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Research Article

Comparison of Si and GaN Semiconductor Based SEPIC DC-DC Led Driver

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Abstract

Recently, in power electronics, studies on creating new semiconductor concept is so popular. As a result of this studies, using of wide band gap semiconductors (WBG) such as Silicon Carbide (SiC) Mosfets and Gallium Nitride High Electron Mobility Transistors (GaN-HEMT) has gained much attention due to the its high switching frequncy capability and providing high power density feature. Furthermore, in the field of illumination, power leds is so eye cathing because of their high efficinecy feature with respect to other kind of illumination such as metal halide and incandesant bulbs. In addition, to operate power leds, DC power is required and the most efficient way to provide required DC power is to use one of the DC-DC converter topologies. Buck-boost derived converter topology is the best solution fort that purpose. One of the flashiest topologies is single ended primary inductor (SEPIC) converter. Therefore, in this paper, comparison of SEPIC DC-DC converter-based power led driver using silicon (Si) and enhancement mode (E-mode) GaN-HEMT based power switch is made. Also, SEPIC led drivers are designed for 10W power led and implementations for both power switches are realized. In addition, switching frequency of converters is chosen as 100kHz and dsPIC30F4011 micro controller is used to produce PWM signal for power switches and to limit maximum current of power leds by using ACS712 current sensor. By means of the applications, power led current, power led voltage, input current, input voltage and input side inductor current, switch voltage, gate resistor voltage are measured and compared for both Si and GaN based power switches. As a result of comparisons, altough similar results are obtained, circuit using Si MOSFET has slightly higher efficiency than E-Mode GaN-HEMT used circuit. Besides, circuit using E-Mode GaN-HEMT is more sensitivity to the noises and needs extra care for its soldering.

Keywords: GaN, Power Led, SEPIC.

Si ve GaN Yarı İletken tabanlı SEPIC DC-DC Led Sürücülerin Karşılaştırılması

Öz

Son zamanlarda, güç elektroniği alanında, yeni yarıiletken konsepti oluşturma üzerindeki çalışmalar çok popülerdir. Bu çalışmalar sonucunda, Silisyum Karbit (SiC) ve Galyum Nitrid Yüksek Elektron Mobilite Transistörleri (GaN-HEMT) gibi geniş bant boşluk yarıiletkenleri (WBG) kullanımı, yüksek frekans anahtarlama kapasitesi ve yüksek güç yoğunluğu sağlama özelliği nedeniyle, çok ilgi çekmektedir. Ayrıca, aydınlatma alanında, güç ledleri, matal halide ve enkandesant lambaları gibi diğer aydınlatma türlerine göre yüksek verim özellikleri yüzünden çok göz alıcıdır. Ek olarak, güç ledlerinin çalıştırmak için DC güç gereklidir ve ihtiyaç olan DC gücü sağlamak için en verimli yol, bir DC-DC converter yapısı kullanmaktır. Bu amaç için en iyi çözüm düşürücü-yükseltici tabanlı dönüştürücü topolojisidir. En gösterişli yapılardan birisi tek sonlu birincil endüktans dönüştürücüdür (SEPIC). Bu nedenle, bu çalışmada, Silisyum (Si) MOSFET ve kanal oluşturmalı mod (E-mod) GaN-HEMT Transistor tabanlı yarı iletken anahtar kullanan, SEPIC DC-DC dönüştürcü tabanlı güç ledi sürücü devrelerinin karşılaştırılması yapılmıştır. Ayrıca, SEPIC led sürücüleri 10W güç için tasarlanmıştır ve her iki güç anahtarı için uygulaması ayrı ayrı gerçekleştirilmiştir. Ek olarak, dönüştürücülerin anahtarlama frekansı 100 kHz olarak seçilmiştir ve güç anahtarları için PWM sinyali üretmek ve ACS712 akım sensörü üzerinden güç ledleri maksimum akımını sınırlandırmak için dsPIC30F4011 mikrodenetleyicisi kullanılmıştır. Gerçekleştirilen uygulamalar üzerinden, güç ledi akımı, güç ledi gerilimi, giriş akımı, giriş gerilimi ve giriş tarafı bobin akımı, anahtar gerilimi, kapı direnci gerilimleri ölçülmüştür ve hem Si hem de GaN tabanlı güç ledi uygulaması için karşılaştırılmıştır. Karşılaştırmalar sonucunda, benzer sonuçlar elde edilmesine ragmen, Si Mosfet kullanan devrenin verimi, E-Mod GaN-HEMT li devreye göre çok az yüksek olarak elde edilmiştir. Ayrıca, E-Mod GaN-HEMT li devrenin gürültülere karşı daha hassas olduğu tespit edilmiştir ve lehimi yapılırken daha fazla dikkat gerekmektedir.
Anahtar Kelimeler: GaN, Güç Ledi, SEPIC.

