



HAL
open science

Experimental and Simulation Study of Parallel-Connected Thyristors in Impact-Ionization Switching Mode

Ejlal Shahriari, Anton Gusev, Thomas Maysonnave, Antoine Silvestre de Ferron, Laurent Pecastaing

► **To cite this version:**

Ejlal Shahriari, Anton Gusev, Thomas Maysonnave, Antoine Silvestre de Ferron, Laurent Pecastaing. Experimental and Simulation Study of Parallel-Connected Thyristors in Impact-Ionization Switching Mode. IEEE Transactions on Plasma Science, 2024, 52 (9), pp.4332-4340. 10.1109/TPS.2024.3405578 . hal-04585533

HAL Id: hal-04585533

<https://univ-pau.hal.science/hal-04585533v1>

Submitted on 6 Jun 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Experimental and Simulation Study of Parallel-Connected Thyristors in Impact-Ionization Switching Mode

Ejlal Shahriari, *Graduate Student Member, IEEE*, Anton I. Gusev, *Member, IEEE*, Thomas Maysonnave, Antoine Silvestre de Ferron, Laurent Pecastaing, *Senior Member, IEEE*

Abstract—This paper investigates the impact-ionization switching mechanism in parallel-connected high-voltage thyristors, aiming to bridge the gap between experimental observations and numerical simulations. A novel experimental setup is designed to study four parallel thyristors triggered in impact-ionization wave mode, marking the first instance of such an arrangement. In addition to the experiment, a numerical simulation is employed to assess the impact-ionization switching of high-voltage thyristors in parallel connection. The numerical simulation adopts a quasi-3D model of the thyristor structure derived from a 2D model, considering cylindrical symmetry. Three distinct scenarios are explored in the simulation: (i) static voltage breakdown, (ii) suppression of unwanted dV/dt triggering, and (iii) delayed impact-ionization breakdown. The paper presents a detailed comparison and discussion of the experimental and numerical simulation results related to impact-ionization switching.

Index Terms—High dl/dt , impact-ionization wave mode, Marx generator, numerical simulation, pulsed power systems, subnanosecond switching time, thyristors.

I. INTRODUCTION

STEEP overvoltage pulses with voltage rise rates (dV/dt) of more than 1 kV/ns applied across high-voltage diodes enable subnanosecond switching, as initially demonstrated at the Ioffe Institute in 1979 [1]. It thereafter led to the development of switches known as Silicon Avalanche Shaper (SAS) diodes [2], [3]. The effect has been called “delayed impact-ionization breakdown of high-voltage p-n junction”. Four-layer structures called Fast Ionization Dynistor (FID) were developed later based on this pioneering advancement in semiconductor physics. Having subnanosecond switching time, FIDs are capable of switching kA currents with a current rise rate (dl/dt) of up to 200 kA/ μ s [4], [5].

In an effort to extend this breakthrough to commercial semiconductors, the successful testing of triggering thyristors in impact-ionization switching mode has been reported in [6], [7]. When standard high-voltage thyristors are triggered in impact-ionization wave mode, they exhibit subnanosecond

switching times and dl/dt capabilities that are hundreds of times higher than their rated values. In this switching mode, a rapid overvoltage pulse (with $dV/dt \geq 1$ kV/ns) is applied to the main electrodes of the thyristors in the forward direction, while the gate terminal remains in an open state. Impact-ionization switching of high-voltage thyristors is a reliable method for achieving fast high-current pulses (100s kA, 10s kA/ μ s) as demonstrated in [8]–[10].

The key distinction between impact-ionization switching and conventional thyristor switching lies in the following aspects. First, in the conventional thyristor switching mechanism, current carriers are injected through the gate electrode [11]. This leads to an injection of electrons and holes from the n and p layers located on the opposite side of thyristors into the space charge region at the p-n junction. Theoretically, nanosecond switching times can be achieved in standard thyristors with a conventional switching mechanism [12]. However, the carrier saturation velocity (10^7 cm/s for electrons in silicon) acts as a limiting factor in this process, resulting in switching times of several nanoseconds for high-voltage thyristors.

On the contrary, in the impact-ionization switching mode, the gate electrode remains floating, and a steep triggering pulse is applied either with a positive polarity to the anode or a negative polarity to the cathode electrode of the thyristor. For impact-ionization triggering, the voltage across the thyristor must have two characteristics: (i) a dV/dt across the thyristor exceeding 1 kV/ns and (ii) a maximum voltage amplitude twice that of the static breakdown voltage. Under this condition, electron-hole plasma is directly generated in the depletion region through the impact-ionization of silicon (Si) atoms under a high electric field ($\sim 2 \times 10^5$ V/cm), leading to subnanosecond switching time.

Based on various experimental and theoretical investigations outlined in [10], [13], the phenomenon of impact-ionization switching occurs in certain regions on the thyristor cross-sectional area. Consequently, during the switching process, the p-n junction area exhibits a dual nature: (i) a conductive, or “active” area where impact-ionization breakdown occurs, and (ii) a non-conductive, or “passive” area, analogous to a charged capacitor. As stated in [13], the switching time is basically defined as the discharge duration of the passive area through the active region, typically with a characteristic value of 100 ps.

The numerical modeling of avalanche breakdown is required for a better understanding of the underlying physics. While

Manuscript received 5 February 2024; revised 5 April 2024; accepted 22 May 2024. This work was supported by the Investissements d’Avenir, a French Program managed by the Agence Nationale de la Recherche (ANR), under the framework of Energy and Environment Solutions (E2S) Université de Pau et des Pays de l’Adour (UPPA) (Pulsed Power Applications (PULPA) Chair and Solid-State Pulsed Power (S2P2) Chair) under Grant ANR-16-IDEX-0002.

Ejlal Shahriari, Anton Gusev, Thomas Maysonnave, Antoine Silvestre de Ferron, and Laurent Pecastaing are with Université de Pau et des Pays de l’Adour, E2S UPPA, SIAME, Pau, France. (e-mail: ejlal.shahriari@univ-pau.fr; anton.gusev@univ-pau.fr; thomas.maysonnave@univ-pau.fr; antoine.deferron@univ-pau.fr; laurent.pecastaing@univ-pau.fr).

