Received: 23 February 2022 | Revised: 28 May 2022 | Accepted: 23 June 2022

DOI: 10.4218/etrij.2022-0077

ORIGINAL ARTICLE

ETRI Journal WILEY

Human body model electrostatic discharge tester using metal oxide semiconductor-controlled thyristors

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Funding information
This material is based upon work supported by the National Research Council of Science and Technology grant funded by the Korea government (MSIP) (CRC-19-02-ETRI).

Abstract

Electrostatic discharge (ESD) testing for human body model tests is an essential part of the reliability evaluation of electronic/electrical devices and components. However, global environmental concerns have called for the need to replace the mercury-wetted relay switches, which have been used in ESD testers. Therefore, herein, we propose an ESD tester using metal oxide semiconductor-controlled thyristor (MCT) devices with a significantly higher rising rate of anode current (di/dt) characteristics. These MCTs, which have a breakdown voltage beyond 3000 V, were developed through an in-house foundry. As a replacement for the existing mercury relays, the proposed ESD tester with the developed MCT satisfies all the requirements stipulated in the JS-001 standard for conditions at or below 2000 V. Moreover, unlike traditional relays, the proposed ESD tester does not generate resonance; therefore, no additional circuitry is required for resonant removal. To the best of our knowledge, the proposed ESD tester is the first study to meet the JS-001 specification by applying a new switch instead of an existing mercury-wetted relay.

KEYWORDS

electrostatic discharge tester, high rate of rising of anode current (di/dt), human body model, mercury-wetted relay, metal oxide semiconductor-controlled thyristor

1 | INTRODUCTION

Electrostatic discharge (ESD) testing is crucial for ascertaining the safety of electronics and electrical devices. As per the ANSI/ESDA/JEDEC JS-001 standards, the human body model (HBM) test is one of the reliability tests required to be conducted during the semiconductor production process [1]. As per the JS-001 standard, performance values such as peak current (I_{ps}), rise time (t_r), decay time (t_d), and ringing current (I_r) are considered to be highly significant factors.

Figure 1 depicts a simplified schematic diagram of a typical ESD tester used in the HBM test. Here, a high-voltage source charges a capacitor (C_1) through a

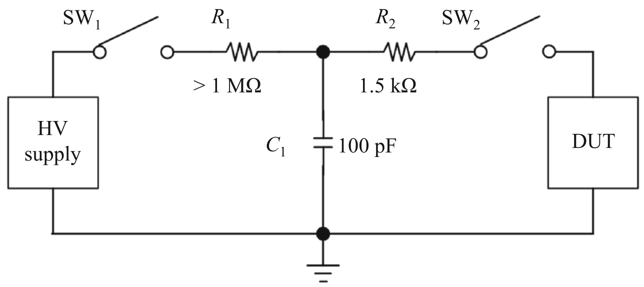

FIGURE 1 Simplified electrostatic discharge tester circuit diagram for human body model (HBM) test

charging resistor (R_1) with a resistance exceeding 1 MΩ when a charging switch (SW_1) is turned on. In this system, C_1 represents the human body, with a capacitance of 100 pF, whereas R_2 represents an arm, with a resistance of 1.5 kΩ. The rising rate of anode current (di/dt) characteristics of mercury-wetted relay switches is similar to those of an ideal switch; therefore, they are commonly used for charging and discharging in ESD testers.

However, the use of mercury relays raises important technical and environmental issues that need to be addressed. For example, owing to the self-inductance of the relay, a considerable voltage spike occurs instantaneously because of sparks when the contact breaks. Additionally, resonances with significantly higher maximum peak currents occur because of the inductance of the relay and parasitic components of the ESD tester.

Figure 2A shows the output current waveforms from an ESD tester using conventional mercury relays acting as switches under the condition of a short-circuiting wire at applied voltages of 250 V, 500 V, and 1000 V. When conventional mercury-wetted relays were applied to the ESD tester without any additional circuits, a substantially higher peak current characteristic than that at the source voltage was observed, as specified by international standards [1]. For example, in the JS-001 standard under a voltage condition of 1000 V, the peak current is defined to be in the range 0.6 A–0.73 A; however, the experimental results show a peak current of ~1.6 A. Furthermore, it is evident that the resonance occurs when the relays are applied as switches without the addition of other circuits. Moreover, the high-current characteristics and resonance phenomenon can adversely affect the peripheral circuitry of the instrument, causing malfunction or destruction of the surrounding circuits. Therefore, an additional resonant removal circuit (RRC) block is generally required to mitigate these potential problems. Figure 2B shows a comparison of waveforms measured under conditions of 1000 V with (w/) and without (w/o) RRC.

