Hazardous Gases Sensing: Influence of Ionizing Radiation on Hydrogen Sensors

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Abstract. The electron irradiation effect on characteristics of the hydrogen sensors based on metal-insulator-semiconductor transistor structures has been investigated by experiment. The models of hydrogen and radiation sensitivity were developed. Using these models the forecast of functional performance of the hydrogen sensors under ionizing radiation and the estimation of critical doses has been done.

Keywords: Hydrogen · Sensor · Irradiation · Sensitivity · Models · Monitoring

1 Introduction

The development of sensors with sensitive elements (SE) fabricated by means of microtechnology is a promising area for creation of small-sized gas-analysis devices and systems. Among the solid-state gas-sensitive SE, the elements based on metal-insulator-semiconductor transistors (MISFETs) possess the best compatibility with the standard elements of integrated circuits [1–3]. The hydrogen sensors based on MISFETs have been studied by many investigators [4–7]. The studies have shown that the sensor performance characteristics depend on many factors: technological processes of sensors, chip temperature, MISFET electrical modes and irradiation [2, 6, 7].

This paper deals with the integrated hydrogen sensors with MISFET sensing element based on Pd-Ta_2O_5-SiO_2-Si structure (named as TSE). These sensor characteristics have been already investigated at normal levels of radiation. However the gas analysis devices can be used for a long time at raised radiation levels.

Study of the effect of radiation on the characteristics of MISFET began in the 1960-ies and is still going on. It was found the common radiation effects in MISFETs: increase the concentration of trapping centers N_t, change charges in the dielectrics Q_t and on its border with the semiconductor Q_{ss}. As a consequence the threshold voltage V_T and transconductance b of MISFETs are changing [9]. The studies have shown that changes of electrical characteristics depend on technological factors, MISFET temperature and electrical modes, as well as on ionizing radiation absorption dose D and its rate P [7–9]. Since TSE has specific features that there are the unexplored issues. What the TSE characteristics and how much should be changed under irradiation? What

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models can be used for the radiation effect simulation on characteristics of the hydrogen sensitive devices and systems based on TSE? To get answers to these questions is the aim of this work.

2 Experiment

2.1 The Sensor Chip Structure and Initial Characteristics of TSE

The integrated sensor chip layout and TSE structure are shown in Fig. 1. This sensor has been fabricated by means of conventional MIS-technology. Technological processes details are presented in [2, 6]. The size of silicon chip is 2×2 mm^2. Structurally-technological and physical parameters TSE are the following: acceptors concentration $N_a = 5 \cdot 10^{15}$ cm^{-3}; length L and width z of the channel are 10 μm and 3.2 mm; dielectric capacitance $C_0 \approx 30$ nF/cm^2; transconductance $b \approx 2.0$ mA/V^2.

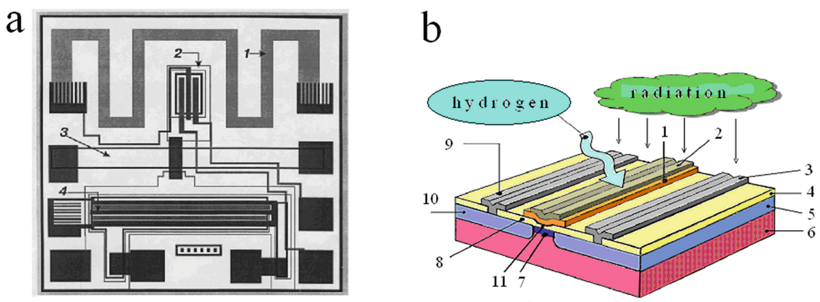

Fig. 1. (a) The sensor chip layout: 1 – Pd-resistor, 2 – test element and thermosensor, 3 – heater, 4 – TSE. (b) The TSE structure: *1* – the gas sensitive layer of a Pd gate (≈70 nm); *2* – the outer part of a gate (Pd + PdO); *3* and *9* – drain and source Al connections; *4* and *8* – a thick (380–450 nm) Ta_2O_5-SiO_2 insulator; *5* and *10* – a drain and a source (n^+-Si); *6* – a substrate *p*-Si; *7* – a channel *n*-Si; *11* – a thin (150–200 nm) Ta_2O_5-SiO_2 gate insulator.

2.2 Experimental Technique

In the first stage of the experiment the transient current-voltage characteristic (the drain current I_D of the gate voltage V_G dependence) of the test TSE were measured. These characteristics were used to determine the initial values of the threshold voltage V_{T0}, the transconductance b_0, the charge in the oxide Q_{t0} and the charge Q_{ss0} at the interface SiO_2-Si.

