Research on Application Validation Methods of Electrical Performance of TVS

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Abstract. Transient Voltage Suppressor (TVS), as an effective protective device in the form of diode, has found wider application in power circuits and signal circuits, which aims to protect secondary power and signal circuits. TVS only operates in case of circuit abnormality, which however is hard to be simulated, and it is also hard to measure whether such abnormality damages other circuits, thus it is necessary to carry out comprehensive application validation on such devices. A validation method about the electrical performance of TVS has been studied in the paper, which is analyzed based on application demands, and the test items and test method for electrical performance validation have been devised as well. Based on this method, the electrical performance of BSY6125 TVS manufactured by Beijing Microelectronics Technology Institute has been subjected to application validation, with a comprehensive evaluation on the electrical performance of the device achieved. This method can also be promoted in the application validation of other TVS.

1. Introduction
High-level TVS involves sophisticated R&D and manufacturing technologies and higher demands on processing. Major manufacturers of such device are mainly located in the US, including Microsemi and Sensitron. Series manufacturing, which features higher automation, has been realized for this product, and its production yield and reliability are also very high [1]. However, R&D for high-level TVS in China started late, with only several common models being researched and developed. The domestic production lacks R&D experience, product readiness and reliability. In order to boost the independent innovation and unbounded development of Chinese TVS for spacecraft, it is an urgent need to carry out application validation on the newly developed TVS in China, to comprehensively validate the performance of the device, thereby ensuring successful application of new devices.

2. Device introduction
Transient Voltage Suppressor (“TVS”) is an effective protective device in the form of diode. When the two poles of TVS are subjected to back transient high-energy impact, the high impedance between the two poles turns into low impedance rapidly, and absorbs transient pulse power, making the voltage between the two poles clamped at a set value, and effectively protecting other circuits from various
damages caused by transient pulse. Featuring rapid response (ps level), high pulse power, and low clamping voltage, among other merits, TVS is being applied more widely in power circuits and signal circuits to protect secondary power and signal circuits [2].

3. Design of Application Validation Method

3.1. Analysis on validation demand

TVS can be divided into unidirectional and bidirectional TVS based on the polarity, and unidirectional TVS is generally applicable to DC circuit, while bidirectional TVS is generally applicable to AC circuit. At present, most models adopt bidirectional TVS, while power is selected specifically based on the application environment. A typical application circuit of TVS in the models is shown in Fig. 1, wherein TVS1, TVS2 and TVS3 are transient voltage suppressors.

![Figure 1](image_url)

**Figure 1.** Typical application circuit of TVS

The TVS is connected at two ends of the secondary power or signal circuit in parallel, rapidly absorbs transient pulse power to protect other circuits. When the circuit operates normally, it is in the cut-off state, without affecting the normal operation of the entire circuit. When abnormal overvoltage occurs to the circuit and reaches its breakdown voltage, TVS quickly turns from high impedance to low impedance, providing low impedance access for transient current, and maintaining the abnormal high-voltage clamping at a safe level, to protect the circuit; when the abnormal overvoltage disappears, TVS is recovered to high impedance, and the circuit resumes normal operation.

3.2. Design of Application of Validation Method

As the application characteristics of TVS is only to work under the conditions where the circuit is abnormal, it is difficult to simulate circuit abnormality in the process of practical application and it is difficult to test whether it causes damage to post-stage circuit, so it is very important to carry out sufficient application validation on such kind of devices used. [3] The application validation on TVS is focused on the validation on the features of the device in application. The circuit for application of the device is divided into two situations: circuit in normal work and circuit in abnormal situation. When the circuit is in normal work, leakage current, power in steady state and thermal resistance of the device shall be paid attention to, the performance of the device shall be fully validated when the circuit has abnormal overvoltage, the validation is not only limited to conventional electrical performance parameters of the device, including breakdown voltage $V_{BR}$, the maximum reverse operating voltage $V_{RWM}$, leakage current $I_R$, the maximum clamping voltage $V_{C(max)}$, reverse pulse peak current $IPP$, reverse pulse peak power $PPR$, steady state power $PD$ and capacitance $CPP$, besides, the application electrical performance of the device shall be paid attention to, including transient suppression characteristics, clamping response characteristics and transient pulse power and thermal resistance, and the validation contents of such device shall be paid attention to according to the characteristics focused on by the application, which is detailed in Table 1.
Table 1. Validation Contents

