

Article

Failure Mechanism Analysis and Electromagnetic Protection Design of Electronic Systems Under High-Power Electromagnetic Pulse

Chenxi Huang, Jinhong Wei , Youjie Yan *, Kaiyue Zhang, Shoulong Zhang, Yifei Sun and Tongyu Wang

Northwest Institute of Nuclear Technology, Xi'an 710699, China; xi_dashao@163.com (C.H.); zhujdl11@163.com (J.W.); zhushi154111915@163.com (Y.S.)

* Correspondence: pine976@163.com

Abstract

In this paper, the failure mechanisms and electromagnetic protection design of an electronic switching system under high-power electromagnetic pulse (HPEMP) effects are studied. By integrating experimental testing and modeling simulation methods, the coupling characteristics of HPEMP energy within the electronic switching system, the response characteristics of sensitive components, and their physical failure processes were analyzed. The research indicates that the root cause of system failure under HPEMP irradiation lies in the intrusion of electromagnetic energy coupled through specific anode or gate cable ports, leading to unintended turn-on of the key thyristor device and consequent system functional failure. Mechanism analysis reveals that when the coupled voltage on the thyristor pins exceeds the gate trigger threshold, a carrier regeneration mechanism is activated within the device, resulting in polarity reversal of the PN junction and the formation of a positive feedback path, ultimately causing false triggering. Experimental and simulation results show good consistency in terms of effect thresholds. Based on these findings, effective electromagnetic protection hardening designs targeting the identified electromagnetic vulnerability paths and sensitive components were proposed, and the effectiveness of the protective measures was validated through experiments.



Academic Editor: Anna Richelli

Received: 7 September 2025

Revised: 13 October 2025

Accepted: 14 October 2025

Published: 15 October 2025

Citation: Huang, C.; Wei, J.; Yan, Y.; Zhang, K.; Zhang, S.; Sun, Y.; Wang, T. Failure Mechanism Analysis and Electromagnetic Protection Design of Electronic Systems Under High-Power Electromagnetic Pulse. *Electronics* **2025**, *14*, 4060. <https://doi.org/10.3390/electronics14204060>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: high-power electromagnetic pulse; electronic switching system; effect mechanism; semiconductor devices

1. Introduction

Thyristor-based electronic switching systems serve as critical actuation components in modern high-reliability applications, such as automotive airbag trigger circuits [1,2] and spacecraft stage separation devices [3,4]. Their precise and reliable operation directly impacts personal safety and mission success. These systems, typically designed with semiconductor switching devices, are used to rapidly and reliably control high-current switching upon specific commands, thereby driving trigger devices. However, the increasingly complex electromagnetic environment—particularly threats from lightning electromagnetic pulse (LEMP), electrostatic discharge pulse (ESD), and high-power microwave (HPM)—poses severe challenges to their security [5–9]. High-power electromagnetic pulse (HPEMP) can couple into systems via cables or apertures, inducing transient high voltages or large currents internally, which may cause unintended triggering, performance degradation, or even permanent damage to power switching devices [10–15]. Meanwhile, HPEMP can induce local thermal effects on

semiconductor devices, leading to permanent failure such as device melting and burnout. In scenarios like enclosed power switchgears and spacecraft equipment cabins, such thermal effects are highly likely to trigger secondary safety hazards including insulation combustion and toxic gas leakage [16–18].

Extensive research has been conducted domestically and internationally on the effects of HPEMP on various typical electronic systems, covering multiple technical approaches from experimental characterization to modeling and simulation [19–24]. In terms of experiments, existing studies primarily employ irradiation and injection methods: Irradiation tests often focus on correlating system-level failure thresholds with parameters such as field strength, repetition frequency, pulse width, and orientation; for instance, in Reference [25], ultra-wideband high-power electromagnetic (UWB-HPHEM) pulse irradiation tests were conducted on a microcontroller, and temporary functional anomalies of the microcontroller occurred when the electric field strength reached 8.9 kV/m. Injection tests are mainly used to locate sensitive components, identify critical coupling paths, and obtain port coupling parameters along with corresponding effect thresholds; for example, in Reference [26], double-exponential pulse current injection was performed on a shortwave receiving antenna system, and the antenna system output an interference signal with an amplitude ≤ 3 V and a duration of approximately 6 μ s under interference. In terms of modeling and simulation, mainstream field-circuit co-simulation techniques are often applied to analyze front-door coupling, reproducing the behavioral responses of systems and devices, such as in Reference [27], where the effect of high-power microwave interference on missile radio fuzes was studied via simulation methods—while device-level simulations explore microscopic processes such as carrier transport, junction ionization, and feedback pathway establishment under HPEMP exposure from a physical mechanism perspective. However, most existing studies rely on a single experimental or simulation method, lacking a systematic multi-methodology synergy for analyzing electronic system effect mechanisms, which hinders effective support for protection hardening design and validation.

In this paper, we select a typical thyristor-based electronic switching system and employ integrated experimental and simulation approaches to investigate its failure mechanisms and protection hardening methods under HPEMP exposure. The structure of the remainder of this paper is organized as follows: Section 2 identifies and validates the electromagnetic vulnerability paths of the switching system using three methods—irradiation tests, numerical simulations, and injection tests—and obtains effect thresholds for port coupling parameters. Section 3 reveals the turn-on mechanism of the core switching device, the thyristor, under HPEMP exposure through device modeling and simulation. Section 4 develops targeted electromagnetic protection designs based on the identified vulnerability paths and sensitive components, and validates the effectiveness of the protection measures experimentally. Finally, Section 5 provides a conclusion of this study.

2. Experimental Investigation of HPEMP Effects on a Typical Electronic Switching System

2.1. System-Level Irradiation Experiments

The irradiation experimental setup for a typical electronic switching system exposed to HPEMP is shown in Figure 1. The experimental system consists of the following equipment: a radiation source, a radiating antenna, the test switching system, a low-dielectric-constant support structure, an effect monitoring system, and a radiation field measurement system.

The electronic switching system adopts a double-layer printed circuit board (PCB) architecture. The upper layer contains a radio frequency (RF) front-end module, which can be connected to various types of antennas to receive target attitude signals and transmit them to the back-end signal processing unit. The lower layer primarily comprises a signal processing

unit and a trigger circuit, responsible for processing and logically evaluating the front-end signals to determine whether they meet the preset switching threshold conditions. Ultimately, the trigger circuit outputs a pulse signal to drive the switching element into conduction.

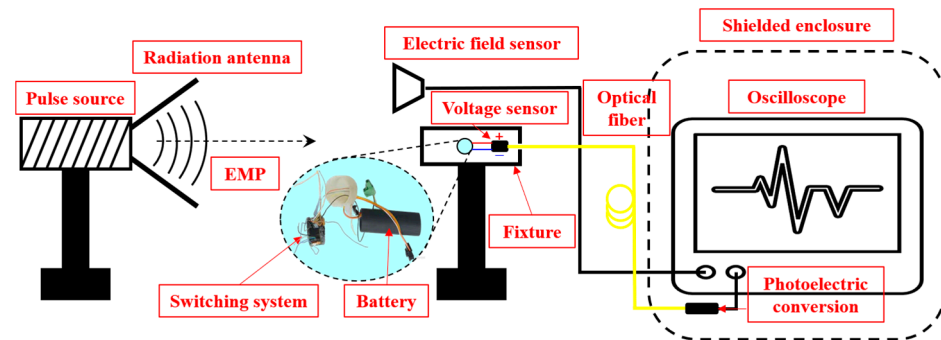


Figure 1. Schematic diagram of the irradiation experiment setup.

During the experiment, the radiating antenna, excited by the radiation source, established a transient electromagnetic environment in space. The radiation field measurement system, consisting of an electric field sensor, an electro-optic converter, and an oscilloscope, was used to measure the spatial electric field strength. The effect monitoring system, composed of a coupled voltage probe and an electro-optic converter, determined whether a malfunction occurred by capturing the output signal of the trigger circuit. To suppress field distortion caused by metal scattering, the test switching system was mounted on a low-dielectric-constant support, and signals collected by the coupled voltage probe were transmitted via optical fiber. The output load of the switching system circuit was equivalently replaced by a resistive load, and the system was powered by a lithium battery to ensure experimental repeatability. The experimental parameters were set as follows: radiation source trigger repetition frequency of 30 Hz, irradiation duration of 1 s, and the long axis of the switching system aligned with the direction of wave propagation.

The irradiation results shown in Table 1 indicate that when the electric field strength reached 6 kV/m, the failure probability of the switching system increased significantly to 85%. Therefore, 6 kV/m is identified as the system's failure effect threshold. In the experiment, the physical connection of the cable to the equivalent resistive load at the output of the trigger circuit was consistent with the actual operational conditions, ensuring that the introduction of the coupled voltage probe did not disturb the original signal transmission path. To accurately identify whether cables, PCB traces, and device pins form critical electromagnetic coupling paths, it is usually necessary to monitor the coupled signals at corresponding ports or circuit nodes in real time. However, directly connecting physical monitoring lines would inevitably alter the system's original electromagnetic coupling characteristics, leading to distorted measurements of coupled voltage. Due to this measurement limitation, the irradiation experiment could not directly quantify the port response characteristics of critical paths. Therefore, this study employs full-wave electromagnetic simulation to further identify the primary pathways of HPEMP energy coupling.

Table 1. Irradiation experiment results.

Field Level (kV/m)	Number of Experiments	Failure Probability (%)
3	5	0 (0/5)
6	20	85 (17/20)

2.2. Numerical Simulation Experiment

The numerical simulation experiment employed a field-circuit co-simulation approach, integrating a three-dimensional electromagnetic field solver with a circuit simulator to achieve transient interaction modeling between electromagnetic fields and circuits. The electromagnetic domain solved Maxwell's equations to obtain spatial field distributions and cable coupling parameters, while the circuit domain computed device responses, with data exchange facilitated through port interfaces. Virtual probes were used to directly extract current density distributions on the circuit board surface, spatial field distributions, and voltages at key nodes, thereby avoiding the issues associated with physical probing in irradiation experiments.

