Fully integrated transformer less floating gate driver for 3D power supply on chip

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Fully integrated transformer less floating gate driver for 3D power supply on chip

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***Abstract*— Power supply on chip (power SoC) has been caught attentions because it can ultimately miniaturize the power supplies. To realize 3D power SoC which is fabricated using mass production process, we need to meet the various electrical requirements. Series and/or parallel connections is mentioned as good method.**

In such a situation, we previously proposed transformer less floating gate driver circuit using Schottky barrier diode (SBD). However, SBD is not suitable for integration. In this paper, we investigate the transformer less floating gate driver using MOS devices.

Keywords—3D power SoC, ISOP DC-DC converter, charge pump, integration

I. INTRODUCTION

3D power SoC, which integrates power device, control and drive circuits, and passive devices, has been caught attention because it can ultimately miniaturize the power supplies [1,2]. In addition, 3D power SoC can realize high efficiency. It can also use mass production processes such as LSI and MEMS processes. Thus, we should develop various applications.

ISOP (Input Series Output Parallel) DC-DC can use lower breakdown power devices. Thus, it has been promising because it can realize high efficiency at high frequency switching [3]. In addition, ISOP topology can use general converter modules. This requires the gate driver with floating power supplies (floating gate driver circuits).

We usually use transformers as power supplies for floating gate driver circuits. However, transformers disturb miniaturization because this needs the winding of large volume. The trench capacitor using Si substrate has been actively studied and realized high density [4,5]. We previously reported the transformer less floating gate driver, which can operate 10 MHz,[6]. This circuit uses the external parts (Schottky barrier diode (SBD)) in bootstrap and charge pump circuit. However, it is hard to integrate SBDs using CMOS process. Approaches of using MOSFETs instead of SBDs have been proposed for charge pump circuit [7-9].

In this paper, we investigate the optimum circuit for the fully integrated transformer less floating gate driver for 3D power SoC.

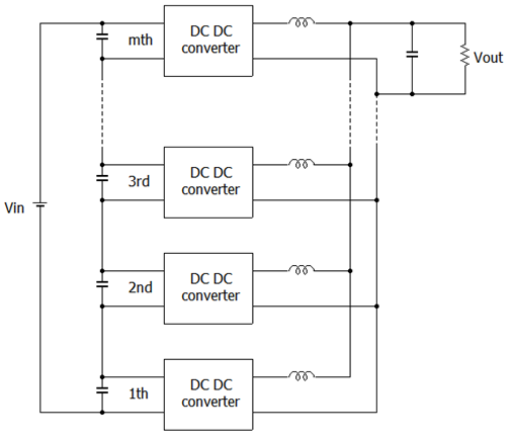


Fig.1 ISOP DC-DC converter

II. TRANSFORMER LESS FLOATING GATE DRIVER

The previously proposed floating gate driver consists of level shifter, charge pump and buffer [6]. This ISOP converter consists of m stage and input voltage is V_{in}, so input voltage of a DC-DC converter is input voltage per stage ($\frac{V_{in}}{m}$). When thinking about the ISOP converter of "n" th stage, V_{ss_L} ($=\frac{V_{in}}{m}$(n-1)) is source voltage of low side switch, V_{ss_H} ($=\frac{V_{in}}{m}n$) is input voltage of "n" th stage and V_{LX} is input voltage of inductor. In short, effective input voltage is V_{ss_H} - V_{ss_L}. When describing about operation principle of this circuit, input pulse is 0 - V_{dd} and voltage drop of SBD is ignored.

First, describing about low side switch. The source voltage of low side switch (V_{ss_L}) boosted to V_{ss_L} + V_{dd} using input pulse (V_{p_L}= 0 - V_{dd}) and charge pump circuit, so the power supply voltage of low side driver is V_{ss_L} + V_{dd}. Input pulse for gate drive circuit (V_{p_L}= 0 - V_{dd}) becomes V_{ss_L} - "V_{ss_L} + V_{dd}" because the pulse is boosted by bootstrap circuit. This circuit consists of a capacitor and a Schottky barrier diode. The current of the low side pulse is amplified by low side driver, so the pulse amplified the current is V_{g_L}. Finally, the signal of V_{ss_L}- "V_{ss_L}+V_{dd}" is inputted gate of low side MOSFET

