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A.Yu.Didyk, W.N.Nazarov, G.G.Gulbekian, W.Wronski*

INVESTIGATION OF RADIATION RESISTANCE OF TRANSISTORS AND INTEGRATED CIRCUITS USING THE HEAVY IONS BEAM OF ENERGY HIGHER THAN 1 MeV/amu AND FAST NEUTRONS

*Institute of Nuclear Chemistry and Technology, Warsaw, Poland

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1. INTRODUCTION

Investigation of the radiation resistance of semiconductor devices interacted by ionizing radiations is of great importance for modern electronic development [1,2]. This research direction is especially connected with the technology progress when production of radiation resistant semiconductor devices used for cosmic and nuclear purposes is concerned. It is to emphasize that such an investigation is of greather value when it is carried out by "in situ" method. This means, if functional parameters degradation is registered during the accumulation of the damage dose in the sensitive area of semiconductor device.

On the other hand, investigation of radiation effects caused by fast reactor neutrons encounter many problems connected with hight temperature, activation effects as well as with long time of irradiation.

The use of accelerated heavy ions for radiation effect modeling caused by fast neutrons has a number of advantages. These are: low activation level, rapid dose accumulation, easy control of irradiation process and the possibility to record parameter changes at any time.

According to the other research direction developed in many research centers, heavy ions are used for modeling of "soft errors" caused by cosmic radiation. It is possible to model the energy spectrum of cosmic radiation as well as the types of particles and characteristic flux densities.

The purpose of the present work is the investigation of the possibility of using accelerated heavy ions for modeling the influence of fast neutrons on functional parameters of semiconductor devices. This work was carried out in the Flerov Laboratory of Nuclear Reactions and the Frank Laboratory of Neutron Physics of JINR - Dubna.

2. PHYSICAL BASIS AND RULES (CRITERIA) OF RADIATION DEGRADATION MODELING OF SEMICONDUCTOR DEVICES

In the semiconductor material (the major components of which are Si- single crystal, and SiO_2-glass), fast neutron bombardment causes crystal defects of the form of interstitial atoms and vacancies. They form, themselves or together with the oxygen atoms (A-center), phosphoric impurities (E-center) and others, isolated unmobile or weakly mobile charged states, which change the electron structure of the semiconductor [3]. Into the semiconductor device, they act in a different manner, depending on that if the radiation sensitive area is Si or SiO_2. In pure Si, which constitutes the base of bipolar transistor, they are recombination centers which decrease the concentration, life-time and mobility of current minority carriers. According to the Nelson's [4] model it causes the decreasing of the current gain coefficient and of the breakdown as well as increasing the reverse current of the n-p junctions. However, in SiO_2, which constitutes an isolating layer of the gate electrode of MOS transistor, they are charged states shielding the electric field, which controls the current in conductive channel. Following the Mitchell's model [5], it causes a threshold voltage change of unipolar MOS transistor. In both cases, the changes of semiconductor device parameters increase uniformly in time and are unreversible.

There are not enough data, concerning the modeling of such effects using accelerated heavy ions, in the literature. The similarity theory between fast neutrons and heavy ions [6] has been elaborated for radiation stimulated mechanical phenomena in constructional and reactor materials. From this theory, one can sometimes derive contradictory conclusions when considering the idea of modeling (the main goal of which is just research acceleration). Taking into account the analysis of physical phenomena and conclusions derived from our experiments, it seems possible to formulate following criteria of modeling (with the use of heavy ions) radiation effects made by fast neutrons in basic types

of semiconductor devices:

- the range of ions should be larger than the thickness of radiation sensitive layer of semiconductor device (it usualy ranges from 0,1 μm to some micrometers from the crystal surface),
- the radiation damages should not form larger homogeneous "disordered regions" than the radiation sensitive areas,
- the ion beem should impinge at uncovered crystal "chip" of the semiconductor device.

The first criterion advices an avoiding of the chemical effect due to semiconductor ion implantation. For that reason the best are ions of noble gases and of the IV-th group elements. Second criterion, which is not opposite to the first one, advices to avoid the breakdown through the radiation sensitive region, which constitutes in the same time the basic functional area of the semiconductor device. The third condition is obvious and means the necessity of cover removal of the semiconductor device.

3. EXPERIMENTAL

3.1. IRRADIATION

During irradiation, the investigated semiconductor devices have been coupled to measuring units by supply of signal cables of the lenght from some to several meters. Due to that fact, the "in situ" conditions were reached while by disconnecting the power supply, it was possible to switch to static conditions.

