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A Simple High-Performance Low-Loss Current-Source Driver for SiC Bipolar Transistors

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Abstract—The paper proposes a novel topology of a simple base drive unit for silicon carbide bipolar junction transistors (BJTs) based on the current-source principle. Energy stored in a small, air-cored inductor is employed to generate a current peak forcing the BJT to turn-on (10-20ns) very rapidly. The driver enables very high switching performance and very low switching losses of the driven BJT. Both the current source and the unit delivering the steady-state current to the base are supplied from the same low-voltage source in order to limit power consumption. Operation principles as well as selected design issues are discussed in the paper and illustrated by experiments. The 1200V/6A SiC BJT driven by the proposed circuit shows a very fast switching speed.

Keywords—Silicon carbide; bipolar transistor; base drive unit, current source

I. INTRODUCTION

Silicon Carbide (SiC) power electronics has been in a kind of waiting-mode for approximately two decades [1]-[5]. The main reason to this is that the material itself has not been sufficiently mature for series production of power semiconductor components. During recent years, however, tremendous improvements in material quality have been achieved, and as a result several power semiconductor components are now available on the market. One of the most promising active switches in SiC is the bipolar junction transistor (BJT) which offers very low on-state voltage drops and very high switching speeds. These properties make the SiC BJT a very interesting switch candidate for a multitude of applications ranging from switch-mode power supplies and photovoltaic converters to converters for hybrid electric vehicles or electric traction applications.

As switching speeds of the order of 20 ns have been reported for SiC BJTs [6] it is very tempting to apply these devices in dc-dc converters, where high switching frequencies can substantially reduce the volume and cost of passive components. In order to fully exploit the benefits of the high switching speed, however, both the main circuit and the base drive unit of the BJT have to be carefully designed for this

purpose. As will be shown below, this is not an entirely trivial task.

The requirements for a SiC BJT base drive unit are higher than for drivers of Si IGBTs, Si MOSFETs, as well as for SiC normally-on JFETs or SiC MOSFETs. Besides providing dynamic current peaks to turn-on/turn-off the device, the second function of the driver is to supply a base current during conduction period [6]. This allows the bipolar transistor to operate in deep saturation with low voltage drop across collector-emitter terminals. The need for a controlling current during the conduction is a property in common with the normally-off (enhancement-mode) SiC JFET. This means that the same kind of base-drive units can be used for the two types of devices, but the gate current of the JFET is lower than the base current for the BJT [7], [8], [9].

The first attempts to design SiC BJT drivers, applied to SiC BJTs with low current ratings, were based on state-of-the-art IGBT/MOSFET driver components. A typical gate driver equipped with a speed-up capacitor (Fig. 1a) is able to drive SiC BJTs with turn-on and turn-off times counted in tens of nanoseconds according to the recommendations of the manufacturer [6]. The disadvantage of this solution is that optimum operation parameters are hard to find as high switching speed requires high supply voltage/capacitor values. In order to reach low power consumption, however, exactly opposite measures should be taken. One solution to this problem is presented in [10] where a dual-source (2SRC) driver is proposed. The authors split two functions of the base drive unit into two stages: a low-voltage stage to optimize power consumption caused by the static base current requirement, and a high-voltage stage capable of driving the BJT very rapidly (see Fig. 1b). With the 2SRC design applied to a 2 kW dc/dc boost converter an efficiency of 98.9 % at 100 kHz was measured while the power consumption of the driver was less than 1.6 W [10], [11]. Further evaluation of the 2SRC driver led to the conclusion that some features could be recognized as drawbacks.

- Two voltage sources (V_{CCH} , V_{CCL}) make the design complicated,

Fig. 1. SiC BJT base drivers: solution with speed-up capacitor (a) dual-source with resistors and capacitor (b) and proposed circuit with current source (c)

- The base capacitor C_B is a source of high-frequency oscillations with parasitic inductances of the transistors package.
- The base capacitor must be discharged to make the driver ready for the next turn-on action and this is the reason to an associated duty-cycle limitation.
- The lack of a negative voltage supply could be a problem when devices operate in a leg configuration and an undesired turn-on may occur.

All mentioned problems were motivations to the search for a new solution to the BJT base drive problem – a solution offering the same or better performance than the 2SRC driver, but with a simpler design.

