GaN-based fast, high output magnetic field pulser

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Abstract
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ABSTRACT

Magnetic field pulsers (MFP) generate a pulsed magnetic field by driving current through an inductor. These pulsers have numerous applications based on the output magnetic flux density and switching time. This investigation will explore the application of gallium nitride-based (GaN) transistor in a MFP design. Based on the advantages of GaN transistors, the investigation looks towards creating a pulser capable of producing magnetic flux density of 500 Gauss with a rise/fall time of less than 500 nanoseconds. This investigation will improve upon findings from prior pulsers designed for magneto-optic switching applications. Simulation results have shown that for a given maximum current level, the GaN transistor pulser displays steeper rise and fall time when compared to a pulser employing a Si transistor. This result further highlights the potential of GaN transistor as the switching device where rapid field switching is preferable.

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I. INTRODUCTION

Magnetic field pulser (MFP) can be found across different fields and applications. For example, in communication systems, the pulser is central to an all-optical switching platform employing the theory of Faraday rotation. In the medical field, pulsers are used in transcranial magnetic stimulation (TMS) to provide safer, noninvasive application of magnetic pulses for treatment of certain mental disorders. Another application area is portable magnetic resonance where pulsed fields are needed to obtain the condition of resonance and different material properties can be identified.

A high-speed, high-current switching device is integral to the pulsed field switching mechanism. Conventionally, a metal-oxide-silicon field-effect transistor (MOSFET) is selected due to its high drain current and nanosecond switching properties. However, recent developments in transistor technologies have enabled the production of gallium nitride (GaN) based transistors. Compared to silicon-based transistors, GaN transistors are lauded to have even higher drain current and extremely fast switching speed due to its different electrical composition, leading to a larger bandgap, faster electron mobility, and good thermal conductivity. These are all desirable properties for a switch in the MFP design.

For an all-optical communication system, which is the authors’ main application space, a well-designed MFP should produce high magnetic flux density (B-field) in the range of 500 Gauss within a short rise and fall time, ideally less than 500 ns. At the same time, the MFP has other sub-requirements. One of which is it should have a proper energy dissipation system. When a pulsed signal is detected at the input of the switching device (defined as HIGH), the system turns on and a large amount of current flows through the inductor coil instantaneously. This rapid change in current in the inductor coil generates the magnetic field. Simultaneously, the inductor coil is also storing energy. After the pulsed signal has passed (defined as LOW), the system returns to its idle state but the stored energy in the inductor coil must be dissipated quickly and safely. Otherwise, the fall time will be prolonged, or the switching device might burnout. This is well documented in the work by Pritchard et al. in which the residual B-field after the demagnetization process results in a slower fall time. Finally, the MFP should have a small footprint. In addition to reducing the parasitic effects of the board, these pulsers usually fit into more complex systems where footprint is obtained at high premium.

II. CONVENTIONAL MAGNETIC FIELD PULSER DESIGN

We can simplify the MFP design into five parts. They are:

A. Charge storage elements
B. Field generation unit
C. Switching device
D. Power dissipation
E. Current measurement

From Fig. 1, we observed that the interaction between different stages of the pulser needs to be controlled to obtain desired magnetic field. The capacitor banks are needed to provide a rapid discharge of energy once the inductor is activated. When an input signal is applied, the switching device completes the circuit and charge from the capacitor bank swiftly flows through the inductor coil hence generating the B-field. When the input signal goes LOW, the switching device behaves as an open circuit. Charge stored in the inductor coil is dispersed through the dissipation loop as heat.

During the HIGH phase, the current sense resistor is in series to the inductor coil. This design choice is to allow measurement and an easy way to estimate the magnetic flux density. Usually, the inductor coil is occupied by a core such as a magneto-optic material. By measuring series current at the current sense resistor, the B-field can be calculated via the following equation:

\[
B = \frac{\mu NI}{\sqrt{l^2 + 4R^2}}.
\]

Whereby \(B\) = magnetic flux density, \(l\) = length of coil, \(R\) = radius of coil, \(\mu = \mu_0\mu_r\) = permeability, \(N\) = number of turns of coil, and \(I\) = current through coil.

It is very common to use a MOSFET as the switching device. MOSFETs are known to have high drain current, rapid switching capability, and fast slew rates. Such switching devices can be used to obtain high B-field output with short rise and fall time.

There is a delicate balance between the output level and rise/fall time. One must be sacrificed for the other to benefit. An MFP can hit very high B-field output, but it will have a long rise and fall time and vice versa. Researchers have been actively searching for the right switching device or design improvement to satisfy both. For example, Wu et al. proposed a design that generates high output with a 2-5 ns rise time but an approximately 200 ns fall time. Alternatively, the two-coil system by Pritchard et al. shows a fall time that is 35% shorter by only sacrificing 10% of the output magnitude.

