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Influence of Electrical Modes on Radiation Sensitivity of Hydrogen Sensors Based on Pd-Ta_2O_5-SiO_2-Si Structures †

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Abstract: The influence of the circuit's electric modes on the radiation sensitivity of hydrogen sensors based on the metal-insulator-semiconductor field-effect transistor with structure Pd-Ta_2O_5-SiO_2-Si (MISFET) was investigated. There were measured the hydrogen responses of output voltages *V* of the MISFET-based circuits at different gate voltages before and after the electron irradiations. The voltages *V* as functions of hydrogen concentration *C* were determined for different ionizing doses *D*. Models of influence of the electric modes on the radiation sensitivity of sensors were based on experimental dependencies of *V*(*C*, *D*). The recommendations for the optimal choice of MISFET-based circuit's electric modes were formulated.

Keywords: hydrogen sensors; MISFET; radiation sensitivity; electric modes

1. Introduction

The hydrogen sensors based on the metal-insulator-semiconductor field-effect transistor (MISFETs) have been studied by many investigators [1–7]. The studies have shown that the conversion characteristics (the sensor output signals *V* as function of the hydrogen concentration *C*) depend on MISFET's technological parameters [3,5] chip temperature [6] and external factors (other gases, irradiation) [4,7].

This work deals with the integrated hydrogen gas sensors with MISFET sensing element based on Pd-Ta_2O_5-SiO_2-Si structure. The characteristics of these sensors have been already investigated at normal levels of background radiation. However, there are cases, when the gas analysis devices must be used for a long time at raised radiation levels. For examples, in nuclear reactors, in uranium mines, into oil underground deposits search tools based on hydrogen-methane-radon discharge from soil, into the upper atmosphere monitoring systems or into space systems. In spite of low dose rates in above examples, the long-time irradiation (during 200–500 days) may result in degradation of performance characteristics of semiconductor sensors. So the question is: how MISFET-based sensors' performance characteristics should change under irradiation?

The radiation effects in MIS-structure-based devices are studying since the 1960-ies [7–13]. It was found the basic radiation effects in MIS structures: increase the concentration of trapping centers under the ionizing radiation, change charges in the dielectrics Q_t and on its border with the semiconductor Q_{ss}. As a consequence the electrical characteristics of MISFETs are changing. The studies have shown that changes of characteristics depend on temperature, structural-technological characteristics of MISFETs, on total ionizing dose *D* (TID) and its rate *P* [9,10,13]. The aim of this work is to investigate the influence of the measuring circuit's electrical modes on the radiation sensitivity of MISFET-based hydrogen sensors, and to develop models for forecasting the performances of gas-analysis MISFET-based devices under action of ionizing radiation.

2. Materials and Methods

The testing MISFET element based on Pd-Ta_2O_5-SiO_2-Si structure was fabricated on single chip (2×2 mm^2) together with (*p*–*n*)-junction temperature sensor, heater-resistor and Pd-resistor by means of conventional *n*-MOS-technology using laser evaporation Pd-films. The integrated sensor chip layout with outputs' pads and the temperature-stabilization circuitry supported chip temperature 130 °C by feedback loop using thermo-sensor and heater are shown in Figure 1.

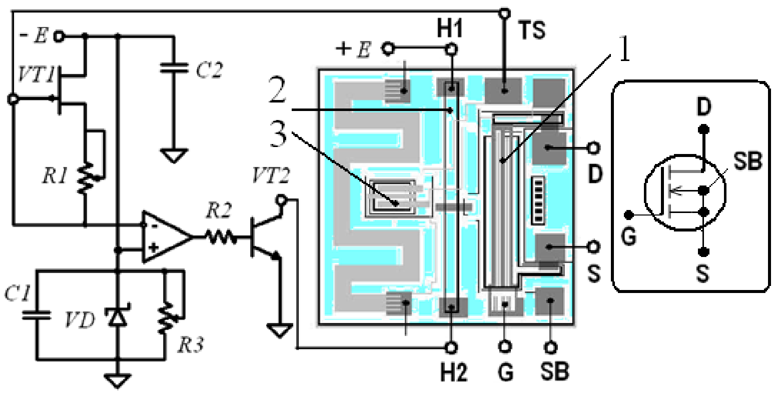


Figure 1. The temperature-stabilization circuitry, the sensor chip layout with output pads' and MISFET's designations: 1—MISFET (G—gate, S—source, D—drain, SB—substrate); 2—heater-resistor (H1–H2); 3—temperature sensor (TS–SB).

