Temperature Effects on the Electrical Characteristics of BJTs and MOSFETs

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Abstract

The aim of the present paper is to shed further light on studying the temperature effects on the static (I-V) and dynamic (C-V) characteristics of bipolar junction- and metal oxide field effect - transistors. In this concern, several parameters were plotted at different temperature levels. The experimental results showed that, for the bipolar junction transistor 2SC2120, a noticeable increase in the collector current and the current gain from 0.198 A and 0.14 up-to 0.25 A and 0.24 by increasing the temperature from 25ºC and 135ºC, respectively. Considering the threshold voltage, its value was shown to be decreased from 0.62 Volt to 0.42 Volt within the same temperature range. In addition, from the traced dynamic characteristics of the same BJT, the diffusion capacitance of the emitter-base junction, as an example, increased from 10.11 nF up-to 45.09 nF by increasing the temperature up-to 135 ºC. On the other hand, for metal oxide field effect transistor 2N6660, the static characteristics showed that a noticeable decrease in the drain current and the forward trans-conductance from 1.2A and 5.0 Ω^{-1} down-to 0.79 A and 1.9 Ω^{-1}, respectively, due to temperature increasing from 25 ºC up-to 135 ºC. While the threshold voltage was hold constant. Finally, the reverse capacitance of the gate-drain junction was shown to be increases from 41.48 pF up-to 47.31 pF within the same range of temperature.

Keywords: Temperature effect, bipolar junction transistor, metal oxide field effect transistor, capacitance, impedance, quality and dissipation factor and phase angle.

1.0 Introduction

Temperature is one of the most common keys design factors in electronic designs. Designers must confirm that semiconductor devices operate correctly across a wide range of temperatures [T. D. Haeffner, 2015]. Temperature can change the operation of semiconductor devices significantly. To make the design of some application possible as an example, biomedical applications, such as breathing sensors, temperature sensors and other applications, the temperature characteristics of the transistors must be considered [S. Bethi, et al, 2014]. In this concern, the present paper targets to study the electrical parameters for two of the most commonly two used electronic devices, namely: NPN bipolar junction Si-transistor (BJT) and N-channel enhancement mode MOSFET under the influence of different levels of temperature.

. 2.0 Experimental Work

The experimental work was based on studying the electrical parameters of NPN (BJT) type 2SC2120 and N-channel enhancement mode MOSFET type 2N6660 under the influence of wide temperature levels, ranging from 25 ºC up-to 135 ºC. In this concern, 370 A Tektronix curve tracer system and programmable automatic Fluke PM6306 RCL bridge were applied for precise measurements.

3.0. Results and Discussions

3.1. Static Characterization of Transistors

3.1.1. Bipolar junction transistors

The output characteristic curves (collector current I_C, collector-emitter voltage V_{CE}, of the Si-2SC2120 transistor were plotted at base current I_B value of 1 mA, under the influence of different temperature levels, ranging from 25ºC up-to 135ºC Fig. (1). It is clearly shown that, I_C increases as a function of temperature level, where at V_{CE} = 3 Volts, I_C reaches a value of 0.25 A, measured at 135 ºC, while its initial value was 0.198 A, measured at 25 ºC [A. S. Sedra, 2004, N. Rinaldi and V. Alessandro,2005].

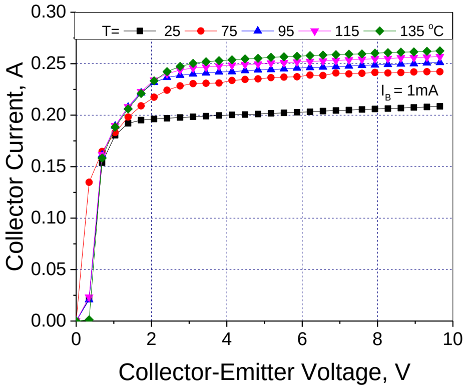


Fig. (1): Dependence of the output characteristics curve on temperature for BJT type 2SC2120.

Besides, the output-resistance (R_{out}) of BJT`s was calculated for the different temperature levels using Eq. (1) and the dependence of its value on temperature was shown in Fig. (2a) [B.L. Theraja, 2008, J. Millman and C.C. Halkias, 1972]. From which, it is shown that R_{out} decreased from an initial value of 15 Ω, measured at 25 ºC down-to 8.54 Ω, at 135 ºC, after that saturation conditions was observed.

$$R_{out} = \frac{\Delta V_{CE}}{\Delta I_C} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Where,

ΔV_{CE}: Change in collector-emitter voltage and

ΔI_C: Change in collector current.

