Radiation Physics and Chemistry 131 (2017) 100–104

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Radiation and annealing effects on integrated bipolar Operational Amplifier

J. Assaf

Atomic Energy Commission, P.O. Box 6091, Damascus, Syria

ARTICLE INFO

Keywords:
Radiation effect
Operational Amplifier
Frequency response
Thermal annealing

ABSTRACT

Integrated bipolar Operational Amplifier (op-amp) type μA 741 was irradiated with neutrons and gamma rays. The radiation on gain factors, slew rate, and power supply current have been evaluated. The experimental results show a decrease of these parameter values after exposing to the radiation. The advantage of the increase of the voltage power supplies and the thermal annealing treatment on the damaged parameters was also explored. The relationship among different frequency response parameters is also studied leading to an analytical formula for the above degraded parameters.

1. Introduction

Bipolar electronics components either in discrete or integrated are well known for their highly sensitive to nuclear radiation (Enlow et al., 1992; Xingji et al., 2009; Assaf et al., 2014; Pien et al., 2010; Ke, 2015; Johnston et al., 1994; Luiz, et al., 2009).

This property is especially important for the integrated op-amps because of their complex internal structure and wide use in electronics instrumentation. The main element in the structure of bipolar op-amps is the bipolar junction transistor(BJT). The radiation effect on BJT is presented mainly by a large drop of the current gain h_{FE} (Xingji et al., 2009; Assaf et al., 2014; Pien et al., 2010). In view of their excellent overall characteristics, the commercial 741-series of bipolar op-amp are widely used in many applications in the electronic systems. Thus, the design of this op-amp type has rapidly become the standard of many related designs (Pien et al., 2010; Rashid, 1999; Tabish, 2005; Gautam, 2012). Special radiation hardness components are usually expensive, whereas commercial components suffer from radiation effects. Accurate study of these effects could result in better design regarding the radiation resistivity and consequently reduction of the device costs. Considerable works are available about the radiation effects on the op-amp DC parameters. However, there appears little studies related to AC properties of op-amp in general, and particularly for 741 type. Despite irradiation damages to the devices, there is a chance to restore some of original parameters. The op-amp recovery effect is mainly referred to the recovering of op-amp composed transistors. This work aims to improve understanding the mechanism of degradation related to two types of radiation on the 741 op-amp frequency behavior. It will focus on the study of the impact of ionization and displacement effects resulted from gamma rays and neutrons, respectively. Experimental results about the recovery by thermal annealing have been also achieved.

2. Op-amp characteristics

2.1. Structure of op-amp

Schematic simplified configuration of a typical op-amp is shown in Fig. 1, which consists in three main stages: input, gain and output, and two external inputs v_{I1} and v_{I2}. These stages have not coupled or bypassed by capacitors, but a compensation capacitor C_x is normally connected across the second stage in order to maintain frequency stability of the op-amp, where frequency parameters are mainly related to the properties of the input stage including the Miller effect of C_x (Rashid,1999; Bernard et al., 2008; Franco et. al., 2005). Another important parameter is the final DC biasing currents I_Q known also as the tail current.

2.2. Parameters of frequency response

The frequency behavior of op-amp is described by two main parameters: frequency response gains and slew rate. The gain of op-amp is defined as the ratio between the output amplitude signal V_{out} and the input amplitude signal V_{in}. Two types of gain are classified: open loop gain(OLG) and closed loop gain (CLG). Most of frequency response of op-amp is based on one dominate pole model. According to this model, an op-amp is just a differential amplifier having an OLG response given by the Eq. (1) (Rashid,1999; Franco et. al., 2005).

$$A(f) = \frac{A_0}{1 + j\frac{f}{f_{CA}}} \quad (1)$$

where A_0 and f_{CA} are the DC gain and the cut-off frequency at −3 dB

E-mail address: pscientific@aec.org.sy.