A more pressing issue than the technical ones mentioned earlier is the restrictions imposed on the use of

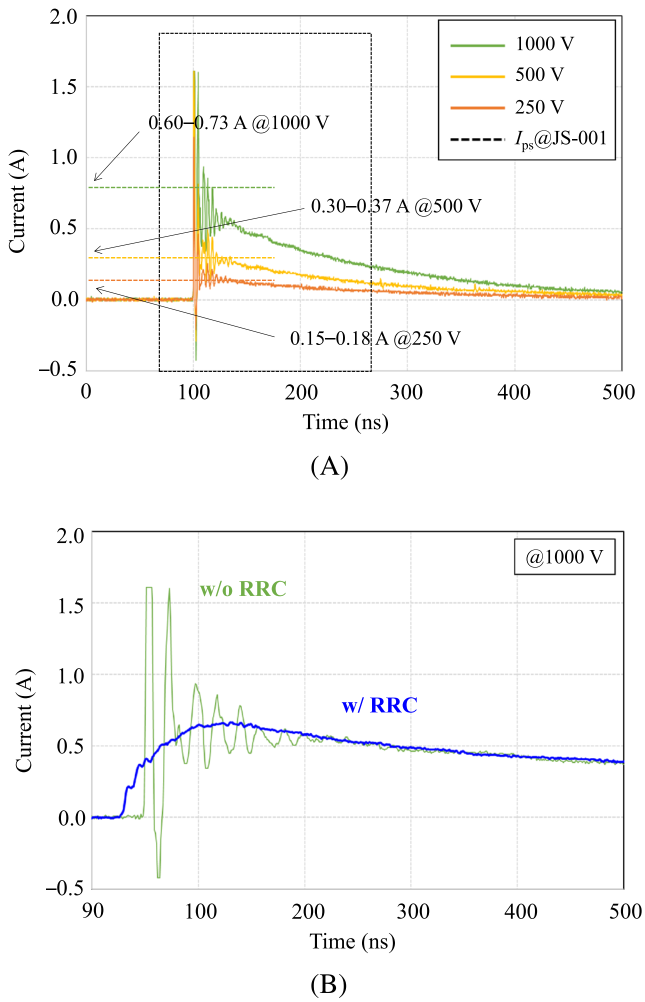

FIGURE 2 Measured current waveforms in HBM tester using mercury relays (A) under 250 V, 500 V, and 1000 V and (B) under 1000 V conditions with and without resonant removal circuit (RRC)

mercury relays owing to global environmental concerns [2–5], which call for the development of a new switch. It is known that a solid-state relay that integrates insulated gate bipolar transistors (IGBTs) or metal oxide semiconductor field-effect transistors (MOSFETs) with photocouplers can replace a mercury-wetted relay; however, its rising time is at the microsecond level, and there have been no reports of results applied to ESD testers for HBM till date [6–8]. Moreover, MOS-controlled thyristors (MCTs) are well-known for their remarkable di/dt properties [9–11].

This paper describes the proposed MCT-based ESD tester, which was developed as per the ANSI/ESDA/JEDEC JS-001 standards in an in-house foundry at the Electronics and Telecommunications Research Institute, for HBM testing. Moreover, for the first time, an attempt has been made to replace the ESD tester using the mercury-wetted relay with an ESD tester using MCTs, which is the novelty of this study.

2 | ESD TESTER BASED ON MCTS

Figure 3 shows the photograph and measured breakdown voltage characteristics of an MCT, which was developed and manufactured at an in-house foundry. The MCT was manufactured using a 6-in. silicon wafer, and the MCT bare die was 5.4 mm × 5.4 mm in size. When the gate voltage is 0 V, the leakage current is ∼12.0 nA for an anode voltage of 2000 V, and the breakdown voltage is ∼3000 V. This paper does not focus on the design and fabrication details of the MCT device; hence, they are not provided here.

