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The role of ^{60}Co γ-ray irradiation on the interface states and series resistance in MIS structures

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ABSTRACT

The effect of γ-ray exposure on the metal–insulator–semiconductor (MIS) structures has been investigated using the electrical characteristics at room temperature. The MIS structures are irradiated with ^{60}Co γ-ray source. The energy distribution of interface states was determined from the forward bias *I–V* characteristics by taking into account the bias dependence of the effective barrier height and ideality factor. The value of series resistance decreases with increasing dose. Experimental results confirmed that γ-ray irradiation have a significant effect on electrical characteristics of MIS structures.

1. Introduction

Metal–insulator–semiconductor (MIS) structures consist of a semiconductor substrate covered by an oxide layer upon which a metal electrode gate is deposited. The MIS structures have been intensively investigated due to their technological applications (Rhoderick and Williams, 1988; Nicollian and Brews, 1982; Quennoughı, 1997; Depas et al., 1992; Konofaos et al., 1997; Haddara and El-Sayed, 1988; Singh, 1985; Tataroğlu et al., 2006; Cova and Singh, 1997; Sands et al., 1992; Card and Rhoderick, 1971). In the presence of an insulator layer, the density of interface states (N_{ss}) and series resistance (R_s), the *I–V*, *C–V* and G/ω–*V* characteristics deviate from those expected for ideal behavior of Schottky diodes (Tataroğlu et al., 2006; Cova and Singh, 1997; Sands et al., 1992; Card and Rhoderick, 1971; Tataroğlu and Altındal, 2006; Türüt and Sağlam, 1992; Gökçen et al., 2008; Szatkowski and Sieranski, 1992).

Recently, the radiation response of these devices has been found to change significantly when these devices are exposed to irradiation stress treatments (Winokur et al., 1976, 1984; Hughes, 1977; Chin and Ma, 1983; Da Silva et al., 1987, 2000; Schwank et al., 1986; Ma, 1989). Winokur et al. (1976) and Ma (1989) were among the first to make a systematic observation of the after irradiation behavior of N_{ss} in MIS devices.

There are two effects of radiation: a transient effect due to the electron–hole pair generation and a permanent effect to the bombardment of devices with radiation which causes changes in the crystal lattice. Radiation generates electron–hole pairs in the insulator that subsequently interact with trapping sites with the insulating film. The radiation generated electrons either recombine with the holes or move out of insulator. The radiation generated holes may diffuse in the insulator, but are less mobile than the electrons; many stationary hole traps are also present. There are some methods to determine values of R_s and N_{ss} (Nicollian and Brews, 1982; Norde, 1979; Sato and Yasamura, 1985; Cheung and Cheung, 1986).

The main aim of this study is to investigate the effects of surface charge states on MIS structures by *I–V*, *C–V* and G/ω–*V* characteristics as a function of the irradiation doses (0–5 kGy) at room temperature. In addition, we investigated the effects of R_s and N_{ss} on these characteristics.

2. Experimental detail

The Al/SiO_2/p-Si (MIS) structures were fabricated on, 2″ diameter float zone ⟨1 0 0⟩ boron-doped (p-type) single crystals Si wafer having thickness of 280 μm and resistivity of 8 Ω cm. The Si wafer was degreased for 5 min in organic solvent of trichloroethylene ($CHClCCl_2$), acetone (CH_3COCH_3) and methyl alcohol (CH_3OH) and then etched in a sequence of sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2), 20% hydrofluoric acid (HF, a solution of nitric acid ($6HNO_3$): 1 HF:35 H_2O, 20% HF and finally quenched in de-ionised water for a prolonged time. Preceding each cleaning step, the wafer was rinsed thoroughly in de-ionized water of resistivity of 18 MΩ cm. After surface cleaning of Si, high purity Al metal (99,999%) with a thickness of ~2000 Å was thermally evaporated from the tungsten filament onto the whole back surface of the Si wafer in

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the pressure of $\sim 1\times10^{-6}$ Torr in oil vacuum pump system. The ohmic contact was formed by sintering the evaporated Al back contact at 650 °C for 60 min in flowing dry nitrogen ambient at a rate of 2 l/min. This process served both to sinter the Al and to form the required thin insulator layer (SiO_2) on the upper surface of wafer. To form the Schottky contacts, the circular dots of $\sim$1 mm diameter and $\sim$2000 Å thick Al are deposited onto the oxidized surface of the wafer through a metal shadow mask in a liquid nitrogen trapped vacuum system in a vacuum of $\sim 2\times10^{-6}$ Torr. The interfacial insulator layer thickness was estimated to be about 40 Å from high frequency (1 MHz) measurement of the interface insulator capacitance in the strong accumulation region for MIS Schottky diode (Szatkowski and Sieranski, 1992).