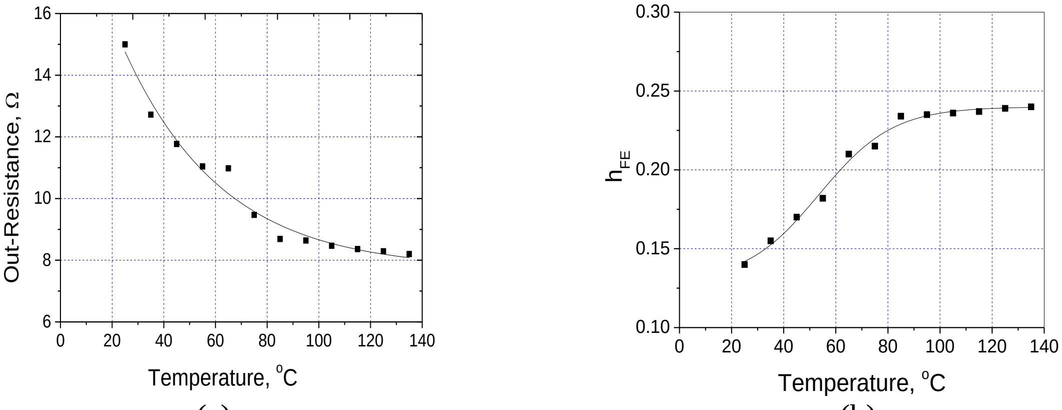
Also, dc current gain (h_{FE}) was calculated applying Eq. (2) and plotted as function of temperature Fig. (2b) [A. S. Sedra, 2004, B.L. Theraja, 2008 and J. Millman and C.C. Halkias, 1972]. From which, it is clear that, h_{FE} increased from an initial value of 0.14, measured at 25 ºC up-to 0.239, at 135 ºC, and at the end, saturation conditions was observed.

$$h_{FE} = \frac{\Delta I_C}{\Delta I_B} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where;

ΔI_C: Change in collector current and

ΔI_B: Change in base current



(a) (b)

Fig. (2): Temperature dependence of the dc current gain (a) and output-resistance (b) of BJT type 2SC2120.

In addition, the study was extended to include the temperature effect on the input characteristics of the investigated transistor. Where, Fig. (3a) shows a set of (I_B-V_{BE}) curves plotted within the temperature range from 25 ºC up-to 135 ºC. As a result, the dependence of the threshold voltage (V_{Th}) on temperature was shown in Fig. (3b). From which, V_{Th} value was shown to be decreased from 0.62 Volt down-to 0.42 Volt, in the temperature range from 25°C up-to 135 °C, this is mainly due to the fact that the increasing temperature leads the electrons in the valance band to be excited, pulling them into the conduction band, resulting an increase in the current. The temperature dependence was shown to be linear decay, following the relation [B. Eslamia and S. Ashrafib, 2016, E. Schurackm, et al, 1992 and Yam Agiwa, et al, 2008]:

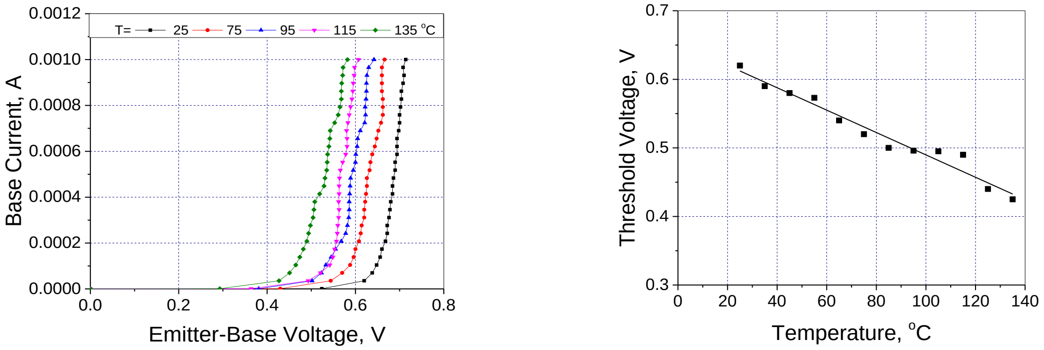
$$V_{Th}(T) = V_{Th}(0) - AT \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where;

$V_{Th}(T)$ and V_{Th} (0): threshold voltages (Cut-in voltage), measured at measuring-and room-temperature level, respectively.

A: slope of the dependence, and

T: temperature



(a) (b)

Fig. (3): Temperature dependence of input curves (a) and threshold voltage (b) for BJT 2SC2120.

3.1.2 Metal Oxide Field Effect Transistor

The static characteristics (output and transfer) of MOSFET type 2N6660 were investigated. In this concern, the output characteristic curves of the investigated MOSFET (drain current I_D as a function of drain-to-source voltage, V_{DS}) was studied and plotted at gate-to-source voltage (V_{GS}) value of 3 Volts for different temperature levels, ranging from 25 ºC up-to 135 ºC as shown in Fig. (4). From which, Fig. (5a) shows I_D as a function of temperature. It was found that, I_D was shown to be decreased from 0.219 A, measured at 25 ºC, down- to 0.158 A, measured at 135 ºC.