1. Introduction

Research about improving the efficiency, power density, switching current and voltage capability and switching frequency of power electronics devices are always an important topic for both engineering and material science. Furthermore, recently, the use of wide band gap semiconductors (WBG) that are silicon carbide (SiC) and Gallium nitride (GaN) based power switches are taking much attention. Such semiconductor is called as wide band gap semiconductor because of the band gap is larger than silicon-based semiconductors and their band gap energy are in the range of 2-4eV, whereas conventional silicon semiconductors have band gap energy between 1-1.5eV (Yoshikawa et al., 2007). Especially for high voltage application, SiC MOSFET is used with good performance, for low voltage, high power and high frequency applications GaN based power switches are seems to be a good solution. Other eye-catching topic of electrical engineering is illumination, and recently, power leds have been used for that purpose due to their high efficiency features with respect to other illumination methods such as incandesant and metal halide bulbs. Furthermore, to drive power leds, DC power is required, and to provide this DC power, use of DC-DC power electronics converter is efficient way. However, there are three main DC-DC converter topology that are buck, boost, buck-boost converters and using buck-boost or buck-boost derived topology is good choice to adjust illumination level of power led in wide range. One of the best buck-boost derived converter topology is SEPIC converter giving sufficient performance.

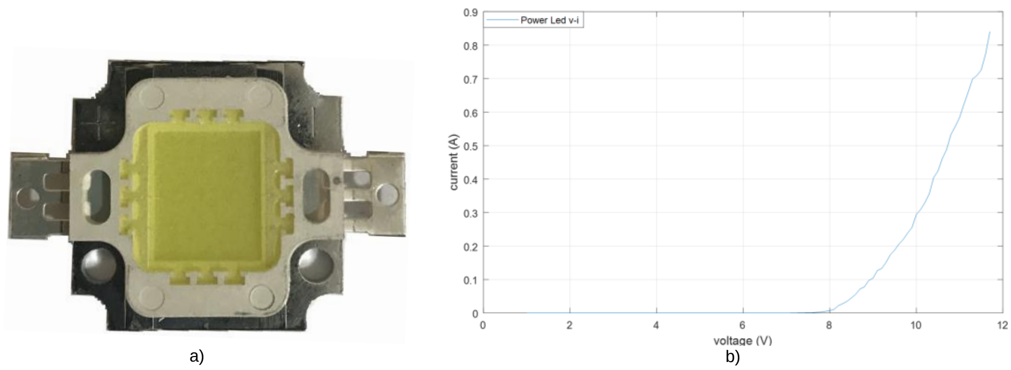
Some of the related studies are conducted in literature as follows; Gao et al. (2020) presents modified SEPIC converter to realize soft switching feature using GaN switch. Gate drivers is designed in Zhang et al. (2017) for GaN switch in resonant converter using isolated SEPIC. Saif et al. (2017) realizes SEPIC converter design for 1.5 MHz switching frequency and 100W power using GaN switch. Isolated SEPIC converter using GaN switch with 2 MHz switching frequency is presented in Xu et al. (2017). Alharbi et al. (2018) realizes interleaved SEPIC converter by using SiC power switch for renewable application. In order to improve power density of high switching frequency SEPIC converter using GaN switch with PCB embedded inductor is presented in Dou et al. (2018). Maharjan et al. (2017) carries out the application of SEPIC converter using separately inductors with SiC and Si power switches for battery charging purpose. Application of coupled inductor-based boost led drive using GaN switch with 500 kHz switching frequency with 120V output voltage is done in Gao et al. (2019). Wang et al. (2017) realizes a study using SEPIC and LLC converter for power led driver with power factor correction.