Figure 4 illustrates the simplified block diagram of an ESD test board that complies with ANSI/ESDA/JEDEC JS-001 specifications; the diagram consists of a control block and an ESD tester. Semiconductor switches, such as high-voltage solid-state relays, MCTs, IGBTs, and silicon carbide (SiC) MOSFETs, can be considered as alternatives to conventional mercury-wetted relays in ESD testers. However, solid-state relays have a long rising time in the order of microseconds [6–8]. The IGBTs and SiC MOSFETs require a minimum voltage of 15 V to turn on the gate [12,13]. Conversely, MCTs exhibit both high peak current and high di/dt slope [9–11]. Moreover, MCTs require a relatively low gate turn-on voltage of 5 V, which is one of the major benefits of replacing mercury relays in the ESD testers.

For the charging (SW_1) and discharging switches (SW_2) shown in Figure 1, the aforementioned self-developed MCTs were used instead of conventional mercury-wetted relays. To drive the gate of the MCT to ±5 V, each boost converter outputs a voltage of 10 V for an input voltage of 5 V from the main instrument. The isolated MCT gate driver for ±5 V operation comprises a switching driver, Zener diodes, capacitors, and resistors. A high-voltage power supply for ESD test voltages, low-voltage power supply, and MCT gate driver are all controlled by a control block (MICOM).

Figure 5 shows the proposed ESD test board and tester module with dimensions of 120 mm × 70 mm and 23 mm × 23 mm, respectively. The inductance of the discharging loop of the ESD tester module can influence the rise time, ringing, and decay time of the output current. To minimize these influences, an MCT bare die was used to fabricate the ESD tester module and minimize the length of the discharging loop by fabricating it as a chip-on-board. Additionally, the cathode of the MCT bare die was connected by four stitch-bonded aluminum (Al) wires with a thickness of 5 mil, as shown in Figure 5D.

Figure 6 depicts the output current waveforms of the proposed ESD tester and an ESD tester with conventional relays under the condition of a short-circuiting wire at 1000 V. The waveforms were measured at a bandwidth of 1 GHz and sampling rate of 5 GS/s using a Tektronix CT1 current probe. Although the developed MCTs were applied to the ESD tester (red) without any additional circuits, no resonance occurred, in contrast with conventional relays (green). The proposed ESD tester exhibited characteristics almost identical to those of an ESD tester with conventional relays, to which relays and an RRC block have been added (blue). From this result, we can see that MCT can solve environmental issues by replacing conventional mercury-wetted relays. Moreover, we can see that the proposed ESD tester does not require RRC because resonance does not occur.

According to the ANSI/ESDA/JEDEC JS-001 standard, the required voltage levels for testing are 250 V, 500 V, 1000 V, 2000 V, and 4000 V. However, as the

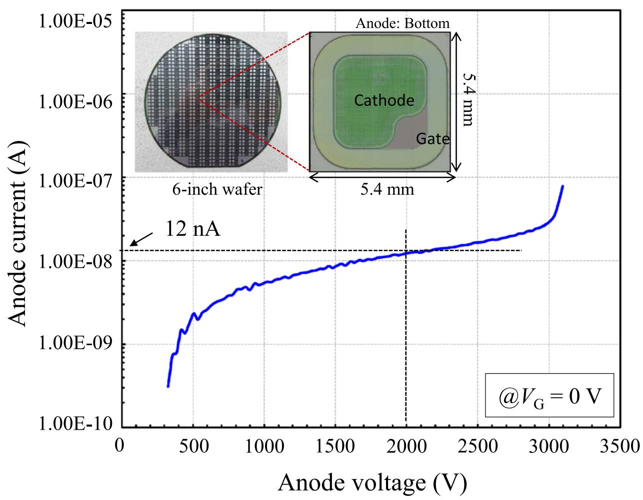

FIGURE 3 Photograph and measured breakdown voltage behavior of the fabricated MCT device

