CASCODE LIGHT - normally-on JFET stand alone performance in a normally-off Cascode circuit

Daniel Domes, Xi Zhang
Infineon Technologies AG, Max-Planck-Straße 5, 59581 Warstein, Germany

Abstract

SiC power devices are known to show best performance in terms of switching losses. Since the SiC Schottky-barrier diodes became commercially available in 2001, transistors are in the focus of development. Because of its electrical behaviour and reliability, the SiC normally-on JFET seems to be one of the best candidates for future low loss unipolar switch application [1]. For safety reasons at startup and in failure mode, circuit designers aiming at normally-off switch characteristic. Therefore, normally-on high voltage SiC JFETs were combined with standard low-voltage MOSFETs forming a normally-off Cascode circuit. This paper analyzes the Cascode function in inverter application and explains drawbacks of the classical solution. To get rid of the Cascode problems, a so called Cascode Light approach was realized combining best JFET stand alone performance with the safety of a standard Cascode.

1. Introduction

Without applying a negative gate-source-voltage, the SiC normally-on JFET devices are in the on-state. This behaviour can be critical in terms of circuit start-up, e.g. if the gate driver supply voltages are generated out of the DC-link. On the other hand, if a failure in the gate drive supply occurs, the transistors don't have to short circuit the DC-link. These days widely known, a Cascode circuit, combining a high-voltage depletion-mode- and a low voltage enhancement-mode-transistor [2], is discussed to solve the normally-on problem.
In Fig. 1 a common Cascode circuit combining a high voltage JFET and a low-voltage MOSFET is shown. While the MOSFET is controlled by its own gate driver GD1, its Drain-Source-voltage acts as a control for the JFET. This is possible because for the normally-on JFET a negative voltage v_{GS} is required for pinch off its channel.

In an inverter application, reverse conductivity of the switches is mandatory, even if the transistor is turned off by its gate driver. In case of the Cascode, the reverse current flows through the body diode of the low voltage MOSFET. Then, $v_{DS(MOS)}$ becomes the negative value of the diode V_F. Thus, the JFET gate-source-path becomes slightly positive biased resulting in a turn on of the JFET channel. As a consequence, if the MOSFET is turned off, reverse current flows through the MOSFET body diode and reverse direction of the JFET channel.

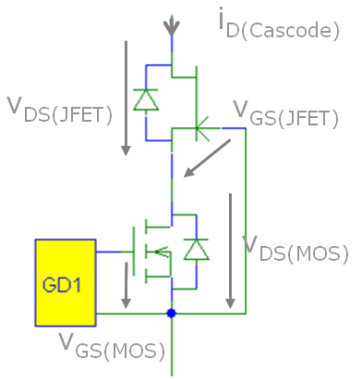

Fig. 1: Common Cascode circuit combining a high voltage normally-on with a low-voltage normally-off transistor

2. Comparison of Cascode and stand alone JFET performance

In order to investigate the differences between Cascode and normally-on JFET behaviour, an inverter circuit was build up with a Cascode (Fig. 2) and a stand alone normally-on JFET. In both cases, the JFET was a 1200V, 100mOhm device. The MOSFET was chosen as a 40V OptiMOS™ 3 with a RDSon of 3.9mOhm. Both circuits were realized in Infineon´s Easy2B modules, which were inserted in practically identical PCBs.

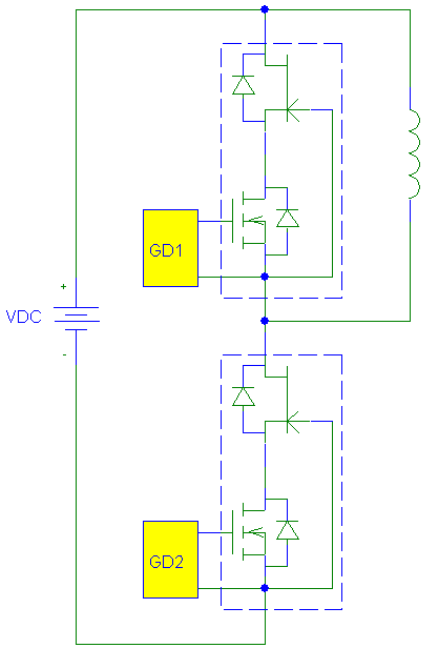

Fig. 2: Cascode-based inverter circuit

The Cascode MOSFETs were driven using Infineon´s 1ED020I12-F gate driver IC. For controlling the JFET directly, the 1ED020I12-F gate driver can also be used by simply connecting JFETs Source to the positive supply voltage of the gate drive IC, while JFETs Gate remains connected as usual.