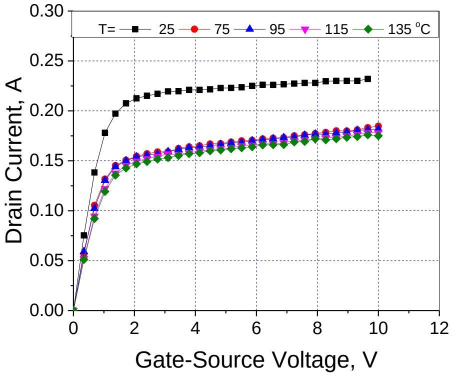


Fig. (4): Temperature dependence of the output characteristics of MOSFET 2N6660.

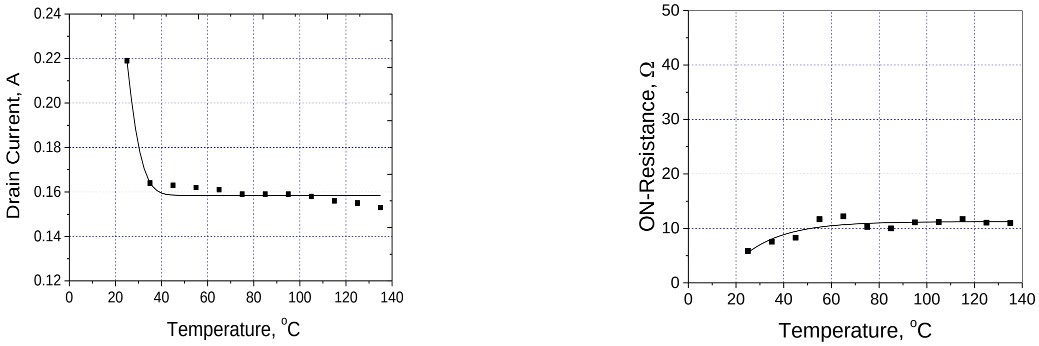
As it is well known that, every MOSFET device has a resistive element known as ON – resistance (R_{on}) and can be calculated using the following [B.L. Theraja, 2008, H. Djelti. et al, 2008 and J. Millman and Ch.C. Halkias, 1972]:

$$R_{on}=\frac{\Delta V_{DS}}{\Delta I_D} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where,

ΔV_{DS}: Change in drain-source voltage and
ΔI_D: Change in drain current

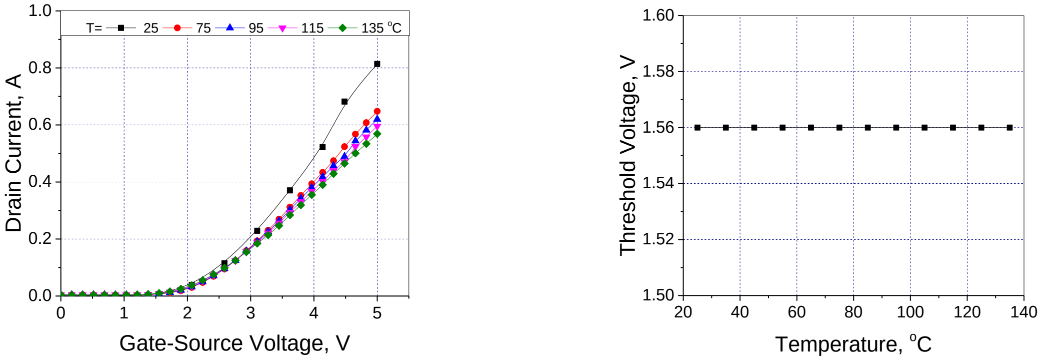
In this concern, the temperature effect on R_{on} was considered (Fig.5b). From which, It is shown that, R_{on} increased from an initial value of 5.77 Ω measured at 25 ºC up-to 11 Ω at 135 ºC



(a) (b)

Fig. (5): Temperature dependence of the drain current (a) and ON-resistance (b) of MOSFET 2N6660.

Figure (6) shows the transfer characteristics (I_D-V_{GS}) of the investigated MOSFET, plotted at different temperature levels Fig. (6a), where the measurements were carried out within the temperature range from 25ºC up-to 135ºC. As a result, the dependence of the threshold voltage (V_{Th}) on temperature was shown in Fig. (6b). From which, it is clearly shown that the threshold voltage isn`t affected by the temperature variations [H. Djelti. et al, 2008].



(a) (b)

Fig. (6): Temperature dependence of the transfer characteristic curves (a) and threshold voltage (b) for MOSFET type 2N6660.