The C–V and G/ω–V measurements were carried out using an HP 4192A LF impedance analyzer (5–13 MHz). The ac signal was generated by a low-distortion oscillator with the amplitude attenuated to 50 mV$_{rms}$ to meet the small signal requirement for thin oxide capacitors. Also, the I–V measurements were carried out using a Keithly 220 programmable constant-current source and a Keithly 614 electrometer. The C–V, G/ω–V and I–V measurements were performed before and after ^{60}Co γ-ray source irradiation with the dose rate of 2.12 kGy/h at room temperature. All measurements were carried out with the help of a micro-computer through an IEEE-488 ac/dc converter card.

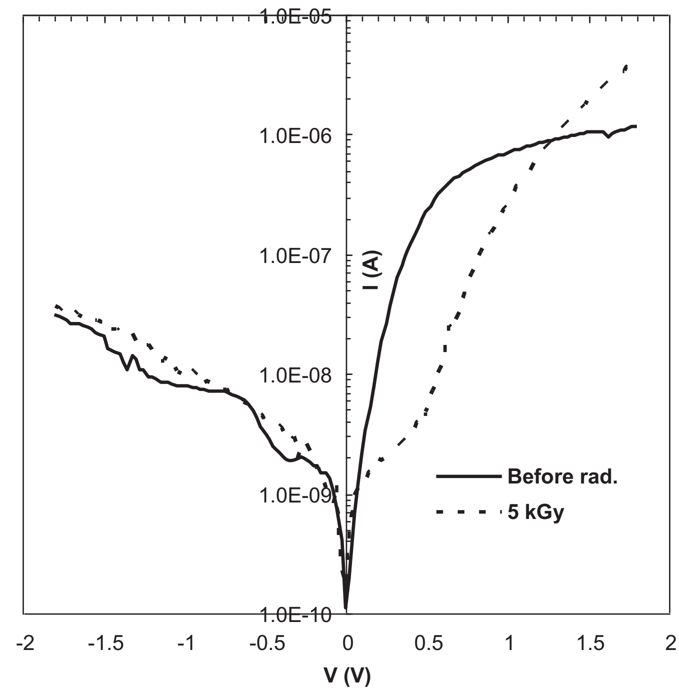

Fig. 1. Forward and reverse bias I–V characteristics of MIS structure before and after γ-ray irradiation.

3. Results and discussion

When the MIS structures have R_s, according to thermionic emission (TE) model, the relation between the V and I can be written as (Rhoderick and Williams, 1988)

$$I = I_o \exp\left(\frac{q(V-IR_s)}{nkT}\right)\left[1-\exp\left(\frac{-q(V-IR_s)}{kT}\right)\right] \quad (1)$$

where I_o in the reverse saturation current and expressed as

$$I_o = AA^*T^2 \exp\left(-\frac{q\Phi_{bo}}{kT}\right) \quad (2)$$

where n is an ideality factor, Φ_{bo} the effective barrier height at zero bias, A the diode area, A^* the effective Richardson constant and equals to 32 A/cm^2 K^2 for p-type Si. Fig. 1 shows Ln I–V characteristics of MIS structures before and after ^{60}Co γ-ray irradiation. The n is calculated from the slope of the linear region of the forward bias Ln I–V plot and can be written from Eq. (1) as

$$n = \frac{q}{kT}\frac{dV}{d\,\mathrm{Ln}\,I} \quad (3a)$$

and also the dependence of n from V can be written as

$$n(V) = \frac{qV}{kT\,\mathrm{Ln}(I/I_0)} \quad (3b)$$

The value of Φ_{bo} is calculated from the I_o at zero bias and is given by

$$\Phi_{bo} = \frac{kT}{q}\mathrm{Ln}\left(\frac{AA^{**}T^2}{I_o}\right) \quad (4)$$