The corresponding turn-off waveforms can be seen in Fig. 3, whereas both circuits were operating at room temperature switching 600V and 10A.

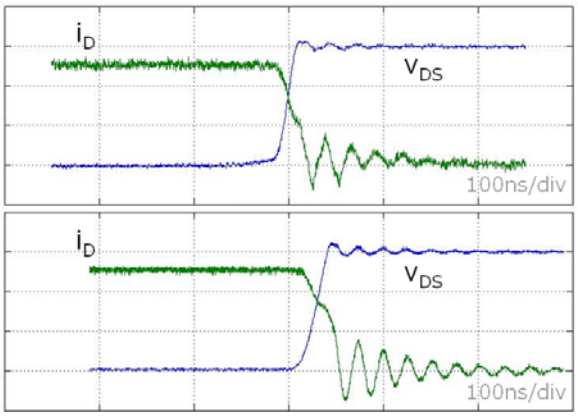

Fig. 3: Turn-off waveform of a Cascode (top) and a stand alone JFET module (1200V, 10A) in the same environment (i_D: 4A/div, v_{DS}: 200V/div, time 100ns/div)

The Cascode waveforms look very similar compared to the JFET stand alone performance. In both cases, the turn-off energy is approx. 100µJ. Regarding the turn-on waveforms in Fig. 4, big differences are visible. In case of the Cascode, a high reverse-recovery-like current peak appears which reaches a peak value of approx. 35A. After this peak, the current drops very fast triggering oscillations in the system. The JFET turn-on waveform shows much less reverse-recovery peak followed by a smooth shape until the static value is reached. Regarding the turn-on energy losses, the Cascode turn-on consumes 440µJ, the JFET stand alone version only 160µJ.

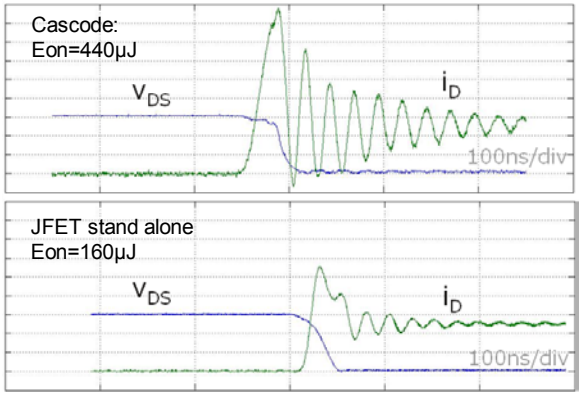

Fig. 4: Turn-on waveform of a Cascode (top) and a stand alone JFET (bottom) module (1200V, 10A) in the same environment (i_D: 4A/div, v_{DS}: 200V/div, time 100ns/div)

3. Discussion of results

To explain these differences, the typical inductive switching behaviour in a half bridge circuit needs to be considered. Assuming the inductive current is freewheeling in reverse direction of the upper Cascode (related to Fig. 2) and the lower switch is turned on, the current fully commutates to the lower switch. If the upper switch is free from load current, it can increase its voltage. This increase in voltage stands for the charging process of the output capacitance of the upper switch. The charging of the much smaller load capacitance should be neglected here.

For charging the output capacitance of a Cascode $Coss_{Casc}$ from zero volt on, first the output capacitance of the MOSFET (CDG(M) and CDS(M) in parallel) must be charged. Fig. 5 indicates, that in parallel to the MOSFET output capacitance the Gate-Source-capacitance of the JFET is connected. Furthermore, as long as the MOSFET Drain-Source-voltage is smaller than the absolute value of JFETs pinch-off-voltage v_{PI}, the JFET is conducting. As a consequence,

its channel connects the Drain-Gate-capacitance of the JFET in parallel to the before mentioned capacitances. For $v_{DS(MOS)}<|v_{PI}|$ one can write:

$$Coss_{Casc\_A}=CDG(M)+CDS(M)+CGS(J)+CDG(J) \quad (1)$$

If $v_{DS(MOS)}$ reaches the level of $|v_{PI}|$, ideally the MOSFET remains at this voltage for the rest of the Cascode charging process. Then, the further increasing voltage across the Cascode is only supported by the JFET, which has no blocking voltage until now. From this point on, the resulting output capacitance of the Cascode circuit is the same as it is for the stand alone JFET starting from $v_{DS(JFET)}=0$:

