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Original Article

Studying the operation of MOSFET RC-phase shift oscillator under different environmental conditions

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ABSTRACT

The present work was mainly concerned with studying the operation of RC-phase shift oscillator based on MOSFET type 2N6660 under the influence of different temperature levels ranging from room temperature (25 °C) up-to135 °C and gamma-irradiation up-to 3.5 kGy. In this concern, both the static (I–V) characteristic curves of MOSFET devices and the output signal of the proposed oscillator were recorded under ascending levels of both temperature and gamma-irradiation. From which, it is clearly shown that the drain current was decreased from 0.22 A, measured at 25 °C, down to 0.163 A, at 135 °C. On the other hand, its value was increased up-to 0.49 A, whenever the device was exposed to gamma-rays dose of 3.5 kGy. Considering RC-phase shift oscillator, the oscillation frequency and output pk-pk voltage were decreased whenever MOSFET device exposed to gamma radiation by ratio 54.9 and 91%, respectively. While, whenever MOSFET device exposed to temperature the previously mentioned parameters were shown to be decreased by ratio 2.07 and 46.2%.

1. Introduction

Oscillator circuits have been invented and employed industrially worldwide. Where, sinusoidal oscillators have been an active area of research in the analog electronics field, from which airborne and ground field gamma-ray surveying systems for nuclear raw materials detection. Besides, modern electronic communication systems use sinusoidal oscillators, find their applications in the most frequently used electronic sub-circuits like TV receivers, biomedical instruments, radar cell phone and so on [1–3]. In this concern, the present paper is a trial to shed further light on studying the operation of sinusoidal RC-phase shift oscillator based on MOSFET under the influence of different temperatures up to 135 °C, where according the device data sheet the device operating from −55 to 150 °C [4] and gamma-irradiation up to 3.5 kGy, where the selected device was damaged after the exposure of higher levels, the matter which was proved to affect seriously the physical parameters and performance of the semiconductor devices [5–7].

I. M. Vikulin et al. (2017), introduced an article to explain a modified method on dosimetry, based on electronic solid state including MOSFETs. For this purpose, behavior of two models of MOSFETs has been studied as a function of the absorbed dose. The MOSFETs were irradiated at room temperature by 137Cs gamma ray source in the dose range of 1–5 Gy. Threshold voltage variation of investigated samples has been studied based on their transfer characteristic curves and also using the readout circuit (RC). For evaluation of laboratory samples sensitivity at different operating conditions, different biases were applied on the gate. In practical applications of radiation dosimetry, a significant change occurs in the threshold voltage of irradiated MOSFETs and sensitivity of these MOSFETs is increased with increasing the bias values. Therefore, these transistors can be excellent candidates as low-cost sensors for systems that are capable of measuring gamma radiation dose [8].

1.1. Effect of temperature on semiconductor

1.1.1. Carrier density

The sufficient control of the concentration of free carriers is vital to the operation of any semiconductor device and is primarily accomplished during device fabrication through the intentional introduction of dopants into the different regions of the device, but dopant atoms are not the only source of electrons and holes in a semiconductor. Even undoped semiconductors have a certain

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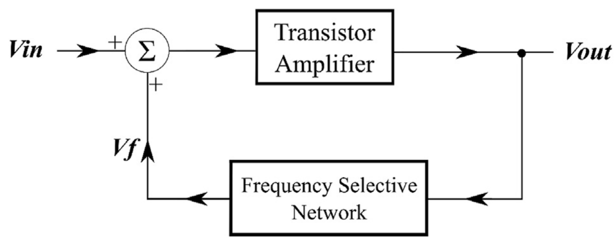

Fig. 1. Basic structure of a sinusoidal oscillator.

$$A_f(s) = \frac{A(s)}{1 - A(s)\beta(s)} \quad (1)$$

number of electron and hole carriers in the crystal. These carriers are called intrinsic carriers because they are an intrinsic property of the semiconductor material at any temperature. The concentration of these intrinsic carriers is dependent exponentially upon the temperature of the semiconductor [9].

1.1.2. Carrier mobility

The carrier mobility is directly related to the conductivity and resistivity of a semiconductor. It describes the ability of carriers to move through a semiconductor crystal. It has a very complex temperature dependence, but conceptually for high temperature it can be described as the following: As temperature increases, lattice vibrations increase and the probability of an electron being scattered by the lattice increases. Hence, carrier mobility decreases as temperature increases [10]. The decrease in carrier mobility reduces the amount of current a semiconductor device can carry, in other words higher resistivity.

