relaxation at room temperature was faster for positive bias than for negative bias. This can be accounted for by the fact that in inversion mode (positive bias) more electrons can tunnel to the SiO_2 layer from the silicon substrate whereas in accumulation (negative bias) electron injection into the oxide layer is largely suppressed.

4. Conclusion

The effect of low-energy electron beam irradiation on the *C–V* curves of a $Al/SiO_2/Si$ MOS structure was studied for a ground metallic contact and for bias application during irradiation. The results suggest that at the electron energy used in the experiment for irradiation, the formation of surface states at the Si/SiO_2 interface can be stimulated not only by nonequilibrium holes as was commonly believed earlier but also by nonequilibrium electrons. The thermal stability of the bulk charge and surface states induced by irradiation was studied. The study showed that annealing of the irradiated MOS structure at 210 °C leads to an almost complete recovery of the initial state of the MOS structure.

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