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Application Note

CHARACTERIZING COLLECTOR-TO-EMITTER AND DRAIN-TO-SOURCE DIODES FOR SWITCHMODE APPLICATIONS

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ABSTRACT

Most power Darlington transistors and power MOSFETs contain integral Collector-to-Emitter (C-E) and Drain-to-Source (D-S) diodes which for certain inductive load applications can be used as commutating diodes. Whether these diodes are fast enough or have adequate power handling capability will be addressed by this paper. Also described is a "real world" test circuit which accurately characterizes the diodes for switching times. The surge current capability and forward characteristics of a number of devices are also listed.

When turning off inductive loads with a semiconductor switch, some means must be used to suppress, limit or clamp the resulting "inductive kick" (e = L di/dt) from exceeding the breakdown voltage of the switch. Various types of suppressors or "snubber" circuits such as Zeners, MOVs, RC networks and clamp or "free-wheeling" diodes are generally used. The energy stored in the inductor and diverted from the transistor at turn-off is harmlessly dissipated in the snubber, thus protecting the transistor switch.

To protect single transistor switches, the snubber can be placed across either the inductor or the transistor. A Zener diode or RC snubber circuit can protect the collector-emitter of the transistor or drain-source of the power MOSFET, but a simple clamp diode across these respective terminals will not, as it will only come into operation if its reverse blocking voltage is exceeded. However, in the multi-transistor configurations commonly used for switching regulators, inverters and motor controllers, clamp diodes across the semiconductor switches are frequently used (Figure 1). The diodes do not protect their respective transistors but rather the complementary transistor. As an example, in the totem-pole configuration of Figure 1C, diode D2 protects transistor Q1 and D1 protects Q2. To illustrate this, assume Q2 is initially conducting, causing load current to flow up through the inductor from ground. When Q2 turns off, the inductive current will continue but now through D1, through the power supply V^+ and return to the ground side of the inductor. Consequently, the fly-back voltage will be clamped to V^+ (from V^-), resulting in an amplitude of 2.0 V when $V^+ = V^-$.

If the output power devices are Darlington transistors with their internal monolithic C-E diodes or power MOSFETs with D-S diodes, the question arises as to whether these diodes are capable of adequately clamping the turn-off inductive load current. In other words, do the diodes switch fast enough and can they take the commutated load current?

The purpose of this paper is to "real world" characterize the C-E and D-S diode of many Motorola Darlingtons and power MOSFETs so that the circuit designer can make the performance/cost trade-offs of either using these internal diodes or discrete outboard ones.

SWITCHING CHARACTERISTICS

The important switching characteristics of clamp diodes in switchmode applications are reverse recovery time t_{rr} and turn-on time t_{on}. Diodes with long t_{rr} times can cause excessive turn-on stress on the transistor they should be protecting as both the diode and the transistors will be conducting during this time interval. The result will be a feed through collector current spike which could exceed the forward bias SOA of the transistor. If the diode has relatively slow t_{on} times or high overshoot voltage—modulation voltage $V_{FM(DYN)}$—then, in a similar manner, the transistor might not adequately be protected during inductive turn-off.

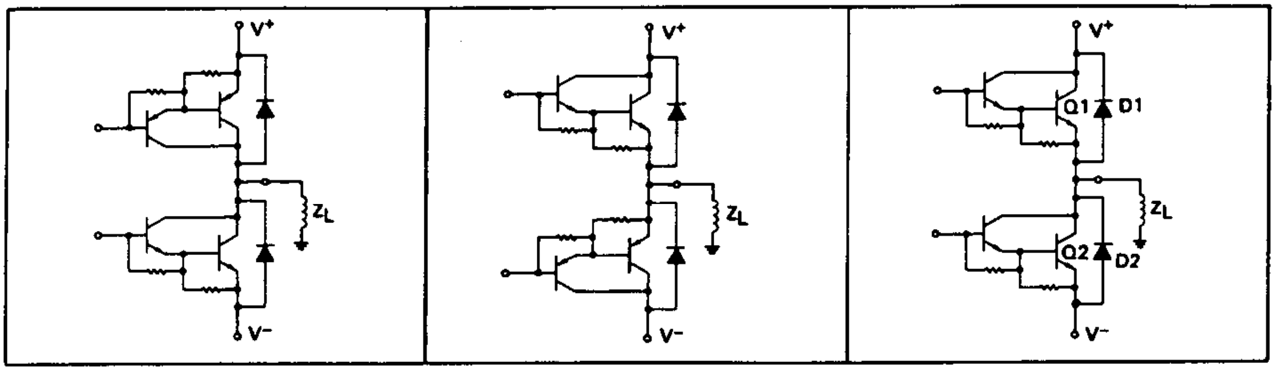


FIGURE 1A — Common Emitter **FIGURE 1B — Common Collector** **FIGURE 1C — Totem-Pole**

Complementary Push-Pull

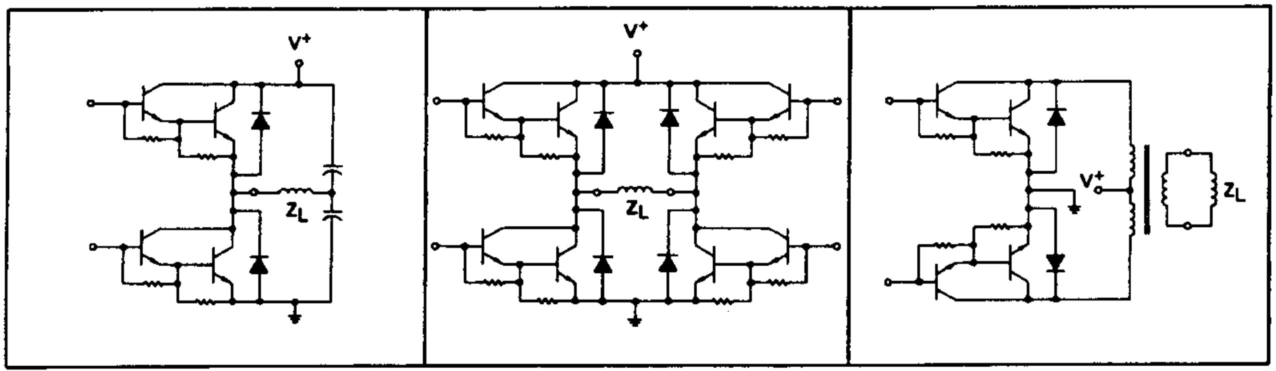


FIGURE 1D — 1/2 Bridge **FIGURE 1E — H Bridge** **FIGURE 1F — Transformer Push-Pull**