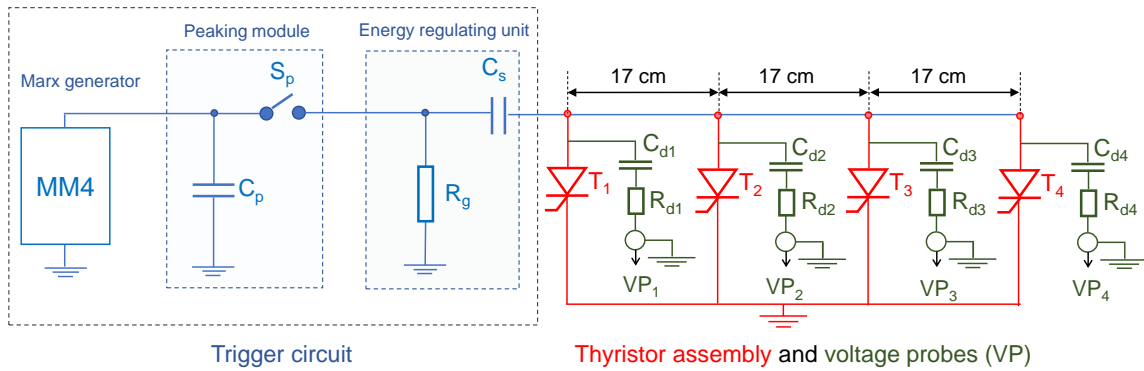


Fig. 1. Equivalent electrical circuit of the experimental arrangement.

numerical simulations of impact-ionization switching of high-voltage devices have been reported in several studies [13]–[16], the physical understanding of this phenomenon lags behind compared to experimental applications. In addition, numerical study on impact-ionization switching of high-voltage thyristors has not been extensively explored and is currently limited to 1D numerical simulations [8], [10].

In terms of experimental work, the demonstration of parallel switching in high-voltage thyristors ($\varnothing 32$ mm, 2.2 kV) stands out as an advantageous approach for high-current switch design [17]. This method serves as a practical alternative to triggering a larger-area thyristor ($\varnothing 100$ mm, 5.2 kV) [18]. The preference for parallel switching primarily results from two key factors: (i) its cost-effectiveness and (ii) increasing the current capability of the switch by eliminating the thyristor wafer area limitations.

This study pursues a better understanding of the fundamental physics behind impact-ionization switching in parallel-connected high-voltage thyristors. In this framework, a novel experimental setup is arranged to trigger four thyristors in parallel in impact-ionization wave mode. In addition to the experiment, a numerical simulation is employed to test impact-ionization switching of high-voltage thyristors in parallel connection employing standard models. A quasi-3D model of the thyristor structure is built from a 2D model considering a cylindrical symmetry in this numerical simulation. Then, three different scenarios are tested: (i) static voltage breakdown, (ii) unwanted dV/dt triggering, and (iii) delayed impact-ionization breakdown. Finally, experimental and numerical simulation results of impact-ionization switching are compared and discussed in detail.

II. EXPERIMENTAL SETUP

The overall experimental arrangement, including the trigger circuit, thyristor assembly, and diagnostics is presented in Fig. 1. In this study, 2.2 kV thyristors of the type T333-250 [19] are tested. These thyristors have a wafer diameter of 32 mm and are manufactured by Proton-Electrotex.

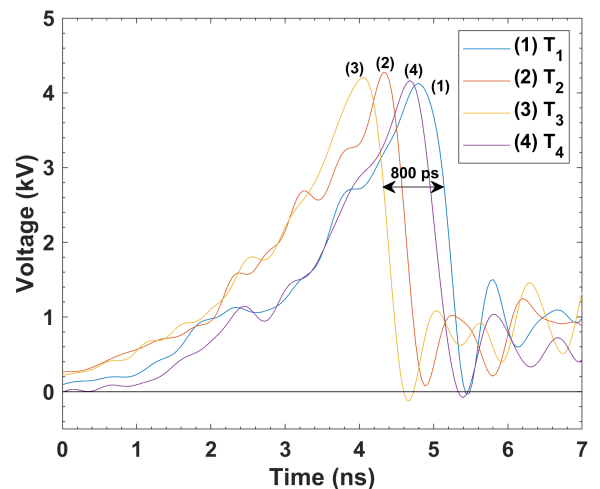


Fig. 2. Measured voltage pulses across four thyristors.

A. Circuit Arrangement

The trigger circuit consists of three main parts as depicted in Fig. 1. A four-stage methodical Marx generator (MM4) is used to produce the high-voltage pulse, more detailed description of this generator can be found in [18]. As this pulse does not reach the required rise rate (i.e. more than 1 kV/ns) for impact-ionization switching, a *peaking module* is employed to sharpen the pulse to achieve the necessary rise rate of overvoltage pulse. Finally, an *energy regulating unit* allows for a boost effect on the pulse.

To control the energy supplied to the thyristor assembly from MM4, series capacitors (C_s) are incorporated into the experimental setup, as illustrated in Fig. 1. Additionally, a grounding resistor (R_g) is employed to ensure that the left side of C_s is close to ground potential. This arrangement facilitates achieving a higher voltage across the thyristors.

The four-thyristor assembly is configured in such a manner that each voltage probe measures the voltage pulse across the connected thyristor, avoiding interference from the voltage wave propagation from neighboring thyristors. This key objective is achieved by arranging the thyristors in the setup with

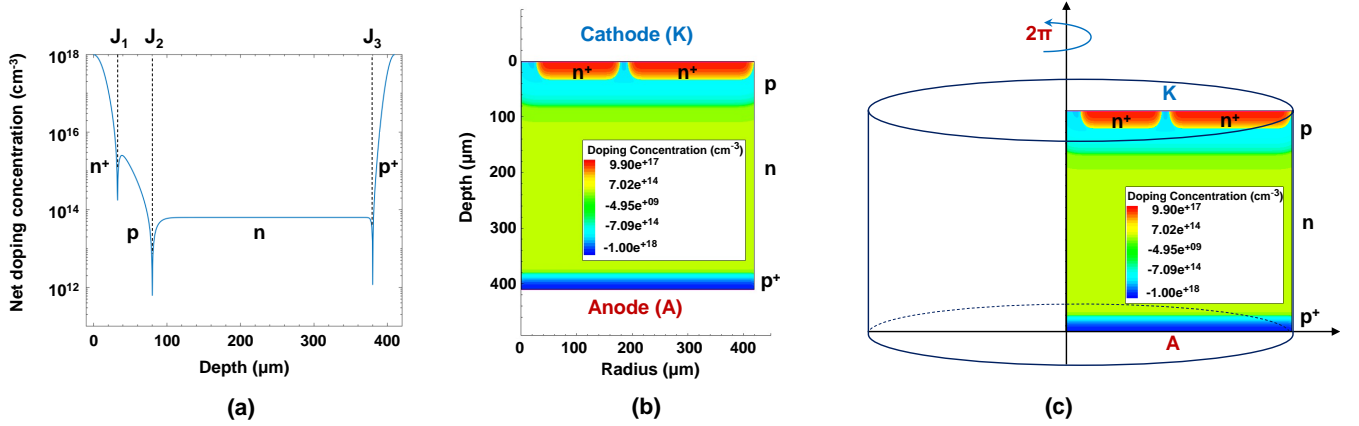


Fig. 3. The thyristor structure and doping profile in (a) 1D, (b) 2D, and (c) quasi 3D.

a distance between neighboring thyristors of approximately 17 cm, as shown in Fig. 1. We assume that electromagnetic waves propagate through the air at the speed of light. Thus, considering the 17 cm distance between two adjacent thyristors, it takes 567 ps for an electromagnetic wave to reach neighboring thyristors, which is more than a thyristor switching time of ~ 300 ps. We believe this demonstrates that each voltage probe measures the voltage across each thyristor without distortion from neighboring thyristors, i.e., all measurements are independent. It is also confirmed by the fact that all four signals (Fig. 2) have unique characteristics of dV/dt , maximum voltage amplitude, switching time and delay.