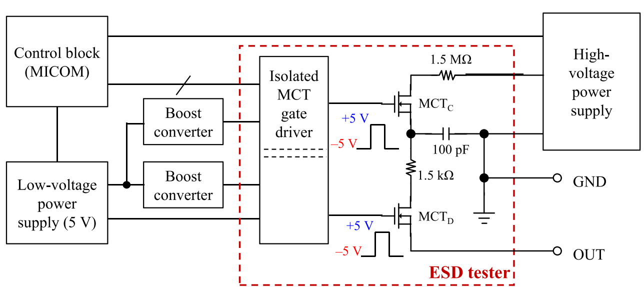

FIGURE 4 Simplified block diagram of an electrostatic discharge test board including the proposed electrostatic discharge tester

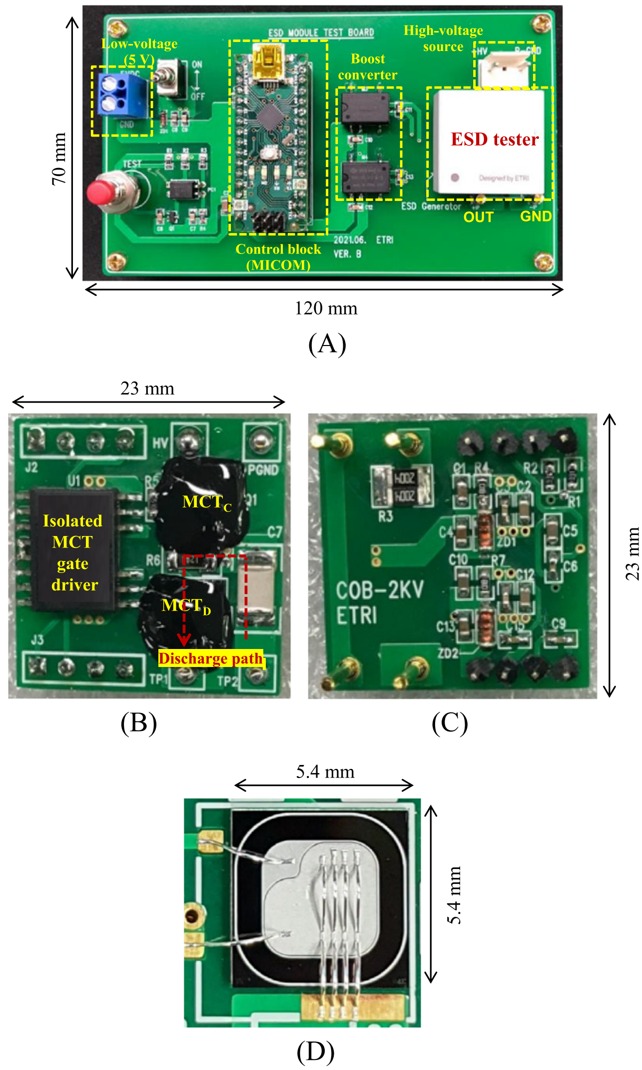

FIGURE 5 Photographs of (A) fabricated electrostatic discharge test board, (B) top and (C) bottom of the ESD tester module, and (D) wire interconnection of the metal oxide semiconductor-controlled thyristor (MCT) bare die for discharge (MCT_D)

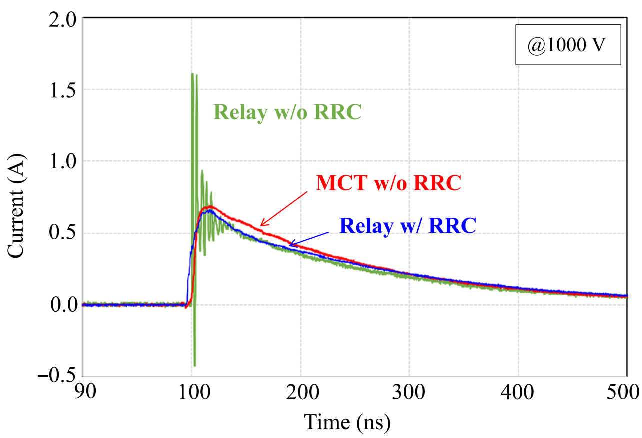

FIGURE 6 Measured HBM waveforms of electrostatic discharge testers under 1000 V conditions