Most of the studies defined in references realized the usage of the GaN switch with higher frequency such as 500kHz-2Mhz as in Saif et al. (2017), Xu et al. (2017), Gao et al. (2019) and more than 12V output voltage with relatively higher power than 10W as in Gao et al. (2020), Saif et al. (2017), Alharbi et al. (2018), Maharjan et al. (2017), Gao et al. (2019). However, in this paper, SEPIC converter based led driver application for up to 10W power with up to 12V output voltage is realized by using Si MOSFET and E-Mode GaN-HEMT based power switches. The converters have also 100kHz switching frequency and switching signal is obtained by dsPIC30F4011. Also, power led maximum current is measured by ACS712 and limited by microcontroller. By means of the applications, power led current, power led voltage, input current, input voltage and input side inductor current, switch voltage, gate resistor voltage are measured and compared for both Si MOSFET and E-Mod GaN-HEMT based power switches. As a result of comparisons, altough similar results are obtained, circuit using Si MOSFET has slightly higher efficiency than E-Mode GaN-HEMT used circuit. Besides, circuit using E-Mode GaN-HEMT is more sensitivity to the noises and needs extra care for its soldering.

2. Material and Method

2.1. Power Led

Recently, in illimunaiton, power leds have been preferred to be used much. In Fig. 1 a), power led produced as a chip, used in this paper is shown. In order to derive, equivalent circuit and to find operating point when its connected to converter, it is required to obtain current-voltage charachteristic. In Fig. 1 b) the current-voltage characteristic of power led is derived by using Fluke 15B-17B multimeters as shown in Fig. 1 b) as in Sehirli (2020). This charachteristic is sketched after measuring current and voltage of power led that is connected to dc power supply by changing power supply voltage from ‘0’ V to close to maximum power led voltage that is 12V with the increment of 0.1V.



a) b)

Figure 1. a) power led, b) Current-voltage charachteristic of power led

By using current-voltage charachteristic of power led obtained as in Fig. 1 b), electrical equivalent circuit of power led used in this study, can be derived in Fig. 2, as in Sehirli (2020). In this equilavelent circuit, it is understood that the thresold voltage of power led, meaning the voltage that power led draws a current from supply, is ‘7.6’ V. Also, average resistance of power led is calculated as 4.88Ω, with the principle of the ratio between power led voltage chagining maximum to minimum with power led current drawning just after thresold voltage to measured maximum power led current.

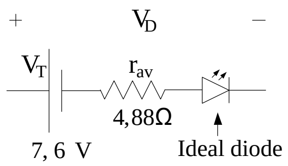


Figure 2. Electrical equivalent circuit of power led

2.2. SEPIC DC-DC Led Driver

In order to provide required DC power to operate power led efficiently, one of DC-DC converter topology should be used. Also, to adjust power led illumination level, buck-boost derived topology providing higher or lower voltage with respect to input voltage, gives flexibility. One of the best buck-boost derived DC-DC converter is SEPIC converter shown in Fig. 3. It is seen by the figure that SEPIC DC-DC converter consists of two inductor, two capacitor, power switch and a diode. In SEPIC converter, inductors can be wounded coupled meaning each inductor can be wound in the same core and it gives the advantage of using just one magnetic core. With SEPIC converter based led driver, power led voltage can be adjusted higher or lower voltage than input DC supply and because of the inductor at input side, input current may not have discontinuity like a conventional buck-boost converter. Furthermore, it can reduce to use of input filter parameters values as in Falin (2008), Zhang (2013), Rashid (2014).

