Solar flare effect on microelectronic circuits assessed for Wigner's disease

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***Abstract*— Heavy energetic charged (HZE) or neutral particles induce atomic and molecular changes in materials. Depending on the absorbed radiation dose, degradation and failure of the electronic components occur in electrical systems installed e.g., for space vehicle control or satellite communication. Galactic cosmic ray (GCR) increases abruptly during solar flares due to the emission of solar energetic particles (SEPs). These are event-related waves of energy ejected from the sun's surface. High energy photons and protons, alphas, neutrons, electrons, and muons among others are released in a time interval sequence of short bursts lasting a few minutes. Ionizing particles lose their energy in matter originating high charge density in a thick layer of material. Electron-hole pairs are produced in semiconductors. Most transistors are made from very pure silicon and have one or two kinds of charge carriers (e.g., field-effect transistors, and bipolar junction transistors). Existing a high-density ion, molecular structures are disrupted by Coulomb repulsion with the consequence of changing the transistor parameters; a phenomenon that alters the functionality of microelectronics circuitry ending in data corruption. We report consequences in microelectronic circuitry of the effect called Wigner disease. Atomic alteration due to solar flare neutron scattering induces dislocations per atom (dpa). For this purpose, the mathematical formalism as an approximate model of Kinchin and Pease is applied. The study is a contribution toward the *Artemis* NASA space program related to the Red Planet exploration.**

Keywords*— *solar flare, radiation damage, Wigner disease, transistors, electronic circuitry.

I SOLAR PARTICLES AND GALACTIC COSMIC RAYS

The intergalactic space as well as the solar system is submerged in a medium where we observe plasma, photons micro/macro meteorites, and endless particles of a wide range of mass and energy. Particles can be emitted by the sun as a continuous process or by solar flares. These produced sporadically release matter with fluencies of approximately 3 x 10^{10} p.cm². Solar particles are superposed to the background radiation of galactic origin (galactic cosmic rays). During space extra-terrestrial exploration the most frequently detected charged particles are primary protons; their energy is around 1 MeV, with an almost constant flux in the energy range between 1 and 200 MeV (~ 3p. cm^{-2}. s^{-1}) [1]. The next group to be reckoned with are neutrons due to their disruptive effect on atomic and molecular structure; charge-less particles penetrate the materials producing primary knock-on atom (PKA) i.e., displacements caused by recoil. That occurs by an indirect mechanism following a given interaction in a matter such as elastic/inelastic scattering, capture process (n, γ); nuclear reactions e.g. (n, p), (n, α), (n, 2n), (n, f). Fast neutron scattering and nuclear reactions are dominating processes when their energy spectrum is above 1MeV. On the other hand, for slower energy regions, the neutron capture mechanism has a higher probability to take place [2]. Given the importance of neutron interaction with matter, a global neutron monitor network has been established [3].

High-energy protons or other high-energy charged particles (HEZ) from solar origin penetrate e.g., Si-wafers producing high-density ionization with characteristic Linear Energy Transfer (LET). The consequence is a Coulomb explosion taking place followed by large atomic arrays disruption. During the mechanism, low Z-nuclei such as, O, Al, and Si often are relocated to a different place from their original position, an effect that alters the matter property often referred to as radiation-induced damage [4].

That is a phenomenon of great importance for materials rich in silicon and silicon oxide-based electronic components conceived for interplanetary exploration. Specifically, we refer to the NASA (USA) Artemis ongoing mission. That is a program having the goal to establish a human settlement on the *Red Planet* Mars. The program starts setting up a sort of base camp, on the Moon, at the lunar south pole region by 2024. The plan is to facilitate manned space missions and at the same time will provide new experiences that could be convenient for the next step i.e., the colonization of Mars.

II RADIATION DOSE DURING AN INTERPLANETARY MISSION

The Artemis project is a continuation of the program named Apollo (Brother of Artemis in Greek mythology); to achieve this goal, several private space-related companies and international partners such as European Space Agency which includes the Hungarian Space Research Office, actively contribute to the NASA (USA) initiative.

Crewed spaceflight programs carried out in the past put in evidence that astronauts are exposed to a relatively high space radiation dose to the extent to be considered Worker's Occupationally Exposed to Ionizing radiation. During long-term spaceflight, doses in the range of 50-2,000 mSv have been reported. Worth to be noted that above 100 mSv radiation sickness and biological anomaly (cancer) are frequently observed.