The value of n and Φ_{bo} were determined from Eq. (3b) and (4), respectively, before and after irradiation. As can be seen in Fig. 1, an interesting feature of the forward bias semi-logarithmic I–V curves is the intersection at a certain bias (1.28 V). As can be seen in Figs 3 and 4, similar results have been observed in the C–V and G/ω–V characteristics. The reason of this behavior can be attributed to the inhomogeneties of Schottky barrier at metal–semiconductor (M–S) interface (Chand, 2004; Osvald, 2006; Dökme and Altındal, 2006; Pakma et al., 2008). Also, the value of R_s is significant in the downward curvature (at high bias voltages) of the forward bias I–V characteristics and it depends on the magnitude of the R_s. Chand (2004) and Osvald (2006) show that the value of R_s plays a subtle role in keeping this intersection hidden. Under γ-radiation, the value of R_s decreases due to the reduction in carrier density in the depletion region of diode through the introduction of traps and recombination centers associated with radiation effect. Therefore, intersection behavior in the forward bias I–V plot will be inevitable.

However, the role of radiation-induced interface traps is not fully understood, especially at the microscopic level, as well as the connection with processing sequences. We think that the study on these questions will undoubtedly continue.

It was found that presence of series resistance in diode causes bending due to current saturation and plays subtle role in keeping this crossing hidden. For our sample, the R_s is shown to play a crucial role in effecting forward bias I–V, C–V and G/ω–V curves of MIS structures. The values of n and Φ_{bo} were found to have a stronger dose rate and range from 3.49 and 0.76 eV at 0 kGy (before irradiation) to 4.61 and 0.83 eV at 5 kGy, respectively.

The effective barrier height Φ_e is assumed to be bias voltage dependent due to the presence of an interfacial insulator layer and the interface states located at Si/SiO_2 interface, which can be expressed as (Cova and Singh, 1997)

$$\Phi_e = \Phi_{bo} + \beta(V-IR_s) = \Phi_{bo} + \left(1-\frac{1}{n(V)}\right)(V-IR_s) \quad (5)$$

by considering the applied voltage dependence of the barrier height (BH), where β is the voltage coefficient of the effective BH (Φ_e) used in place of the BH (Φ_{bo}) and it is a parameter that combines the effects of N_{ss} which is in equilibrium with the semiconductor (Winokur et al., 1976; Hughes, 1977; Cheung and Cheung, 1986).

Furthermore, in a p-type semiconductor, to evaluate the distribution of the interface states $N_{ss}-(E_{ss}-E_V)$ having energy of N_{ss}, E_{ss} with respect to top of the valance band at the surface of the semiconductor is given by (Rhoderick and Williams, 1988; Card and Rhoderick, 1971)

$$E_{ss}-E_V = q(\Phi_e - V) \quad (6)$$

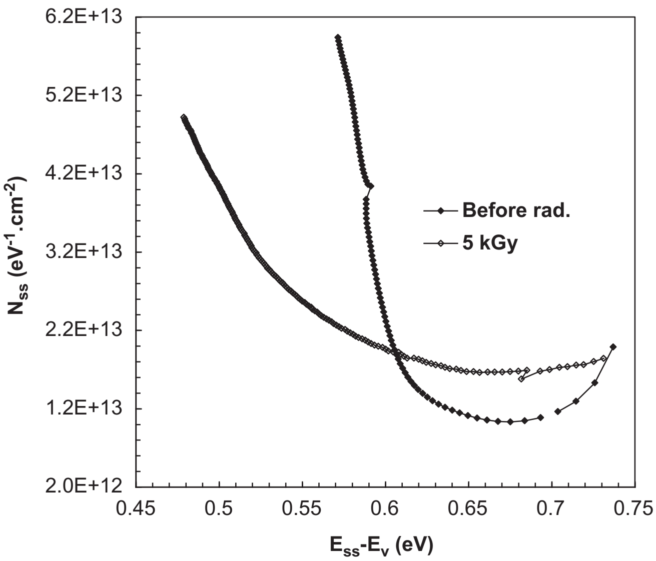

Fig. 2. The density of interface states (N_{ss}) distribution profiles as a function $E_{ss}-E_v$ obtained from the forward bias *I–V* characteristics.

where E_{ss} is the energy of interface states N_{ss} and E_V is the valance bend edge.