II. CURRENT-SOURCE DRIVER IDEA

A new current-source (CS) base-drive unit, proposed in this paper, is presented in Fig. 1c. The main difference, in comparison to the 2SRC driver, is that the part delivering the dynamic current at turn-on is supplied from the same low-voltage source as the static part. This is possible thanks to the use of an inductor L_R which is the key part of a simple current source [12]. The operation principles of the CS driver are illustrated in Fig. 2 where the control signals of three transistors and the current through the inductor L_R as well as the base current can be seen.

The analysis starts when the driver control signal (IN) is low and the BJT is in the off-state. Switches T_1 and T_2 are off but T_3 is in the on-state providing negative bias. The rising edge of the control signal IN (observed at time t_A) turns on the switch T_1 . The sum of the voltages V_{CC} and V_{EE} applied to the inductor L_R leads to a linear increase of the current. At a certain instant when the inductor current has reached the desired peak value I_{LRP} (t_B), the switch T_3 is turned off. This breaks current path to the negative pole V_{EE} and the inductor current is now conveyed into the base of the SiC BJT. Energy stored in L_R is consumed to build up the current peak necessary to turn the transistor on. The turn-on of the upper switch T_2 initiates the steady-state current delivered to the base from V_{CC} . Note, that the inductor current starts falling at t_B as the applied voltage is reduced to merely the difference

between V_{CC} and v_{BE} . The rise time of the base current is limited by the time t_C , when the peak base current I_{BP} is close to the inductor current. This means that most of the inductor energy is employed and switch T_1 should be turned off at t_C . During the time between t_C and t_D the inductor current falls to zero and the base current reaches the fixed value I_{BM} required for the collector current conduction.

The turn-off process starts with the falling edge of the input control signal IN (t_E). Switches T_2 and T_3 are turned off and turned on respectively. The negative voltage V_{EE} applied to the base-emitter terminals results in the dynamic current peak of the base current which turns off the SiC BJT. This process ends at t_F when the base current equals zero again.

As the base resistor R_B , adjusting steady-state base current, is moved to the supply side, the dynamic current slope is limited only by the parasitic inductances and resistances. Thus, a very fast turn-on, usually expected from SiC transistor, can be easily achieved. The switching speed at turn-

Fig. 2. Illustration of operation principles of the proposed current-source base driver

on can be adjusted by means of I_{LRP} by changing the rise times t_R (between t_A , t_B , and t_C) or the value of L_R . Both the turn-on and turn-off switching speeds may be controlled by application of an additional resistor R'_B as illustrated with the dashed lines in Fig. 1c.

The application of the inductor as an energy buffer for current peaks limits the problem of ringing caused by parasitic inductances. Aiming for effective utilization of the inductor current to build up the base current peak, the value of L_R should be one order of magnitude higher than the parasitic inductance of the package (TO-247).

In the solution presented in [12] for the MOSFET, the inductor stage is also applied to achieve a fast turn-off. This could obviously be established by adding more transistors to the schematic in Fig. 1c. This would, however, make the circuit more complex, not to mention the special signal sequence for the, at least five, transistors which would need additional logic circuits. Actually, the desired fast turn-off is possible using only the three transistors in the proposed circuit in combination with the negative supply voltage V_{EE} .

Another important difference between the solution in [12] and the proposed simple driver design is the lack of inductor energy regeneration. Actually, this feature is not required as the remaining energy of the inductor after turn-on is not wasted. After the turn-on process of the main transistor (the duration between t_B and t_C) the decreasing inductor current supports the steady-state current of the base. All in all, the majority of the power consumption of the base-drive unit is associated with the steady-state base current and possible savings would be significantly lower than 10%.

III. PRACTICAL REALIZATION

The proposed CS base driver circuit was designed to control a 1200V/6A SiC BJT [13] with the use of two totem-pole MOSFET drivers from IXYS (see schematic in Fig. 3a). The IXDD614 offers low on-state resistance, a peak current of 14 A, and short nanosecond switching times [14]. A series diode (low-voltage Schottky) is added to the inductor L_R to block the low-side transistor, complementary to T_1 .

Taking into account operation conditions (short current peaks), the inductor L_R was designed with an air core. With this design the saturation current is high, but the simplicity was also important benefit. The number of turns was experimentally determined to be 15 while the diameter of the inductor was approximately 3 mm. As can be seen in Fig. 4, the physical size of the inductor L_R is comparable to other electronics parts of the circuit. The inductance value, less than 200 nH, was chosen to be one order of magnitude higher than the expected parasitic inductance of the TO-247 package. It is the opinion of the authors, that this type of inductor design may be more reliable and stable than the capacitors applied in the dynamic part of a comparable 2SRC driver [10].