3.1.1. FAST NEUTRONS

The high-flux pulse reactor IBR-2 has been used as a neutron source. The neutron spectrom at the "Regata" system (supplied by a pneumatic post) has purely fissionable character. The fast neutron flux density amounts to 1.4×10^{12} n $cm^{-2}s^{-1}$. At the other, "biophysical" channel, the fast neutron flux density amounts to 4.9×10^{8} n $cm^{-2}s^{-1}$, with slightly changed spectrum.

3.1.2. HEAVY IONS

The following ions have been used: $^{22}Ne^{+4}$ and $^{40}Ar^{+7}$ (which have been accelerated up to the energies of 27.9 MeV and 46 MeV, respectively, at IC-100 cyclotron) , as well as $^{12}C^{+3}$ ions accelerated up to energy of 91 MeV at the U-200 cyclotron.

The experimental conditions (for which also belongs the possibility of registration of radiation induced changes by suitable measuring units) sometimes force to diminish the generation speed of radiation demages caused by ions. The simple method of the ion beam parameters adaptation to the measurement requests, relay on suitable choice of the mass number Z and energy E of the accelerated ions. Application of this method is posible only in the best equipped research centers. The change of the mass number Z often requires construction of a new ion source. The acceleration of a given ion up to another energy is possible only at another cyclotron. The other method is the use of the scattered beam.

The choice of the ion parameters is illustrated at fig.1. The radiation damages density along the penetration distance of ^{22}Ne ion (of energy 27.9 MeV) in silicon expressed in dpa/ion/cm^2 units has been calculated using the computer programme TRIM-90. This ion has been used in our present work. The other curves are shown only for illustration, because ions with the given parameters are not obtainable at cyclotrons working in JINR. At the picture, thin surface layer of the thickness of 2,0 μm (which constitutes the radiation sensitive region of semiconductor device) has been indicated. As has been shown, the effectiveness of the radiation damage generation at that area is smaller for the ions having smaller mass number (for the same energy) and higher energy (for the same mass number Z). The total result is a product of these factors.

As a result of the described above analyses and preliminary measurements, the following ions have been choosen for investigation of radiation resistance of:

- Planar transistors - ^{22}Ne (27.9MeV) and ^{12}C (91MeV),
- NAND logic gates- ^{12}C (91MeV), ^{22}Ne (27.9MeV) and ^{40}Ar(46MeV).

3.2. MEASUREMENTS

The radiation resistance of the investigated semiconductor devices has been determined using the diagrams of functional parameter degradation of given device during its irradiation. As a resistance parameter, the value of maximal exposition dose EDL has been choosen. This EDL is a dose for which the degradation of a choosen functional parameter reaches a critical value. This critical value is established by the user or producer (e.g. in a catalogue). A similar approach was used by Battisti et all [7], who have presented the wide review of the radiation effects caused by gamma-rays and fast neutrons in majority of produced electronic elements and semiconductor devices.

In the present work two types of semiconductor devices have been examinated: planar transistors p-n-p and NAND logic gates. They represent the two most wide spread constructions and technologies: bipolar devices working on the p-n junctions, and IC based on MOS structure. The simple measuring instruments, resistant for electromagnetic field in the neighbourhood of the cyclotron have been used.

3.2.1. TRANSISTORS

Planar transistors p-n-p of the type BC177 (produced by TEWA-Poland) have been investigated. The coefficient of the direct current gain in the circuit with common emitter β_Φ (where Φ denotes the particle's flux at the measurement moment) has been measured. The measuring system is shown at fig.2a. The EDL value corresponds to the flux $\Phi_{1/2}$ for which the lowering of the current gain reaches 50% of its initial value β_Φ.

3.2.2. NAND LOGIC GATES

NAND gates of the type of MCA 54012, produced by TEWA-Poland, have been tested. These are the double (four-inputs) CMOS gates, mounted into ceramic casing of the type DiL14 with removable cover. This cover has been taken off before the irradiation in the cyclotron. The voltage at the gate output of the inverter system shown at fig.2b has been measured. According to the producer's cataloque, this voltage cannot be less than +4 Volts when supplying with +5 Volts. To the EDL value corresponds the flux Φ_{4V}, for which the absolute value of the output voltage amounts to +4 Volts. Measuring system shown at fig.2b enables also the measurement of the output voltage at logical state "0". However, for the initial value equal to 1.8 Volts, this voltage also decreases by the radiation interaction and never exceeds the value of +2.0 Volts.

4. RESULTS

4.1. TRANSISTORS

Fig.3 illustrates the current gain degradation of the p-n-p (low power) transistor of the type BC-1772, expressed in relative units $\beta_{\Phi}:\beta_0$, where β_0 has been measured before the irradiation. The crystal has been uncovered by careful removal of the upper part of the cover. Transistors, two or three in the same time, were irradiated in special holder by direct beem of Ne and C ions and fast neutrons. As can be seen, the transistor functional degradation for fast neutrons undergous analogically to that of heavy ions. No significant difference between ions from the IV-th group of elements and noble gases ions has been observed.