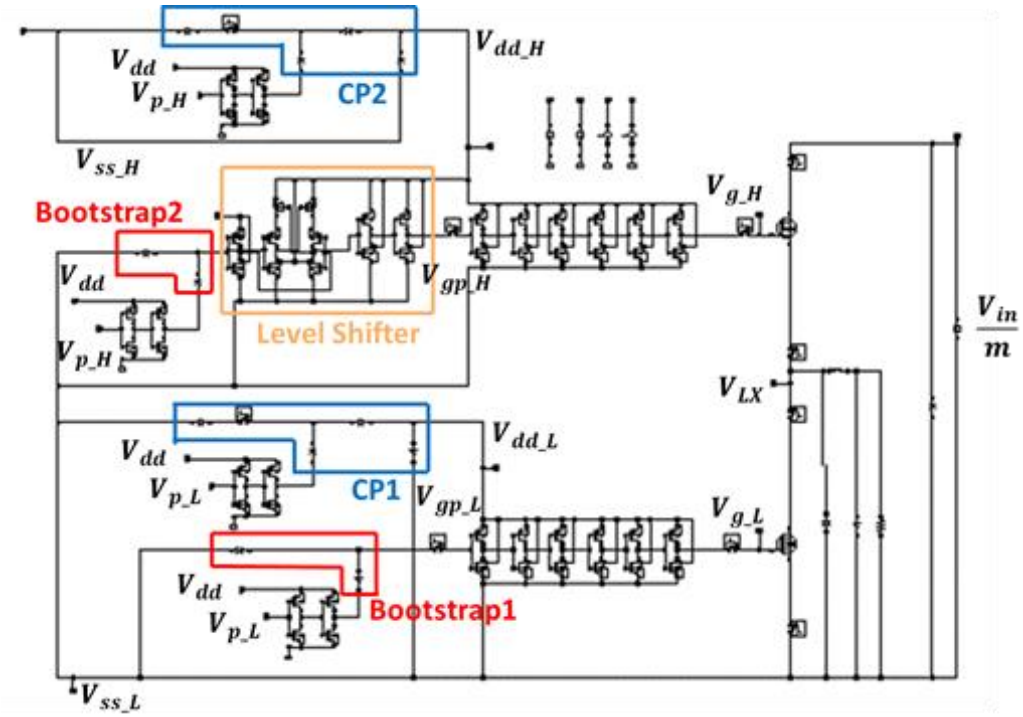
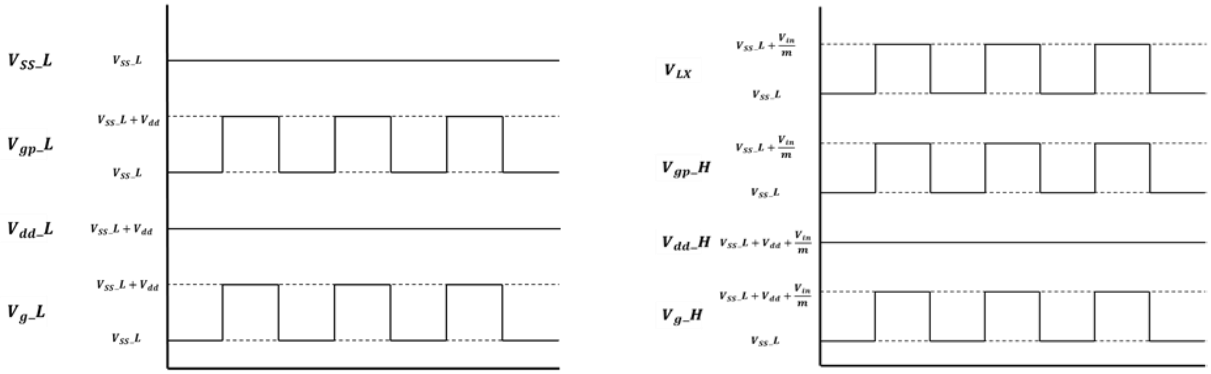


Fig.2 Transformer less floating gate driver



(a)Low side (b)High side

Fig.3 Timing chart

Second, describing about high side switch. The source voltage of high side switch (V_{ss_H}) boosted to V_{ss_H} + V_{dd} using input pulse (V_{p_H} = 0 - V_{dd}) and charge pump circuit, so the power supply voltage of high side driver is V_{ss_H} + V_{dd} . Difference between V_{p_L} and V_{p_H} is phase inversion. Input pulse for gate drive circuit (V_{p_H}) becomes V_{ss_L}- "V_{ss_L} + V_{dd}+ $\frac{V_{in}}{m}$" because the pulse of is boosted by bootstrap circuit and level shifter. The current of the high side pulse is amplified by high side driver, so the pulse amplified the current is V_{g_H}. Finally, the signal of V_{ss_L}- "V_{ss_L} + V_{dd}+ $\frac{V_{in}}{m}$" is inputted gate of high side MOSFET.

