A novel TLP-based method to deliver IEC 61000-4-2 ESD stress

Yize Wang, Yuan Wang\textsuperscript{a)}, Guangyi Lu, Jian Cao, and Xing Zhang\textsuperscript{b)}

Key Laboratory of Microelectronic Devices and Circuits (MoE), Institute of Microelectronics, Peking University, Beijing 100871, China
\textsuperscript{a)} wangyuan@pku.edu.cn
\textsuperscript{b)} zhx@pku.edu.cn

Abstract: The electro-static discharging (ESD) gun test method is widely used and admitted for systems, but it will also bring some unwished factors to influence the accuracy and stability such as radiated electromagnetic (EM) and the unstable hand-held operational approach. In order to avoid the above factors, a traditional work uses a modified transmission line pulse (TLP) tester to deliver the IEC 61000-4-2 stress. However, the modification and recovery process of a TLP tester is complicated in addition to the potential damaging risks. Thus, this work proposes a novel TLP-based method to generate the IEC stress by adding an extra circuit network outside the TLP tester. Further, the proposed method with no need for internally modifying a TLP tester can efficiently solve the above issues.

Keywords: electrostatic discharge (ESD), transmission line pulse (TLP) test, SPICE model

Classification: Electron devices, circuits and modules

References

[1] V. A. Vashchenko and A. Shibkov: 	extit{ESD Design for Analog Circuits} (Springer, 2010) 395.
[2] P. Tamminen, et al.: “ESD and disturbance cases in electrostatic protected areas,” Proc. EOS/ESD Symp. (2015) 1 (DOI: 10.1109/EOSESD.2015.7314792).
[3] Q. Chen, et al.: “Systematic transient characterization of graphene interconnects for on-chip ESD protection,” IEEE IRPS (2016) 3B-6 (DOI: 10.1109/IRPS.2016.7574521).
[4] J. Cao, et al.: “A novel SPICE circuit model of electrostatic discharge (ESD) generator,” IEICE Electron. Express 13 (2016) 20160238 (DOI: 10.1587/elex.13.20160238).
[5] Y. Xi, et al.: “Correlation between TLP, HMM, and system-level ESD pulses for Cu metallization,” IEEE Trans. Device Mater. Reliab. 14 (2014) 446 (DOI: 10.1109/TDMR.2013.2292039).
[6] M. Honda: “Measurement of ESD-gun radiated fields,” Proc. EOS/ESD Symp. (2007) 5B.4 (DOI: 10.1109/EOSESD.2007.4401770).
[7] E. Grund, et al.: “Delivering IEC 61000-4-2 current pulses through transmission lines at 100 and 330 ohm system impedances,” Proc. EOS/ESD...
1 Introduction

From manufacturing of integrated circuits (ICs) to assembling of a system, various electro-static discharge (ESD) events will impact the components or systems [1]. According to the ESD protected area (EPA), ESD events are divided into component- and system-level models [2]. A common component-level test method is using the transmission line pulse (TLP) tester. Initially, TLP tester is used for better characterizing the robustness of devices as an energy equivalent with component-level ESD human body model (HBM) [3]. As for the system-level, the most common standard is IEC 61000-4-2 [4]. Generally, two kinds of ESD stress generators can deliver a double peak current waveform prescribed in the IEC 61000-4-2 standard [5]. One is human metal model (HMM) tester, which is usually applied to measuring component-level devices. The other is ESD gun tester. Although the ESD gun is developed for system-level measurement, some factors caused by the ESD gun itself will influence the stability of the measurement. Specifically, it is reported that the ESD gun can produce large radiated electromagnetic (EM) influencing the efficient signal [6]. In addition, an unstable handheld ESD gun increases uncertainty compared with the machinery test platform [7]. Thus, the IEC current stress is generated by a modified TLP tester to promote the stability of the system-level measurement [7].

As shown in Fig. 1, the mainly modified part of a TLP tester is the internal transmission line and discharging currents of two-stage charged lines can super-

![Diagram of modified TLP tester](image-url)

**Fig. 1.** The schematic of the modified TLP tester for delivering an IEC standard stress.
impose a double peak IEC stress [7]. However, the TLP tester is an expensive and delicate test-bed. The modified process inside the TLP tester presents attendant risks and may influence or damage the TLP system in addition to complicated debugging and operation. Thus, this work proposes a method to generate IEC stress by adding an extra circuit model outside the TLP tester. The adding circuit can shape the TLP stress into the IEC standard stress. Further, the method without modifying the internal structure of the TLP tester can avoid the above attendant risks.