Assuming the voltage dependent *n* values, ε_s=11.8ε_o, ε_i=3.8ε_o, δ=40 Å and W_D=5 μm in Eq. (5), the energy distribution profile of N_{ss} was obtained before and after irradiation and is given in Fig. 2.

$$N_{ss}(V) = \frac{1}{q}\left[\frac{\varepsilon_i}{\delta}(n(V)-1) - \frac{\varepsilon_s}{W_D}\right] \tag{7}$$

where ε_i and ε_s are the permittivity of the insulator layer (SiO_2) and the semiconductor, respectively; W_D width of the depletion region and δ the thickness of the interfacial insulator layer.

As shown in Fig. 2, the increase in the N_{ss} from mid gap towards the bottom of E_V is very apparent. The mean value of N_{ss} was found about $3\times10^{13}\,cm^{-2}\,eV^{-1}$.

The *C–V* and G/ω characteristics were measured before and after irradiation at 1 MHz and are given in Figs 3 and 4. As the forward bias *I–V* curves, both the *C–V* and G/ω–*V* curves show an intersection behavior at a certain bias voltage. These behaviors may be attributed to the lack of free charges under irradiation. By the inspection of Figs 3 and 4, *C* and G/ω increase at high forward and reverse voltages (Candelori et al., 1999; De Vasconcelos and Da Silva, 1997), but decreases in the range of low forward and reverse biases. The increase in *C* and G/ω with radiation especially at forward bias is a result of the decreasing in the semiconductor depletion width. Also, the *C–V* measurements at high frequency are relatively easily and rapidly carried out, and these measurements can yield interesting and meaningful results to show the negligibility of excess capacitance. This makes the contribution of interface state capacitance to the total capacitance negligibly small (Hung and Cheng, 1987; Akkal et al., 2000). Since the presence of N_{ss}, the device behavior is different than ideal case of *C–V* and G/ω–*V* characteristics. These N_{ss} can easily follow the ac signal especially at low frequencies and yield excess capacitance, which depends on their relaxation time and cause a bias shift of the *C–V* and G/ω–*V* curves. Therefore, the *C–V* and G/ω–*V* measurements are carried out at sufficiently high frequency of 1 MHz.

We believe that the trap charges have enough energy to escape from the traps localized at Si/SiO_2 interface. These interface states usually cause a bias shift, and the frequency and capacitance dispersion of the *C–V* and G/ω–*V* curves. In addition, the series

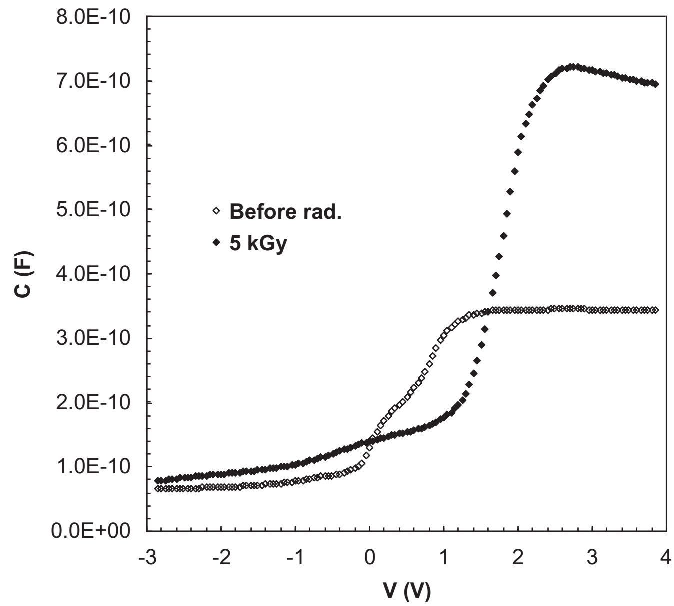

Fig. 3. The *C–V* characteristics of the MIS structure before and after γ-ray irradiation obtained at 1 MHz and room temperature.

