Protection of the electronic components of measuring equipment from the X-ray radiation

N O Perez Vasquez, D K Kostrin and A A Uhov
Department of electronic instruments and devices, Saint Petersburg Electrotechnical University “LETI”, 197376, Saint Petersburg, Russia
E-mail: dkkostrin@mail.ru

Abstract. In this work the effect of X-ray radiation on the operation of integrated circuits of the measurement equipment is discussed. The results of the calculations of a shielding system, allowing using integrated circuits with a high degree of integration in the vicinity of the X-ray source, are shown. The results of the verification of two measurement devices that was used for more than five years in the facility for training and testing of X-ray tubes are presented.

When X-ray or γ-ray radiation passes through a substance part of their energy is absorbed by the material, resulting in ionization of atoms of this substance. Thus X-ray radiation is one of the types of the ionizing radiation [1]. The ionizing radiation leads to changes in properties of matter due to the violations of their structure (breaking of chemical bonds, formation of free radicals, coloration, etc.).

The dominant mechanism of action of the pulsed ionizing radiation on the semiconductor devices and integrated circuits (ICs) is the volumetric ionization of semiconductor regions, i.e. the generation in them of nonequilibrium electron–hole pairs. Diffusion and drift of the generated by the radiation nonequilibrium charge carriers results in the temporary or permanent changes in the device parameters, which may lead to the device malfunction [2]. The ionization reaction is defined by the primary and secondary volumetric ionization effects that occur under the exposure to pulsed radiation.

Primary volumetric ionization effects occur due to the ionization of the different areas of IC and the associated short-term (commensurate in duration with working times) changes in the parameters of the devices. Secondary ionization effects are determined by reaction of the irradiated object to the ionization (increase of the ionization current, “latch-up” effect, induced secondary breakdown, etc.) and can have a long-term character.

The dominant mechanisms of failure in the CMOS ICs are connected with ionization effects. Surface ionization effects are mainly related to the accumulation of charges in thin layers of the passivating dielectric under the gate electrode and at the interface of Si/SiO₂. These effects are dominant when exposed to a stationary ionizing radiation (gamma, X-ray and electronic).

Of particular interest is the impact of ionizing radiation on operational amplifiers (op-amps), because they are the electronic components necessary to create measuring devices. Impact of the ionization effects is primarily in the form of a significant increase in the leakage and channel currents, which leads to an increase of input offset and shift currents.

Specialized operational amplifiers, including circuits with high input impedance, precision micropower op-amps and high-speed amplifiers, are usually more sensitive to residual radiation effects, as circuit design and technological measures used to achieve extreme performance for any
parameters usually reduce their radiation resistance. The best option to work under the influence of the ionizing radiation is the elements with low and medium degree of integration, based on analog or combinational elements. If there is a need to use microcontroller (μC) and other complex ICs (such as analog-to-digital converter or ADC) it is required to take additional precautions, since information stored in their memory is under a threat of removal.

Current converter must operate in conditions where, depending on the type of the X-ray tube, the maximum quantum energy does not exceed 320 keV [3]. Device protection can be a screen of iron and lead, which is simultaneously the housing of the device. The casing is a metal shell made of stainless steel with a wall thickness of 0.5 mm, in which the batteries and lead boxing, where a PCB with ICs is mounted, are placed (figure 1). The box is made of lead plates with a thickness of about 5–6 mm.

The calculation showing the degree of attenuation of radiation was made for the X-ray tube with anode made of tungsten for the maximum operating current of 50 mA. Calculations were made on the basis of developed in SPbETU “LETI” techniques [4] with the help of Mathcad software (figures 2, 3). It was assumed that X-rays must pass through: beryllium window, air, iron filter and lead filter before irradiating the ICs, μC and ADC.

![Figure 1. Protective housing of the current converter.](image)

**Figure 1.** Protective housing of the current converter.

![Figure 2.](image)

**Figure 2.** Spectra of a braking X-ray radiation: before (dashed line) and after (solid line) the steel filter.

![Figure 3.](image)

**Figure 3.** Spectrum of a braking X-ray radiation after the lead filter with thickness of 5 mm.
The calculation was carried out using expressions describing the spectrum of a braking X-ray radiation according to the formula of Kramers [5] taking into account attenuation in: target of the X-ray tube, exhaust (beryllium) window, two filters, installed on the beam path in the air gap between the tube and the detector. Graphs of the received functions are displayed in figures 2, 3.

From calculations it can be seen that the layer of steel attenuates X-ray radiation by about 2.5 times, but only the radiation with quantum energy less than 50 keV is attenuated. Hard radiation is almost completely not absorbed in the metal layer.

Figure 3 shows spectrum of a braking X-ray radiation passed through the two screens – made of steel and lead. The graph shows that ionizing radiation is almost completely absorbed in a lead filter with a thickness of 5 mm. Calculation shows that the radiation passing through the lead filter is weakened by $1.636 \times 10^5$ times, and the total absorption coefficient of two filters is $4.107 \times 10^5$.

Thus, this X-ray equipment can cause damage to the conversion module, so the measures of protection against the ionizing radiation confirm its necessity. The harm that may cause the ionizing radiation is the increase in the generation currents, which can lead to undesirable errors, growth of the space charge in thick SiO$_2$ layers, which can lead to increased power consumption, and various kinds of spurious connections between the internal cells of integrated circuits.

During the calculation was made assumption that the metal plates (filters) are directly placed in the path of the X-ray beam. In fact, they are not, and the microammeter stands apart from the main beam of radiation, so the device gets even fewer quanta of radiation and, accordingly, there will be less absorbed radiation (figure 4).

![Figure 4](image-url)

**Figure 4.** Placement of the measuring devices and X-ray tubes in the test chamber.

When training X-ray tubes for the medical diagnosis of BD-150 series with a rotating anode in the CJSC “Svetlana-X-Ray” is used a pulsed high voltage power supply, assembled on a three-phase bridge rectification circuit [6]. On the trained X-ray tube voltage pulses with amplitude from 10 to 250 kV are provided with the duration from 10 ms to 10 s. Under these conditions, the amplitude of the X-ray tube current can vary from 5 to 500 mA and the potential at which the measuring circuit is located can be up to 250 kV.

Analysis of the factors determining the total error of the developed measuring devices under the stable external conditions showed that theoretically the relative error of measurement may be below 1 %. After five years of operation of these devices under the influence of the high voltage electric field and X-ray radiation a test was conducted to check the amplitude transmission characteristics of the developed ammeters (figure 5).
Figure 5. Test results for two measuring devices after 5 years of operation.

As the result, it was found that the measurement error after 5 years of operation have deteriorated to 5 % at the end of the conversion scale, that is still acceptable during training of the X-ray tubes. As can be seen from figure 5 response of the instrument retained after 5 years of operation its linearity and only a small change in the angle of inclination of the characteristics can be seen, which can be easily fixed by adjusting the calibration constants.

References
[1] Shirshev L G 1969 Ionizing radiation and electronics (Moscow: Sovetskoe radio)
[2] Vavilov V S and Uhin N A 1969 Radiation effects in semiconductors and semiconductor devices (Moscow: Atomizdat)
[3] Perez Vasquez N O, Kostrin D K and Uhoff A A 2017 Journal of Physics: Conference Series 808 012007
[4] Lukianchenko E M and Gryaznov A Yu 2003 Proceedings of SPb ETU “LETI” 8 10–4
[5] Kliuev V V 1993 X-ray technique (Moscow: Nauka)
[6] Bystrov Yu A, Kostrin D K, Peres Waskes N O and Ukhov A A 2013 Biotechnosphere 4 60–4