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The Effect of Power MOSFET Materials on their Switching Performance

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Abstract

Power semiconductor devices have a great impact on the modern society electronic system applications. The study aims to improve the switching performance of power MOSFET devices based on materials with different bandgap structures and technologies. In this concern, the static electrical characteristics of three power MOSFET devices made of Silicon (Si-MTP20N15E; Eg = 1.12 eV), Silicon Carbide (SiC-TW107N65C; Eg = 3.25 eV) and Gallium Nitride (GaN-TPH3208PS-ND; Eg = 3.44 eV), operating at the enhancement mode were tested. Moreover, the design and implementation of their switching circuits were investigated at frequency of 1.0 kHz. In addition, the influence of their materials on the switching times was studied. From which, it is noted that, GaN MOSFET has the fastest switching ON/OFF times (0.3µs /0.34µs), rather than SiC and Si. Where, their switching ON/OFF times were reported to be (0.37µs /0.52µs and 0.76µs /0.8µs), respectively. These findings underscore the potential of wide bandgap materials in enhancing the performance of power electronic devices.

Keywords: Switching times, power devices, MOSFET materials, Silicon, Silicon Carbide and Gallium Nitride.

1.0. Introduction

The expansion of the renewable energy and electronic sectors increases the need for high power density and high switching performance of power devices in the applications at different frequencies. However, increasing switching frequency results in higher switching losses in power transistors, which may reduce the efficiency of power systems [1, 2].

Power MOSFET devices having different materials and energy band gap such as Si (Eg=1.12eV), SiC (Eg =3.25 eV) and GaN (Eg = 3.44 eV) have been subjected to extensive research [3]. They are characterized by high operating temperatures (Si: 150°C, SiC: 175°C

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and GaN: 150°C) and switching speeds, in addition they are considered to be the next evolutionary step for future in modern power applications [4,5].

In the present paper, the effect of the power MOSFET materials (Si, SiC and GaN) on their dynamic switching charecteristics are investigated at frequency of 1.0 kHz. In this concern, the switching circuits based on the tested power devices are designed and implemented for testing their dynamic switching characteristics.

2.0. Methodology and Circuit-setup

In this work, power MOSFET device with different materials (Si; MTP20N15E, SiC; TW107N65C and GaN; TPH3208PS-ND) operating at the enhancement mode are selected and tested, where their static electrical characteristics (I–V) are plotted using Tektronix curve tracer type 370A. From which, the ON-resistance (R_{ON}), generated power ($P_{gen.}$), dissipated power ($P_{dis.}$),and forward transconductance (g_{fs}), are calculated as follows [6-9].

The resistive parameter is described as R_{ON} and is given as:

$$R_{ON} = \frac{\Delta V_{DS}}{\Delta I_D} \quad \text{(1)}$$

The ON-resistance is equivalent to different components which are;

$$R_{ON} = R_{source} + R_{ch} + R_A + R_J + R_D + R_{sub} \quad \text{(2)}$$

Where:
R_{source}: MOSFET source resistance,
R_{ch} : MOSFET channel resistance,
R_A : MOSFET accumulation resistance,
R_J : JFET region resistance,
R_D : MOSFET drift region resistance and
$R_{sub.}$: MOSFET substrate resistance.

Output power generation of MOSFET device could be calculated using the following equation:

$$P_{gen.} \approx I_D V_{DS} \quad \text{(3)}$$

As well, the dissipated power of MOSFET device could be calculated using the following equation:

$$P_{dis.} = \text{Conduction Loss} + \text{Switching Losses} \quad \text{(4)}$$

Where:

$$\text{Conduction Loss} = I_D{}^2 R_{ON} \quad \text{(5)}$$

As well, switching losses are composed of the total gate charge loss, C_{OSS} loss and rise and fall time loss.

Switching loss = Total Gate Charge loss + C_{out} loss + rise and fall time loss…..(6)

Where:

C_{out} : the output capacitance of MOSFET device.

Moreover, the forward transconductance of MOSFET device could be calculated using the following equation;

$$g_{fs} = \frac{\Delta I_D}{\Delta V_{GS}} |V_{DS} \quad \text{……………………………………………………………………… (7)}$$

Where:

V_{DS}: drain-source voltage,
ΔI_D: drain current change and
ΔV_{GS}: gate-source voltage change.

2.1. Switching Circuit-setup

The investigated switching circuit-setup is shown in Fig. (1), it consists of power MOSFET device, external gate resistance ($R_{gex.}$), as well load resistance (R_L).

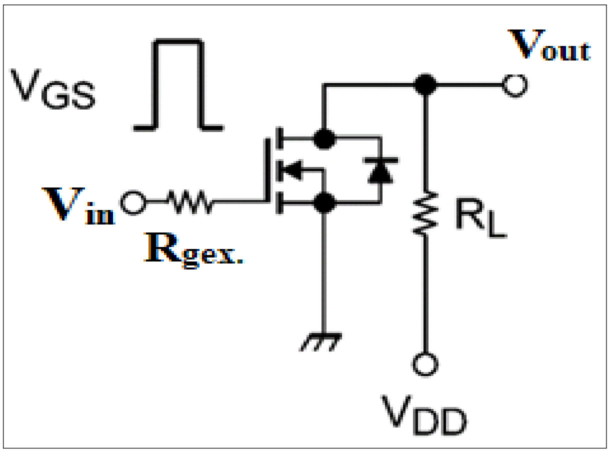


Fig.(1): Tested switching circuit.

2.2. Dynamic Switching Transient Times

Theoritically, the switching input/ output voltage waveforms combined with its dynamic switching transient times (delay/rise times; t_d/t_r, as well storge/fall times; t_s/t_f) are shown in Fig. (2). For insuring the best switching performance for the power MOSFET devices, the optimum circuit elements are selected carefully [10-12].

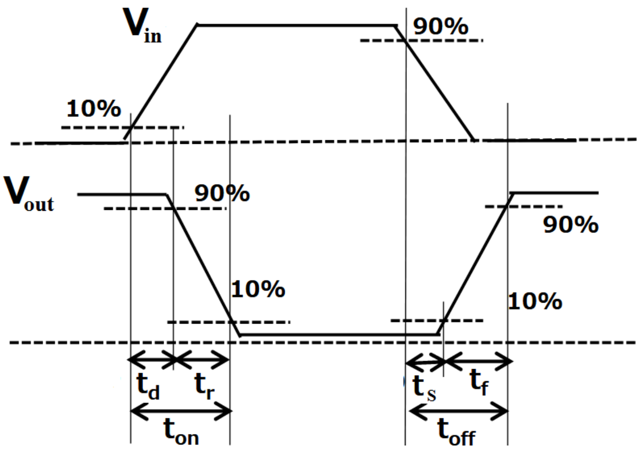


Fig.(2): Input/Output voltage waveforms.

The time required for a power device to switch to its conduction state (ON-time), is given by the following equation[11]:

$$t_{ON} = t_d + t_r \qquad (8)$$

Where:
t_{ON}: ON-time,
t_d: delay time and
t_r: rise time.

From Fig. (2), it is shown that the time needed from the transistor switch to start responding to a rising edge of the driving pulse (input) is called the delay time (t_d). Furthermore, the rise time is the finite time needed for the output voltage (V_{out}) to fall 90% to 10% of its maximum value.