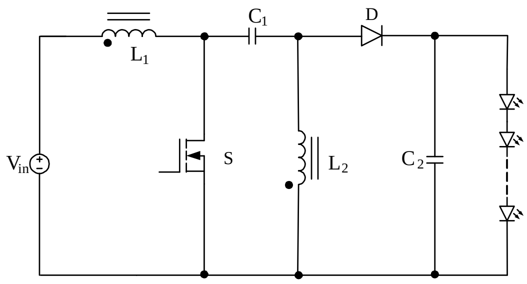


Figure 3. SEPIC DC-DC Converter Based Led Driver

The operation of SEPIC converter is summarized as follows; when switch is on position, inductor L_1 is energized and begin to store energy and its current increases linearly, also capacitor C_1 transfer its energy to inductor L_2, and energy stored in capacitor C_2 is transfered to the power led. When the switch is of position, input power supply and inductor L_1 charges capacitor C_1, also power suppy, inductor L_1 and inductor L_2 feed the power led. Passive components, L_1, L_2, C_1 and C_2 of the converter can be chosen by using (1-2) as in Falin (2008), Zhang (2013), Rashid (2014).

$$L_{1m} = L_{2m} = D\frac{V_i}{2\Delta I_L f_{sw}} \tag{1}$$

$$C_1 = C_2 \geq \frac{I_o D}{V_{rip} f_{sw}} \tag{2}$$

In (1), L_{1m} and L_{2m} means maximum inductance values of L_1 and L_2 in order to provide the operation of SEPIC converter in disconntinuous conduction mode (DCM), if the values of L_1 and L_2 is higher than L_m, converter will be oprated in continuous conduction mode (CCM). Also, in (1-2), V_i, ΔI_L, f_{sw}, D, I_o, V_{rip} mean input voltage, inductor current ripple, switching frequency, duty cycle, output current and voltage ripple, respectively.

3. Results and Discussion

3.1. Applications

Phisical implementation of SEPIC led driver circuits for both Si MOSFET and E-Mode GaN-HEMT power switch are realized. Both circuits are designed with the same specification with respect to parameters used and identical. In the first designed SEPIC led driver, IRF540N MOSFET is used as a power switch. In second, SEPIC led driver, GS61004B E-Mode GaN-HEMT Transistor having equivalent current, voltage rating with IRF540N is used. Applications are realised with 100kHz switching frequency for 12V output voltage and 10W output power. To produce PWM signal, dspic30F4011 microcontroller is used. Also, maximum power led current is measured by ACS712 current sensor and limited by microcontroller. In Fig. 4, a), b) SEPIC led driver circuits and application environment are shown, respectively.