For voltage measurement across the thyristors, we manufactured four wideband voltage probes with a usable rise time of approximately 200 ps. This voltage probe comprises a resistive divider consisting of a ceramic resistor ($R_d = 1$ k Ω) as the high-voltage arm resistance and a 50 Ω coaxial cable as the low-voltage arm [20]. All 4 signals were measured simultaneously by a 4-channel real-time digital oscilloscope (DPO70604 TEKTRONIX, 6 GHz, 25 GS/s).

B. Experimental Results

To investigate the impact-ionization switching in parallel connection of four thyristors, an experimental setup is arranged for a non-energy switching mode, i.e., switching without load. The primary aim of this experiment is to illustrate the triggering of all four thyristors in impact-ionization mode through the demonstration of subnanosecond switching times. In this experimental configuration, the triggering pulse is directly applied across the thyristor assembly with zero bias voltage, as depicted in Fig. 1.

To trigger the thyristor in impact-ionization mode without energy switching, the following procedure is adopted. A triggering pulse generated by the Marx generator and enhanced by the peaking module, with respect to the rise rate, is applied across the main electrodes of thyristors in parallel connection as the gate electrode remains open.

In the Fig. 2, the voltage pulses across four thyristors (T_1 , T_2 , T_3 and T_4) measured by high-frequency voltage probes are demonstrated. The trigger pulses measured across 4 parallel

thyristors, as shown in Fig. 2, demonstrate a rise rate from 1.05 to 1.65 kV/ns, a maximum voltage from 4.1 to 4.3 kV, and a switching time from 200 to 320 ps. Notably, in Fig. 2, the time delay between the switching times of 4 thyristors is less than the time of wave propagation from neighboring thyristors.

One may notice that T_1 and T_4 have similar switching conditions regarding delay time, voltage amplitude, and switching time. The same can be observed for the T_2 and T_3 . From the setup, we can explain this by the symmetry of T_1 and T_4 to T_2 and T_3 with respect to the trigger generator connection.

In order to examine the reproducibility of experimental results, this test was repeated over 10 shots. The average value of the rise rate of overvoltage pulses varies from 1.29 kV/ns to 1.48 kV/ns. In addition, a fast switching time from 193 ps to 293 ps on average is measured across four thyristors in 10 experiments. Subnanosecond switching time proves the possibility of further scaling of parallel connection for switching of high-voltage thyristors in impact-ionization wave mode.

III. NUMERICAL SIMULATION

To gain a more comprehensive insight into the physics of impact-ionization switching, a numerical study of this phenomenon is conducted using Synopsys TCAD [21], [22]. A mix-mode device with circuit simulator is employed to simulate impact-ionization switching of parallel thyristors. In this numerical simulation, the drift-diffusion model was selected as the carrier transport model. Then, the transport equations are solved alongside the Poisson equations to consider the mutual influence of charge carriers and the electric potential. The coupling of these two sets of equations is necessary because the distribution of charge carriers affects the electric field, and the electric field influences the movement of charge carriers. Moreover, the activation of the generation-recombination process involves employing impact-ionization generation models, as well as Shockley-Read-Hall and Auger recombination mechanisms. More theoretical details can be found in [23]. The specifics of the simulated structure and the series of simulation tests are presented as follows.

A. Thyristor Structure and Doping Profile

The initial step involves defining the thyristor structure using Synopsys TCAD. In this numerical simulation, we construct a quasi-3D model of the thyristor by rotating a 2D model 360° that results in a cylindrical structure similar to the thyristor wafer assuming the cylindrical symmetry for the thyristor structure. This model of the thyristor is developed, taking into account cathode shorts existed in a real thyristor [12], [24]. The cathode shorts are the parts near the cathode surface in which the p layer reaches the cathode. The cathode shorts provide substantial improvement in the forward blocking capability for thyristors, leading to a higher electric field level over the reverse bias p-n junction compared with thyristors without cathode shorts. As illustrated in Fig. 3, a cross-sectional cutline through the 2D structure provides insight into the doping profile, extracted from the literature [12], [24] and adapted for a 2.2 kV thyristor. The structure of a four-layered thyristor ($n^+ - p - n - p^+$) is formed by diffusion of phosphorous (n^+), aluminum (p), phosphorous (n), and boron (p^+). In order to match the characteristics of the 2.2 kV thyristor, the width of the n-drift layer and its doping concentration are adjusted to $300 \mu\text{m}$ and $6.34 \times 10^{13} \text{ cm}^{-3}$, respectively. These values are specifically chosen to reach the static voltage breakdown of $\sim 2.2 \text{ kV}$, as investigated in Section III (B).

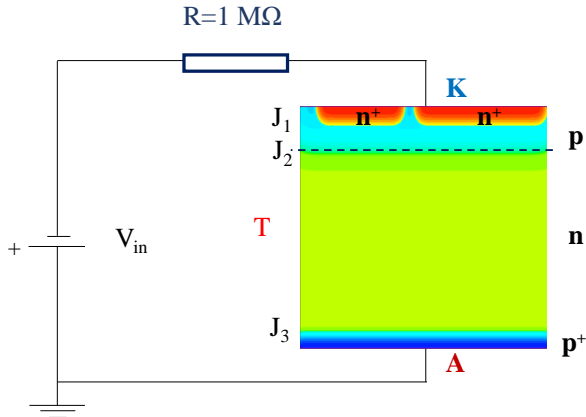


Fig. 4. The simulation circuit to test the thyristor static voltage breakdown.