While the turn OFF-time (t_{OFF}), is the time required for a MOSFET to switch to its disconduction state is given by the following equation [10]:

$$t_{OFF} = t_s + t_f \qquad (9)$$

Where:
t_{OFF}:OFF-time,
t_s: storage time and
t_f: fall time.

The storage time (t_s) is the time needed for the switch to start responding to a falling edge of the input voltage (V_{in}). While, the fall time (t_f) is the finite time needed for the output voltage (V_{out}) to rise from 10% to 90% of its maximum value.

The dynamic switching performance of the power switches are affected by several factors which are the operating conditions [input voltage (V_{in}) and the circuit elements such as [external gate resistance ($R_{gex.}$) as well, load resistance (R_L)].

2.2.1. Effect of the Input Voltage and the External Gate Resistance

The effect of the input voltage and external gate resistance variations on the dynamic switching transient times of the power devices are studied. The dynamic switching transient times of the tested MOSFET devices could be calculated using the following equations [8,13].

$$t_d \cong R_G C_{in} \ln\left(\frac{1}{1-\frac{V_{gp}}{V_{GS}}}\right) \quad (10)$$

Where:

R_G: the equivalent gate resistor ($R_G = R_{gi} + R_{gex.}$), R_{gi}: the internal gate resistance and $R_{gex.}$: the external gate resistance,

C_{in}: the equivalent input capacitance ($C_{in} = C_{GS} + C_{GD}$) as seen by the gate input circuit, where; C_{GS}: the internal gate-source capacitance and C_{GD} : the internal reverse transfer gate-drain capacitance (miller capacitance) where $C_{GD} > C_{GS}$.Using Miller theorem [14],[$C_{in} = C_{GS} + (1 + g_m R_L) C_{GD}$], where; g_m: the product of the slope of I_D and V_{GS} with operating dc point (Q),

V_{gp}: gate miller plateau voltage and

V_{GS}: gate-source voltage.

Considering $t_r \cong R_G C_{gd}\left(\frac{V_{DS}}{V_{GS}-V_{gp}}\right)$ ......(11)

Moreover $t_s \cong R_G C_{iss} \ln\left(\frac{V_{GS}}{V_{gp}}\right)$ ......(12)

As well $t_f \cong R_G C_{gd}\left(\frac{V_{DS}}{V_{gp}}\right)$ ......(13)

2.2.2. Effect of the Load Resistance

For the tested power MOSFET switches, the dynamic switching transient times dependency on the load resistance are studied. Concerning the fall time (t_f) dependency could be calculated using by the following equation [15-18]:

$$t_f = -R_L C_L \ln(V_{out\,10\%}/V_{out\,90\%}) \quad (14)$$

Where:

R_L: load resistance and

C_L: load capacitance.

3.0. Results and Discussions

The main aim of this work is to investigate the influence of the tested power MOSFET materials for the (Si-MTP20N15E, SiC-TW107N65C and GaN-TPH3208PS-ND) on their static characteristics as well their dynamic switching characteristics.

3.1. Devices Characteristics

The output and transfer static characteristics ofthe tested power MOSFET devices are carried out and plotted at different V_{GS} values depending on their materials.

3.1.1. Static Output Characteristics

The device materials effect on their (I-V) static output characteristics plotted at different V_{GS} values are shown in Fig. (3).For Si-device (3.5 – 6.0 Volts), and SiC (6.5 – 9.5 Volts) as well GaN (2.5 – 3.25 Volts).

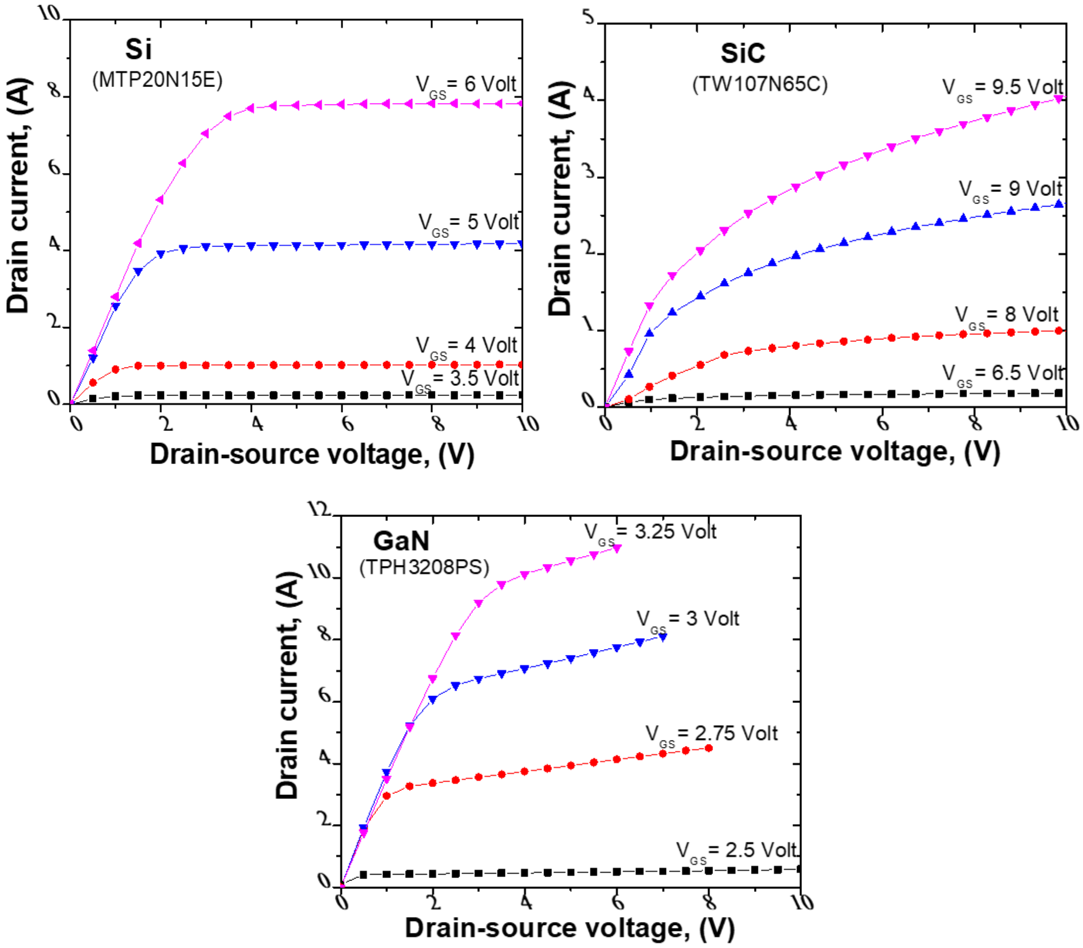


Fig. (3): (I-V) Characteristic curves of different MOSFET device materials, plotted at different V_{GS} values.

