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Reverse Recovery Testing of Small-Signal Schottky Diodes

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***Abstract*—Ideally, Schottky diodes have little to no reverse recovery charge due to the lack of a PN junction or associated minority carriers. However, commercial Schottky diodes incorporate a PN junction guard ring under the electrode edge. At high currents, conduction through the guard ring structure can occur, injecting minority carriers and increasing reverse recovery charge. This behavior can lead to adverse circuit effects and increased loss, especially in high frequency dc-dc converters. Moreover, this effect is little-discussed in technical literature, not captured in datasheet provided values, and not typically incorporated into manufacture provided simulation models. This paper provides an open source and low-cost diode recovery test circuit and uses it to evaluate a selection of small-signal Schottky diodes and rectifiers. In several of the diodes, we find a significant increase in the recovery charge at high currents, characteristic of the PN junction guard ring's conduction.**

***Index Terms*—schottky diode, reverse recovery loss**

I. Introduction

Compared to PN diodes, Schottky diodes are commonly treated as having little or no reverse recovery charge because of the lack of minority carrier injection as part of the device's normal functioning. However, almost all modern Schottky diodes are fabricated with a PN junction based guard ring under the electrode edge, which is needed to normalize field gradients in the diode structure, reducing leakage current and providing controlled avalanche behavior under over-voltage conditions. The guard ring's PN junction is parallel to the Schottky diode structure and under high current densities can conduct current, causing the injection of minority carriers and a level of reverse recovery charge typically associated with a PN diode [1], [2]. This behavior is dependent on the relative threshold voltages of the guard ring PN junction and the Schottky diode and is determined by the doping during manufacturing. Although there is relatively little discussion of the circuit impacts due to recovery losses in Si Schottky diodes, there is a somewhat greater amount of literature discussing the mechanism of the PN guard ring related recovery loss in SiC Schottky diodes and the core mechanism is the same [3].

The reverse recovery charge due to the guard ring structure is typically not reflected in the values provided in the manufacture datasheets due to the magnitude of the test current used nor captured in most provided device models. However, the added reverse recovery charge can have significant impact on circuit operation. This additional reverse recovery charge first came to the authors' attention when investigating anomalous circuit losses in a dc-dc converter that was ultimately traced to the excessive reverse recovery loss of a small-signal Schottky diode that was used as a bootstrap diode for a gate drive circuit. Other researchers have published test data for the use of silicon Schottky diodes as high frequency rectifiers that shows anomalous losses in a subset of tested diodes, which may be suggestive of guard ring related recovery loss, but have not investigated the root cause [4].

This paper provides a low-cost diode recovery test circuit that does not require any external voltage or current probes, only an oscilloscope with 50 Ω inputs, a function generator, and two power supplies. The test circuit is released under an open source license and is available at https://github.com/westonb/diode-testing. We use this test circuit to measure the reverse recovery behavior of a selection of small-signal Schottky diodes and low current Schottky rectifiers, typical of diodes that may be used for rectification in small dc-dc converters or bootstrap diodes for gate drivers. In several of these diodes, we observe significant increases in the diode recovery loss at higher currents, characteristic of the PN junction guard ring's conduction. This behavior departs significantly from the simulation models and can cause significant losses, which underscores the importance of testing.

II. Test Circuit

A. Prior Test Circuits

Diode recovery charge is measured by first forward biasing the diode with a known current and then abruptly reversing the voltage across the diode. The reverse current that flows through the diode during the transition is integrated to yield the reverse recovery charge. Diode manufacturers typically use the standardized test circuit of Fig. 1 to measure the recovery time values listed in the datasheets of small diodes. The circuit consists of signal generator, a bias tee, a power supply, and an oscilloscope with a 50 Ω input [5]. Abstracted as I_F in Fig. 1, the inductance of the bias tee acts as a constant current source at high frequency and the power supply is put into constant current mode to set the average DC diode current. The

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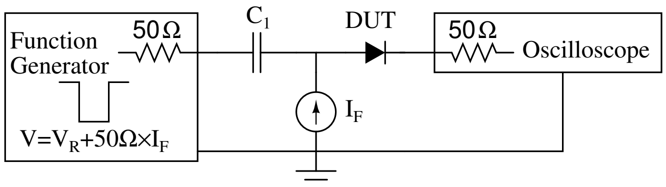


Fig. 1: Standard test circuit for reverse recovery testing of small signal diodes. [5]

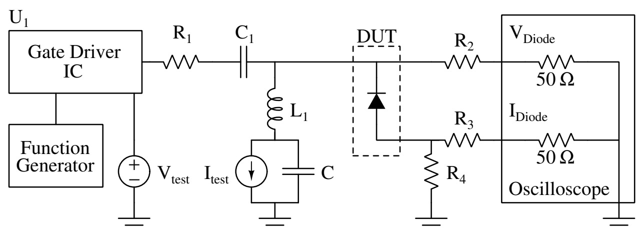


Fig. 2: Simplified schematic of diode test circuit used in this paper.

