A Pulse-Based Semiconductor Reverse Breakdown Voltage Meter Using Inductive Flyback Energy Transfer

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Abstract. Reliable testing of semiconductor protection devices is important for embedded power electronics. This paper presents a compact pulse-based platform for measuring reverse breakdown and dynamic clamping behaviour using inductive flyback energy transfer. A controlled inductor current generates short high-voltage pulses through MOSFET switching, while an analog peak detector and embedded ADC capture the clamped voltage. The prototype was evaluated using SMAJ48CA, P6KE68CA, and 1.5KE170CA TVS diodes. Measurements agreed with expected datasheet ranges, and the highest verified voltage reached 177 V. The proposed method enables low-cost testing with reduced continuous thermal stress.

Keywords. reverse breakdown voltage, TVS diode, inductive flyback, pulse-based measurement

1 Introduction

Reliable verification of semiconductor protection devices is important in electronics manufacturing, diagnostics, and embedded power systems. Among their electrical parameters, the reverse breakdown voltage V_{BR} represents a key indicator of the functional state and operating limits of semiconductor junctions (Baliga, 2019). This parameter is particularly relevant for Transient Voltage Suppression (TVS) and Zener diodes, where the ability to enter reverse breakdown and clamp overvoltage transients directly determines the protection capability of the device (Littelfuse, 2020, 2025; Vishay General Semiconductor, 2026).

In practical diagnostics, catastrophic failures can often be detected as permanent short or open circuits. Partial degradation is more difficult to identify because a protection device may remain conductive and apparently functional while its breakdown or clamping characteristics have shifted outside the expected range. Experimental verification of reverse-bias behaviour is therefore useful for component screening, quality control, and evaluation of devices exposed to electrical overstress.

Conventional breakdown-voltage characterization is typically based on direct-current (DC) excitation, where a controlled current is applied to the device under test (DUT) and the corresponding voltage is measured. Although simple, continuous current injection causes power dissipation and local junction heating. Since semiconductor breakdown voltage is temperature-dependent, self-heating can introduce measurement drift and, under prolonged stress, may further degrade the tested component (Baliga, 2019).

Professional semiconductor characterization systems address this problem using short-pulse measurements. Source Measure Units (SMUs), for example, can limit the duration of electrical stress and thereby reduce junction self-heating during high-voltage or high-current characterization (Keithley Instruments, 2016). However, instruments combining accurate current control, fast pulse generation, and high-voltage measurement are relatively expensive and may therefore be impractical for educational laboratories, small-scale production environments, repair diagnostics, or portable embedded applications.

Existing approaches therefore exhibit a trade-off between simplicity, thermal stress, and instrumentation cost. Static DC methods are inexpensive but expose the DUT to continuous dissipation, whereas professional pulsed instruments provide improved control at significantly higher cost and complexity. Furthermore, conventional implementations generally rely on dedicated high-voltage sources and measurement equipment. This creates an opportunity for a compact system in which the excitation energy itself is inherently limited and generated only during a short measurement interval.

Low-cost embedded measurement platforms have been successfully applied in various sensing and monitoring applications, including road-traffic monitoring using MEMS sensors (Hodoň et al., 2021) and energy-efficient wireless data acquisition involving mains-voltage measurements (Karpiš et al., 2022), demonstrating the practical potential of compact

microcontroller-based measurement systems.

Inductive energy storage provides a suitable principle for such excitation. When current through an inductor is rapidly interrupted, the stored magnetic energy produces a flyback voltage transient whose amplitude is determined by the circuit conditions and connected load (Mohan et al., 2003). If a semiconductor protection device is connected to the switching node, the generated transient can force it into reverse breakdown while the delivered energy remains limited by the inductor current and switching duration. The resulting voltage can subsequently be captured using a peak detector, which converts the short transient into a stable voltage suitable for acquisition by a low-speed embedded Analog-to-Digital Converter (ADC) (Mancini, 2002).

Based on this principle, this paper presents a compact pulse-based semiconductor reverse-voltage measurement platform that combines inductive flyback excitation, Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) switching, analog peak detection, and microcontroller-based acquisition. Before each measurement, a controlled current is established in the inductor. During a short measurement interval, the MOSFET periodically interrupts the current path and produces high-voltage transient pulses that are clamped by the connected DUT. The clamped peak voltage is attenuated, captured, and digitized by the embedded control system.

