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COMPARISON OF THE RESISTANCE OF THE MOS INTEGRATED CIRCUITS WITH VARIOUS TYPES OF NUCLEAR RADIATION

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1. INTRODUCTION

An investigation of radiation resistance of semiconductor devices when exposed to different radiation ionization is one of the topical problems of up-to-date electron technology [1,2]. This problem is of a significant interest for developing production technology of devices finding use in nuclear facilities and also in the equipment employed in space technology. It is worth noting that such investigations should be carried out in the dynamic mode, i.e. one should evaluate the degree of parameter degradation of semiconductor devices immediately as the damage doses are collected.

The study of radiation effects in nuclear reactors being in service today, presents certain difficulties associated with elevated temperature in radiation zone, sample activation and one should need a long period of time for collecting necessary dose.

Under neutron radiation of accelerated heavy ions, the use of radiation effects for simulation has a number of advantages, namely, a relatively low activation level, high velocities of fluence collection, irradiation parameters which are safely controlled and moreover, there is a possibility of measuring parameters of semiconductor devices with required frequency while collecting fluences.

A testing of semiconductor devices for simulating failures under space radiation using heavy ions for this purpose presents an individual direction of investigations, that allows one to simulate both the energy radiation spectrum and typical flux density and types of particles. This direction of investigations is widely developed in a number of centres on heavy ions, e.g., at GANIL (France) and such testing is obligatory for all types of semiconductor devices, which are going to be applied in space.

The goal of the present work is to study the possibilities of using accelerated heavy ions for simulation of fast neutrons and particles of space radiation spectrum influence on characteristics of semiconductor devices.

2. RADIATION EFFECTS IN SEMICONDUCTORS AND SEMICONDUCTOR DEVICES

Monocrystal silicon, usually as plates of up to 300 μm thickness and oxide of silicon (SiO_2) as thin plates with thickness of 0.1-0.5 μm produced by oxidation or deposited from gas phase onto silicon plates are the basic materials applied in electronics. Lately, gallium arsenide (GaAs) has got an application, but at present this material is not widely used.

Single crystal silicon and SiO_2 have a high sensitivity to nuclear and space radiation which, affecting these materials, form primary radiation defects - Frenkel pairs in them. As a result of irradiation the vacancies capturing free carrier outside are stabilized and turn out to be as isolated charged centres which change the electron system of semiconductor and parameters of current carriers (concentration, lifetime and mobility). More complex vacancy configurations with oxygen atoms always being in silicon, the so-called A-centres or vacancies with atoms of hydrogen or phosphor which is the alloying impurity in silicon, the so-called E-centres and also multicomponent J(C)- and B-centres (see e.g. [3]) serve as such centres.

At the even distribution of radiation damages by semiconductor volume the parameter degradation of the material itself and of the device made of this material irreversible increases with absorbed dose within the increase of the fluence. As a rule, such changes are of smooth and monotone nature. Contrary to them, defect clusters and the so-called large destructional regions, the sizes of which are comparable with macroscopical sizes of semiconductor devices and large integrated circuits could result in their functional failures.

Therefore, one can suppose different mechanisms of damages in semiconductor devices. One should note that the above-mentioned mechanisms can be recognized only in terms of dynamical investigations, i.e. of such when one can observe the radiation effect at all times during irradiation of semiconductor device. However, to provide such conditions is a difficult technical problem.

That's why the basic experimental results in the region of radiation stability of semiconductor devices to neutron radiation are obtained by static method. This method is in alternating of irradiation and measuring of the effects from irradiation, the decrease of induced activity is usually achieved over this interval. In the work [4], which is recognized as the classical one in this region, the limiting values of absorbed dose at which the device begins to make errors are obtained.

Let us next consider the mechanisms of radiation influence on particular semiconductor devices.

The theory of radiation effects in the MOS (metal-oxide-semiconductor) structures is based on the following experiments determined under radiation in the oxide layer: first, if the oxide is grown on the backing of silicon of p-type, then the constant space positive charge is formed, if it is grown on the backing of n-type, then the negative one is formed; secondly, the value of this charge depends on full integral radiation dose (it doesn't depend on energy dose) and tends to saturation; thirdly, saturation depends on the oxide nature ("dry" or "wet" et al) and on sign and value of electric voltage on the gate (it doesn't depend on the value of electric field in the oxide); fourthly, space charge in the oxide is concentrated near the backing even, if there is no gate polarization outside.

The quantitative analysis of radiation effects in this structure has been performed in the work [5]. The basic positions of its physical model are shown in fig. 1.

The electron-hole pairs symbolized as (+ -) appear under radiation over all volume of the oxide layer of h thickness. They are separated by the electric field of the gate polarization with voltage V_g: the more mobile electrons elapse from the oxide through "transparent" contact of the oxide-metal gate, and low-mobile holes are collecting in the layer of "d" thickness near the silicon backing.

The charge inserted into the oxide layer by radiation changes the value of threshold voltage on the gate $V_g = V_{th}$ at which the

conducting channel in silicon being under gate is opened, and it also changes the characteristic slope of the *F* channel conductivity.