The space radiation dose is considered so far one of the barriers against manned planetary missions. Before some practical solution can be applied to shield radiation, a robot system will be employed for the *Artemis* mission. The three-stage plan starts with phase 1 going back to the moon, with a command center heavily relying on massive electro-mechanical, communication, and computing systems.

During space flight and the permanence on the planet, electronic equipment must operate in a rather harsh radiation environment and cumulative adverse effects are expected. Reliability will be reduced by radiation damage of SiC or GaN power electronics and generally space electronics. Their active lifetime will shorten and under particular conditions for instance during solar flare higher electron-hole pairs will be formed [5] and [6]. The space radiation generated damage, in vital electronic components relying on Si-lattice, silicon dioxide, and other elements employed in insulators and casing, is one major obstacle with other, for future human safety, [7] and [8].

III Radiation effects and nuclear displacement damage

The most vulnerable components are based on semiconductor elements. The estimated radiation dose for electronic devices and insulation used in magnet coil is given by Liu et al [9] and matter simulating space suit as well as human elemental body compound [10].

The main issue is the total energy absorbed by matter that deteriorates electronic systems' performance. Since a mission time interval may be of several years, often it is convenient to carry out a test on electronics intended for space use by supplying high dose employing accelerators. The advantage of the method in a short time high dose rate values can be achieved for electronic components in the range of values between 0.5-3.0 Gy·s^{-1}. As an example, the technique could be applied to e.g., an electronic device based on SiO_2 with 6mm of Al radiation shield to obtain values corresponding to an average space mission (around 1MGy.a^{-1}).

The dose rate may increase considerably during solar events such as i.- proton rich Coronal Mass Ejections and ii.- heavy ion rich Impulsive Solar Flares. In both cases particles or heavy nuclei penetrating a transistor structure induce ions along their path; for illustration, we give a schematic representation of the phenomenon for a semiconductor substrate in fig.1.

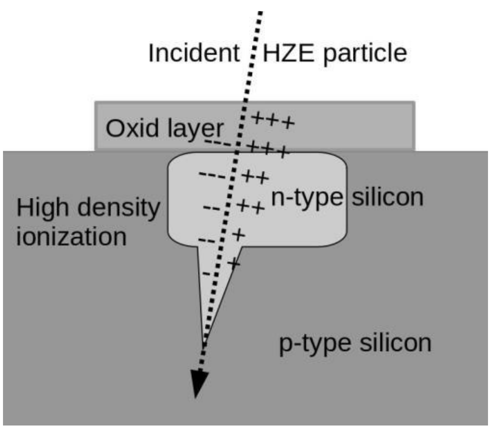

Fig.1 HEZ-particle track, indicated by the arrow, is where high-density Coulomb ionization is originating in a semiconductor layer.

Solar activities are related to a sporadic phenomenon where neutral particles originate by nuclear reaction with solar corona elements namely: protons, 3He, 4He, C, N, O, Ne, Mg, Si, and Fe. The first on the list, are precursors of solar flare neutrons are those that increase the probability to induce permanent failure in space electronics.

The targeted matter suffers both elemental and molecular modifications, that depend strongly on the neutron spectral energy. The latter is characterized by three energy regions namely thermal, fast, and between them an interval corresponding to resonances. This thought of a relatively small energy interval is the most damaging.

Thermal neutrons absorbed by an electronic device under power, induce often the so-called single event effect or SEE; a phenomenon produced mainly through two nuclear processes namely elastic and inelastic reactions.

In the latter cases, the n-type substrate suffers severe disruption in its atomic structure; reaction fragments release a large amount of energy in a short range (1-10^5 keV.μm^{-1}) as illustrated in fig. 2.

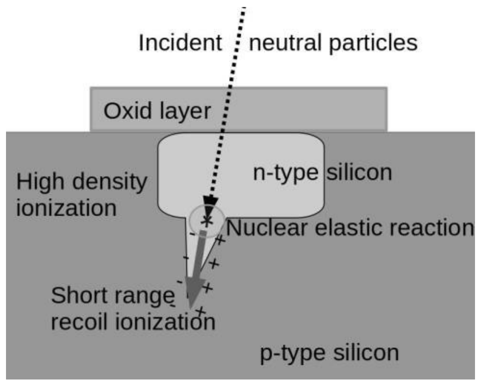

Fig.2. Schematic drawing showing atomic displacement by incoming neutrons; high LET particles are induced by a nuclear reaction (involving neutrons) or elastic scattering occurring in a transistor layer.