1.2. Total ionizing dose effects on MOSFET

In MOSFETs, the electron-hole pair creation is the main physical process that causes all of the total ionizing dose effects. The creation of the new electron hole pairs in the device's oxide, which is usually SiO_2. The radiation induced electron-hole pairs are created in the oxide; the holes are relatively immobile to the contrary of the electrons which are swept out of the oxide in picosecond to the gate. This is due to the possible presence of an electric field in the oxide which will drift both electrons and holes in the opposite direction with their respective mobility. Hence, only a small number of the new carrier pairs recombine, and therefore the oxide layer

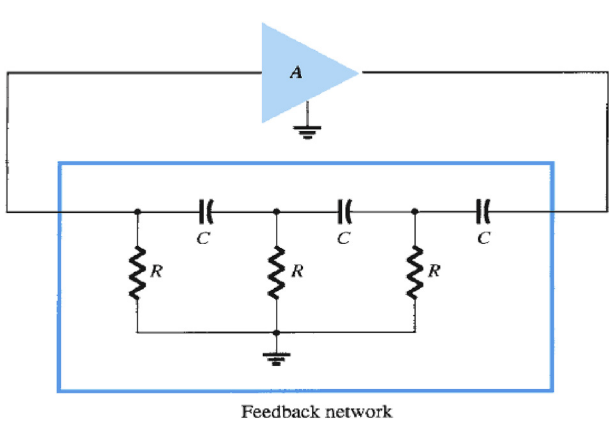

Fig. 2. RC- phase shift oscillator circuit.

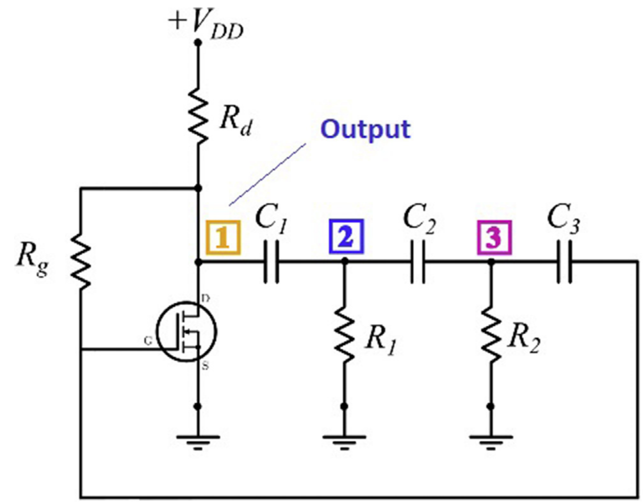

Fig. 3. RC- phase shift oscillator circuit based on MOSFET.

starts to accumulate charges (holes). These generated holes will start to drift in the direction of the applied field. When the holes reach the Si/SiO_2 interface they get trapped in deep energetic defects and behave as a fixed positive charge, this effect is called oxide traps. The oxide usually contains hydrogen, and due to the accumulated holes, hydrogen ions (protons) are produced, which will move towards the Si/SiO_2 interface causing another effect, which is called interface traps. Large concentration of interface traps can decrease the mobility of carriers and will tend to decrease the drive of transistor and degrade their timing parameters [11,12].

1.3. Oscillator circuits

Oscillators are classified into two main types: relaxation and sinusoidal. Relaxation oscillators generate the square and other non-sinusoidal wave-forms. While sine-wave oscillator is a circuit that produces a sine waveform ranging from low audio frequencies up to ultrahigh radio and microwave frequencies. The basic concept of an oscillator is shown in Fig. (1), where, an amplifier is essentially for gain (either discrete transistor or integrated op-amp) and a positive feedback circuit that produces phase shift (between input and output of circuit) [13,14].Where:

$A_f(s)$: gain of feedback amplifier.
A(s): gain of amplifier.
β: feedback factor and
s: Time domain = jω.

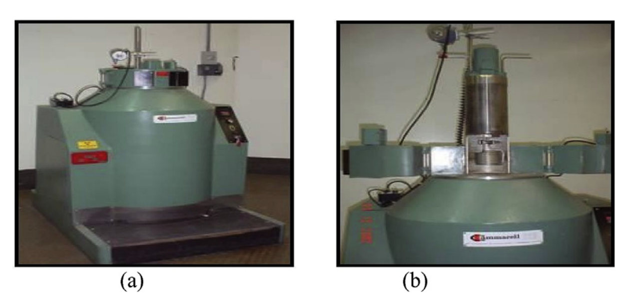

Fig. 4. Gamma-irradiators: (a) overall view of gamma cell- Eye 4000A Cooler and (b) sample chamber.