III. GALLIUM NITRIDE

The material GaN has advanced beyond its initial creation purpose. The material is gaining a lot of momentum as the possible replacement to silicon (Si) in the high-power semiconductor industry. Research has shown GaN-based transistors are capable of outputting high power levels, handling high frequency electrical signals, and withstanding extreme heat well beyond silicon, gallium arsenide, or silicon carbide fabricated transistors. These properties made GaN the ideal candidate for the next advancement in technology especially in advanced communication networks and power electronics. The caliber of GaN shines as it takes over the amplifiers, modulators, and other key components in these systems. As society push for faster data transmission and higher power consumption within a small, convenient formfactor, GaN transistors can be found in the cell towers, satellites, cell phones, power grid, solar power systems, electric vehicles, etc.
A. Advantages of GaN over Si

This research has pinpointed four electric properties of GaN as shown in Table I below.

First and foremost is the large bandgap of GaN. Bandgap is the measurement of energy needed to excite valence electrons into the conduction band. The bandgap of GaN is thrice that of Si. As a result, GaN holds an advantage with its larger breakdown voltage and high thermal stability at higher temperatures.

The larger bandgap of GaN supports a larger breakdown voltage. The critical breakdown field of GaN is ten times larger than Si. Alternatively, we can say GaN supports ten times more power before burnout. With its greater power density, GaN supports higher drain current at a smaller circuit footprint. In an all-optical communication system, the higher drain current (hence stronger B-field output) means a better control over the polarization rotation of the light signals.

The second electrical property is the electron mobility. GaN is 33% faster than Si under influence of an applied electric field. This characteristic is what allows GaN to handle faster switching with acceptable signal deterioration rate. This is important if we seek to pursue the true transmission rate of an all-optical communication system. The faster electron mobility helps to reduce both the rise and fall times while ensuring reduced ringing effects at turning points. The shorter output signals (from shorter rise and fall time) allows higher rate of signal transfer since idle period in between transmitting signal can be reduced without crosstalk. The cleaner output signal on the other hand increases the precision of the polarization rotation in the light signals. As a result, the system is transferring data faster with less errors.

Finally, the last parameter of interest is the thermal conductivity. Both GaN and Si have similar thermal conductivity. So, GaN can match Si in terms of thermal load. An example of a thermal load would be the discharging of the energy in the inductor coil as heat.

A brief conclusion from these four electrical properties is that GaN-based transistors support higher power level, faster and cleaner switching, runs cooler under repetitive load, and has a smaller footprint than an equivalent Si-based transistor. This is what made the authors consider the GaN transistor as an ideal switching device for an MFP.

B. Disadvantages of GaN

Research have shown the bonding between GaN compounds during fabrication can be a problematic hurdle.10 This is well-documented in Singh et al. as it shows that microscopic blisters form on the surface of GaN materials impairing the formation of even layers.11 This can lead to discontinuity or lattice mismatch. As a result, manufacturability of GaN wafers is challenging. The limited wafer diameters and higher number of defects per area limit fabrication of GaN transistors and drive its cost higher.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

For the experiment phase, the authors present the result of three MFP designs. Two designs have a MOSFET as its switching device while the third design will have a GaN transistor. The authors will present the results for comparison in terms of maximum B-field output and rise and fall time. As shown in Equation (1) in Section I A above, the B-field is directly proportional to the current through the inductor coil. So, the authors will present data in terms of current.

A. Experiment Setup

The three designs (with transistor model and on-resistance) will each be called the following:

- “Si transistor (prior work)” – optimized circuit from previously published work (IRF540)
- “Si transistor” – latest optimized circuit based on best result from sample pool of MOSFETs (PSMN4R0_30YLD)
- “GaN transistor” – latest optimized circuit that best match output level of “Si transistor” (TPH3206)

The “prior work” is based on designs published in previous works.12 Meanwhile, the “Si transistor” design is an updated version of the “prior work.” Ten newer MOSFETs were selected based on their electrical characteristics and put through an optimization process to integrate them into the “prior work” design. The design with the most promising result, is presented here. Finally, a third derivative of the “prior work” design is optimized for a GaN transistor. The design is optimized to have a similar output B-field as “Si transistor”. This is to allow a comparison study on the rise and fall time of the two designs when the output level is kept constant.

The input signal is kept constant with a 0-5 V pulse and a pulse width of 1 µs. The inductor coil used in the measured test has a value of 109 nH with a length of 0.006 m, coil radius of 0.0015 m, and μ0 = 1. For simulation, the authors used a 100 nH inductor.

While setting up the experiment, the authors noticed the “GaN transistor” does not respond well to smaller input signals (low current). The authors deduced this is due to the large bandgap of GaN material requiring more energy to trigger the gate voltage of the “GaN transistor.” To curb this, the authors have included a gate driver into “GaN transistor” design.