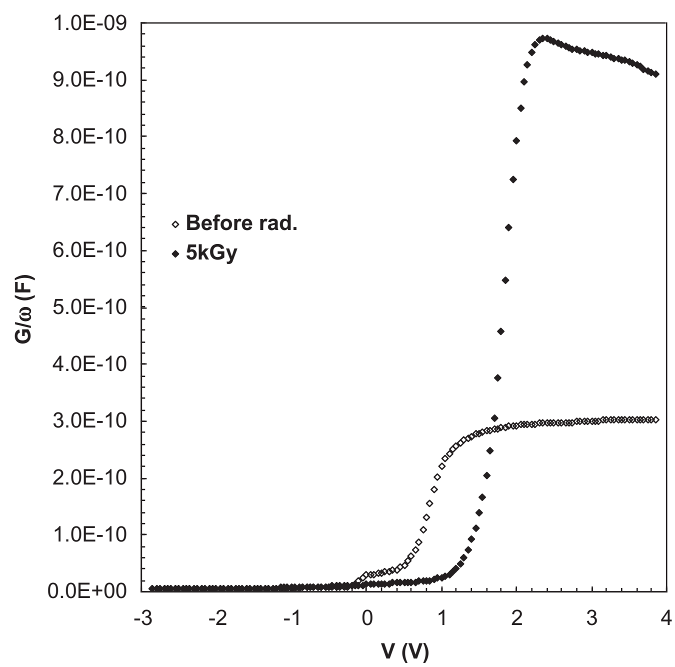

Fig. 4. The G/ω–*V* characteristics of the MIS structure before and after γ-ray irradiation obtained at 1 MHz and room temperature.

resistance is an important parameter, which causes changes in the electrical characteristics for Schottky structures (Nicollian and Brews, 1982).

There are several methods to extract the series resistance of MIS structure in literature (Norde, 1979; Sato and Yasamura, 1985). In this study we have used the conductance method developed by Nicollian and Goetzberger (Nicollian and Goetzberger, 1965; Nicollian and Goetzberger, 1967). The real series resistance of MIS structures can be subtracted from the measured capacitance (C_m) and conductance (G_m) in strong accumulation region at high frequency ($f \geq 500$ kHz) (Hung and Cheng, 1987; Nicollian and Goetzberger, 1965, 1967). In addition, the voltage

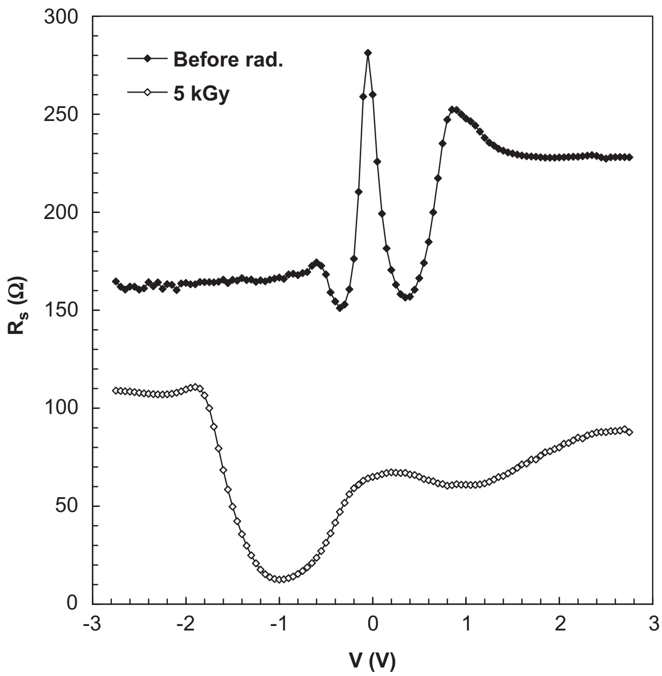

Fig. 5. Series resistance (R_s) vs gate bias under irradiation dose at 1 MHz.

and frequency dependence of the series resistance profile can be obtained from the C–V and G/ω–V curves. To determine series resistance R_s, the MIS structure is biased into strong accumulation at sufficiently high frequency. The measured impedance (Z_m) at strong accumulation of MIS structure using the parallel RC circuit (Nicollian and Brews, 1982) is equivalent to the total circuit impedance as

$$Z_m = \frac{1}{G_m + j\omega C_m} \tag{8}$$

Comparing the real and imaginary part of the impedance, the series resistance is given by (Nicollian and Brews, 1982; Norde, 1979; Nicollian and Goetzberger, 1967)

$$R_s = \frac{G_m}{G_m^2 + (\omega C_m)^2} \tag{9}$$

where C_m and G_m represent the measured capacitance and conductance in strong accumulation region.

The series resistance is an important parameter to designate the noise ratio of device as dependent on radiation dose. Therefore, both the real values and voltage dependence of the series resistance R_s were calculated from Eq. (9) according to Ref. Nicollian and Goetzberger (1965) and are given in Fig. 5. As can be seen in Fig. 5, the value of the series resistance decreased with increasing dose for each voltage.