50 Ω input impedance of the oscilloscope is used as a current shunt, allowing direct measurement of the diode recovery current. This circuit is simple and allows for high bandwidth measurements, but given the maximum output power of most function generators and the maximum power dissipation rating of most 50 Ω terminations, the maximum diode test current is quite limited.

A typical test fixture for higher power diodes is the double pulse test, which requires a high speed switch and a current probe [6]. Current probes typically have lower bandwidth than voltage probes, posing challenges for high bandwidth measurements with the double pulse test.

B. Proposed Test Circuit

Our test circuit uses a gate driver IC as a high current and high speed buffer, allowing for testing of low voltage diodes at high speeds and higher currents than are achievable with just a function generator. Measurements are taken via resistive networks that drive an oscilloscope with 50 Ω input impedance, which allows for high bandwidth and low cost measurement circuits. Figure 2 shows a simplified schematic diagram of the test circuit we use for testing and Table I lists all relevant component values. The test circuit requires

TABLE I: Component values for the diode test circuit shown in Fig. 2.

Component	Value	Implementation
U_1	±10 A Gate Driver	NCP81074AMNTBG
L_1	47μH, 500mA	ADL3225V-470MT
C_1	2μF	2x SMD 0402 ceramic chip
R_1	1Ω	SMD 0402 thick film
R_2	450Ω	3x series SMD 0402 thick film
R_3	47Ω	SMD 0402 thick film
R_4	1.1Ω	2x parallel SMD 0402 thick film

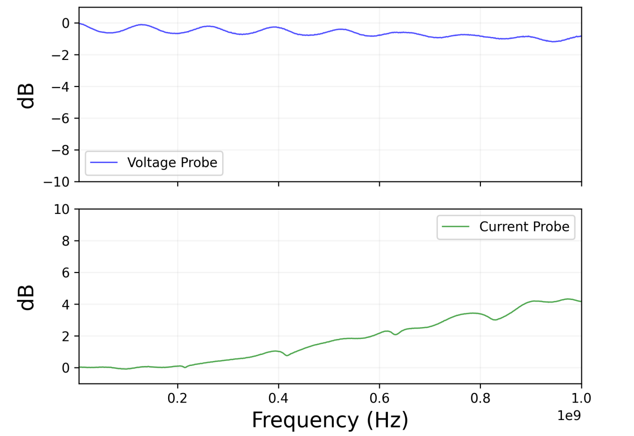


Fig. 3: Transfer functions of voltage and current sensing circuits as measured with a vector network analyzer. Gain is normalized to the nominal transfer ratio of 1/10 V/V for the voltage probe and 0.55 V/A for the current probe.

an external function generator to drive the gate driver IC and two external power supplies to supply V_{test} and I_{test}.

The gate driver is AC coupled to the diode under test with C_1 and bias current is provided through L_1, which acts as a constant current source at high frequency while a power supply in constant current mode controls the average current, I_{test}. The AC coupling of the gate driver ensures that its operation does not perturb the bias conditions of the diode. The duty cycle of the function generator, D, impacts the relation between I_{test} and the current flowing through the diode:

$$I_{diode} = I_{test} \cdot \frac{1}{1-D}$$

In operation, I_{test} is provided by a power supply in constant current mode. As most power supplies can only source power this forces a constraint of $D < 0.5$, as the direction of net power flow changes at $D = 0.5$. Gate drive thermal limitations and the current rating of L_1 limit I_{test} to 500 mA.

Diode current is measured with a resistive shunt, R_4, and R_3 is used to match the shunt impedance to 50 Ω coaxial cables and reduce signal reflections. Voltage sensing is based on the principle of a transmission line or "low-Z" probe where a series resistor, R_2, forms a voltage divider with the 50 Ω input of the oscilloscope [7]. Compared to traditional oscilloscope probes, transmission line probes have a low input resistance but almost negligible input capacitance, which is advantageous for high frequency measurements. As implemented, the transmission line probe has a 10:1 voltage division ratio and a 500 Ω input resistance. This impedance minimally loads the output of the gate driver IC.