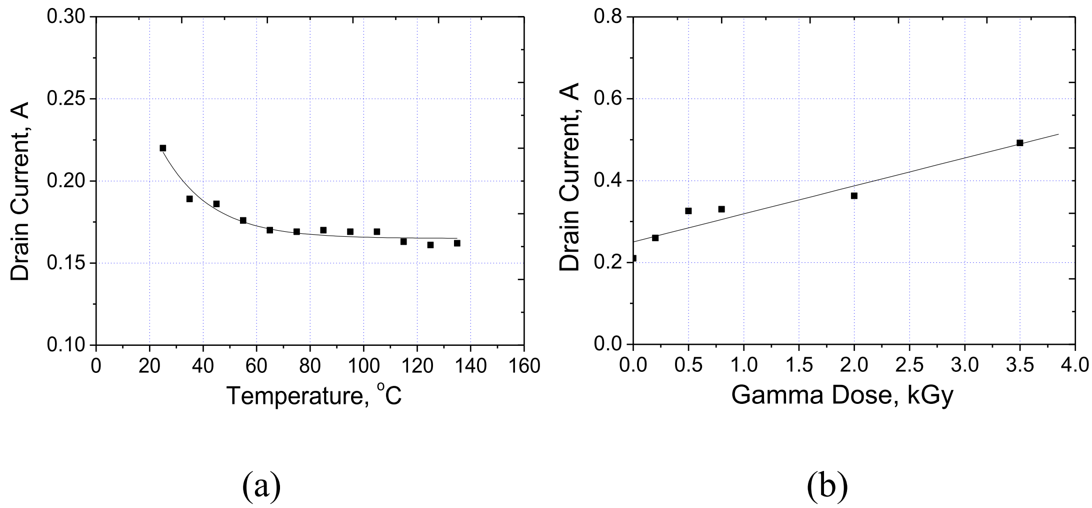

Fig. 5. Dependence of drain current on (a) temperature and (b) gamma dose.for 2N6660 MOSFET.

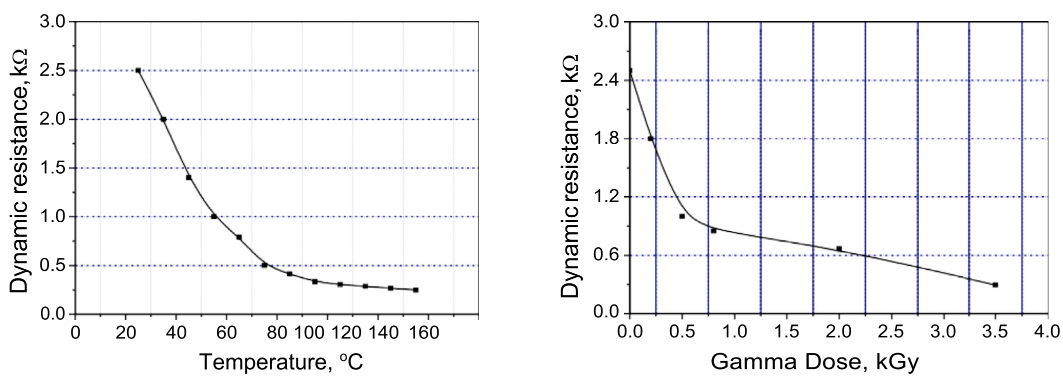

Fig. 6. Dependence of dynamic resistance on (a) temperature and (b) gamma dose for 2N6660 MOSFET.