B. Static Breakdown Voltage

In the second step, to confirm the accuracy of the thyristor model, a simple simulation test is conducted to investigate the static breakdown of a 32 mm, 2.2 kV thyristor, as illustrated in Fig. 4. When the anode voltage is adjusted to be positive in relation to the cathode, junctions J_1 and J_3 are forward-biased, while junction J_2 is under reverse bias. Consequently, only a minimal leakage current traverses from the anode to the cathode, indicating that the thyristor is in a blocking mode. Upon increasing the anode-to-cathode voltage to a sufficiently high level, the reversely biased junction J_2 undergoes avalanche breakdown, leading to the establishment

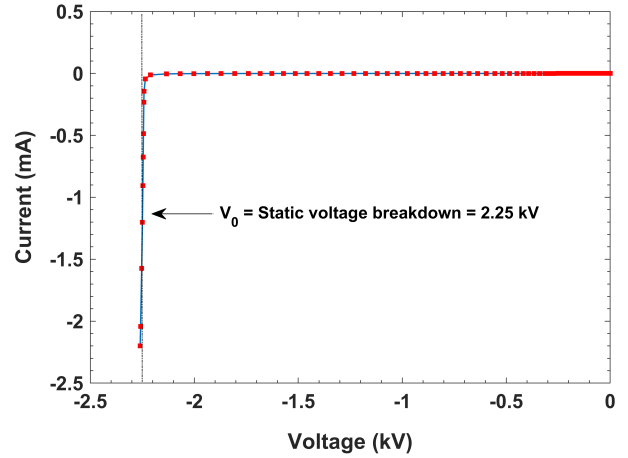


Fig. 5. The simulation result of the thyristor static voltage breakdown.

of the static breakdown voltage (V_0). Given that junctions J_1 and J_3 are already in a forward-biased state, there is free movement of carriers across all three junctions, resulting in a substantial forward anode current. At this point, the device transitions into a conducting state. In the conducting state, the anode current is limited by an external resistance ($R = 1 \text{ M}\Omega$).

In Fig. 5, the simulation results of the thyristor static breakdown voltage test are illustrated. Notably, the breakdown voltage is observed at 2.25 kV, exhibiting a favorable correlation with experimental data. This promising agreement motivates the exploration of additional tests employing the developed thyristor model.

C. Suppression of Unwanted dV/dt Triggering

During transient conditions, a forward-blocking thyristor may transition to its conducting state at voltages below the static breakdown voltage. This undesirable phenomenon, known as dV/dt triggering (where V is the voltage across anode with respect to cathode), can unintentionally switch on a thyristor under transients. The dV/dt effect is a consequence of the rapidly changing anode-cathode voltage, resulting in a displacement current across junction J_2 , given by $C \times \frac{dV}{dt}$, where C is the depletion capacitance of J_2 . The origin of dV/dt triggering can be explained as follows. In the forward-blocking state, most of the applied voltage will be across junction J_2 . Any change in voltage alters the depletion width of J_2 , causing majority carriers on both sides of J_2 to flow, generating the displacement current. This displacement current functions similarly to the gate current [24].

In power thyristors, dV/dt ratings must be high to prevent false triggering. An effective method to improve the dV/dt rating involves the use of cathode shorts, as illustrated in Fig. 3. The displacement current (holes) into the J_1 junction is redirected through the shorts. Cathode shorts significantly enhance the dV/dt capability of high-voltage thyristors. Whereas typical ratings of $20 \text{ V}/\mu\text{s}$ achievable in thyristors without cathode shorts, the dV/dt rating can be increased by a factor of 10 to more than 100 in shorted devices [24].

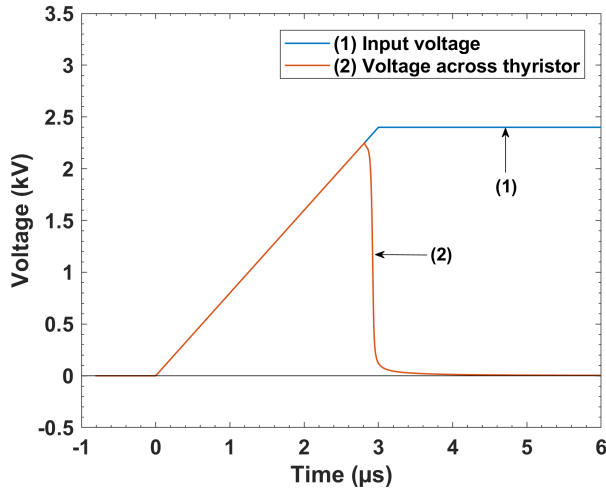


Fig. 6. Simulation results illustrating the resilience of the modeled thyristor toward unwanted dV/dt triggering, particularly at low voltages.

Thus, an unwanted dV/dt triggering is simulated by applying an input voltage with a typical rise rate of $0.8 \text{ kV}/\mu\text{s}$. In the context of this simulation, we conduct a test on the high-voltage thyristor with modeled cathode shorts, particularly to observe the occurrence of dV/dt triggering. As illustrated in Fig. 6, the model demonstrates robustness against undesired dV/dt triggering at low voltages. Specifically, the thyristor triggering occurs only after exceeding the static voltage breakdown value, i.e., 2.2 kV .

It is noteworthy that the dV/dt of the input voltage is far below the threshold value for the impact-ionization switching (1 kV/ns). Additionally, the result indicates a switching time of 100 ns , underscoring the comparatively slow nature of this phenomenon when compared with impact ionization switching, where the switching time is typically less than 1 ns .

D. Delayed Impact-Ionization Breakdown

To initiate the impact-ionization switching mechanism, a steep overvoltage pulse is applied across the anode and cathode, with the gate electrode remaining unconnected. This overvoltage pulse has a rise rate exceeding 1 kV/ns and an amplitude of more than twice the static voltage breakdown (V_0).

For the numerical simulation of impact-ionization switching of high-voltage thyristor, various standard models such as van Overstraeten-de Man [25], Okuto-Crowell [26], Lackner [27] and the new University of Bologna [28]–[30] are tested. The aim is to reach a better agreement with the characteristics of the overvoltage pulse derived from experiments. These characteristics include over-voltage pulse rise rate, maximum voltage, and switching time.

During the transient analysis phase, the thyristor undergoes impact-ionization switching in wave mode, and we compare different impact-ionization models to identify the most accurate one. All models exhibit a rise rate exceeding 1 kV/ns , reaching a maximum of around twice the static breakdown. After simulation result evaluation, the van Overstraeten-de Man

model is selected due to its similarity to experimental results, particularly its accurate representation of maximum overvoltage when compared with the experimental result, as illustrated in Fig. 7.

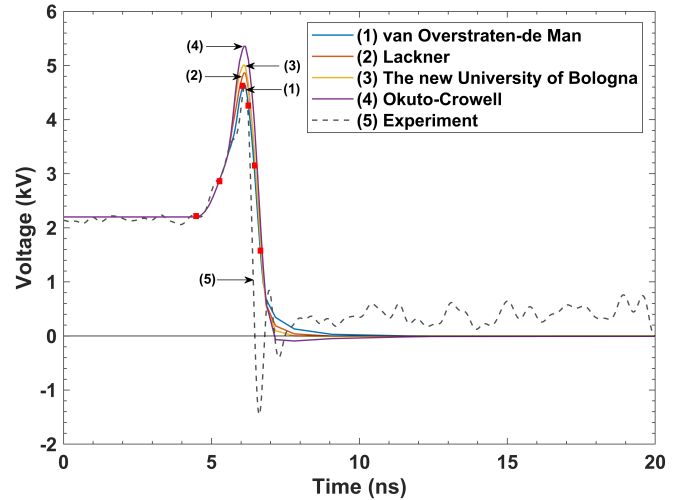


Fig. 7. The numerical simulation result of the voltage across thyristor for four different impact-ionization models in comparison with the experimental result. The red square marks indicate the time points at which the simulation results are captured for analysis (shown in Fig. 8, Fig. 9, and Fig. 10).