Due to the 50 Ω impedance of the measurement circuits, the frequency response can be measured with a standard vector network analyzer by removing the gate drive IC, replacing the diode with a short, and soldering a RF connector to where L_1 normally connects to the DUT. In Fig. 3 we present transfer

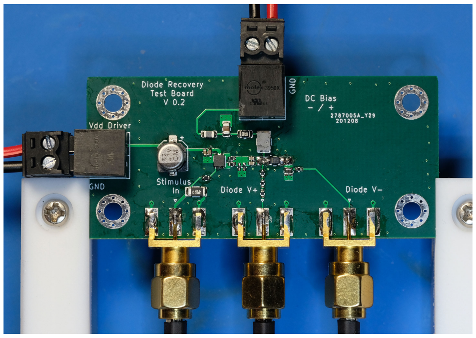


Fig. 4: Photograph of diode test circuit PCB. The PCB has dimensions of 65 mm by 30 mm.

functions of the voltage and current monitoring circuit up to a frequency of 1 GHz. The voltage monitoring circuit has a flat frequency response to within 1 dB, with minor ripple caused by impedance mismatches. The current shunt circuit has a +3 dB point at around 750 MHz due to the inductance of the shunt resistors. Given that the gate driver IC has a rise time in excess of 1 ns, high frequency signal content above this frequency will be limited, so the effect of the elevated current sensing gain will be minimal.

In Fig. 4 we provide a photograph of the measurement circuit. The PCB is 4 layers and 65 mm by 30 mm.

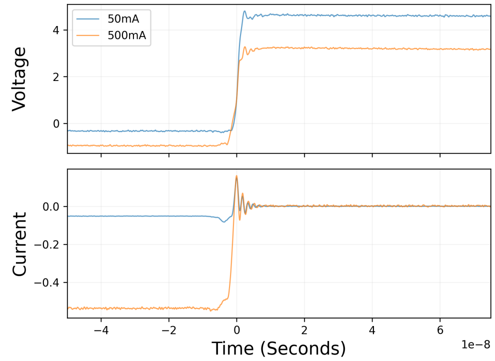
III. Diode Testing

A number of diodes were tested at a low forward current of 50mA and at a higher forward current equal to the the lesser of the rated diode current and the 500mA limit of the test circuit. Additional data points were collected for diodes exhibiting significant reverse recovery charge.

Testing was conducted with a fixed voltage swing of 5V and function generator duty cycle of $D = 0.1$ at a frequency of 1MHz. Waveform data was captured through an oscilloscope with 50 Ω inputs (MSO9404A, 1GHz bandwidth setting). Diode reverse voltage was controlled by adjusting the supply voltage of the gate driver IC while the diode current was controlled by adjusting the current limit of a second power supply providing I_{test}.

After data collection, the recovery current waveforms were numerically integrated to obtain the reverse recovery charge values. Current was integrated from the zero crossing of the current until the recovery current fell to 10% of the peak value. By subtracting the reverse recovery charge measured at the low test current from the reverse recovery charge measured at the high test current, a lower bound on the true reverse recovery charge can be obtained, independent from the diode junction capacitance or test fixture capacitance.

In Table II we present the measured reverse recovery charges for the Schottky diodes tested. ΔQ_{rr} is the difference between the high current Q_{rr} and the low current Q_{rr}. From the table it can be seen that some diodes have a large positive ΔQ_{rr}, which is indicative of guard ring reverse recovery occurring at higher current densities. Some diodes have a



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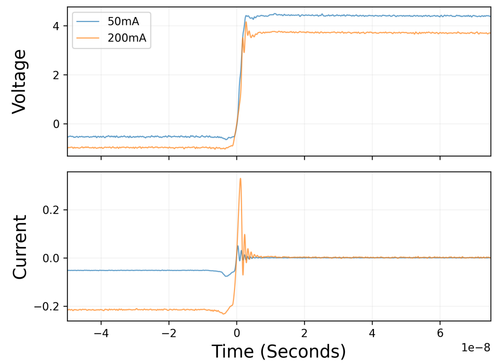

