Performance Comparison of MOSFET Switch & GaN Diode based MOSFET Switch

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Abstract— The technology advancement semiconductor materials have most improvement in performance, efficiency and reduction in cost, weight. Since the fundamental materials like silicon and germanium are approaching material limits, it is the right time to introduce new material. Nowadays GaN wide bandgap semiconductor materials mostly used in the semiconductor devices for high frequency applications. In this paper, the GaN diode based MOSFET switch designed. Two circuits were designed to compare the switching losses of MOSFET switch and GaN diode based MOSFET switch. The measured characteristics are conduction loss, switching loss, total power loss and efficiency.

Key words: GaN Diode, MOSFET Switch

I. Introduction

The applications of Si-based power transistors are limited due to low junction operating temperatures and low blocking voltage per devices. Megawatt power applications require efficient and high power density converters that are capable of operating at elevated temperatures. With the improved performance of wide band gap power semiconductors, such as like silicon carbide (SiC), gallium nitride (GaN) and diamond semiconductors. GaN switching power devices have been developed throughout the last decade, to compliment GaN diodes already available in the market.

Power electronic applications in the field of power distribution and transmission systems have received attention because of their large-scale application. Market restructuring, environmental, and efficiency regulations in the world have led to innovations in power electronics for electrical power systems. Utility market restructuring and new regulations are aimed to improve the existing generation capacity, increase in efficiency, better use of existing plants, and provide environmentally acceptable ways of power transmission.

A variety of power semiconductor devices like diodes, thyristors, gate turn–off thyristors, metal-oxide semiconductor field–effect transistors, insulated bipolar gate bipolar transistors (IGBT), and metal-oxide semiconductor turn off thyristors (MOSFET) are commonly used in the power electronics circuits. The need for improved performance of the electronic systems in high density applications has brought advancement in Si technology. However, Si devices are limited to operate at low junction temperatures and low blocking voltages. In megawatt power applications, which require more efficient, lightweight, high-density power converters operating at high temperatures, the development of wide band-gap semiconductors such as SiC, GaN, and diamond, are needed.

parameters	Ge	Si	GaN
Crystal structure	Diamond	Diamond	Wurtzite
Band gap energy(eV)	0.66	1.1	3.4
Lattice constant(Å)	5.646	5.431	5.185
Melting point($°c$)	937	1412	>2500
Specific heat ($Jg^{-2}°c^{-2}$)	0.31	0.7	0.49
Thermal conductivity(W $cm^{-2}°c^{-2}$)	0.58	1.5	1.3
Thermal diffusivity ($cm^2 s^{-2}$)	0.36	0.8	0.43
Electron mobility (cm^2/Vs)	3900	1500	2000
Hole mobility (cm^2/Vs)	1900	450	350

Table 1: Comparison of Si, Ge & GaN

In this table clearly show, the Gallium Nitride has some unique properties, which make it a good material to overcome the limitations of silicon. The wide band gap makes the device operate at high electric fields, and the reduction in intrinsic carrier concentration with increase in band gap enables the device to operate at high temperatures. GaN is a wide band gap semiconductor material with high warm conductivity, high breakdown electric field strength, high-saturated drift velocity, and high thermal stability. Therefore, Gallium Nitride is extremely durable and useful for many high power, high frequency, and high temperature applications.

II. Proposed System

In this system, the gallium nitride based MOSFET switch is used. The MOSFET switch is connected to AC voltage and RLC load. Power MOSFETs are essentially voltage-driven devices. The basic principle of a MOSFET device is that the voltage on the oxide-insulated gate electrode can induce a conducting channel between source and drain. The MOSFET conduct the peak current to exceed its average current. It is a voltage controlled device with gate current flow during operation.