http://dx.doi.org/10.1016/j.radphyschem.2016.11.002
Received 24 July 2016; Received in revised form 3 November 2016; Accepted 7 November 2016
Available online 11 November 2016
0969-806X/

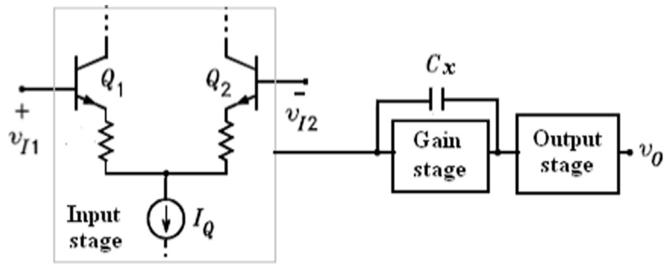

Fig. 1. Simplified schematic configuration shown the main stages of a typical op-amp.

gain, respectively. The CLG response *G*(*f*) has also one cut-off frequency f_{CG} and DC gain G_O, where A_0»G_O and f_{CA}»f_{CG}. The frequencies f_{CA} and f_{CG} determine also the bandwidth of *A(f)* and *G(f)*, respectively. Both *G*(*f*) and *A*(*f*) have the same cut-off frequency f_u at 0 dB gain, where f_u is defined then as the gain-bandwidth product. Since, f_u is corresponding to the unity gain, the following equality can be expressed: $f_u = G_0 \times f_{CG} = A_0 \times f_{CA}$. For a typical Bipolar op-amp, the relationship between f_u, I_Q and C_x is presented by the Eq. (2) (Enlow et al., 1992; Rashid,1999):

$$f_u = \frac{I_Q}{4\pi V_T C_x} \quad (2)$$

Concerning the slew rate (S_R), it specifies the maximum rate of the output signal can be changed when a large signal is applied on the differential input, that is $S_R = (\partial v_{out}/\partial t)_{Max}$. In fact, S_R is limited by the maximum current transferred from input stage to gain stage to get charged C_x (I_Q in Fig. 1). In other word, C_x is charged and discharged by I_Q. Thus, S_R is described as the ratio given by the Eq. (3) (Rashid,1999; Franco et. al., 2005).

$$S_R = \frac{I_Q}{C_x} \quad (3)$$

As a results from the above presentation, all of *A(f)*, *G(f)*, S_R, and f_u are directly linked to the value of the current I_Q.

3. Irradiation facilities and tests procedure

Many samples of μA741 chips have been irradiated. Only those chips exhibiting similar behavior were considered, and their results are presented. The tested chips were exposed to gamma rays from a gamma irradiation cell (Co-60), and to neutrons inside a reactor miniature neutrons source reactor (MNSR). This reactor is classified as a thermal neutron reactor, with a maximum flux about of 1×10^{12} neutrons s^{-1} cm^2. Moreover, neutrons with higher energy and associated fission gamma rays were also present.

The test measurements of this work was carried-out by the following setup: pulse generator, power supply unit, and a storage digital Oscilloscope. The op-amp circuit is built as a typical inverting amplifier circuit. The measurement of *G(f)* was achieved by injection a sinusoidal signal of V_{in}=500 mV on the inverting input of the op-amp. The V_{out} was measured for the frequency range from 10 Hz to 1 MHz, where V_{out} decreases by increasing the frequency. Thus, the *G(f)* curve was obtained by calculation the ratio (V_{out}/V_{in}), and G_O was equal to 8.4. The frequency f_u is calculated then as $f_u = G_0 \times f_{cG}$. However, it is difficult to measure directly the OLG parameters. Where f_{CA} can be obtained from the specific data sheet, and A_0 is then deduced as A_0=f_u/f_{CA}.