4. Conclusion

The effect of γ-ray on MIS structure has been investigated using the I–V, C–V and G/ω–V characteristics at room temperature. The MIS structures are irradiated with ^{60}Co γ-ray source in the dose range of 0–5 kGy. The values of n increase with irradiation dose due to an increase of induced by radiation. The density of N_{ss} distribution profiles as a function $E_{ss}-E_v$ was extracted from the forward bias I–V characteristics before and after irradiation by taking into account the bias dependence of the Φ_e and n. The values of N_{ss} showed an experimental decrease with bias from the top of the valance band towards the mid gap. The measured C–V and G/ω–V characteristics of MIS structures show fairly large radiation dispersion. The R_s profile of sample was extracted from the measured C_m and G_m/ω measurements according to admittance method and its value decreases with increasing dose rate. In addition, the experimental I–V, C–V and G/ω–V curves exhibit intersection behavior at a certain bias voltage. These behaviors may be attributed to the lack of free charges under irradiation. Experimental results show that γ-ray irradiation have a significant effect on MIS structures.

References

Candelori, A., Paccagnella, A., Cammarata, M., Ghidini, G., Ceschia, M., 1999. Electron irradiation effect on thin MOS capacitors. J. Non-Cryst. Solids 245, 238–244.

Singh, A., 1985. Characterization of interface states at Ni/nCdF_2 Schottky barrier type diodes and the effect of CdF_2 surface preparation. Solid State Electron. 28 (3), 223–232.

Tataroğlu, A., Altındal, Ş., Bülbül, M.M., 2006. ^{60}Co γ irradiation effects on the current–voltage (I–V) characteristics of Al/SiO_2/p-Si (MIS) Schottky diodes. Nucl. Instrum. Methods A 568, 863–868.

Tataroğlu, A., Altındal, Ş., 2006. Electrical characteristics of ^{60}Co γ-ray irradiated MIS Schottky diodes. Nucl. Instrum. Methods A 252, 257–262.

Türüt, A., Sağlam, M., 1992. The determination of the density of Si-metal interface states and excess capacitance caused by them. Physica B 179, 285–294.

Akkal, B., Benamara, Z., Gruzza, B., Bideux, L., 2000. Characterization of interface states at Au/InSb/InP (1 0 0) Schottky barrier diodes as a function of frequency. Vacuum 57, 219–228.

Sands, D., Brunson, K.M., Najaran, M.H., 1992. Measured intrinsic defect density throughout the entire band gap at the ⟨1 0 0⟩ Si/SiO_2 interface. Semicond. Sci. Technol. 7, 1091–1096.

De Vasconcelos, E.A., Da Silva Jr., E.F., 1997. Correlation between dopant reduction and interfacial defects in low-energy X-ray-irradiated MOS capacitors. Semicond. Sci. Technol. 12, 1032–1037.

Da Silva Jr., E.F., Nishioka, Y., Ma, T.P., 1987. Radiation response of MOS capacitors containing fluorinated oxides. IEEE Trans. Nucl. Sci. NS-34 (6), 1190–1195.

Da Silva Jr., E.F., De Vasconcelos, E.A., Freire, V.N., 2000. Time evolution of SiO_2/Si interface defects and dopant passivation in MOS capacitors. Microelectron. Eng. 51/52, 567–574.

Nicollian, E.H., Brews, J.R., 1982. MOS Physics and Technology. John Wiley & Sons, New York.

Nicollian, E.H., Goetzberger, A., 1965. MOS conductance technique for measuring surface state parameters. Appl. Phys. Lett. 7, 216–219.

Nicollian, E.H., Goetzberger, A., 1967. The Si–SiO_2 interface electrical properties as determined by the metal–insulator-silicon conductance technique. Bell Syst. Tech. J. 46, 1055–1131.

Rhoderick, E.H., Williams, R.H., 1988. Metal Semiconductor Contacts. Oxford, Clarendon Press.

Hughes, G.W., 1977. Interface-state effects in irradiated MOS structures. J. Appl. Phys. 48, 5357–5359.

Card, H.C., Rhoderick, E.H., 1971. Studies of tunnel MOS diodes I. Interface effects in silicon Schottky diodes. J. Phys. D 4, 1589–1601.