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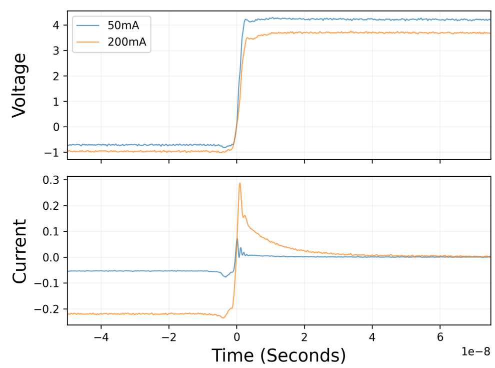


(c)

Fig. 5: Reverse recovery test waveforms of **(a)** PMEG2010EA, **(b)** BAT54WS-HE3-08, **(c)** NSR02100HT1G diodes at two different forward currents, showing different reverse recovery behavior with increasing forward current.

small negative ΔQ_{rr}, this is due to the lowered voltage swing across the diode at higher currents due to IR voltage drop, but is otherwise indicative of no issues with guard ring reverse recovery.

In Fig. 5 we provide some of the captured waveforms, qualitatively showing how the diode behavior changed with increasing forward bias current. Fig. 5(a) shows a diode with recovery charge that does not change with increasing forward current, exhibiting close to ideal Schottky diode behavior. Fig.

TABLE II: Measured diode recovery charge for two different test currents.

Diode	**Rated V** [V]	**Rating I** [mA]	**Test I** [mA]	Q_{rr} [pC]	**Test 2** [mA]	Q_{rr} [pC]	ΔQ_{rr} [pC]
1PS76SB70	70	70	50	129	70	341	212
BAT54WS-HE3-08	30	200	50	24	200	276	252
CMDSH05-4	40	500	50	112	500	103	-9
CMHSH5-4	40	500	50	303	500	249	-54
DSS13UTR	30	1000	50	424	500	343	-81
MBR180S1-7	80	1000	50	134	500	983	849
MSS1P2L-M3	30	1000	50	466	500	370	-96
NSR02100HT1G	100	200	50	42	200	1510	1468
NSR0320MW2T3G	20	1000	50	217	500	185	-32
PMEG2010EA	20	1000	50	142	500	127	-15
RB168LAM100TFTR	100	1000	50	376	500	1080	704
SD107WS-7-F	30	100	50	183	100	217	34
SS16T3G	60	1000	50	445	500	347	-98
SMMSD701T1G	70	200	50	396	200	2360	1964
STPS1L60ZF	60	1000	50	464	500	368	-96

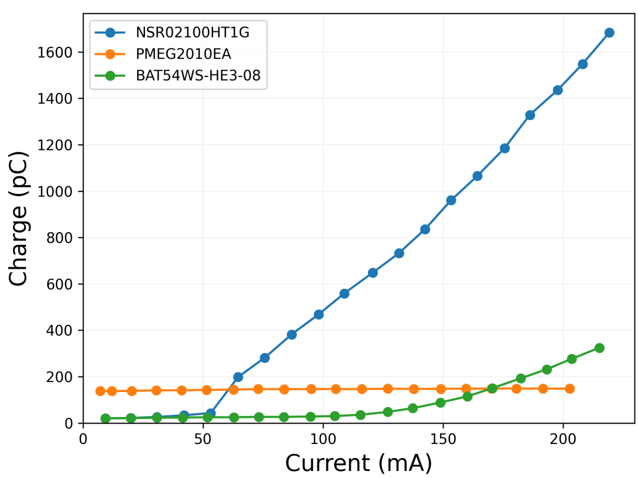


Fig. 6: Measured reverse recovery charge as a function of forward current for BAT54WS-HE3-08, NSR02100HT1G, and PMEG2010EA diodes.

5(b), shows a diode with increasing recovery charge with increasing forward current, indicative of conduction of the guard ring PN structure. However, the recovery time is short, indicative of a short minority carrier lifetime. Fig. 5(c) shows a diode with strongly increasing recovery charge with increasing forward current. This is indicative of a long minority carrier lifetime and this behavior has the potential to cause significant switching losses in circuits with high dv/dt, a behavior not expected of Schottky diodes.

Additional data was collected on a subset of the diodes to create plots of the reverse recovery charge as a function of forward current. In Fig. 6 we provide a plot of this data. For the BAT54WS-HE3-08 and NSR02100HT1G diodes that demonstrate increased recovery charge at higher currents it can be seen that recovery charge stays constant until some current is reached, at which point recovery charge strongly increases as a function of current. This is suggestive that guard ring conduction which only occurs at higher current densities.