On the basis of EDL values determined from fig.3., the effectivity coefficients for Ne and C ions in relation to fast neutrons have been calculated. Experimental as well as calculated results are presented in Table 1. The effectivity coefficient

indicates the number of fast neutrons which effect as one ion of given parameters.

Table 1. EDL values for BC177 transistors and the effectivity coefficients for ions and fast neutrons

Radiation type / Result	^{22}Ne	^{12}C	n_{fast}
EDL ($\Phi_{1/2}$) (particles/cm^2)	4.1×10^8	5.1×10^9	2.0×10^{12}
Effectivity coefficient (neutrons/ion)	4900	390	1

4.2. NAND LOGICAL GATES

Fig.4. showes the voltage decreasing of the logical state "1" for NAND gate MCA 54012.

As can be seen, the radiation degradation of NAND gates is more rapid for fast neutrons than for ions. The doted line presents the expected degradation curve which could be obtained under fast neutrons interaction. The experimental result (fig.4.) and calculated radiation effectivity coefficients of Ne and C ions in comparision with fast neutrons have been given in Table 2.

5. CONCLUSION

Investigation carried out shows, that the beems of accelerated heavy ions of energy ranging from 1MeV/nucleus to 10 MeV/amu and atomic numbers from 5 to 18 can be applied for the simulation of influence of fast neutrons on semiconductor devices. It accelerates investigation and avoids problems connected with the sample activation.

Table 2. EDL values for NAND gates and the effectivity coefficients for ions and fast neutrons

Radiation type / Result	^{22}Ne	^{12}C	n_{fast}
EDL (Φ_{4V}) (particles/cm^2)	$1.2x10^{10}$	$2.8x10^{11}$	$1.6x10^{14}$
Effectivity coefficient (neutrons/ion)	13000	570	1

Satisfactory correlation between the calculated and experimental results has been observed. First of all it concerns the damage generation velocity calculated for the radiation sensitive region of semiconductor device. These damage becomes recombination centers in the area of bipolar transistor basis or charged centers in oxide layer of the MOS structure.

This statement has been confirmed by the values of the effectivity coefficients for different types of radiation, which have been determined experimentally for the ions choosen, accordingly to theoretical calculation.

Experimentally determined values of the dose limits EDL, and effectivity coefficients, which are characteristic parameters for groups producing semiconductor devices, are of great practical importance and will be continued.

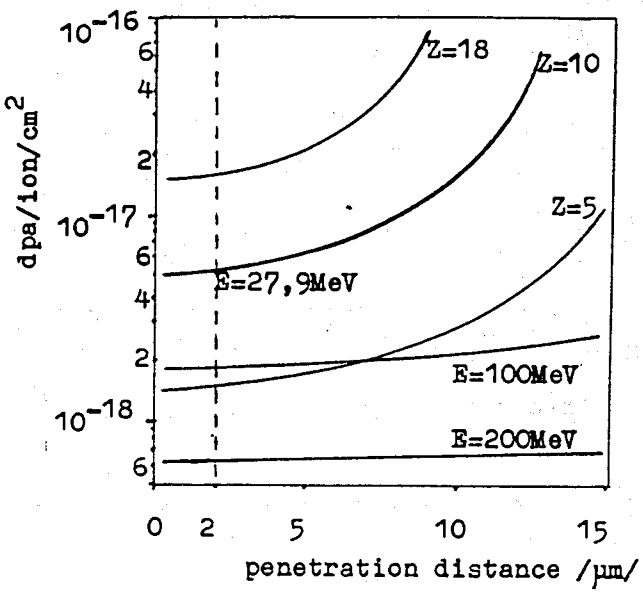

Fig. 1. Atom displacements density on the penetration distance in Si for different Z and E of incident ions. Theoretical curves.