3.1.1.1 ON-Resistance of MOSFET Devices

ON-resistance (R_{on}) represents the internally resistance element of MOSFET device which is responsable for power disspation. Figure (4) explores the influence of increasing V_{GS} on R_{on} of the tested MOSFET materials. From which, it is clearly shown that, for Si-MOSFET, the value of R_{ON} decreases from 9.09 Ω to 0.6 Ω, measured at V_{GS} value of 3.5 Volt up-to 4.5 Volt, respectively. Also, SiC MOSFET, the value of R_{ON} decreases from 10 Ω to 0.46 Ω, measured at V_{GS} value of 6.5 Volt up-to 8.9 Volt.Whenever GaN MOSFET, the values of R_{on} decreases from 3.1 Ω to 0.31 Ω, measured at V_{GS} value of 2.5 Volt up-to 3.25 Volt, respectively. For higher values of V_{GS} a saturation conditions on R_{on} were observed.

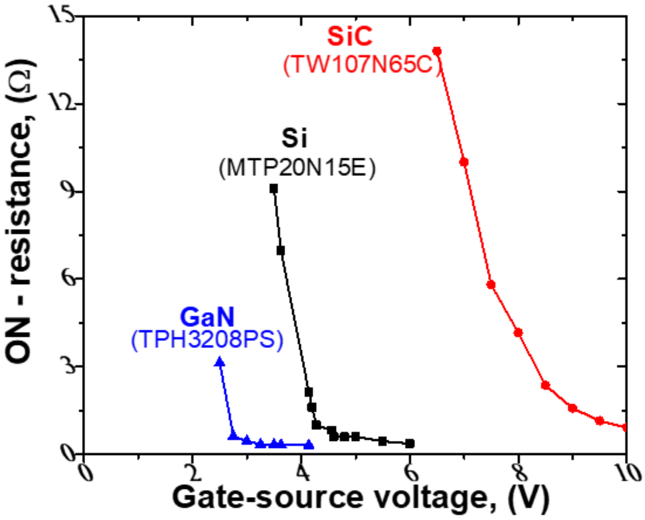


Fig. (4): Effect of V_{GS} on R_{on} for different MOSFET device materials.

3.1.1.2 Output Power Generation of MOSFET Devices

The influence of MOSFET materials on their output power generated are investigated and plotted for different V_{GS} values as shown in Fig. (5). It is clearly shown that, generally the output power generated depends on both voltages V_{GS} and V_{DS}. The higher power generated reaches the value of 79.8 W at V_{GS} = 6 Volt and 40 W at V_{GS} = 9.5 Volt, while the values of 60 W at V_{GS} = 3.25 Volt, for Si and SiC as well GaN, respectively.

It is noted that, these variations in output power generated may be attributed to the difference in their threshold values, as shown in Table (1).

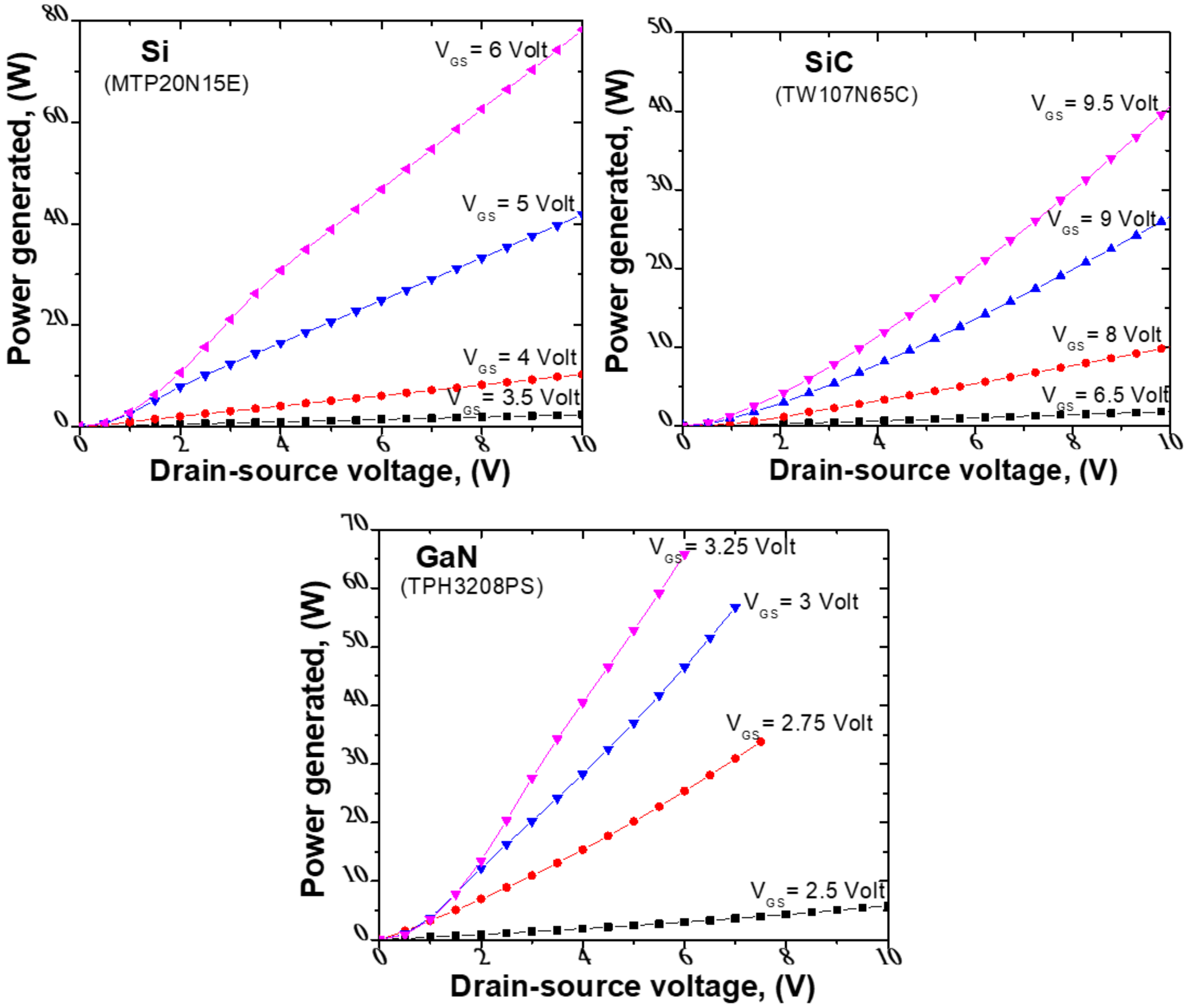


Fig. (5): (P-V) Characteristic curves of different MOSFET device materials, plotted at different V_{GS} values.

3.1.2. Transfer Characteristics of MOSFET Devices

The device materials influence on their transfer characteristics (I_D-V_{GS}) plotted at constant (V_{DS}= 6.0 Volt) are illustrated in Fig. (6). Their threshold voltage values are recorded to be 3.4, 6 and 2.1 Volt for Si, SiC and GaN MOSFET devices, respectively. After these values there is a remarked rapid increase in their drain current (I_D) values which reflected that, the devices are in conducting state. It is to be noted that, the tested GaN device has the lowest threshold value (2.1 Volt).