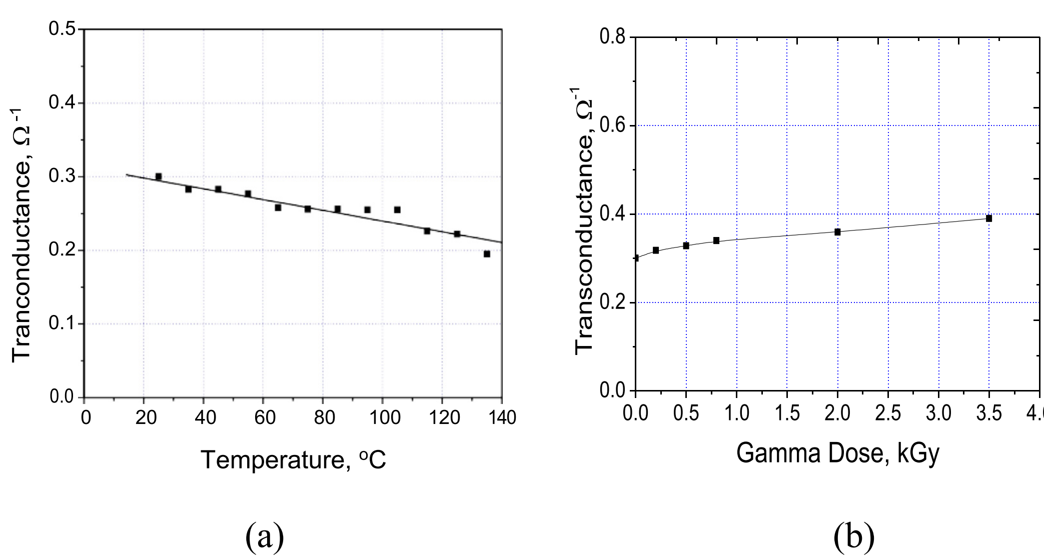

Fig. 7. Dependence of drain current on (a) temperature and (b) gamma dose for 2N6660 MOSFET.

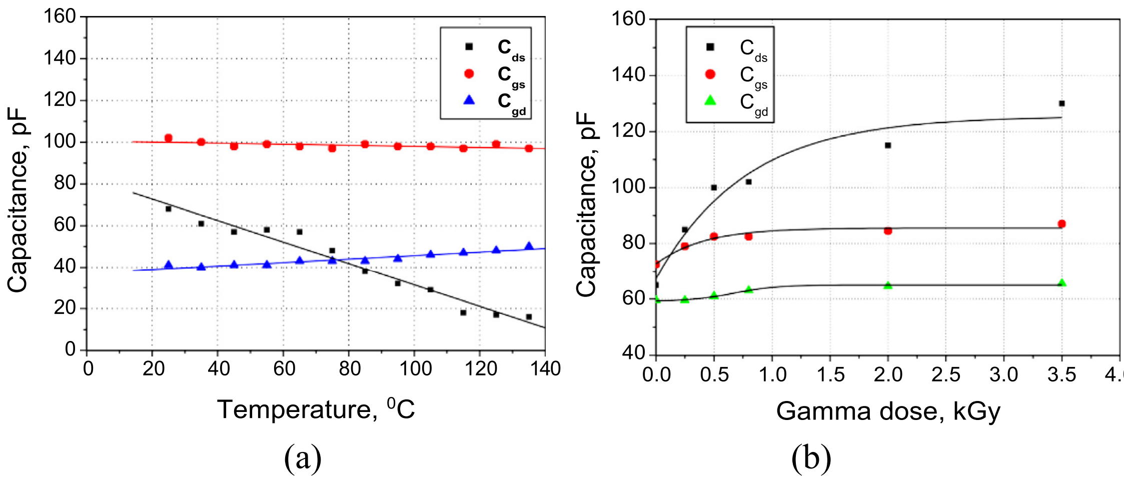

Fig. 8. Dependence of parasitic capacitances for 2N6660 MOSFET on (a) temperature and (b) gamma dose.

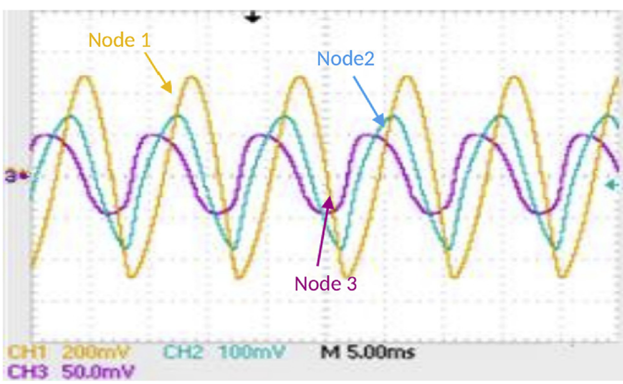

Fig. 9. Snapshot of RC-phase shift oscillator waveforms based on 2N6660 MOSFET.