In this study, we assume the 3D stacking structure shown in Fig. 4 taking into the consideration of removal of the heat and minimizing the wiring impedance. GaN power devices, which generate the most heat, should be placed bottom [10]. A driver chip should be put on the GaN power devices to minimize the wiring impedance.

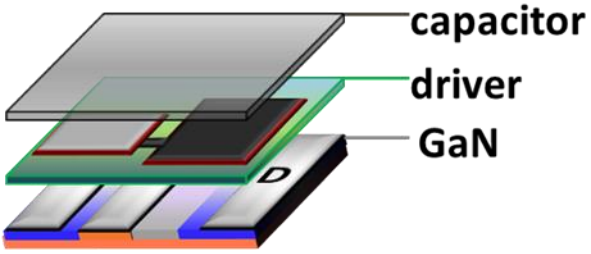


Fig.4 Stacking of GaN, driver and capacitor

III. CIRCUIT INTEGRATION

One of the most famous charge pumps consist of two capacitors and two switches. Generally, SBD is used as switches. However, SBD is difficult to integrate when we use CMOS process. In this situation, there are two methods to integrate part of charge pump.

First, using MOSFET as diode connected transistor. When connected gate and drain in MOSFET, drain-source voltage (V_DS) is equal to gate-source voltage (V_GS). Drain current flows in this circuit by V_DS exceeding threshold voltage of MOSFET (V_TH). This operation is similar to diode, so we can use MOSFET as diode.

Second, using special charge pump. In this paper, we consider three charge pump circuits.

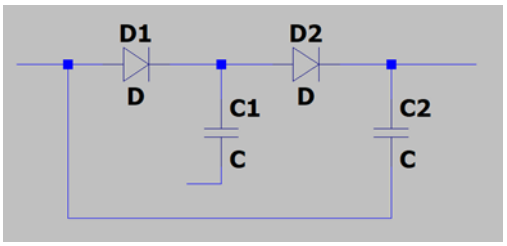


Fig.5 General charge pump

A. *Dual-Branch charge pump*

Dual-Branch charge pump [7] realizes lower ripple and transfer intervals of T/2. Also advantages of these structures are V_DROP reduction, higher switching frequencies and so on. However, this circuit is not suitable for low voltage operation and cold-start circuits.

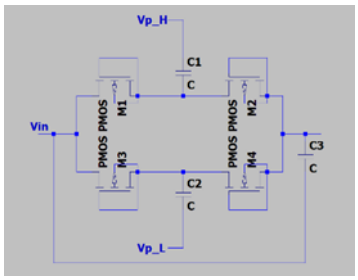


Fig.6 Dual-Branch charge pump [7]

B. *Cross-coupled charge pump*

Cross-coupled charge pump has dual compensated structures which is similar to dual-branch structures [8]. This charge pump realizes high efficiency (89%), fast pump speed (0.1ms), high capacitive drivability, charge transferability. However, like dual-branch, this is not suitable for low voltage operation (minimum start-up voltage is 320mV).

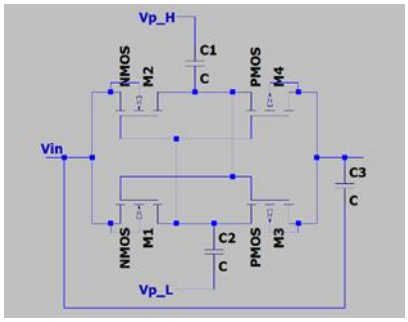


Fig.7 Cross-coupled [8]

C. *Adiabatic charge pump*

Adiabatic charge pump uses adiabatic switching to lower power consumption [9]. This circuit can recycle energy by rerouting charge transfer path back to the load. This operation is realized high efficiency because of reducing power consumption.

