Ideal Power

White Paper

B-TRAN™ – Device Structure, Performance and Applications

1. Introduction

Semiconductor power switches are critical components in power conversion for a wide variety of high efficiency and clean energy applications including electric vehicles, renewable energy generation, energy storage, solid-state circuit breakers and motor drives. Improving the efficiency and performance of semiconductor power switch components can have wide benefits, improving the economics and accelerating deployment of these applications.

Ideal Power Inc. has received over 70 patents worldwide for the topology and method of operation of a new kind of semiconductor power switch, which we call a Bidirectional Bipolar Junction Transistor (B-TRAN™), a novel four quadrant power switch with ultra-low forward voltage and low switching losses that can be used in both unidirectional and bidirectional switching applications. B-TRAN™ offers a significant performance improvement over conventional power switches such as SCRs, IGBTs and MOSFETs, as implemented in silicon or wide-band-gap materials such as silicon carbide. 0.6V $V_{CE(on)}$ at 30A load current has been demonstrated in silicon with driving power of 8.4W (1.2V x 7A). The total power loss is 26.4W, which is much lower than IGBTs.

This white paper provides technical background on the B-TRAN™ device structure and operation, as well as B-TRAN™ performance. A summary of B-TRAN™ applications and addressable markets is also provided. This paper assumes that the reader has some knowledge of power semiconductors, but the lay audience may benefit as well.

2. Device Structure

B-TRAN™ may be viewed as the logical end point of the evolution of power semiconductor topologies. This progression, from left to right, may be described as shown in Figure 1 Power Semiconductor Topologies.

Figure 1 – “open” Pure silicon. This is a non-conductive device, so is useful only for insulating.

Figure 1 – “resistor” Doped silicon. This is silicon which has an impurity that causes the silicon to become partially conductive, hence the term “semiconductor”. It may be used as an electrical resistor, which is a device which conducts electric current with significant resistance, as opposed to a material such as copper which conducts with very little resistance. Some impurities produce this partial conduction by providing an extra electron per atom of impurity, and others do so by removing an electron per atom of impurity. The former is

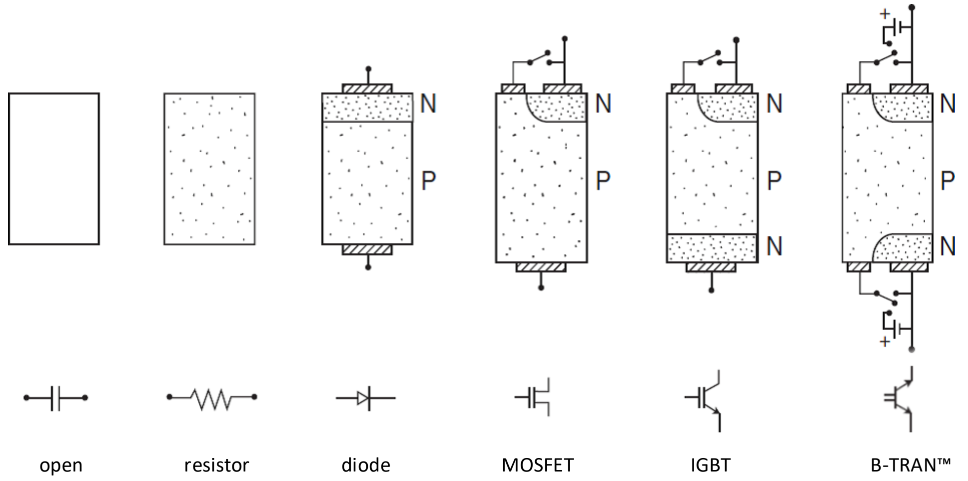


Figure 1 Power Semiconductor Topologies

referred to as “N” type and the latter as “P” type silicon. High concentrations of N are referred to as N+, while low concentrations are N-. The same is true for the P impurity. This structure of Figure 1 “resistor” has been lightly doped with a P impurity, so it is P-.

Figure 1 – “diode” This structure takes the P- resistor of Figure 1 “resistor” and adds a heavily doped layer of N material on one surface, making a P-/N+ diode. Due to differing properties of the impurities of the P- and N+ regions, the interface (or “junction”) between the two regions takes on special characteristics. The junction prevents current flow in one direction (reverse bias), but allows current flow in the other direction (forward bias). In this case, current flow is blocked from the N+ to P- regions (top to bottom), but is allowed in the other direction (bottom to top), except that a voltage drop of about 0.7 V is required to generate current flow in that direction. When this occurs, the diode is said to be “forward biased”, and current flow may occur at a much lower total voltage drop as compared with the resistor of Figure 1 “resistor”. This happens because the forward biased junction produces many additional P and N “charge carriers”, which greatly exceed in number the original amount of P charge carriers in the P- region. This voltage blocking in one direction and current conduction with low resistance in the other direction is the fundamental building block of all bipolar power semiconductors. “Bipolar” refers to the two polarities of charge carriers – P and N.