B. Experimental results

Data was collected and plotted in the Fig. 2 below. The input voltage was included to observe the instantaneous response of the

| Material | Bandgap (eV) | Electron mobility @300 K (cm²/Vs) | Critical breakdown field (MV/cm) | Thermal conductivity (W/cm-K) |
|----------|--------------|-----------------------------------|---------------------------------|-------------------------------|
| GaN      | 3.49         | 2000                              | 3.0                             | ~1.5                          |
| Si       | 1.1          | 1500                              | 0.3                             | 1.5                           |

TABLE I. Electrical properties of GaN and Si. }

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three design when the signal goes HIGH and LOW. For analysis purposes, Table II shows the maximum output level, rise and fall time, and rise and fall rate of the three designs.

C. Experiment analysis

From Fig. 2 above, the authors observe that the two newer designs can output five times larger level of current compared to “prior work.” In the case of “Si transistor,” this is attributed to the smaller on-resistance compared to the “prior work.” Besides its lower output level, the “prior work” was also limited by longer oscillation period before achieving a steady state. The “GaN transistor” had a uniform steady state response.

From the zoomed in rise time image as seen in Fig. 2(b), the authors made a few observations:
- “GaN transistor” has a slight delay due to the gate driver. The ~25 ns delayed time is consistent to the value reported in the datasheet of the gate driver.
- Despite the delay, “GaN transistor” achieved steady state before “Si transistor” with delta ~53 ns
- As reported in Table II, the rise rate of the “GaN transistor” is the highest (0.149 A/ns) followed by the “Si transistor” and finally the “prior work”

From the zoomed in fall time image as seen in Fig. 2(c), the authors made a few observations:
- “GaN transistor” again has a slight delay due to the gate driver before falling
faster and maintains it longer. This characteristic is also beneficial in terms of ringing towards the end. “GaN transistor” displayed less ringing than “Si transistor” or the oscillations decayed faster. As reported in Table II, the fall rate of the “GaN transistor” is the highest at 3.09 A/ns which is five times higher than the second highest (“prior work”) and finally the “Si transistor” played less ringing than “GaN transistor” or the oscillations decayed faster.

V. CHALLENGES AND FUTURE WORK

Ringing is a prevalent issue for many fast-switching circuits including the pulser. While the ringing observed on the “GaN transistor” in this study is relatively small, the authors understand the need to reduce it further as it can easily wreak havoc in a high-speed system. The ringing might superimpose onto the next incoming data and cause a false HIGH/LOW. Snubber circuits are a possible solution here and should be investigated further.

Meanwhile, the higher bandgap of the GaN material means the transistor will need a significantly higher input signal to trigger its gate voltage. This is not possible for small signals found in most high-speed systems. The authors have tested a gate driver to mitigate this challenge, but the gate driver does come with its set of disadvantages such as the delay observed here. The author’s investigation into gate drivers and methods of reducing the time delay will be part of a future investigation. The authors are also exploring alternative methods to obtain GaN transistors to operate with small amplitude signals. These are potential solutions in further reducing the rise and fall time when using GaN transistor technology and will be part of the authors’ future work.

VI. CONCLUSION

From the reported results, the author learnt that the “GaN transistor” can easily match the output current/field level of the “Si transistor” but with the benefit of a much shorter rise and fall time and cleaner output steady state current/field. For an all-optical communication system, this allows faster signal transfer without sacrificing error rate, potentially closing the gap between current fastest signal transmission rate and the full potential of a light signal’s propagation speed in a medium. The GaN MFP design also reaches steady state faster and maintains it longer. This characteristic is also beneficial for TMS as its overall pulse width is therefore closer to the medically required amount. There is also the added benefit of a cleaner output magnetic field therefore leading to a lower risk of over or under stimulation of the patient’s brain cells.

This research supports the idea that GaN-based transistors are the key to design higher output, faster, and better MFP. The authors are convinced that integrating the key benefits of the GaN transistor including the higher power level, higher switching frequencies, higher efficiency, better temperature management, and smaller footprint into the MFP is the way forward for design improvements.

AUTHORS’ CONTRIBUTIONS

All authors contributed equally to this work.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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**TABLE II. Breakdown of maximum output, rise and fall time, and rise and fall rate for the three designs.**

| Design         | Max Current (A) | Rise time (ns) | Rise rate (A/ns) | Fall time (ns) | Fall rate (A/ns) |
|----------------|-----------------|----------------|------------------|---------------|-----------------|
| Prior work     | 8.11            | 68.5           | 0.118            | 12.2          | 0.665           |
| Si transistor  | 43.31           | 316.6          | 0.137            | 182.2         | 0.238           |
| GaN transistor | 43.24           | 290.1          | 0.149            | 14.0          | 3.09            |

Time from zero to max steady state.
Time from max steady state to zero.