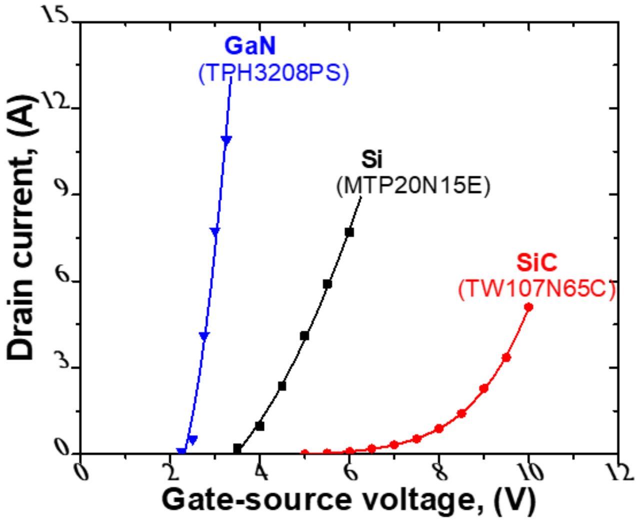


Fig. (6): Transfer characteristics for different MOSFET device materials.

In addition, the effect of the tested power device materials on their threshold voltage and the forward transconductance (g_{fs}) are summarized and tabulated in Table (1). It is observed that, GaN device has a higher conductivity (11.5 Ω^{-1}) which is attributed to its lower threshold voltage value (2.1 Volt).

Table (1): MOSFET device materials effect on their static electrical parameters.

Electrical Parameters	**Power MOSFET Devices**		
	Si	**SiC**	**GaN**
V_{Th}, Volt	3.4	6.0	2.1
g_{fs}, Ω^{-1}	3.08	1.14	11.5

3.2. Switching Characteristics

The switching characteristics of the tested MOSFET devices are experessed as their switching transient times (t_{ON}, t_{OFF}).

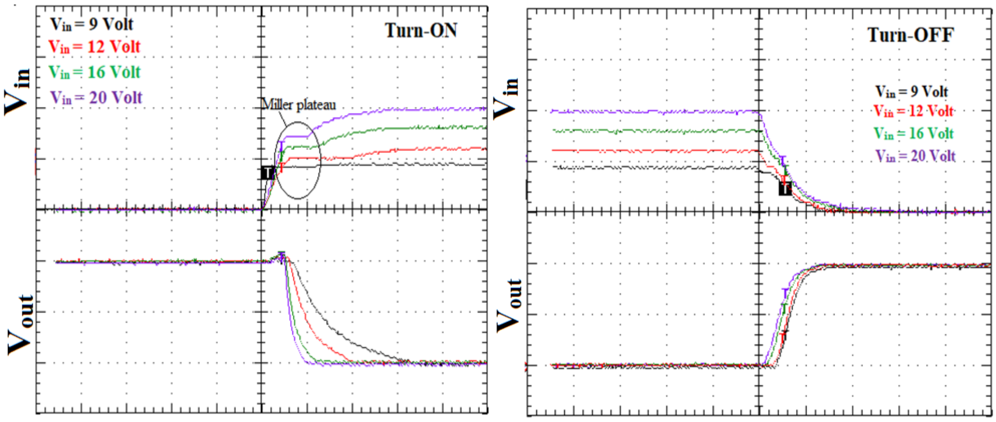
The switching output voltage waveforms of different MOSFET materials, are affected by different factors. Namely; input voltage (V_{in}) and external gate resistance ($R_{gex.}$) as well, load resistance (R_L).

3.2.1. Effect of the Input Voltage

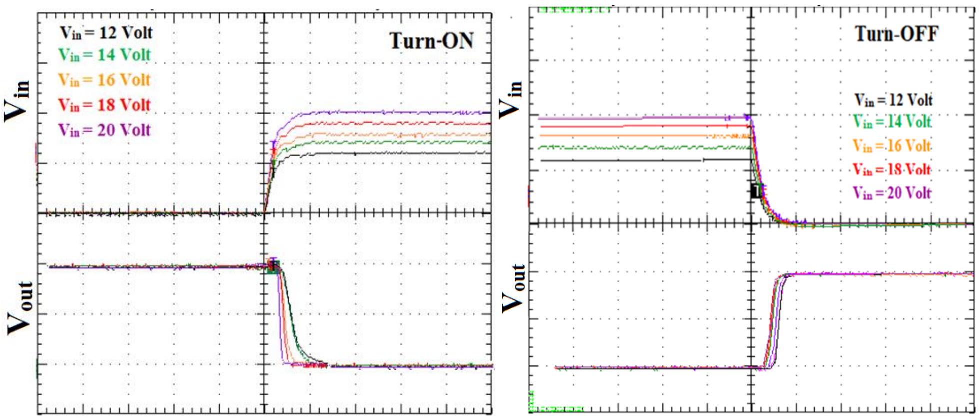
In this concern, Fig. (7) displays the cuptured input / output voltage waveforms (Y-axis: 10 V/div. and X-axis: 1.0 µs/div.) illustrating the switching behaviour of three different MOSFET materials under the influence of varying input voltage (V_{in}) from 9.0 volt up to 20 volt.

It is noted that, a Miller plateau is clearly observed in certain MOSFET device. Figure (7.a) highlights its presence in Si-MTP20N15E MOSFET waveform. This plateau arises due to the combined effects of input capacitance and the Miller capacitance.

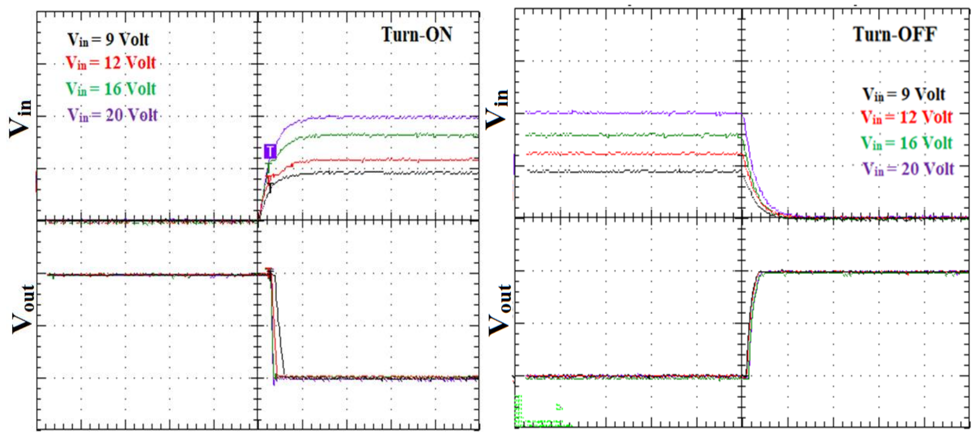
Conversely, SiC and GaN exhibit lower Miller capacitance compared to conventional MOSFETs, leading to lower switching losses and faster switching speeds as shown in Fig. (7.b, 7.c). Notably, The cascode topology of employed in GaN manages the Miller effect during transients (dv/dt), as evident in Fig. (7.c).