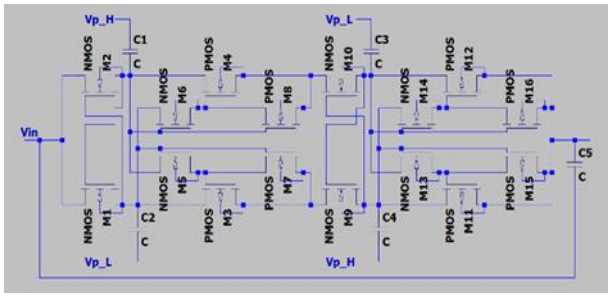


Fig.8 Adiabatic charge pump [9]

IV. SIMULATION RESULTS

We simulated the transformer less floating gate driver by using circuit simulation[11]. All circuit parameters are listed in Table 1.

In Fig.2, bootstrap1 and bootstrap2 are adopted diode connected transistor. Figure.9 shows the voltage by bootstrap using diode and Fig.10 shows it using MOSFET. These figures show that bootstrap circuit operates without any trouble. As the reason not to use special bootstrap circuit, it is hard to adjust the timing.

Also Table 2 shows the simulation results of these circuits. From Figures.9-13 show the gate-source voltage of simulations of five circuit configrations.

According to figures about gate-source voltage, transformer less floating gate driver could operate even if using the diode. However Table 2 shows the some differences between these circuits.

The amplitude of output gate drive voltage of Cross-coupled charge pump is highest (3.5V). From the point of view of the current consumption, Adiabatic is the lowest (0.1961A). Also Adiabatic charge pump shows the highest efficiency (95.74%) when the circuit used in buck converter.

Table 1 Circuit parameters

Input voltage $\frac{V_{in}}{m}$	5[V]
Input pulse V_p	0-4[V]
Power supply voltage V_{dd}	4[V]
Source voltage of low side switch V_{ss_L}	10[V]
Switching frequency	10[MHz]
Duty ratio	46[%]
Level shift capacity	10[nF]

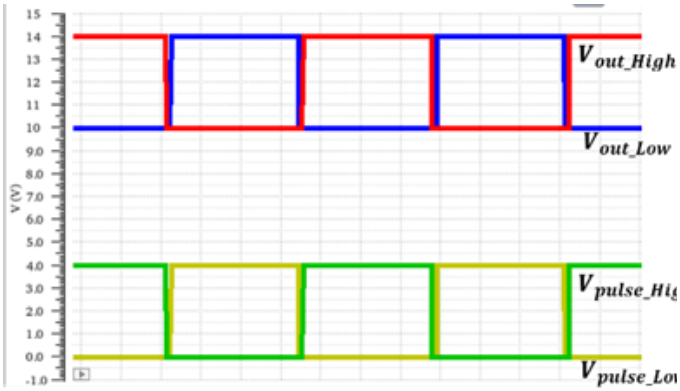


Fig.9 Pulse wave form using SBD based bootstrap

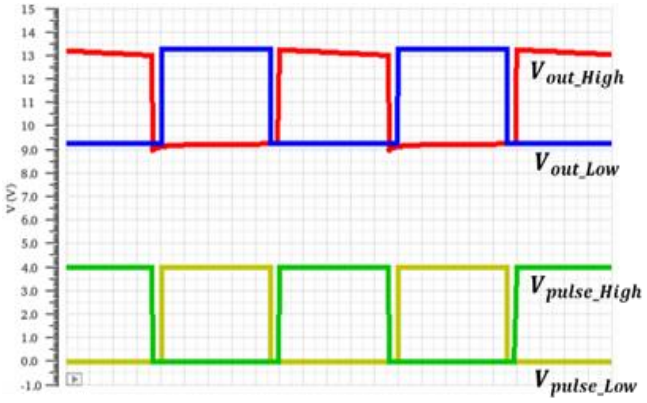


Fig.10 Pulse wave form using diode connection MOSFET based bootstrap

Table 2 Simulation results

	gate-source voltage[V]	current consumption[A]	quantity of MOSFET	efficiency[%]
Dual-Branch	2.55	0.70841866	4(all p-MOSFETs)	25.98087031
Cross-coupled	3.5	0.263435449	4(2 n-MOSFETs and 2 p-MOSFETs)	69.75143273
Adiabatic	2.88	0.196130286	16(8 n-MOSFETs and 8 p-MOSFETs)	95.74248008
diode	3.45	0.330211714	2 diodes	65.22058148
diode connected transistor	2.48	0.25904329	2 p-MOSFETs	73.5506409