2.2.1. Modeling Considerations

Focusing on identifying the coupling pathways of HPEMP, the numerical simulation modeling incorporated the following considerations:

(1) Simplified Modeling of the Front-End RF Circuit Module

HPEMP coupling mechanisms are primarily categorized into front-door and back-door coupling. For electronic systems, front-door coupling mainly causes informational interference: since the back-end processing circuit employs strict logic discrimination for input signals, most front-door coupled interference only affects front-end components. When interference signals propagate to the back-end circuit, their amplitude is generally insufficient to trigger a malfunction. Studies indicate that only when front-door coupled signals exhibit specific characteristics (e.g., pulse width, modulation mode, frequency domain properties) can they potentially cause unintended triggering of the switching system [27]. These signal characteristics are highly dependent on the frequency band and transceiver architecture of the RF front-end antenna, exhibiting significant system-specificity, resulting in a low probability of front-door coupling-induced malfunctions and a lack of generalizability. In contrast, back-door coupling infiltrates the system through apertures and cables, directly affecting the back-end trigger output circuit in the form of conducted energy interference [28]. This coupling mechanism exhibits universal sensitivity to factors such as circuit board layout and cable topology, enabling the derivation of general conclusions.

The modeling strategy for this part is: ① neglect the cable coupling path from the RF circuit to the signal processing circuit; ② retain the geometric structure and copper layers of the circuit board to ensure field distribution authenticity; ③ omit the internal device circuit models of the RF circuit board.

(2) Selective Modeling of the Back-End Signal Processing Circuit Module

As a precision system, the electronic switching system features a highly complex back-end signal processing circuit, making complete modeling of signal transmission integrity between modules challenging. The absence of models for numerous nonlinear devices in the circuit leads to incomplete signal transmission modeling, while accurate characterization of port impedances at inter-module cable connections also affects the accuracy of port responses. Since the primary objective of this numerical simulation is to identify coupling paths, and peripheral circuit modules of the trigger circuit have limited impact on critical coupling paths, simplified modeling was applied to these peripheral modules, with emphasis placed on modeling the trigger circuit module and cables.

The modeling strategy for this part is: ① Prioritize modeling of inter-board cables and simplify the port impedance modeling of some modules. Cables are modeled based on their physical dimensions and materials. For circuit modules connected behind cable ports, the routing topology of all signal and dielectric layers, via interconnect structures, and the

parameters and layout information of all RLC components are fully retained. For nonlinear components, some are modeled by importing SPICE models or substituting with similar SPICE devices. If certain models are indeed unavailable, they are equivalent to a 50-ohm lumped parameter to maintain electrical connection integrity. ② Prioritize modeling the execution-stage circuit module, constructing this module completely. For modeling the sensitive thyristor device, since its SPICE model does not account for impedance characteristics across a wide frequency range, its S-parameters for the anode-cathode and gate-cathode ports were measured from 9 kHz to 3 GHz using a Vector Network Analyzer (VNA). Based on this, a multi-port impedance network model was created and imported into the full-wave simulation model. It should be noted that while the current circuit model achieves broadband equivalence at the impedance level, its behavioral logic does not encompass the nonlinear response under transient pulses. This simplification aims to prioritize the accuracy of port coupling parameter calculations.

2.2.2. Model Construction

Based on the precise dimensions of the physical switching system, a three-dimensional electromagnetic simulation model was constructed in 3D Electromagnetic Simulation Software (CST 2024), with the PCB design files imported into their corresponding positions. The full-wave simulation model is shown in Figure 2a.

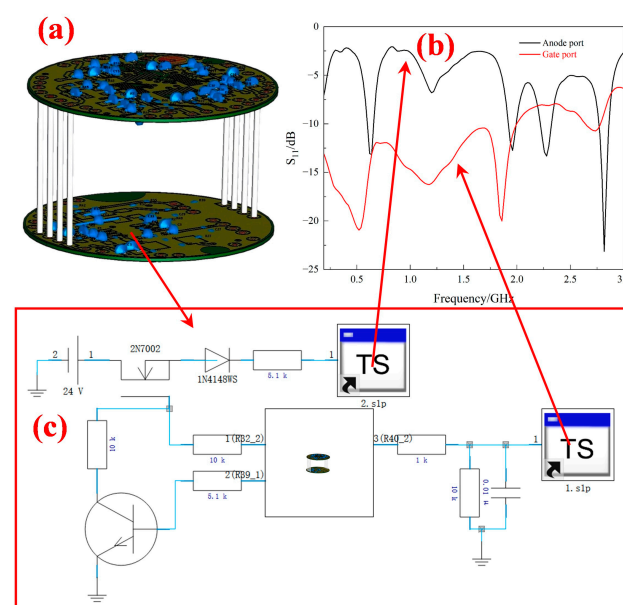


Figure 2. Field-Circuit Co-Simulation model: (a) 3D electromagnetic simulation model, (b) S-Parameters of the Anode–Gate port, and (c) trigger circuit model.

The trigger circuit model was built by the circuit simulation module in the Software, where the thyristor was characterized using a two-port network equivalent model. Its S-parameters between anode-cathode and gate-cathode were measured using a vector network analyzer, as shown in Figure 2b,c (TS1 represents S₁₁ for gate-cathode, TS2 represents S₁₁ for anode-cathode). The core advantage of this modeling strategy lies in accurately replicating the device's high-frequency response through experimentally calibrated broadband impedance characteristics, thereby enhancing the accuracy of port coupling parameters in field-circuit coupling simulations. The acquisition of thyristor S-parameters was accomplished using a device test board designed with microstrip line structures controlled to 50-ohm impedance, connected to the vector network analyzer via SMA connectors to minimize measurement errors. For cable-PCB interconnection ports, due to the lack of a standard TEM wave transmission path in the actual structure,

direct measurement of input impedance would cause significant mismatch errors; hence, experimental testing was not used for port impedance equivalence.

In the full-wave simulation setup, the excitation waveform was employed using the monitored field waveform from the irradiation experiments. A plane wave irradiation with a peak field strength of 6 kV/m was applied. Spatial field probes, surface current probes, and cable port voltage probes were set up to acquire the simulation results.

2.2.3. Results and Analysis

As shown in Figure 3, the simulation results are presented. In Figure 3a, the magnitude and waveform of the cable port coupling are displayed. It can be observed that under irradiation at this field strength, the coupling voltage at the cable port is on the order of hundreds of volts, approximately 776 volts. The cable length set in the simulation is consistent with that of the physical prototype, which is 20 mm. In Figure 3b, the spatial field distribution is shown, indicating a stronger electric field around the inter-board cables compared to the trace areas on the circuit board (approximately 5 dB higher). In Figure 3c, the surface current distribution on the trigger circuit PCB is illustrated, revealing high induced current density around the thyristor pins and adjacent regions, highlighting the thyristor as a sensitive component requiring special attention. Meanwhile, we also observed the variation in the cable port coupling voltage by changing the cable length: when the simulated cable length was 10 mm, the port coupling voltage decreased to 392 V, and the difference between the two (20 mm and 10 mm) is significant, indicating that cable length has a substantial impact on HPEMP coupling parameters.

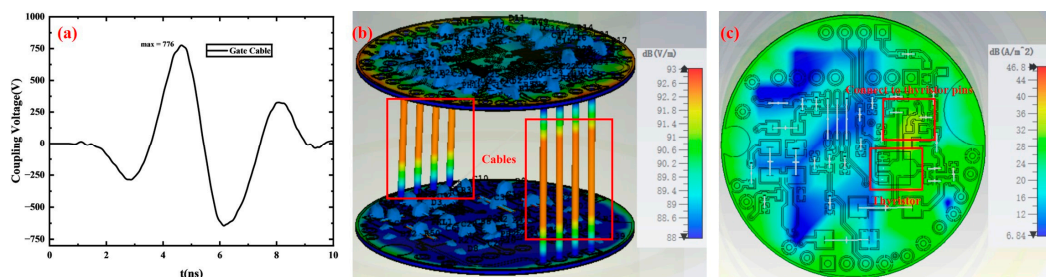


Figure 3. Simulation results: (a) cable port coupling parameters, (b) spatial electric field distribution, and (c) surface current distribution on the PCB.

In summary, both the cable port coupling voltage and field distribution results indicate that cables are a critical pathway for HPEMP coupling, and cable length exerts a significant influence on the coupling magnitude. The surface current distribution suggests strong signal coupling may occur around the sensitive thyristor device. By further analyzing the switching system structure and circuit schematic, the key coupling paths were identified: the gate of the core switching device (thyristor) is connected via PCB traces to the signal cable port (leading to the upper board), while its anode is connected through a diode-FET cascaded path to the power cable port (leading to the upper board). Given the high sensitivity of the thyristor's turn-on characteristics to transient pulses—where either a gate trigger signal or anode overvoltage can cause unintended turn-on—it is highly probable that the anode power cable and the gate signal cable serve as the primary interference coupling channels.

It is worth noting that the conventional turn-on parameters of the thyristor are typically on the microsecond scale, whereas the interference signals coupled from HPEMP to the cables are expected to be on the nanosecond scale. In terms of time scale, such signals are far below the device's nominal turn-on threshold. However, unintended turn-on phenomena were still observed in experiments. This suggests that the amplitude of the HPEMP-

induced coupled voltage may significantly exceed the critical turn-on value of the thyristor, potentially exceeding the limitations of conventional turn-on models through nonlinear mechanisms such as dielectric breakdown or carrier avalanche multiplication. This aspect also necessitates injection experiments to quantify the thyristor's turn-on characteristics under transient pulse conditions.

2.3. Injection Experiments

Based on the critical coupling paths identified in the numerical simulations, we conducted the injection experiments, which include system-level bulk current injection and device-level voltage injection on the core switching device (thyristor). These experiments aimed to validate the simulation results and further investigate the malfunction mechanism of the switching system and the response of the thyristor under transient pulses.