Figure 1 – “MOSFET” Metal Oxide Semiconductor Field Effect Transistor. This structure essentially combines the resistor with the diode, and incorporates a switch that selects between resistor and diode modes of operation. When the switch is open, it can be seen that the MOSFET is a diode, thereby blocking voltage in one direction (top to bottom), and conducting as a diode in the other direction. When the switch is closed, the diode is bypassed, allowing the MOSFET to conduct from top to bottom, but as a resistor. It can also conduct bottom to top as a resistor. As a resistor, it can turn on and off very quickly, limited only by the speed of the switch. And, as a resistor, the voltage drop is given by the doping level and thickness of the P- section, with heavier doping and less thickness giving a lower voltage drop. However, as with the diode, the maximum voltage the MOSFET can block with the switch open, while acting like a reverse biased diode, is limited by the doping level and device thickness. Increasing the doping to lower the resistance results in a reduced ability to block voltage, so the resistance, and therefore efficiency, of the MOSFET is related to its ability to block voltage. Higher voltage capable MOSFETs have higher resistance. The switch in an actual MOSFET is built into the surface of the device, and is voltage controlled. MOSFETs may be constructed in either polarity of N+/P- and P+/N-.

Figure 1 – “IGBT” (Insulated Gate Bipolar Transistor). In this structure, an additional doping layer is added to the bottom of the device, in this case another N+ layer, which significantly alters the behavior of the device. Now, when the switch is closed, instead of conduction occurring through a purely resistive P- region, conduction is now through the forward biased P-/N+ diode, and, as explained above, this results in a large reduction in the resistivity of the device, allowing it to conduct much higher current levels with lower voltage drop. This is referred to as “conductivity modulation”, but is essentially just the device conducting as a forward biased diode. The diode junction does, however, impose a minimum voltage drop of about 0.7 volts (for silicon devices). There is an additional voltage drop associated with the switch, which, as with the MOSFET, is built into the surface of the device. But since the resistance of MOSFETs rises rapidly with increased voltage ratings, this conductivity modulation enables high voltage capable IGBTs to conduct much higher current at lower voltage drop as compared with MOSFETs of comparable voltage rating.

There is a price to be paid for this higher conductivity in the on-state because turn-off is much slower than with a MOSFET. That is because, when the IGBT is on, the P- region is filled with extra charge carriers supplied by the forward biased P-/N+ junction, and when the switch is opened to turn the device off, those charge carriers have nowhere to go, and the device remains partially conducting via the upper N+ layer. Conduction stops (device turns off) only when those extra charge carriers combine with each other and disappear. In a pure, high-quality P- region, this can take a very long time, and such a high-quality device has a low voltage drop, but it takes very long to turn off. Imperfections are intentionally introduced during the manufacturing process to accelerate the destruction of charge carriers (referred to as “recombination”), but such imperfections also increase the voltage drop while in the on-state. Thus, with IGBTs, there is an inherent conflict between low on-state voltage drop and turn-off time, with longer turn-off times causing higher switching losses. IGBT development therefore concentrates on minimizing this trade-off between conduction losses and switching losses.

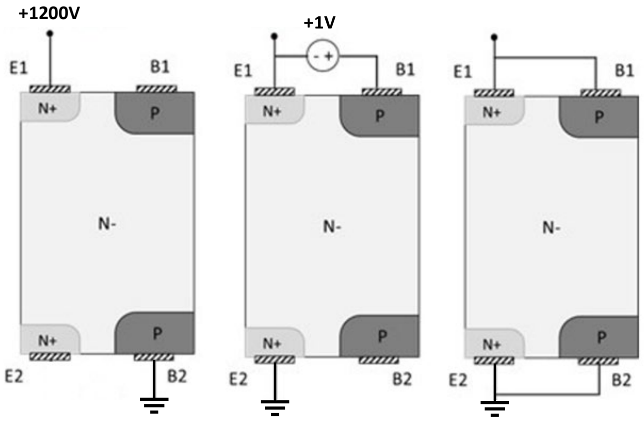
A note – most, if not all, IGBTs are made with the doping polarities opposite of that shown (PNP rather than NPN), but the operating principles are the same.

Figure 1 – “B-TRAN™” (Bi-directional Bi-polar Junction Transistor) - This device has the same three-layer PNP or NPN structure of the IGBT but has a control switch on each side. To improve performance, reliability and manufacturability, the device has been further optimized. Figure 2 shows B-TRAN™ fabricated on n-type substrates, which provides a PNP structure with higher current amplification and larger current density. Operating principles and driving strategies are also optimized and validated on silicon. Figure 2 shows the device structure in which lightly doped N- FZ substrate serves as the drift region, heavily doped N+ and P+ regions on both sides are emitters (E1, E2). B1, B2 serve as minority carrier injectors in each side. A cascode MOSFET that connects to E1 in the power module allows B-TRAN™ to act as a normally-off power switch like an IGBT.