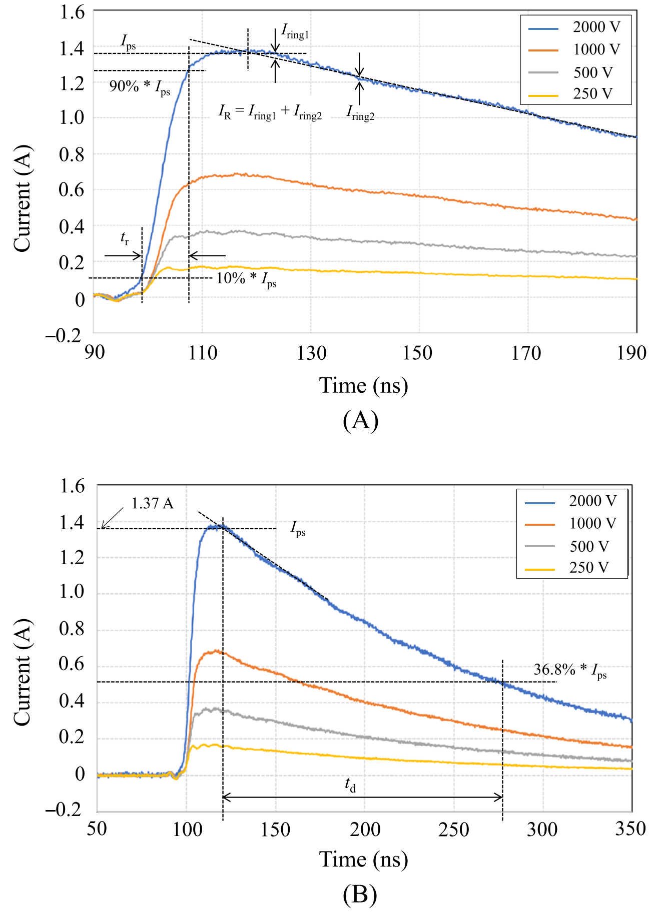

FIGURE 7 Measured HBM waveforms from which (A) peak current and rise time and (B) peak current and decay time were extracted under the voltage conditions of 2000 V or less

breakdown voltage of the developed MCT is ~3000 V, as shown in Figure 3, it was evaluated only under the voltage conditions of 2000 V or less.

Figure 7 depicts the output current waveforms of the proposed ESD tester with MCT relays without RRC under a short-circuiting wire for the voltage of 250–2000 V. Following the JS-001 standard, the peak current (I_{ps}) was determined using a linear extrapolation of the exponential current decay curve back to the time t_{max} of peak current $I_{ps,max}$, rise time t_r (the time required for the current to increase from 10% to 90% of I_{ps}), and decay time t_d (the time required for the current to decrease from 100% to 36.8% of I_{ps}). The measured I_{ps}, t_r, t_d, and I_r values at a voltage of 2000 V were 1.37 A, 8.0 ns, 158.4 ns, and 0.05 A, respectively.

Table 1 compares the JS-001 standard requirements with the measured values of the proposed ESD tester under the conditions of a short-circuiting wire at an applied voltage of 2000 V or less. The table shows that using the proposed MCT components, the ESD tester satisfies all the requirements defined by the international

TABLE 1 Comparison of JS-001 standard and measurement results of proposed electrostatic discharge tester under short-circuiting wire conditions

Voltage level (V)	250	500	1000	2000
JS-001				
Peak current, I_{ps} (A)	0.15–0.18	0.30–0.37	0.60–0.73	1.20–1.47
Rise time, t_r (ns)	2.0–10.0 (10%–90% of I_{ps})			
Decay time, t_d (ns)	130–170 (150 ± 20)			
Maximum ringing current, I_r (A)	15% of I_{ps}			
This work				
Peak current, I_{ps} (A)	0.16	0.36	0.68	1.37
Rise time, t_r (ns)	9.0	7.8	7.2	8.0
Decay time, t_d (ns)	148.0	151.0	158.8	158.4
Maximum ringing current, I_r (A)	0.015	0.04	0.05	0.05

