Radiation hardness improvement of analog front-end microelectronic devices for particle accelerator

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Abstract. Series of schematic techniques for increasing radiation hardness of the current mirrors is developed. These techniques can be used for the design of analog front-end microelectronic devices based on the operational amplifiers. The circuit simulation of radiation degradation of current transmission coefficients was performed for various circuit solutions in LTSpice software.

1. Introduction

The analog front-end microelectronic devices are widely used in modern accelerators technology [1]. For experimental physics research in nuclear physics, it is necessary to use particle accelerators and detectors for particle flow registration. The analog front-end microelectronic devices are a part of the ionizing radiation detector which forms the current signal. It enables to measure the energy and pulse of charged particle. Primary signal gain, usually, are carried out using the operational amplifier. Location of the electronic functional units based on operational amplifiers in the zone of ionizing radiation impact requires the use of radiation-hardened electronic components.

Radiation degradation of integrated circuits (ICs) is the result of the accumulation of positive charge in silicon dioxide and interface trap buildup at the Si/SiO2 interface over the passive base region of the semiconductor structure during irradiation. It leads to a change of threshold voltages of MOS-structures and to decrease of the current gain of bipolar transistors [2]. As the result, there are arise functional and parametric failures of electronic equipment under ionizing radiation impact.

One of the basics elements in operational amplifier schematic is a current mirror, which usually consist of bipolar transistors susceptible to radiation degradation of the current gain [3]. Therefore, there is the dependence of the current transmission coefficient on the total absorbed dose. It leads to radiation drift of input electrical parameters of operational amplifiers, such as input current and offset voltage. The increase of radiation hardness of the current mirrors will improve the reliability of electronic equipment, which includes the operational amplifiers. Currently, there is series of schematic and topological techniques for radiation hardness increase of bipolar transistors, such as additional implantation of dopant in subsurface areas of the semiconductor structure and the use of protective rings. For the implementation of these methods, it is necessary to complicate the technological process additionally. This complication leads to degradation of electrical parameters of semiconductor devices. In this work the schematic techniques, which will increase the radiation hardness of current mirrors of bipolar transistors without technology complication and deterioration of ICs parameters, are presented. The proposed methods are based on the use of radiation drift compensation circuit in current mirrors outputs.

2. Bipolar transistor radiation degradation model

For the schematic techniques development to radiation hardness increase of current mirror circuits, it is necessary to understand the physical mechanism of radiation degradation of bipolar transistors under irradiation. At the Si/SiO$_2$ interface over the passive base region, occurs buildup of interface traps, which acts as recombination centers. As the result, the surface recombination rate increases. It leads to an increase of recombination component of the base current and to rising of charge carrier injection from the lateral emitter surface to passive base region. The above process does not affect the collector current. This process is controlled by the gradient of concentration of the minority charge carriers in the base active areas along the way from the emitter to collector. This mechanism shows that ionizing radiation leads to increase of base and emitter currents, without affecting the collector current. The irradiation of bipolar p-n-p transistors 2N2907 was performed by Co-60 isotope to validate this conclusion [4]. Transistors samples were irradiated at room temperature (25 ± 2 °C) to total dose 72 krad (SiO$_2$), the dose rate was 10 rad(SiO$_2$)/s. The dependences of the collector current, base current and static transistor gain on the emitter-base voltage are presented in Fig.1 and Fig.2.
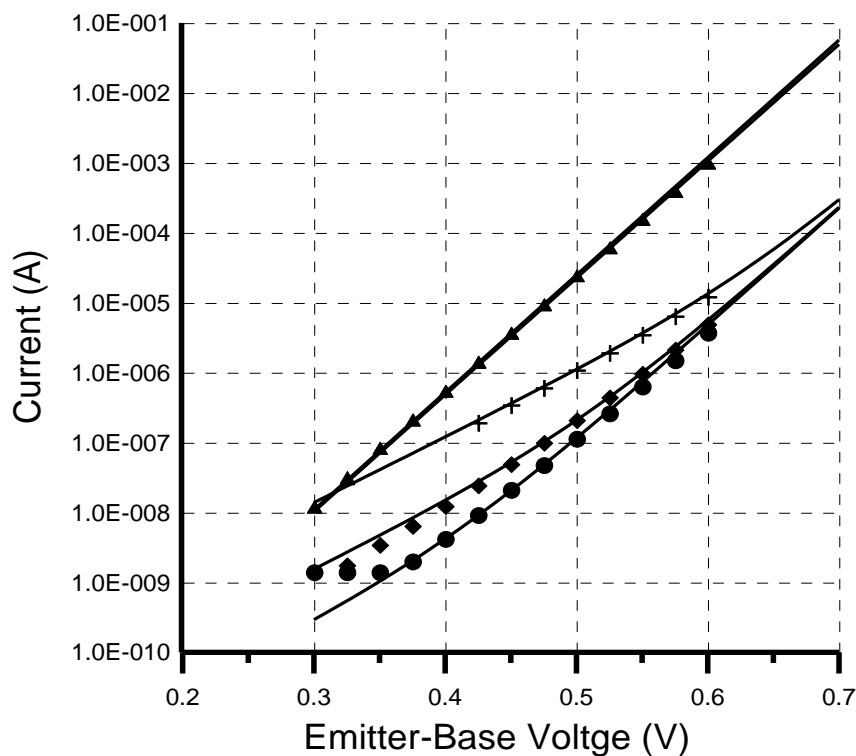