1.3.1. *RC-phase shift oscillator*

A phase-shift oscillator is shown in Fig. (2), where, basically it is shown to be consist of a negative gain amplifier (A) with three RC network in the feedback [14]. The requirements for oscillation are that the loop gain (βA) should be greater than unity and the RC-stages is calculated so that the total phase shift is exactly 180°. Therefore, the phase shift between input and output should be 360°. The output impedance of the amplifier stage should be small compared to the impedance seen looking into the feedback network so that no attenuation due to loading occurs. If the field effect transistor (FET) act as amplifier in the phase shift oscillator circuit, the amplifier stage gain (A) shown in Eq. (2) is then selected larger than the needed factor of 29 to ensure oscillator action [2].Where:

$$A = g_m R_L \tag{2}$$

$$R_L = \frac{R_D r_d}{R_D + r_d} \tag{3}$$

g_m: FET transconductance,
R_L Load resistance,
R_D: Drain resistance, and
r_d: Dynamic resistance of FET

The frequency at which the phase shift is exactly 180° is given by:

$$\omega = \frac{1}{RC\sqrt{6}} \tag{4}$$

$$2\pi f = \frac{1}{RC\sqrt{6}} \tag{5}$$

$$f = \frac{1}{2\pi RC\sqrt{6}} \tag{6}$$

2. Experimental details

The design, implementation and operation of RC-phase shift oscillator based on MOSFET type 2N6660 (Fig. 3) with dimensions (8.89 mm width, 18.8 mm height), as illustrated in the data sheet was investigated as:

- The selected MOSFET was characterized under normal conditions (25 °C, 0 gamma dose) using 370A curve tracer.
- RC-phase shift oscillator based on the selected MOSFET was designed, based on the parameters illustrated in Table 1.
- To conduct the circuit and observe the output waveform and measure its amplitude and frequency, the following instruments were used; a digitizing oscilloscope, model TDS2024C and regulated DC-power supply (0–30 V), model PW36-1 were used.
- For the investigated circuit, its parameters were all measured before and after exposure to different ascending temperature levels, from room temperature level (25 ^{O}C) up to 135 ^{O}C using electrical furnace or gamma-irradiation doses up to 3.5 kGy, using the Indian Gamma-irradiator of the National Center for Radiation Research and Technology (Fig. 4). Gamma-irradiator has Co-60 source and the chamber with approximately 100 mm diameter by 250 mm tall. The gamma radiation dose rate is1.208 kGy/h.

3. Results and discussions

3.1. *MOSFET characteristics*

The static characteristics of the investigated MOSFET were firstly studied as a function of temperature and radiation doses. In this concern, Fig. 5a shows plot of the drain current (I_D) as a function of