The main contribution of the proposed approach is a low-cost architecture for measuring pulse-induced reverse breakdown and dynamic clamping behaviour without requiring a continuously operating high-voltage source or laboratory-grade SMU. In comparison with static DC testing, the pulsed excitation reduces continuous thermal loading of the DUT, while the peak-hold front-end enables transient-voltage acquisition using standard embedded hardware. The developed prototype is experimentally evaluated using several TVS diode families with different nominal voltage ratings to assess measurement repeatability, agreement with datasheet breakdown ranges, and behaviour at increasing excitation currents.

The remainder of this paper is organized as follows. Section 2 describes the proposed measurement platform, including the system architecture, inductive pulse generation, analog signal conditioning, embedded control, and experimental verification. Section 3 presents and discusses the experimental results obtained for the tested TVS diodes. Finally, Section 4 summarizes the main findings and outlines directions for future development.

2 Materials and Methods

The proposed system was designed as a compact cyber-physical diagnostic platform for pulse-based reverse breakdown voltage measurement of semiconductor protection devices. The physical layer of the system generates controlled high-voltage transient pulses using inductive energy storage, while the embedded control layer configures the test conditions, drives the switching sequence, acquires the analog response, and presents the measured value to the operator. This architecture enables low-cost and repeatable verification of semiconductor devices without exposing the DUT to continuous thermal stress.

2.1 System Architecture

The measurement system consists of five main functional blocks: a digitally controlled excitation stage, an inductive energy storage loop, a MOSFET-based switching stage, an analog signal-conditioning circuit, and a microcontroller-based control unit. The general topology of the proposed system is shown in Fig. 1. The excitation stage establishes a predefined current through the inductor. This current is set indirectly by a controlled voltage source whose output is adjusted by an external Digital-to-Analog Converter (DAC). The DAC value is selected by the operator through the local user interface before the measurement sequence is initiated.

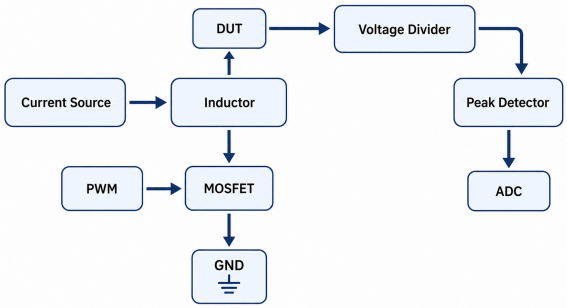

Figure 1. Functional block diagram of the proposed pulse-based reverse breakdown voltage measurement system.

The controlled voltage source is connected in series with a current-limiting resistor network and a power inductor. Under steady-state excitation, the target inductor current can be approximated as

$$I_{\mathrm{exc}} \approx \frac{V_{\mathrm{drv}}}{R_{\mathrm{eq}}}, \tag{1}$$

where I_{exc} is the excitation current, V_{drv} is the drive voltage generated by the controlled source, and R_{eq} is the equivalent resistance of the current-limiting resistor network. As expressed in Eq. (1), the excitation current is determined primarily by the applied drive voltage and the equivalent resistance of the excitation path. Therefore, the measurement energy can be controlled by adjusting the DAC-controlled drive voltage. In the implemented prototype, the operator selects the target current through the embedded interface, and the microcontroller configures the corresponding DAC output

value.

This configuration provides a simple means of controlling the initial energy stored in the inductor before the switching transient is generated. Since the excitation current directly influences the magnetic energy available in the inductor, adjusting the drive voltage also changes the energy released during the flyback event. In this way, the system can adapt the excitation level to semiconductor devices with different reverse-breakdown voltage ranges while avoiding unnecessarily high current settings. The digitally controlled excitation stage therefore provides both repeatability and flexibility during the measurement process, as the same hardware can be used for multiple DUT types without manual modification of the resistor-inductor path.

The physical implementation of the developed prototype is shown in Fig. 2.