$$Coss_{Casc\_B}=CDS(J)+CDG(J) \quad (2)$$

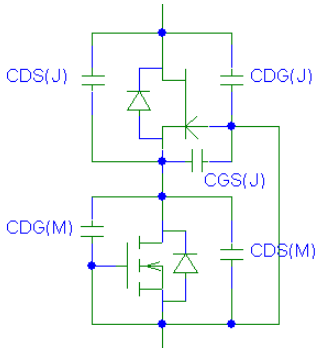

Fig. 5: Cascode circuit with parasitic capacitances

Fig. 6 shows the amount of charge needed for a beginning turn-off from 0 to a benchmarking voltage of 30V of three different switches. The mentioned stand alone JFET, the low voltage MOSFET needed for the Cascode and the combination of both transistors as Cascode were measured. A constant current source of 1mA is used to charge all three candidates one by one.

The stand alone JFET consumes only 15nC whereas the Cascode needs 6 times more ending up with 91nC. The MOSFET charge lies in-between. One can see clearly, that the Cascodes behaviour shows more flat shape compared to the MOSFET curve until the JFET pinch-off voltage is reached. Remember, until that point equation (1) is valid.

Once the MOSFETs Drain-Source-voltage has reached the $|v_{PI}|$ level (here approx. 16V), only the JFET is responsible for further voltage increase resulting in a much stiffer slope.

4. Proposed solution

Regarding the output capacitance the Cascode behaves like a JFET with a charge offset of more than 80nC. This charge-offset need to be supplied in the first 15V of a turn-off process resulting in a high initial current peak. This clearly shows, that from the dynamic point of view the JFET stand alone switching is much more desired than switching a conventional Cascode circuit.

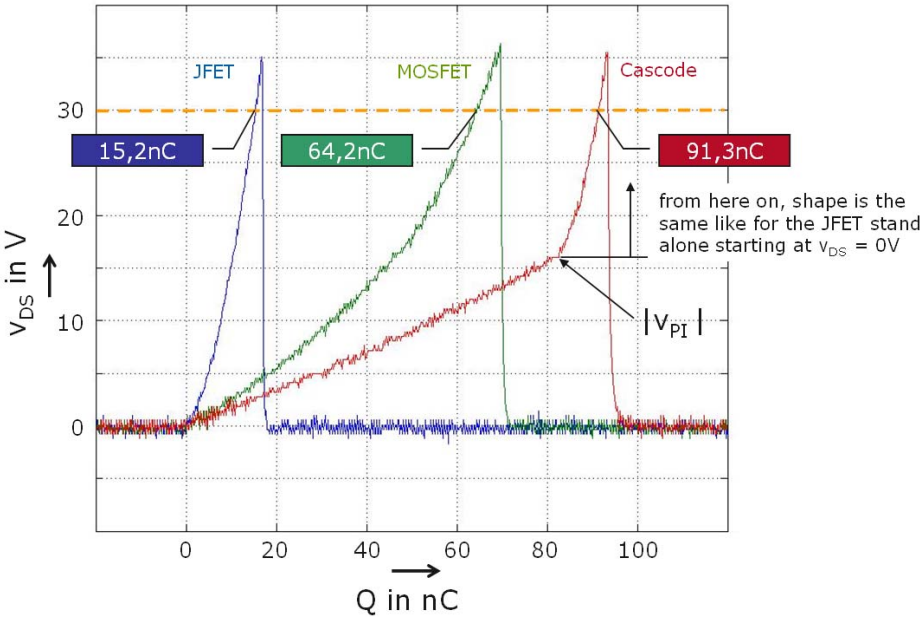

Fig. 6: Results of constant-current-charging (1mA) of the output capacitance of a 1200V, 100mOhm SiC JFET; the 30V, 3.9mOhm OptiMOS®3 and the Cascode consisting of mentioned JFET and MOSFET

In [3] the idea of using a modified Cascode is proposed, where the JFET and the MOSFET are driven directly by means of its own gate drive circuits (Fig. 7). This approach should be entitled as Cascode Light.

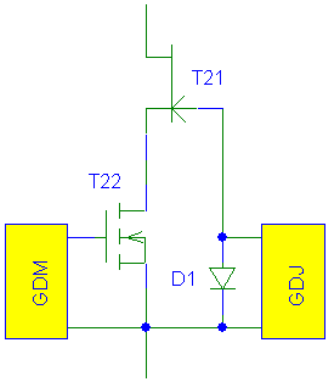

Fig. 7: Modified Cascode circuit, called "Cascode light", MOSFET and JFET are driven by its own gate drive circuit, independently

A simple diode D1 ensures that in case of circuit start-up or failure in the gate drive supply chain the classic Cascode solution comes into being and serves as a normally-off switch. If the supply voltage for GDJ is sufficient to block the JFET, the MOSFET is turned on and stays in that mode for the rest of the normal operation of the circuit. The JFET is performing switching controlled by its gate drive circuit GDJ.

