

ESD Robustness of Low-Voltage/High-Speed TVS Devices with Epitaxial Grown Films

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Abstract— A transient voltage suppression (TVS) diode with abrupt junctions has been developed using the low-temperature epitaxy and process technology. The triggering voltage at 6 V could be precisely controlled by the thickness and dopant concentration. The reliability of TVS device is confirmed based on its electrostatic discharge (ESD) strength in conjunction with the transmission line pulse (TLP) test. As a result, the device could exceed 28 A TLP, ± 8 kV MM, and could withstand IEC 61000-4-2 up to ± 19 kV. Moreover, TVS diode exhibited very low leakage current, small capacitance, fast respond time and high cut off frequency of 2 nA, 60 pF, 8 ps, and 52 MHz, respectively. TVS diode can be also used for a digital communication line as well as an ESD/EMI filter attenuating the RF noise in MHz range.

Keywords: IEC, MM, ESD, TVS, TLP

I. INTRODUCTION

Electrostatic discharge (ESD) is major affects the reliability of electronic devices. Recent developing of electronic devices based on ICs are not only increasing data transmission speed and clock frequency, but become portable device, battery operation, low power consumption, thin, small, contain multiple interface connectors, and used touch-screens, which cause more sensitive to ESD. Therefore, the low voltage with high stability and reliability ESD protection devices are required for these applications. TVS diodes are usually widely used as protecting electronic devices and ICs from damages of electrostatic discharge (ESD) because of small size, very low impedances and capacitance [1, 2]. The reliability and performance of TVS diode is usually confirmed by low leakage current and ESD strength. The conventional component level ESD test methods such as human body model (HBM), machine model (MM), and charge device model (CDM) don't guarantee good component level behaviors [3, 4]. The meanwhile, transmission line pulse (TLP) systems have been used to evaluate the ESD behavior of silicon devices and integrated circuits [5, 6], and accepted as ESD test standard of the semiconductor industry [7, 8].

Therefore, in this work, we purpose to develop a high performance, reliability and low voltage TVS diode. The

device performance and reliability are evaluated using MM, IEC 6000-4-2 (also called IEC) and TLP testing method.

II. EXPERIMENT

The p-type (100) Silicon wafer with resistivity of 0.003 $\Omega\cdot\text{cm}$ were used as starting material. A TVS diode has a planar junction with an abrupt distribution of dopant profile (gradient $10^{24} \sim 5 \times 10^{25} \text{ cm}^{-4}$) at epitaxial grown junctions of $p^{++}(\text{B}, \sim 10^{20} \text{ cm}^{-3})/p(\text{B}, \sim 10^{16} \text{ cm}^{-3})/n^{++}(\text{P}, \sim 10^{20} \text{ cm}^{-3})$ structure by using a low-temperature process with an epitaxial growth system. Low-temperature (LT) epitaxy enabled the formation of thin layers and precise dopant concentrations. Consequently, the LT process has been employed to the device fabrication in combination with a well-established CMOS fabrication technology.

Temperature dependency current-voltage (I-V) characteristics were analyzed using a semiconductor parameter analyzer (HP4155A) equipped with a probe station, temperature was controlled using a thermal chuck attached inside a shielded cover. The capacitance is measure at frequency of 100 MHz. The ESD property was first analyzed using the NoiseKenESS-6008 model as MM and the ESS-2000 with a discharge gun TC-815R as IEC simulator. The ESD immunity test requires at least 10 discharges of both positive and negative polarity. The TLP property was analyzed using the Barth TLP 4002 system, positive TLP with pulse width of 100 ns and pulse rise time of 2 ns was applied to device.

III. RESULT AND DISCUSSION

The TVS diode has breakdown voltage of 6 V (at 1 μA) that could be precisely controlled by the thickness and dopant concentration. Fig. 1 shows I-V curves of the TVS diode measured at various temperatures which range from 300K to 400K, the reverse leakage current increases as the temperature increasing. The temperature coefficients of the breakdown voltage (V_B) and the leakage current obtained from the device were $\sim 1 \text{ mV/K}$ (at 1 μA) and 0.12 nA/K (at -4 V). These are

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reasonable value because the carriers in the semiconductor follow the Boltzmann statistics