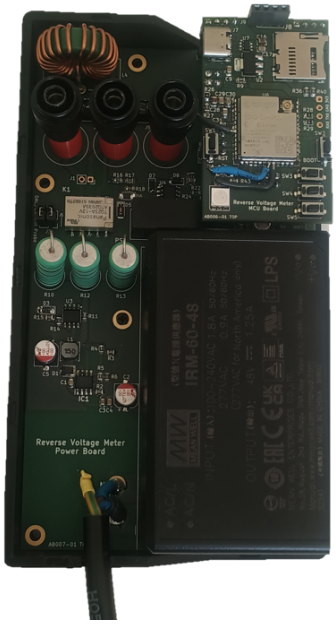

Figure 2. Implemented hardware prototype of the proposed pulse-based semiconductor reverse breakdown voltage meter.

2.2 Inductive Pulse Generation

The core measurement principle is based on inductive flyback energy transfer. During the charging phase, the MOSFET switch is turned on by a Pulse-Width Modulation (PWM) signal generated by the microcontroller. The inductor current flows through the MOSFET to ground, and magnetic energy is stored in the inductor. The stored energy is given by

$$E_L = \frac{1}{2} L I_{\text{exc}}^2, \tag{2}$$

where E_L is the magnetic energy stored in the inductor and L is the inductance. As shown in Eq. (2), the stored magnetic energy depends quadratically on the excitation current. Therefore, the selected test current directly determines the amount of energy available during the transient event and consequently the electrical stress applied to the DUT.

When the MOSFET is rapidly switched off, the inductor current cannot change instantaneously. As a result, a high-voltage transient is generated at the switching node. The induced voltage follows the basic inductor relation

$$v_L(t) = L \frac{di_L(t)}{dt}, \tag{3}$$

where $v_L(t)$ is the instantaneous inductor voltage and $di_L(t)/dt$ is the rate of change of the inductor current. According to Eq. (3), a rapid change in the inductor current produces a corresponding transient voltage across the inductor. The DUT, represented by a TVS diode, Zener diode, or another semiconductor junction, is connected to the switching node. When the generated flyback voltage exceeds the reverse breakdown threshold of the DUT, the semiconductor enters its breakdown region and clamps the transient voltage. The measured peak voltage therefore represents the pulse-induced reverse breakdown and dynamic clamping response of the tested component, depending on the selected excitation current and stored inductive energy.

2.3 Analog Signal Conditioning and Voltage Measurement

Because the generated transient voltage can significantly exceed the safe input range of the microcontroller, the signal is first attenuated using a high-impedance voltage divider. The relationship between the peak reverse voltage at the DUT and the voltage at the ADC input is expressed as

$$V_{\text{ADC}} = V_{\text{DUT,peak}} \frac{R_2}{R_1 + R_2}, \tag{4}$$

where V_{ADC} is the attenuated voltage applied to the analog input, $V_{\text{DUT,peak}}$ is the peak reverse voltage across the DUT, and R_1 and R_2 are the upper and lower resistors of the voltage divider. Equation (4) describes the attenuation introduced by the voltage divider before the transient signal reaches the analog acquisition stage.

The peak reverse voltage at the DUT can therefore be reconstructed as

$$V_{\text{DUT,peak}} \approx V_{\text{ADC}} \frac{R_1 + R_2}{R_2}. \tag{5}$$

Using Eq. (5), the original peak voltage across the DUT can be estimated from the measured ADC input voltage and the known voltage-divider ratio.

To allow the microcontroller to acquire the transient peak reliably, the attenuated pulse is processed by an analog peak detector. The peak detector captures the maximum amplitude of the pulse train and stores it on

a capacitor, creating a quasi-static voltage suitable for ADC conversion. This approach avoids the need for high-speed digitization of the transient waveform and enables the use of a low-cost embedded acquisition platform.

The ADC output code is converted to voltage according to

$$V_{\mathrm{ADC}} = \frac{N_{\mathrm{ADC}}}{2^n - 1} V_{\mathrm{ref}}, \tag{6}$$

where N_{ADC} is the digital ADC value, n is the ADC resolution, and V_{ref} is the ADC reference voltage. According to Eq. (6), the measured ADC code is converted into the corresponding analog voltage using the ADC resolution and reference voltage.