Off-Mode: the top E1 is connected to high voltage (1200V) and the B2 is connected to ground. The depletion region from E1 to B2 blocks the high voltage, as shown in Figure 2 (a).

On-Mode: the top B1-E1 has a positive driving bias of 1V, as shown in Figure 2 (b). By adding the positive bias, the minority carriers are injected into the drift region, increasing the carrier density in the N- drift region, so the resistance between the top E1 and bottom E2 is significantly reduced.

Pre-turn-Off Mode: A pre-turn-off stage is required to reduce the turn-off loss. The base and emitter terminals on the top and the bottom sides are shorted (B1-E1 and B2-E2), as shown in Figure 2 (c). As a result, the drive current at B1 will reduce to zero. The recombination process is forced, and it will reduce the stored charge.



(a) Off-Mode (b) On-Mode (c) Pre-Turn Off

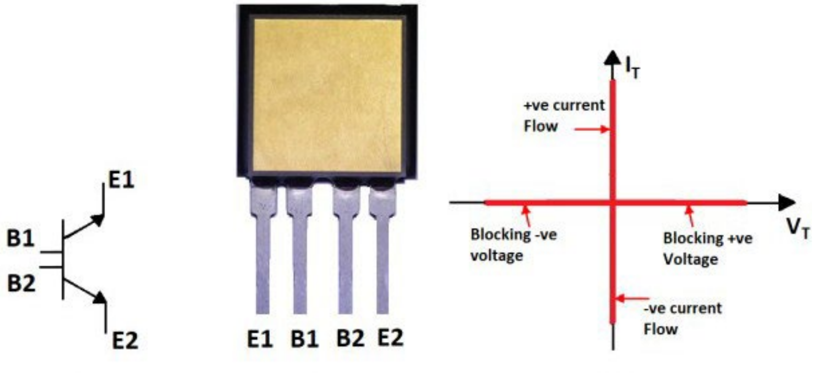
B-TRAN^{TM} Operating Modes:

1) Turn on B-TRAN^{TM}:
   Off-Mode → On-Mode.
2) Turn off B-TRAN^{TM}:
   On-Mode → Pre-Turn Off → Off-Mode.

Figure 2 Optimized B-TRAN^{TM} structure with operating modes

3. B-TRAN^{TM} Performance

Figure 3 (a) and (b) shows the circuit symbol and the device. Figure 3 (c) shows its bidirectional operating characteristics. With its two control inputs (B1 and B2), it can block the voltage in both polarities (positive and negative) and conduct current in both directions (positive and negative). It can also be used in unidirectional applications such as voltage source inverters or battery chargers. Power MOSFETs or IGBTs are unidirectional power semiconductor devices and cannot be used as a bidirectional switch (BDS). To make a BDS, two MOSFETs or two IGBT + two diodes (Fast Recovery Epitaxial Diodes or SiC diodes) must be connected in a common-emitter configuration, which would quadruple the part count for bidirectional power converters.

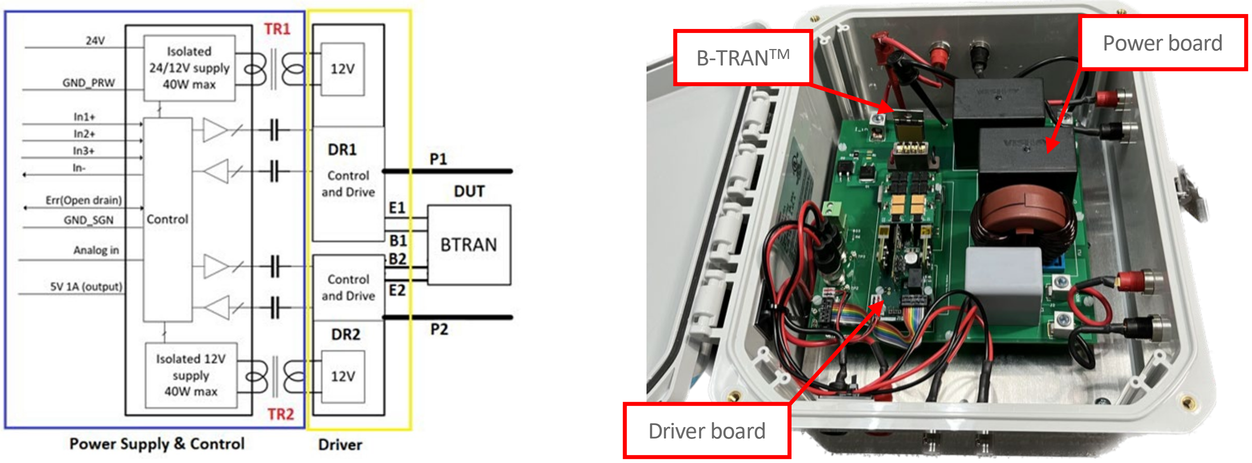


(a) (b) (c)