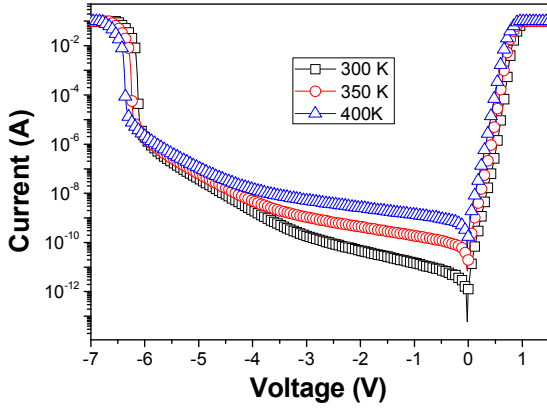
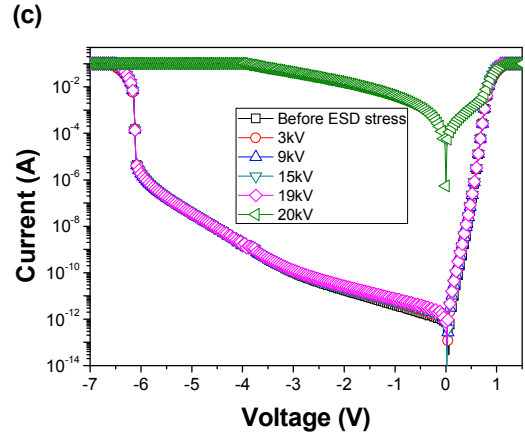
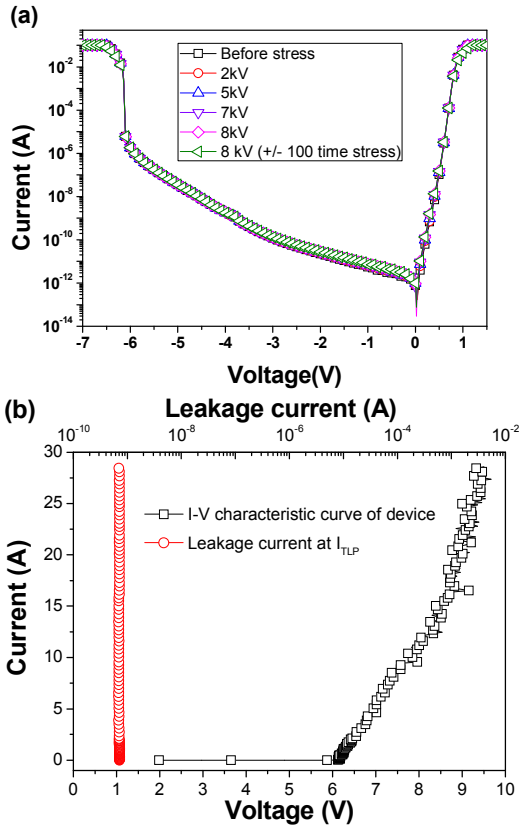


Figure 1. I-V characteristic measured at various temperatures of 300, 350, and 400K.

The device presents MM ESD strength which can be survived ± 8 kV without degradation in I-V curve. Even though increasing stress time up to 100 times in both positive and negative polarity, but the device is still maintained normal I-V curve as shown in Fig. 2(a). Similarly, the device under positive TLP test as shown in Fig. 2(b), it is observed the device begins breakdown at 6 V which is defined as first breakdown trigger voltage (V_{tl}) and current of this point called first breakdown trigger current (I_{tl}), hence $V_{tl}=6$ V and $I_{tl}=2$ mA. It is notable the leakage current of device under test maintain low as less than 1 nA even through TLP current increase and it is could surpass 28 A TLP current (maximum system value) at clamping voltage of 9.5 V which leads to 266 W of peak pulse power. It is seen that the device can handle the peak pulse power (PPP) exceed 266 W without catastrophic failures.



(d)

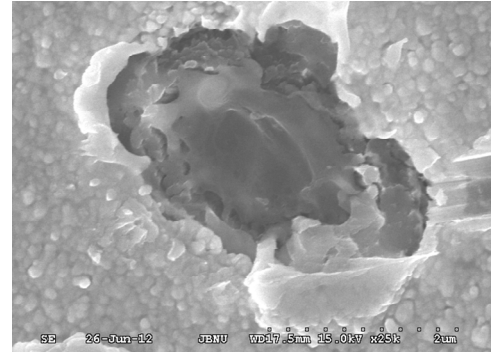


Figure 2. I-V characteristic the bidirectional TVS Zener diode under TLP and ESD test: (a) MM, (b) Positive TLP, (c) IEC; and (d) The SEM picture showing the damaged region by the ± 20 IEC stress.

In the case of IEC test, the TVS diode still shows excellent ESD strength up to ± 19 kV IEC voltage, the leakage current are maintain value, but the failure showing a serious degree of leakage current level was caused by the ± 20 kV IEC as shown in Fig. 2(c). The SEM picture in Fig. 2(d) reveals the surface of the TVS diode damaged by ± 20 kV IEC shocks, it is clearly that the ESD induced metal pad burning, the junction layer breaking and pin holes creating in device which these are cause of device failure.

Fig. 3 (a) reveals the differential resistance (R_D) versus voltage that derived from TLP testing; it is observed the R_D at the breakdown point is 0.32Ω , then exponential decrease to 0.08Ω at 9.5 V. Low differential resistance lead to low dynamic resistance (R_d) of 0.13Ω which could guarantee the low clamping voltage and smaller resistive heat that generally becomes the major cause of degradation at the p-n junction region.