FIGURE 1 — Multiple Transistor Drive Configurations Using Clamp (C-E) Diodes

In the past, most semiconductor manufacturers would characterize and specify the internal diodes for switching using the JEDEC suggested circuits of Figures 2A and 2B. There are several problems associated with these circuits; for one, they were originally developed for sine wave rectifier applications. As such, the t_{rr} test circuit would produce a half sine wave of controllable current amplitude I_{FM} and di/dt of the current fall time. However, since the current waveform was derived from a capacitor dump, tuned circuit, the resultant current duration t_p was dictated by I_{FM} and di/dt. Under some high di/dt conditions, t_p can become

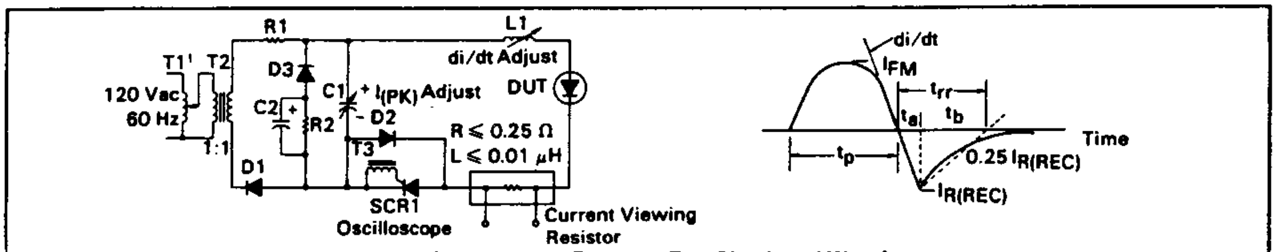


FIGURE 2A — Reverse Recovery Test Circuit and Waveform

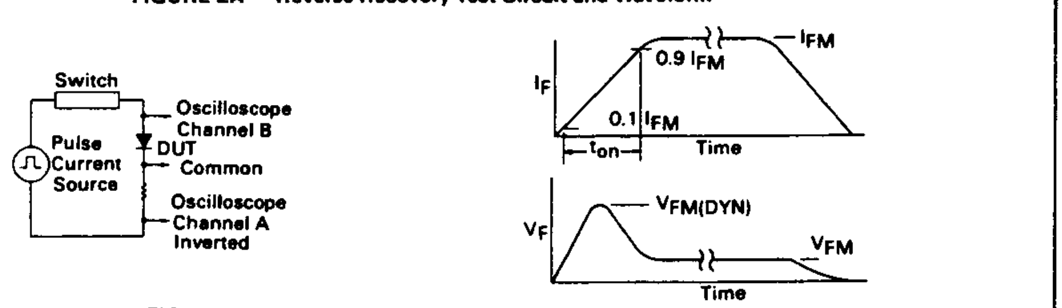


FIGURE 2B — Diode Turn-On Test Circuit and Waveforms

FIGURE 2 — JEDEC Suggested Diode Switching Test Circuits

relatively short compared to the t_{rr} of the Device Under Test (DUT) and consequently the diode is not fully turned on, thus producing inaccurate t_{rr} measurements. To ensure adequate DUT turn-on, t_p should exceed five times t_{rr}.

Second, since t_{rr} is dependent on I_{FM} and di/dt, what should these variables be set to? I_{FM} is obvious: it should be the diverted collector (or drain) current, but di/dt could be anything, be it 25 A/μs or 100 A/μs, etc. In reality, this diode current turn-off time is controlled by the complementary transistor turn-on time.

The problem with the t_{on} test circuit was the difficulty in defining and controlling the rise time of the current pulse applied to the DUT. Since this current pulse affects the measured $V_{FM(DYM)}$ and t_{on} of the DUT, its shape should be related to the real world conditions.

This is what the proposed test circuit does. Its configuration is derived from a typical two transistor switchmode applicaton, be it a totem-pole for characterizing NPN Darlington C-E diodes (N-channel D-S diodes) or a complementary common emitter for characterizing PNP C-E (P-channel D-S) diodes (Figure 3). These configurations reduce to the simple, single-ended inductive clamp circuit (Figure 3E) whereby the clamp diode would be the C-E diode of either the NPN Darlington (totem-pole) or the complementary PNP Darlington.