Figure 3 B-TRAN^{TM} (a) Symbol (b) Real B-TRAN^{TM} and (c) B-TRAN^{TM} characteristics

3.1 B-TRAN^{TM} Driver and Double Pulse Testing (DPT)

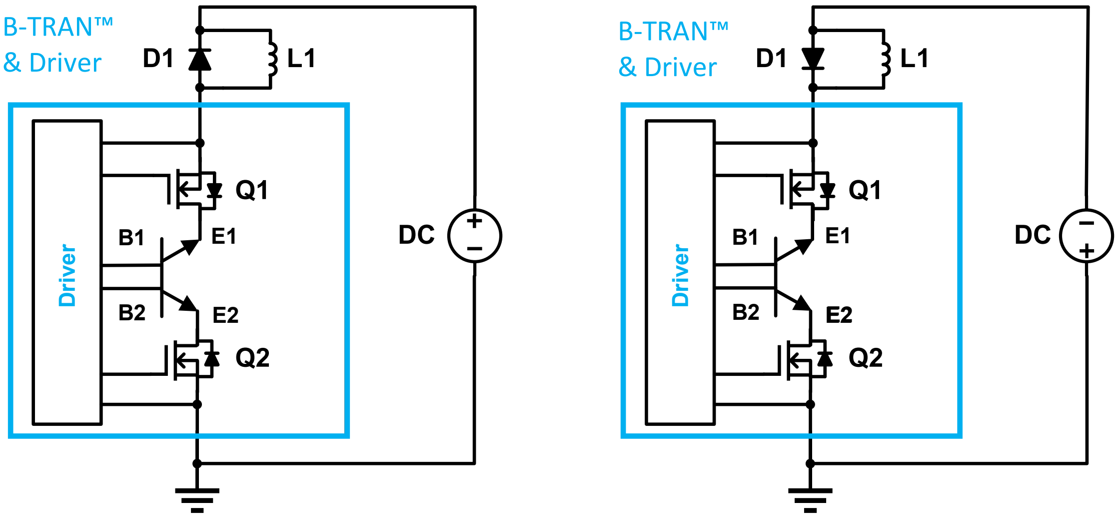
A specially designed double pulse testing (DPT) system evaluates the switching performance. Figure 4 (a) shows B-TRAN^{TM} Test System in a block diagram. The power supply & control, driver, and device under test (DUT) are the three major sections of the system. The top emitter and base terminals are E1 and B1, and the bottom terminals are E2 and B2, respectively. Figure 4 (b) shows the B-TRAN^{TM} driver with one B-TRAN^{TM} and power board developed for this test.



(a) (b)

Figure 4 (a) Test System (b) Driver board with one B-TRAN™ and Power board designed for DPT

For the bidirectional switching test, the circuit schematic for the specific current direction is illustrated in Figure 5 (a) and (b). Low $R_{DS(on)}$ cascode MOSFETs (<3mOhm), Q1 and Q2 shown in the schematic allow driving B-TRAN™ as a normally off switch like an IGBT. These devices can block high voltage in their off-state and conduct high current with very low loss in their on-state but have no high energy switching capability. Figure 5 (a) set up is tested when the current flows from high side to low side (E1 to E2) and Figure 5 (b) is tested when the current flows from low side to high side (E2 to E1). An inductor L1 and a fast recovery diode, D1 is connected across the inductor as part of the DPT.



(a) (b)

Figure 5 (a) Current flow from E1 to E2 (b) Current flow E2 to E1

3.2 B-TRAN™ Characterization

A Keithley high power test system is used for initial measurements of B-TRAN™ dies and packaged devices. For breakdown voltage and leakage current measurement, a voltage is ramped up across the device while monitoring the current. A breakdown voltage of 1280V is measured, as shown in Figure 6. Other measurements such as leakage currents, 25µA at 1000V, and 45µA at 1200 V confirm the basic steady-state performance parameters. The emitter-emitter saturation voltage, and current gain (β) is measured to be 0.6-0.8 V, and 7, respectively.

Figure 7 shows the output characteristics for three values of V_{BE}. The base bias voltage for turning on the device is about 1V. For each base-emitter voltage (V_{BE}), the device indicates an almost linear relationship between the forward voltage drop, V_{E1E2}(on), and the output current (I_{E1}). It means that when the output current increases, the forward drop also increases linearly. However, by injecting more current into the base by increasing the base-emitter voltage, (for example, from 1V to 1.05V and then 1.1V), the forward voltage drop is significantly reduced. It is an essential feature of the B-TRAN™ that on-state resistance can be modulated with minority carrier injection by changing the base-emitter voltage. The same output characteristics are obtained in the opposite direction, where the emitter terminals are reversed.