Another example is related to the element Boron (with isotopic composition of 80% 11B+20% 10B) often employed in the insulating layer. Thermal neutrons may induce a 10B binary reaction having a high transversal cross-section (3838[b]). The nuclear neutron capture mechanism follows two processes one of which is a gamma-less reaction:

$$n_{th} + {}^{10}B \Rightarrow$$

$$\begin{cases} {}^{7}Li + \alpha & E_{Li} = 1.01MeV;\ E_{\alpha} = 1.78MeV\ (6\%) \\ {}^{7}Li^{*} + \alpha + \gamma\,(0.48MeV) & E_{Li} = 0.84MeV;\ E_{\alpha} = 1.47MeV\ (94\%) \end{cases}$$

In these reactions, ${}^{7}Li$, ${}^{4}He$ fragments leave high ionization tracks (LET in silicon up to 1keV.μm^{-1}) moving in the opposite direction so that one of them probably alters the electronic device performance e.g., through SEE.

The other process that has a high impact is neutron scattering on Si atoms, SiO_2 molecule, or carbon nanotubes for space applications as given by Bohus et al. These are found in transistors, integrated circuits (IC), and generally in space electric devices.

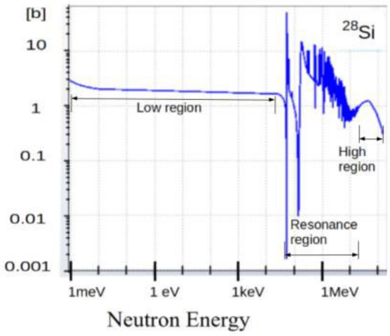

Fig.3. Scattering cross section for ^{28}Si selected for three neutron energy regions (data taken from: https://www.nndc.bnl.gov/sigma).

Neutrons depending on their translational energy, interact with different probability with ^{28}Si, (92.23%), ^{29}Si (4.67%), and ^{30}Si (3.10%) isotopes. The elastic transversal cross section is given in Fig. 3, to show the large variability in the function of the energy.

The most significant aspect is related to the resonance region where scattering cross section may change almost five orders of magnitude.

The displacement per atom (DPA) due to neutrons at the mentioned energy region may change in the same order of magnitude. In the case of ^{28}Si, the number of displacements per neutron collision could be high near a sensitive region to induce a single event upset (SEU). The accumulated effect related to neutron scattering correlates to the absorbed dose rate. A faulty circuit performance can be observed for a dose rate of 0.1 [mGy.s^{-1}]; Vibishna et al. [11], reported a type of SEU i.e., single-event effects impact on Avionic system and radiation-induced alteration on Si-rich electronic components e.g., FPGA in that a single HZE particle induces not at all or highly destructive and nondestructive damage.

Silicon technology today forms the basis of a worldwide, component industry. The reason for this expansion can be found not only in the physical properties of silicon but also in the unique properties of the silicon-silicon dioxide interface. However, silicon devices show a kind of instabilities that is related to crystal lattice structure (voids and clusters). In the case of exposure to an intense neutron or protons field the mentioned instabilities increases due to the occurring atomic displacement and the formation of new recombination centers. These through trapping of holes provide current leakage, loss of amplifier gains, and in deteriorate image quality camera sensors, (e.g., CCD and CMOS devices among others).

The major impact of data corruption, noise on images, and system shutdowns are on the reference stars' localization. Even a limited failure could be catastrophic from the crew safety point of view.

Depending on the Coulomb field intensities originating inside any electronic component the following cases are possible: Single Event Upset, Single Event Latchup, Single Event Gate rupture, and Single Event Out; the most disruptive of the mentioned, are the last two. These induce faulty responses leading to hardware or transitory failure even to the so-called ¨no fault found¨. The latter could be of gravity since under normal control that may go undetected.

IV NEUTRON DAMAGE BY WIGNER DISEASE

The neutron energy range during space missions is a relevant issue due to the radiation risk involved; the range is quite large since covers an interval of values between 0.1 and 200 MeV; relevant information on this subject is given in ref Palfalvi et al [12]. Any solid interacting neutron radiation can display atomic structure alteration known otherwise as the Wigner effect or Wigner's disease.

Silicon crystal and silicon oxide ionization energy are respectively 3.6 and 18.0 eV/ion pair. The corresponding number of ions produced by a charged particle along the penetration length of a few microns is between 2,8 x 10^4 and 11.1 x 10^6 ion pair. As mentioned, a high-intensity Coulomb field originates followed by rapid recombination that often results in a detriment of matter.