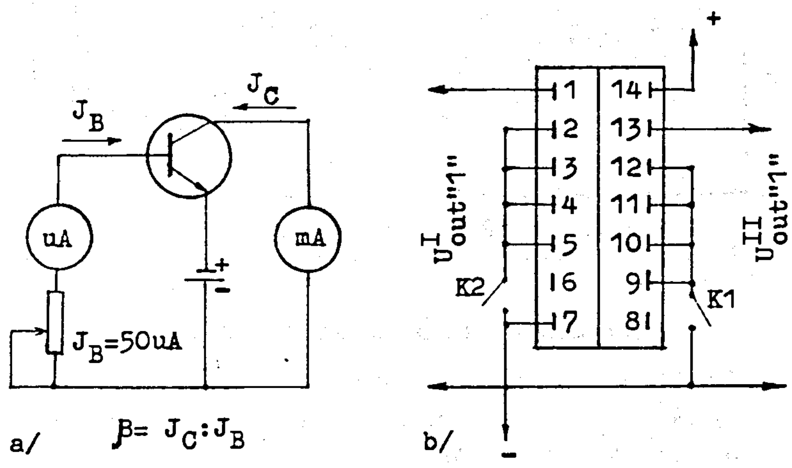

Fig. 2. Measuring systems: a) for the dc gain of bipolar transistors - β, b) for output voltage of NAND gates - $U_{out"1"}$.

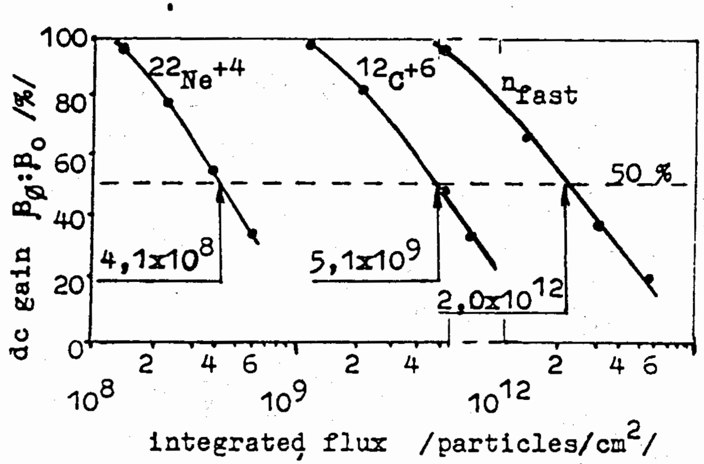

Fig. 3. BC 177 transistors gain degradation vs incident ion flux. Ion parameters: Ne - 27.9 MeV, C - 91 MeV.

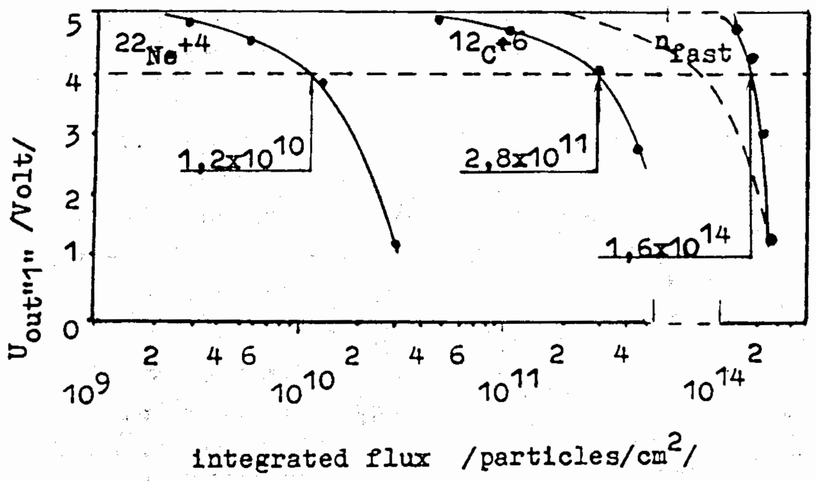

Fig. 4. MCA 54012 NAND gate degradation of output voltage for logical state "1" vs incident ion flux. Ion parameters: Ne - 27.9 MeV, C - 91 MeV.

REFERENCES

1. D.V.Akinshin, N.M.Borisova, N.U.Goleminov, A.Yu.Didyk, V.A.Skuratov, W.I.Smirnov. Devices and Tech.of Exp., 1990, N 6, p.49-50.
2. Ion Implantation and Radiation Technology, Kiev 1988, p.358.
3. V.S.Vavilov, N.A.Ukhin. Radiation Phenomena in Semiconductors and Semiconductor Devices, PWN, Warsaw, 1971.
4. D.L.Nelson, R.J.Sweet. Mechanism of Ionizing Radiation Surface Effects on Transistor, IEEE Trans., NS-13, N-6, 1966.
5. J.Mitchell, K.Wilson. Surface Effects of Radiation on Semiconductor Devices, Moscow, 1971.
6. V.V.Gann, O.V.Judin. Voprosy At.NiT-Fiz.Rad.PiR Mat., vol.3, 1982.
7. S.Battisti, R.Rossart, H.Schonbacher, M.Van de Voorde. Radiation Damage to Electronic Components. Nucl.Instr.and Meth., v.136, N 3, 1976.

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