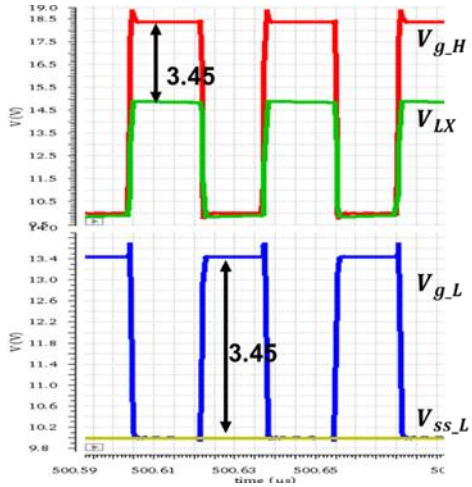


Fig.11 Gate-source voltage wave form of general charge pump

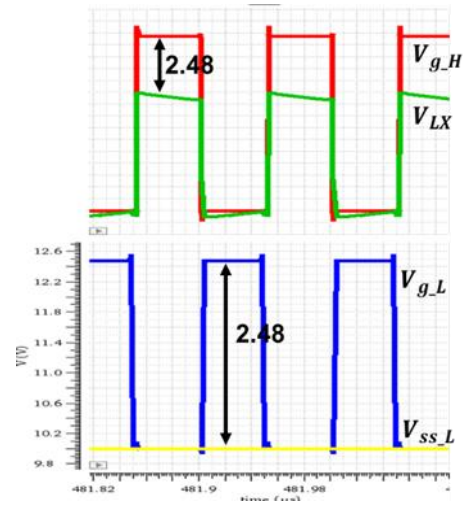


Fig.12 Gate-source voltage wave form of diode connected transistor

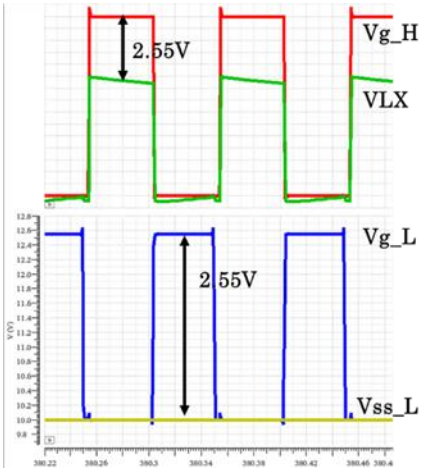


Fig.13 Gate-source voltage wave form of Dual-Branch

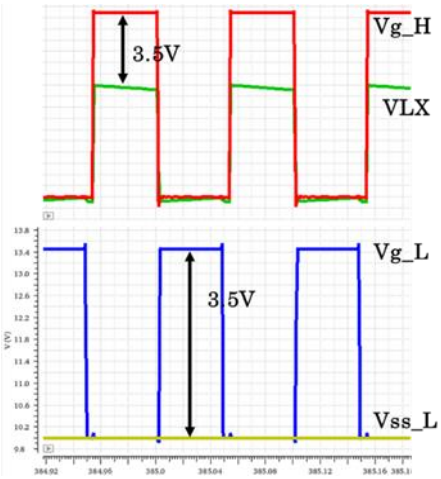


Fig.14 Gate-source voltage wave form of Cross-coupled

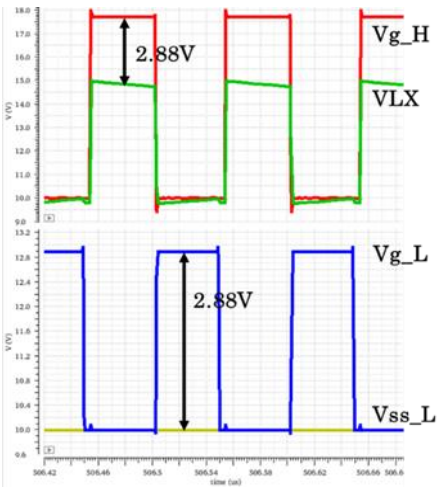


Fig.15 Gate-source voltage wave form of Adiabatic

V. Conclusion

We investigate the suitable circuit configuration for fully integrated transformer less gate driver circuit. The simulation results show that Adiabatic is the best.

Acknowledgements

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