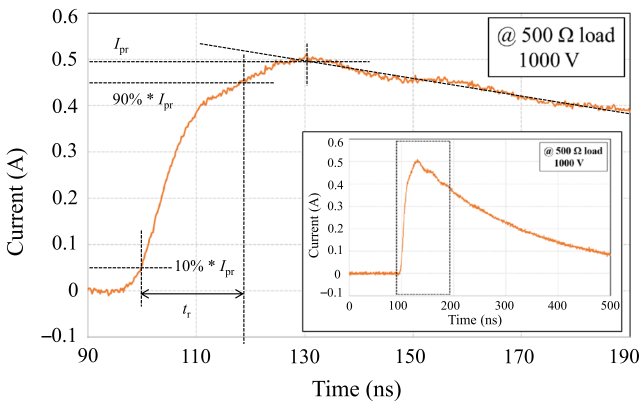

FIGURE 8 Measured HBM waveforms from which key metrics were extracted under the conditions of a 500 Ω load at 1000 V

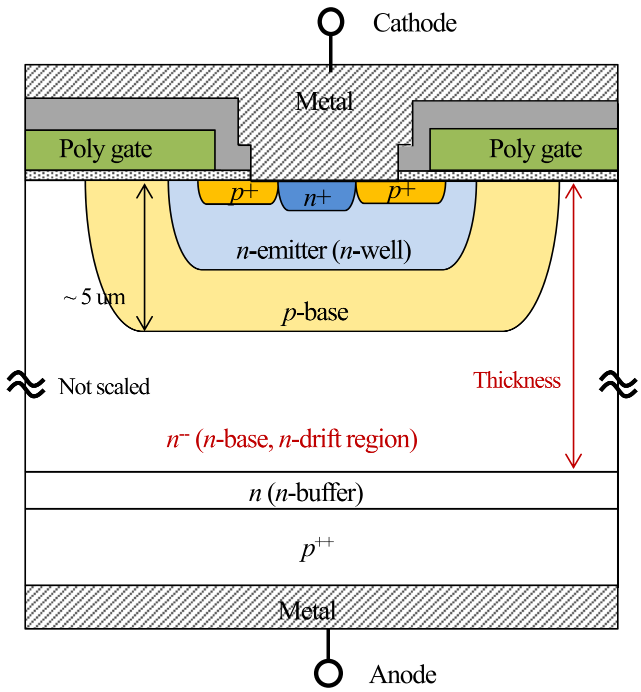

FIGURE 9 Simplified conceptual diagram of the MCT structure [11]

TABLE 2 Comparison of JS-001 standard and measurement results of the proposed electrostatic discharge tester under conditions of a 500 Ω load at 1000 V

Parameter	JS-001 [1]	This work
Peak current, I_{pr} (A)	0.37–0.55	0.49
Rise time, t_r (ns)	5.0–25.0 (10% to 90% of I_{ps})	19.8

standard. To the best of our knowledge, this is the first attempt to replace conventional mercury-wetted relays with semiconductors. Moreover, we predict that ESD testers satisfying the JS-001 international standard can be developed using MCTs with higher breakdown voltages even at voltages beyond 2000 V.

The JS-001 standard further defines peak current and rise time characteristics under 500 Ω load conditions at two voltage levels: 1000 V and 4000 V. As mentioned above, the proposed ESD tester was evaluated only at 1000 V given the breakdown voltage characteristics of the developed MCT; the results are shown in Figure 8. The measured peak current and rise time under 500 Ω load conditions at 1000 V were 0.49 A and 19.8 ns, respectively. These values satisfy the requirements of the JS-001 standard (Table 2).

As mentioned earlier, an ESD tester that uses MCT was proposed and evaluated up to 2000 V for HBM. To satisfy all the requirements of the JS-001 standard, an MCT with breakdown voltage characteristics of 4000 V or more is needed. The factors that affect the breakdown

TABLE 3 Summarization of breakdown voltage for changes in thickness and resistivity values of the N-drift region in the MCTs

Thickness (μm)	Resistivity (Ω·cm)	Breakdown voltage (V)	Ref.
150	75	1700	[11]
475	175	3000	This work
550	850	>4000	Expected

voltage of high-voltage power semiconductors, including the structural design and process conditions of the device, vary widely; however, they are largely dependent on the thickness and resistivity of the N-drift region, as shown in Figure 9 [11,14,15].