Once again, our TVS diode is not only shows ESD strength and low dynamic resistance, but it represents low capacitor of 60 pF, which obtained from C-V measurement as shown in Fig. 3(b). Therefore, very low dynamic resistance and capacitance indicated high speed device because of small time constant (RC) of ~ 8 ps, the device also exhibited fast response time for absorbing transient energy.

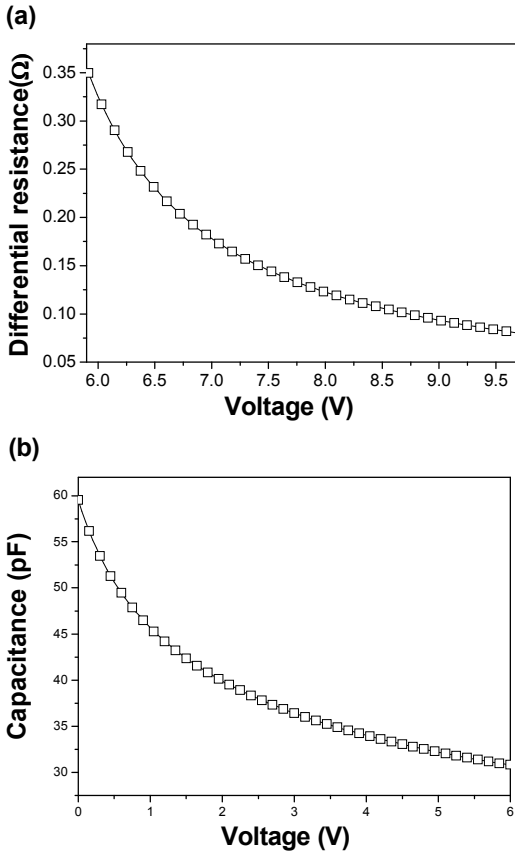


Figure 3. (a) Differential resistance of TVS diode, and (b) the C-V measurement at 100 kHz.

In addition, the cut off frequency act as important parameter in communication application, The cut off frequency could estimate from equivalent circuit as shown in Fig. 4, the output signal given as

$$V_{out} = \frac{\sqrt{R_d^2 + X_c^2}}{\sqrt{(Z + R_d)^2 + X_c^2}} \times V_{in} \quad (1)$$

where Z is network impedance (usually $Z = 50 \Omega$), R_d is dynamic resistance of device (Ω), V_{in} is input signal (V), and X_c is resistance of capacitance (Ω). The cut off frequency f_c is defined as the signal strength reduced by 3dB which means

$V_{out} / V_{in} = 1 / \sqrt{2}$. Hence, the cut off frequency, f_c given as

$$f_c = \frac{1}{2\pi C \sqrt{(Z + R_d)^2 - 2R_d^2}} \quad (2)$$

by replacing $Z = 50 \Omega$, $R_d = 0.13 \Omega$ and $C = 60 \text{ pF}$, the cut off frequency is derived as $f_c = 52 \text{ MHz}$. The estimated f_c confirms that the TVS diode can be used for a digital communication line as well as an ESD/EMI filter attenuating the RF noise in MHz range.

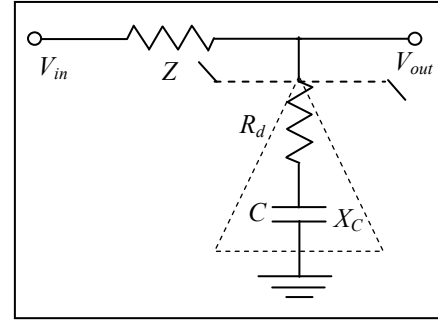


Figure 4. Equivalent circuit for the cut off frequency derivation.

The experiment results reveal our TVS diode is an excellent TLP and ESD strength. Such advantageous features are very useful for the AC electricity products like the lighting device assembled with the serial connection of GaN LEDs in particular. Never the less our device shows ESD strength up to $\pm 19 \text{ kV IEC}$ which can be equivalent to 63 kV HBM and 31 A TLP ($600 \text{ V IEC} \approx 2 \text{ kV HBM} \approx 1 \text{ A TLP}$ [3]). Moreover, fast responds time, high cut off frequency which suitable for high reliability and speed application. In addition, small die ($140 \mu\text{m} \times 140 \mu\text{m}$) is appropriate for portable equipment.

IV. CONCLUSION

A TVS diode developed using the LT epitaxy and process technology presented ESD and TLP strength with triggering voltage of 6 V and the leakage current $< 1 \text{ nA}$. Both high performance and reliable operation properties are attributed to the dynamic resistance 0.13Ω and the capacitance 60 pF , which leads to the cut off frequency of 52 MHz . The TVS diode demonstrated promising ESD features for various high performance applications.

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