In addition, the forward trans-conductance (g_{fs}) was calculated using Eq.(5), and plotted as function of temperature [B.L. Theraja, 2008] as shown in Fig. (7). It is clear that g_{fs} was decreased from 0.292 Ω^{-1} down-to 0.215 $\Omega^{-1,}$ whenever the devices were exposed to temperature within the investigated range [A.A. Osman and M. A. Osman, 1998].

$$g_{fs} = \frac{\Delta I_D}{\Delta V_{GS}} = \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Where,

ΔI_D: Change in drain current and
ΔV_{GS}: Change in gate-source voltage.

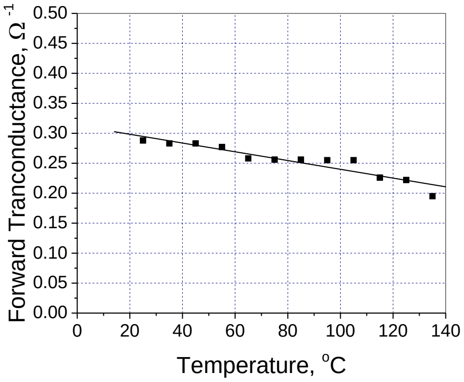
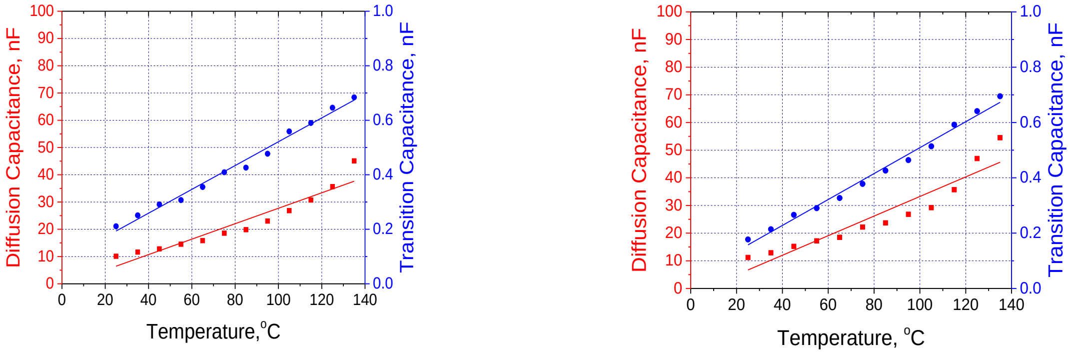


Fig. (7): Temperature dependence of the forward trans-conductance for MOSFET type 2N6660.

3.2. Dynamic Characterization of Transistors

3.2.1. Bipolar junction transistors

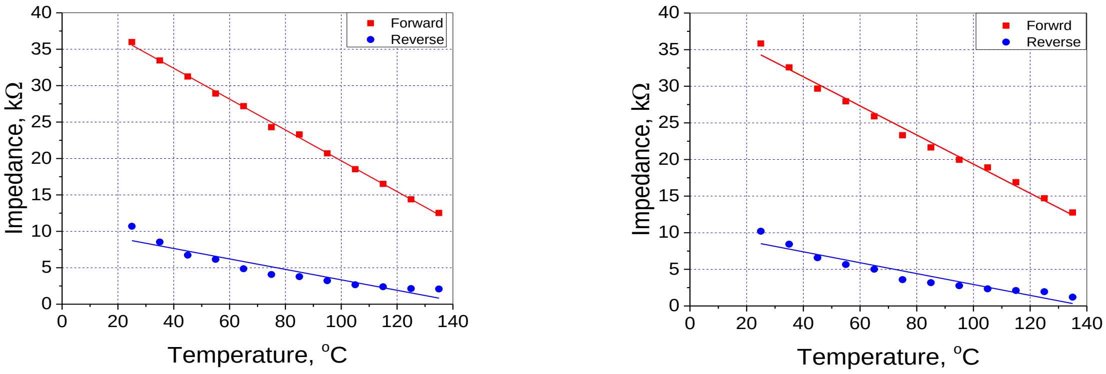
The dependence of both the diffusion (C_d) and transition (C_T) capacitances, for emitter- and collector- base junctions of BJT type 2SC2120 on temperature (in the range from 25 °C up-to 135 °C) was shown in_Fig. (8). From which, it is clear that C_d, for both emitter- and collector- base junctions increased from 10.11 nF up-to 45.09 nF and from 11.2 nF up-to 54.5 nF, respectively measured at the temperature range from 25 °C up-to 135 °C. While for the C_T, it is clearly shown that, a noticeable increase on the capacitance value, from 0.21 nF up-to 0.68 nF for the emitter-base and for the collector-base junction from 0.177 nF up-to 0.69 nF [H. Mnif, et al, 2002].