2.3.1. System-Level Bulk Current Injection Experiment

The BCI technique utilizes a non-contact current injection probe to induce currents on target cables, simulating common-mode interference coupling under intense electromagnetic field irradiation. The probe acts as a mutual inductor, converting radio frequency interference signals into common-mode currents in the cable harness through electromagnetic induction. These currents propagate along the cable to the ports of the equipment under test, replicating the physical process of energy coupling into the system via cables in an irradiated environment. For this study, BCI effectively simulated the coupling signals induced on cables by HPEMP.

The current injection experiment was conducted using a high-voltage pulse source as the excitation, as illustrated in Figure 4. A current injection clamp (400 MHz) was used for injection, a current monitoring clamp (500 MHz) for monitoring the injected current, a high-impedance oscilloscope probe (400 MHz) for measuring the terminal coupled voltage on the cable, and a line impedance stabilization network (LISN) was employed to protect the power supply and match impedances.

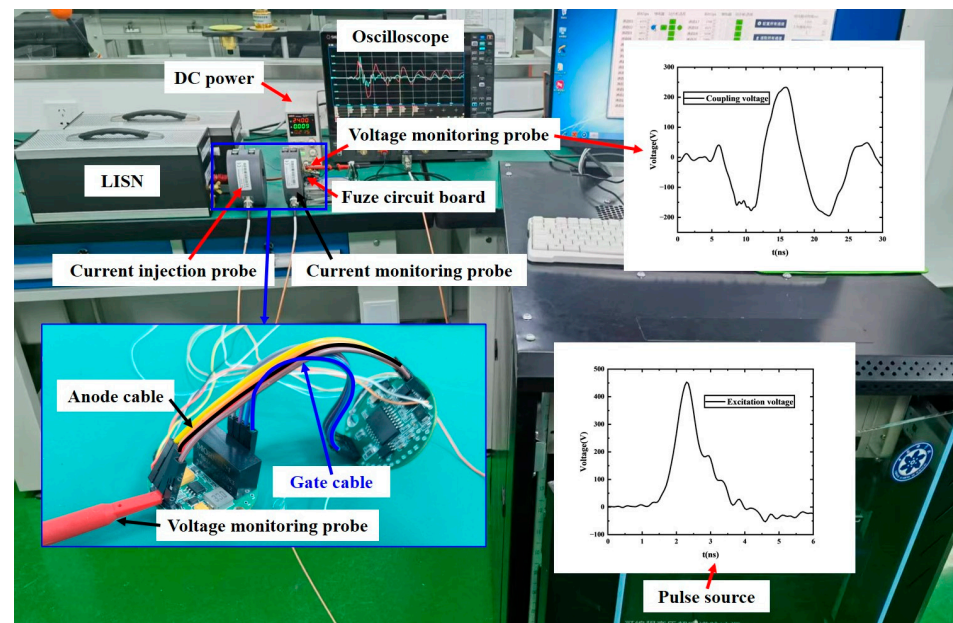


Figure 4. Current injection experiment setup.

Current injection was performed on individual cables. The output amplitude of the pulse source was gradually increased from low to high levels, and we monitored whether the electronic system experienced unintended turn-on. The thyristor cathode was grounded;

a transition of the anode potential to 0 V was considered indicative of system malfunction. To prevent the cumulative effect of HPEMP damage on the thyristor, a new thyristor was replaced for subsequent experiments once two instances of unintended turn-on occurred during the tests.

(1) Anode Cable Injection

As shown in Table 2, under the maximum output voltage of the pulse source, 20 tests were conducted, with unintended turn-on observed in 3 instances. Thus, the effect threshold due to coupling at the anode cable port was determined to be above 2.1 kV.

Table 2. Injection test results 1.

Thyristor Number	Average Coupling Voltage (kV)	Thyristor Unintended Turn-on Probability (%)	
1	2.12	20 (1/5)	15 (3/20)
2	2.11	20 (1/5)	
3	2.10	0 (0/5)	
4	2.11	20 (1/5)	

(2) Gate Cable Injection

Results in Table 3 show that the unintended turn-on threshold caused by coupling at the gate cable port was approximately 613 V.

Table 3. Injection test results 2.

Thyristor Number	Average Coupling Voltage (V)	Thyristor Unintended Turn-on Probability (%)	
5	556	66.6 (2/3)	57 (4/7)
6	552	50 (2/4)	
7	612	100 (2/2)	
8	614	100 (2/2)	100 (10/10)
9	615	100 (2/2)	
10	613	100 (2/2)	
11	613	100 (2/2)	

(3) Other Cable Injections

The remaining cables—one power line, one ground line, and four signal lines—were tested under worst-case injection conditions. No unintended turn-on was observed in any of these experiments.

The system-level BCI experiments demonstrated that the effect voltage threshold for the anode power cable port exceeds 2.1 kV, while the threshold for the gate signal cable port is about 613 V. Other cables were not considered critical coupling paths. The results confirm that both the anode and gate coupling paths can lead to unintended turn-on in the switching system, and that the noise immunity of the anode cable is significantly higher than that of the gate path (threshold difference approximately 3.3 times).

2.3.2. Device-Level Voltage Injection Experiment

Based on the analysis of the switching system's trigger circuit operation, the thyristor, as the core switching device, controls the discharge process of the energy storage capacitor. If HPEMP can cause the thyristor to turn on unintentionally, it may lead to abnormal discharge of the energy storage capacitor, resulting in system-level failure. Therefore, a device-level voltage injection experiment was conducted to quantitatively characterize

the turn-on characteristics of the thyristor under nanosecond-level transient pulses and to investigate its malfunction threshold and failure mechanism.

In accordance with the gate trigger condition test recommendations for thyristors outlined in IEC 60747-6, a test PCB was designed as shown in Figure 5a. In the test circuit, the thyristor anode was connected to a DC +12 V supply, the cathode to ground, and the gate to the positive terminal of an SMA port, with the SMA negative terminal grounded. The excitation voltage was injected into the thyristor gate through the SMA port. Oscilloscope Channel 1 was used to acquire the excitation signal, and Channel 2 was used to measure the anode voltage of the thyristor.

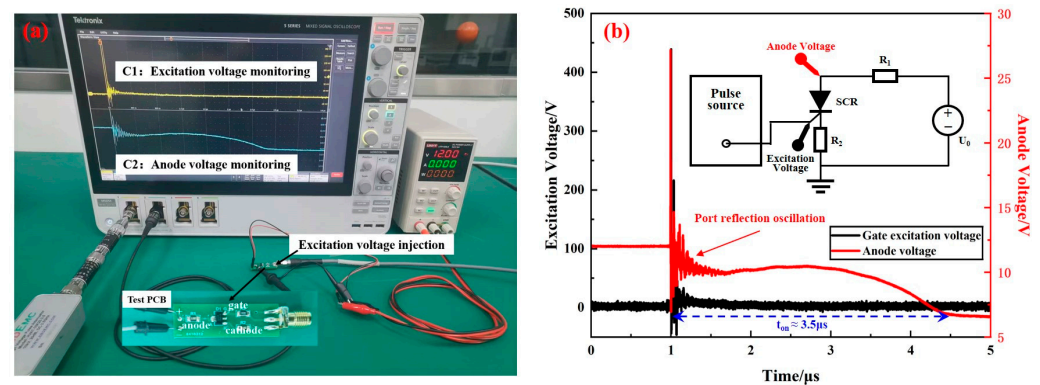


Figure 5. Voltage injection experiment setup and results: (a) experiment setup and (b) thyristor turn-on characteristic curves.

When the pulse source applied voltages of different amplitudes, we observed the turn-on status of the thyristor. The criterion for thyristor turn-on was a drop in the anode voltage from 12 V to 6 V due to resistive voltage division after conduction. The typical excitation waveform from the voltage source was generally consistent with the waveform shown in Figure 5b. To investigate the sensitivity of the thyristor gate to pulse polarity, injection experiments were conducted using both positive and negative pulses.

As shown in Table 4, when a positive-polarity pulse with a peak value of approximately 452 V was injected into the thyristor gate, turn-on occurred, as illustrated in Figure 5b, with a turn-on duration of about 3.5 microseconds. Under the same experimental conditions, no turn-on response was observed for negative-polarity pulse injection.

Table 4. Injection test results 3.

Thyristor Number	Average Coupling Voltage (V)	Thyristor Unintended Turn-on Probability (%)
12	402	0 (0/5)
13	452	100 (2/2)
14	452	100 (2/2)
15	451	100 (2/2)
16	451	100 (2/2)
17	452	100 (2/2)
18	−451	0 (0/10)

2.4. Comparison of Experimental Results

The results obtained from the irradiation experiments, numerical simulations, device-level voltage injection experiments, and system-level current injection experiments are summarized as Table 5. The irradiation tests yielded a system-level unintended turn-on field strength threshold of 6 kV/m. Under equivalent field strength input (6 kV/m), the numerical simulation extracted a peak coupled voltage of 776 V at the thyristor gate cable port. The device-level

voltage injection experiment, employing direct port excitation, measured a thyristor unintended turn-on voltage threshold of 452 V. The system-level current injection experiment, conducted via cable coupling injection, obtained a measured gate port voltage threshold of 613 V. Furthermore, the critical coupling paths and sensitive components identified in the numerical simulations were validated through the injection experiments.

Table 5. Effect thresholds for each experiment.

Simulation Experiment	Voltage Injection Experiment	Current Injection Experiment
776	452	613

While the above experimental framework determined the unintended turn-on field strength threshold and port voltage thresholds of the switching system under HPEMP exposure, it could not elucidate the underlying turn-on mechanism of the thyristor under nanosecond-level transient pulses. Therefore, further investigation was carried out using the Technology Computer-Aided Design (TCAD) software (Silvaco 2019) to construct a two-dimensional thyristor model. This aims to explore carrier transport characteristics during high-field transient events and lay the foundation for establishing a theoretical framework linking microscopic carrier dynamics to macroscopic failure behavior.