The numerical simulation results enable us to observe the electric field development inside the thyristor structure, providing insights into the inner dynamics of the impact-ionization mechanism. To examine electric field development, square marks on the voltage pulse highlight the simulation time, as shown in Fig. 7 (curve number 1). The simulation time is from 4.45 ns to 6.65 ns , with a time interval of 800 ps for the first two intervals and 200 ps for the rest of the intervals. The simulation starts at a bias voltage of 2.2 kV , allowing an increase in the electric field near the reversed bias p-n junction (J_2). Meanwhile, the n-drift layer has a comparatively lower electric field. Subsequently, an overvoltage pulse characterized by a steep voltage rise rate (1 kV/ns) is applied. The first point captured at bias voltage, and $t = 4.45 \text{ ns}$ shows an electric field of $1.91 \times 10^5 \text{ V/cm}$ right below the electric field threshold for delayed impact-ionization breakdown, as shown in Fig. 8 (a). In this condition, the space charge region predominantly occupies the n-drift layer (Fig. 9, curve number 1).

Further increase in the overvoltage pulse results in a higher electric field, surpassing the electric field threshold for delayed impact-ionization breakdown. Within a short time frame of 800 ps from the applied trigger pulse, the electric field at the p-n junction surpasses the threshold required for avalanche breakdown ($2.14 \times 10^5 \text{ V/cm}$), as depicted in Fig. 8(b). From this point, a further increase in the electric field initiates an intense impact ionization process that generates the electron-hole plasma. Fig. 8(c) illustrates a high electric field of $2.5 \times 10^5 \text{ V/cm}$ right before the thyristor switching time.

Following the thyristor dynamics in impact-ionization wave mode, the electric field near the p-n junction J_2 decreases,

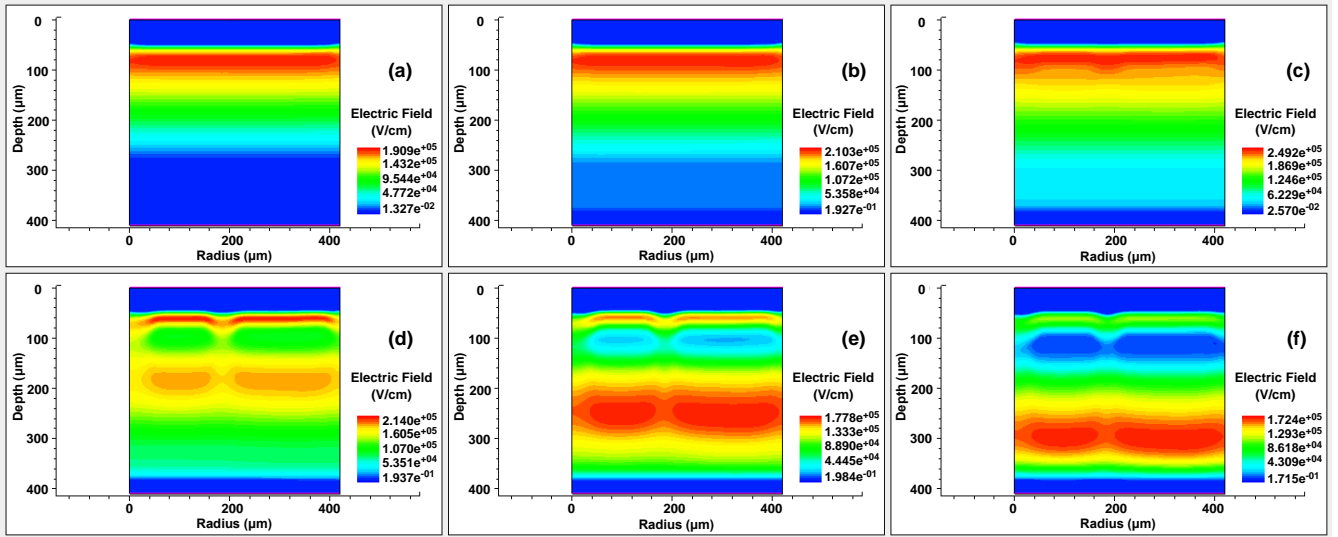


Fig. 8. The 2D simulation result of electric field development inside the thyristor. The simulation time is considered from 4.45 ns to 6.65 ns with a time interval of 800 ps for the first two intervals and 200 ps for the rest of the intervals (shown as square marks in Fig. 7).

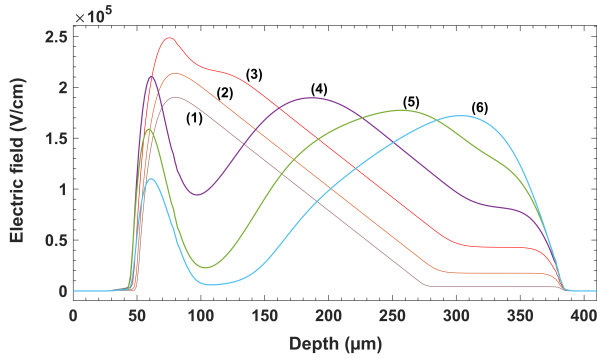


Fig. 9. The 1D simulation result of electric field development inside the thyristor. The simulation time is considered from 4.45 ns to 6.65 ns with a time interval of 800 ps for the first two intervals and 200 ps for the rest of the intervals (shown as square marks in Fig. 7).

being pushed out by the electron-hole plasma, while at the same time intensifying in the adjacent part of the space charge region (Fig. 8(d) and curve number 4 in Fig. 9). This process facilitates the direct injection of electron-hole plasma within the vicinity of the breakdown p-n junction, as depicted in Fig. 10 (a) and Fig. 10 (b), curve number 4. Consequently, as illustrated in Fig. 8 (e) and Fig. 8 (f), the ionization zone shifts, indicating the propagation of the impact-ionization front. This superfast ionization front moves within the depletion region at an average velocity of $V_f = \frac{210\mu\text{m}}{600\text{ps}} = 3.5 \times 10^7 \text{ cm/s}$, as shown in Fig. 9 from curve number 3 to 6. The velocity of the ionization front is 3.5 times faster than the saturation velocity of electrons in silicon. This eventually results in a subnanosecond switching time in impact-ionization switching mode.