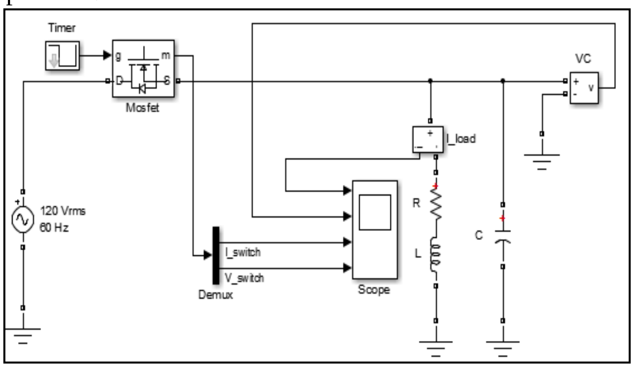


Fig. 1: MOSFET Switch in Switching Circuit

Figure 2 illustrates a MOSFET equivalent circuit where the gate drive circuit is supplying the MOSFET to raise the gate voltage with a specified value of off state drain-to-source voltage. The gate charge is the total charge on the gate-to-drain and the gate-to-source capacitance supplied by the gate drive circuit. The drain current change is dependent on the rate at which the gate-to-source capacitance is charged by the gate drive circuit. Since the energy stored in this capacitance is lost during the transistor turn-on transition. In general, there is a body diode inherent with the power MOSFET devices. It enables the MOSFET to conduct in full rated current. Here GaN diode based MOSFET switch is used.

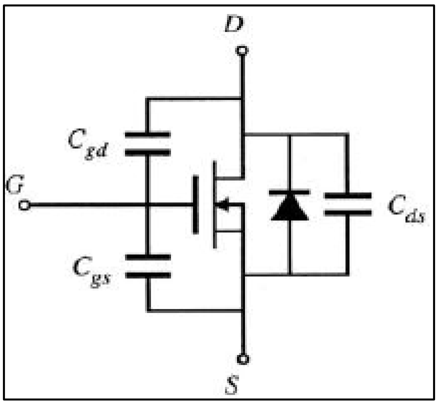


Fig. 2: MOSFET Switch Equivalent Circuit

Power loss in any semiconductor switch is caused by the combination of the switching losses, conduction losses, blocking (leakage) losses, body diode conduction loss, and gate drive loss. Normally the leakage losses and other losses are being neglected. Power loss of MOSFET switch equation is,

$$P_{MOSFET} = P_{switching} + P_{conduction}$$

In this equation, $P_{switching}$ is the switching power loss and $P_{conduction}$ is the conduction loss. The Switching power loss equation is,

$$P_{sw} = (t_{sw.on} + t_{sw,off}) \times V_{off} \times I_{on} \times f_{sw} / 4$$

Where, $t_{sw,ON}/t_{sw,off}$ is the time, it takes turn the MOSFET on/off, V_{off} is the Drain source voltage when the MOSFET is off and f_{sw} is the Switching frequency. The Conduction loss equation is,

$$P_{conduction} = I_{on}^2 * R_{DS,on}$$

Where, I_{on} is the Drain current when the MOSFET is on and $R_{DS,on}$ in Drain-source resistance of the MOSFET when it is on. The Efficiency equation is,

$$Efficiency = V_{out} / V_{in}$$

Where, V_{out} is the Output voltage and V_{in} is the Input voltage

A. *Device Design*

The gallium nitride diode placed parallel to the MOSFET. The GaN diode fabricated with bulk GaN substrates and the substrate thickness is 180µm. The desired breakdown voltage is determined by the drift layer doping density and the region thickness. So the drift region thickness is 6µm and the doping density is $2x10^{16} cm^{-3}$. As a result the breakdown voltage is 0.7KV. Then the magnesium doped p-type GaN layer on top of the n-type GaN region and the thickness of the region is 0.5µm. The doping density of the p-type region is $1x10^{19} cm^{-3}$.