| S/N | Test Item                                  | The Specific Contents                                                                 |
|-----|-------------------------------------------|---------------------------------------------------------------------------------------|
| 1   | Evaluation of Electrical Performance of Device | Electrical Stress Limit Characteristics of Transient Suppression Characteristics (Step Current, until the Device is invalid) |
| 2   | Transient Suppression Characteristics     | Electrical Stress Limit Characteristics of Transient Suppression Characteristics (Step Pulse Width, until the Device is invalid) |
| 3   | Transient Suppression Characteristics     | Electrical Stress Limit Characteristics of Transient Suppression Characteristics (Step Pulse Times, until the Device is invalid) |
| 4   | Transient Pulse Power-Pulse Width Curve  | Transient Pulse Power-Pulse Width Curve                                                |
| 5   | Clamping Response Characteristics         | Transient Suppression Response Waveform                                               |
| 6   | Clamping Response Time                    | Clamping Response Time                                                                |
| 7   | Static Power                              | Reverse Leakage Current at Different Temperatures and Different Voltages               |
| 8   | Thermal Effect Characteristics            | Steady Pulse Power-Temperature Derating Curve                                          |
| 9   | Analysis on Consistency of Parameters of a Batch of Devices | Carry out Consistency Analysis on Test Data of a Batch of Devices                      |
| 10  | Function Test at Common Temperature and Sophistication | Function Test at Common Temperature and 150-hour Sophistication                        |
| 11  | Soaking at High Temperature               | Soaking at High Temperature for 300 Hours                                              |
| 12  | Temperature Circulation                   | Temperature Circulation at -35°C~+75°C                                                |

Test at device level shall include conventional electrical performance parameters at least, including breakdown voltage $V_{BR}$, the maximum reverse operating voltage $V_{RWM}$, leakage current $I_R$, the maximum clamping voltage $V_{C(max)}$, reverse pulse peak current $I_{PP}$, reverse pulse peak power $P_{PP}$, steady state power $P_D$ and capacitance $C_{PP}$, besides, validation items for the device are designed in terms of the characteristics the application pays attention to, transient suppression characteristics and clamping response characteristics of the device are mainly paid attention to during the application; electrical stress limit characteristics of transient suppression characteristics (step current), electrical stress limit characteristics of transient suppression characteristics (step pulse width), electrical stress limit characteristics of transient suppression characteristics (step pulse frequency), transient pulse power-temperature derating curve, transient pulse power-pulse width curve and other validation items are carried out in terms of transient suppression characteristics, transient suppression response waveform, clamping response time and other validation items are carried out in terms of clamping response characteristics, reverse leakage current at different temperatures and under different voltages, steady pulse power-temperature derating curve and other validation items are carried out in terms of static power, and thermal resistance to the environment $Z_{thj-a}$ and thermal resistance to leading-out terminal $Z_{thj-e}$ and other validation items are carried out in terms of thermal resistance. Accelerated life test shall be done in case of the device applied to model. In addition, validation in the state of application shall be done when necessary, and the validation in the state of application is mainly to carry out function test at common temperature and sophistication in breakdown state, soaking at high temperature and temperature circulation.
4. Validation Results and Analysis
Validation on electrical performance application of BSY6125 silicon TVS produced by Beijing Microelectronics Technology Institute is carried out in accordance with this Method for Validation, and it mainly includes evaluation on electrical performance and life test of the device.

4.1. Introduction to the Device Validated
BSY6125 is 500W silicon bidirectional TVS, which is limited to the application with the transient pulse power of not higher than 500W (10/1000μs exponential wave); encapsulated in the same axis with glass without cavity, the device adopts metallurgy welding at Grade I, which mainly plays a role in transient overvoltage protection, surge current shock protection and so on. The maximum rated value and main electrical performance of TBSY6125 silicon TVS are shown in Table 2 and Table 3.

| Parameter                              | Sign | Rated Value | Unit |
|----------------------------------------|------|-------------|------|
| Reverse Operation Peak Voltage         | V<sub>RWM</sub> | 47.1 | V     |
| Maximum Clamping Voltage               | V<sub>C(MAX)</sub> | 89.3 | V     |
| Maximum Peak Pulse Current             | I<sub>P</sub> | 5.6 | A     |
| Peak Pulse Power                       | P<sub>PP</sub>@T<sub>α</sub>=+25°C (10/1000 μs Exponential Wave) | 500 | W     |
| Static Power                           | P<sub>D</sub>@T<sub>α</sub>=+25°C | 2 | W     |
| Static Power                           | P<sub>D</sub>@T<sub>L</sub>=+75°C | 3 | W     |
| Junction Temperature                   | T<sub>J</sub> | -55~175 | °C   |
| Storage Temperature                    | T<sub>stg</sub> | -55~175 | °C   |