(a) (b)

Fig. (8): Temperature dependences of diffusion- and transition- capacitance of the emitter-base- (a) and collector-base- (b) junctions for BJT 2SC2120.

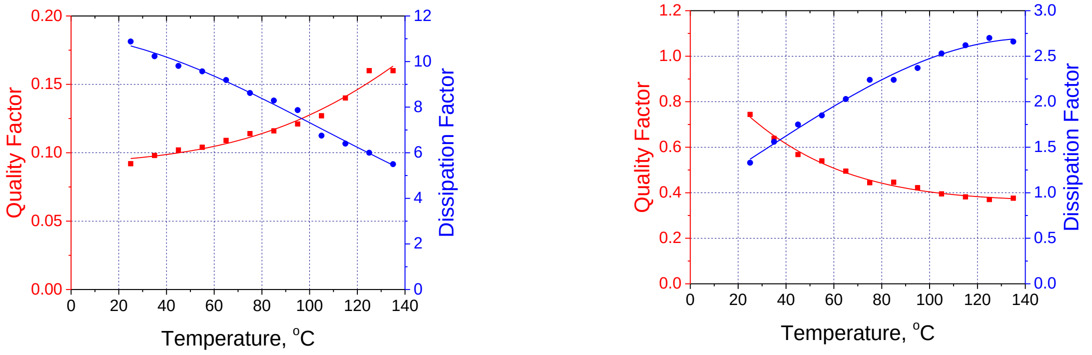
Moreover, Fig. (9) shows the effect of temperature on the impedance (Z) of the emitter- and collector- base junctions, for both the forward and reverse bias directions, plotted at the same temperature levels. It is clear a pronounced decrease on the impedance values of both bias directions was observed. Where, for the forward emitter- and collector- impedance a values of 35.98 kΩ and 35.84 kΩ, measured at 25°C, were shown to be decreases down-to 12.52 kΩ and 12.76 kΩ, measured at 135 °C, respectively. On the other hand, for the reverse emitter- and collector- impedance, values of 10.7 kΩ and 10.2 kΩ, measured at 25 °C, were shown to be decreased down-to 2.09 kΩ and 1.2 kΩ, measured at 135°C.



(a) (b)

Fig. (9): Temperature dependences of forward- and reverse- impedances of the emitter-base- (a) and collector-base- (b) junctions for BJT 2SC2120.

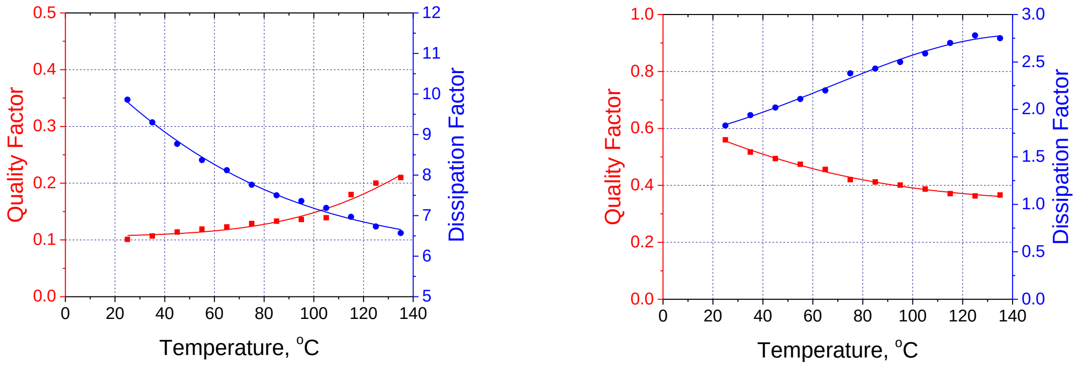
Figure (10) shows the effect of temperature on the quality factor (Q), plotted at both the forward and reverse bias directions of the emitter-base junction of BJT 2SC2120. From which, a pronounced increase in its value was observed for the forward bias, where a value of 0.092, measured at 25 °C, was shown to be increased up-to 0.16, at 135 °C. On the other hand, for the reverse bias, a pronounced decrease on Q value from 0.74 down-to 0.37, for the same range of temperature levels. Also, the same figure shows the effect of temperature on dissipation factor (D) for the forward and reverse bias of the emitter-base junction. It is clear that, for the forward bias, a pronounced decrease in D value was observed, where it was shown to be decreased pronouncedly from 10.88, measured at 25 °C down-to 5.5, measured at 135 °C. While, for the reverse bias, its value increased from 1.33 up-to 2.66 was reported in the same temperature range [R. M. Fox and S. G. Lee, 1991].



(a) (b)

Fig. (10): Temperature dependences of the emitter-base junction forward (a) - and reverse (b) - quality and dissipation factors of the BJT 2SC2120.

