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The influence of a single radiation defect cluster forming on the transistor structure channel conductivity

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The effect of a single radiation defects cluster formation on the characteristics of short-channel structures was studied. Estimates of the nuclear particle energy, capable of forming a cluster of radiation defects, causing a failure and modern silicon transistors failure with various channel sizes.

Keywords: short channel transistor, radiation defect cluster, single event.

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1. Introduction

The radiation effect of the flow of single nuclear particles (SNPs) leads to the deterioration of such parameters of semiconductor materials as the concentration and mobility of the main charge carriers. The reason for these changes is the occurrence of accumulations of structural damage i.e clusters of radiation-induced defects (CRIDs) caused by the elastic interaction of SNPs (proton, neutron, α-particle, heavy charged particle or primary recoil atom) with atoms of the crystalline lattice of matter [1]. These accumulations of defects act as energy traps for the majority charge carriers, reducing their concentration in the volume of a semiconductor. Since the electroneutrality of the irradiated sample remains after radiation exposure, the clusters of radiation-induced defects are surrounded by a space-charge region (SCR), which forms a scattering potential inside and around the disordered region. Therefore, clusters of radiation-induced defects act as centers for scattering of carriers, reducing their directed velocity and, as a consequence, their mobility.

Since SNPs can transfer energies up to several megaelectronvolts to atoms of matter, the dimensions of the CRID can be much larger than the characteristic relaxation lengths of the energy and momentum of electrons, the Debye length, etc. In modern devices, where the energy of charge carriers can reach 1/eV and more, the electron wavelength becomes shorter than the distances between the SCRs of subcascades in a cascade of displaced atoms. Thus, extended clusters of radiation defects break up into a chain of independent inclusions that are opaque for high-energy charge carriers i.e. subclusters of radiation-induced defects (SRIDs).

Ionization processes proceed in parallel with the elastic interaction. Ionization under radiation exposure occurs due to two processes: the Coulomb interaction of a charged particle with the electrons of the outer orbitals of atoms of the crystal lattice and the impact interaction of two atoms, as a result of which the initially resting atom of the crystal lattice acquires the velocity greater than the velocity of orbital electrons in the approximation of the semiclassical model of Bohr atom.

The processes of defect formation and ionization under the action of SNPs have different spatial and temporal scales, therefore, as the topological dimensions of transistor structures and the characteristic switching times of static memory cells based on them decrease, the phenomena described above affect the processes of carrier transfer to a different extent. In semiconductor structures, the dimensions of the operating regions of which are much larger than the characteristic energy relaxation length of the electron-hole gas, the transfer of charge carriers is mainly carried out by a flow of electrons and holes with a temperature close to the temperature of the crystal lattice. In this case, even in strong electric fields, the directional component of the carrier velocity is less than the chaotic component caused by the thermal motion of particles. As the size of the operating regions of the elements decreases, the number of scattering of carriers decreases, so the nature of the motion of electrons and holes changes to the quasi-ballistic one [2] with preferred transfer of hot particles.

It is known that electrons with energies on the order of several $k_{\mathrm{B}}T$ are scattered at the CRID as a whole. For hot electrons with high energies, CRID is represented as a set of closely spaced, partially overlapping potentials of radiation defect subclusters (SRIDs) [3]. Thus, the formation of defects in a transistor channel imposes additional conditions on the nature of electron motion (diffusion or quasi-ballistic) in it [4].

It is traditionally believed [5] that the fault tolerance of the static memory cell is determined by the ratio between the critical charge value, i.e. the value of the charge in the transistor channel, causing the switching of the static memory cell, and the value of the collected charge, i.e. the charge of non-equilibrium carriers in the part of the track of SNP passing through the operating region of the transistor. If the value of critical charge is less than the value of collected charge, then the switching causing the failure occurs; otherwise, switching and, as a result, failure does not occur. In this case, the nature of carrier motion is not taken into account in this model, which leads to an error in assessing the fault tolerance of submicron structures [6].

In this work, for the first time, we analyzed the influence of the process of formation of a single cluster of radiation-induced defect on the characteristics of short-channel transistor structures.

2. Mathematical model

At present, there is a wide range of methods for modeling the development of cascades of atomic collisions in matter [7], which can be divided into 4 classes: quantum-mechanical methods from first principles, methods of classical molecular dynamics, stochastic methods (Monte Carlo algorithms) and continuum methods based on the laws of heat-and-mass transfer in continuous medium. In this work, the SRIM [8] program, whose algorithm is based on the model of elastic interaction of hard balls, was used to estimate the dimensions of the CRID, and the LAMMPS [8] program was used to estimate the dynamics of the formation of the CRID and accompanying ionization processes [9], which implements the method of classical molecular dynamics together with the two-temperature model of the atomic and electronic subsystems of the crystal lattice [10].