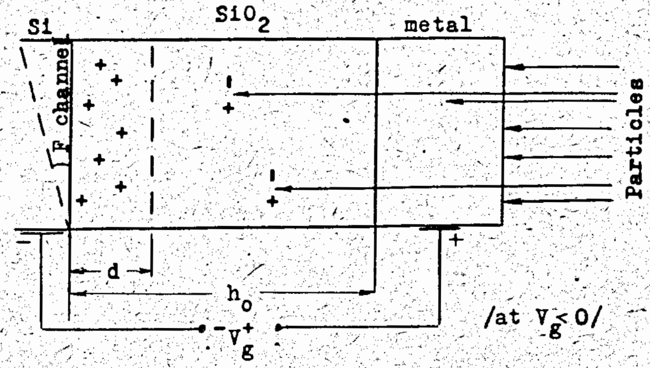

Fig. 1. The model of radiation effects in the MOS-structure [5].

In order to hold the channel open, one should change the voltage on the gate by the value $V_g = \Delta V_{th}$, which reaches the saturation value $\Delta V_{sat.th}$ equal according to:

$$\Delta V_{sat.th} = V_g \quad \text{at } V_g < 0 \text{ and}$$

$$\Delta V_{sat.th} = -V_g (2h/d - 1) \text{ at } V_g > 0$$

The $\Delta V_{sat.th}$ difference can be explained qualitatively as follows: at negative gate polarity the charge of radiation origin is moved to metalic gate electrode and due to high backing remoteness it effects the channel conductivity less effectively (quite (2 h/d -1) times less effectively) than the charge being near the backing surface (at $V_g < 0$).

For simulating radiation effects in semiconductor devices under the influence of fast neutrons with the use of accelerated heavy ions one can state the following basic criteria:

- ratio between ion fluence and neutron one has to be in inverse proportion to the ratio of their damaging abilities (defect production cross sections);
- range of accelerated ions R_p has to exceed the thickness of radiosensitive region of semiconductor device (h in fig.1);
- ion irradiation should be carried out in vacuum and on opened crystal of the device.

3. PROCEDURE OF IRRADIATION AND MEASURUMENT OF SHIFT REGISTER PARAMETERS

Radiation resistance of semiconductor devices has been investigated in vacuum on heavy ion extracted beams of the IC-100 (ions B^{11}, Ne^{22}, Ar^{40} with the energies of 13,6 MeV, 26,9 MeV and 46 MeV, respectively) and U-200 (ions C^{12} with the energy of 91 MeV) accelerators, and also on the IBR-2 reactor (LNP). In table 1 ion beam characteristics with calculated values of projective range (R_p) and defect production cross sections (σ_d) obtained using the TRIM-90 program are presented.

Table 1. Heavy ion characteristics

Ion	Z	Energy (MeV)	MeV/amu	R_p (μm)	σ_d (dpaxcm^2)
^{4}He	2	5.5	1.375	27.1	1.0×10^{-19}
^{11}B	5	13.6	1.2	16.4	8.4×10^{-19}
^{12}C	6	91.0	7.6	162.0	3.2×10^{-19}
^{22}Ne	10	26.9	1.2	13.5	5.1×10^{-18}
^{40}Ar	18	46.3	1.16	12.3	1.6×10^{-17}

The choosing of a necessary defect production velocity (flux particle density) has been realized by varying the ion beam

intensity both at once (direct ion beam irradiation) and with using the technique of ion scattering on a scattering foil (in our case from Au with thickness less than 5×10^{-5}cm). This allowed one to decrease the ion flux density on target approximately 10^3 times in comparison with the direct beam density and thus, to have safely registered low intensities up to 10^3 ion/cm^{2}sec).

Semiconductor detector has been set to register the energy and to measure the ion flux density on the target using the method of scattering symmetrically to the ion beam axis. To determine parameters of irradiated semiconductor devices while collecting necessary fluence, a special holder has been developed.

In order to decrease the ion flux density up to the value which is required according to the terms of simulation the defocusing beam has been used at irradiation on the IC-100 cyclotron. Fast neutron irradiation has been carried out on the IBR-2 reactor of the Laboratory of Neutron Physics.

The source "Mineyola" on the base of radioactive isotope ^{60}Co has been applied for γ-irradiation (Institute of Nuclear Chemistry and Technology (Warsaw)). The γ-quanta energy was 1.25 MeV and the energy of radiation dose was 250 crad/hour. β-particle irradiation with the energy in the range from 0,2 up to 0,8 MeV on the source Sr(Y^{90}) with activity of 74 MBk has been also performed there. α-particle irradiation with the energy of 5.5 MeV has been carried out on radioactive source ^{238}Pu with efficiency of 2×10^6 particles/min. During irradiation with the use of radioactive sources the square equally irradiated has been varied form 0.5 up to 1 cm^2.

The measuring system is illustrated in fig.2a. The measured parameter was $U^{I}_{"1"}$ and $U^{II}_{"1"}$-the voltage at the output I and II is in a logical state "1"(when the gate input is shorted with the key K1 or K2, respectively). Fig. 2b shows the principle of critical fluence determination from experimental degradation curve.