In the practical implementation, the voltage-divider ratio and ADC conversion characteristics are calibrated experimentally to compensate for component tolerances and analog front-end deviations. The calibrated peak reverse voltage can be expressed as

$$V_{\mathrm{DUT,peak,cal}} = aV_{\mathrm{ADC}} + b, \tag{7}$$

where a and b are calibration coefficients obtained from reference measurements. Equation (7) represents the experimentally determined calibration relationship used to convert the acquired ADC voltage into the final peak reverse-voltage estimate.

2.4 Embedded Control and Measurement Sequence

The embedded control unit coordinates the entire measurement process. The system is built around an ESP32-S3 microcontroller, which provides the required digital control signals, ADC acquisition, user-interface handling, and potential wireless communication capabilities.

The local user interface used for selecting the excitation current and initiating the measurement sequence is shown in Fig. 3.

After the user confirms the selected test configuration, the microcontroller performs the following sequence:

1. the selected current setting is converted into a DAC output value;
2. the excitation stage establishes the target current through the resistor-inductor network;
3. the PWM signal activates the MOSFET switching stage for a predefined short measurement window;
4. inductive flyback pulses are generated and clamped by the DUT;
5. the peak detector captures the maximum transient voltage;

Figure 3. Local user interface used for excitation current selection and manual initiation of the measurement sequence.

6. the ADC samples the stabilized peak-detector output;
7. the calibrated peak reverse voltage is calculated and displayed to the operator.

The measurement is intentionally restricted to a short active time window in order to reduce the accumulated energy delivered to the DUT and limit junction self-heating. The energy dissipated in the DUT during a pulse can be generally described as

$$E_{\mathrm{DUT}} = \int_0^{t_p} v_{\mathrm{DUT}}(t) i_{\mathrm{DUT}}(t)\, dt, \tag{8}$$

where t_p is the pulse duration, $v_{\mathrm{DUT}}(t)$ is the instantaneous voltage across the DUT, and $i_{\mathrm{DUT}}(t)$ is the instantaneous current through the DUT. As expressed in Eq. (8), the total energy delivered to the DUT depends on the instantaneous voltage and current over the duration of the pulse. Limiting the active measurement interval therefore reduces the accumulated energy compared with continuous DC excitation and helps suppress junction self-heating and associated thermal distortion during breakdown-voltage measurement.

2.5 Experimental Verification

The prototype was experimentally evaluated using selected semiconductor protection devices with different nominal breakdown voltage ranges. The tested components included TVS diodes from the SMAJ, P6KE, and 1.5KE series. These devices were selected because they represent common overvoltage protection components used in embedded electronics, power interfaces, and energy-related systems.

Each DUT was connected to the measurement terminals and tested under a selected excitation current. The excitation-current values were determined experimentally during preliminary measurements. For each

device, the lowest practical excitation current capable of storing sufficient energy in the inductor to generate a stable and measurable reverse-breakdown response was preferred. Preliminary tests showed that substantially higher excitation currents, approximately 500 mA to 1 A, produced stronger voltage transients but also increased the energy delivered during the switching event and could introduce additional junction heating. Therefore, excessive excitation currents were avoided unless a higher stored energy was required to reach the breakdown region of a higher-voltage device.

It should be emphasized that the excitation current represents the current established in the inductor before the switching transient and does not correspond directly to the instantaneous current flowing through the DUT during breakdown. During the flyback event, the DUT current is transient and depends on the stored magnetic energy, switching dynamics, inductance, and the nonlinear current-voltage characteristic of the tested semiconductor. Consequently, the selected excitation currents should be interpreted as operating parameters of the pulse-generation stage rather than as conventional DC test currents specified in semiconductor datasheets.

The tested excitation-current levels were configured through the local interface and reached up to 300 mA. The measured peak reverse voltage was obtained from the ADC value after voltage-divider scaling, peak detection, and calibration. The experimental verification focused on three main aspects:

- whether the prototype can safely force the DUT into the reverse breakdown region;
- whether the low-energy measurement produces a voltage consistent with the expected datasheet breakdown range;
- whether increasing the excitation current produces a physically consistent increase in the measured clamping voltage.