The following methodology was used to estimate the average parameters of the CRID (the dimensions of the SRID, the number of SRIDs in one CRID, and the distance between the SRIDs). For each energy of the primary recoil atom, using the SRIM program, one hundred realizations of atomic displacement cascades were simulated with subsequent averaging of the estimated parameters. To solve the clustering problem (partitioning a separate displacement cascade into separate sub-cascades) for each implementation of the disordered region, the DBSCAN [11] algorithm was used, the input parameters of which are the minimal number of radiation-induced defects $N_{cl}^{(\min)}$ required for the formation of subcluster, and the minimum distance $L_{cl}^{(\min)}$ between neighboring point defects. Based on the considerations that each SRID is surrounded by the SCR, $L_{cl}^{(\min)}$ is determined by the Debye length in the material. The minimal number of radiation-induced defects $N_{cl}^{(\min)}$ forming the SRID was chosen to be four for calculations. The dimensions of the SRID were estimated using the minimum ellipsoid algorithm [12].

To estimate the magnitude of the radiation-induced charge generated during the formation of a disordered region, the approach described in the work [13] was used. At each moment of time, using the LAMMPS program, the amount of energy transferred from the atomic subsystem to the electronic one is calculated. Taking into account the average formation energy of the electron-hole pair (3.6 eV in silicon), one can calculate the total radiation-induced charge, since the generation rate significantly exceeds the recombination rate of non-equilibrium carriers.

After radiation exposure, the disordered region is formed in the transistor channel, the specific conductivity of which is close to the specific conductivity of the intrinsic semiconductor σ_i. To estimate the change in the conductivity of the channel of the transistor structure after exposure to σ_{rad} neutrons, the Weiner equation [14] was used:

$$\frac{\sigma_{rad} - \sigma_{ch}(N_d)}{\sigma_{rad} + 2\sigma_{ch}(N_d)} = \frac{V_{cl}}{V_{ch}} \frac{\sigma_i - \sigma_{ch}(N_d)}{\sigma_i + 2\sigma_{ch}(N_d)}, \tag{1}$$

where σ_{rad} is conductance of the transistor structure channel after exposure to neutrons, σ_i is conductance of intrinsic semiconductor, σ_{ch} is conductance of the transistor structure channel before radiation exposure, V_{cl} is the volume of the cluster of radiation defects, V_{ch} is the volume of the channel of the transistor structure, N_d is concentration of the donor impurity.

3. Calculation results and discussion

3.1. Disordered region parameters

Fig. 1 and 2 show the results of simulating the dependence of the number of defects N_{def} and the temperature of the electron-hole gas T_e on the depth d during the formation of the CRID by the primary recoil atom Si with energy 50 keV for different moments of time.

It follows from the obtained results that during the formation of a cluster of radiation-induced defects, four characteristic stages can be distinguished, associated with a change in the size and concentration of defects: the initial

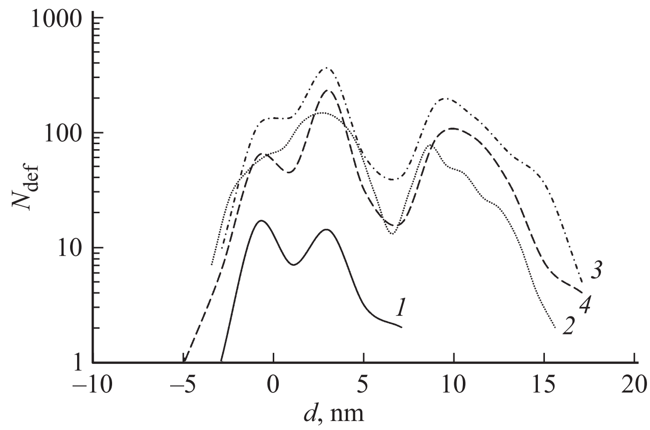

Figure 1. Distribution of the number of defects N_{def} from the depth d for different moments of the process of formation of a cluster of radiation defects: *1* — 0.05, *2* — 0.15, *3* — 2.2, *4* — 102 ps. The origin of coordinates corresponds to the cluster initiation point.