Table 3. Main Electrical Characteristics

| Parameter                              | Sign (Unit) | Testing Conditions | Prescribed Value |
|----------------------------------------|-------------|--------------------|------------------|
| Breakdown Voltage                      | V<sub>BR1</sub> (V) | I<sub>BR</sub>=20mA, Duty Ratio≤2%, t<sub>P</sub>≤300ms | ≥55.8            |
| Reverse Leakage Current                | I<sub>D1</sub> (A) | V<sub>RWM</sub>=47.1V, Pulse Width≤20ms | ≤1               |
| Reverse Leakage Current                | I<sub>D2</sub>(A) | V<sub>RWM</sub>=47.1V,T<sub>α</sub>=150°C, Pulse Width≤20ms | ≤100             |
| Maximum Clamping Voltage               | V<sub>C(MAX)</sub> (V) | I<sub>P</sub>=5.6A,t<sub>p</sub>=1ms, T<sub>α</sub>=25°C | ≤89.3            |

4.2. Validation Results and Analysis on Electrical Performance
a. Electrical Stress Test of Step Transient Suppression Characteristics

Table 4. Conditions for Electrical Stress Test of Step Transient Suppression Characteristics

| Test Item                                      | Test Method      | Test Conditions                                                                 | Test Result        |
|-----------------------------------------------|------------------|---------------------------------------------------------------------------------|--------------------|
| Electrical Stress Test of Transient Suppression Characteristic | GJB128A-1997 Method 4023 | Initial Conditions: T<sub>α</sub>=25°C±3°C, I<sub>PP</sub>=5.6A when pulse time width is respectively t<sub>p</sub>=100us, 250us, 500us, 750us, 1ms, 1.5ms and 2ms. | Shown in Table 5   |
|                                              |                  | Step: Reverse peak current I<sub>PP</sub> steps 0.2A when t<sub>p</sub>=500us, 750us, 1ms, 1.5ms and 2ms; Reverse peak current I<sub>PP</sub> steps 0.5A when t<sub>p</sub>=250us; Reverse peak current I<sub>PP</sub> steps 1A when t<sub>p</sub>=100us. |                    |
|                                              |                  | Termination conditions: the device is invalid.                                 |                    |

Conditions for electrical stress test of BSY6125 transient suppression characteristics are shown in Table 4.
The test results of electrical stress test of BSY6125 transient suppression characteristics are shown in Table 5 and Fig. 2.
Table 5. Results of Electrical Stress Test of Step Transient Suppression Characteristics

| Pulse Time Width tp(μs) | 30  | 50  | 100 | 250 | 500 | 750 | 1000 | 1500 | 2000 |
|-------------------------|-----|-----|-----|-----|-----|-----|------|------|------|
| Limit Value of Reverse Peak Current $I_{pp}$ (A) (Square Wave) | 44  | 36  | 28  | 17.5| 13  | 10.6| 9    | 7.8  | 6.8  |
| Limit Value of Reverse Peak Power $P_{pp}$ (W) (Square Wave) | 3727| 3047| 2273| 1410| 1055| 827.8| 714.3| 612.9| 523.9|
| Limit Value of Reverse Peak Power $P_{pp}$ (W) (Exponential Wave) | 4472| 3656| 2727| 1692| 1266| 993.3| 857  | 735.4| 628.7|

Figure 2. Results of Electrical Stress Test of Transient Suppression Characteristics

b. Impact Stress Test of Step Reverse Peak Pulse Current
Reverse peak pulse current is added to both ends of the device to carry out pulse impact stress test, it is carried out for 100 times, key parameter test is done for every 100 times, and the test conditions and results are shown in Table 6.

Table 6. Conditions and Results of Impact Stress Test of Step Reverse Peak Pulse Current

| Test Item | Test Method | Test Condition | Test Result |
|-----------|-------------|----------------|-------------|
| Impact Stress Test of Reverse Peak Pulse Current | GJB 128A-1997, Method 1027 | Initial Condition: $I_{p}=5.6$A, impact 100 times respectively on both ends. Step: step current is 2A, and step impact times is 500 times. Termination condition: the device is invalid | It is not invalid after reverse peak pulse current impacts 500 times respectively in the test when $I_{pp}=5.6$A, $I_{pp}=7.6$A and $I_{pp}=8.6$A. |

*aReverse peak pulse current impact is limited to the test equipment, and interval time of pulse is set to be 1min.

c. Transient Pulse Power Characteristic Curve
Transient pulse power $P_{pp}$-$t_p$ characteristic curve in different pulse widths is shown in Fig. 3.
Figure 3. Transient Pulse Power Characteristic Curve of the Device

The \( P_{PP} - T_J \) derating curve between transient power of the device and junction temperature is shown in Fig. 4.