The excitation-current sweep was performed for the SMAJ48CA as a representative device. Its purpose was not to obtain a complete current-voltage characteristic for every tested component, but to verify that the proposed measurement platform responds consistently to changes in the energy stored in the inductor. Increasing the excitation current increases the stored magnetic energy and shifts the transient operating point of the TVS diode further into its breakdown region. Since the clamping voltage of a TVS diode depends on the transient current, a corresponding increase in the measured peak voltage is expected. The remaining devices were primarily used to verify the ability of the prototype to identify the reverse-breakdown region across different nominal voltage classes.

The measurement chain was calibrated and verified using a precision laboratory digital multimeter as a reference instrument. For each tested component, the prototype measurement was compared with the expected breakdown voltage range specified in the corresponding manufacturer documentation. The resulting measurements were summarized in a comparative table and used to evaluate the functional behaviour and basic consistency of the developed system.

The presented experimental verification should therefore be interpreted as a functional validation of the developed prototype and its measurement chain rather than as a complete metrological characterization. Detailed uncertainty analysis, long-term repeatability testing, and waveform-level validation will be addressed in future work.

2.6 Relevance to Cyber-Physical and Intelligent Energy Systems

From a cyber-physical systems perspective, the developed prototype integrates physical transient generation, embedded control, analog measurement, and human-machine interaction into a single diagnostic node. The physical process is represented by inductive energy storage and semiconductor breakdown behaviour, while the cyber layer performs configuration, timing control, signal acquisition, calibration, and result interpretation.

The proposed system is particularly relevant for intelligent energy and embedded power applications, where semiconductor protection devices are used to protect power converters, renewable energy interfaces, battery-powered nodes, and sensor systems against transient overvoltage events. By enabling low-cost pulse-based testing of these protection devices, the developed platform supports preventive diagnostics, component screening, and reliability assessment in energy-aware electronic systems.

3 Results

The experimental evaluation was performed to verify the capability of the proposed pulse-based measurement platform to induce and measure the reverse breakdown and dynamic clamping response of selected semiconductor protection devices. The tested components covered nominal breakdown voltage ranges from approximately 48 V up to 170 V. The obtained results are summarized in Table 1.

For the SMAJ48CA device tested at an excitation current of 50 mA, the measured voltage reached 56 V, which lies within the nominal breakdown range specified by the manufacturer (Littelfuse, 2025). The P6KE68CA device produced a measured voltage of 67 V, which is also consistent with its specified range of 64.60–71.40 V (Littelfuse, 2020). Similarly, the 1.5KE170CA device reached 177 V, remaining within the expected range of 162–179 V (Vishay General Semiconductor, 2026). These results indicate that the

Table 1. Experimental results obtained with the proposed reverse breakdown voltage meter.

Component type	Nominal V_{BR} range (V)	Excitation current (mA)	Measured voltage (V)
SMAJ48CA	53.30–58.90	50	56
SMAJ48CA	53.30–58.90	150	65
SMAJ48CA	53.30–58.90	250	73
P6KE68CA	64.60–71.40	50	67
1.5KE170CA	162–179	300	177

proposed platform can identify the reverse breakdown region of TVS protection devices across different voltage classes.

The current-sweep measurements of the SMAJ48CA device show a clear dependence of the measured clamping voltage on the selected excitation current. Increasing the excitation current from 50 mA to 150 mA increased the measured voltage from 56 V to 65 V, while a further increase to 250 mA resulted in 73 V. This monotonic behaviour is consistent with the dynamic clamping characteristic of TVS diodes, where higher transient energy shifts the operating point further into the breakdown region and increases the observed clamping voltage.

It should be noted that the current values reported in Table 1 represent the target excitation current established in the inductor path before the switching transient. They do not correspond to a static DC current continuously forced through the DUT. During the flyback event, the actual DUT current is transient and depends on the stored magnetic energy, switching dynamics, inductance, and semiconductor clamping behaviour.

The highest measured voltage was 177 V for the 1.5KE170CA device, demonstrating that the analog front-end, voltage divider, peak detector, and ADC acquisition chain can process high-voltage transient events within the tested operating range. For the SMAJ48CA device, increasing the excitation current from 50 mA to 250 mA increased the measured voltage by 17 V, corresponding to approximately 30.4% relative to the 50 mA measurement. This result confirms that the measurement chain responds consistently to changes in excitation energy.