Figure 1. Experimental and theoretical (solid curve) dependences of the base current on the emitter-base voltage for 2N2907 transistor before irradiation (●) and for various doses (12 krad(Si) – (♦), 72 krad(Si) – (+)); the dependence of the collector current on the emitter-base voltage before and after irradiation (▲).

From the data, it is clear, that collector current remains practically constant during irradiation, while the gain degradation, which is determined by a base current increase. Analysis of experimental data also shows that the base current depends on total ionizing dose approximately linearly at a fixed emitter-base voltage. Since the base current does not change significantly, the reciprocal value of static gain $1/B = I_b/I_c$ is directly proportional to the total ionizing dose and can be used in modeling for comparative evaluation of various schematic techniques radiation hardness.

3. Comparative analysis of radiation hardness of the current mirrors on bipolar transistors

The circuit of the current mirror is presented in Fig. 3a. This circuit is a simple current source on bipolar transistors. This circuit has low output resistance. It connected with the Early effect in

the transistor (T2). Cascode circuit in the current mirror presented in Fig. 3b. It enables to increase the output resistance and to suppress Early effect.
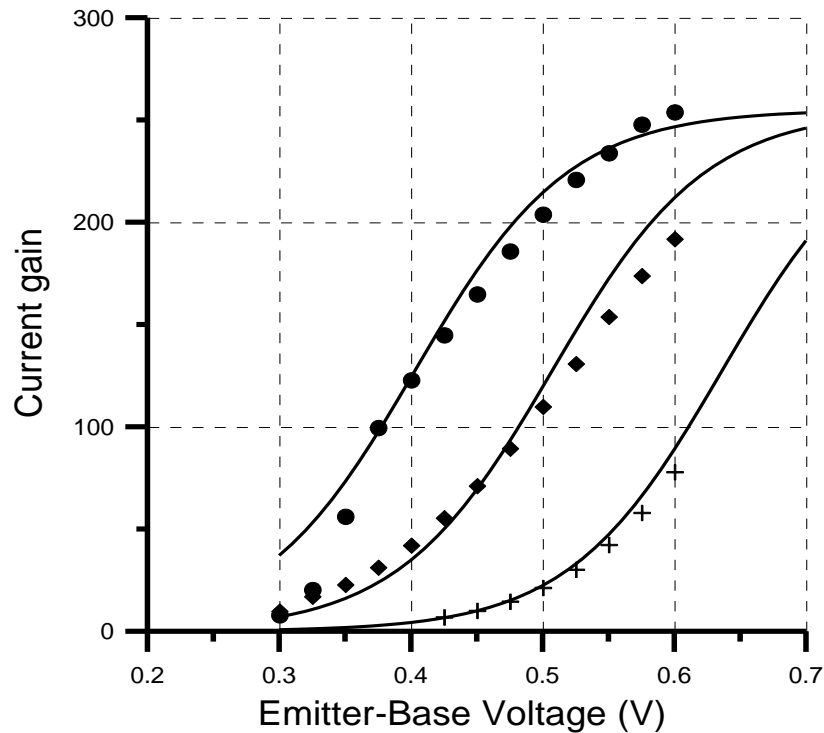
Figure 2. The dependence of the static gain of the transistor on the emitter-base voltage before irradiation (●) and various doses (12 krad(Si) – (♦), 72 krad(Si) – (+)) [4].