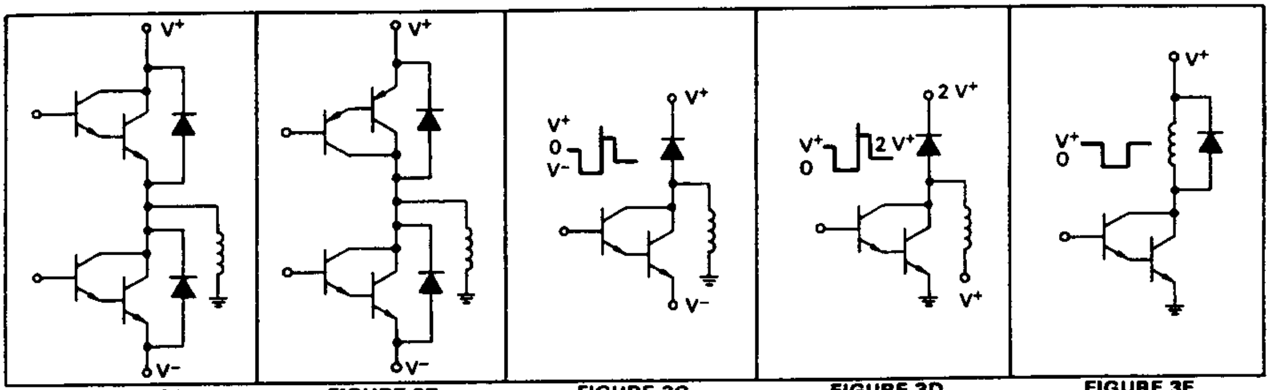


FIGURE 3A
Totem-Pole

FIGURE 3B
Complementary

FIGURE 3C
Simplified Clamp Circuit

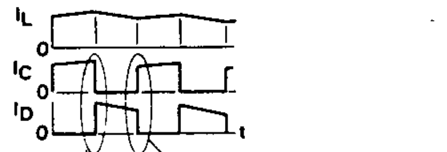
FIGURE 3D
Level Translated

FIGURE 3E
Test Circuit

FIGURE 3 — Evolution of Inductive Clamp Test Circuit

The reverse recovery time is of greatest significance for continuous load currents common in switching inductive loads. Figure 4A describes the idealized current waveforms when a continuous inductive load current I_L is commutated between the transistor (I_C) and clamp diode (I_D). Figure 4B shows the time expansion of both the leading and trailing edges of I_C and I_D. Note that the collector current falltime t_{fIC} controls the diode current rise time t_{fID} (or t_{on}) and in a similar manner, the dI_C/dt (or t_{rIC}) of the collector current turn-on time dictates the dI_D/dt of the diode current turn-off time. Thus, the faster the transistor switches, the greater is the di/dt applied to the diode. The diode di/dt then dictates the magnitude of the reverse recovery time t_{rr} and current $I_{RM(REC)}$. Since the current through the inductor is equal to I_C plus I_D, the peak collector current I_{CM} at turn-on will consequently have the magnitude of I_{RM} impressed on it. This is well illustrated in Figure 5 whereby the switching times of I_C and I_D are the mirror image of each other; the sum of the two waveforms would yield the inductor current, whose ripple magnitude is dependent on the switching frequency and load inductance.

FIGURE 4A — Idealized Current Waveforms



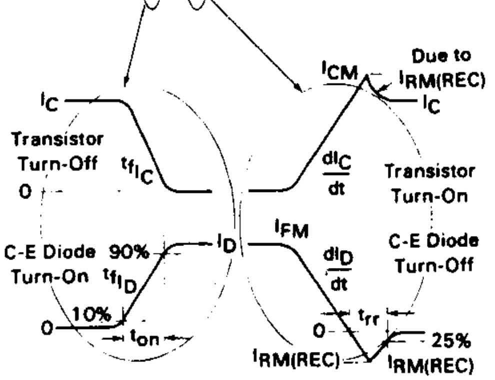


FIGURE 4B — Waveforms Time Expansion

FIGURE 4 — Continuous Load Current Switching Waveforms

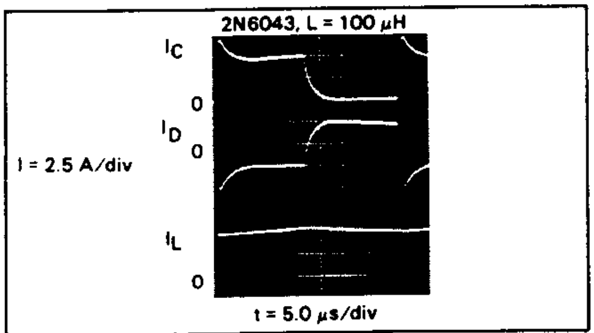


FIGURE 5 — Switching Currents of a Darlington Clamped Inductive Load

An example of discontinuous and continuous load current waveforms are shown in Figures 6A and 6B respectively. Note that for the discontinuous case, where the inductor current I_L is allowed to completely discharge, the di/dt of I_D is extremely low, thus producing no I_{RM} or t_{rr}. For the continuous current case, the resultant di/dt produces significant I_{RM} and t_{rr}.

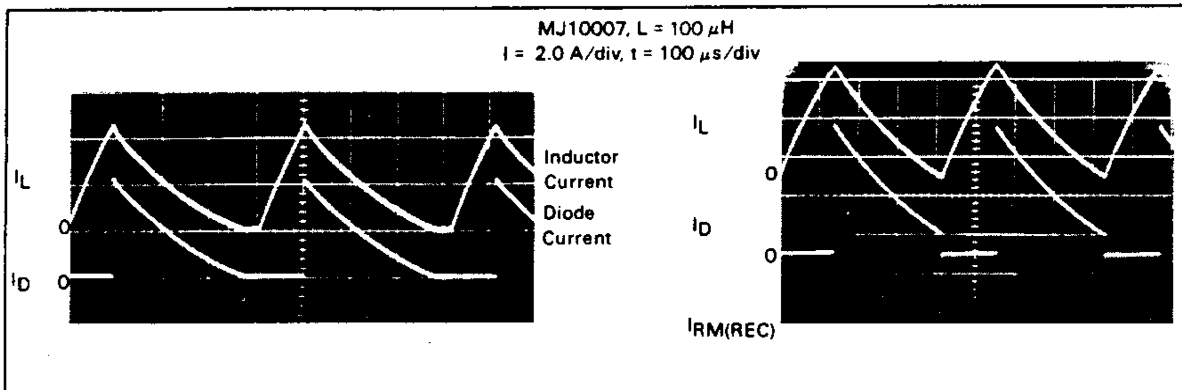


FIGURE 6A — Discontinuous Load Current **FIGURE 6B — Continuous Load Current**

FIGURE 6 — The Effect of Switching Inductive Load Current on t_{rr} and $I_{RM(REC)}$ of C-E Diode

The size of the inductor used has little, if any, effect on the t_{rr} measurements as shown in Figures 7A and 7B; Figure 7A shows the full cycle and time expanded waveform of diode current for inductances of 100 μH (air core) and Figure 7B for a 10 mH (iron core) inductor. The major differences is the magnitude of the ripple current, the larger inductor producing a more constant current source.