Considering the SiC BJT requirements regarding the steady-state base current the base resistor value was selected to be 5.6 Ω . The positive supply voltage was chosen to be $V_{CC}=5V$ aiming for minimum power dissipation in the base resistor [10]. The negative supply voltage could also be

Fig. 3. Schematic of practical design of the simple current-source driver: power part (a) and logic circuit (b).

$V_{EE}=5V$ in order to reduce the number of isolated dc/dc converters, but in this design $V_{EE}=15V$ was selected to ensure good dynamics at turn-on and turn-off. A base driver with more negative voltage is also less sensitive to noise when the SiC BJT is operating in a bridge leg. Finally, two isolated dc/dc converters from TRACO (TMH2405S, TMH2415S) were employed to provide the positive and negative supplies.

The advantage of the proposed CS base-drive unit in reference to the solution presented in [12] is the simple control sequence which is merely constituted by a slightly modified input logic signal (see Fig. 2). As three switches T_1 - T_3 are inside two totem-pole drivers (Fig.3a), only two control signals are required. Basically, the control signal of T_1 (upper totem-pole) is a short high-state pulse triggered by the rising edge of the input signal IN (originating from an optocoupler). The second required signal for T_2/T_3 equals the signal IN with a delayed rising edge (Fig. 2a). The delay of the control signal T_2/T_3 and the width of the T_1 pulse are expected to be adjustable.

Due this simple control sequence both totem-pole drivers could be controlled with the use of a simple logic circuit (see Fig. 3b). Only four 2-input NAND gates (single IC) and two

RC delay circuits are employed. Changing the time constant R_1C_1 , the duration between times t_A and t_B is changed (see Fig. 2). This means that the rise time of the current through L_R can be adjusted. The second delay circuit R_2C_2 controls the T_1 pulse width (between t_A and t_C). Obviously, the R_2C_2 time constant should be longer than R_1C_1 to set the duration between t_B and t_C , necessary to build up the peak of the base current as can be seen in the sequence presented in Fig. 2.

The operation of the logic circuit is illustrated in Fig. 5, where experimental waveforms of the input signal IN (output from optocoupler) and the two control signals of the totem-pole drivers T_2/T_3 and T_1 are presented. The experimental results in Fig. 5 are in agreement with the ideal waveforms shown in Fig. 2. Delay times between the input IN and control signals, caused by propagation delays of the applied NAND gates, are in the range of 100 ns.

IV. BASE-CURRENT ADJUSTMENT

The output from the proposed driver circuit, the base current waveform, can be adjusted to meet the BJT driving requirements. Current peaks at turn-on and turn-off influence the switching behavior, the slopes of the collector-emitter voltage and collector current. The steady-state base current keeps device in deep saturation where very low voltage drops are achievable.

As mentioned above, the steady-state value I_{BM} can be chosen by means of V_{CC} and R_B . Both values should be as low as possible to reduce the power loss. A more detailed discussion can be found in [10]. Considering a 1200 V/6 A SiC BJT with a built-in BE voltage in the range of 3V, $V_{CC}=5$ V and $R_B=5.6 \Omega$ were selected to obtain $I_{BM}=320$ mA.

The peak value of the current at turn-on I_{BP} was determined, similarly, based on the experiences from the 2SRC driver presented in [10]. The required range of I_{BP} is assumed to be up to 10 A, but 5 A would be enough to switch the SiC BJT rapidly. Considering for simplicity the case with $R_B'=0$, $V_{CC}+V_{EE}=20$ V, $L_R<200$ nH, di_{LR}/dt should be approximately 1 A/10 ns (100 A/ μ s) – see Fig. 6. Then, the duration between t_A and t_D is expected to be shorter than 200 ns, even for maximum peak. This value seems to be a good tradeoff between the duty-cycle limitation issue and the magnitudes of the supply voltage and inductance. The shape of the base current at turn-on is adjustable within this range with the use of the variable resistors R_1 and R_2 .

The peak value of the inductor current I_{LRP} should be set by R_1 changes to be slightly higher than required I_{BP} due to the negative slope of i_{LR} after t_B – see (see Fig.6). Then, using this method exactly the required value of I_{BP} is reached at time t_C when i_B equals i_{LR} .