Figure 4. Transient Pulse Power-Temperature Derating Curve of the Device

d. Transient Suppression Response Curve
Clamping voltage response curve corresponding to different reverse pulse currents is shown in Fig. 5.

Figure 5. Clamping Voltage Response Curve with Reverse Pulse Current \( I_{PP} = 5.6 \text{A} \)
It can be seen from the Figure that the peak value of reverse pulse current $I_{PP}$ is about 5.6A (the amplification times of ampere meter pen is 200 times) and that clamping voltage $V_C$ is about 69V (the amplification times of voltmeter pen is 20 times).

e. Clamping response time

1) Theoretical estimation of clamping response time of the device

The operation of TVS can be equivalent to a RC circuit composed of capacitance and internal resistance. The clamping response time can be simplified into capacitance delay time based on the theoretical estimation, with the calculation equation being as follows:

$$T = -R \cdot C \cdot \ln\left(\frac{E - V}{V}\right)$$

Wherein: $R$ is the internal resistance of the device, $C$ is the capacitance, $V$ is the device’s clamping voltage value, and $E$ is the value of the voltage imposed on two ends of the device.

Calculation based on theory: $C = \frac{\varepsilon_0 \varepsilon_{Si} A_C}{X_d}$

Wherein $A_C$ is the effective junction area of the device, $X_d$ is the width of the depletion layer during operation of the device, $V_Z$ is the clamping voltage of the device, $N_C$ is the dosage concentration of the device, $\varepsilon_0$ is the permittivity of vacuum, $\varepsilon_{Si}$ is the Si relative dielectric constant; by substituting the design parameters of the device into the equation, the clamping response time of the device can be estimated as $T=187.4$ps.

2) Test on response time of the device

During test of the clamping response time of the device, DC voltage source is used to provide critical clamping voltage value, which is coupled with the pulse voltage excitation generated by the high-frequency signal generator, and signals are captured by use of high-frequency probe. As coupling capacitor is used to isolate DC voltage source from high-frequency pulse excitation source, delayed effect can be found in the circuit test.

In case of mere pulse voltage excitation without addition of DC voltage source, the measured delay time of the coupling capacitor is shown in Fig. 6.

![Figure 6. Delay time of coupling capacitor](image)

It can be seen from Fig. 6 that the delay time of the coupling capacitor is around 3.33ns. When coupling the voltage pulse excitation by adding critical DC voltage source, the TVS works in the clamping state, and test result of the device is shown in Fig. 7.
Figure 7. Clamping response time of TVS

It can be seen from Fig. 7 that the delay time of the circuit is 3.33ns. The total delay time of the circuit during operation of TVS is the same with the delay time of the coupling capacitor, which demonstrates that the clamping response time of the device should be within the error range of the test instrument (far lower than 3.33ns).

g. Stepping steady state power stress test
The conditions and results of stepping steady state power stress test are shown in Table 7.

| Test item              | Test method                  | Test conditions                      | Test results                                      |
|------------------------|------------------------------|--------------------------------------|---------------------------------------------------|
| Stepping steady state  | GJB 128A-1997, Method 1038   | Initiation condition: $P_D=2\text{W}$ | In case of $P_D=2.5\text{W}$, the test will be invalid. |
|                        |                              | Termination condition:               |                                                   |
|                        |                              | $P_D=2.5\text{W}$ or 50% fails      |                                                   |

Figure 8. Steady state pulse power -temperature derating curves of the device
h. Reverse current curves under different temperature and voltages
The characteristic curves of reverse leak current $I_R - V_R$ under different voltages respectively at $25^\circ C$, $75^\circ C$, $125^\circ C$ and $150^\circ C$ are shown in Fig. 9.

![Figure 9. $I_R - V_R$ characteristic curve](image)

i. Thermal response characteristic curve
The junction-ambient thermal resistance $Z_{thj-a-t}$ relationship curve in different heating time is shown in Fig. 10, and it is suggested to be calculated based on $R_{SA} = 75^\circ C/W$ in actual application.

![Figure 10. Junction-ambient thermal resistance $Z_{thj-a-t}$ relationship curve](image)

The junction-lead thermal resistance $Z_{thj-a-t}$ relationship curve in different heating time is shown in Fig. 11.

![Figure 11. Junction-lead thermal resistance $Z_{thj-a-t}$ relationship curve](image)
j. Analysis on parameter consistency of a batch of devices

45 devices are selected, and key parameters of the device are tested, and consistency of the parameters of the batch of devices is analyzed.