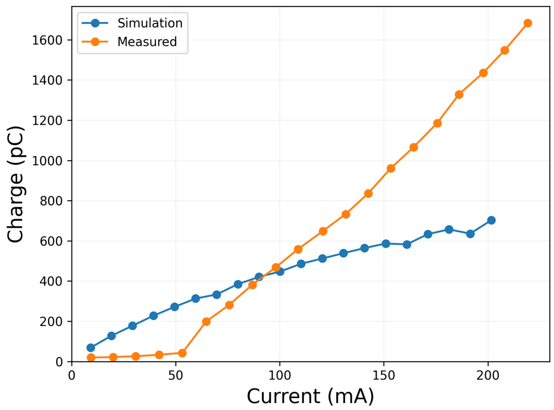
The data from the PMEG2010EA diode serves as a control, showing a diode which has no increasing recovery charge with increasing current.

IV. Analysis

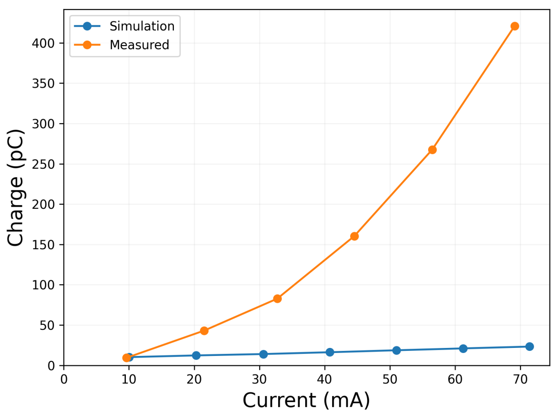
The datasheets for the tested diodes provide little guidance that would aid in avoiding devices with high reverse recovery loss as few provide reverse recovery times and none provide reverse recovery charge values. From our testing results it is apparent that higher voltage rated Schottky diodes are more likely to have increased reverse recovery charge at higher currents. A likely explanation for this is that higher blocking voltage Schottky diodes have a higher forward voltage drop which comes closer to the threshold voltage of the PN guard-ring structure, allowing greater charge injection under typical operating conditions.

In addition to datasheets, some manufactures provide simulation models for diodes. To see if these manufacture models capture the observed effects we simulated the test circuit, including parasitic circuit elements, with the manufacture diode models in SPICE. The waveform data was then extracted and processed with the same scripts used to calculate the recovery charge from the captured oscilloscope waveforms. In Fig. 7 we present plots comparing the measured and simulated reverse recovery charge as a function of forward current for the NSR02100HT1G and 1PS76SB70 diodes. From these plots we can see that the neither diode model accurately captured the reverse recovery behavior. Most noticeably, neither model demonstrated the sharp increase in reverse recovery charge once a specific current is reached, indicative of conduction of the guard ring. This is somewhat expected, as the models are a parameter set for the standard SPICE diode model and therefore incapable of accurately modeling the parallel combination of the Schottky junction and the PN guard ring.

Additionally, despite coming close to the measured values at some points, the model for the NSR02100HT1G did not accurately capture the long reverse recovery time, with the model exhibiting a reverse recovry time of less than 1 ns while the measured diode had reverse recovery times close to 20 ns.



(a)



(b)

Fig. 7: Comparison of measured and simulated reverse recovery charge as a function of current for **(a)** NSR02100HT1G and **(b)** 1PS76SB70 diodes.

If used in a converter, this difference in reverse recovery time could lead to significant loss.

V. Conclusion

In this paper we provide a low cost circuit for measuring the reverse recovery loss of small signal diodes that can test diodes up to currents of 500 mA at high bandwidth. This design is available under an open source licence at https://github.com/westonb/diode-testing. We use this circuit to measure the reverse recovery loss in a selection of small signal Schottky diodes and rectifiers. In a subset of these diodes we identify a sharply increasing reverse recovery charge with increasing forward current. The idealized model of the Schottky diodes has no reverse recovery charge but modern Schottky diodes have a guard ring structure consisting of a PN diode junction. This PN junction conducting at elevated current densities is the most likely mechanism for the anomalous reverse recovery charge.

Datasheets for Schottky diodes typically make no mention of reverse recovery charge and we also demonstrate that this anomalous charge is not accurately captured by manufacture provided diode models. Given the magnitude of the charge and the excessive reverse recovery time demonstrated in some of the tested diodes, these discrepancies can lead to significant losses in some applications. As Schottky diodes with otherwise similar ratings exhibited large differences in reverse recovery charge at elevated currents it is difficult to predict which diodes will be poorly performing based on publicly available data. This underscores the importance of a low cost and simple test circuit.

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