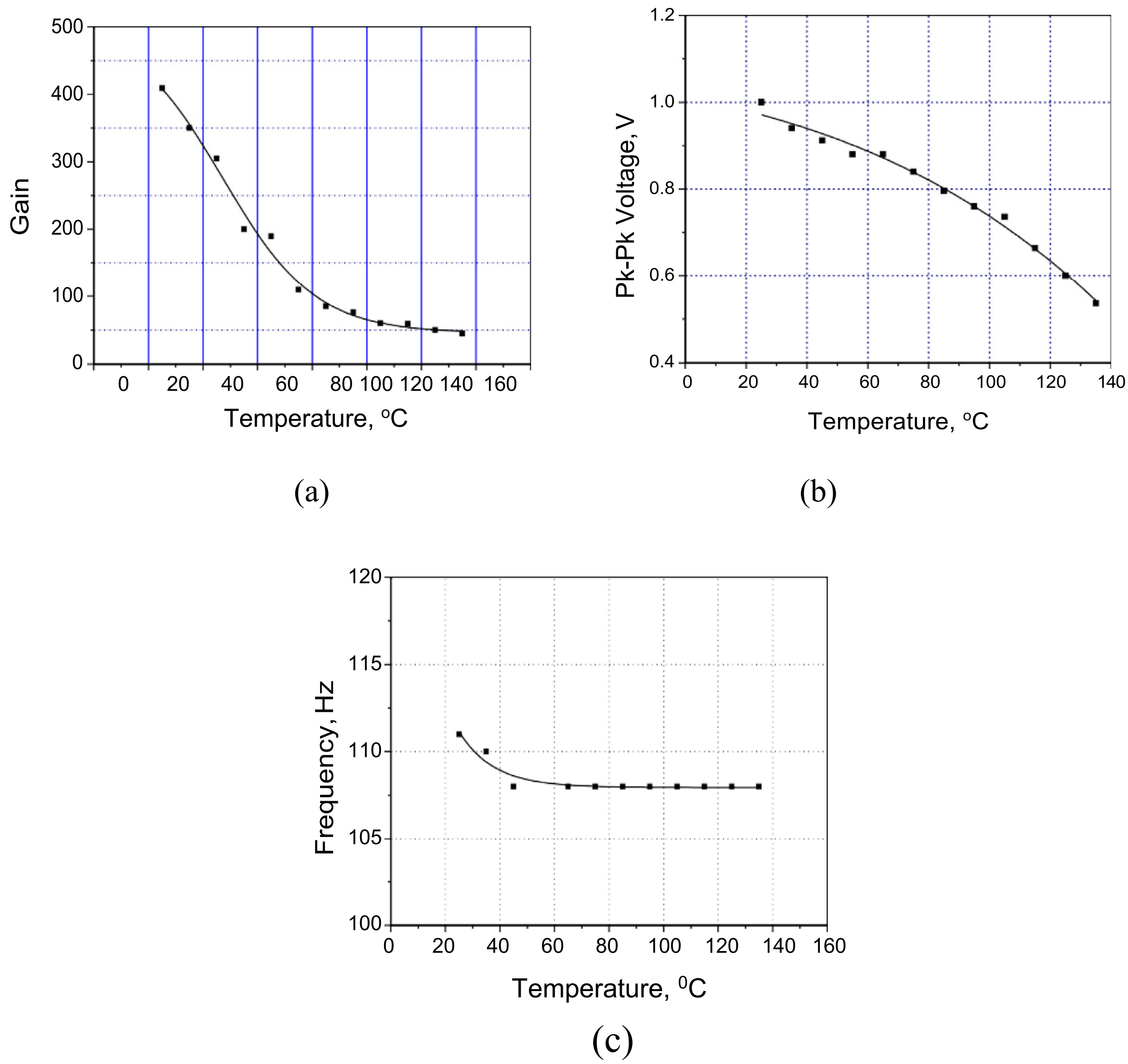

Fig. 10. Dependence of oscillation (a) gain (b) Vp-p and (c) frequency for RC-phase shift oscillator based on MOSFET type 2N6660 on temperature.

temperature and gamma radiation. It was found that, at VGS value of 3.0 V, as an example, I_D was decreased from 0.22 A, measured at 25 °C, down to 0.163 A, measured at 135 °C. On the other hand, Fig. 5b shows I_D as a function of γ-dose, where it is shown that I_D value was increased from an initial value of 0.22 A up-to 0.49 A, whenever the device was exposed to gamma-rays up to 3.5 kGy. The same phenomenon was discussed by R. Sujatha et al. (2018), where they studied the effect of gamma radiation on the parameters of MOSFET type 2N6796 and observed the following; the threshold voltage, leakage current, drain saturation current, mobility and transconductance are all affected by gamma radiation. In their paper, they explained the gamma radiation effect on MOSFET parameters as follow; gamma radiation generally results in the degradation of by ionization when the energetic particles deposits energy as it is passes through the matter. The energy of the incident particles produces electron-hole pairs, which is responsible for the device performance degradation that occurs in the passivation oxide layer, so it is surface effect. The ionizing radiation generated changes is mainly responsible for threshold voltage shift, which in turn leads to an increase in the leakage current and saturation drain current [15].

Moreover, as shown in Fig. (6) the dynamic resistance was decreased from 2.5 kΩ down-to 0.25 kΩ, due to temperature increasing from 25 °C up-to 135 °C (Fig. 6a). Also, its value was shown to be decreased from 2.5 kΩ down to 0.295 kΩ, due to gamma-irradiation up-to 3.5 kGy (Fig. 6b).

Moreover, the work was extended to include the dependence of the forward transconductance (gm) of the selected MOSFET on both the temperature and γ-dose (Fig. 7). In this concern, Fig. 7a shows that g^m value was decreased from 0.3 Ω^{-1} down-to 0.215 Ω^{-1}, whenever the device was exposed to temperature within the investigated range. On the other hand, and considering g^m, its value was shown to be slightly increases from 0.3.0 Ω^{-1} up-to 0.38 Ω^{-1}, within the investigated range of gamma-irradiation (Fig. 7b).