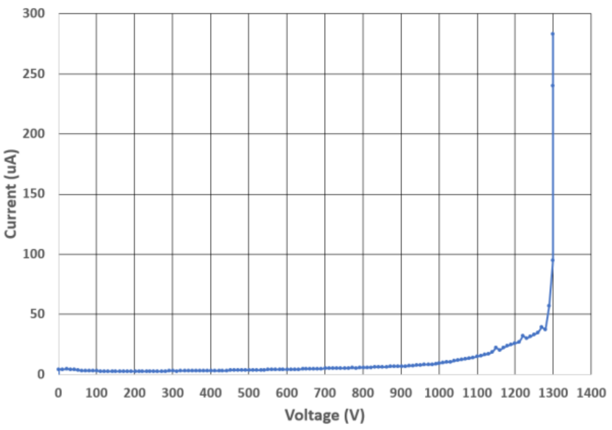


Figure 6 On-wafer level measured breakdown voltage curve

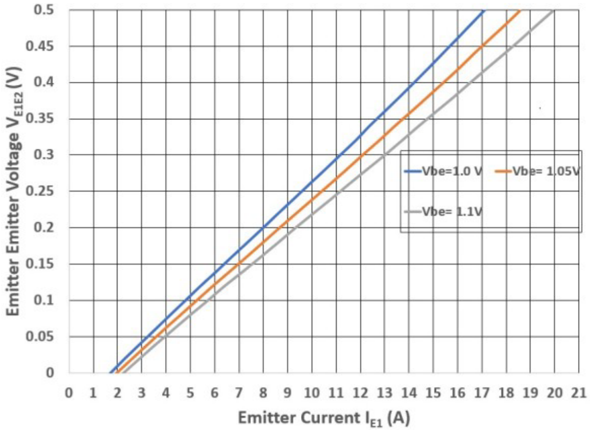
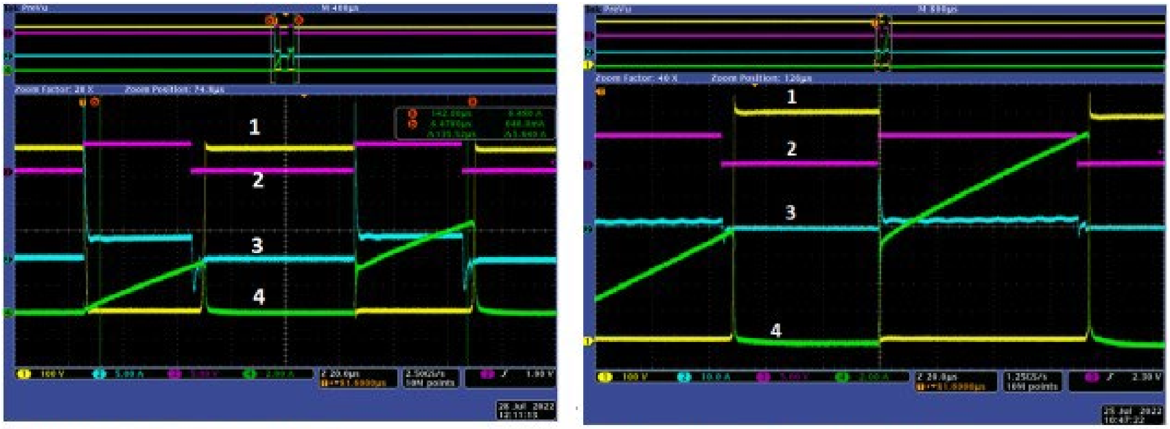


Figure 7 Forward drop, V_{EE}(on) versus current I_E (A) for different V_{BE} levels

Figure 8 shows the DPT waveforms at 800V/14A. The measured parameters during this test are summarized in Table 1. It shows one control signal with two control pulses (labeled as 2), the emitter-emitter voltage (labeled as 1), the base current (labeled as 3) and the emitter current (labeled as 4).