(a) Si-MTP20N15E MOSFET



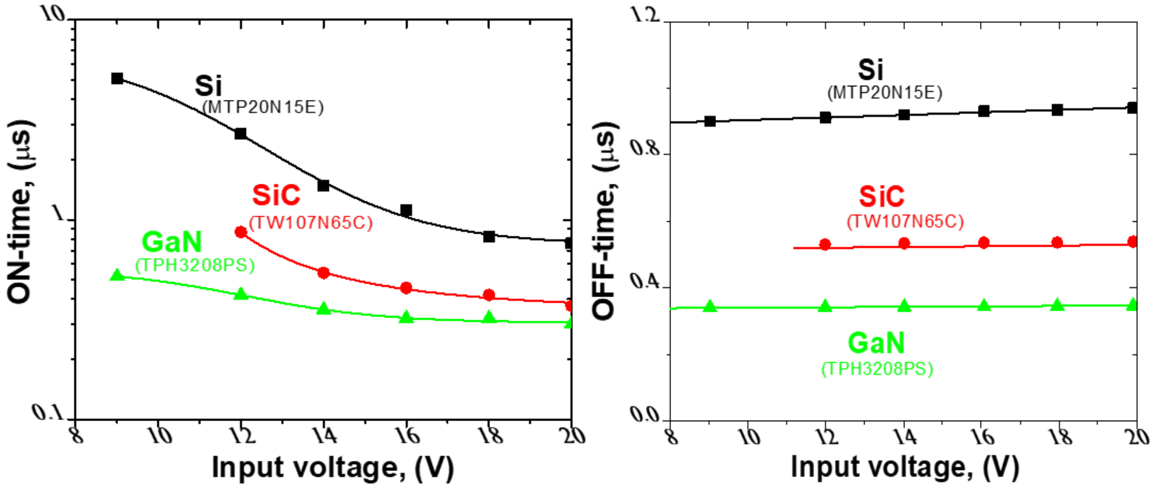
(b) SiC-TW107N65C MOSFET



(c) GaN-TPH3208PS-ND MOSFET

Fig. (7): The switching output voltage waveforms of different MOSFET materials dependency on the varitions of input voltage values.

In addition, depending on the switching output voltage waveforms (Fig.7), the switching transient times(t_{ON}, t_{OFF})of the tested MOSFET device materials are illustrated in Fig. (8). It is clearly shown that, their ON-times decreases by increasing input voltage value. Where its value decreases from 5.08 to 0.76 for Si, 0.865 to 0.37 for SiC and 0.52 to 0.3 for GaN by increasing of input voltage from 9 Volt to 20 Volt. In addition, the OFF-time of switch decreasesby increasing the input voltage value. Where its value slightly decreases from 1.04 to 0.9 for Si, 0.65 to 0.52 for SiCand 0.355 to 0.34 for GaN.

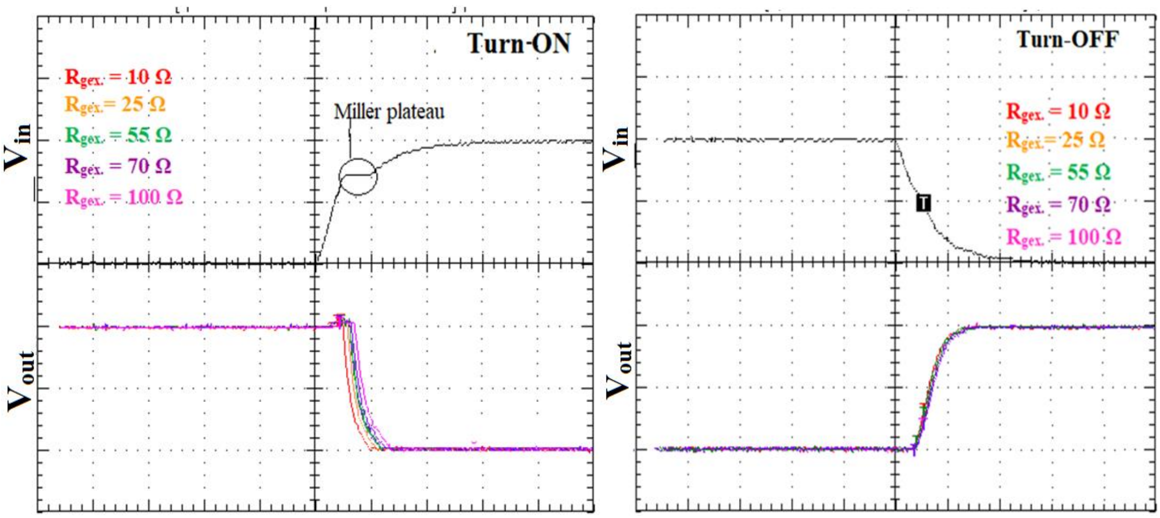


(a) (b)

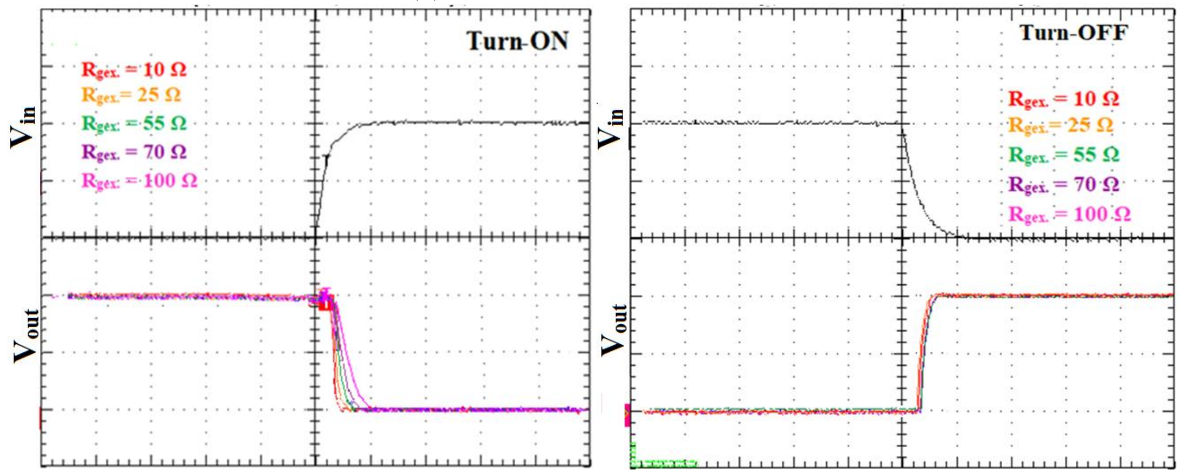
Fig. (8): Switching transient times of different MOSFET materials (a) ON-time and (b) OFF-time, plotted at different input voltage values.