Circuit simulation of radiation degradation of the current transmission coefficients of simple and cascode circuits was performed in LTSpice IV, assuming that the reciprocal value of the static current gain of bipolar transistors is proportional directly with total ionizing dose during irradiation. The simulation results are presented in Fig.4.
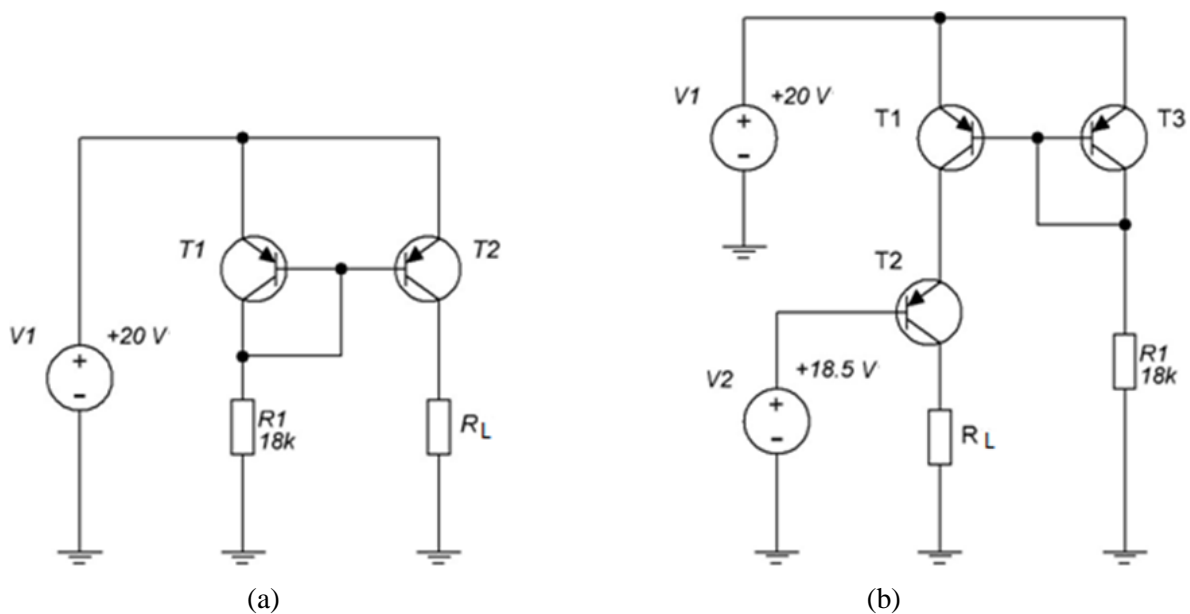
(a)   (b)

Figure 3. Simple (a) and the cascode (b) circuit of current mirror.
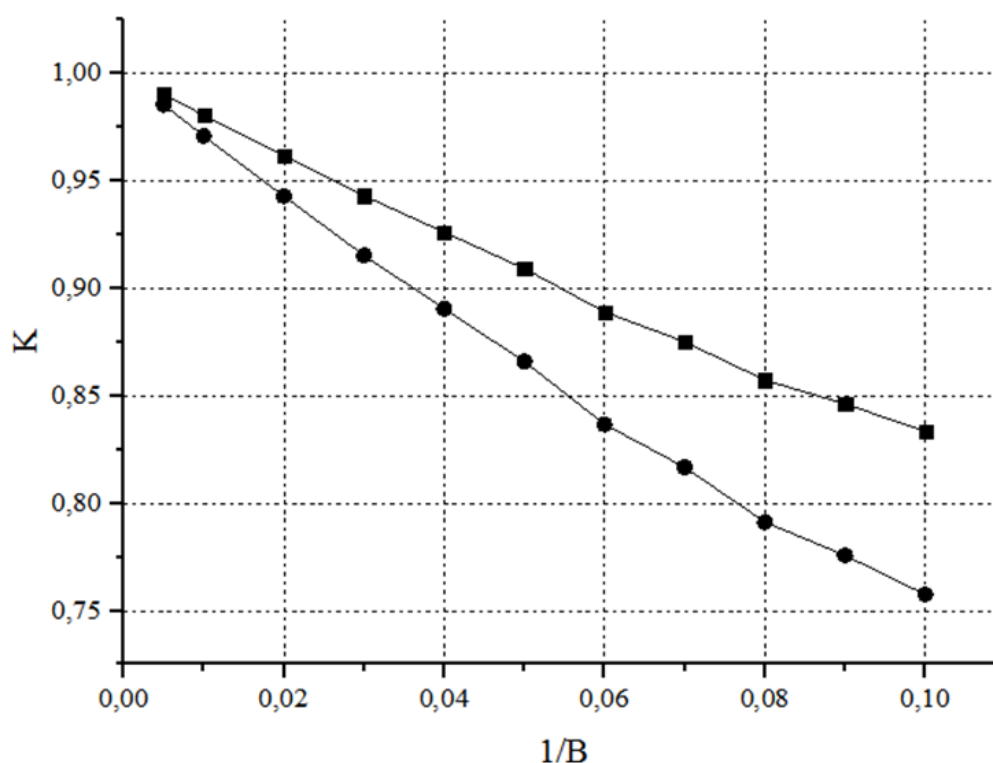
Figure 4. The dependence of the current transmission coefficients of simple (—■—) and cascode (—●—) circuits of current mirror on the reciprocal value of static gain of bipolar transistors.