The parameters of MISFET are the following: acceptors concentration $N_a = 5 \times 10^{15}$ 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 $b_0 \approx 2.0$ mA/V^2. In the first stage of experiments the I_D–V_G characteristics (V_G is the gate voltage) of MISFETs were measured using the measuring system MERA-3 and of circuit No. 1 (Figure 2a; position 2). These characteristics were used to determine the initial values of the threshold voltage V_{T0}, the transconductance b_0, the charges in the oxide Q_{t0} and at SiO_2-Si interface Q_{ss0} as in [13]. In the next stages of the experiments before and after the electrons' irradiations there were measured the hydrogen responses of output voltages *V* at step-rising concentration *C* (e.g., Figure 3a) for two types circuits (Figure 2a,b) at different electrical modes, as well as I_D–V_G characteristics. The sensors were 4 times exposed to electron radiation (6 MeV energy) by the following TID(Si): 50 Gy, 100 Gy, 250 Gy and 850 Gy. The dose rate *P*(Si) ≈ 2.0 Gy/s.

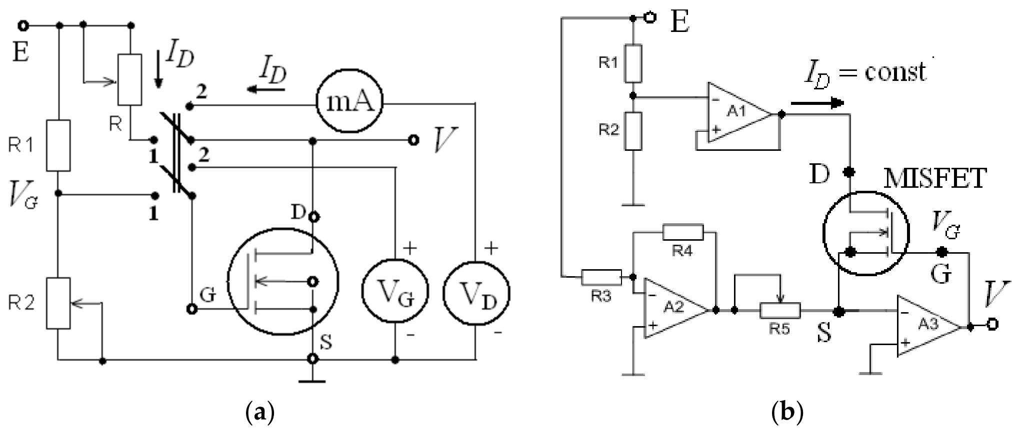
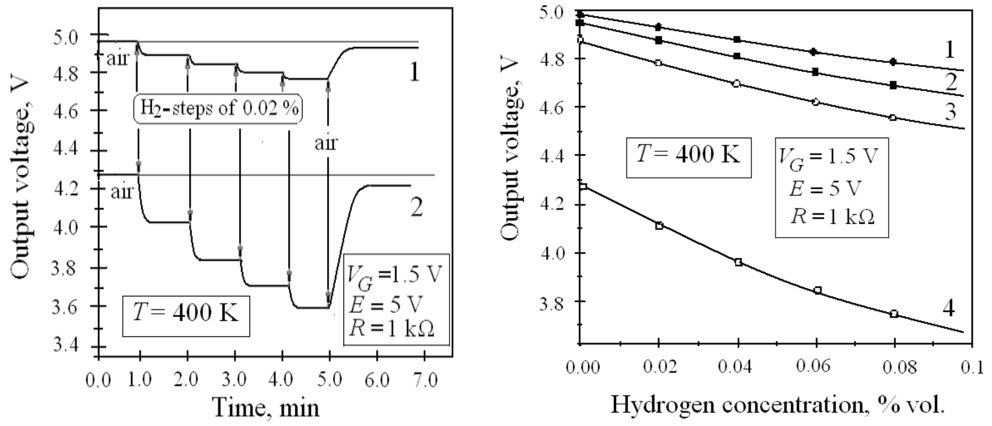