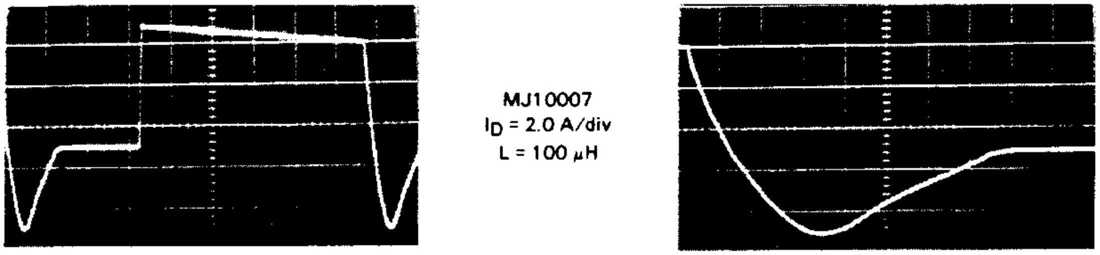


FIGURE 7A — 100 μH Inductor

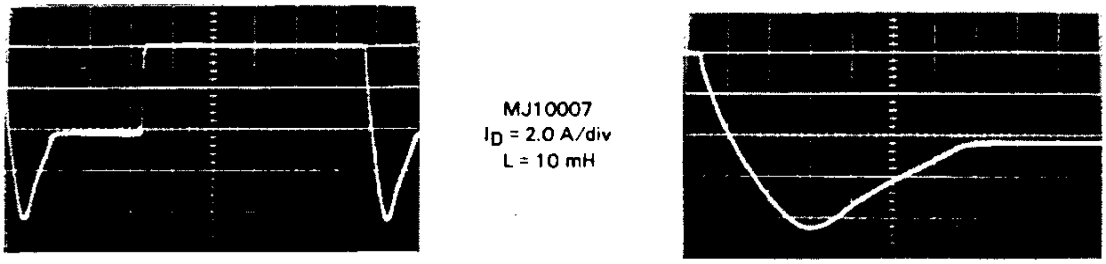


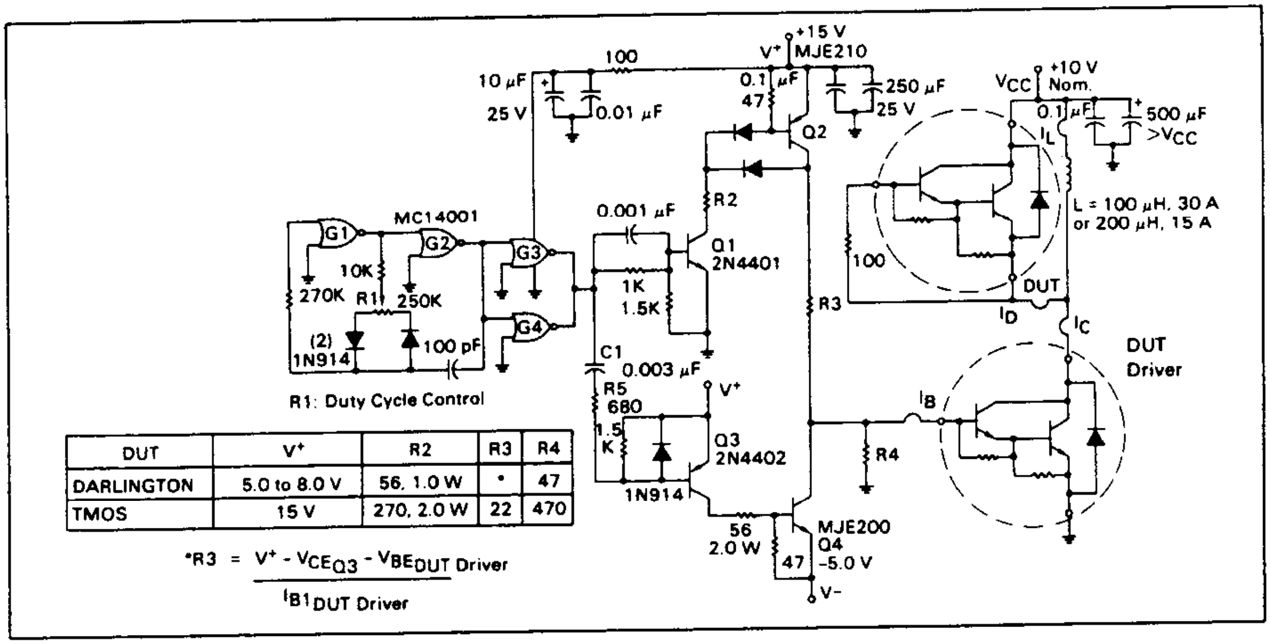
FIGURE 7B — 10 mH Inductor

FIGURE 7 — The Effects of Load Inductance on C-E Diode Reverse Recovery Characteristics

TEST CIRCUIT

The test circuit used for generating the diode switching characteristics, a translation of the "real world" circuit of Figure 3D, is shown in Figure 8. It consists of a CMOS, astable multivibrator (Gates G1 and G2) driving two parallel connected Gates 3 and 4 as a buffer. Potentiometer R1 varies the duty cycle of the approximately 25 kHz output which therefore sets the magnitude of the DUT current (along with V_{CC}). The positive-going output from the buffer is direct-coupled to turn on the NPN transistor Q1 and the following Baker clamped PNP transistor Q2. By selecting V^+, and limiting resistor R3, the forward base current to the DUT driver can be varied, e.g., $V^+ = 6.0$ V, R3 = 1.5 ohm, 10 W, an $I_{B1} = 2.0$ A results.