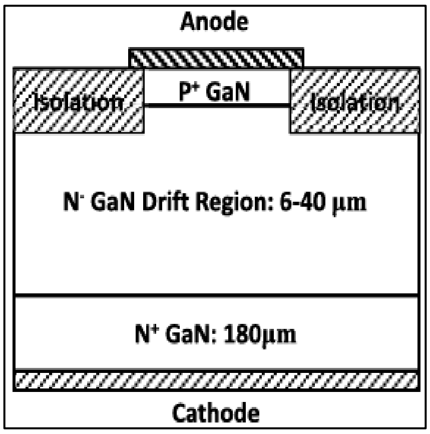


Fig. 3: Schematic Cross-Section of GaN Diode

The current equation relating the voltage V and current I, is represented by,

$$I = I_o [e^{(\frac{V}{\eta V_T})} - 1]$$

Where, I is the diode current, I_o is the saturation current at room temperature, V is the external voltage applied to the diode and η is the constant. The thermal voltage equation is represented by,

$$V_T = kT/q$$

Where, K is the Boltzmann's constant ($1.38x10^{-3}$J/k), Q is the Charge of the electron ($1.602x10^{-19}$c) and T is the Temperature of the PN junction (k). The contact potential equation is represented by,

$$V_o = \frac{kT}{q} \times \ln \left(\frac{N_A x N_D}{n_i^2}\right)$$

Where, N_A is the Number of acceptors, N_D is the Number of donors and N_i is the intrinsic concentration. The semi conducting equation is represented by,

$$\sigma = nq\,(\mu_n + \mu_p)$$

Where, μ_n is the Mobility of electrons, μ_p is the Mobility of holes and q is the Charge of the electron ($1.602x10^{-19}$c). The electric field equation is represented by,

$$E = \frac{qN_D}{\omega} \in$$

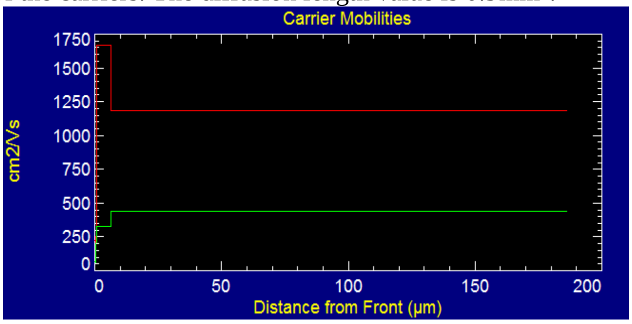
Where, ∈ is Permitivity and W is the Width. The diffusion length is the average length of carrier moves between generation and recombination. The semiconductor materials that are heavily doped have greater recombination rates and consequently, have shorter diffusion length. Diffusion length depends on the life time and mobility of the carriers. The diffusion length equation is represented by,

$$L = \sqrt{D\tau}$$

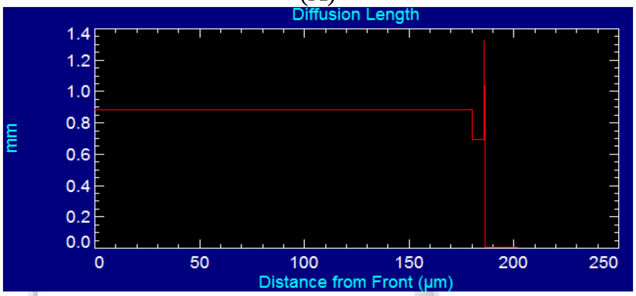
Where, D is the Diffusion coefficient, τ is the Carrier life time and L is Diffusion Length.

III. RESULT & DISCUSSION

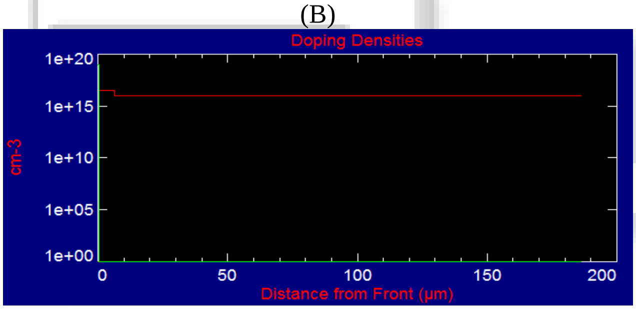
This section provides an experiment result that illustrates the performance of proposed GaN diode based MOSFET switch and the GaN diode characteristics results are disscused here. Doping is added the level of the conduction band is reduced and the level of the valance band is increased, such that the electron can easily move from conduction band to valance band. The GaN diode doping density is $3x10^{15}$ cm^{-3}. The electron mobility of the diode is reduced and the hole mobility of the diode is increased. The electron mobility characterizes how quickly an electron can move through a metal or semiconductor. Diffusion length is the normal length a carrier moves between generation and recombination semiconductor materials that are heavily doped have greater recombination rates and consequently, have shorter diffusion length. Diffusion length depends on the life time and mobility of the carriers. The diffusion length value is 0.9mm^2.