3. Simulation Study on Turn-On Characteristics of Thyristors Under HPEMP

3.1. Basic Structure and Characteristics of Thyristors

A unidirectional thyristor is a four-layer, three-terminal (P-N-P-N) semiconductor power device. Its unique topology, formed by three critical PN junctions, endows it with controllable unidirectional conduction characteristics, making it a core switching component in power electronics. As shown in Figure 6a, the three electrodes are defined as follows: the anode (A) is connected to the outermost P-type semiconductor layer, the cathode (K) to the outermost N-type semiconductor layer, and the gate (G) to an internal P-type semiconductor layer. This three-terminal design enables the thyristor to combine the unidirectional conductivity of a diode with gate-triggered controllability. When a forward bias is applied to the anode relative to the cathode, junctions J_1 and J_3 are forward-biased, while junction J_2 is reverse-biased. Under this condition, only a microampere-level off-state leakage current flows, and the device remains in the forward blocking state. When a sufficient gate trigger current is injected, a carrier regeneration positive feedback mechanism causes junction J_2 to transition from reverse bias to forward bias. All three PN junctions then conduct simultaneously, forming a low-resistance path and switching the device to the on-state. The anode current is limited by the external circuit impedance. Maintaining the on-state requires two conditions: the anode current must exceed the latching current (the critical value that sustains self-locking after the gate signal is removed) and remain above the holding current. Otherwise, a decrease in carrier concentration will restore the depletion layer of junction J_2 , returning the device to the blocking state. When the cathode voltage is higher than the anode voltage, junction J_2 is forward-biased, while junctions J_1 and J_3 are reverse-biased, causing the device to exhibit reverse blocking characteristics with only a reverse leakage current [29]. Once the thyristor is turned on, it enters a self-locking state, and the gate loses control over its operation. The switching mechanism and typical current-voltage (I–V) characteristics are illustrated in Figure 6b [30].

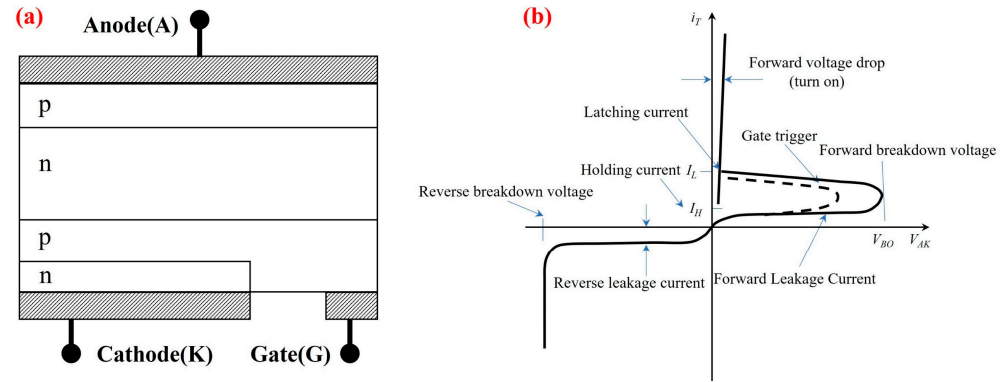


Figure 6. Basic structure and characteristics of the thyristor: (a) typical device structure and (b) typical I-V characteristic curve.

3.2. Fundamental Principles of Thyristor Turn-On

The turn-on mechanism of a thyristor can be analyzed using its equivalent inter-coupled dual transistor model. The thyristor is conceptualized as two inter-coupled transistors [31]: Q_1 , a PNP transistor, and Q_2 , an NPN transistor, with the specific structure shown in Figure 7a,b. The collector current I_C of a transistor is related to its emitter current I_E and the collector-base junction leakage current I_{CBO} by the following relationship:

$$I_C = \alpha I_E + I_{CBO} \quad (1)$$

where the common-base current gain is defined as $\alpha \approx I_C/I_E$. For transistor Q_1 (PNP), the emitter current is the anode current I_A . Its collector current I_{C1} can be derived from Equation (1):

$$I_{C1} = \alpha_1 I_A + I_{CBO1} \quad (2)$$

where α_1 and I_{CBO1} are the current gain and leakage current of Q_1 , respectively. Similarly, for transistor Q_2 (NPN), the collector current I_{C2} is:

$$I_{C2} = \alpha_2 I_K + I_{CBO2} \quad (3)$$

where α_2 and I_{CBO2} are the current gain and leakage current of Q_2 , respectively, and I_K is the cathode current. Combining I_{C1} and I_{C2} , and noting their relationship within the coupled structure, we get:

$$I_A = I_{C1} + I_{C2} = \alpha_1 I_A + I_{CBO1} + \alpha_2 I_K + I_{CBO2} \quad (4)$$

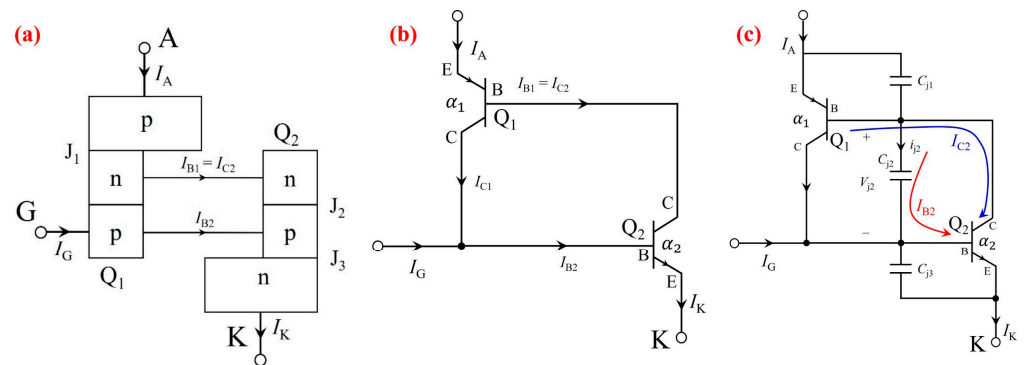


Figure 7. Dual transistor model of the thyristor: (a,b) Basic structure, (c) Equivalent structure under transient conditions.

Considering the gate current I_G , the cathode current is $I_K = I_A + I_G$. Substituting and solving for I_A yields:

$$I_A = \frac{\alpha_2 I_G + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)} \quad (5)$$

The current gains α_1 and α_2 vary with the anode current I_A and the gate current I_G , respectively. If a gate trigger signal is applied, the anode current I_A increases rapidly, causing α_1 and α_2 to rise. An increase in α_1 and α_2 further promotes the increase of I_A , creating a positive feedback effect. If $\alpha_1 + \alpha_2$ approaches 1, Equation (5) indicates that the anode current I_A becomes very large, leading to the turn-on of the thyristor.

The influence of PN junction capacitances on thyristor characteristics must be considered during transient processes. As shown in Figure 7c, if the thyristor is in its blocking state, a transient pulse with a fast rise time applied across the device will cause a large current to flow through the junction capacitances.

The current flowing through the junction capacitance C_{j2} of junction J_2 can be expressed as:

$$i_{j2} = \frac{d(q_{j2})}{dt} = \frac{d}{dt}(C_{j2}V_{j2}) = V_{j2}\frac{dC_{j2}}{dt} + C_{j2}\frac{dV_{j2}}{dt} \quad (6)$$

where C_{j2} and V_{j2} are the capacitance and voltage across junction J_2 , respectively; q_{j2} is the charge in the base region of transistor Q_2 . Junction J_2 , being reverse-biased in the blocking state, has a wide space charge region. When the rate of voltage rise (dv/dt) is high, its substantial junction capacitance generates a large transient displacement current. Junctions J_1 and J_3 are in a forward-biased state, possess much smaller junction capacitances, and thus contribute negligible displacement current under the transient voltage. When this displacement current i_{j2} becomes sufficiently large, Equation (6) shows that it effectively acts as a gate trigger signal. This initiates the positive feedback process described earlier, leading to the unintended or false turn-on of the thyristor [29].

3.3. Investigation of Thyristor Turn-on Mechanism Under Transient Pulse Effects

The nominal turn-on characteristic parameters of conventional unidirectional thyristors primarily describe their electrical response on microsecond timescales. However, these parameters are insufficient for characterizing the dynamic behavior of the device under nanosecond-level transient pulse excitation, particularly the false turn-on mechanism under HP EMP effects. Existing research predominantly focuses on the experimental observation of macroscopic patterns in thyristors under transient stress [32], but lacks systematic exploration of the turn-on mechanism at the physical microscopic level. This study utilizes TCAD to construct a thyristor device model. By solving the coupled Poisson's equation, carrier continuity equations, and energy transport equation, it aims to reveal the microscopic physical picture of carrier transport and energy conversion within the device under ns-level strong-field excitation, providing mechanism-level support for the HP EMP protection design of electronic switching systems.

3.3.1. Device Structure

A two-dimensional device model was constructed based on the four-layer PNP structure of a thyristor, with the specific structure shown in Figure 8.

Model Doping Process:

- ① Substrate Preparation: A uniformly doped common base region (N-type, concentration $1 \times 10^{14}/\text{cm}^{-3}$) was formed across the entire area, serving as the interconnection for the two transistors.

- ② PNP Emitter Formation: Gaussian P-type doping (concentration $5 \times 10^{19}/\text{cm}^{-3}$) was performed in the top region ($0 < x < 100$ micrometers, $162 < y < 180$ micrometers) to form the PNP transistor emitter.
- ③ NPN Base Formation: Gaussian P-type doping (concentration $1 \times 10^{16}/\text{cm}^{-3}$) was performed in the mid-lower region ($0 < x < 100$ micrometers, $16 < y < 25$ micrometers) to form the NPN transistor base.
- ④ NPN Emitter Formation: Gaussian N-type doping (concentration $5 \times 10^{18}/\text{cm}^{-3}$) was performed in the bottom region ($0 < x < 50$ micrometers, $0 < y < 16$ micrometers) to form the NPN transistor emitter.

Electrode Configuration:

- ① Anode: Top region, $0 < x < 100$ micrometers.
- ② Cathode: Bottom surface region, $0 < x < 50$ micrometers.
- ③ Gate: Bottom surface region, $80 < x < 100$ micrometers.

PN Junction Locations:

- ① J_1 Junction: $y = 16$ micrometers (NPN emitter–base interface).
- ② J_2 Junction: $y = 25$ micrometers (NPN base–common base interface).
- ③ J_3 Junction: $y = 162$ micrometers (PNP emitter–common base interface).