Fig. 10 (a) and Fig. 10 (b) (curve number 1 to 6) depict electron and hole densities during the aforementioned simulation time, illustrating the gradual increase in electron and hole densities within the thyristor structure. As indicated in

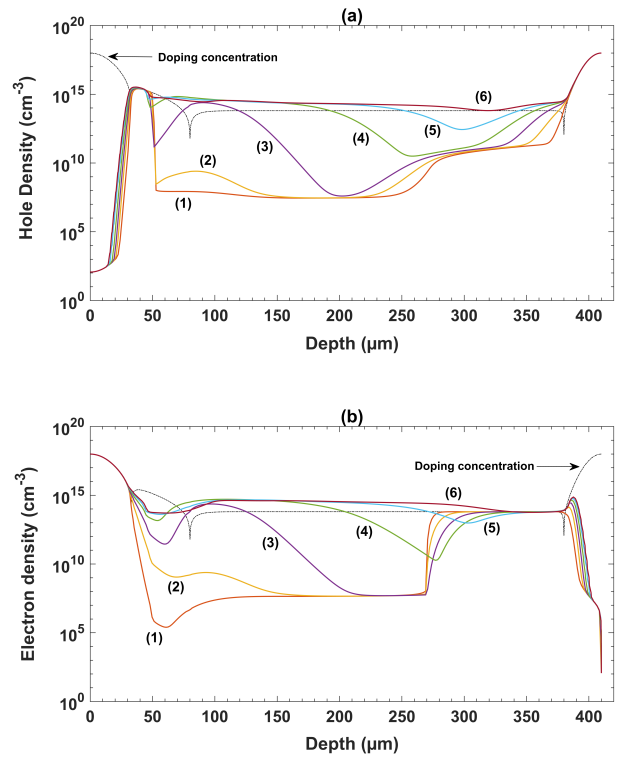


Fig. 10. The simulation result of the thyristor inner dynamics in impact-ionization switching mode (a) hole density, and (b) electron density. The simulation time is considered from 4.45 ns to 6.65 ns with a time interval of 800 ps for the first two intervals and 200 ps for the rest of the intervals (shown as square marks in Fig. 7).

Fig. 9 (curve number 3), the initiation of a superfast ionization front right before switching time leads to an increase in electron-hole plasma near the p-n junction (J_2), as shown in Fig. 10 (a) and (b) (curve number 3). Then, as the impact-ionization front moves forward within the n-drift layer of the

thyristor, the further injection of electrons and holes from the heavily doped n^+ and p^+ layers allows further increase in electron-hole plasma, as illustrated in Fig. 10 (a) and (b) (curve number 4, 5, and 6). These processes collectively result in the rapid filling of the n-drift layer of the thyristor structure with electron-hole plasma within mere hundreds of picoseconds. Consequently, the thyristor undergoes a transition to the conducting state.

The simulation results presented in Fig. 9 and Fig. 10 can be validated through either theoretical analysis of impact-ionization phenomena as discussed in prior works [13]–[16], [31] or experimental verification. Firstly, the simulation results in this article comply with the developed theory of the phenomenon including (i) the formation of a superfast impact-ionization wave at peak overvoltage pulse amplitude and its movement inside the structure during switching time, and (ii) the increase in electron-hole densities near the p-n junction at the initial phase of the breakdown, which pushes away superfast ionization front inside n-drift layer. Secondly, in terms of the experiment, we analyze the accuracy of electric field development and the electron-hole densities inside the structure by comparing the measured voltage pulse with numerical simulation results in Section IV. This can indirectly confirm the numerical simulation accuracy of the electric field and electron-hole densities inside the thyristor.

IV. EXPERIMENTAL VERSUS NUMERICAL SIMULATION RESULTS

In this section, experimental results of parallel switching of two thyristors (T_1^* and T_2^*) in impact-ionization wave mode are compared with the numerical simulation. In the experimental work described in detail in [17], a bias voltage of 2.2 kV is applied across two parallel thyristors. The overvoltage pulse across each parallel thyristor is measured employing the high-frequency voltage probe described in Section II. The voltage waveforms are shown and compared with the numerical simulation in Fig. 11 (a) and (b).

During parallel triggering, a voltage rise rate of 1.6 kV/ns and 1.3 kV/ns for the thyristors T_1^* and T_2^* , respectively, results in maximum voltages of 4.6 kV and 3.8 kV. We believe that these different values of voltage rise rate are due to different inductive path connections from the trigger circuit to the thyristors T_1^* and T_2^* . Subnanosecond switching times are measured for T_1^* and T_2^* as 230 ps and 400 ps, respectively. A faster switching time of T_1^* compared to T_2^* resulted from a better-triggering condition namely higher dV/dt and higher maximum voltage amplitude.

Three notable findings can be stated from the experimental and simulation results comparison. (i) An accurate agreement between experimental results and numerical simulation is observed in terms of voltage rise time and maximum overvoltage pulse. (ii) Both the experimental and simulation results affirm that an improved triggering condition, characterized by higher dV/dt and a greater maximum voltage amplitude, leads to a faster switching time. (iii) Although the numerical simulation indicates subnanosecond switching times for parallel thyristors, a longer switching time of 600 ps and 820 ps is reached

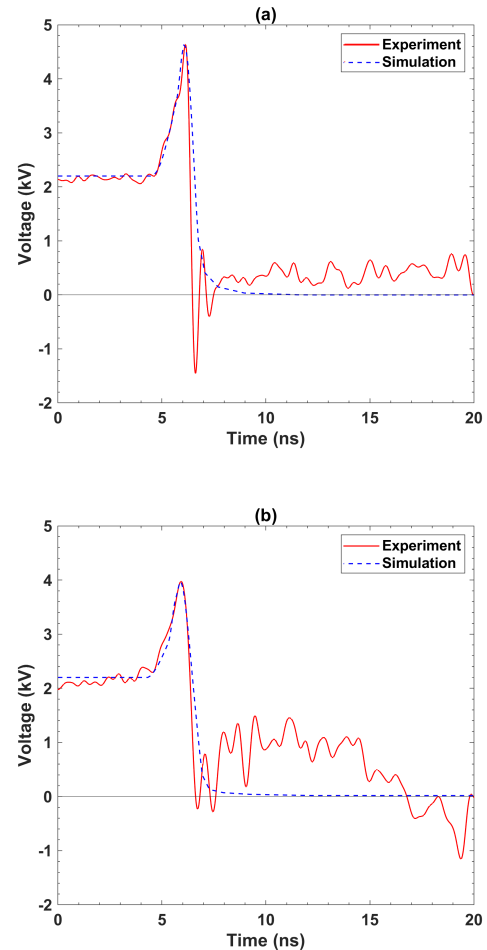


Fig. 11. The experimental and simulation result comparison of the overvoltage pulse in parallel connection (a) T_1^* , and (b) T_2^* .

(for T_1^* and T_2^* , respectively) when compared to experimental results. This mismatch may be attributed to standard impact-ionization models, wherein the entire area of the thyristor structure is involved in the formation of the impact-ionization front. Recent theory in impact-ionization switching suggests that only a fraction of the thyristor cross-section is active during avalanche breakdown. Further research is necessary to achieve a better theoretical understanding of impact-ionization switching phenomena in high-voltage thyristors.