Finally, the temperature and γ-dose dependence of the parasitic capacitances for the investigated MOSFET was studied and plotted as shown in Fig. (8). From which, it is clearly shown that the drain-source capacitance (C_{ds}), gate-drain capacitance (C_{gd}) and gate-source capacitance (C_{gs}) values were changed due to temperature and γ-dose exposure.

3.2. Transistor oscillator

3.2.1. Initial conditions

The work was extended to include the temperature and radiation dependences on the output characteristics of the RC-phase

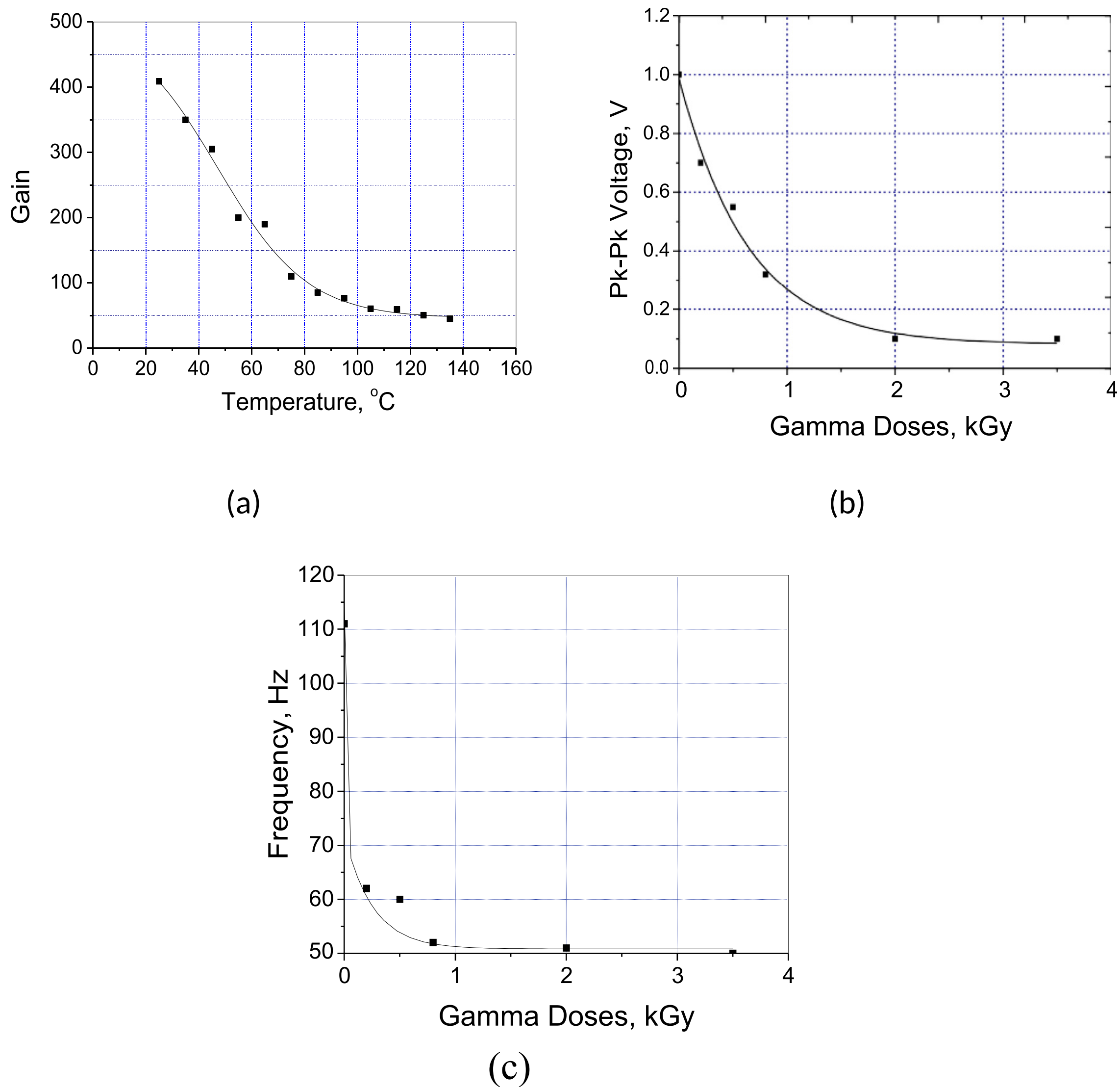

Fig. 11. Effect of gamma dose on (a) gain (b) $V_{p\text{-}p}$ and (c) frequency of the oscillation of RC- phase shift oscillator.