From the data, it is clear, that the degradation of input current in cascode circuit is faster than in simple circuit. Assuming that a parametric failure of the devices occurs if the current transmission coefficients differ from 1.0 by more than 10% ($K = 0.9$), we can obtain that the parametric failure of cascode circuit occurs at total dose level which is lower by 1.54 times that in simple current mirror circuit. The decreasing of failure total dose level is connected with the degradation of the emitter current transmission coefficient of transistor T2 (Fig. 3b).

To increase the radiation hardness of cascode circuit without losing its advantages, including the high output resistance, the circuit of a current mirror which presented in Fig.5, can be used. The circuit simulation results of the dependence of the current transmission coefficient on the reciprocal value of the static current gain of bipolar transistors for the radiation hardened circuit, and traditional cascod circuits are presented in Fig.6. From the data, it is clear, that the improved circuit of the current mirror enables to increase the radiation hardness by 1.54 times. The radiation hardness is increased by the compensation of the collector current decrease of transistor T2 using a base current of transistor T4. The emitter current of transistor T4 is fixed by the circuit of a current source which includes transistors T1, T3 and resistor R1.

The values of output resistance for all the schematic techniques of current mirrors, which were described above, were obtained by the circuit simulation. The values of output resistance and critical reciprocal value of static gain, which corresponds to parametric failures of bipolar transistors, are presented in Table 1. From the data, it is clear, that the improved circuit of cascode current mirror is more radiation-hardened than the traditional cascode circuit of the current mirror. Nevertheless, the improved circuit of cascode current mirror has significantly less output resistance than traditional cascode circuit of the current mirror.