In the second stage the threshold voltage of TSE as function of hydrogen concentration was determined. For this purpose the sensor hydrogen responses were measured with using special circuitry [7]. The measuring circuitry provides the constant $I_D \approx 0{,}1$ mA and source-drain voltage $V_D \approx 1$ V and the output voltage $V_{out} = V_G$. For this measuring circuitry the threshold voltage

$$V_T = V_{OUT} - \sqrt{2I_D/b} \quad (1)$$

The chip temperature 130 °C is supported by means of special temperature-stabilization circuitry with feedback loop using on-chip thermosensor and heater [6]. Each sensor was 3 times exposed to hydrogen pulses (τ_i ≈20–30 s with period $\tau \approx 60$ s) with concentrations (*C*): 0.005, 0.01, 0.05, 0.1 and 0.2 % vol. The computerized instrumentation with gas chamber was used for experiment. Typical hydrogen response (for $C \approx 0.05$ % vol.) and the response parameters are presented in Fig. 2.

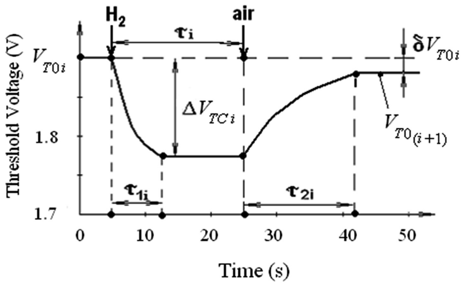

Fig. 2. The parameters of response for hydrogen concentration 0.05 % vol.

The following parameters of hydrogen responses were measured: initial threshold voltage V_{T0}, amplitude of response ΔV_{TCi}, residual value of response δV_{Ti}, response τ_{1i} and relaxation τ_{2i} times (*i*-ordinal number of hydrogen injection). Then average values of all the response parameters were determined as in [9, 10].

In the third stage of experiments the sensor radiation sensitivity was investigated. For this purpose 8 sensors with identical initial characteristics have been selected (dispersion V_{T0} was less than 10 %). The sensors were divided by two sorts: 3 – as the comparative samples (not be irradiated) and 5 samples have being irradiated. Before and after each irradiation all the sensors were 3 times exposed to hydrogen pulses with concentrations: 0.05 and 0.1 % vol. The sensors were 5 times exposed to electron radiation (6 MeV energy) with various doses in the linear accelerator U-28"MEPhI". The fluencies accepted the following values: 10^{11}; $2{\cdot}10^{11}$; $5{\cdot}10^{11}$; $2{\cdot}10^{12}$ and 10^{13} e/cm^2. These fluencies correspond to the accumulated absorption doses *D*(Si): ≈30, 90, 260, 920 Gy and 4,22 кGy. (1 Gy = 100 rad). The absorption dose rate *P*(Si) ≈2.0 Gy/s, during irradiations $V_G = V_D = 0$ V.

3 Results and Discussion

3.1 The Experimental Results

The average values and relative variation indices of V_{T0}, ΔV_{TC} and δV_T, as well as the time parameters of hydrogen responses (at $C = 0.1$ %) before and after irradiation are demonstrated in Table 1.

Table 1. Experimental results.

Quantities, parameters	Radiation absorbed dose D, Gy					
	0	30	90	260	920	4220
V_{T0}, V	1.89	1.83	1.78	1.57	1.13	0.277
ρ_1, %	1.3	1.3	1.4	1.45	1.45	1.6
ΔV_{TC}, mV	290	289	290	288	260	180
ρ_2, %	6–8	6–8	4–6	4–5	4–5	<4
δV_T, mV	7	6	5	4	4	<3
ρ_3, %	17.5	17.5	16	13	11	9
τ_1, s	9.5	9.5	8	6.5	6.5	6.5
τ_2, s	20	20	17.5	13.5	13.5	13.5

3.2 The Models of Hydrogen and Radiation Sensitivities TSE

The mathematic models of hydrogen and radiation sensitivity TSE were used as in [9, 10].