3.2.2. Effect of the External Gate Resistance

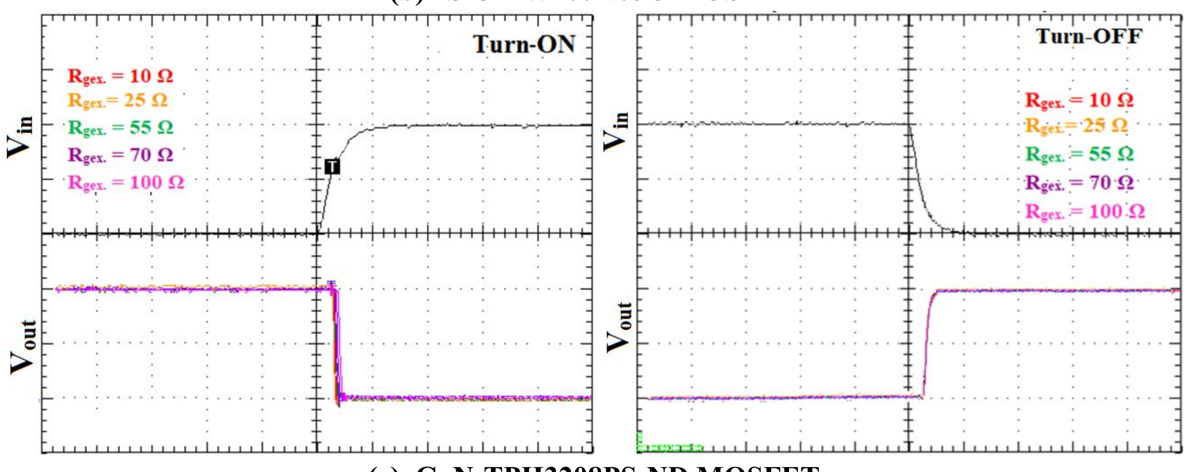
The influence of the external gate resistance ($R_{gex.}$) variation ranging from 10.0 Ω up to 100.0 Ω on the switching output voltage waveforms for different MOSFET materials is shown in Fig. (9). From which, it is clearly shown that, the external gate resistance variation show a remarked effect on the switching output voltage waveforms for different MOSFET materials. It is observed that, GaN-MOSFET device has the lowest dependency on $R_{gex.}$ than the other tested materials.



(a) Si-MTP20N15E MOSFET



(b) SiC-TW107N65C MOSFET

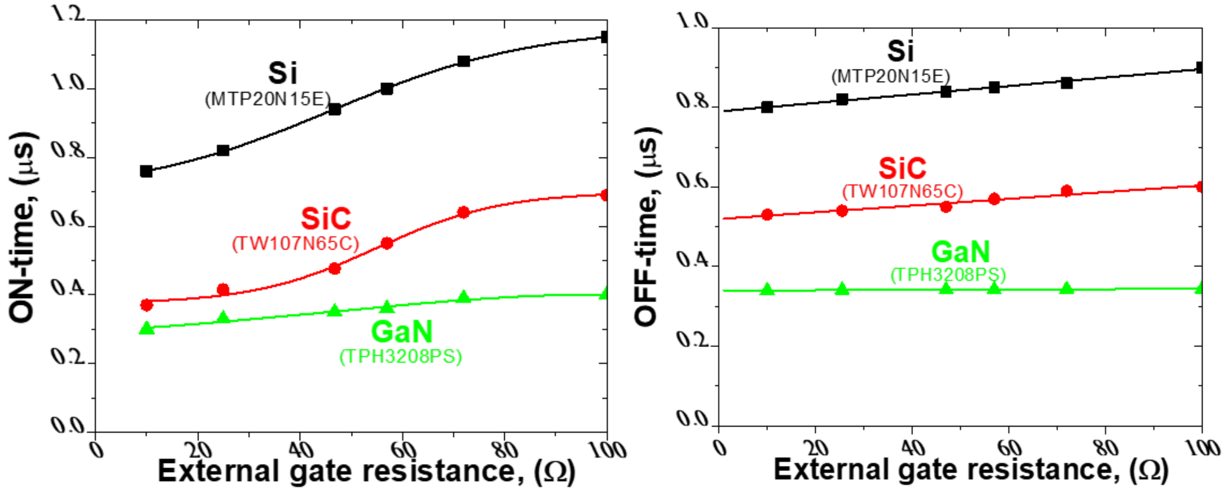


(c) GaN-TPH3208PS-ND MOSFET

Fig. (9): The influence of the external gate resistance on the switching output voltage waveformsfor different MOSFET materials.

In this concern, depending on the influence of the external gate resistance on the switching output voltage waveforms Fig. (9), the switching transient times (t_{ON}, t_{OFF}) of the tested MOSFET device materials are shown in Fig. (10). From which it is clearly shown that, their ON-times are affected by chaning of $R_{gex.}$ values. It is observed that, considering GaN switch its ON-time shows a little increases (from 0.3 up to 0.4 µs - duration time = 0.1µs) than SiC (from 0.37 up to 0.69 µs -duration time = 0.32 µs) and Si (from 0.76 upto 1.15 µs - duration time = 0.39 µs), respectively.

Moreover, for GaN switch its OFF-time shows a little increases (from 0.34 upto 0.344 µs -duration time = 0.004 µs) than SiC (from 0.52 up to 0.6 µs - duration time = 0.08 µs) and Si (from 0.8 up to 0.9 µs - duration time = 0.1 µs), respectively.

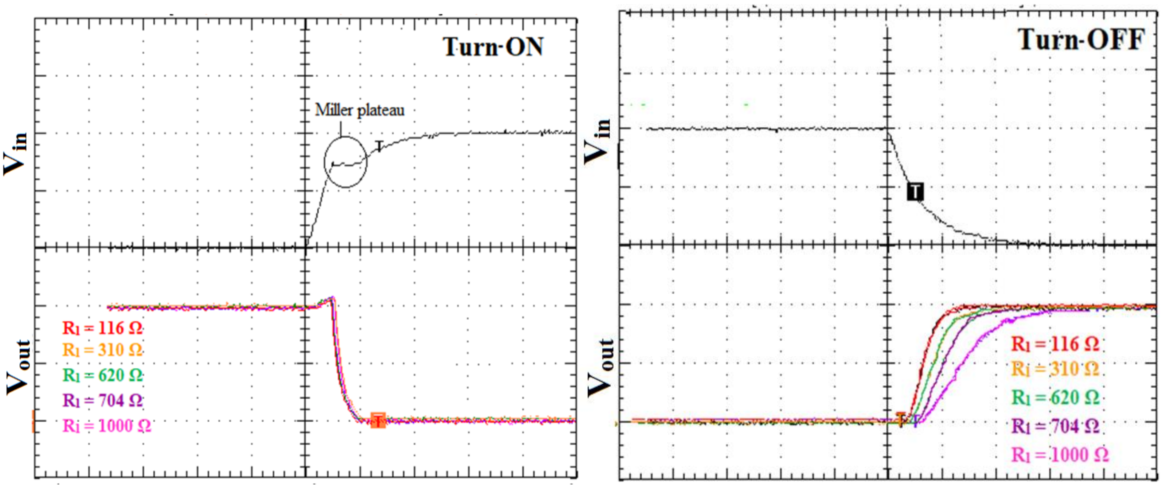


(a) (b)