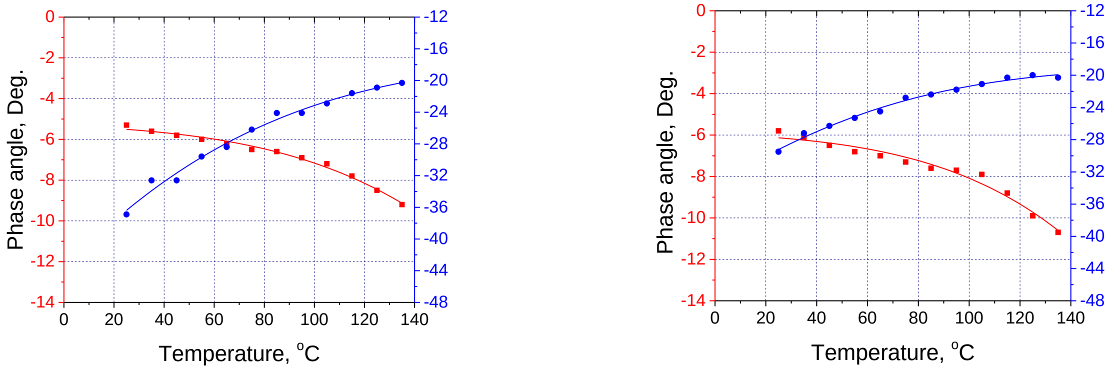
For the forward Q of collector-base junction Fig. (11a), a pronounced increase in its value was observed, where a value of 0.1 measured at 25 °C, was shown to be increased up-to 0.21, at 135 °C. On the other hand, for the reverse Q of collector-base junction (Fig.11b). It is clearly shown that, starting from 25 °C up-to 135 °C, a pronounced decrease on its value from 0.56 down-to 0.36 for the same range of temperature levels. Besides, the effect of temperature on both the forward and reverse D of the collector-base junction of the investigated BJT in the temperature range from 25 °C up-to 135 °C. It is clear that both of forward and reverse D are a direct function of temperature level. For the forward D, a pronounced decreased in its value was observed, where it decrease pronouncedly from 9.86 down-to 6.57, measured at 25 °C and 135 °C, respectively. On the other hand, for the reverse D, it is clearly shown that, starting from 25 °C, an increase in its value, from 1.83 up-to 2.75 was reported [M. A. Hopcroft, et al, 2007].



(a) (b)

Fig. (11): Temperature dependences of the collector-base junction forward (a)- and reverse (b)- quality and dissipation factors of the BJT type 2SC2120.

The phase angle (ϕ) of emitter- and collector- base for BJT, as a function of temperature levels was plotted for the forward bias condition (Fig.12a), ϕ shows decreasing dependence on temperature, where its value decreased from -5.3° down-to -9.2° for emitter-base junction and for the collector-base it`s value was shown to be decreased from -5.8° to -10.7° .On the other hand, for the reverse bias direction, ϕ value was shown to be increased from -36.9° up-to -20.3° and for the collector-base increased from -29.5° up-to -20.3° for the same range of temperature levels.

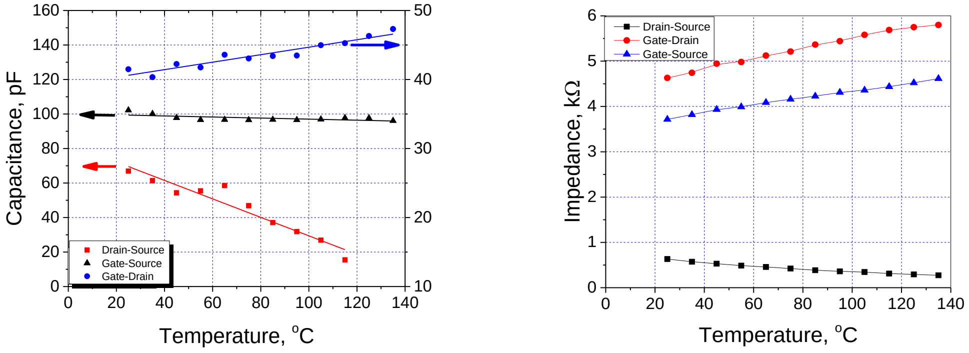


(a) (b)

Fig. (12): Temperature dependences of forward- and reverse- phase angle of the emitter-base-(a), and collector-base-(b) junctions for BJT type 2SC2120.