V. CONCLUSION

This study proves the impact-ionization switching mechanism in parallel-connected high-voltage thyristors. Experimental and numerical approaches are employed to understand and validate the impact-ionization switching process.

The experimental setup involves triggering four thyristors in parallel with a novel configuration. The trigger circuit, thyristor assembly, and diagnostics are carefully arranged to ensure accurate measurements. Parallel switching is emphasized for its cost-effectiveness and enhanced current-handling capability, overcoming limitations related to the wafer's cross-sectional area.

Numerical simulations using Synopsys TCAD complement the experimental work, providing insights into the physics of impact-ionization switching. The simulations include tests for static breakdown voltage, unwanted dV/dt triggering, and delayed impact-ionization breakdown. The impact-ionization models are compared to find a better alignment with experimental characteristics, such as rise rate, maximum voltage, and switching time. Whereas numerical simulation suggests a subnanosecond switching time for parallel thyristors, the actual switching time achieved is longer when compared to the experimental results. Additional investigation is required to enhance the theoretical comprehension of impact-ionization switching phenomena in high-voltage thyristors.

REFERENCES

- [1] I. V. Grekhov and A. F. Kardo-Sysoev, "Subnanosecond current drops in delayed breakdown of silicon pn junctions," *Sov. Tech. Phys. Lett.*, vol. 5, no. 8, pp. 395–396, 1979.
- [2] R. Focia, E. Schamiloglu, C. Fleddermann, F. Agee, and J. Gaudet, "Silicon diodes in avalanche pulse-sharpening applications," *IEEE Transactions on Plasma Science*, vol. 25, no. 2, pp. 138–144, 1997.
- [3] L. M. Merensky, A. F. Kardo-Sysoev, D. Shmilovitz, and A. S. Kesar, "The driving conditions for obtaining subnanosecond high-voltage pulses from a silicon-avalanche-shaper diode," *IEEE Transactions on Plasma Science*, vol. 42, no. 12, pp. 4015–4019, 2014.
- [4] I. V. Grekhov, S. V. Korotkov, and P. B. Rodin, "Novel closing switches based on propagation of fast ionization fronts in semiconductors," *IEEE Transactions on Plasma Science*, vol. 36, no. 2, pp. 378–382, 2008.
- [5] I. Grekhov, S. Korotkov, A. Stepaniants, D. Khristyuk, V. Voronkov, and Y. Aristov, "High-power semiconductor-based nano and subnanosecond pulse generator with a low delay time," *IEEE Transactions on Plasma Science*, vol. 33, no. 4, pp. 1240–1244, 2005.
- [6] A. I. Gusev, S. K. Lyubutin, S. N. Rukin, and S. N. Tsyranov, "High power thyristors triggering providing a subnanosecond closing time," in *2014 IEEE International Power Modulator and High Voltage Conference (IPMHVC)*, 2014, pp. 31–34.
- [7] A. Gusev, S. Lyubutin, S. Rukin, and S. Tsyranov, "A thyristor switch with a subnanosecond switching time," *Instruments and Experimental Techniques*, vol. 58, no. 3, pp. 376–380, 2015.
- [8] A. I. Gusev, S. K. Lyubutin, S. N. Rukin, and S. N. Tsyranov, "Superfast thyristor-based switches operating in impact-ionization wave mode," *IEEE Transactions on Plasma Science*, vol. 44, no. 10, pp. 1888–1893, 2016.
- [9] A. Gusev, S. Lyubutin, V. Patrakov, S. Rukin, B. Slovikovskiy, M. Barnes, T. Kramer, and V. Senaj, "Fast high-power thyristors triggered in impact-ionization wave mode," *Journal of Instrumentation*, vol. 14, no. 10, pp. 10 006–10 006, 2019.
- [10] A. Gusev, S. Lyubutin, A. Ponomarev, S. Rukin, B. Slovikovskiy, and S. Tsyranov, "High current and current rise rate thyristor based switches," in *2017 IEEE 21st International Conference on Pulsed Power (PPC)*, 2017, pp. 1–5.
- [11] J. Lehr and P. Ron, *Foundations of Pulsed Power Technology*. Hoboken, NJ, USA: Wiley, 2018, pp. 147–250.
- [12] B. J. Baliga, *Fundamentals of Power Semiconductor Devices*. Boston: New York, Springer, 2008.
- [13] M. Ivanov, V. Brylevskiy, I. Smirnova, and P. Rodin, "Picosecond-range switching of high-voltage si diode due to the delayed impact-ionization breakdown: Experiments vs simulations," *Journal of Applied Physics*, vol. 131, p. 014502, 01 2022.
- [14] H. Jalali, R. Joshi, and J. Gaudet, "Effects of transverse doping variations on the transient response of silicon avalanche shaper devices," *IEEE Transactions on Electron Devices*, vol. 45, no. 8, pp. 1761–1768, 1998.
- [15] P. B. Rodin, A. M. Minarsky, and I. V. Grekhov, "Numerical simulation of spatially nonuniform switching in silicon avalanche sharpening diodes," *Technical Physics Letters*, vol. 38, pp. 535–539, 2012. [Online]. Available: <https://api.semanticscholar.org/CorpusID:121657719>.
- [16] V. I. Brylevskiy, I. A. Smirnova, N. I. Podolska, Y. A. Zharova, P. B. Rodin, and I. V. Grekhov, "Picosecond-range avalanche switching of bulk semiconductors triggered by steep high-voltage pulses," *IEEE Transactions on Plasma Science*, vol. 47, no. 1, pp. 994–999, 2019.
- [17] E. Shahriari, T. Maysonnave, A. I. Gusev, A. S. de Ferron, L. Pécastaing, and B. M. Novac, "Impact-ionization switching of high-voltage thyristors connected in parallel," *IEEE Transactions on Plasma Science*, vol. 51, no. 10, pp. 2878–2884, 2023.
- [18] E. Shahriari, T. Maysonnave, A. I. Gusev, A. S. de Ferron, and L. Pécastaing, "A study of a 5.2-kv/100-mm thyristor triggered in impact-ionization mode toward fast high-current applications," *IEEE Transactions on Plasma Science*, vol. 50, no. 10, pp. 3452–3458, 2022.
- [19] P.-E. *Phase Control Thyristor Type T333–250–24*. Accessed: Mar. 26, 2024. [Online]. Available: https://www.proton-electrotext.com/files/project_5610/tmp_download_file/T333-250-24_eng_v1.2.pdf
- [20] V. S. Belkin and G. I. Shulzchenko, "Generators of powerful nanosecond and picosecond pulses based on a semiconductor element base," *Inst. Nucl. Phys., Novosibirsk, Russia, Tech. Rep. 91-51*, 1991.
- [21] *Sentaurus Device User Guide*. Synopsys, Mountain View, CA, USA, 2021.
- [22] *Compact Models User Guide*. Synopsys, Mountain View, CA, USA, 2021.
- [23] R. Pierret, *Advanced Semiconductor Fundamentals*, 2nd ed., ser. Modular series on solid state devices. Pearson Education, Inc., 2002.
- [24] S. Sze, *Semiconductor Devices: Physics and Technology*. John Wiley & Sons Singapore Pte. Limited, 2012.
- [25] R. Van Overstraeten and H. De Man, "Measurement of the ionization rates in diffused silicon p-n junctions," *Solid-State Electronics*, vol. 13, no. 5, pp. 583–608, 1970.
- [26] Y. Okuto and C. Crowell, "Threshold energy effect on avalanche breakdown voltage in semiconductor junctions," *Solid-State Electronics*, vol. 18, no. 2, pp. 161–168, 1975.
- [27] T. Lackner, "Avalanche multiplication in semiconductors: A modification of chynoweth's law," *Solid-State Electronics*, vol. 34, no. 1, pp. 33–42, 1991.
- [28] E. Gnani, S. Reggiani, M. Rudan, and G. Baccarani, "Extraction method for the impact-ionization multiplication factor in silicon at large operating temperatures," 2002, pp. 227–230.
- [29] S. Reggiani, M. Rudan, E. Gnani, and G. Baccarani, "Investigation about the high-temperature impact-ionization coefficient in silicon," in *Proceedings of the 30th European Solid-State Circuits Conference (IEEE Cat. No.04EX850)*, 2004, pp. 245–248.
- [30] S. Reggiani, E. Gnani, M. Rudan, G. Baccarani, C. Corvasce, D. Barlini, M. Ciappa, W. Fichtner, M. Denison, N. Jensen, G. Groos, and M. Stecher, "Experimental extraction of the electron impact-ionization coefficient at large operating temperatures," in *IEDM Technical Digest. IEEE International Electron Devices Meeting, 2004.*, 2004, pp. 407–410.
- [31] M. Levinshtein, J. Kostamovaara, and S. Vainshtein, *Breakdown Phenomena in Semiconductors and Semiconductor Devices*, ser. International journal of high speed electronics and systems. World Scientific, 2005.