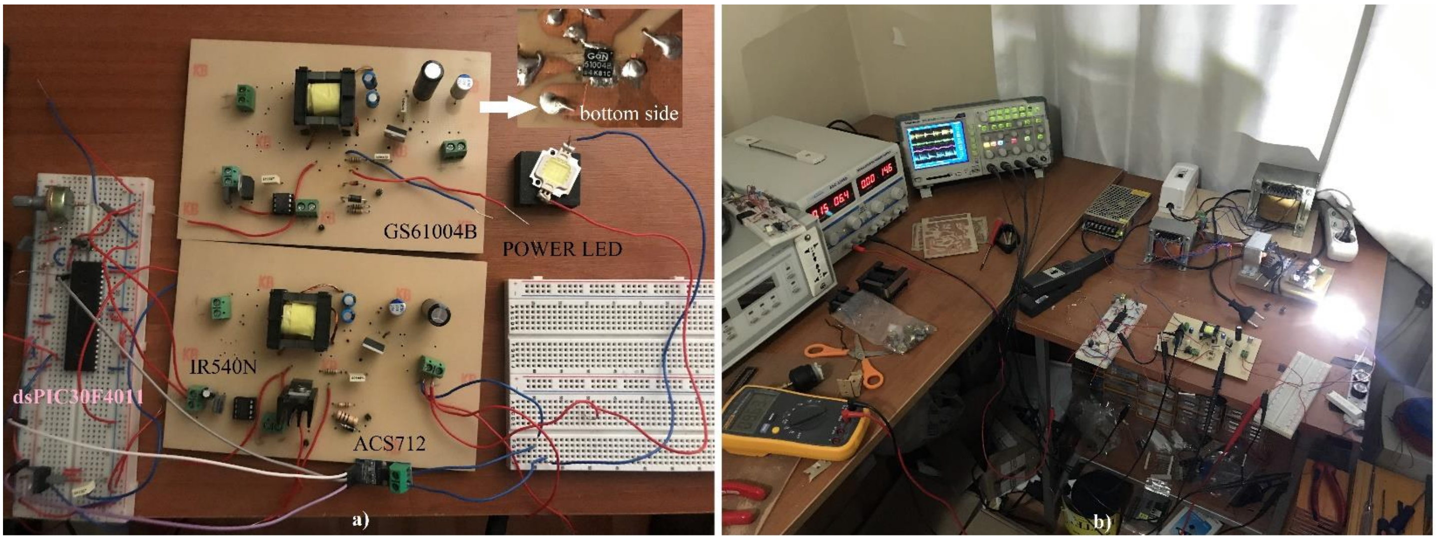


Figure 4. a) SEPIC Led Driver Circuits, b) Application Environment

By means of the applications, power led voltage, power led current, input supply voltage and current, power switch PWM signal, power switch gate resistor voltage are measured for both SEPIC converter using Si MOSFET and E-Mode GaN-HEMT. All the measurements are conducted by using TPS2024P four isolated channel Tektronix oscilloscope, A622 current probe, voltage probes and Fluke 15-17B multimeters.

Parameters that are L_1, L_2, C_1 and C_2 are chosen after calculation with respect to (1-2) and used in application is summarized in Table 1.

Table 1. Application Parameters

L_1	L_2	C_1	C_2	C_{in}	f_{sw}
18µH	*14,5µH*	*20µF*	*1220µF*	*10µF*	*100kHz*

In Fig. 5, IRF540N Si MOSFET and GS61004B E-Mode GaN E-HEMT Transistor used in this paper is shown with their dimensions. It is understood by the figure that dimension of the GS61004B is much smaller than IRF540N.

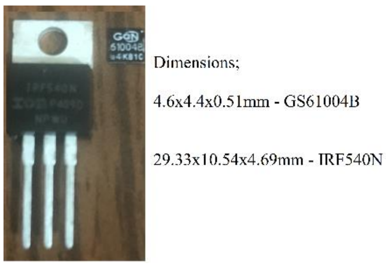


Figure 5. Si MOSFET and E-Mode GaN-HEMT Power Switch

In Fig. 6. Application circuit of SEPIC converter based led driver is shown. As a filter, a capacitor is added in input of the converter. Also, ACS712 current sensor is series connected with the power led.

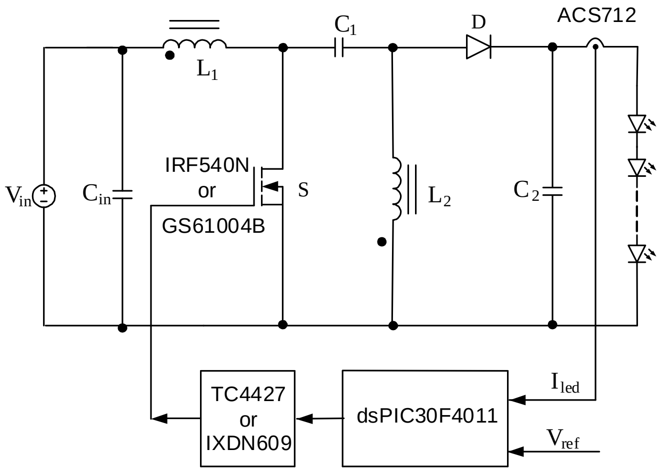


Figure 6. Application Circuit

Furthermore, for IRF540N Si MOSFET, TC4427 driver IC and for GS61004B E-Mod GaN-HEMT, IXDN609 driver IC is used. PWM signal for power switches is produced by dsPIC30F4011 microcontroller and maximum power led current is limited by microcontroller as well.