3.2.2 Metal Oxide Field Effect Transistor

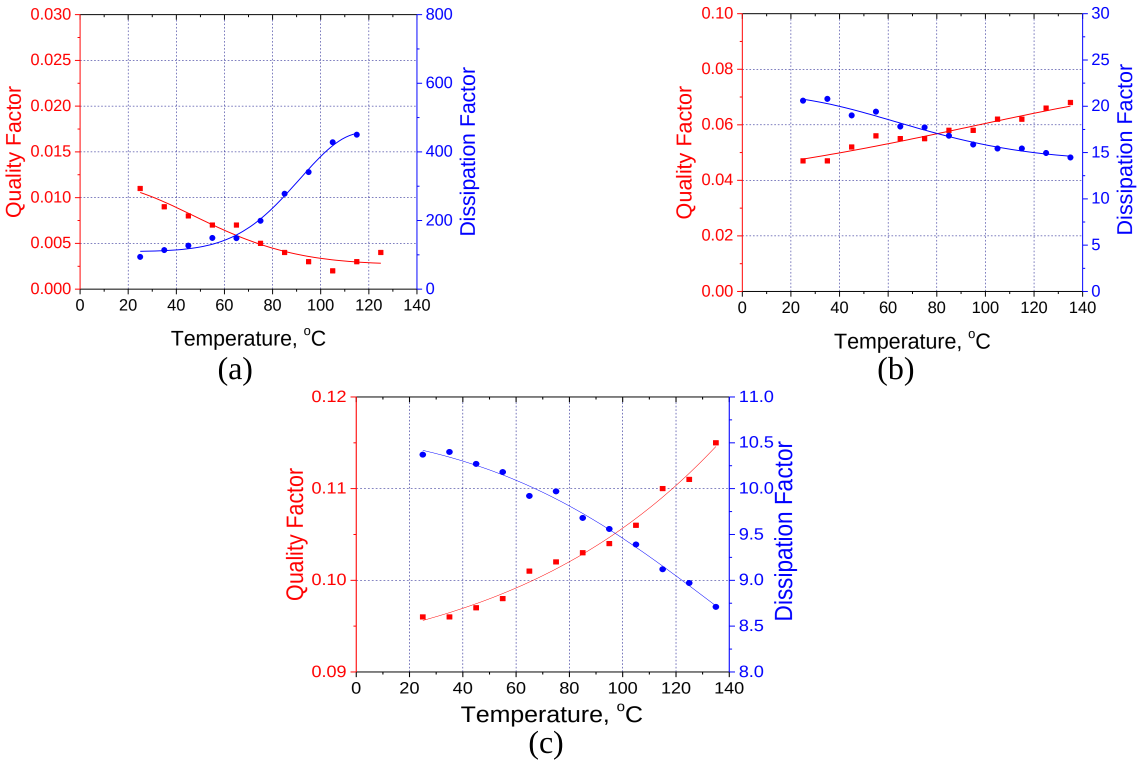
The temperature dependence of junction capacitance for the investigated MOSFET was studied and plotted. In this concern, the drain-source, gate-drain and gate-source junction capacitances of MOSFET type 2N6660 were studied and plotted as function of temperature Fig. (13a). From which, it is clearly shown that, the drain-source capacitance decreased from 66.91 pF, measured at 25 °C, down to 15.48 pF at 135 °C. On the other hand, for the reverse capacitance, its value was shown to be increased from 41.48 pF up-to 47.31 pF with increasing temperature from 25 °C up-to 135 °C. Moreover, for gate-source junction capacitance, it is clearly shown that, the junction capacitance decreased with increasing temperature from 102.22 pF down-to 96.13 pF. In addition, the temperature dependence of junction impedance (Z) for drain-source, gate-drain and gate-source junctions of MOSFET device are shown in Fig. (13b). From which, it is obviously shown that for the drain-source junction Z values was shown to be decreased from 0.63 kΩ, measured at 25 °C, down-to 0.27 kΩ at 135 °C. On the other hand, for the gate-drain junction, its value was shown to be increased from 4.63 kΩ up-to 5.79 kΩ with increasing temperature from 25 °C up-to 135 °C, respectively. Moreover, for the gate-source junction impedance, it is showed that, its value increased from 3.71 kΩ up-to 4.61 kΩ, with increasing the temperature within the investigated range.



(a) (b)

Fig. (13): Temperature dependences on the drain-source-, gate-drain- and gate-source- junctions-capacitance (a) and junctions impedance (b) for MOSFET 2N6660.

The dependence of Q on temperature for the different junctions is shown in Fig. (14). From which, it is clearly shown that for drain-source junction, Q value decreased from an initial value of 0.011 down-to 0.004 on increasing temperature up-to 135 °C. On the other hand, for gate-drain junction and gate-source junction, respectively Q values increased from 0.047 and 0.096, measured at 25 °C up-to 0.068 and 0.096, at 135 °C. At the same time, it is clearly shown that for drain-source junction, D was shown to be increased from an initial value of 93.9 up-to 450 for the same temperature levels. On the other hand, for gate-drain- and gate-source - junctions, D values decreased from the initial value of 20.6 and 10.37, at 25 °C down-to 14.47 and 8.71 at 135°C [V. V. Orlov, V. A. Felitsyn, G. I. Zebrev, 2016].