Ejlal Shahriari (Graduate Student Member, IEEE) was born in Nowdesheh, Kurdistan, Iran. He received the M.Sc. degree in power system engineering from the K.N. Toosi University of Technology, Tehran, Iran, in 2014, and the master's degree in electrical engineering for sustainable development (E2SD) from Université de Lille, Lille, France, in 2019.

From 2020 to 2021, he worked on modular multilevel converter (MMC)-based HVDC control systems at EnergyVille Genk, Belgium. He is currently working toward the Ph.D. degree in high power thyristors triggered in impact-ionization wave mode with the Laboratoire des Sciences de l'Ingénieur Appliquées à la Mécanique et au Génie Électrique (SIAME Laboratory). His research interests include high voltage pulsed power systems, picosecond impact-ionization switching of high voltage thyristors, and HVDC power systems control.

Mr. Shahriari was a recipient of the IEEE Nuclear and Plasma Sciences Society (NPSS) Outstanding Student Paper Award at the IEEE Pulsed Power and Plasma Science Conference in 2023.



Anton I. Gusev (Member, IEEE) was born in Miass, Russia, in 1988. He received the M.S. degree in electrophysics from Ural Federal University (UrFU), Yekaterinburg, Russia, in 2012, and the Ph.D. degree in engineering sciences from the Institute of Electrophysics, Ural Branch of the Russian Academy of Sciences (IEP), Yekaterinburg, in 2019.

From 2008 to 2019, he was with IEP as an Intern, a Ph.D. Student, and a Junior Researcher with the Pulsed Power Laboratory. At the same time, from 2014 to 2019, he was with UrFU as a Senior Teacher.

In 2019, he became a Post-Doctoral Researcher with the Université de Pau et des Pays de l'Adour (UPPA), Pau, France, where he has been an Assistant Professor with the Laboratoire des Sciences de l'Ingénieur Appliquées à la Mécanique et au Génie Électrique (SIAME Laboratory) since 2020. His research interests include semiconductor physics, high-power semiconductor switches, and high-voltage solid-state generators, which provide nano- and subnanosecond pulses.

Dr. Gusev is a member of the International Society on Pulsed Power Applications (ISP) and the Association for the Advancement of Pulsed Power (A2P2). He has been awarded the Young Researcher at major international pulsed power conferences (the Energy Fluxes and Radiation Effects (EFRE) 2016, the Euro-Asian Pulsed Power Conference (EAPPC) 2018, and the Gas Discharge Plasmas and Their Applications (GDP) 2021), including two supported by IEEE Pulsed Power Conference (PPC) 2017 and the IEEE International Power Modulator and High Voltage Conference (IPMHVC) 2018.



Laurent Pecastaing (Senior Member, IEEE) received the Ph.D. and Research Directorship Habilitation degrees in electrical engineering from the Université de Pau et des Pays de l'Adour (UPPA), Pau, France, in 2001 and 2010, respectively. He is currently a Full Professor in pulsed power with University of Pau. He is the director of the SIAME laboratory and he is also the Director of a Common Laboratory between UPPA and CEA, France.

His current research interests include high-power microwave sources, compact pulsed power systems, and ultrafast transient probes. Dr. Pecastaing was the chairperson of the Euro-Asian Pulsed Power Conference/High-Power Particle Beams/Megagauss Magnetic Field Generation and Related Topics (EAPPC/BEAMS/MEGAGAUSS) Conference, France, in 2021. He is also a member of the International Steering Committees for both the BEAMS Conferences and the Euro-Asian Pulsed Power Conferences.



Thomas Maysonnave was born in Orthez, France, in 1985. He received the Ph.D. degree in electrical engineering from the Université de Pau et des Pays de l'Adour (UPPA), Pau, France, in 2013. He was Researcher with the International Technologies for High Pulsed Power (ITHPP), Thégra, France, from 2010 to 2020. He is currently a PostDoc with the Laboratoire des Sciences de l'Ingénieur Appliquées à la Mécanique et au Génie Électrique (SIAME Laboratory). His current research interests include high-pulsed power generation, including Marx generators

and pulse-forming lines.



Antoine Silvestre de Ferron was born in Tarbes, France, in 1977. He received the master degree in electrical and electronic engineering from the University of Toulouse, Toulouse, France, and the Ph.D. degree in electrical engineering from the University of Pau, Pau, France, in 2002 and 2006, respectively.

From 2006 to 2008, he was a Researcher with the Atomic Energy Commission (CEA), a French government-funded technological research organization in Le Barp, France. He is currently an engineer at the head of the High Voltage Processes Teams in

the SIAME laboratory of the University of Pau, France. His research interests include high-pulsed power generation, with military and civil applications. He is specialized in Marx generator and pulse forming lines in high voltage generation, in high voltage transient probes associated and in high current discharges in liquids.