1: V_{CE} , 2: Control Sig. , 3: I_B and 4: I_E

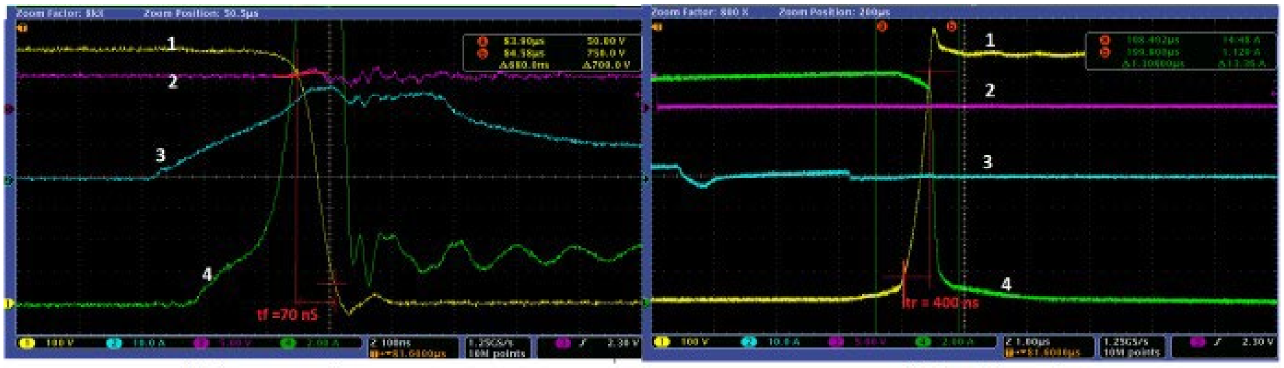
(a)

1: V_{CE} , 2: Control Sig. , 3: I_B and 4: I_E

(b)

Figure 8 (a) DPT waveforms from E1 to E2 and (b) from E2 to E1 at 800V and current at 14A

For the bidirectional switching test, high voltage switching is measured in the opposite direction by the same connection setup shown in Figure 5 except that the diode (D1) and V_{DC} polarities are reversed to shows the current flow from E2 to E1 terminals. The measurement steps in both directions remain the same. Figure 8 (b) shows the current flow from E2 to E1.



(a) Turn on waveforms

(b) Turn off waveforms

1: V_{EE}, 2: Ground, 3: I_B, 4: I_E

Figure 9 DPT test (a) rise time and (b) fall time at V_{EE}=800V and I_{EE} =14A

Figure 9 (a) and (b) show the waveforms with turn-on rise time 70 ns and turn-off fall time 400 ns. The figure has the control signal labeled as 2, the emitter-emitter voltage labeled as 1, the base current labeled as 3 and the emitter current labeled as 4.

Table 1: B-TRAN™ DPT Testing Results

Parameters	Symbols	Test Conditions	Typ.	Max.	Units
E-E (on-state) voltage	$V_{E1E2(on)}$	V_{dc}=10V, V_{B1E1}=1V, I_{E1E2}=30A, (max. peak)	0.6	0.9	V
Rise Time	t_r	V_{E1E2}=800V, V_{B1E1} =1V, I_{E1E2}=14A	70		ns
Fall Time	t_f		400		ns
Turn-on Energy	E_{ON}		0.5		mJ
Turn-off Energy	E_{OFF}		1.8		mJ

4. B-TRAN™ Applications

B-TRAN™ can be used in both unidirectional and bidirectional applications. As a BDS, B-TRAN™ can perform direct AC-AC conversion and enable applications that require bidirectional transfer of power between the AC mains and the load. B-TRAN™ can be used in applications such as electric vehicles, renewable energy generation, energy storage, solid-state circuit breakers and motor drives. Figure 10 shows a typical EV power system with red ovals where B-TRAN™ can be used.

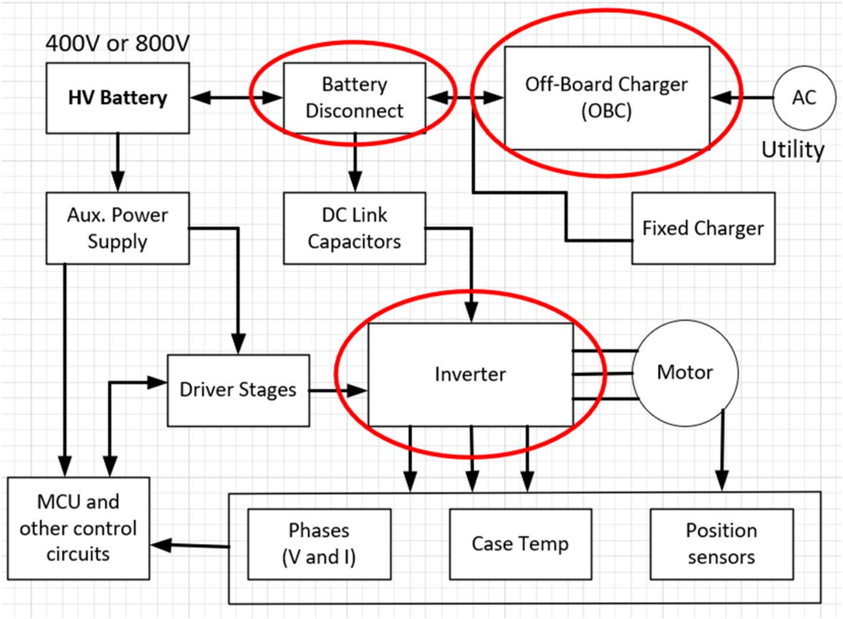
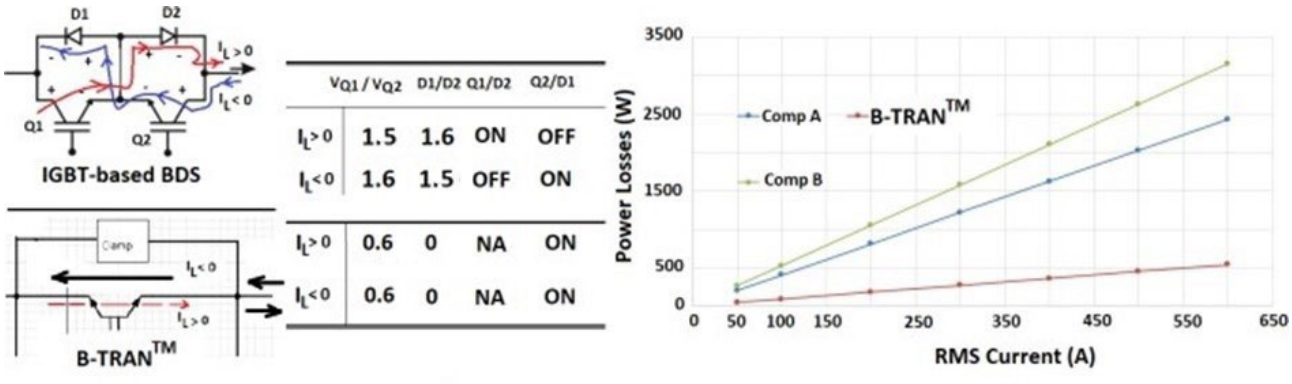