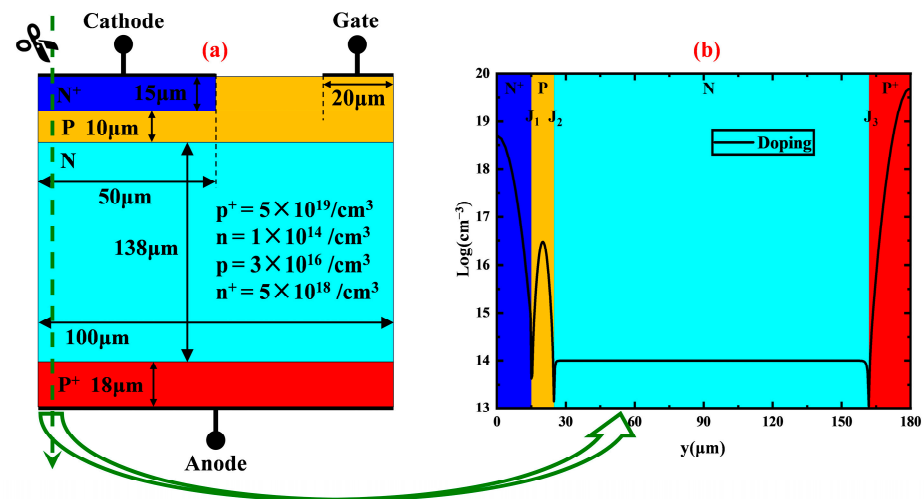


Figure 8. Thyristor Device Model: (a) Device Structure and (b) Doping Parameters.

3.3.2. Simulation Results and Mechanism Analysis

(1) Gate Transient Pulse Excitation

Based on the device-level voltage injection experimental design and results, a positive-polarity square wave was applied to the gate to simulate the transient pulse, with a peak value of 450 V, a rise time of 0.3 nanoseconds, and a pulse width of 1.5 nanoseconds. The simulation circuit layout was consistent with the injection test board design. The results in Figure 9 indicate that under the excitation of this transient pulse, the thyristor turned on with a duration of approximately 3.5 microseconds, which is in good agreement with the voltage injection test results described in Section 2.3.2.

In the initial state, with a forward bias voltage applied between the thyristor anode and cathode, junctions J_1 and J_3 are forward-biased, forming narrow depletion layers. The peak electric field strength is about 4×10^4 V/cm, concentrated mainly at the J_1 junction interface, dominated by the space charge distribution of ionized donor/acceptor ions. Junction J_2 is reverse-biased, forming a wide space charge region (SCR) of about 20 micrometers. The carrier concentration within this region is below $10^6/\text{cm}^{-3}$, far less than the doping concentration on the order of $10^{14}/\text{cm}^{-3}$. The peak electric field strength is as high as 1.7×10^5 V/cm. This high-field region becomes the key physical site for subsequent turn-on triggering (Figure 10a). At this stage, carrier transport is dominated by

thermally generated equilibrium carriers from impurity ionization, and the device exhibits high impedance characteristics.

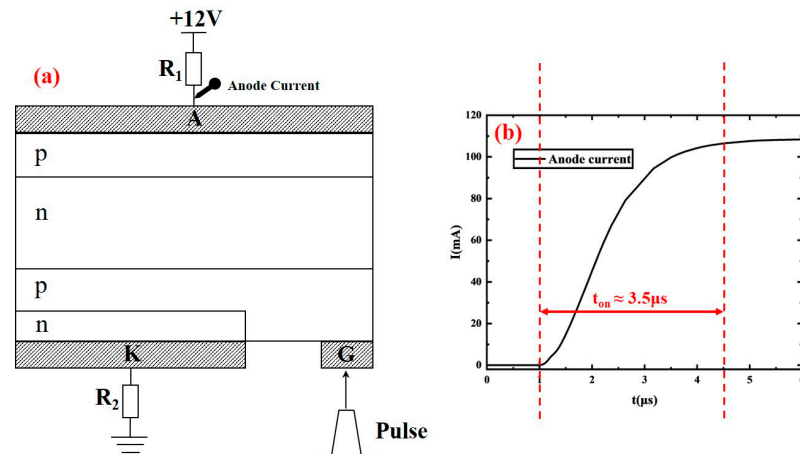


Figure 9. Simulation parameter settings and results: (a) equivalent circuit for simulation and (b) simulation results of thyristor turn-on characteristics.

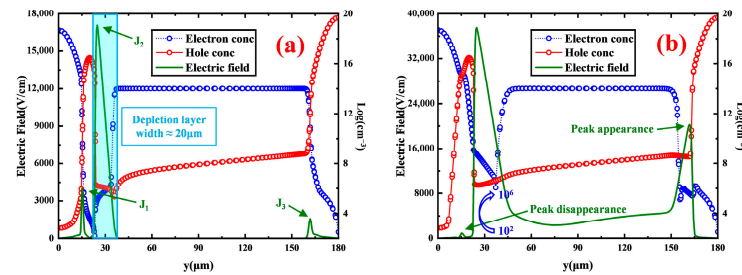


Figure 10. Electric field and carrier concentration simulation results: (a) 0 nanoseconds and (b) 0.4 nanoseconds.

When a positive-polarity transient pulse is applied to the gate, injected electrons diffuse through the P base region to the boundary of the N⁺ base. This process significantly reduces the potential barrier height of the J₁ junction, causing the original electric field spike of 4×10^5 V/cm at the J₁ junction to basically disappear (Figure 10b). As electrons enter the high-field region of the J₂ junction, they gain kinetic energy exceeding the silicon bandgap under the acceleration of the strong electric field. This leads to the generation of a large number of electron-hole pairs through the impact ionization process, increasing the electron concentration in the N region from an initial $10^2/\text{cm}^{-3}$ to $10^6/\text{cm}^{-3}$. The newly generated electrons drift towards the N region under the influence of the J₂ junction electric field, while holes drift towards the N⁺ region. Macroscopically, this gradually forms the initial collector current I_{C2} of the NPN transistor. Electrons reaching the J₃ junction trigger hole injection from the anode region. The electron-hole concentration difference near the J₃ junction gradually increases, leading to the emergence of a peak electric field strength.

During the actual trigger pulse injection process, considering factors such as the pulse front, peak value, and the electron concentration gradient in the depletion region, the number of electrons diffusing into the depletion region in the initial time state is limited. The carrier concentration at this stage is still much lower than the doping concentration. The internal electric field strength is still dominated by donor and acceptor ions, and the positive feedback flow of carriers has not yet been established. The device remains in a high-impedance state. Macroscopically, the collector current I_C of the NPN transistor is very weak at this point, insufficient to drive the base of the PNP transistor to form positive feedback. Only a weak current flows between the anode and cathode.

As the gate transient pulse continues to be injected, the internal carrier positive feedback process begins to establish. In this process, the drift of electrons forms the initial collector current I_{C2} of the NPN transistor. After the electrons from I_{C2} enter the N^+ region, they lower the J_1 junction potential barrier. Holes are injected from the P^+ anode region into the N region, forming the emitter current I_{E1} of the PNP transistor. The holes injected into the N region then diffuse to the P region, becoming the collector current I_{C1} of the PNP transistor. The holes from I_{C1} entering the P region further increase the base current I_{B2} of the NPN transistor. The increase in both I_{C2} and I_{B2} in turn injects more electrons into the N^+ region, promoting hole injection in the PNP transistor. This forms a positive feedback loop. As the positive feedback process proceeds, the carrier concentrations in the P and N regions continuously rise. When the carrier concentration difference in the N region exceeds the doping concentration, the J_2 junction switches from reverse bias to forward bias, and conduction between the anode and cathode begins gradually. Due to the lack of gate-injected electrons, the carrier concentration difference at J_1 and J_3 tends to equalize, the peak electric fields on both sides disappear, and the internal regions transform into low-field strength areas. Because the saturated electron drift velocity is higher than that of holes, a hole accumulation layer forms near the J_2 junction, creating a residual peak electric field. When the electron injection rate and the hole recombination rate reach a dynamic balance, the device completes the transition to the on-state [33].

Figure 11 presents the simulation results of the device turn-on process under HPEMP injection conditions. Figure 11a shows the two-dimensional distribution of the electric field and conduction current density. During the pulse action period ($t < 1.5$ nanoseconds), a significant increase in electric field and current density is observed near the gate region, indicating the gradual establishment of a positive feedback process. By $t = 40$ nanoseconds, the positive feedback continues to develop, and the device begins to turn on progressively. At $t = 4$ microseconds, the device reaches full conduction, characterized by a reduced internal electric field strength and a uniformly high current density throughout the structure. Figure 11b illustrates the variation in current density along the y-direction over time. The continuously increasing trend reflects the progressive completion of the device turn-on process. Figure 11c displays the electric field distribution along the y-direction after turn-on. The overall field strength remains at a low level, with a peak observed near Junction J_2 . This peak is caused by hole accumulation resulting from the higher electron drift velocity compared to the hole drift velocity.

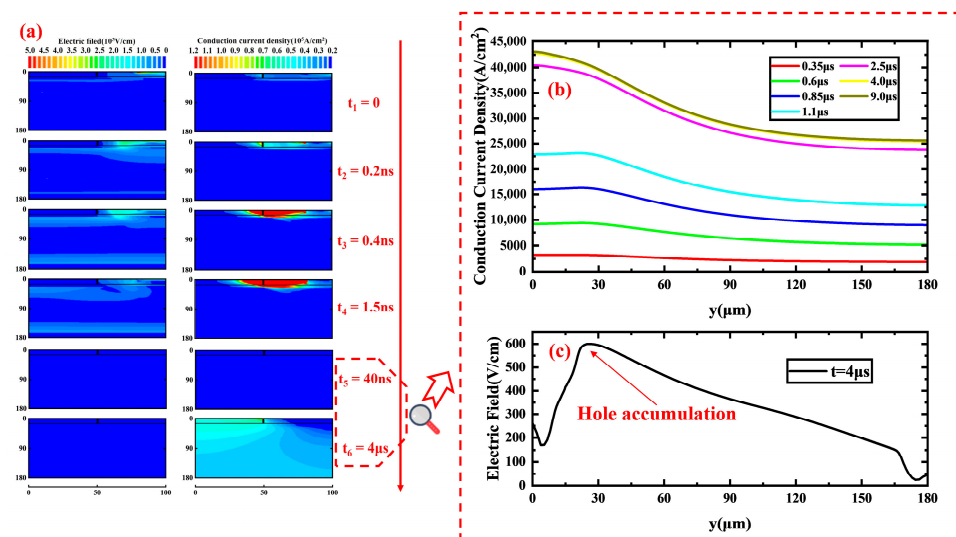


Figure 11. Electric field and conduction current density simulation results: (a) 2D distribution and (b,c) 1D variation curves.