Table 1
Circuit elements and parameters of RC-phase shift oscillator.

R_g kΩ	R_D kΩ	C_1,C_2,C_3 nF	R_1,R_2 kΩ	V_{DD}, Volts
470	3	100	3.3	11

Table 2
Summary of the electrical parameters of RC- phase shift oscillator based on MOSFET-device, measured at different operating conditions.

Oscillator	Temperature Effect				Radiation Effect			
	Temp. (°C)		Ratio (%)		Gamma dose, kGy		Ratio (%)	
	25	135	Inc.	Dec.	0	3.5	Inc.	Dec.
Freq. (Hz)	111	108.7	–	2.07	111	50	–	54.9
Gain	408	135	–	66.9	408	95	–	76.7
Node 1, $V_{p\text{-}p}$ (V) (Output voltage)	1	0.538	–	46.2	1	0.1	–	90

shift oscillator circuit based on MOSFET. Primarily, the initial characteristics of the oscillator were plotted under normal laboratory conditions, where the typical output waveforms of the three RC sections are shown in Fig. (9). The oscillation frequency was shown to be 111 Hz and $V_{p\text{-}p}$ of the output signals at nodes 1, 2 and 3 were 1, 0.322, and 0.096 V, respectively. The oscillation frequency was shown to be 111 Hz, while its theoretical value was calculated using Eq. (6) to be 196 Hz, while the simulated value was 123 Hz, respectively. At the same time, the pk-pk voltage of the output signals (Vp-p) at nodes 1, 2 and 3 were 1, 0.322, and 0.096 V, respectively.

3.2.2. *Temperature effect*

During the present part of the work, the selected MOSFET was exposed to different temperature levels during the operation of oscillator circuit. In this concern, the effect of temperature on the gain, pk-pk voltage value and frequency of the output signal are shown in Fig. (10). From which, it is clearly shown that, the oscillation gain value which calculated using Eq. (2), was decreased from 408 down-to 135, due to temperature increasing from 25 °C up-to 135 °C (Fig. 10a). While, $V_{p\text{-}p}$ value of the output signal was decreased from 1.0 V down-to 0.538 V, for the same temperature range (Fig. 10b). In addition, the oscillation frequency value was slightly decreased from 111 Hz down to 108.7 Hz as temperature increased from room temperature up-to 45 °C (Fig. 10c). For further increase in temperature levels, it is noticed that there is no significant effect on frequency value. By changing the values of R and C, the frequency of oscillator can be changed [16]. Hence if parasitic capacitances of MOSFET device are changed duo to temperature effect as shown from Fig. 8a, the frequency value will be changed.

3.2.3. Radiation effects

The study was extended to include the effect of γ-dose on the operation of RC- phase shift oscillator based on MOSFET. From Fig. 11, it is clear that, the gain value was shown to be decreased from 408 down to 95 due to gamma up-to 2 kGy (Fig. 11a). Hence, Vp-p of the output signal was shown to be decreased from the initial value of 1.0 V down-to 0.1 (Fig. 11b) due to reduction in the gain oscillation [2], as shown in Fig.11a. In addition, the oscillation frequency was shown to be decreased from 111 Hz down-to 50 Hz (Fig. 11c). For higher γ-dose levels up-to 3.5 kGy, the previously mentioned parameters were shown to be almost constant where Vp-p and frequency changing related to the changing in dynamic resistance, transconductance and parasitic capacitances of investigated device (see Table 2).

4. Conclusions

From the experimental work, results and discussions, it could be concluded that:

- The electrical parameters of MOSFET devices are direct degraded functions of the gamma-irradiation dose. On the other hand, it shows more stable behaviors under the influence of temperature levels up to 135 °C.
- During the operation of RC-phase shift oscillator, the oscillation gain and pk-pk voltage were decreased whenever MOSFET device exposed to temperature or gamma radiation duo to the changing in dynamic resistance and transconductance of the device.
- The oscillation frequency will become unstable due to changing of parasitic capacitances of MOSFET device as a result of gamma exposure.
- The oscillation frequency is more stable during the oscillator operation in the temperature range up to 135 °C due to the stability of C_{gs} and C_{gd} values of the MOSFET in the same temperature range.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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