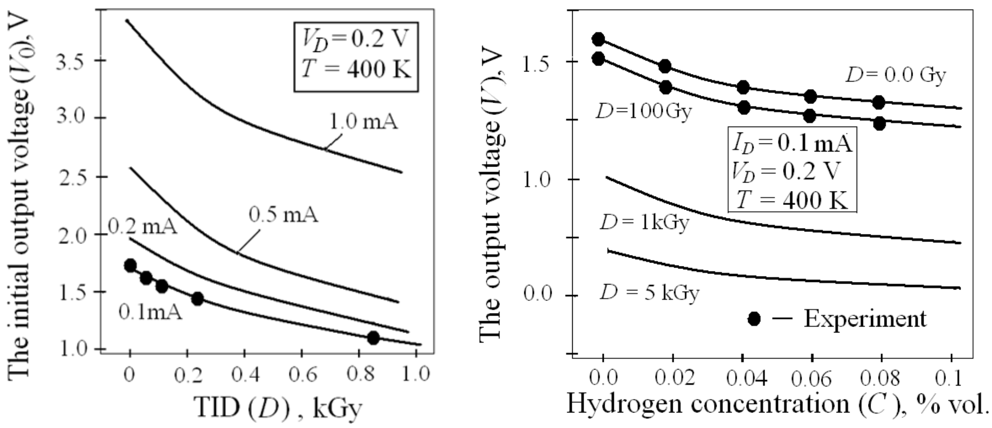
Figure 2. (**a**) The circuit No. 1 for measurement the MISFET-based sensors' conversion functions *V*(*C*; *D*) (position 1) and (I_D–V_G) characteristics (position 2); (**b**) The circuit No. 2.

3. Results Are Presented in Figures 3 and 4



(**a**) (**b**)

Figure 3. (**a**) The hydrogen responses before (1) and after (2) the irradiation by 850 Gy(Si) for circuit No. 1; (**b**) The output voltages V vs. C at doses D: 0(1); 100 Gy(Si) (2); 250 Gy(Si) (3); 850 Gy(Si) (4) for circuit No. 1.



(**a**) (**b**)

Figure 4. (**a**) The initial voltage V_0 vs. D at different drain currents for circuit No. 2; (**b**) The conversion characteristics V vs. C of circuit No. 2 for different TIDs.

4. Discussion

To describe the results there was used the 4-component model of V vs. (C; D) as in [13]:

$$V(C;D) = V_0(D) - \Delta V_C(C;D) = V_{00} - \Delta V_{te}(D) + \Delta V_{ss}(D) - \Delta V_C(C;D);\ \Delta V_{te} = \Delta V_{teM}[1-\exp(-k_1 D)];$$
$$\Delta V_{ss} = \Delta V_{ssM}[1-\exp(-k_2 D)];\quad \Delta V_C(C;D) = \Delta V_{CM}[1-\exp(-kC)]\cdot\{1-\exp[-k_3(D_3 - D)]\} \quad (1)$$

In circuit No. 1 the voltage V is equal to V_D, the voltage V_G is the controlling parameter:

$$V = E - 0.5\beta\cdot(U)^2 \text{ at } 0 < U \le U_m;\ V = 1/\beta + U - [(1/\beta + U)^2 - 2E/\beta]^{0.5} \text{ at } U > U_m = [(1+2\beta E)^{0.5} - 1]/\beta;$$
$$U(C;D) = V_G - V_{T0} = V_G - V_{T00} + \Delta V_C + \Delta V_{te} - \Delta V_{ss};\ \beta = bR. \quad (2)$$