Table 1. Spatial and temporal scales of the process of formation of a cluster of radiation-induced defects

Scale	Subject			
	Pair Frenkel	Electron-Hole pair	Cluster of radiation-induced efects	Current of ionization
Distance, nm	2	3	11	24
Time, ps	10^{-4}	10^{-3}	100	0.2

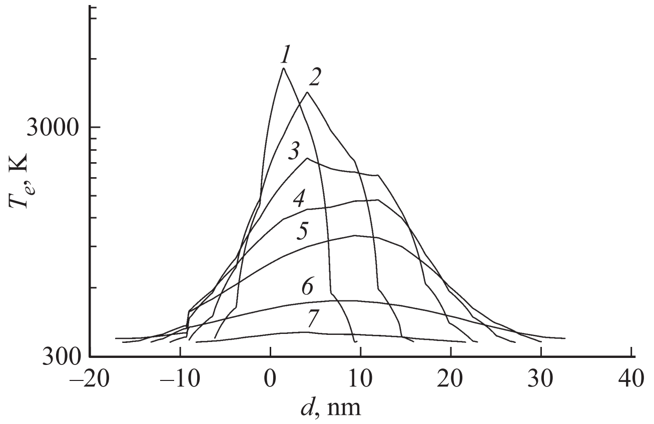

Figure 2. Temperature distribution of electron-hole plasma T_e versus depth d for different time moments of the formation of cluster of radiation defects: *1* — 0.03, *2* — 0.05, *3* — 0.1, *4* — 0.15, *5* — 0.22, *6* — 0.42, *7* — 1.22 ps. The origin of coordinates corresponds to the cluster initiation point.

ballistic region (Fig. 1, curve *1*), during which the primary recoil atom moves with a minimum number of collisions; the section of thermal expansion (Fig. 1, curves *2* and *3*), within which the number of defects in the cluster and its size rapidly increase; the primary stabilization stage, which is characterized by sharp decrease in the number of defects due to the recombination of close Frenkel pairs, and the rapid annealing stage (Fig. 1, curve *4*), which can last several nanoseconds, accompanied by a gradual decrease in the number of defects and cluster sizes as compared to the primary stabilization stage due to annealing. In this case, the processes of heating of the electron-hole plasma, which accompany the formation of cluster of radiation defects, proceed much faster than the processes described above. By the end of the stage of thermal expansion, the temperature of the electron-hole plasma is established in the region of equilibrium values, which were observed before radiation exposure.

Summarizing the above, Table 1 presents the characteristic spatial and temporal scales of the process of formation of a cluster of radiation defects in silicon, among which the stages of generation of electron-hole pairs and the formation of individual point defects, subclusters, and clusters as a whole are singled out.

It follows from the results obtained that the spatial and temporal scales of the processes of elastic interaction and ionization differ significantly. Therefore, to estimate the influence of the formation of a single cluster on the operation parameters of transistor structures, these processes can be considered independently.

4. Change in the conductivity of the channel of the transistor structure

To simulate the conductance changes of the transistor structure channel, it is necessary to estimate the size of a cluster of radiation-induced defects that form primary recoil atoms with different energies. Fig. 3 and 4 show the dependences of the size distribution of subclusters, the number of subclusters, and the distance between them for different energies of the primary atom.

From the presented results, it follows that with increase in the energy of the primary recoil atom, the nature of the size distribution of subclusters changes. In this case, for low energies, at which the cluster does not split into separate sub-cascades, the size distribution has a form close to normal. As the energy of the primary recoil atom increases, the number of small subclusters in the cascade of atomic collisions increases, since the energy losses due to elastic interaction decrease, which leads to a change in the nature of distributions.

The parameters of modern transistor structures, such as topological dimensions, voltage, gate capacitance, and critical charge, the value of which determines the minimum

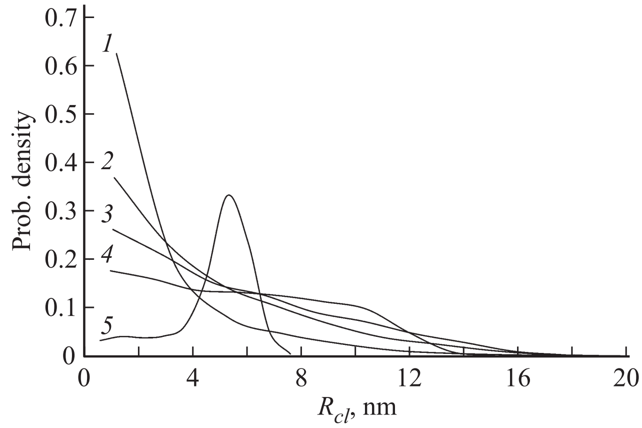

Figure 3. Distribution of subcluster sizes R_{cl} for different energies of the primary recoil atom: *1* — 800, *2* — 90, *3* — 60, *4* — 30, *5* — 10 keV.

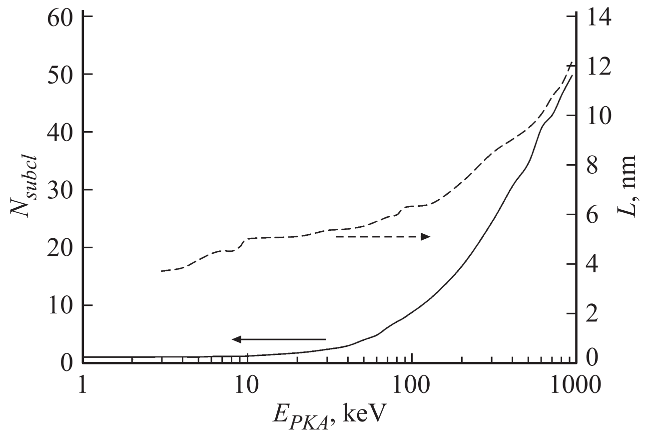

Figure 4. Dependences of the average number of subclusters N_{subcl} in one cluster (solid line) and the average distance between them L (dotted line) on the energy of the primary recoil atom E_{PKA}.