The slew rate is normally defined for large signal, its measurement process is accomplished by the following steps: a- the V_{in} is increased at low frequency to a maximum value before the V_{out} to be saturated, b- the amplitudes V_{in} and V_{out} are maintained fix, while the frequency is increased slowly until the V_{out} starts to have a slewed shape, and c- the output signal rise time (in μs) and its amplitude (in Volt) are measured at this time, the ratio between them (in V/μs) is then calculated which equals to S_R.

Most of experimental tests were carried-out using voltages power supply (VPS) equal to ± 5 V (+V_{CC} and −V_{EE}), which is compatible with the Transistor-Transistor Logic (TTL) standard circuits.

4. Results and discussion

During presentation the results and for a single radiation type, the dose is precisely indicated: either by gamma source dose in kGy, or by irradiation times in seconds inside the reactor. While in case of presentation of two radiation types (two curves on the same figure), the “Dose" in kGy represents either the direct measured of gamma source dose, or the total equivalent dose resulted from irradiation inside the reactor *i.e* the conversion from the irradiation times to kGy. Results based on a previous modeling of similar transistors structure and MNSR have been used to calculate this equivalent dose (Assaf et al., 2014). According to this results, the total dose in Gy is equaled to the irradiation time in seconds multiplied by a factor of 20.824 Gy.

4.1. Radiation effect on gain and slew rate

The results of two responses for *G(f)* of non irradiated (pre-rad.) samples and irradiated samples with gamma rays source and neutrons were compared and presented in Fig. 2a and b, respectively. As it is shown, some *G(f)* response parameters such as the frequency f_u have been changed after irradiation. This frequency is corresponding to

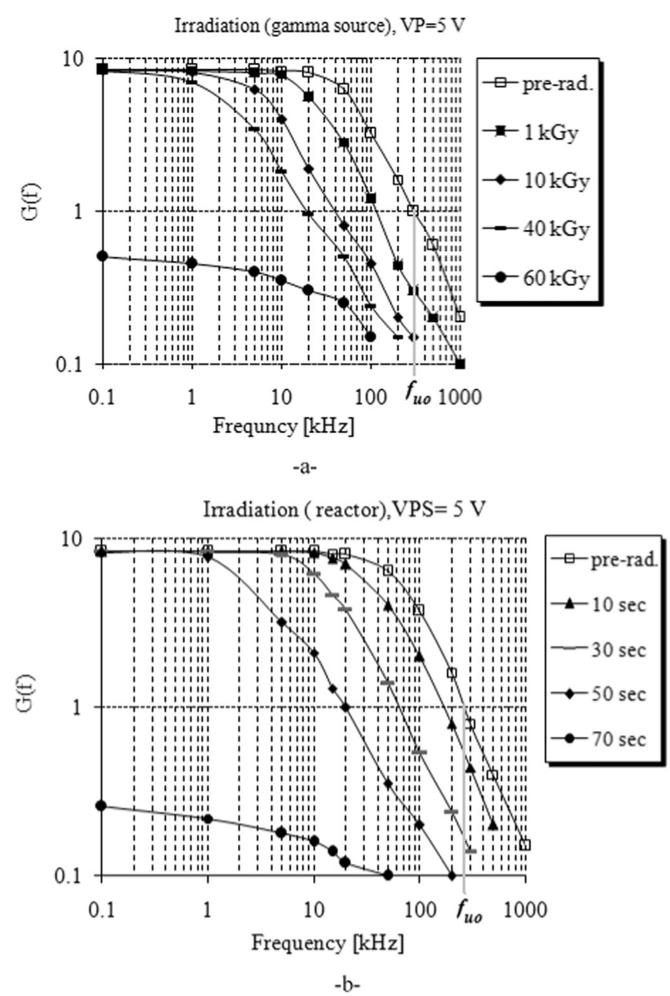

Fig. 2. Comparison of the *G(f)* response before irradiation (pre-rad.) with the responses after irradiation by (a) gamma rays source for several doses, and (b) inside the neutrons reactor during different irradiation time.