In circuit No. 2 the voltage V is equal to V_G, the current I_D is the controlling parameter:

$$V = U(I_D) + V_{T00} - \Delta V_C - \Delta V_{te} + \Delta V_{ss};\ U = \{2[I_D/b - (\phi_T)^2]\}^{0.5}, \text{ if } V_D \ge U;\ U = I_D/(bV_D) + 0.5V_D, \text{ if } U > V_D \quad (3)$$

The MISFET's parameters and the model parameters are presented in [13] and in Table 1. The hydrogen and radiation sensitivities $S_C(C) = |dV/dC|$ and $S_D(D) = |dV/dD|$ are decreasing in both circuits. Results of experiments and calculations have shown how the conversion functions $V(C)$ and the hydrogen sensitivity S_C depend on TID for different gate voltages and drain currents. In circuit

No. 1 the sensitivity S_C increases with dose's rising, when MISFET is working in the saturation region of the I_D (V_D) characteristic ($U \leq U_m$). Calculated optimum parameters (V_G = 1.36 V and R = 3.2 kΩ) correspond to the maximum hydrogen sensitivity $S_{CM} \approx 46$ V/% for TID < 850 Gy (Si). In circuit No. 2 the voltage $V_0(D)$ and dose swipe $\Delta V(D)$ are increasing with the growth of I_D, but the sensitivity S_C is not depending on I_D.

Table 1. Average values (dispersion < 10%) of MISFET's, circuit's and the model parameters.

Parameters	V_{T00}, **V**	b_0, **mA/V2**	ΔV_{teM}, **V**	ΔV_{ssM}, **V**	*k* **(1/%)**	k_1, **Gy**$^{-1}$	k_2, **Gy**$^{-1}$	k_3, **Gy**$^{-1}$	D_3, **kGy(Si)**
Values	1.35	2.0	1.65	1.5	14	6×10^{-4}	3×10^{-5}	2×10^{-4}	15
TID, Gy(Si)	ΔV_{TCM}, V	ΔV_{te}, V	ΔV_{ss}, V	V_{T0}, V	V_0, V		SCM, %/V		*b*, mA/V^2
					V_G = 1.5 V	V_G =2 V	V_G = 1.5 V	V_G = 2 V	
50	0.47	0.06	0.002	1.32	4.96	4.50	2.76	9.34	2.0
100	0.47	0.10	0.005	1.26	4.94	4.44	3.29	9.87	2.0
250	0.47	0.23	0.012	1.13	4.86	4.24	4.85	12.1	1.9
850	0.45	0.66	0.04	0.73	4.28	3.39	8.9	14.5	1.7

5. Conclusions

TID effects in the MISFET-based hydrogen sensors depend on electrical modes, which are determined by the type of circuit and its electrical parameters. In circuit No. 1 the conversion characteristics $V(C, D)$ depend on the selected operating voltage V_G and value resistor R, which determine the initial value of the output voltage V_0 (D) and the hydrogen sensitivity S_C. The maximum hydrogen sensitivity S_{CM} is proportional to $k\beta \cdot \Delta V_{TCM} \cdot U(D)$. So the sensitivity S_C is rising with the growth of TID, if parameter U is less than U_m. There were determined the optimum parameters V_G and R, corresponding to the maximum sensitivity S_{CM} for D < 850 Gy(Si). In circuit No. 2 the initial value of output voltage $V_0(D)$ depends on the current drain I_D. With the growth of I_D the voltages $V_0(D)$ and the swipe of dose characteristic $\Delta V(D)$ are increasing. The sensitivity S_C is equal to MISFET's hydrogen sensitivity $|dV_T/dC|$, which is not depending on I_D. Under irradiation doses of $D \leq 700$ Gy(Si) the hydrogen sensitivity does not change.

Conflicts of Interest: The authors declare no conflict of interest.

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