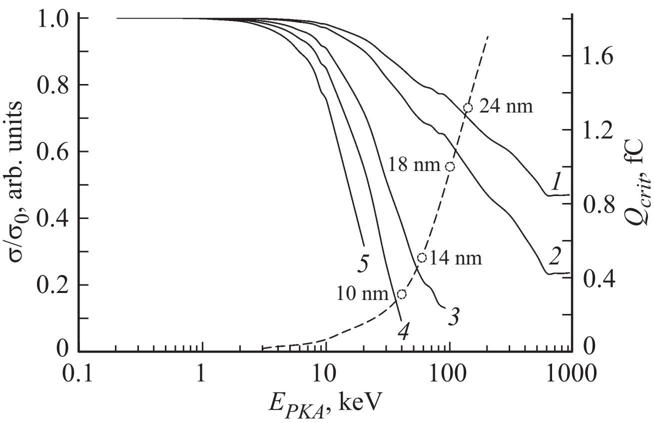

Figure 5. Relative change in the conductivity of the channel of transistor structures σ/σ_0 for various design rules (solid line) and the value of the critical charge Q_{crit} (dotted line) on the energy of the primary recoil atom E_{PKA}: The graph number corresponds to the configuration number in Table 2.

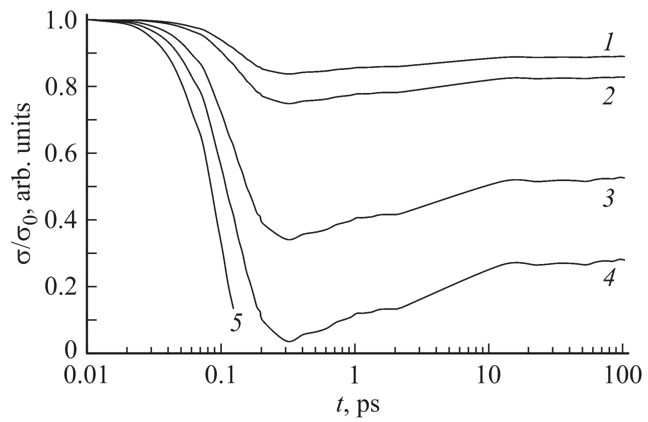

Figure 6. Relative change in the conductivity of the channel of transistor structures σ/σ_0 for different design standards in time during the formation of a cluster of radiation defects: The graph number corresponds to the configuration number in Table 2.

Table 2. Parameters of modern transistor structures

Parameter	Technical process				
	1	2	3	4	5
Channel length, nm	24	18	14	10	10
Channel width, nm	92	90	56.5	56.5	56.5
Channel depth, nm	21	18	12	10	6
Voltage, V	0.8	0.75	0.7	0.65	0.55
Gate capacitance fF/μm	1.81	1.49	1.229	0.97	1.04
Critical charge, fC	1.33	1	0.49	0.36	0.33

charge collected by the drain output, necessary for switching the static memory cell, for which the changes in the channel conductivity were estimated, are presented in Table 2 [15].

In accordance with expression (1), as well as the data presented in Table 2, the dependences of the relative change in the conductivity of the transistor channel at zero gate bias and the value of the radiation-induced charge on the energy of the primary recoil atom were calculated for various topological norms, shown in Fig. 5.

It follows from the obtained results that for technological processes № 3, 4 and 5, the transistor failure associated with decrease in the channel conductivity occurs earlier than the failure caused by abnormal switching of the transistor cell. However, for technological processes № 1 and 2 the situation is reversed.

Fig. 6 shows the dependences of the relative change in the conductivity of the channel of the transistor structure for different gate lengths during the formation of the CRID by the primary recoil Si atom with energy of 50 keV.

From the presented results, it follows that with a decrease in the size of the transistor channel, a situation is possible when, for a short period of time, the channel conductivity drops to almost zero, followed by recovery. In this case, a reversible failure of the transistor structure occurs, unrelated to ionization processes.

5. Conclusion

Summing up, it should be noted that more accurate estimates are possible when using approaches based on the methods of physical-and-topological modeling. In this case, the change in the channel conductivity will be estimated from the change in the mobility and concentration of charge carriers.

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Conflict of interest

The authors declare that they have no conflict of interest.

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