(a)

(b)

(c)

Fig. (14): Temperature dependences on the quality and dissipation factors of the drain-source (a), gate-drain (b) and gate-source (c) junctions for MOSFET 2N6660.

The dependence of ϕ on temperature is shown in Fig. (15), from which it is clearly shown that for drain-source junction, ϕ value increased from the initial value of - 0.6° up-to 0° on increasing the temperature from 25 °C to 135 °C. On the other hand, for gate-drain and gate-source -junctions, ϕ values decreased from the initial values of -2.8° and -5.5° down-to -3.8° and -6.5° at 25 °C and 135 °C, respectively.

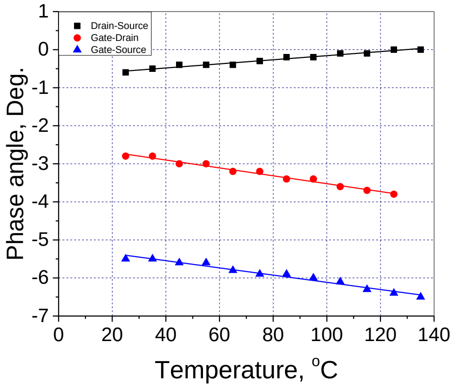


Fig. (15): Temperature dependences of the drain-source, gate-drain- and gate-source- phase angles for MOSFET 2N6660.

4.0 Conclusions

From the study, experimental work, results, analysis and discussions, it could be concluded that temperature dependence of the electrical characteristics of BJTs and MOSFETs is a great interest, where severe effects were registered. So, carefully selected transistor and its temperature level is very important for electronic systems design.

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الملخص العربى

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٢. هيئة المواد النووية- ص ب. ٥٣٠ - المعادى- ١١٧٢٨- القاهرة- جمهورية مصر العربية

تناول البحث المعروض دراسة عملية تطبيقية على الخصائص الكهربية الاستاتيكية (منحنيات التيار والجهد) والديناميكية (منحنيات السعة والجهد) لنبيطتي ترانزستور ثنائي القطبية وترانزستور تأثير المجال الأكسيدي المعدني تحت تأثير الحرارة المرتفعة ، فى المدى من درجة حرارة الغرفة ٢٥ºC حتى 135ºC درجة مئوية. حيث أظهرت النتائج العملية أن تأثير الحرارة على ترانزستور ثنائي القطب 2SC2120 يؤدي إلى زيادة ملحوظة في تيار المجمع وكسب التيار من 0.198A حتي 0.25A ومن ٠.٠١٤ حتى ٠.٢٤ على التوالي فى المدى من درجة حرارة الغرفة 25ºC حتى 135ºC. بينما يقل جهد العتبة له من 0.62V حتي 0.42V ، مقاسة عند نفس المدى المشار إليه من درجات الحرارة. وعلى الجانب الآخر للخصائص الديناميكية، فقد تم دراسة العلاقة بين السعة والجهد عند درجات حرارة مختلفة ، الامر الذى أوضح حدوث زيادة فى قيمة سعة المكثف بين وصلتي الباعث والقاعدة في حالة التوصيل الأمامي للترانزستور حيث زادت من 10.11nF حتى 45.09nF .

أما بالنسبة إلى تأثير الحرارة على ترانزستور تأثير المجال الأكسيدي المعدني 2N6660 فقد تم ملاحظة حدوث اضمحلال فى قيمة كلاً من تيار المصرف والتوصيلية وذلك من القيم من 1.2 A, 5 Ω^{-1} حتى 0.79 A, 1.9 Ω^{-1} ابتداءاً من درجة حرارة الغرفة 25 ºC حتى 135 ºC على التوالي. بينما لم تؤثر الحرارة علي قيم جهد العتبة. وعلى الجانب الآخر للخصائص الديناميكية، فقد تم دراسة العلاقة بين السعة والجهد عند درجات حرارة مختلفة، ومن ذلك على سبيل المثال ، فقد تم ملاحظة حدوث زياده فى قيم السعة العكسية على الوصلة بين البوابة والمصرف من 41.48 pF حتى 47.31 pF بزيادة الحرارة في المدى المذكور.

اسماء المشاركين بالبحث :

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٢- د./ صفاء محمد رشدي الغنام (أستاذ مساعد الإليكترونيات – قسم الفيزياء – كلية البنات للآداب والعلوم والتربية – جامعة عين شمس).

٣- د./ سها محمد عبد العظيم أحمد (مدرس الإليكترونيات - قسم الفيزياء – كلية البنات للآداب والعلوم والتربية – جامعة عين شمس).

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