To produce an off-bias to the driver, which can shape its turn-off time and consequently the diode turn-on time, the negative-going edge of the output pulse from the buffer is used. Capacitor C1 and resistor R5 form a differentiating circuit to produce the negative pulse for turning on PNP transistor Q3 and the following NPN transistor Q4. This transistor acts as the off-bias switch, applying to the driver a negative voltage pulse (approximately V^-) coincident with the trailing edge of the input pulse and lasting as long as the R5C1 time constant, about 5.0 μs for the component values shown.



DUT	V^+	R2	R3	R4
DARLINGTON	5.0 to 8.0 V	56, 1.0 W	*	47
TMOS	15 V	270, 2.0 W	22	470

$$^*R3 = \frac{V^+ - V_{CE_{Q3}} - V_{BE_{DUT\ Driver}}}{I_{B1_{DUT\ Driver}}}$$

FIGURE 8 — Darlington C-E Diode, TMOS D-S Diode Switching Time Tester

SWITCHING TEST RESULTS

When testing Darlingtons, the power supply V^+ should be set for the +5.0 V to +8.0 V range to minimize the power dissipation in the current limiting resistors. For testing power MOSFETs, V^+ should be about +15 V to ensure adequate gate drive.

The collector current of the Darlington driver is generally adjusted to about one half of the rated maximum continuous current with the forward base current I_{B1} set to produce the listed β_F. TMOS devices are usually run at the rated continuous drain current. The supply voltage V_{CC} (or V_{DD}) should be greater than 5.0 V to ensure that the DUT driver is operating with typical betas (or trans-conductance). Since the DUT current is a function of duty cycle and/or V_{CC}, reducing the input pulse width will allow a greater V_{CC} to be used, if so required.

Although it is not always possible to test the DUT with its "real world" supply voltage (i.e., high voltage devices with higher V_{CC}s than low voltage devices), the results would be more indicative if it were possible, since β and switching speeds will vary somewhat with V_{CC}.

Testing of several different Darlingtons as a function of V_{CC} showed a second order variation in t_{rr} measurements. At any rate, to ensure measurement repeatability, V_{CC}, frequency, duty cycle and inductor specification should be listed. For most of the Darlingtons and TMOS FETs tested, the inductor was either one 200 µH, 15 A rated air core or two in parallel (100 µH, 30 A). Whatever the conditions, the DUT driver and diode under test should be adequately heat sunk to minimize excessive case temperature rise.

Most of the Darlingtons tested showed substantial t_{rr}s (Figure 7A) whereas the TMOS t_{rr}s, were quite low (Figure 9B). The complete switching results for the Darlingtons and the TMOS FETs tested are compiled in Tables 1 and 2 respectively.