3.2. SEPIC Led Driver with Si Mosfet

SEPIC led driver is first realized by using IRF540N Si MOSFET as a power switch. Its maximum drain current and drain-source voltage are 33A, 100V respectively and it needs maximum ∓ 20V gate-source voltage for switch on and off. In the application, as a V_{GS} voltage, PWM with 16V magnitude is applied.

In Fig. 7 power led voltage, input voltage, input current and switch voltage is shown, repectively. Because of the switch off, power led voltage has some pulses. However, input voltage has not got any distortion due to the switching. Also, the peak voltage value of the power switch is obtained as 58-64V.

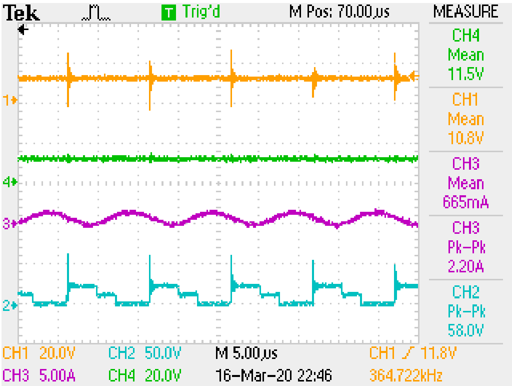


Figure 7. Led Voltage, Input Voltage-Current, Switch Voltage Waveform, respectively

In Fig. 8. Power led voltage, input voltage, power led current, power switch voltage is shown, respectively. Similar pulses in power led voltage as in Fig.7 because of the switching off is also obtained in this figure. Also, there is no distortion on input voltage because of switching. Furthermore, power led current is obtained as pure dc without any distortion.

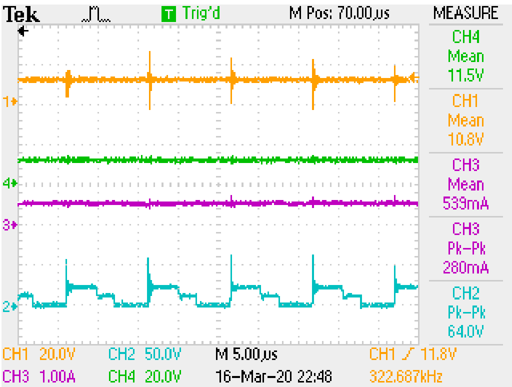


Figure 8. Led Voltage, Input Voltage, Led Current, Switch Voltage Waveform, respectively

In Fig. 9 gate resistor voltage, PWM signal, input side inductor L_1 current and switch voltage is shown. It is seen that gate resistor voltage is obtained as voltage spikes, which is why the input impedance of Si MOSFET is too high and MOSFET does not draw continous gate current. Also, frequency of PWM signal meaning the swicthing frequency is measured as 97,92 kHz wheras it is applied by microcontrolled as 100kHz. It seems that %2 measurement error is occured. Also, L_1 inductor current shows that converter is operated in DCM mode meaning currents drop to ‘0’ A and with limited time it has ‘0’ A value. Power switch voltage is obtained the same as in Fig. 8 and Fig. 7.