The next step in the procedure of the current peak setting is to choose the pulse width of T_1 by adjusting the value of R_2 . As can be seen in the example presented in Fig. 6a, the duration between t_B and t_C , necessary to increase the base current, is less than 1/2 of the total T_1 pulse width (90 ns). This seems to be a fair ratio to obtain a suitable shape of the current peak. Another example (Fig. 6b) illustrates an

Fig. 4. Photo of the PCB design (45x42mm) of the simple CS driver.

Fig. 5 Example of the control sequence – from the top: input signal, control signal of T1 and T2/T3 and T1 (all 2V/div, 40ns/div): a) turn-on, b) turn-off

extended T_1 pulse ($(t_C - t_B) > 50\%$) which increases the width of the base current. This results in increased RMS values of inductor and base currents and, consequently, higher power losses. Usually, the 6 A SiC BJT is turned on approximately 20-30 ns after t_B (see Fig. 8) but for devices with bigger chip sizes extended pulses of the base current may be necessary.

The base current peak at turn-off can also be adjusted but not that precisely as at turn-on. Changing the values of V_{EE} and R_B' , the shape of the negative current peak can be set. Two examples of the base current at turn-off are presented in Fig. 7. Without the resistor R_B' , when the rise of the current

Fig. 6. Example of the base current adjustment at turn-on: correct current pulse (a) pulse with extended width (b). Waveforms: T_1 (light blue) and T_2/T_3 (dark blue) totem-pole output, inductor L_R (green) and base (violet) currents. All voltages 10 V/div, currents 1 A/div, time scale 20 ns/div.

Fig. 7. Example of the base-current adjustment at turn-off: $R_B' = 0$ (a) and $R_B' = 4.7 \Omega$ (b). Waveforms: T_1 (light blue) and T_2/T_3 (dark blue) totem-pole output and base current (violet) currents. All voltages 10 V/div, current 1 A/div, time scale 20 ns/div.

peak is limited only by the parasitic inductances and the totem-pole driver resistance, the maximum (negative) value I_{BP-} is approximately 2 A (Fig. 7a). Application of $R_B' = 4.7 \Omega$ reduces this value by a factor two (Fig. 7b). The current oscillations visible in Fig. 7a are strongly damped.

V. DOUBLE-PULSE MEASUREMENTS

The model of the CS base drive unit was applied to control the SiC BJT [13] tested in a standard double-pulse procedure. The 1200 V/6 A SiC BJT with 1200 V/5 A SiC Schottky were switched using a direct voltage of 600 V and nominal current. The voltage measurement was conducted with a high-voltage P5200 probe while two Rogowski coils (CWT mini) were employed to measure current.

The turn-on performance of the SiC BJT with CS driver is presented in Fig. 8 where base and collector currents and the collector-emitter voltage can be seen. The base current peak was set by changing R_B' from 0 to 4.7Ω while the value of the

peak inductor current was constant. In result, the measured current peak reaches 10 A (Fig. 8a) and 7 A (Fig. 8b) respectively, which is lower value than observed when $V_{CE} = 0V$. The reason for being that could be an increased parasitic base-collector charge Q_{BC} from 0 to 47nC with the switched voltage rise from 0 to 600V [13]. Moreover, Rogowski coil which measures the base current is placed close to collector and emitter terminals due to a very limited space. It is also possible that the coil is influenced by flux generated by the collector/emitter current peaks.

The observed voltage slopes at turn-on are very fast: 15 ns and 25 ns, corresponding to 40 (Fig. 8a) and 24 kV/ μ s (Fig. 8b). A comparison of the two cases reveals that the measured collector current speed is rather influenced by parasitic inductances than by the driver circuit. In spite of some differences, both current slopes are measured to be approximately 100 A/ μ s. The waveforms suggest some parasitic capacitance in the circuit as the collector-emitter voltage starts falling before collector current reaches the

Fig. 8. SiC BJT turn-on process for two different values of I_{BP} : $R_B' = 0$ (a) and $R_B' = 4.7 \Omega$ (b) (time scale 20 ns/div).

steady-state value. This means very low turn-on losses (E_{ON} equals 4 and 16 μJ for Fig. 8a and Fig. 8b respectively), close to the soft turn-on case.