2 TLP model and verification

The discharging of a transmission line can generate a TLP stress. Two relay switches control the charging and discharging of the transmission line, respectively [8]. Meanwhile, a filter adjusts the rise time of the TLP stress delivered from the ‘Pulse OUT’ port as shown in Fig. 1. The TLP POD is used for connecting the oscilloscope and device under test (DUT). For the above understanding of a TLP tester, this work proposes a SPICE TLP model as shown in Fig. 2. The transmission line model has two main parameters: the characteristic impedance $Z_0$ and time delay $T_d$. The type and material of the transmission line are the decisive factors for the $Z_0$ [9]. The typically value of $Z_0$ is 50Ω which is also the internal resistance of a TLP tester. In TLP tester model, the summation of the 25Ω $Z_0$ and 25Ω $R_2$ is equal to the aforesaid 50Ω internal resistance. As for the time delay, it determines the pulse width of the TLP stress [10]. In the SPICE tool, a 50-ns delay of the transmission line will deliver a 100-ns pulse width due to the refection. In addition, using a voltage controlled switch triggered by $V_{pulse}$ can build the model of the relay switch and the relevant specific parameters are all shown in Fig. 2. For other parts of TLP model, $V_1$ is the pre-charge voltage and $C_1$ can adjust the rise time of the simulated TLP stress. When the load of the TLP model is short, the simulated transient current curves of the TLP model are shown in Fig. 3 with different pre-charge voltages from 50 V to 200 V.

![Fig. 2. The SPICE TLP model with relevant specific parameters.](image)

In order to verify the accuracy of the TLP model, this work uses measured stress curves of a Thermo TLP to compare with the simulated results [8]. The step size of the Thermo TLP pre-charge voltages are set the same with the simulated ones. Finally, the compared results are also shown in Fig. 3 where the matched transient current curves illustrate the accuracy the TLP model.
3 Proposed TLP-based IEC 61000-4-2 ESD stress model

The pre-charged 150-pF capacitor inside an ESD gun releases a double peak stress which is conformed to IEC 61000-4-2 standard. IEC ESD stress is mainly applied to system-level test. Moreover, Table I summarizes the four main parameters prescribed in the IEC stress standard [11].

The aforesaid traditional TLP-based method of delivering the IEC stress can increase the accuracy and stability. However, the method has to internally modify a TLP tester and it may influence or damage the TLP tester in addition to complex modification and recovery process. Based on these factors, this work proposes a TLP-based method to deliver IEC stress by adding a circuit network outside the TLP tester. The equivalent circuit model of the proposed method is shown in Fig. 4.

Table I. The IEC 61000-4-2 standard which focuses on four parameters.

|                      | IEC 61000-4-2 Standard |
|----------------------|------------------------|
| First Wave           | Rising Time            |
|                      | 0.8 ns ± 25%           |
|                      | Current Peak Amplitude |
|                      | 3.75 A/KV ± 10%        |
| Second Wave          | Current at 30 ns       |
|                      | 2 A/KV ± 30%           |
|                      | Current at 60 ns       |
|                      | 1 A/KV ± 30%           |

The principle of the proposed method is to transfer the total energy of a TLP stress to the two capacitors of the adding circuit network. After 140-ns delay, the relay3 is on and the discharging of the above two capacitors can deliver an IEC 61000-4-2 stress in R5 branch. The discharging curves of the two charged capacitors are equivalent to two waves of IEC standard, respectively [12]. The transmission line of the TLP tester will be charged within 20 ns then the relay2 is on. As previously mentioned, the pulse width of the TLP stress is about 100 ns and all the TLP stress energy will transfer outside of the TLP tester during about this 100 ns. After the TLP stress, enough time is needed for the two capacitors to be charged. Hence this is the reason why the relay3 is set to turn on at 140 ns. As for
the other parts of the adding circuit network, \( D_1 \) is a one-way direction device. The purpose of adding \( D_1 \) is to prevent the energy from returning into the TLP tester. \( C_4 \) is used for adjusting the amplitude and rise time of IEC stress. The value of the standard load \( R_5 \) for IEC stress measurement is 2 \( \Omega \).

\[
 I(s) = \frac{U}{L \cdot s^2 + R \cdot s + 1/C},
\]

where \( L \) is the totality of the inductance in the circuit and it is the same with \( C \) and \( R \). As for the circuit for delivering the first wave, the parameters accord with

...
In this state, the transform function from frequency domain to time domain can be expressed as

\[ F(s) = \frac{c \cdot b}{(s + a)^2 + b^2} \Rightarrow f(t) = c \cdot e^{-at} \sin bt, \]

where \( a, b \) and \( c \) are constant. The equivalent equation of Eq. (1) is

\[ I_1(s) = \frac{U}{L} \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2} \left( s + \frac{R}{2L} \right)^2 + \left( \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \right)^2}. \]

According to Eq. (3), when substituting the relevant parameters in Fig. 5, the transient current of the first wave is

\[ I_1(t) = \frac{U}{122.6} \cdot e^{-4.1 \times 10^9 t} \sin(8.2 \times 10^8 t). \]