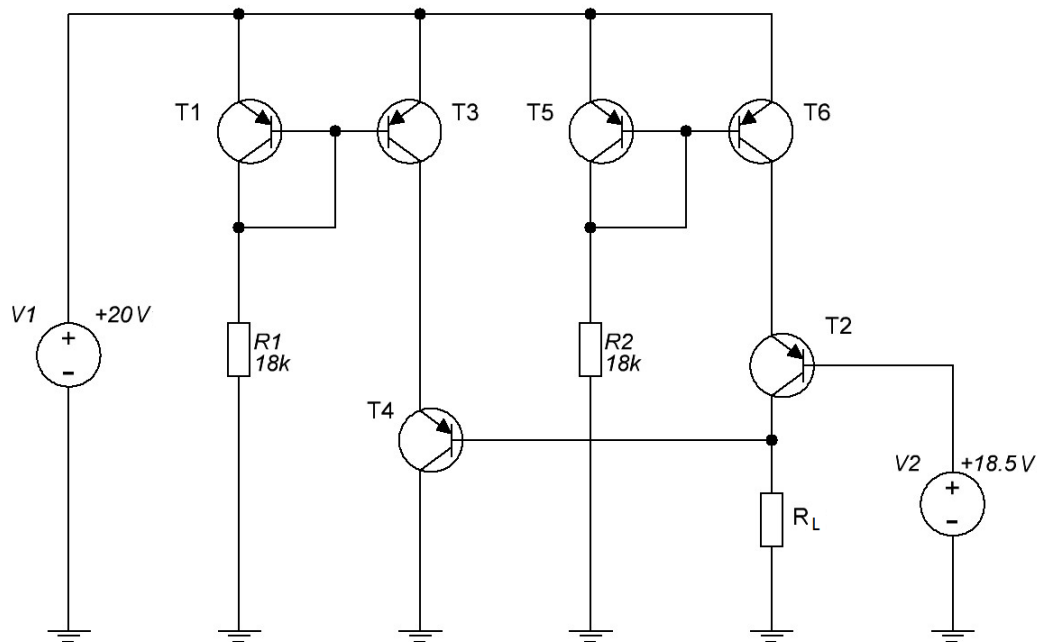
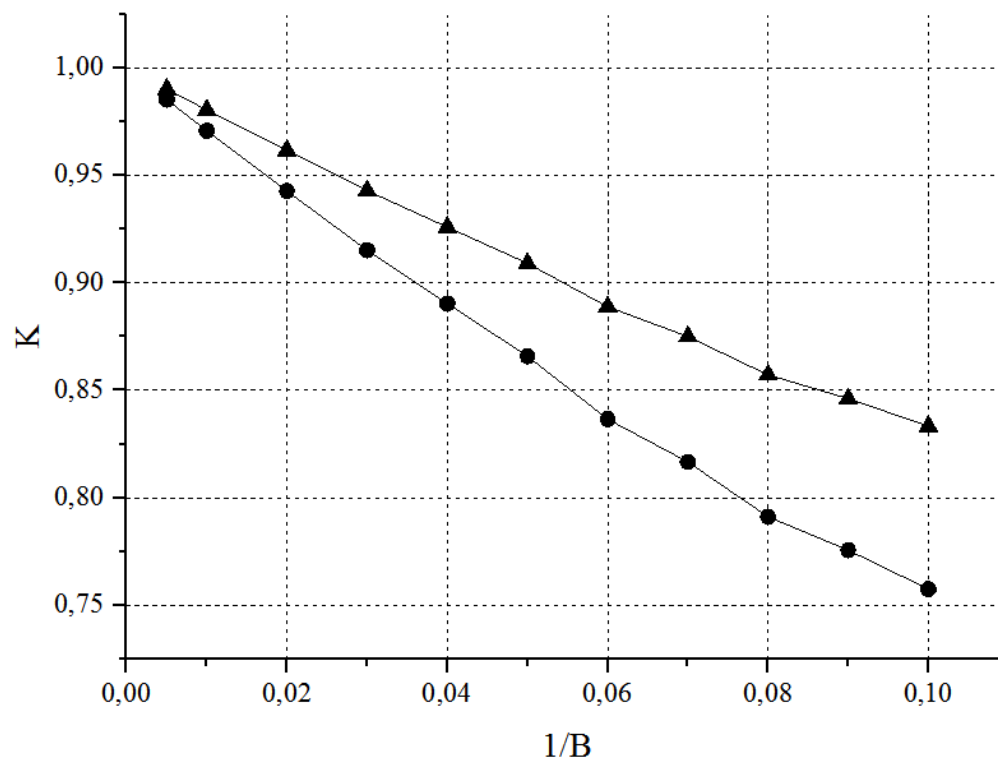**Figure 5.** The radiation-hardened cascode circuit of current mirror.

Figure 6. The dependence of current transmission coefficient of the radiation-hardened circuit (——▲——) and the traditional cascode circuit (——●——) on the reciprocal value of static gain of bipolar transistors (circuit modeling results)

Table 1. The characteristics of simple, traditional cascode and radiation-hardened circuits of current mirrors

	Simple circuit of current mirror	Traditional cascode circuit of current mirror	Radiation-hardened circuit of current mirror
Output resistance	100kOhm	5 MOhm	2 MOhm
$(1/B)_{critical}$	0,054	0,035	0,054

4. Conclusion

Based on the physical model of radiation degradation of the bipolar transistor and experimental data showing that the reciprocal value of static current gain is proportional directly to the total ionizing dose, a comparative analysis was performed for the various schematic techniques of current mirrors by the use of this statement during circuit simulation in LTSpice.

The circuit simulation enables us to estimate the value of the output resistance for each of the considered circuits. The improved circuit of cascode current mirror has less output resistance than traditional cascode circuit of the current mirror. The improved circuit of cascode current mirror is more radiation-hardened than the traditional cascode circuit of the current mirror.

Therefore, these techniques will potentially enable to increase the operation time of electronics in conditions of ionizing radiation impact.

References
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