It was assumed that at a supply voltage of +5V the critical value of this voltage is +4V.

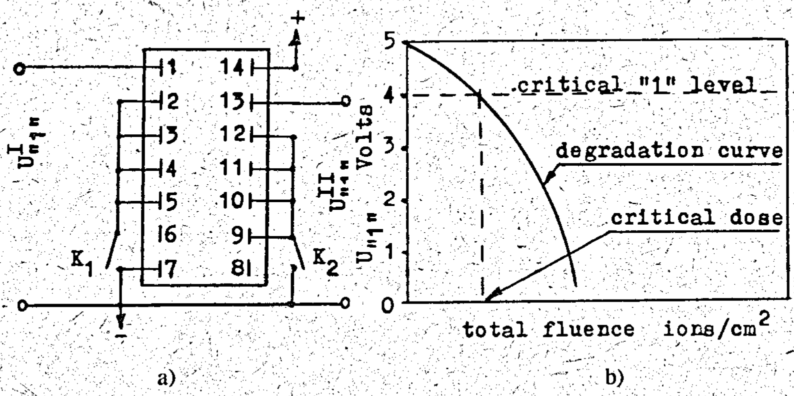

Fig. 2. a) Measuring system of the output voltage $U_{"1"}$ of logic NAND gate of the MCA 54012 type, b) the example of the result showing the principle of critical dose determination.

5. EXPERIMENTAL RESULTS

The processes of parameter degradation of shift registers of the MCA 54012 type (Poland production) have been investigated hereof during fluence collecting-the dynamical mode of operation.

In fig. 3 experimental dependencies of decreasing the "unit" voltage at the output of the "NAND" integrated circuits on particle fluence of different types are illustrated. According to the accepted agreement the values of critical fluences for every particle type are determined.

A table of radiation effectiveness of different types with respect to one for another, which are presented in table 2, is constructed on experimentally obtained data. Analogous coefficients from the work [6] are indicated in the brackets.

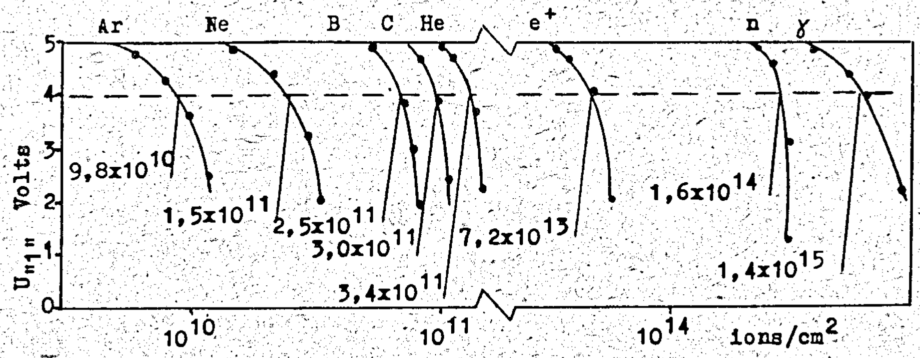

Fig. 3 Dependencies of decreasing the voltage of logic "unit" at the output of the "NAND" logic circuits for different particle types. The values of critical threshold fluences are shown.

Table 2. Coefficients of radiation effectiveness based on $U_{"1"}$ (V) of logic NAND gate

	^{40}Ar 46 MeV	^{22}Ne 27MeV	^{11}B 13.6 MeV	^{12}C 91 MeV	^{4}He Pu-238)	$n^{*)}$ reactor	e^+ Sr(Y)	$\gamma^{*)}$ ^{60}Co
^{40}Ar	1	1.5	2.5	3.1	3.5	1600	730	14000
^{22}Ne	0.6	1	1.7	2.0	2.3	1100	480	9300
^{11}B	0.4	0.6	1	1.2	1.4	290	640	5600
^{12}C	0.3	0.5	0.8	1	1.1	240	530	4700
^{4}He	0.3	0.43	0.7	0.9	1	470	210	4100
						(140)	(700)	(150000)
$n^{*)}$	6.2×10^{-4}	9.1×10^{-4}	3.5×10^{-3}	4.2×10^{-3}	2.1×10^{-3}	1	0.45	9
							(50)	(1100)
e^+	1.4×10^{-3}	2.1×10^{-3}	1.6×10^{-3}	1.9×10^{-3}	4.7×10^{-3}	2.2	1	20
								(22)
$\gamma^{*)}$	7.1×10^{-5}	1.1×10^{-4}	1.7×10^{-4}	2.2×10^{-4}	2.4×10^{-4}	0.11	0.05	1

*) IC caps of 0.2 g/cm^3, for bipolar transistor, after [6].

6. CONCLUSION

The obtained coefficients differ from those given in [6] for bipolar transistors. This is due to different operation of devices investigated. The degradation of bipolar transistor results from increase of recombination velocity of minority carriers on vacancies, effectively produced by heavy particles. Whereas, in the MOS integrated circuits the main role is played by charge centres, formed as a result of ionization in the oxide layer of the MOS structure, which cause the shift of threshold voltage of the MOS FET transistor. These centres are more effectively produced by electrons and γ-rays.

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