The MCTs developed by our group demonstrated breakdown voltage characteristics of 1700 V under the conditions of thickness and resistivity in the N-drift region of 150 μm and 75 Ω·cm, respectively [11]. The MCTs used in this study were fabricated under conditions with the thickness and resistivity of the N-drift region of 475 μm and 175 Ω·cm, respectively, and showed the breakdown voltage properties of ∼3000 V, as shown in Figure 3. To develop MCTs with a breakdown voltage above 4000 V, we have been studying MCTs with the condition that the thickness and resistivity of the N-drift region are 550 μm and 850 Ω·cm, respectively, while referring to prior studies. Table 3 summarizes the breakdown voltage characteristics of the MCT for changes in thickness and resistivity of the N-drift region.

3 | CONCLUSIONS

The mercury-wetted relay has been restricted from use owing to global environmental concerns. MCTs with excellent di/dt properties were developed in-house, applied to EDS testers, and evaluated for testing as replacements for the mercury-wetted relay, which have been used in the ESD testers for HBM. The proposed ESD tester is demonstrated to satisfy all the requirements for the HBM test as defined by ANSI/ESDA/JEDEC JS-001 standards for voltages of 2000 V or less. The results showed that the proposed ESD tester can solve the environmental issues posed by the ESD tester using the mercury-wetted relay. Moreover, the proposed ESD tester does not need additional resonance removal circuits, which is a considerable advantage. This is the world's first attempt at replacing the ESD tester using the mercury-wetted relay.

ACKNOWLEDGMENTS

The authors would like to thank Mr. Choi and Mr. Jang from JMJ Korea for their help with die and wire bonding.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

AUTHOR CONTRIBUTIONS

Dong Yun Jung conceptualized the study, designed the methodology, curated the data, performed the formal analysis, acquired the funding, performed the investigation, supervised the study, validated the results, and prepared the original draft of the manuscript. Kun Sik Park curated the data, acquired the funding, performed the investigation, validated the results, and reviewed and edited the manuscript. Sang In Kim conceptualized the study, designed the methodology, curated the data, performed the investigation, and reviewed and edited the manuscript. Sungkyu Kwon performed the formal analysis and reviewed and edited the manuscript. Doo Hyung Cho curated the data and reviewed and edited the manuscript. Hyun Gyu Jang performed the formal analysis and reviewed and edited the manuscript. Jongil Won designed the methodology and reviewed and edited the manuscript. Jong-Won Lim acquired the funding, validated the results, and reviewed and edited the manuscript.

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Hyun Gyu Jang received his BS degree in Electronics Engineering from the Tech University of Korea, Siheung, Republic of Korea, in 2013, and his MS in Advanced Device Technology from the University of Science and Technology, UST, Republic of Korea, in 2015. He mainly studied Gallium nitride power devices. In 2015, he joined the Electronics and Telecommunications Research Institute in Daejeon, Republic of Korea, as a research engineer. His research interest includes power devices, power conversion applications, and pulsed power applications.

Jongil Won received his BS and MS in Electronic Engineering from Seokyeong University, Seoul, and Republic of Korea in 2008 and 2010, respectively. He studied electrostatic discharge (ESD) protection devices. Currently, he is a senior researcher at ETRI, Daejeon, Republic of Korea, since 2011. His research interests include TCAD simulation, design, fabrication, and electrical evaluation of power semiconductor devices based on silicon and silicon carbide such as SBD, MOSFET, and IGBTs.

Jong-Won Lim received the BS, MS, and PhD degrees in Physics from Chung-Ang University in Seoul, Korea, in 1988, 1990, and 1998, respectively. In 2000, he joined the Electronics and Telecommunications Research Institute (ETRI) of Korea as a member of Senior Research Staff, where he has been engaged in research on compound semiconductor MMIC developments for wireless telecommunications. Since 2019, he has been working as a managing director in the Defense Materials and Components (DMC) Convergence Research Department in ETRI. His current research interests include the process development, fabrication, and characterization of GaN-based HEMT devices and MMICs for millimeter-wave applications.

How to cite this article: D. Y. Jung, K. S. Park, S. I. Kim, S. Kwon, D. H. Cho, H. G. Jang, J. Won, and J.-W. Lim, *Human body model electrostatic discharge tester using metal oxide semiconductor-controlled thyristors*, ETRI Journal **45** (2023), 543–550. https://doi.org/10.4218/etrij.2022-0077