Design of Semiconductor Synchronous Buck Converter based on GaNWide-bandgap

Ma Jing-ran¹, Qu Yao-jun², Song Yan-xia¹*, Kanae Shunshoku³, BaiJing¹
¹College of Electrical and Information Engineering, Beihua University, Jilin 132021, China
²China Petroleum JiLin Chemical Engineering Co., Ltd, Jilin 132021, China
³Department of engineering, Fukui University of technology, Japan
*Corresponding author. Email:309972666@qq.com

Abstract: Aiming at the limited switching frequency of traditional silicon (Si) based devices and its huge switching loss when working under the high-frequency conditions, this paper proposes a synchronous buck converter based on GaN power devices with good switching performance and low loss. In this paper, the detailed parameter design method and simulation circuit were given. This paper also conducts thermal stability analysis. Finally, the simulation experiment proves the feasibility and effectiveness of this theory.

1. Introduction
Switching power supply is constantly pursuing reduction in volume and weight while pursuing high efficiency, low loss, safety and stability [1-2]. Now it has been applied to daily life, medical treatment, new energy vehicles, 4G / 5G communication technology, national defense, etc.

Traditional Si-based devices are bulky and high-loss. Its switching frequency is limited to less than 300 kHz and even reduces to 100 kHz in high-voltage applications. So it can no longer meet people’s requirements of electronic products. GaN has the outstanding physical characteristics of wide band gap, high saturation electron drift speed[3], high thermal conductivity, high junction temperature[4], critical breakdown electric field[5] and so on, which ensures that its power devices can work well under the conditions of high power, high frequency, large-scale integration, high efficiency, high temperature and high voltage[6-7]. And GaN power device can be made smaller under certain breakdown voltage conditions[8].It being applied in synchronous buck converter not only improves its switching performance and reduces loss[9], but also enhances the ability to work under the high-temperature and high-voltage conditions, which is undoubtedly of long-term and irreplaceable significance for the new energy industry, electrical industry and medical field[10-11].

2. Comparative analysis of gallium nitride and silicon
This paper introduces some characteristics of low-voltage gallium nitride power transistors and compares them with traditional silicon transistors [12].

| Material Science | Band Bandwidth /eV | Relative Permittivity | Critical Breakdown Electric Field | Electron Saturation Drift (cm²/Vs) | Electron Mobility (W/cm·K) | Thermal Conductivity |
|------------------|-------------------|-----------------------|-----------------------------------|-----------------------------------|-----------------------------|---------------------|

Table 1 Characteristics comparison of gallium nitride and silicon semiconductor materials
### Table 1: Comparison of Velocity (10^7 cm/s) and Voltage Drop (mV/cm)

| Material | Voltage Drop | Velocity |
|----------|--------------|----------|
| Si       | 1.12         | 11.9     |
| GaN      | 3.39         | 9.0      |

In the case of the same on-resistance, the gate charge of the GaN power tube is smaller than that of the Si MOSFET. So the driving loss of the GaN power tube is smaller, which is beneficial to increase the frequency of its operation [13]. Si MOSFET has body diodes and gallium nitride power tubes do not, which is a significant difference between gallium nitride power tubes and silicon tubes. [14].

### 3. Synchronous Buck Converter

Buck converter is a widely-used step-down converter at present, which is mainly suitable for some low current step-down situations. The schematic diagram of the Buck converter is shown in Figure 1:

![Figure 1: Schematic diagram of Buck converter](image)

A large part of the loss of Buck converter comes from the forward voltage drop of diode (D) in the circuit. MOSFET can be used to replace diodes and the conduction loss can be effectively reduced. By using gallium nitride transistors with smaller conduction resistance, the conduction loss can be reduced even more, while putting forward higher requirements for the driver circuit.

The constituent circuit of the synchronous buck converter using the power MOSFET includes: power, switch network, filter network and load. The filter network adopts RLC series circuit and the switching network consists of two MOSFETs.

### 4. Circuit Design

#### 4.1 Calculation and selection of filter inductance

Firstly calculate according to the performance indicators of the circuit design and select the model of the inductor.

The input voltage ranges 4V ~ 6V and the output voltage is 1.6V. So the duty cycle is:

\[
D_{\text{max}} = \frac{V_o}{V_{\text{in}}} = \frac{1.2}{4} = 0.3
\]

\[
D_{\text{nom}} = \frac{V_o}{V_{\text{in}}} = \frac{1.2}{5} = 0.24
\]

\[
D_{\text{min}} = \frac{V_o}{V_{\text{in}}} = \frac{1.2}{6} \approx 0.2
\]

The switching period can be calculated as:

\[
T_S = \frac{1}{f_s} = \frac{1}{2.5 \times 10^5} = 4 \times 10^{-6} \text{s}
\]

Calculation of inductance value:

\[
L = \frac{(1-D)V_{\text{in}}}{2f_Sn_o} = 0.63 \times 10^{-6} \text{H}
\]

In conclusion, the required inductance value is about 1μH. In order to leave a certain margin, a commercial inductor with an inductor value of 5μH and a current of 20A can be chosen.