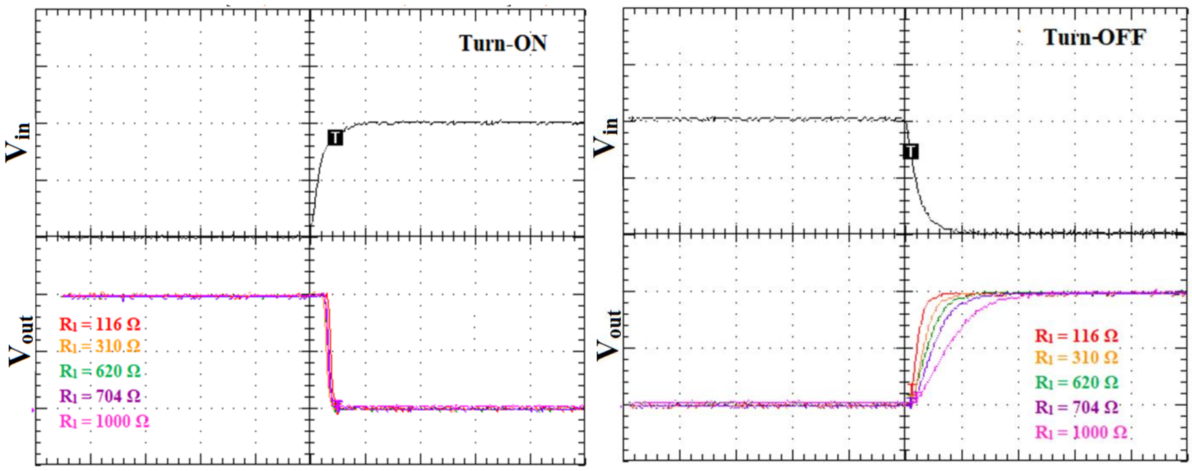
Fig. (10): Switching transient times of different MOSFET materials (a) ON-time and (b) OFF-time, plotted at different external gate resistance values.

3.2.3. Effect of the Load Resistance

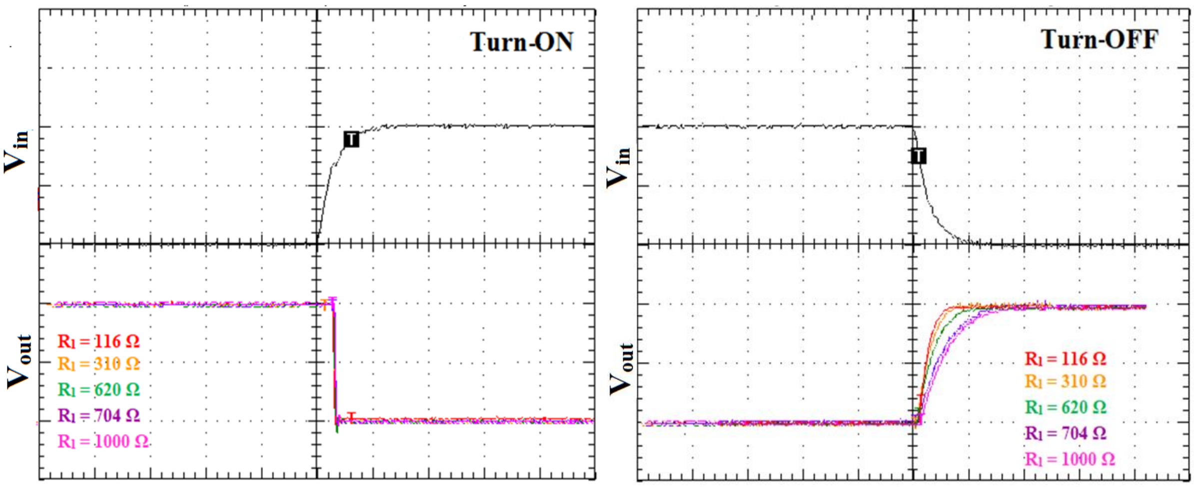
The dependency of output voltage waveforms for different MOSFETs materials on load resistance (R_L) variations from 116 Ω up to 1.0 kΩ is studied and plotted as shown in Fig. (11). The results clearly demonstrate a significant effect of R_L variation on the output waveforms for all materials. Notably, GaN MOSFETs exhibit the least dependence on changing R_L values compared to the other tested devices.



Si-MTP20N15E MOSFET



(b) SiC-TW107N65C MOSFET

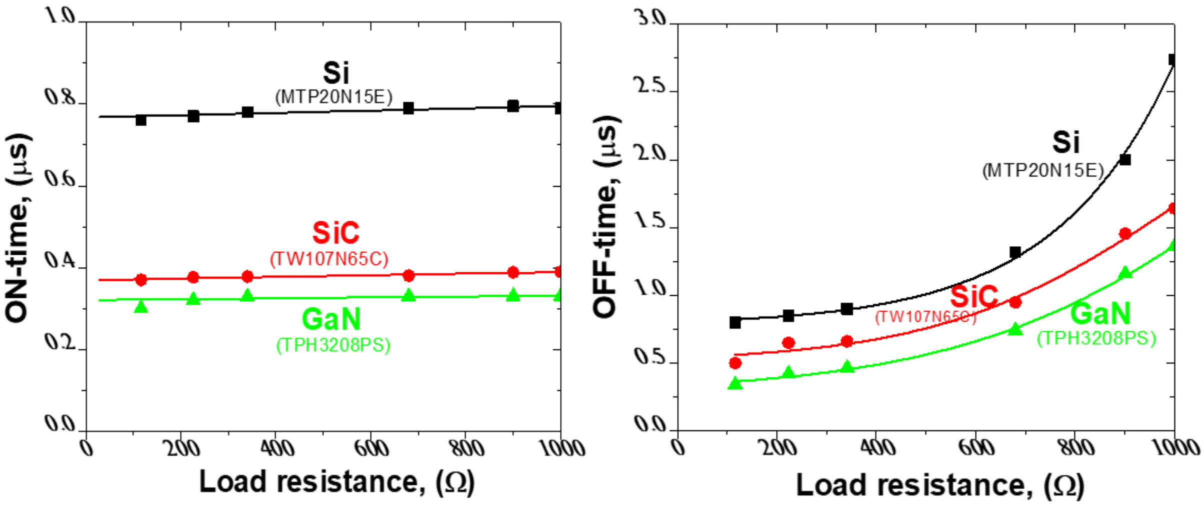


(c) GaN-TPH3208PS-ND MOSFET

Fig. (11): Influence of load resistance on the switch output voltage waveforms for different MOSFET materials.

Concerning the influence of the load resistance on the switching output voltage waveforms (Fig.11), the switching transient times (t_{ON}, t_{OFF}) of the tested MOSFET device materials are illustrated in Fig. (12). From which it is clearly shown that, their ON-times are slightly increases by increasing $R_L$values. It is observed that, considering GaN switch its ON-time shows slightly increase (from 0.3 up to 0.32 µs - duration time = 0.02 µs) compared with SiC (from 0.37 up to 0.395 µs - duration time = 0.025 µs) and Si (from 0.76 up to 0.79 µs - duration time = 0.03 µs), respectively.

On the other hand, their OFF-time shows a remarkable increase with increasing the load resistance value which is consistent with (Eq. 13). Considering GaN switch its OFF-time shows the lowest increase (from 0.34 up to 1.36 µs - duration time =1.02 µs) followed by SiC (from 0.52 up to 1.64 µs - duration time =1.12 µs) and Si (from 0.8 up to 2.74 µs - duration time = 2.06 µs), respectively.



(a) (b)

Fig. (12): Switching transient times of different MOSFET materials(a) ON-time and (b) OFF-time, plotted at different load resistance values.

The proposed switching circuit is designed after selecting the optimum suitable operating conditions and circuit element values (V_{GS} = 20 Volt, $R_{gex.}$=10 Ω and R_L= 116 Ω) according to the obtained results as shown in Fig. (13).