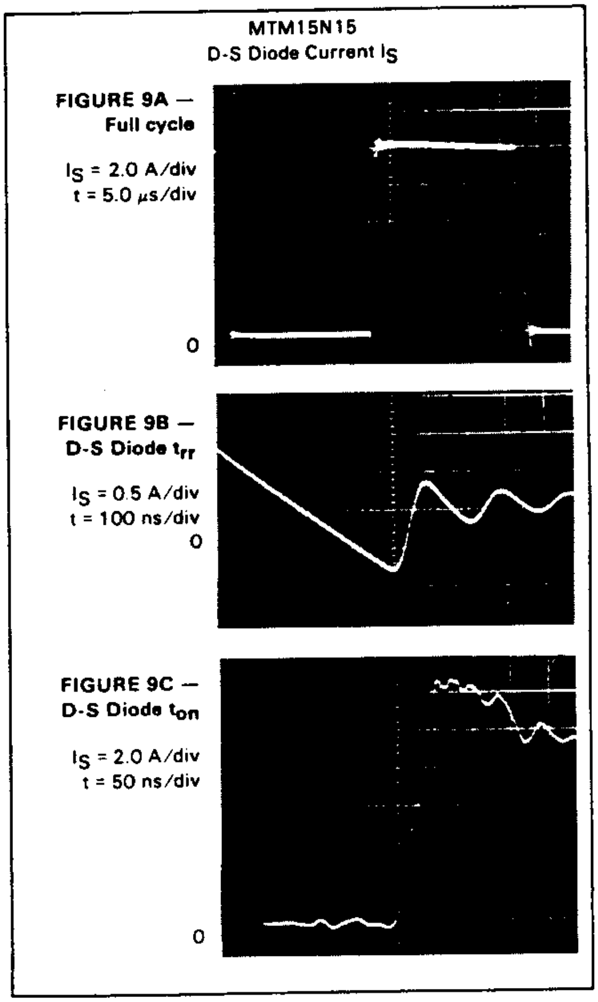


FIGURE 9 — Switching Characteristics of a TMOS D-S Diode

Device	Type	Spec I_C Cont (A)	Switching					Surge Current	
			I_{FM} (A)	di/dt (A/μs)	I_{RM} (A)	t_{rr} (μs)	t_{on} (μs)	300 μs 60 pps (A)	1.0 s 1 Shot (A)
2N6282	NPN	20	10	8.0	4.1	4.0	2.5	90	25
2N6285	PNP	20	10	8.0	3.2	5.0	2.4	100	30
2N6057	NPN	12	5.0	5.0	2.3	2.4	2.5	45	12
2N6050	PNP	12	5.0	6.0	3.0	3.5	2.6	45	13
MJ11018	NPN	15	10	5.3	3.3	10	9.0	90	25
MJ11017	PNP	15	10	5.3	3.6	3.9	9.0	110	35
MJ11028	NPN	50	30	13	13	7.0	3.3	160	55
MJ11029	PNP	50	30	11.4	12	6.6	3.4	170	60
MJ10005	NPN	20	10	7.5	8.0	5.6	0.25	100	25
MJ10007	NPN	10	5.0	6.3	6.2	4.8	0.28	30	11
MJ10021	NPN	60	30	18	25	5.0	0.35	140	50
MJ10023	NPN	40	20	5.0	11	10	1.1	140	38
2N6043	NPN	8.0	5.0	5.0	2.4	4.2	4.0	12	3.0
2N6040	PNP	8.0	5.0	5.0	2.5	2.8	4.2	20	8.0
MJE5740	NPN	8.0	4.0	3.0	3.6	13	9.5	21	9.0
MJE3302	NPN	4.0	1.5	3.1	0.7	1.1	0.35	16	8.0
MJE3312	PNP	4.0	1.5	3.3	0.5	0.5	0.3	15	9.0
MJE270	NPN	2.0	0.5	2.5	0.44	1.5	0.9	6.5	4.0
MJE271	PNP	2.0	0.5	2.6	0.47	0.9	0.9	7.0	4.5
MJE803	NPN	4.0	2.0	5.0	0.7	5.1	4.0	8.0	3.0
MJE703	PNP	4.0	2.0	5.0	1.5	3.2	4.0	4.0	3.0

TABLE 1 — Switching and Surge Current Characteristics of Darlington C-E Diodes

Device	Type (Chan)	Spec I_D Cont (A)	Switching					Surge Current	
			I_{FM} (A)	di/dt (A/μs)	I_{RM} (A)	t_{rr} (μs)	t_{on} (μs)	300 μs 60 pps (A)	1.0 s 1 Shot (A)
MTM8N10	N	8.0	6.0	8.5	1.0	0.20	0.20	30	11
MTM15N06	N	15	10	9.0	1.0	0.24	0.29	80	24
MTM15N15	N	15	10	5.0	0.8	0.28	0.05	120	19
MTP1N60	N	1.0	1.0	10	0.3	2.0	0.03	25	6.0
MTP5N06	N	5.0	5.0	3.7	0.24	0.14	0.09	50	12
MTP25N06	N	25	25	10	1.0	0.20	1.0	140	35

TABLE 2 — Switching and Surge Current Characteristics of TMOS D-S Diodes

Also shown (Figure 10) for comparison, are switching photos of discrete rectifiers versus Darlington C-E diodes. Note that the fast recovery rectifier, as expected, had the lowest t_{rr} and that the standard rectifier, the largest t_{rr}. But of even more interest, the TMOS D-S diode had the lowest t_{rr} of all diodes tested (Table 2).

From this data, the circuit designer can now decide if the switching characteristics of the diode are adequate for his application.