When a negative-polarity transient pulse is applied to the thyristor gate, J_1 is reverse-biased. Under this condition, free electrons in the N^+ region are driven away from the J_1 junction interface by the electric field force and migrate towards the cathode metal contact layer, forming a reverse leakage current flowing from the cathode to the gate. This process also suppresses the possibility of electrons injecting into the internal P base region through the J_1 junction, interrupting carrier injection at the emitter junction of the Q_2 (NPN) transistor. Due to the lack of initial electron injection, the Q_2 transistor cannot generate a collector current and thus cannot provide base drive current for the Q_1 (PNP) transistor. Consequently, the positive feedback process cannot be established. The J_2 junction remains reverse-biased, its space charge region maintains a high electric field strength, and the device remains stably in the reverse blocking mode. The simulation results under negative pulse excitation are shown in Figure 12, Figure 12a displays the distribution curves of the electric field and carrier concentration, indicating that the carrier concentration remains dominated by donor ions, and the high electric field strength at Junction J_2 demonstrates that the device is in the blocking state; Figure 12b shows that the conduction current density remains nearly zero even after 10 microsecond of pulse application, further confirming that the device does not turn on.

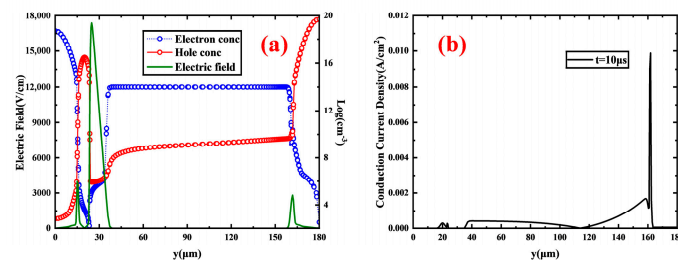


Figure 12. Simulation results under negative pulse excitation: (a) electric field and carrier concentration and (b) conduction current density.

Meanwhile, in order to investigate the influence of variations in the excitation pulse's amplitude and width on the turn-on threshold, the two parameters were adjusted near the critical threshold to observe the thyristor's turn-on response. The simulation results are shown in Table 6:

Table 6. Simulation results under different pulse parameters.

Pulse Width (ns)	Amplitude (V)	Conduction Status
2	245	conduction
1.5	245	None
20	240	none
21	240	conduction

When the pulse amplitude was 245 V, the device remained in the blocking state for pulse widths ≤ 1.5 nanoseconds, but turned on when the pulse width was increased to 2 nanoseconds. This indicates that 245 V is the critical turn-on threshold for a 2-nanosecond pulse width. When the amplitude was reduced to 240 V, a turn-on was only achieved when the pulse width was increased to 21 nanoseconds (a 20-nanosecond width still resulted in blocking). This confirms 240 V as the turn-on threshold for a 21-nanosecond pulse width.

The simulation results demonstrate that, regarding the effect of HPMP on thyristors, the turn-on threshold is more sensitive to the pulse amplitude than to the pulse width. A difference of merely 5 V in amplitude requires a compensation of approximately 10 times in pulse width to achieve the same effect. Crucially, if a nanosecond-scale pulse is insufficient

to trigger thyristor turn-on, merely increasing its width to tens of nanoseconds will still be ineffective in establishing successful conduction.

We have conducted a preliminary analysis of the above conclusion, and the reason for the amplitude-dominated effect is considered to be as follows: the unintended turn-on of the thyristor requires the polarity reversal of the space charge region at Junction J_2 , which relies on the rapid accumulation of carriers under a strong electric field. When the amplitude increases, the peak electric field at Junction J_2 rises, and the kinetic energy acquired by electrons in the strong electric field increases significantly, accelerating the establishment of carrier positive feedback. Although the extension of pulse width increases the energy action time, if the amplitude does not reach the threshold, the electric field strength will never be able to drive carriers to reach the critical concentration required to trigger positive feedback; it will only cause a small amount of carriers to accumulate slowly in the depletion layer, making it impossible to achieve the polarity reversal of Junction J_2 .

(2) Anode Transient Pulse Excitation

Based on the design and results of the device-level voltage injection experiment, the anode excitation signal was set as a positive-polarity square wave to simulate a transient pulse. The square wave had a peak value of 2 kV, a rise time of 1 nanosecond, and a pulse width of 5 nanoseconds. The results in Figure 13 show that the thyristor turns on under this transient pulse excitation, with a turn-on time of approximately 1 microsecond, which is faster than the turn-on observed during gate injection.

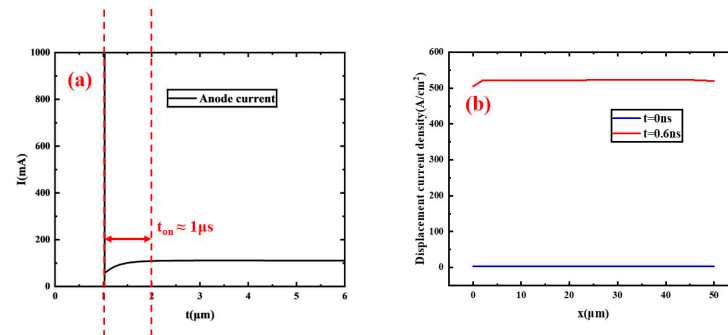


Figure 13. Simulation results: (a) turn-on characteristic curve and (b) displacement current variation curve.

When a transient positive pulse is applied between the anode and cathode, its fast rate of voltage change (dv/dt) generates displacement currents across the junction capacitances. Since junctions J_1 and J_3 are forward-biased with narrow depletion layers, their junction capacitances are small. Junction J_2 is reverse-biased with a wide depletion layer, resulting in a larger junction capacitance. Therefore, during the rising edge of the transient pulse, the displacement current near the J_2 junction increases rapidly. Compared to the localized and intense changes in carrier concentration during gate injection, the carrier changes induced by the varying electric field in this case are more uniformly distributed. The displacement current and electron concentration in the part of the J_2 junction corresponding to the cathode electrode rise uniformly. When the pulse has a sufficiently fast rise time, the displacement current provides an equivalent base current for the PNP transistor that is large enough to meet the triggering condition for the positive feedback process. Furthermore, if the pulse duration is sufficiently long, it allows the positive feedback process to fully establish itself, ultimately leading to the conduction between the anode and cathode of the thyristor. The avalanche ionization integral is calculated as follows [34]:

$$\int_0^w \alpha_p \exp \left[\int_0^x (\alpha_n - \alpha_p) \right] dx = 1 \quad (7)$$

where w is the depletion region width, α_n and α_p are the impact ionization coefficients for electrons and holes, respectively. An avalanche ionization integral greater than 1 indicates the occurrence of an avalanche process, while a value less than 1 signifies no avalanche process. Based on Equation (7), the calculated avalanche ionization integral is approximately 3×10^{-4} , indicating that the strong electric field did not reach the avalanche threshold. Meanwhile, considering the possibility of local avalanche processes caused by local field enhancement, field monitoring was conducted on the injection region near the anode. The results show that the local maximum electric field strength is approximately 2×10^5 V/cm, which does not reach the avalanche breakdown threshold of 3×10^5 V/cm for silicon material set in the simulation. Therefore, we conclude that for this study, the essence of thyristor turn-on under anode injection is the displacement current triggered by the high voltage rise rate activating the positive feedback of the dual-transistor structure, rather than avalanche breakdown dominated by impact ionization. However, the above results also indicate that local field enhancement may indeed increase the probability of avalanche processes. In actual semiconductor manufacturing processes, defects such as oxide traps and impurity agglomeration may exist; these defects can cause local electric field distortion, increase the value of the avalanche ionization integral, and significantly raise the potential risk of avalanche occurrence.

3.4. Considerations on Key Issues

(1) Equivalence between Cable Port Coupled Voltage and Numerical Simulation Port Voltage

Limited by the bandwidth constraint of the current injection probe (400 MHz), the measured port-coupled voltage waveform exhibits pulse broadening compared to the injection excitation waveform, with its spectral energy shifting towards lower frequencies. This implies that the port voltage effect threshold (voltage amplitude) obtained from current injection experiments might be lower than the simulation results from numerical experiments under equivalent field effect threshold input. This is because, given the same energy accumulation, a narrower pulse requires a higher peak amplitude than a wider pulse. However, constrained by experimental conditions and the lack of a high-voltage pulse source with a continuously adjustable pulse width covering several nanoseconds, it is impossible to directly quantify the coupling influence of pulse width and amplitude on sensitive components. Therefore, we conducted simulation studies on the impact of varying pulse width and amplitude on the sensitive thyristor device. The simulation results based on the physical-layer model of the thyristor (Section 3.3.2. (1)) show that the turn-on threshold is more sensitive to the pulse amplitude than to the pulse width. Changes in pulse width on the order of tens of nanoseconds do not affect the state transition if the amplitude does not reach the threshold. This characteristic ensures the equivalence of the current injection experiment. Although pulse broadening in the experiment leads to a reduced peak amplitude, the threshold determination criterion remains universally applicable.