Watanabe et al. [24], have extensively studied neutron production (Solar Neutron Event) in connection to the Solar sudden outbreak. Lockwood [22], outlined space neutron existence and Lario [13] computed values for the total fluence of solar neutrons at energies: 1, 10, 100 and 1000 MeV and primary neutron fluence respectively 0.87; 0.72; 0.12 and 0.0013 x 10^6 neutrons cm^{-2}; The measured values are considerably higher due to secondary neutron-producing reactions; we mention the most important: (p; n), (p; pn), and (p; 2pn). As the solar flare protons escape, they have a non-zero probability to interact with nuclei such as ^{13}C, ^{15}N, ^{18}O, ^{22}Ne, ^{25,26}Mg, ^{29}Si, and ^{54}Fe.

Si atoms and SiO_2 structure under neutron exposure can be displaced from their original position as described by Eugene Wigner [14]; here we refer to it as Wigner's Disease (WD). The phenomenon originated from a neutral particle carrying kinetic energy above the threshold value of 25eV following an elastic scattering with Si-nuclei.

In a crystal structure, atoms are positioned a tetrahedral lattice from which they are displaced by the nuclear scattering mechanism. That could be a singular event or a cascade displacement in a silicon wafer depending on e.g. Solar flare neutron's energy.

The importance of the WD effect in semiconductors, microchip components, or highly packed transistors is highlighted through primary knock-on atoms PKA. If energy is available, then higher-order knock-ons; this process originates atom displacement (DPA) giving a measure on the radiation damage e.g., in silicon crystals by non-ionized field, [15]. The energy required to carry out the process values are given for some elements by [16] and [17]

To determine the DPA value an approximation given by Kinchin and Pease referred to as the K-P model is most conveniently applied [18]. Some assumptions make the basis of the model namely: pure elastic collisions between neutron and nuclei; there is a threshold energy E_d below that no atomic displacement is possible; annihilation process or radioactive decay does not intervene during lattice displacement. A schematic drawing of a DPA is given in Fig.4.

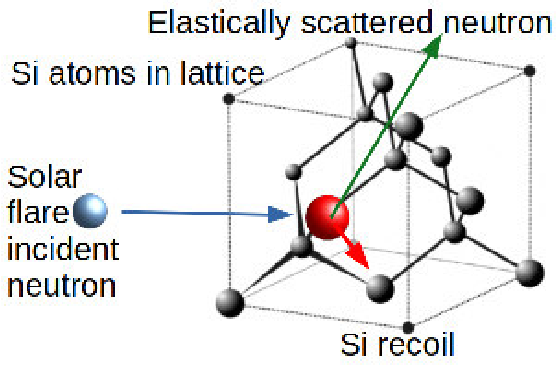

Fig.4. An artistic view of a neutron impinging onto a Si atom lattice. The small arrow indicates the atom recoil to occupy a new permanent site. The other two arrows show the impinging and the elastically scattered particle directions.

The damage rate equation Rd provides a value to quantify radiation damage in the unit time or DPA rate, by the following equation [17]:

$$R_d = N\int_{l}^{\infty} \varphi(E_n)\,dE_n \int_{E}^{\Lambda E_n} \sigma_d(E_n,E)\,\nu(E)\,dE$$

Where:

N= number of lattice atom density exposed to neutrons

$\sigma_d(E)$= microscopic scattering cross section [b]

$\phi(E_n)$ = particle fluence [n/cc-s]

$\nu(T)$ is the number of displaced atoms resulting from neutron scattering given by Kinchin and Pease, (or K-P model) as $E_n/2E_d$

E_n= incident neutron energy [MeV].

E_d= threshold Energy [ev], i.e., the threshold displacement energy that is the minimum kinetic energy necessary to displace an atom in a solid from its lattice site to the defect position.

To remove an atom or induce a displacement (DPA) in a lattice, a given amount of energy Ed is required to break electronic bonds. At the target surface, its value is lower than the Lattice Binding Energy since less atom surrounds each other; consequently, it is expected to have a larger number of DPA. Electronic components made of thinner layers (lower number of targeted atoms) would experience less damage.

From the theory of elastic scattering [17], we find that

$$\sigma_n(E_n,E) = \frac{\sigma_n^{el}(E_n)}{\Lambda E_n}$$

and as mentioned the elastic collision cross-section $\sigma_n^{el}(E_n)$ is neutron energy dependent, for light elements is almost constant for incident neutron energies up to 1 MeV, above that value, several resonance peaks dominate then again, the spectrum shows a constant value. Detailed information is given with specific values at international data libraries available at nuclear data centers [19].