Overall, the results demonstrate that the proposed pulse-based reverse breakdown voltage meter provides physically consistent measurements for different TVS diode families. The system enables rapid reverse breakdown verification without continuous DC stress and supports its intended use as a low-cost embedded diagnostic platform for cyber-physical measurement systems, power electronics, and intelligent energy applications.

4 Conclusion

This paper presented a compact pulse-based semiconductor reverse-voltage measurement platform designed as an embedded cyber-physical diagnostic system for characterizing pulse-induced breakdown and clamping behaviour. The proposed system combines inductive flyback energy transfer, MOSFET-based switching, analog peak detection, voltage scaling, and microcontroller-based control into a standalone measurement device. Unlike conventional continuous DC testing methods, the presented approach applies short transient pulses to the DUT, thereby reducing the accumulated thermal stress and limiting the risk of measurement distortion caused by junction self-heating.

The experimental verification demonstrated that the developed prototype is capable of characterizing the pulse-induced reverse breakdown and dynamic clamping response of different TVS protection devices across a broad voltage range. The measured values for the SMAJ48CA, P6KE68CA, and 1.5KE170CA components were consistent with the expected breakdown and clamping behaviour specified by the corresponding manufacturer documentation. The highest measured voltage reached 177 V, confirming that the proposed analog front-end and voltage-scaling stage can process high-voltage transient events while maintaining compatibility with embedded ADC acquisition.

The results also showed that increasing the excitation current leads to a physically consistent increase in the measured clamping voltage. This behaviour was observed particularly for the SMAJ48CA device, where the measured voltage increased from 56 V to 73 V as the excitation current was raised from 50 mA to 250 mA. This confirms that the proposed measurement method does not only detect a static breakdown threshold, but also enables the evaluation of dynamic clamping behaviour under controlled pulse-energy conditions.

From the perspective of cyber-physical systems and intelligent energy applications, the developed prototype demonstrates the feasibility of integrating physical high-voltage transient generation with embedded control, signal acquisition, and local diagnostic interpretation. Such a solution is relevant for testing protection components used in power electronics, renewable energy interfaces, battery-powered sensor nodes, and other energy-related embedded systems where overvoltage protection reliability is critical.

Future work will focus on extending the voltage range of the system, improving the calibration procedure, implementing automatic current sweeping, and adding wireless telemetry for remote monitoring and data logging. These enhancements would allow the proposed platform to evolve from a standalone diagnostic prototype into a more flexible intelligent measurement node suitable for laboratory, educational, and field-deployment scenarios.

References

Baliga, B. J. (2019). *Fundamentals of power semiconductor devices*. Springer International Publishing. https://doi.org/10.1007/978-3-319-93988-9

Hodoň, M., Karpiš, O., Ševčík, P., & Kociánová, A. (2021). Which digital-output MEMS magnetometer meets the requirements of modern road traffic survey? *Sensors*, *21*(1), 266. https://doi.org/10.3390/s21010266

Karpiš, O., Olešnaníková, V., Formanek, L., Hodoň, M., Čechovič, L., Šarafín, P., & Ševčík, P. (2022). Compressed sensing – a way to spare energy in WSN for UAV. *IFAC-PapersOnLine*, *55*(4), 170–176. https://doi.org/10.1016/j.ifacol.2022.06.028

Keithley Instruments. (2016). *Optimizing pulsed semiconductor measurements with the model 2461 high current SourceMeter SMU instrument* [Application Note]. Tektronix. Beaverton, OR, USA.

Littelfuse. (2020). *P6KE series TVS diodes datasheet* [Product Data Sheet]. Littelfuse. Chicago, IL, USA.

Littelfuse. (2025). *SMAJ series surface mount TVS diodes specifications* [Product Data Sheet]. Littelfuse. Chicago, IL, USA.

Mancini, R. (Ed.). (2002). *Op amps for everyone* [Design Reference Document No. SLOD006B]. Texas Instruments. Dallas, TX, USA.

Mohan, N., Undeland, T. M., & Robbins, W. P. (2003). *Power electronics: Converters, applications, and design* (3rd ed.). John Wiley & Sons.

Vishay General Semiconductor. (2026). *1.5KE series TransZorb transient voltage suppressors datasheet* [Product Data Sheet]. Vishay Intertechnology. Malvern, PA, USA.