It can be calculated that \( I_1 = 3.6 \) A, when \( t = 0.8 \) ns with \( 1 \) kV pre-charge voltage. Similarly, as for the circuit for delivering the second wave, the parameters accord with

\[ R - 4L/C < 0. \]

In this state, the transform function from frequency domain to time domain can be expressed as

\[ F(s) = \frac{c}{(s + a)(s + b)} \Rightarrow f(t) = \frac{c}{b - a} (e^{-at} - e^{-bt}), \]

where \( a, b \) and \( c \) are constant. The equivalent equation of Eq. (1) is

\[ I_2(s) = \frac{U}{L} \left[ s - \left( \frac{R}{2L} + \frac{1}{2} \sqrt{\frac{R^2}{L^2} - \frac{4}{LC}} \right) \right] \left[ s - \left( \frac{R}{2L} - \frac{1}{2} \sqrt{\frac{R^2}{L^2} - \frac{4}{LC}} \right) \right]. \]

According to Eq. (7), when substituting the relevant parameters in Fig. 5, the transient current of the second wave is

\[ I_2(t) = \frac{U}{113.5} (e^{-30 \times 10^9 t} - e^{-61 \times 10^9 t}). \]

When \( t = 30 \) or \( 60 \) ns with \( 1 \) kV pre-charge voltage, \( I_2 = 2.2 \) A and \( 1.2 \) A, respectively. In addition, the discharging of \( C_2 \) will do some contributions to the first wave. When \( t = 0.8 \) ns, \( I_2 = 0.2 \) A. Thus the final amplitude of the first wave is 3.8 A. Obviously the results of formula derivation conform to the IEC standard prescribed in Table I. Further, the IEC stress simulated transient curves are shown in Fig. 6 with \( 0.5 \) kV step size pre-charge voltage from \( 0.5 \) kV to \( 2 \) kV. Obviously, the curves are well conformed to the four IEC standard parameters, which also illustrates the validity of the proposed TLP-based method to generate IEC 61000-4-2 ESD stress.
4 Verification of the loading effect

Using the proposed TLP-based IEC stress generating method, the circuit model with loading is shown in Fig. 7. The loading (DUT) is a kind of ESD clamping circuit based on a 65-nm CMOS process and the equivalent model is also presented [4].

In order to further verify the accuracy of the proposed method, this work uses ESD gun test method to compare the loading effect with the proposed one. As mentioned above, ESD gun test is still a widely used and approved for systems. Moreover, both the proposed TLP-based method and ESD gun are used to generate ESD stress prescribed in IEC 61000-4-2 standard. Thus, in terms of the stability, the ESD gun is not as good as a TLP-based IEC tester due to the EM effect and hand-held operation, but it does not influence on verifying the loading effect under IEC stress.

Fig. 8 shows the test environment and two 10 cm Dupont lines is used for connecting the DUT. Generally, the practical delay of a transmission line with 50Ω $Z_0$ is 70 ps/cm [10]. When an IEC stress discharges into the Sub Miniature A (SMA) joint, the current probe will capture the transient current flowing into the DUT. Finally, the simulated and measured transient current curves are shown in Fig. 9 with 0.5 kV step size pre-charge voltage from 0.5 kV to 2 kV. The compared
results illustrate that the loading effect of the proposed TLP-based method is valid. Obviously, the mismatches are observed at around 70 ns and some reasons may cause this phenomenon. As was mentioned before, the EM may influence the loading effect. In addition, the IEC standard is universal for all kinds of stress testers, so the loading effect of the above stress testers will be approximately alike. However, the aforesaid factors such as EM can influence the loading effect and the compared results among some IEC stress testers will show some discrepancies [7].

Fig. 8. ESD gun test environment.

Fig. 9. Simulated and measured transient current curves.

5 Conclusions

This paper proposes a novel TLP-based method to generate IEC 61000-4-2 ESD stress which has obvious advantages over the previous method of modifying a TLP tester. Generally, the verification of the proposed method focuses on three aspects.
Firstly, a Thermo TLP tester is modeled and the measured transient current curves are coincident with the simulated ones illustrating the accuracy of the TLP tester model. Apart from the IEC standard focusing on four parameters, the parameters of the extra added circuit are also explained in detail. Moreover, the added energy transfer network outside the TLP tester can shape a TLP stress into an IEC standard stress. And the relevant formula derivation and simulation results are used to illustrate the above conclusion. In order verify the loading effect of the novel TLP-based IEC stress generating method, ESD gun test as a comparison is used. Finally, the coincident simulated and measured transient current curves illustrate the validity of loading effect with the proposed method.

Acknowledgments

This work was supported by Natural Science Foundation of Beijing, China (Grant NO. 4162030) and National Science and Technology Major Project of China (Grant NO. 2013ZX02303002). The authors would like to thank to Compliance Certification Services (CCS) Inc., Shanghai, P. R. China for the help with the IEC stress testing.