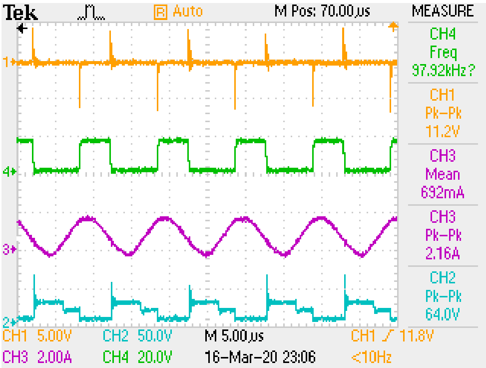


Figure 9. Gate Resistor Voltage, PWM Signal, L_1 current, Switch Voltage Waveform, respectively

In order to determine gate current, gate resistor voltage is measured, the gate resistor value is 10Ω. So, the gate current is obtained dividing gate resistor voltage to 10Ω. As it seen by Fig. 9, gate current is obtained by current spikes because of the gate-source capacitance and its value is around 0.5A.

3.3. SEPIC Led Driver with GaN Based Power Switch

SEPIC led driver is also realized by using GS61004B E-Mode GaN-HEMT Transistor. Its maximum drain current and drain-source voltage is 38A, 100V respectively. To drive this E-Mode GaN-HEMT transistor, the gate-source (V_{GS}) voltage should be between -10V, +7V. In the application, as a V_{GS} voltage, PWM with 6V magnitude is applied.

In Fig. 10, power led voltage, input voltage, input current, and power switch voltage are shown. Similar to the results obtained in Si MOSFET application, power led voltage has also some pulses because of switching off. Also, input voltage has not got any high frequency distortion. Besides, power switch voltage has relatively higher peak value than previous application, more than 68V.

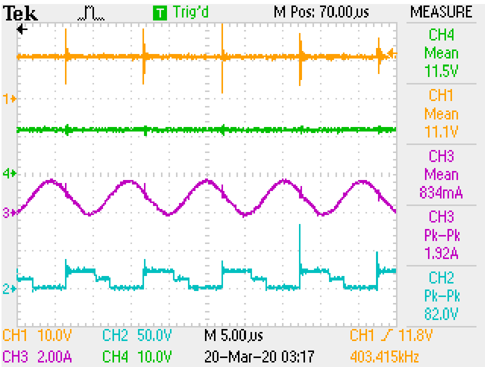


Figure 10. Led Voltage, Input Voltage-Current, Switch Voltage Waveform, respectively

In Fig. 11. Power led voltage, input voltage, power led current, power switch voltage is shown, respectively. Similar results are also obtained with applicaiton used IR540N but, power led current is not as pure as previous application and has some small distortions.

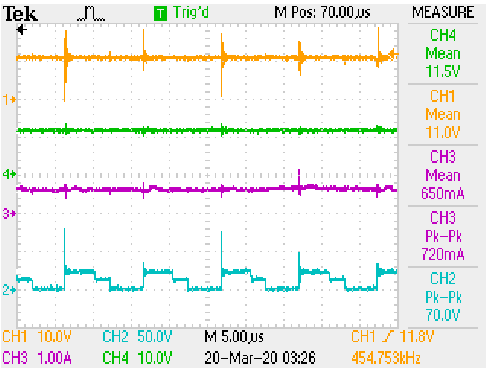


Figure 11. Led Voltage, Input Voltage, Led Current, Switch Voltage Waveform, respectively

In Fig. 12 gate resistor voltage, PWM signal, input side inductor L_1 current and power switch voltage is shown. It is seen that continuos voltage drop on the gate resistor meaning there is continous gate-source current whereas in Si MOSFET application, there is no continus gate-source current. Also, PWM switching frequency is measured as 97,21 kHz, with around %2 measurement error. Furthermore, input side inductor L_1 current decreses to ‘0’ A and staying with limeted time in ‘0’ A showing DCM opearation.