(A)



(B)



(C)

Fig. 4: Characteristics Of Gan Diode A) Doping Density, B) Carrier Mobility C) Diffusion Length

The above switching circuit (fig.1) uses the Si diode based MOSFET switch to switch an RLC load with a 120Vrms, 60Hz AC power supply simulated with MATLAB/Simulink. The switch is initially closed and will be turned off after 3 cycles, then reclose at 8.25 cycles. In this fig.4, shows the simulation result observed by Simulink from Fig.1 circuit. The results show that the inductor current chopping produced the high frequency overvoltage. When the switch reclosed, the capacitor reached maximum source voltage and created the highest switch current spike.

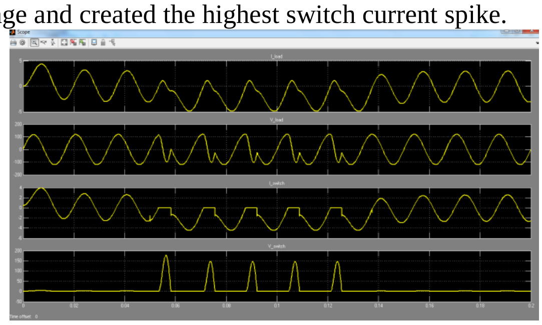


Fig. 5: Si Diode Based MOSFET Characteristic Simulation Result from Switching Circuit

The same circuit (Fig.1) was used to measure the behavior of GaN diode based MOSFET switch. The observed waveforms are shown in Fig.5, the switch turns on, the current is rises and the voltage is zero. The same time switch turns off, the voltage is rises and the current is zero. The GaN diode based MOSFET switch is lightly similar to the ideal switch.

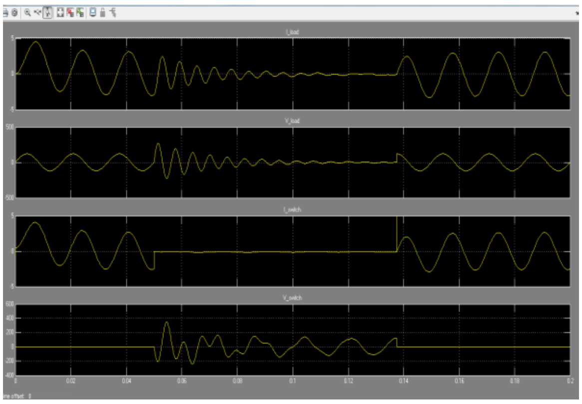


Fig. 6: Gan Diode Based MOSFET Characteristic Simulation Result from Switching Circuit

Parameters	Si diode based MOSFET switch	GaN diode based MOSFET switch
Conduction loss(W)	0.9	0.09
Switching loss(W)	8.77	5.04
Total power loss(W)	9.67	5.13
Efficiency (%)	83.3	91.6

Table 2: Performance Comparison of Si & GaN Diode based MOSFET Switch

In this table compared the performance of Si diode based MOSFET switch and GaN diode based MOSFET switch. As a result the GaN diode based MOSFET switch have small power loss and high efficiency than the Si diode based MOSFET switch.

IV. Conclusion

In this paper, Gallium Nitride diode based MOSFET switch designed. GaN diode based MOSFET switch should substantially reduce cost and system size. The characteristics of Si diode based MOSFET switch and GaN diode based MOSFET switch were discussed here. As a result the GaN diode based MOSFET switch was reduce the power loss and increase the efficiency than the Si diode based MOSFET switch.

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