The atomic mass parameter Λ is determined by the expression: $\Lambda=4A/(1+A)^2$. Since the isotopic effect has little influence on the parameter Λ, in this instance, we use the value of the naturally most abundant isotope mass.

Following arguments given in ref. [4 Ch.17], the coefficient, that provides the average number of displacements produced by a neutron of energy E, is determined by the compact expression: Λ.En/4Ed. The Ed defined above depends on the chemical elements. Its values, for some of those found in space electronic devices, are reported in Tab. 1

TABLE 1. MINIMUM ENERGY VALUES I.E., DISPLACEMENT THRESHOLD ENERGIES, ED FOR SOME CHEMICAL ELEMENTS OF CONCERN [20].

Element	C	O	Al	Si	Fe	Cu
E_d [MeV]	32	24	25	25	24	30

We understand that the Ed magnitude depends on several parameters such as the crystallographic direction [hkl], temperature, applied strain, and other factors, however, for convenience in Table 1 the average or effective value, is reported i.e. Ed = ave (Ed(θ,ϕ)), averaged over all lattice directions.

The neutron average energy and the solar flare-induced neutron flux are given respectively by the expressions:

$$\overline{E}_n = \frac{\int_0^{\infty} E_n \phi(E_n)\,dE_n}{\varphi} \qquad \Phi = \varphi t = t\int_0^{\infty} \phi(E_n)\,dE_n$$

where all variables have been already defined, except t, which is time [s]. Neutron spectra given by Hua et al [21], is used to determine the average neutron energy $E_{n,av}$ for three energy intervals < 5 ; 5-20; 100 MeV respectively as E_n=1; 5; 10; 50 MeV.

Watanabe [24] indicates a neutron flux on the Sun's surface is 690 x 10^{28} n.sr. This is a value that during a solar flare may increases considerably at least 35 times [22]. Considering the Moon's surface and the inverse square law the expected number of neutrons is around 1x10^{10} n.sr. Gorvacheva et al. [6] employing on board Resurs-DK1 satellite, reported on a single solar flare a neutron count rate of 660 n.sec^{-1}. This rather low counting rate is observed probably due to the existing radiation shielding.

V RESULTS AND DISCUSSION

Displaced atoms per neutron collision for the concerned elements are given in Table 2.

TABLE 2. DISPLACED ATOMS BY NEUTRON COLLISION FOR ENERGIES ABOVE ED / Λ [20]

Element	C	O	Al	Si	Fe	Cu
E_d / Λ [eV]	83	145	116	187	348	363
DPA/n 10^3	3.0	1.7	2.2	1.3	0.7	0.69

The specific displacement rate Rd per targeted element is determined by the expression (9) in its simplified form:

$$R_d = \frac{N \wedge \sigma^{el}}{4E_d}\,\overline{E}_n \phi$$

Where: N is the number of atoms/cm³; σel is the neutron elastic cross section on average for a given energy average Ẽn; Φ is the number of n.cm⁻².s⁻¹.

The threshold energy values change with the atomic reduced mass value as given in Fig. 5.

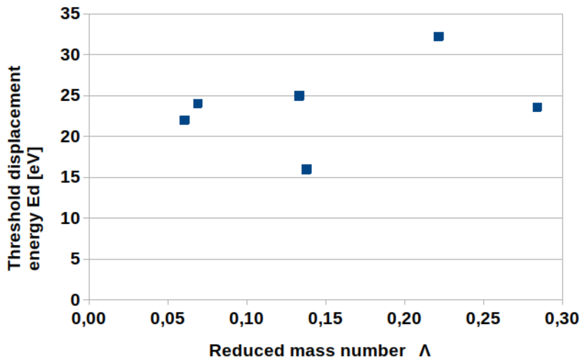

Fig. 5. Threshold energy variation in function of the coefficient Λ.

The Rd-values in units of [disp. cm^{-3}. s^{-1}] are given in Table 3 considering values already reported in the previous tables.

TABLE 3. COEFFICIENTS USED TO DETERMINE SPECIFIC DPA FOR NEUTRON AVERAGE OF 1 MEV AND A FLUENCE

	C	O	Al	Si	Fe	Cu
N at.cc $x10^{23}$	1.05	0.27	0,6	0.5	0.84	0.84
σ^{el} [b]	6	5	3	2	3	2
Φ [n.cm^{-2}]	10^{15}	10^{15}	10^{15}	10^{15}	10^{15}	10^{15}

Elastic reaction cross section values are reported in the literature, e.g. Konobeyev et al. [19], reported some for structural materials below 800 MeV.