Diode Current I_D = 0.5 A/div, t = 1.0 µs/div

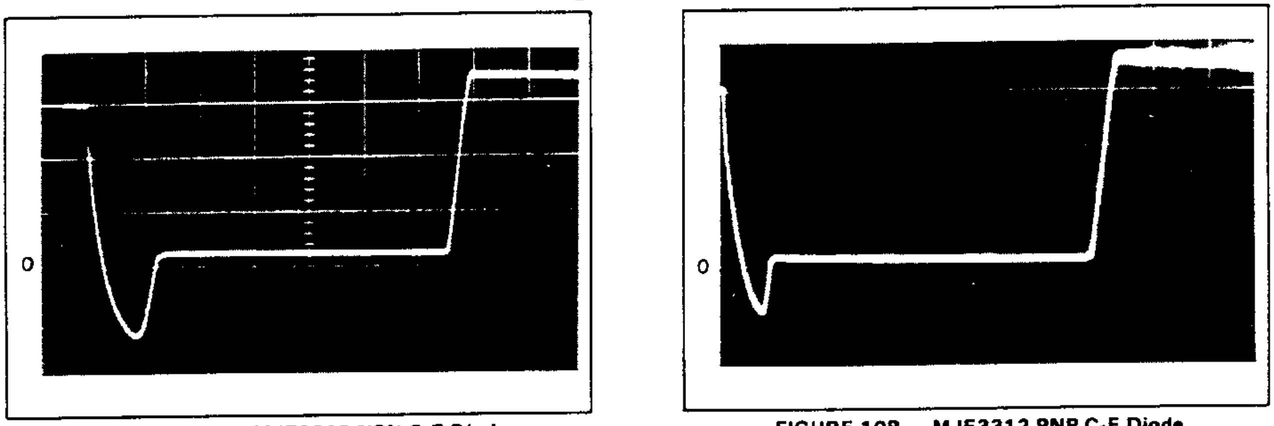


FIGURE 10A — MJE3302 NPN C-E Diode

FIGURE 10B — MJE3312 PNP C-E Diode

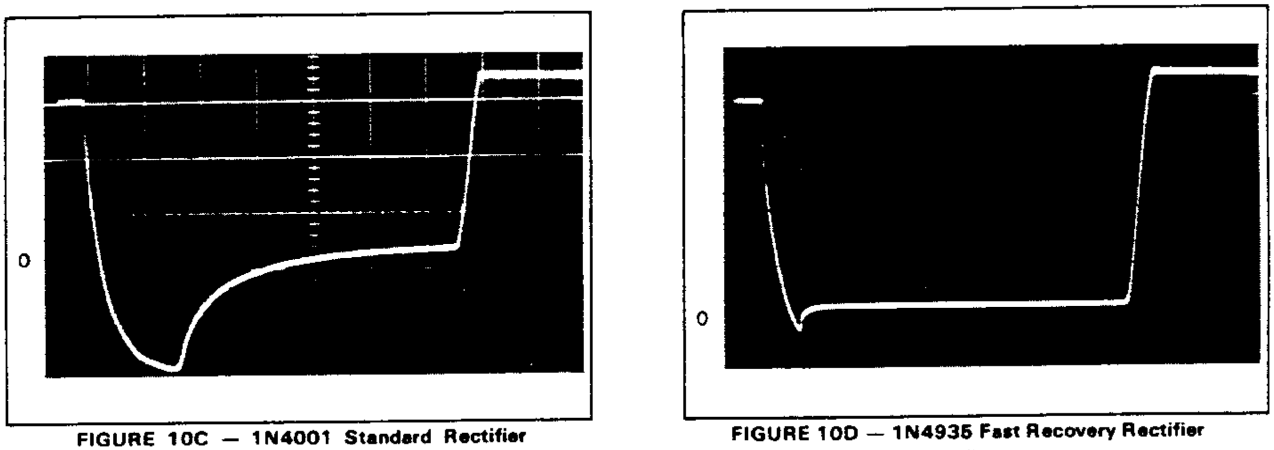


FIGURE 10C — 1N4001 Standard Rectifier

FIGURE 10D — 1N4935 Fast Recovery Rectifier

FIGURE 10 — Comparison of Darlington C-E Diodes with Discrete Rectifiers for Reverse Recovery Characteristics

SURGE CHARACTERISTICS

An equally important consideration in whether the diode can handle the commutated load current in which, under continuous load conditions, the energy can be quite high.

The C-E and D-S diodes are inherent in their respective devices. For the Darlington, the C-E diode is the result of the emitter metallization partly overlaying the base to produce the monolithic base-emitter resistor of the output stage. Consequently, the now direct path for current flow across the collector-base junction forms the effective C-E diode. The total area of this junction can be small relative to the total die area and thus the diode current density is high. Motorola has recognized this limitation and has redesigned the C-E diode area to handle in most cases a diode forward current I_{FM} at least equal to the maximum continuous collector current rating of the Darlington. In general, the low voltage Darlingtons (< 200 V) have I_{FM} equal to I_C and the high voltage Darlingtons, the triple diffused and double diffused epitaxial collector processes, have I_{FM} ratings equal to $I_C/2$.

The TMOS D-S diode is the result of the parasitic NPN transistor across the FET and as such, actually has more die area available to conduct diode current than the FET has for drain current. For data sheet purposes, the drain-source diode current, labeled I_S, is made equal to the drain current I_D.

To verify these current ratings, the C-E and D-S diodes were subjected to two different pulse width surge tests, a one second, one-shot pulse and a 300 µs, 1.8% duty cycle (60 Hz rep rate) pulse train. The one second test, which approximates a dc test was run with the DUT bolted to a four inch square copper heat sink, initially water cooled and then in free air. The DUT forward current was then increased until the device was destroyed. The test results on one product line for the water cooled versus free air cooled were virtually identical so all subsequent tests were done in free air. The results of these tests are shown in the surge current sections of Tables 1 and 2.

For power dissipation purposes and clamping efficiency determination, the typical forward characteristics of the diodes were also taken, as shown in Figures

11A through 11E. The V_F-I_F curves were derived from a curve tracer using a 300 μs current pulse at 60 pps; the low duty cycle ensured low case temperature readings. For comparison purposes, Figure 12 describes the forward characteristics of discrete diodes under the same test conditions. Knowing the voltage drop and current, the diode dissipation can be calculated. For any combination of power dissipation, the total diode and transistor dissipations should not exceed the rating of the device.

Knowing the switching characteristics and the power handling capability of the diodes, a cost/performance trade-off can be made. If the switcher is in the development phase, it becomes relatively simple to determine the effects of using the internal monolithic diode over a discrete, outboard diode, i.e., measuring case temperature rise, current and voltage waveforms, load lines to ensure safe SOA, device and system efficiency, etc.