Figure 10 B-TRAN™ usages in an EV power system

4.1 B-TRAN™ Solid-State Circuit Breakers (SSCB)

Figure 11 (a) shows an IGBT-based BDS, which needs four power devices (two IGBTs and two diodes), and one B-TRAN™, which can perform the same BDS function. Specific B-TRAN™ characteristics critical to SSCB are forward voltage drop and conduction characteristics which reduce breaker power loss significantly. Figure 11 (b) shows an on-state voltage drop comparison between an IGBT-based BDS and one B-TRAN™. When the load current is positive (IL>0), in the red line direction, the voltage drops across the IGBT + Diode are about (1.75+1.0) = 2.75V, and the B-TRAN™ drop is 0.6V which is more than 4 times lower in conduction power loss. The bidirectional nature of B-TRAN™ allows a similar on-state voltage in the opposite direction. Figure 11 (c) shows the power loss comparison between one B-TRAN™ and comp A and comp B. At 200A load current, the power losses for comp A and B are 1100W and 1500w respectively whereas the conduction loss for B-TRAN™ is about 150W.

For a bidirectional application, B-TRAN™ will reduce the number of high voltage switches in a circuit by half. Conduction losses are at least 4-times lower (2.75V versus 0.6V) and the switching losses are also lower. For this reason, the SSCB design using B-TRAN™ can reduce the system components and improve the efficiency drastically. A simple SSCB circuit where one B- TRAN™ can replace two IGBTs + two diodes is shown in Figure 12.



	V_{Q1}/V_{Q2}	D1/D2	Q1/D2	Q2/D1
$I_L > 0$	1.5	1.6	ON	OFF
$I_L < 0$	1.6	1.5	OFF	ON
$I_L > 0$	0.6	0	NA	ON
$I_L < 0$	0.6	0	NA	ON

(a) (b) (c)

Figure 11 Conduction loss comparison between two competing commercially available IGBT+ diode common emitter bidirectional switches and one B-TRAN^{TM}

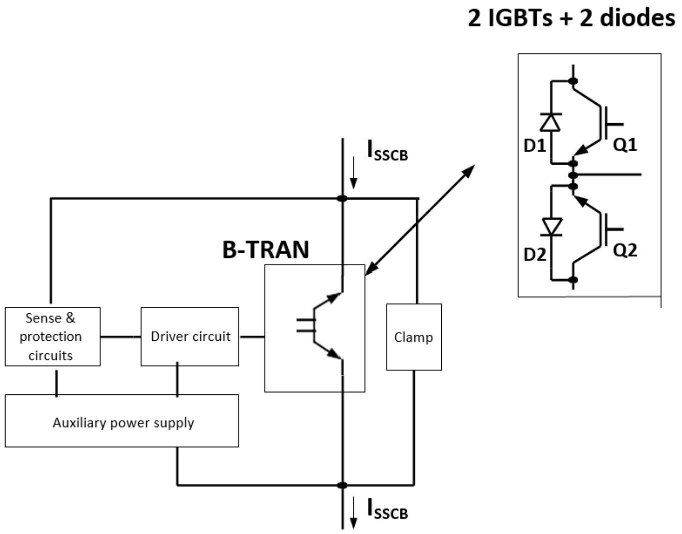


Figure 12 SSCB using B-TRAN^{TM}

4.2 B-TRAN^{TM} Matrix Converter

A B-TRAN^{TM} based Matrix Converter (MC) circuit is depicted in Figure 13. The number of B-TRAN^{TM} devices required is 9 compared to 18 if the converter is based on SiC MOSFETs or Si MOSFETs or RB-IGBTs (Reverse Blocking IGBTs) or 36 if the BDS is implemented using IGBTs and fast diodes.