TABLE 4. AVERAGE NEUTRON ENERGY AND NEUTRON FLUX Φ (EN) [N.CM^{-2}.S^{-1}] VALUES WERE USED IN THIS STUDY.

Parameter	Case 1	Case 2	Case 3	Case 4
E_n (MeV)	1	10	100	150
Φ (E_n)	10^7	10^8	10^9	10^{10}

For case 1, employing the equation and data provided by mentioned tables, the number of displaced atoms per cm^{-3} per unit time in [s] and the resulting DPA for a selected neutron flux is given in Table 5:

TABLE 5. NUMBER OF ATOMS DISPLACED FOR CASE 1 OF TAB.4 (EN=1MEV AND Φ (EN) = 10^7 [N.CM^{-2}. S^{-1}]

Displaced atoms	C	O	Al	Si	Fe	Cu
Rd (cm^{-3}.s^{-1}) $x10^8$	18	1.4	3.8	0.69	1.8	2.1
DPA (s^{-1}) $x10^{-15}$	18	8.6	6.5	2.7	2.2	1.4

In Fig. 5 The number of displacements per atom for the case when only solar flare neutrons are of concern, energy, and fluence values are respectively 1MeV and 10^9 [n .cm^{-2}.s^{-1}]. We may observe that the expected contribution to the total radiation damage is negligibly low.

On the other hand, a recent study [23] did show that solar flare protons interacting with solar matter produce a considerable number of neutrons. Solar protons observed during the solar event from August 4, 1972, had a fluence, in the energy range 10-100 [MeV], between 10^{+10} and 10^{+8} [p.cm^{-2}] observed during an average solar flare time interval of 2 days (172800 [s]). To illustrate the impact on space electronics we report in Fig. 6 that the DPA displaced atoms due to solar flare neutrons value for an extreme case when the flux is 10^9 n.cm^{-2}. s^{-1} and that due to proton interaction with solar matter (1,7 x 10^{10} n.cm^{-2}. s^{-1}).

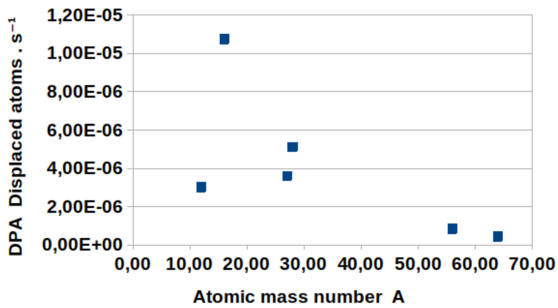

Fig.6 Neutron-induced displacement of some structural components employed in space electronics.

Figure 6, shows the general tendency for targeted matter; it is worthwhile to note that Si-atom (A=27) during solar flare will experiment approximately 10^{-6} displacements per second meaning that during exposure each atom suffers dislocation every 10^6[s] from its normal lattice site.

VI CONCLUSION

Space electronics during any mission can be exposed to the radiation dose of several kGy.a^{-1}. Primary and secondary neutrons originating in solar flare and those produced by primary protons (p,n) nuclear reaction taking place, could induce atomic displacement of high frequency defined by the DPA-value. The related damage induces SEE in space electronic components ending in permanent damage. In the case of components employed in IC with two or more processors for parallel computing, the solar flare neutron flux could be of such an intensity to displace every Si-atom in a few weeks compromising the device performance. Currently, the *Wigner effect* is one of the obstacles that burden long-term astronaut missions and space habitats

VII SUMMARY AND FURTHER RESEARCH

Space electronic devices are exposed to radiation-induced damage due displacement of lattice atoms. The impact is related to the single-event effect process. Ionizing dose absorbed enhances the mechanism disrupting the electronic component response. An interplanetary journey could take several years during that time the space electronic devices could be exposed to solar flare neutrons. In the case of exposure, this study pointed out that in the extreme case the impact is negligible. That is in opposition to results when solar flare protons induce (p, xn) reactions with solar matter-producing reactions are included. In fact, the secondary neutron flux can be considerably high to the extent that almost weekly every single Si-atom suffers site displacement referred to as *Wigner disease*. The annealing provides a recovery process often unsuccessful to re-establish the original structure with an outcome of deteriorating effect on the space electronic performance. To reduce radiation damage in the matter, shielding is devised. Some new mitigation strategies such as manufacturing smaller components and 3D circuits could be the solution for long-term space human exploration.

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