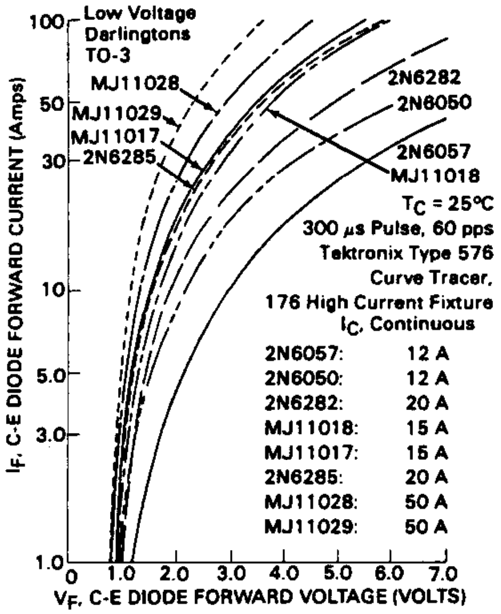


FIGURE 11A — Forward Characteristics of Darlington C-E Diodes

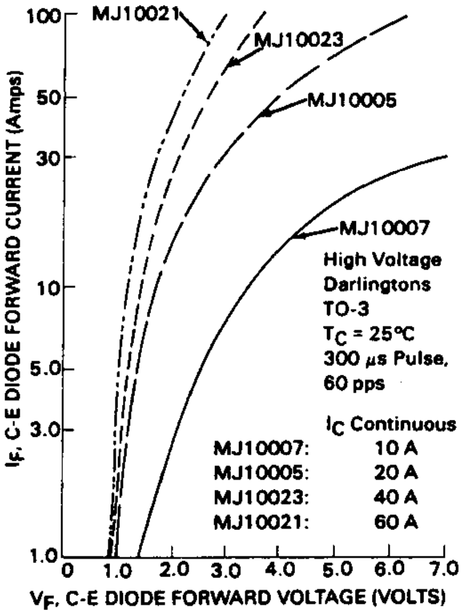


FIGURE 11B — Forward Characteristics of Darlington C-E Diodes

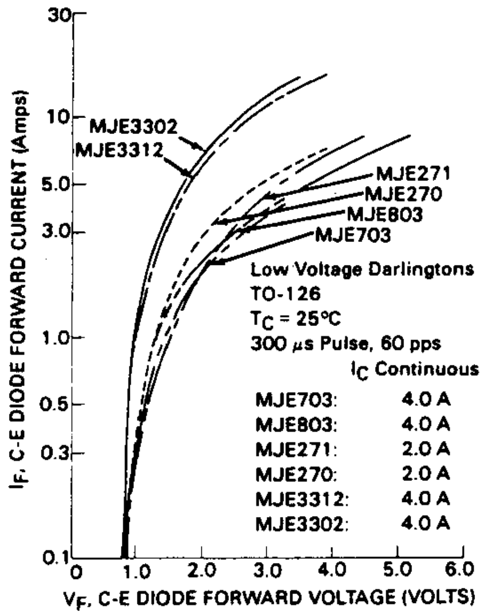


FIGURE 11C — Forward Characteristics of Darlington C-E Diodes

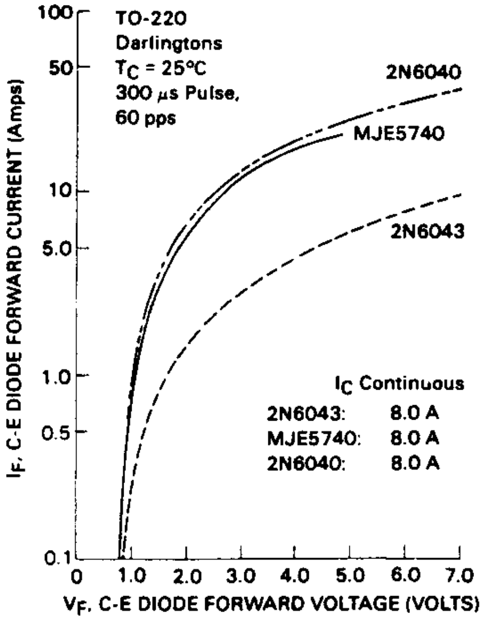


FIGURE 11D — Forward Characteristics of Darlington C-E Diodes

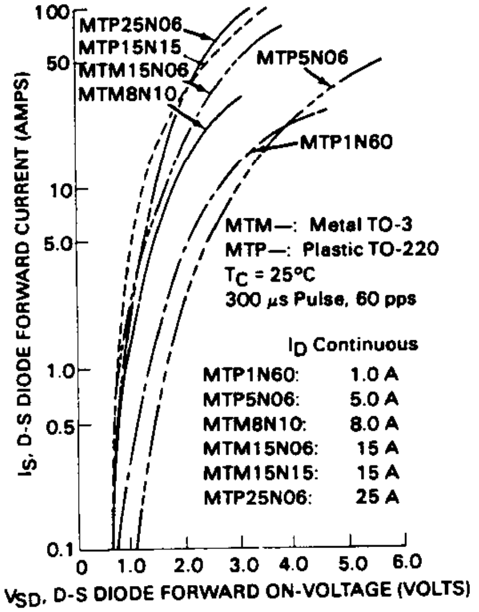


FIGURE 11E — Forward Characteristics of Power MOSFETs D-S Diodes

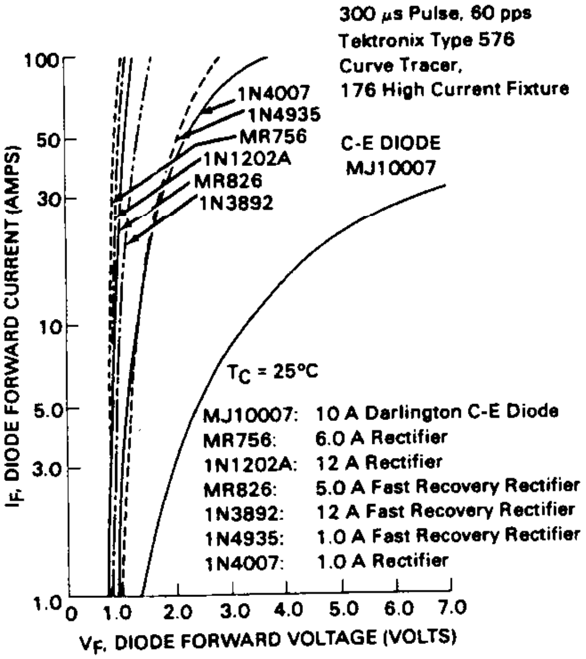


FIGURE 12 — Forward Characteristics of Discrete Rectifiers

CONCLUSION

Using the data obtained from the "real world" test circuit, designers should now be able to make the judgment of whether the internal collector-emitter and drain-source diodes of power Darlington transistors and power MOSFETs are adequate for their applications or whether faster outboard discrete diodes should be used.

REFERENCE:

1. Pshaenich, A., "Driving Inductive Loads? Take Advantage of Collector-Emitter Diodes in Monolithic Power Darlingtons", Electronic Design 4, February 15, 1977.
2. Pshaenich, A., "Use Pulse-Width Modulation to Control D.C. Motors", Electronic Design, February 1, 1974.

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