#### 4.2 Calculation and selection of output capacitance

Capacitance usually has parasitic inductance and equivalent series resistance (ESR), which will affect the stability of the system. According to the experience, the conventional approach is to select multiple small capacitors in parallel to reduce ESR. In this paper, the ripple voltage is required to be less than 25mV. The capacitance value is calculated as follows:
3

\[ C = V_i \frac{(1-D)}{8l f_s^2} = 1.206 \times 10^{-5} \text{F} \]  

(6)

In order to reserve a certain margin, 1600 \( \mu \text{F} \) capacitance is selected in this paper.

### 4.3 Selection of power devices

In this paper, the input voltage is 5V, the output voltage is 1.2V and the maximum current is 16A. The alternative devices selected in this paper are shown in table 2:

| Device type | Vds(V) | Rds(mΩ) | \( I_D \) (A) | \( Q_G \)(nC) | \( Q_{GS} \)(nC) | \( Q_{GD} \)(nC) |
|------------|--------|---------|---------------|--------------|----------------|----------------|
| EPC2024    | 40     | 1.5     | 90            | 18           | 5.1            | 2.4            |
| EPC2015C   | 40     | 4       | 53            | 8.7          | 2.7            | 1.2            |
| EPC2023    | 30     | 1.3     | 60            | 20           | 5.8            | 1.9            |

EPC2023 is a N-channel FET with a drain source voltage of 30V and a drain current of 60A. The leakage source voltage of EPC2015C is 40V, the leakage current is 53A, and the driving voltage is 5V. These two types of pipes can perfectly meet the requirements of this design, and leave enough margin to prevent burnin.

### 4.4 Design of driving circuit

Gallium nitride has a narrow driving voltage range. LM5113 is specially designed for the enhanced GaN FET. It can effectively protect GaN FETs and ensure that the grid is in a low-level state and avoid misdirection when switching. The input of LM5113 is independent and controlled by the linear input threshold. And it can withstand voltages up to 14V. These mean that it can be connected directly to the output port of a PWM controller with up to 14V supply and save buffer levels between the output ports of the high voltage supply controller.

Due to the high operating frequency of gallium nitride, all parasitic parameters between the pin of LM5113 and the gate of gallium nitride transistor cannot be ignored. Otherwise it will exert a serious impact on the driving signal and even burn down the GaN power transistor.

### 5. PCB layout design

Firstly, since the high-frequency and strong current of the switching power supply and the weak signal of the control are on the same board, it is necessary to distinguish the strong current loop to reduce its interference to the outside. Then when switching, a very high \( \frac{di}{dt} \) will be produced. At this time, there will be a noise spike which will reduce the performance of the system and lead to abnormal control behavior. Therefore, the control elements should be placed as far away from the power devices as possible.

Due to the high working frequency of gallium nitride power tube, the layout of PCB should be specially designed for gallium nitride while taking full account of the sensitive circuit, heating and impedance matching of the device.

The main problem to be considered in impedance matching is the length and width of the conductor. The system can attain maximum power when the impedance of the output is equal to the impedance of the input source. Therefore, when wiring, you can adjust the width, length, thickness and material of the wire to make the output impedance equal the impedance of the input source. This design of the PCB board totally has four layers:
6. System analysis and Simulation Design

6.1 Circuit level simulation analysis of the system
Firstly, the simulation of the whole circuit level is carried out with the help of the new version of LTSpice XVII released by Lingte company. The simulation results are shown in Figure 6:

![Simulation diagram](image1)

Through circuit level simulation, it is found that the basic functions of the designed circuit can be realized but the loss is larger than the theoretical calculation. Through the detection of each node, it is found that the driving signals of the upper and lower tubes are distorted and overlapped.

![Upper and lower tube drive signal distortion](image2)

6.2 Board level simulation analysis of the system
Firstly the PCB file generated by the Altium Designer version should be converted into the ".hyp"
format supported by HyperLynx for simulation. Then perform a thermal simulation to see whether the drawn board has problems such as device overheating and observe the heat distribution of the board. The thermal simulation results are shown in Figure 8. The picture on the left is an overall analysis and the right is about each device.

![Simulation results](image)

Through the analysis of the simulation results, it is found that the driver chip LM5113 reached the temperature that can affect the normal operation of the device. Therefore, the heat dissipation problem of the device needs to be considered in the subsequent improvement.

Next, batch-processing simulation analysis of the board should be adopted. It will quickly scan the entire board and check if the network connection is reasonable, and find out the problem. The simulation shows that NetPAD3-1, NetPAD1-1, NetC5-1, NetC5-2NetL-2 are too long!

The simulation results shows that five of the network designs are too long. It indicates that there is a problem with the layout of some devices in the PCB design, which causes that the long network in the system will affect the quality of signal.

7. Conclusion
Applying GaN to a synchronous buck converter can improve the performance of synchronous buck converters. But it puts forward higher requirements for the design of driving circuit and PCB layout.

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