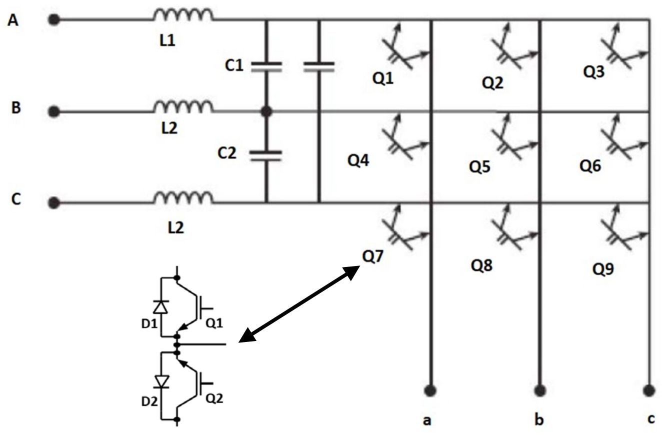
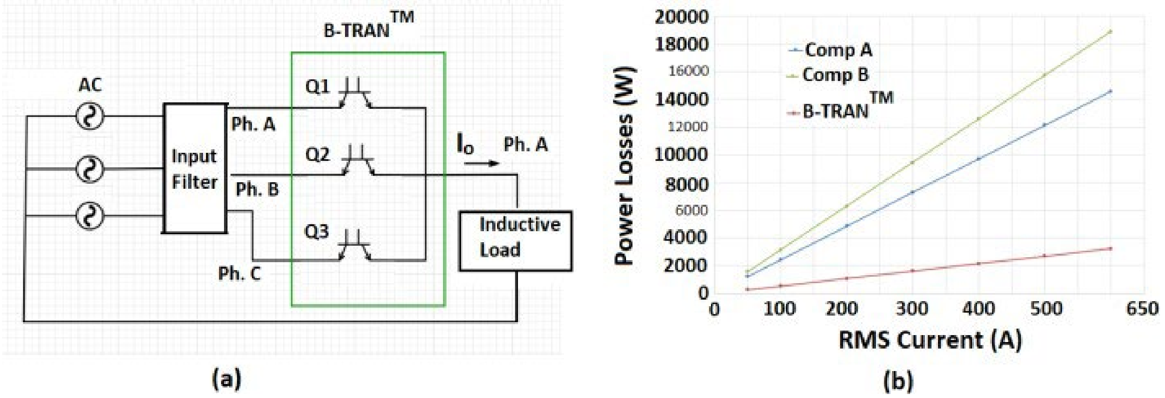


Figure 13 Three-phase MC using B-TRAN^{TM} switches

For an MC, an array of BDS switches is needed to directly connect a three-phase source to a three-phase load so that a variable output voltage of desired amplitude and frequency can be generated. Typical applications would be for motor drives for rolling mills, elevators, and escalators, and renewable energy applications such as Photovoltaic (PV), Wind and Fuel Cell power conversion for Smart Grids.

Figure 14 (a) shows a single-phase of a three-phase matrix converter and 14 (b) shows the switching power loss comparison between B-TRAN^{TM} and comp A and B (see Figure 11) under different load currents.



(a) (b)

Figure 14 Single-phase MC circuit and comparison of power losses in a three-phase Matrix Converter

For a three-phase 300A load, IGBT-based BDS A and B show power losses of 7000W and 9000W respectively, and a B-TRAN^{TM} based system has power loss of about 1900W, which produces ~ 72% and 78% loss reduction.

5. Summary

B-TRAN^{TM} offers a simple, yet radically different topology for power semiconductors. It combines the fast, low loss switching of a MOSFET, the high current density of the IGBT, the low forward voltage drop of the BJT, and unique bidirectionality, which allow for its use in highly advantageous AC link converter topologies. B-TRAN^{TM} offers the potential to improve efficiency and system economics of a wide variety of power converter applications including variable frequency motor drives, electrified vehicle traction drives, PV inverters and wind converters.

B-TRAN^{TM} shows symmetrical bidirectional performance with a breakdown voltage of more than 1200V and on on-state voltage drop of 0.6V at high currents (30A). Both conduction and switching losses of the B-TRAN^{TM} are considerably lower compared to existing power semiconductor devices for bidirectional applications. A specific TO-264 package with double-sided cooling capability has been developed for B-TRAN^{TM}, and a bidirectional driver has been developed and optimized for switching characterization and controlling current conduction in both directions.