A similar, but opposite, phenomenon is observed during the SiC BJT turn-off presented in Fig. 9. The collector current contains a capacitive component which results in a current peak and increases the delay time before the current slope is falling. This time, the switching energy is increased and only slightly depends on the speed of the current and voltage slopes. The switching speed is again influenced by a change of R_B' from 0 to 4.7 Ω . The switching energy E_{OFF} equals 118 and 135 μJ for Fig. 9a and Fig. 9b respectively. The voltage rise is again very fast. Values of 12 and 16 ns are observed (speed 50 and 37.5 kV/ μs).

Presented measurements prove that the proposed base driver is able to force the SiC BJT to switch very fast (low switching losses: total energy 122 and 151 μJ) and to deliver a steady-state current to the base during the conduction period. Furthermore, adjustment of the switching speed is perfectly possible.

Fig. 9. SiC BJT turn-off process for two different values of $I_{BP(-)}$: $R_B' = 0$ (a) and $R_B' = 4.7 \Omega$ (b) (time scale 20 ns/div).

VI. POWER CONSUMPTION

A very important issue for the BJT base driver is the power consumption which depends on a number of parameters as supply voltage ranges, magnitude of the base current in the dynamic and steady-state, resistor and inductor values, frequency, and duty ratio. An initial test, conducted when the driver was operating at 100 kHz with 50% duty ratio and steady-state/dynamic current equal to 320 mA/2 A shows that the power consumption equals 1.9 W for +5/-15 V supply, 1.6 W for +/-5 V supply, and 1.15 W for +5/0 V supply, respectively. Obviously with the reduction of negative supply the current peaks are smaller but also logic circuitry (operating with ground connected to $-V_{EE}$) does not need a linear regulator. Another test shows that the driver consumes in off state (-15V) 767 mW with or without the transistor connected. The same test conducted for constantly on driver (+5V) results in 540 mW/2.4 W with SiC BJT. The next two series of measurements, presented in Fig. 10, were conducted for +5/-15V supply, constant duty ratio 50%, current peak $I_{BP} = 5A$ and various frequency values. The measured power losses, with or without main transistor, depend on frequency as more energy is required to generate current peaks. Most of the power loss is dissipated in the driver itself (1.1 W from 1.9 W @

100 kHz) which is subject to future optimization. An estimation made on the base of various measurements shows that:

- parts of the driver operating at +5V level (TRACO supply, IXDDs, base resistor and SiC BJT) consume 1.1 W
- parts of the driver operating at negative voltage (TRACO supply, linear regulator, logic circuit, IXDDs, SiC BJT) consume 0.5 W
- inductor L_R , series diode and positive current peaks are responsible for 0.3 W of total power loss

while the CS driver is operating at 100 kHz with duty ration 50%. Accordingly, the proposed simple driver design has a power consumption that is slightly higher to the one of the 2SRC driver. On the other hand, the power loss distribution shows that optimization is very possible (i.e. by use 15 V logic and optocoupler).

Fig. 10 Measured power consumption of the CS driver (50% duty ratio, 5A base current peak, +5/-15V supply).

VII. CONCLUSIONS

The paper proposes a novel topology of a base-drive unit for SiC BJTs which employs the current-source principle to force the BJT to a very fast turn-on. The main advantage is that both parts of the driver: the steady-state and the dynamic are fed from the same low-voltage supply (i.e. 5 V) which simplifies the design. The driver may be equipped with a negative supply voltage which would speed-up the turn-off process and keep the transistor in the off-state when used in a bridge-leg configuration. Both, speeds of turn-on and turn-off can be adjusted by circuit parameters.

The control sequence of the driver transistors cannot be described as complicated as only one additional, short pulse triggered by rising edge of input signal is required. That is why the logic circuitry is very simple and can be realized with four NAND gates and two RC circuits. The same can be said about

power part of the driver: besides supply two totem-pole drivers with base resistor and light air-cored inductor are necessary.

The presented measurements show correct operation of the proposed driver: dynamic as well as static currents to the base are delivered as required. The power consumption, as was measured, is in the same range as for the 2SRC driver. Double-pulse tests performed to verify the switching performance of the 6 A SiC BJT confirmed very good dynamic properties, especially the turn-on switching forced by the current source is very fast. This will lead, together with very low on-state losses of the BJT, to very low semiconductor power losses when the BJT operates in a power converter.

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