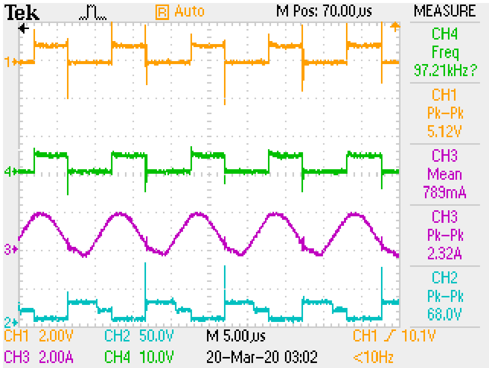


Figure 12. Gate Resistor Voltage, PWM Signal, L_1 current, Switch Voltage Waveform, respectively

Also, in order to determine gate current, gate resistor voltage is measured. For turning on the switch 10Ω resistor, for turning off the switch 1 Ω resistor is used. So, the gate current is found dividing gate resistor voltage in Fig. 12 to 10. The gate current is obtained as 0.04A. Besides gate current has the shape of gate voltage and it is continuous at the turn on duration, not a current spike as in Si MOSFET application.

Furthermore, measurement should be done so carefully by using E-Mode GaN-HEMT power switch, because wrong measurements may result a high frequency noise, as in Fig. 13. Also, this high frequency noise can cause the damage of power switch and improper operation of the converter.

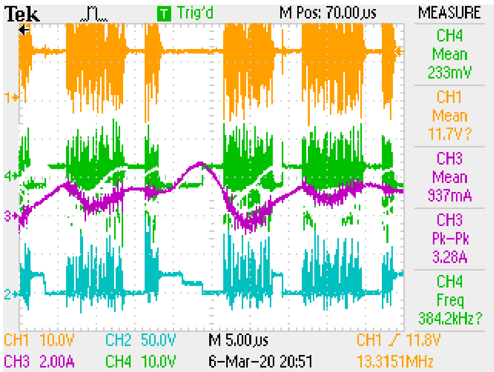


Figure 13. High frequency noise because of wrong measurements.

By using Fig. 7-8, 10-11, the efficiency of each converter is calculated. The efficiency of Si MOSFET application is obtained as %76 and the efficiency of E-Mode GaN-HEMT application is obtained as %75. The efficiency of the led driver using E-Mod GaN-HEMT is obtained %1 lower than Si-MOSFET, in small power, lower frequency, low output voltage application such as 10W, 100kHz, 12V, it seems normal for E-Mode GaN-HEMT power switch as in Rooij et al. (2018). Furthermore, it needs extra care to soldering E-Mode GaN-HEMT, and exceeding 260°C temperature of hot air gun, gives damage to the power switch.

4. Conclusions and Recommendations

In this paper, SEPIC DC-DC converter based led drivers are realized by using both Si MOSFET and E-Mode GaN-HEMT Transistor based power switches with 100kHz switching frequency. Also, dsPIC30F4011 micro controller is used to produces PWM signal for power switches and to limit power led current over ACS712 current sensor. Although, the switching frequency seems to be quite lower for E-Mode GaN-HEMT, it is moderate for Si MOSFET. The converters are designed and implemented for 10W output power. SEPIC led drivers using Si-MOSFET and E-Mode GaN-HEMT are implemented and are compared with low ouput power up to 10W, low ouput voltage up to 12V and relatively low switching frequency up to 100 kHz.

Thanks to the application of SEPIC led drivers, similar input voltage, input current, power led voltage and power led current charachteristics are obtained for power switches. However, it is seen that the switch voltage peak spike of the E-Mode GaN-HEMT seems higher than Si Mosfet, also E-Mode GaN-HEMT needs continuous gate current, and its affected much by noise even occurred by measurements. On the contrary, Si Mosfet does not need continuous gate current and is not so sensitive to the noises. However, E-Mode GaN-HEMT switch can be operated in higher frequencies and its size is smaller than Si Mosfet. So, the power density in the case of using E-Mode GaN-HEMT is higher. In addition, in low power, low voltage and low switching frequency application realized in this paper, led driver efficiency of Si MOSFET based led driver is obtained %1 higher than E-Mode GaN-HEMT based led driver.

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