(2) Equivalence of Cable Lengthening

The cable length in the actual switching system irradiation experiment was 2 cm, but it was extended to 10 cm for the injection experiments. The equivalence of this operation is based on transmission line theory analysis: under ideal conditions, the transient signal excited on the cable by field coupling travels at nearly the speed of light. Upon reaching a port, it reflects, creating a superimposed oscillation of the incident and reflected waves. For a 2 cm cable, this time $t_1 \approx 2 \times 2 \text{ cm} / (3 \times 10^8 \text{ m/s}) \approx 0.13$ nanosecond. For a 10 cm cable, $t_2 \approx 2 \times 10 \text{ cm} / (3 \times 10^8 \text{ m/s}) \approx 0.67$ nanosecond. Given that the coupled signal pulse width is on the order of nanoseconds, the signal transmission delay is negligible compared to the main waveform duration. Although lengthening the cable increases the oscillation period, the oscillation amplitude decays exponentially. Furthermore, the simulation results

regarding the relationship between pulse width and amplitude for the thyristor can verify that the cable lengthening method is feasible for this experiment. The extended cable does not fundamentally alter the nature of the initial transient pulse coupling that drives the thyristor's response, thus maintaining the validity of the injection experiment results.

4. Electromagnetic Protection Hardening Design

Based on the analysis of the identified electromagnetic vulnerability paths and the turn-on mechanism of sensitive components, targeted electromagnetic protection measures have been implemented for critical paths and vulnerable devices. The specific measures are as follows:

(1) Circuit Board Structure Optimization

Numerical simulation results indicated that the distance between the upper and lower circuit boards is a major factor affecting the coupling strength of HP EMP. An increase in the board spacing enhances coupling energy. Therefore, the circuit board structure was optimized by reducing the inter-board distance to suppress coupling. The original structure, shown in Figure 14a, featured a DC-DC module with a height comparable to the board spacing, occupying the entire space. Without replacing components, the module was relocated below the lower board, significantly reducing the inter-board distance from 20 mm to 7 mm. The optimized structure is illustrated in Figure 14b.

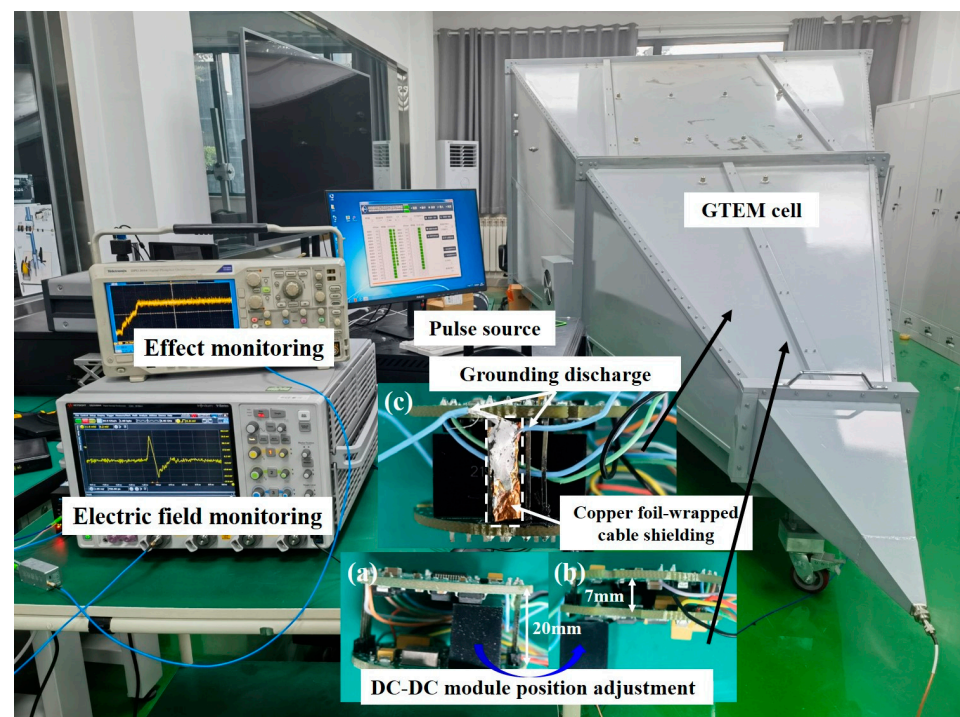


Figure 14. Electromagnetic protection verification experiment setup: (a) the initial circuit board structure, (b) the new structure with reduced board spacing, and (c) the structure after cable shielding.

(2) Shielding and Grounding of the Gate Cable

The injection experiment results identified the gate cable as an electromagnetic vulnerability path. To protect this cable, shielding and grounding measures were applied: an insulation layer was wrapped around the cable, followed by a copper foil shielding layer. Two ground wires were soldered to the copper foil and connected to the ground networks of the upper and lower boards, respectively. This structure effectively diverts coupled HP EMP energy to the ground plane, providing electromagnetic shielding and energy dissipation. The configuration is depicted in Figure 14c.

(3) Replacement of the Thyristor

The originally used thyristor had a nominal forward breakover voltage of 400 V. Since the turn-on of the thyristor under transient pulses depends on whether the space charge region of Junction J_2 undergoes polarity reversal and establishes positive feedback, different device structures significantly affect the turn-on threshold. Generally, a higher forward breakover voltage corresponds to a wider space charge region at Junction J_2 , enhancing the impact ionization effect when carriers traverse it. This weakens the gate's control over the triggering process, requiring a larger trigger current for turn-on. Therefore, a PJX121SQ-type thyristor (Dongguan Pingjing Microelectronics Technology Co., Ltd., Guangdong, China) with a forward breakover voltage of 1200 V was selected as a replacement to increase the trigger threshold. Its protective effectiveness was validated through experiments.

To evaluate the protection effectiveness, irradiation experiments were conducted in a GTEM cell: an ultra-wideband high-voltage pulse source was connected to the GTEM cell's feed port to create a uniform high-field region inside. The circuit board was powered by the switching system's original lithium battery, and the thyristor trigger signal was monitored via a coupled voltage probe and recorded using an oscilloscope. The protective effectiveness of each measure was assessed by comparing the failure field strength under different protection configurations.

Experimental results in Table 7 demonstrated that all three protection measures effectively enhanced the system's immunity to HPEMP. Reducing the board spacing and shielding the gate cable each approximately doubled the effect threshold, significantly reducing the field-circuit coupling efficiency and validating the accuracy of the earlier vulnerability path identification. The device replacement further improved the noise tolerance of the trigger channel, indicating that transient pulse-induced unintended turn-on can be effectively suppressed through device-level selection. Comprehensively, the multi-level protection design in this study systematically enhances the electromagnetic protection capability of the electronic switching system from three dimensions: structure, link, and device, achieving the goal of electromagnetic protection hardening. In future work, we plan to implement electromagnetic protection hardening for the entire system in terms of circuit design, such as optimizing the impedance matching between cables and the front-end circuit, and configuring filter networks at cable ports to suppress high-frequency coupling components [35]. Additionally, we will further expand this research by integrating big data and AI technologies [36,37]: for example, we will construct a sample database by collecting the system's operating parameters (e.g., field strength, coupling voltage, device temperature) under different electromagnetic environments, and use machine learning algorithms to explore the implicit correlation between "electromagnetic interference parameters and system failure modes". This will enable early warning of HPEMP interference risks, thereby providing a new technical path for the intelligent electromagnetic protection of electronic switching systems.

Table 7. Effect thresholds corresponding to different electromagnetic protection measures.

Electromagnetic Protection Measures	Effect Threshold (kV/m)
none	5.76
Overall PCB architecture design	12.50
Cable shielding with copper foil and grounded drainage	12.50
Component selection and substitution	9.90

5. Conclusions

This paper investigated the failure mechanisms and protection hardening methods of a typical electronic switching system under HPEMP effects. The main conclusions are as follows:

- (1) The switching system is susceptible to HP EMP interference, with cables exhibiting high sensitivity as back-door coupling paths. HP EMP couples into thyristor-related ports via cables, causing device malfunction and subsequent system failure. Since the failure threshold of the thyristor gate port is lower than that of the anode port, gate cable coupling is identified as the primary cause of system failure.
- (2) Analysis of the thyristor failure mechanism reveals that under gate-injected transient pulses, carrier injection causes the internal PN junction of the thyristor to transition from reverse bias to forward bias, triggering a positive feedback mechanism that ultimately leads to complete device turn-on. This process has a turn-on duration of approximately 3.5 microseconds, which aligns well with experimental results. Under anode injection, the displacement current induced by the high transient voltage change rate (dv/dt) acts as an equivalent gate trigger current, also initiating the positive feedback process and turning on the device. This method results in a faster response, with a turn-on time of about 1 microsecond. Furthermore, the study indicates that the turn-on threshold of the thyristor is more sensitive to changes in pulse amplitude than to pulse width.
- (3) Based on the identified electromagnetic vulnerability paths and sensitive components, targeted electromagnetic protection hardening measures were implemented. These included optimization of the circuit board structure, copper foil shielding and grounding design for cables, and replacement of critical devices. The effectiveness of these measures was validated through irradiation experiments. Results demonstrate that all methods improved the system's anti-interference capability, with board structure improvement and cable shielding providing the most significant protection.

In the next step, we will further expand the technical boundaries by integrating data-driven methods to construct a “field coupling-device failure” prediction model. This model will enable the transition from static mechanism analysis to dynamic early warning. Meanwhile, by targeting scenarios such as power systems and aerospace, we will optimize the integration of the protection scheme proposed in this paper with industrial monitoring systems, promoting the extension of HP EMP protection technology to engineering applications in multiple fields.