In Fig. 8 the practical realization of Cascode Light can be seen. In a first approach, two of Infineons 1ED020I12-F coreless transformer gate drivers are used to control the JFET and the MOSFET of each Cascode Light switch.

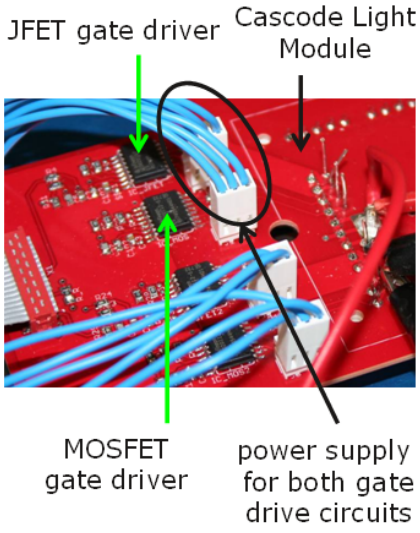

Fig. 8: First laboratory realization of Cascode Light approach

The secondary side under-voltage-lock-out UVLO of the JFET gate drive IC can be used to control the MOSFET gate drive IC. In this approach, the UVLO affects the primary side RDY-output of the JFET gate drive IC and this signal is connected to control the MOSFET gate driver. Doing this, only the JFET needs to be controlled from outside, while failure-mode- and start-up-safety is ensured by gate drivers interconnection.

It should not be unstated that for a more practical solution of a Cascode Light switch there is no need for a second gate drive IC with isolating barrier. Because of the fact that the MOSFET potentials are close to the JFET ones, a simple inverter IC can also be used to control the MOSFET.

In the lab the functionality of Cascode Light was successfully proven. Charging the DC link without gate drive supply or gate drive supply disconnection and reconnection under full DC link voltage shows good results (see Fig. 9).

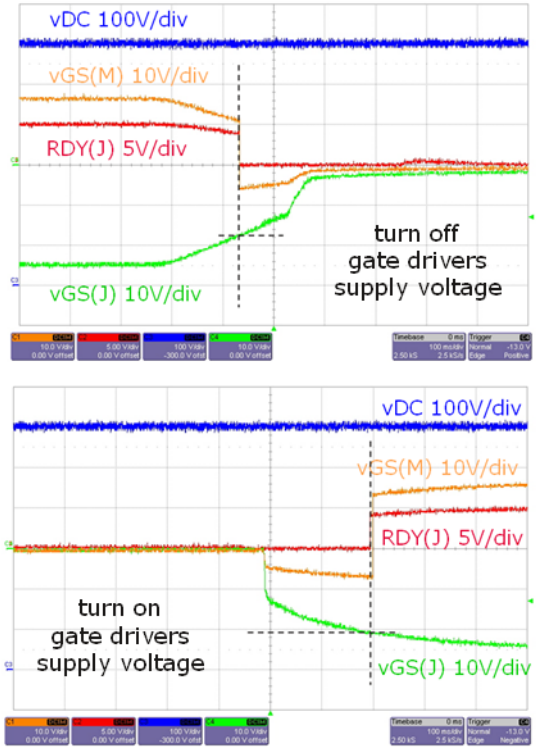

Fig. 9: Measurement results based on circuit from Fig. 8: turn-on and –off of gate drivers supply voltage under full DC-link voltage (100ms/div)

5. Conclusion

In this paper the poor behaviour of classical Cascode solution in inverter circuits is shown and explained. To make use of the outstanding JFET stand alone switching performance accompanied by the safety of a Cascode approach, the Cascode Light solution is proposed. Independent control of the JFET as well as the MOSFET gives maximum freedom for operation. Practical results based on a first demonstrator module prove the basic concept idea.

6. Literature

[1] Treu, M.; Rupp, R.; Blaschitz, P.; Rüschenschmidt, K.; Sekinger, T.; Friedrichs, P.; Elpelt, R.; Peters, D.: Strategic considerations for unipolar SiC switch options: JFET vs. MOSFET, Proc. IAS 2007.

[2] Baliga, B. J.; Adler, M. S.: Composite Circuit for Power Semiconductor Switching. European Patent EP 0 063 749 B1, 1982.

[3] Melkonyan, A.: Elektronische Schalteinrichtung mit zumindest zwei Halbleiterschaltelementen. German Patent DE 10 2006 029 928 B3, 2006.