$$V_T(C,D) = V_{T0}(D) - \Delta V_C(C,D) \tag{2}$$

$$V_{T0}(D) = V_{T00} - \Delta V_t(D) + \Delta V_{ss}(D) \tag{3}$$

$$\Delta V_C = 0.5 \cdot [1 - \exp(-15 \cdot C)] \cdot \{1 - \exp[-k_3 \cdot (D_0 - D)]\} \tag{4}$$

$$\Delta V_t = [\Delta Q_{t0} + k_0 \cdot (V_G - V_T)] \cdot [1 - \exp(-k_1 \cdot D)]/C_0 \tag{5}$$

$$\Delta V_{ss} = \Delta V_{ssM} \cdot [1 - \exp(-k_2 \cdot D)] \tag{6}$$

Experimentally determined the model parameters: $V_{T00} \approx 1.9$ V; $\Delta V_{ssM} \approx 1.65$ V; $D_0 \approx 1.7 \cdot 10^4$ Gy; $k_0 \approx 25$ nC/V·cm^2; $k_1 \approx 10^{-4}$ Gy^{-1}; $k_2 \approx 3 \cdot 10^{-5}$ Gy^{-1}; $k_3 \approx 2 \cdot 10^{-4}$ Gy^{-1}; $\Delta Q_{t0} \approx 45$ nC/cm^2. The formulas are based on the classical physical models of MISFET by using the approximation and extrapolation of the experimental data for TSE.

3.3 Discussion on the Experimental Results

The threshold voltages of TSE as a function of hydrogen concentration were determined before and after irradiations (Fig. 3a). It is found that the transfer functions V_T (C,D) of irradiated samples are monotonically drifting up to 0.7 V under radiation doses $D \leq D_1 \approx 730$ Gy without changing of the hydrogen sensitivity $S_C = dV_T/dC$. That is only V_{T0} (D) were decreasing. For voltage error 1 mV the threshold values of dose $D_T \approx 3.8$ Gy and of dose rate $P_T \approx 0.4$ µGy/s. After following irradiations the hydrogen sensitivity S_C is steadily decreasing. The radiation sensitivity $S_D = dV_{T0}/dD$ gets the maximum values ~0.2 mV/Gy under doses ~10 Gy and $S_D \approx 0$ at doses ~20 kGy. The hydrogen sensitivity gets the maximum values ~4 V/% at $C \sim 0.002$ % and $S_C \approx 0$ at $C \sim 1$ % according to models (3) and (5).

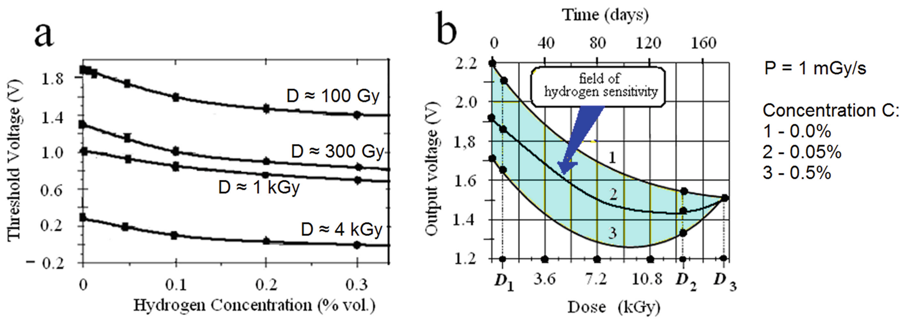

Fig. 3. (a) The threshold voltage V_T as a function of hydrogen concentration C before (1) and after irradiations. (b) Forecast dose and time dependences of output voltages of the hydrogen sensor based on TSE under ionizing radiation.

Using the models (2)–(6) the forecast of performance of the hydrogen sensors based on TSE under ionizing radiation has been done and is presented in Fig. 3b.

4 Conclusion

The electron irradiation influence on hydrogen sensitivity of the integrated sensors with palladium-gate MISFET has been studied. It was shown that the threshold voltage as a function of hydrogen concentration V_T (C) are monotonically drifting under radiation doses up to $D_1 \sim 730$ Gy without changing of the hydrogen sensitivity. After following irradiations the hydrogen sensitivity are decreasing in addition the V_{TO} (D) drift and decreasing parameter δV_T. The ionizing radiation doses less than 3.8 Gy and dose rate $P_T < 0.4$ µGy/s are not dangerous for the sensors.

According to used models the hydrogen sensitivity to diminish in 2 times under doses $D_2 \sim 10$ kGy and should be decreased to zero after irradiation by very high doses (more than 15 kGy). Such absorbed doses, for example, could be only under long time uninterrupted space irradiation ~200 days or ~1500 days into the upper atmosphere. For most applications of gas-analysis devices and systems based on TSE the irradiation is weak influencing factor.

In order to decrease the radiation sensitivity the sensors and monitoring systems TSE could be preliminary irradiated under dose ~50 Gy. In addition an irradiation can be used as technological means of improving sensor metrological characteristics [7].

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