Author Contributions: Software, C.H., J.W. and S.Z.; Investigation, C.H. and K.Z.; Data curation, C.H., J.W., K.Z., S.Z., Y.S. and T.W.; Writing—original draft, C.H.; Writing—review & editing, J.W. and Y.Y.; Project administration, Y.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Chen, S.; Li, X.; Liu, P.; Hu, M.; Li, J. Design Research of Semiconductor Bridge Electric Igniter for Automotive Airbags. *Initiat. Pyrotech.* **2016**, *4*, 22–23. [[CrossRef](#)]
2. Shen, C. Design and Fabrication of a Monolithically Integrated Radio Frequency and Electrostatic Discharge Protection Circuit for Semiconductor Bridge Pyrotechnic Devices. Master's Thesis, Shanghai Jiao Tong University, Shanghai, China, 17 January 2020. [[CrossRef](#)]
3. Kiun, K.; Jeon, I.N.; Ahns, W. Effect of Time Gap between Two Pyrotechnic Thrusters. *J. Spacecr. Rocket.* **2011**, *48*, 221–224. [[CrossRef](#)]
4. Li, D.; Han, J.; Jang, H. Shock Response Prediction of a Low Altitude Earth Observation Satellite during Launch Vehicle Separation. *Int. J. Aeronaut. Space Sci.* **2010**, *11*, 49–57. [[CrossRef](#)]

5. Radasky, W.A.; Hoad, R. Recent developments in high power EM standards with emphasis on high altitude electromagnetic pulse and intentional electromagnetic interference. *IEEE Lett. Electromagn. Compat. Pract. Appl.* **2020**, *6423*, 62–66. [\[CrossRef\]](#)
6. Radasky, W.A.; Baum, C.E.; Wik, M.W. Introduction to the special issue on High-Power Electromagnetics and intentional Electromagnetic Interference. *IEEE Trans. Electromagn. Compat.* **2004**, *46*, 314–321. [\[CrossRef\]](#)
7. Li, Y.; Wang, J.; Zuo, Y.; Zhu, J.; Niu, S. Numerical simulation of the intermediate-time high-altitude electromagnetic pulse. *IEEE Trans. Electromagn. Compat.* **2022**, *64*, 1423–1430. [\[CrossRef\]](#)
8. Tesche, F.M.; Barnes, P.R. Transient response of a distribution circuit recloser and control unit to a high-altitude electromagnetic pulse (HEMP) and lightning. *IEEE Trans. Electromagn. Compat.* **1990**, *32*, 113–124. [\[CrossRef\]](#)
9. Huang, C.; Zhang, K.; Wei, J.; Yan, Y.; Wang, T. Research on Monitoring Technology of Intense Electromagnetic Pulse Effects on Electronic Systems Based on Oscilloscope Cascading. In Proceedings of the 6th National Conference on Complex Electromagnetic Environment Technology and Application (CEME), Changsha, China, 27–30 April 2025.
10. Wang, J.; Liu, L.; Zuo, Y.; Niu, S.; Li, X.; Zhu, J.; Gao, Y.; Zhang, X.; Ouyang, X. Research Progress in Numerical Simulation of Environmental Parameters Generated by the High-Altitude Nuclear Explosions. *IEEE Trans. Nucl. Sci.* **2025**, *72*, 884–900. [\[CrossRef\]](#)
11. Zhang, D.; Chen, Y.; Cheng, E.; Zhang, Q. Electromagnetic radiation effects on dynamic datalink of UAV. *J. Terahertz Sci. Electron. Inf. Technol.* **2020**, *18*, 643–649. [\[CrossRef\]](#)
12. Zhou, L.; Zhang, S.; Yin, W.; Mao, J. Investigating a thermal breakdown model and experiments on a silicon-based low-noise-amplifier under high-power microwave pulses. *IEEE Trans. Electromagn. Compat.* **2016**, *58*, 487–493. [\[CrossRef\]](#)
13. Xie, H.; Wang, J.; Fan, R.; Liu, Y. A Hybrid FDTD-SPICE method for transmission lines excited by a nonuniform incident wave. *IEEE Trans. Electromagn. Compat.* **2009**, *51*, 811–817. [\[CrossRef\]](#)
14. Yuan, K.; Wang, J.; Xie, H.; Fan, R. SPICE model of a single twisted wire pair illuminated by a plane wave in free space. *IEEE Trans. Electromagn. Compat.* **2015**, *57*, 574–583. [\[CrossRef\]](#)
15. Wei, J.; Yan, Y.; Wang, S.; Jiang, T.; Gao, F. FDTD-TL Method for the Prediction of the Transient Response of Shielded Cable Above the Ground. In Proceedings of the 2021 International Applied Computational Electromagnetics Society (ACES-China) Symposium, Chengdu, China, 1–5 August 2021. [\[CrossRef\]](#)
16. Li, W.; Zhang, C.; Cha, J.; Zheng, G.; Li, W.; Zhang, X. Electromagnetic sensitivity study of NMOS tube under the action of electromagnetic pulse. *J. Ordnance Equip. Eng.* **2023**, *44*, 25–31. [\[CrossRef\]](#)
17. Liu, Y.; Chai, C.; Yu, X.; Fan, Q.; Yang, Y.; Xi, X.; Liu, S. Damage effects and mechanism of the GaN high electron mobility transistor caused by high electromagnetic pulse. *Acta Phys. Sin.* **2016**, *65*, 038402. [\[CrossRef\]](#)
18. William, A.R. High Power Electromagnetic (HPEM) Threats to the Smart Grid. *Interf. Technol.* **2011**, *5*, 1–12.
19. An, Q.; Chai, C.; Li, F.; Wu, H.; Yang, Y. Electromagnetic pulse effect and mechanism of GaAs based PHEMT low noise amplifier. *Mod. Appl. Phys.* **2022**, *13*, 1–3. [\[CrossRef\]](#)
20. Liang, Q.; Chai, C.; Wu, H.; Liu, Y.; Li, F.; Yang, Y. Mechanism Analysis and Thermal Damage Prediction of High-Power Microwave Radiated CMOS Circuits. *IEEE Trans. Device Mater. Reliab.* **2021**, *21*, 444–451. [\[CrossRef\]](#)
21. Zhang, W.; Shi, Y.; He, Y. Study on damage effects of lightning electromagnetic pulse on typical airborne GPS module. *High Power Laser Part. Beams* **2021**, *33*, 033001. [\[CrossRef\]](#)
22. Zhao, K. Damage of Bipolar Transistors by Intense Electromagnetic Pulse and Its Protection. Master's Thesis, Nanjing University of Information Science and Technology, Nanjing, China, 8 June 2023.
23. Liu, J.; Chen, Y.; Tan, Z.; Chen, X. Research on the Irradiation Effect of Electrostatic Discharge Electromagnetic Pulse. *J. Beijing Inst. Technol.* **2011**, *31*, 1205–1207.
24. Dai, Y. Research on the Effect of Electrostatic Discharge Electromagnetic Pulse on CPLD Systems and Protection Hardening. Master's Thesis, Wuhan University of Technology, Wuhan, China, 8 June 2010. [\[CrossRef\]](#)
25. Hwang, S.M.; Hong, J.I.; Han, S.-M.; Huh, C.S.; Choi, J.-S. Susceptibility and Coupled Waveform of Microcontroller Device by Impact of UWB-HPEM. *J. Electromagn. Waves Appl.* **2012**, *24*, 1059–1067. [\[CrossRef\]](#)
26. Wu, G.; Yue, B.; Yang, Y.; Wang, H.; Cui, Z.; Peng, L.; Wu, W.; Chen, W. High-altitude electromagnetic pulse survivability test study on shortwave receiving antenna system by pulsed current injection. *High Power Laser Part. Beams* **2019**, *31*, 093205. [\[CrossRef\]](#)
27. Zeng, X.; Xiong, B.; Yu, D.; Xing, Y. Simulation of Electromagnetic Pulse Effects on Missile Radio Fuzes. *J. Nav. Aeronaut. Astronaut. Univ.* **2012**, *27*, 444–445.
28. Wei, G.; Pan, X.; Wan, H. Mechanism of Ultra-Wideband Electromagnetic Radiation Effects on Radio Fuzes. In *Patterns of Equipment Electromagnetic Radiation Effects and Interaction Mechanisms*; National Defense Industry Press: Beijing, China, 2018; pp. 75–78. ISBN 9787118117219.
29. Mohan, N. Thyristor. In *Power Electronics: Circuits Devices and Applications*; China Machine Press: Beijing, China, 2019; pp. 315–338. ISBN 9787111607939.
30. Grafham, D.R.; Golden, F.B. *SCR Manual*, 6th ed.; Prentice Hall: Englewood Cliffs, NJ, USA, 1982; ISBN 0137967632.

31. Ebers, J.J. Four-Terminal P-N-P-N Transistors. In Proceedings of the IRE, New York, NY, USA, 24 November 1952. [[CrossRef](#)]
32. Yang, J.; Wang, B.; Wang, P. Research on the Law of Thyristor dV/dt Triggered Conduction Under ESD Action. *Chin. J. Radio Sci.* **2019**, *34*, 512–517. [[CrossRef](#)]
33. Wang, H.; Qiao, H.; Cheng, J.; Hu, L.; Li, X.; Wang, X.; Fang, X. Turn-on Mechanism of Base-Triggered Avalanche Transistors. *Semicond. Mater. Devices* **2024**, *49*, 432–441. [[CrossRef](#)]
34. Xiong, J.; Huang, H.; Zhang, Z.; Zhang, G. Investigation of Avalanche Multiplication Factor in 4H-SiC p-n Junctions Based on an Accurate Impact Ionization Model. *Microelectronics* **2023**, *53*, 333–337. [[CrossRef](#)]
35. Pullano, S.A.; Oliva, G.; Titirsha, T.; Shuvo, M.M.H.; Islam, S.K.; Laganà, F.; Gatta, A.L.; Fiorillo, A.S. Design of an Electronic Interface for Single-Photon Avalanche Diodes. *Sensors* **2024**, *24*, 5568. [[CrossRef](#)]
36. Laganà, F.; Pellicanò, D.; Arruzzo, M.; Praticò, D.; Pullano, S.A.; Fiorillo, A.S. FEM-Based Modelling and AI-Enhanced Monitoring System for Upper Limb Rehabilitation. *Electronics* **2025**, *14*, 2268. [[CrossRef](#)]
37. Praticò, D.; Laganà, F.; Oliva, G.; Fiorillo, A.S.; Pullano, S.A.; Calcagno, S.; Carlo, D.D.; Foresta, F.L. Sensors and Integrated Electronic Circuits for Monitoring Machinery On Wastewater Treatment: Artificial Intelligence Approach. In Proceedings of the IEEE Sensors Applications Symposium(SAS), Naples, Italy, 23–25 July 2024. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.