Haddara, H.S., El-Sayed, M., 1988. Conductance technique in MOSFETs: study of interface trap properties in the depletion and weak inversion regimes. Solid State Electron. 31 (8), 1289–1298.

Norde, H., 1979. A modified forward IV plot for Schottky diodes with high series resistance. J. Appl. Phys. 50, 5052–5053.

Dökme, İ., Altındal, Ş., 2006. On the intersecting behavior of experimental forward bias current voltage (I–V) characteristics of Al/SiO_2/p-Si (MIS) Schottky diodes at low temperatures. Semicond. Sci. Technol. 21, 1053–1058.

Osvald, J., 2006. Intersecting behavior of nanoscale Schottky diodes I–V curves. Solid State Commun. 138 (6), 39–42.

Schwank, J.R., Winokur, P.S., Sexton, F.M., Fleetwood, D.M., Perry, J.H., Dressendorfer, P.V., Sanders, D.T., Turpin, D.C., 1986. Radiation-induced interface-state generation in MOS devices. IEEE Trans. Nucl. Sci. 33 (6), 1177–1184.

Szatkowski, J., Sieranski, K., 1992. Simple interface-layer model for the non-ideal characteristics of the Schottky-barrier diode. Solid State Electron. 35, 1013–1015.

Hung, K.K., Cheng, Y.C., 1987. Characterization of Si–SiO_2 interface traps in p-metal-oxide semiconductor structures with thin oxides by conductance technique. J. Appl. Phys. 62, 4204–4211.

Sato, K., Yasamura, Y., 1985. Study of forward I–V plot for Schottky diodes with high series resistance. J. Appl. Phys. 58, 3655–3657.

Chin, M.R., Ma, T.P., 1983. Gate-width dependence of radiation-induced interface traps in metal/SiO_2/Si devices. Appl. Phys. Lett. 42, 883–885.

Depas, M., Van Meirhaeghe, R.L., Laflere, W.H., Cardon, F., 1992. A quantitative analysis of capacitance peaks in the impedance of Al/SiO_x/p-Si tunnel diodes. Semi. Sci. Tech., 1476–1483.

Gökçen, M., Tataroğlu, A., Altındal, Ş., Bülbül, M.M., 2008. The effect of ^{60}Co (γ-ray) irradiation on the electrical characteristics of Au/SnO_2/n-Si (MIS) structures. Radiat. Phys. Chem. 77, 74–78.

Konofaos, N., McClean, I.P., Thomas, C.B., 1997. Characterization of the interface states between amorphous diamond-like carbon films and (1 0 0) silicon. Phys. Status Solidi (a) 161, 111–123.

Pakma, O., Serin, N., Serin, T., Altındal, Ş., 2008. The influence of series resistance and interface states on intersecting behavior of *I–V* characteristics of Al/TiO_2/p-Si (MIS) structures at low temperatures. Semicond. Sci. Technol. 23, 105014 (9pp).

Cova, P., Singh, A., 1997. A self-consistent technique for the analysis of the temperature dependence of current–voltage and capacitance–voltage characteristics of a tunnel metal–insulator–semiconductor structure. J. Appl. Phys. 82 (10), 5217–5226.

Winokur, P.S., McGarrity, J.M., Boesch, H.E., 1976. Dependence of interface-state buildup on hole generation and transport in irradiated MOS capacitors. IEEE Trans. Nucl. Sci. NS-23, 1580–1585.

Winokur, P.S., Schwank, J.R., McWhorter, P.J., Dressendorfer, P.V., Turpin, D.C., 1984. Correlating the radiation response of MOS capacitors and transistors. IEEE Trans. Nucl. Sci. NS-31, 1453–1460.

Chand, S., 2004. On the intersecting behavior of current–voltage characteristics of inhomogeneous Schottky diodes at low temperatures. Semicond. Sci. Technol. 19, 82–86.

Cheung, S.K., Cheung, N.W., 1986. Extraction of Schottky diode parameters from forward current–voltage characteristics. Appl. Phys. Lett. 49, 85–87.

Ma, T.P., 1989. Interface trap transformation in radiation or hot-electron damaged MOS structures. Semicond. Sci. Technol. 4, 1061–1079.

Quennoughı, Z., 1997. On the minimum in the forward capacitance in MIS tunnel diodes. Phys. Status Solidi (a) 160, 127–132.