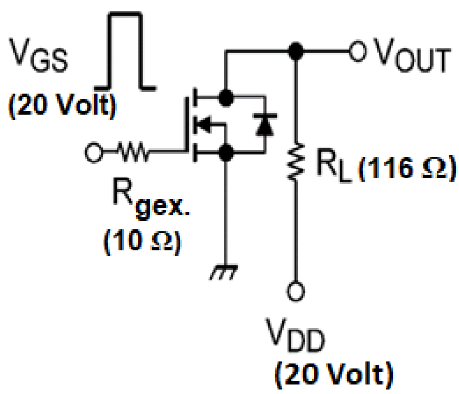


Fig. (13): The proposed switching circuit.

Figure (14) compares the switching output voltage waveforms of the three tested MOSFET device materials. Notably, GaN MOSFETs exhibit superior performance in terms of both transient times and Miller plateau suppression over the other tested devices.

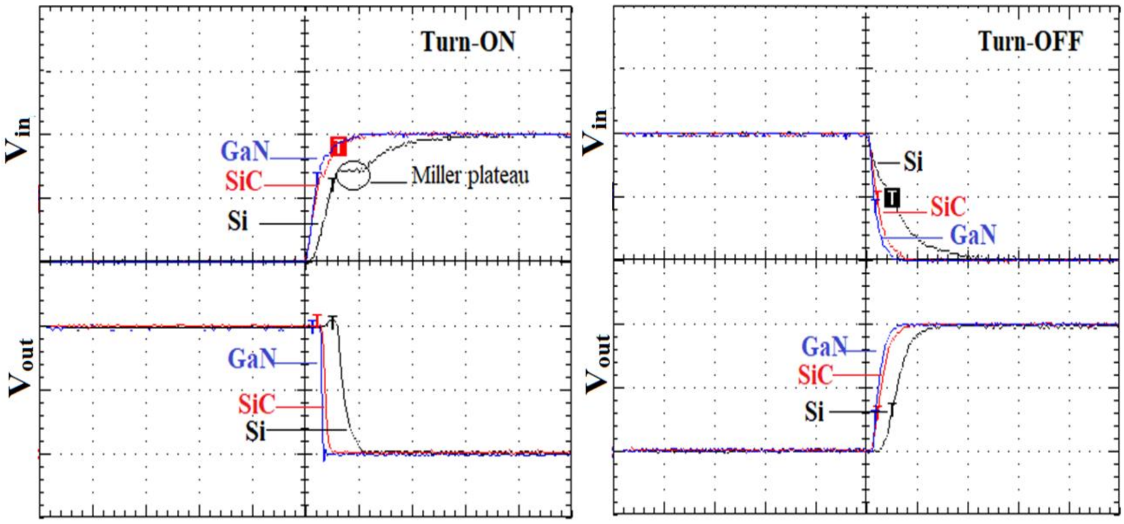


Fig. (14): The influence of different MOSFET device materials on the switching output voltage waveforms.

For comparison, Fig. (15) shows the effect of MOSFET device materials on the switching transient times. From which, it is observed that, for GaN MOSFET has the best switching transient times with ON-time of 0.3 µs and OFF-time of 0.34 µs at 1.0kHz. This is significantly faster than both Silicon Carbide (SiC) and Silicon (Si). Where, SiC MOSFET has ON- and OFF-times of 0.37 µs and 0.52 µs, respectively, while Si has ON- and OFF-times of 0.76 µs and 0.8 µs, respectively.

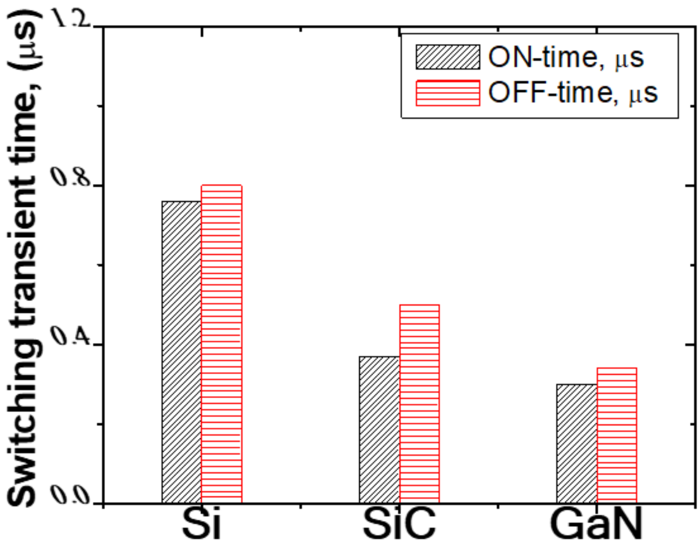


Fig. (15): Effect of MOSFET device materials on the switching transient times.

4.0. Conclusions

From the experimental work, results, analysis and interpretation, it could be concluded that**,** GaN power MOSFET (TPH3208PS-ND**)** emerges as a superior switching technology based on its electrical characteristics. This advantage stems from its lower ON-resistance and faster switching times. Additionally, SiC power MOSFET (TW107N65C**)** offers significant improvements over traditional Si power MOSFET (MTP20N15E).The timing performance of a switch is influenced by several factors inherent to the operating conditions and system design. These factors include load resistance, input voltage, and external gate resistance. For optimal switching circuit performance, a lower load resistance, lower external gate resistance, and higher input voltage are preferred.

5.0 Conflicts of Interest

The authors confirm that there are no known conflicts of interest associated with this publication and there is no relevant financial or non-financial interests to disclose.

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الملخص العربى

تأثير نوع مواد ترانزستور المجال الأكسيدي المعدني ذات القدرة على أدائها كمفاتيح الكترونية

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المخلص العربى :

تناول البحث المعروض دراسة عملية وتطبيقية عن جدوى إستخدام نبائط أشباه الموصلات ذات القدرة (MOSFET) في بعض تطبيقات الأنظمة الإلكترونية التي تخدم المجتمع الحديث، حيث تم تطويرتلك النبائط باستخدام مواد ذات نطاق طاقي مختلفة لتحسين أداء عملها كمفاتيح إلكترونية. في هذا الصدد، تم إختيار ودراسة الخصائص الكهربائية المميزة لثلاثة نبائط مختلفة مصنعة من السيليكون (Si-MTP20N15E; Eg = 1.12 eV) وكربيد السيليكون (SiC-TW107N65C; Eg = 3.25 eV) ونيتريد الجاليوم (GaN- TPH3208PS-ND; Eg = 3.44 eV). حيث تم إستنتاج المعاملات الكهربائية المختلفة بهدف تصميم و تنفيذ دوائر المفاتيح الإلكترونية، تعمل عند تردد ١,٠ كيلو هرتز، بنمط تشغيل المعزز(Enhancment mode). حيث أثبتت الدراسة أن نبيطة الترانزستور من مادة نيتريد الجاليوم سجلت أسرع إستجابة بأقل زمن تشغيل / إيقاف (0.32μs /0.34 μs)، عن مادتي كربيد السيليكون و السيليكون. حيث سجلت أزمنة تشغيل / إيقاف الخاصة بهم (0.37μs/0.52μs and 0.76μs /0.8μs)، على الترتيب. حيث أكدت هذه النتائج على إمكانية المواد ذات النطاق الطاقي الواسع في تعزيز أداء نبائط أشباه الموصلات ذات القدرة (MOSFET).