Table 8. Analysis on consistency of test data of parameters at 25°C

| Parameter | Terminal A | | Terminal B | |
|-----------|------------|------------|-------------|-------------|
|           | $V_{BR}(V)$ | $I_R$ (uA) | $V_{CMAX}$   | $V_{BR}(V)$ | $I_R$ (uA) | $V_{CMAX}$ |
| Specification requirement | $\geq 55.8V$ | $\leq 100uA$ | $\leq 88.9V$ | $\geq 55.8V$ | $\leq 100uA$ | $\leq 88.9V$ |
| Minimum value | 58.46 | 0.001 | 66.6 | 58.46 | 0.001 | 66.7 |
| Maximum value | 62.28 | 0.037 | 69.3 | 62.28 | 0.037 | 69.2 |
| Average value | 60.706 | 0.011 | 68.738 | 60.706 | 0.011 | 68.624 |
| Standard deviation | 0.9162 | 0.0090 | 0.6147 | 0.9162 | 0.0090 | 0.6256 |

Table 9. Test data of capacitance parameters

| Test conditions | $V_R=10V$ dc, $f=1$Mhz $V_{sig}=50mV(p-p)$ | $V_R=5V$ dc, $f=1$Mhz $V_{sig}=50mV(p-p)$ |
|-----------------|------------------------------------------|------------------------------------------|
| $T_A=25^\circ$C | $V_{BR}=85pF$ | $V_{BR}=102pF$ |
| 1               | 85pF | 102pF |
| 2               | 86pF | 103pF |
| 3               | 85pF | 101pF |
| 4               | 85pF | 103pF |
| 5               | 84pF | 102pF |

Table 10. Analysis on consistency of test data of parameters at -65°C and 150°C

| Parameter | Terminal A | | Terminal B | | Terminal A | | Terminal B | |
|-----------|------------|------------|-------------|-------------|------------|------------|-------------|
|           | $V_{BR}(V)$ | $I_R$ (uA) | $V_{BR}(V)$ | $I_R$ (uA) | $V_{BR}(V)$ | $I_R$ (uA) | $V_{BR}(V)$ |
| Specification requirement | $\geq 55.8V$ | $\leq 100uA$ | $\geq 55.8V$ | $\leq 100uA$ | $\geq 55.8V$ | $\leq 100uA$ |
| Minimum value | 55.93 | 0.001 | 55.8 | 0.001 | 65.61 | 0.216 | 64.49 | 0.244 |
| Maximum value | 57.87 | 0.029 | 57.7 | 0.036 | 68.46 | 1.245 | 68.41 | 1.325 |
| Average value | 56.880 | 0.005 | 56.558 | 0.005 | 67.415 | 0.575 | 66.943 | 0.610 |
| Standard deviation | 0.5282 | 0.0055 | 0.4740 | 0.0074 | 0.6496 | 0.2905 | 0.9122 | 0.2909 |

k. Validation results analysis of electrical performance

BSY6125 is a 500W silicon bidirectional TVS manufactured by Beijing Microelectronics Technology Institute, which is only used in the situation where the transient pulse power is no greater than 500W (10/1000μs exponential wave) and pulse interval is greater than 1 minute. An application feature is that it can only work in case of abnormality of circuits, and the application circuits of the device consist of two conditions: normal operation of the circuit and abnormal operation of the circuit. When the circuit functions well, the characteristics to be noticed mainly include leak current, steady state power and thermal resistance; the indicators and curves of leak current, steady state power and thermal resistance should be able to meet R&D and application requirements, and the steady state power has a certain design margin. In case of abnormal operation of the circuit, the application electrical performances to be noticed mainly include transient suppression characteristics, clamping response features, transient pulse power and thermal resistance; both the electrical stress capacity of transient suppression characteristics of the device, and the capacity of resisting reverse peak pulse current impact have a larger design margin. The transient pulse power characteristic curve, derating curve and thermal...
response characteristic curve of the device are presented, and at the same time, the theoretical calculation value and measure value of the clamping response time of the device are given, to provide reference for the designer to engage in circuit design.

5. Conclusion
In this paper, an application validation method is studied to test the electrical performance of TVS, which is analyzed based on application demands. The test items and specific test content of the electrical performance validation are designed. The BSY6125 electrical performance of the TVS manufactured by Beijing Microelectronics Technology Institute has been subjected to application validation with a comprehensive evaluation of its electrical performance being obtained. This method can be promoted to application validation of other TVS.

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