Electronic Materials Letters, Vol. 5, No. 2 (2009), pp. 59-62
DOI: 10.3365/eml.2009.06.059

Development of Transient Voltage Suppressor Device with Abrupt Junctions Embedded by Epitaxial Growth Technology

S. S. Choi,[1] D. H. Cho,[2] and K. H. Shim[1,*]

[1]Semiconductor Physics Research Center, Department of Semiconductor Science and Technology, Chonbuk National University, Jeonju 561-756, Korea
[2]Sigetronics Inc., R&D Division, SPRC, 664-14 Deokjindong, Deokjinku, Jeonju 561-756, Korea

A new Zener transient voltage suppressor (TVS) consisting of abrupt junctions of epitaxial layers has been developed. Differential resistance in the breakdown region is obtained as low as 5 Ω, and the reverse leakage current is substantially suppressed by one to two orders of magnitude compared to a conventional Zener diode. The reliability of the TVS is confirmed based on its maximum allowed reverse current level and the robustness of its electrostatic discharge endurance against ±8 kV of the human body model (HBM) at a wide range of operating temperatures (30°C to 180°C). This significant improvement is primarily attributed to the abrupt junction profile formed by low-temperature processes, followed by epitaxial growth technology prohibiting redistribution of dopant elements.

Keywords: Zener, TVS, ESD, HBM, epitaxy, avalanche, breakdown, LED

1. INTRODUCTION

A transient voltage suppressor (TVS) is necessary to protect the reliable performance of electronic equipment against electrostatic discharge/electrical overstress (ESD/EOS), electrical fast transient, and lightning surges.[1] Very low impedances and capacitances represent a trend toward smaller, more mobile systems for increased data transmission and connectivity.[2] In addition, small die and package footprints need to be achieved in production to reduce the size of portable equipment in a cost-effective way. Fast response time is also required to absorb transient energy at low voltage.

Reverse biased p-n junctions, using current injection of the Zener effect (tunneling of the carriers through the forbidden gap) and/or avalanche multiplication, have been widely chosen as TVS devices.[3,4] However, leakage current, capacitance, power limits (~3 kW, 1 ms pulse), and reliability problems make them unsatisfactory for high performance technology applications.[5,6] Although Zener diodes of three typical types (Zener, bipolar, and silicon controlled rectifier) have been employed for a long time, few studies have focused on low voltage TVS performance. The present TVS trend, which is making efforts to upgrade the snap-back problem and response speed, needs to satisfy practical issues such as low voltage, low cost, and small size.

*Corresponding author: khshim@chonbuk.ac.kr

In this work, we developed a new Zener TVS with epitaxial layers consisting of very sharp planar junctions. Based on a comparison with conventional Zener devices made from the diffusion process, we demonstrate that the new Zener TVS is very promising in terms of low differential resistance, good thermal stability, and strong ESD protection capability.

2. EXPERIMENTAL PROCEDURE

Figure 1 shows the basic device structures implemented in this work, in which the gradient of the doping concentration is usually the most predominant parameter in determining the Zener breakdown voltage. A high-temperature diffusion process is used to drive in the dopant atoms for the conventional structure, as illustrated in Fig. 1(a), in which the gradient of carrier concentrations is usually maintained at 10^{24}~10^{25} cm^{-4} in a linearly-graded junction. The bathtub shape of the p^{++} profile shown in Fig. 1(a) delivers a large effective area of *p-n* junction, a nonuniformly-concentrated electric field and a broad depletion. Therefore, it is difficult to obtain low differential resistance and to avoid the nonuniform electric field locally concentrated in the oxide and semiconductor interfaces, which deteriorates the leakage current flow.

On the contrary, the new Zener TVS, as shown in Fig. 1(b), reveals the planar junction formed with abrupt distribution of dopant profile (gradient > 5 × 10^{25} cm^{-4}) at epitaxial grown junctions of p^{++}(~10^{20} cm^{-3})/n^{-}(~10^{16} cm^{-3})/n^{++}(~10^{20}

cm^{-3}) structure. This structure formation became possible by using a low-temperature process with an epitaxial growth system in combination with a well-established CMOS fabrication technology.

Silicon substrates with ρ = 0.003 Ω·cm and (100) orientation were used in these experiments. A reduced pressure chemical vapor deposition system was useful for the growth of thin silicon films with various doping conditions and thicknesses. The silicon substrates were chemically cleaned *ex situ* using SC1, 50:1 HF solution, rinsed in deionized water to remove surface oxide, and inserted into a nitrogen-purged load-lock chamber. Immediately after the silicon wafers were transferred onto a silicon carbide-coated graphite susceptor, *in situ* cleaning was performed by baking the substrate at 950°C for 5 min in hydrogen ambient. Then, the substrate temperature was controlled down to the growth temperature, and subsequently the epitaxial film growth was started at a reduced pressure of 30 torr. The flow rates of H_2 and SiH_4 gases were set to 20 slm and 20 sccm, respectively. The growth temperatures were controlled as low as 600~800°C to prohibit the diffusion of dopant atoms or matrix elements.[7]

Current-voltage (*I-V*) characteristics were analyzed using a parameter analyzer (Agilent 4156C) equipped with a probe station. The measurement temperature was controlled using a thermal chuck attached inside a shielded cover. The ESD property was analyzed using an ESD simulator (Noiseken ESS-6008), which was designed to supply a voltage output of up to ±8 kV of the human body model (HBM).

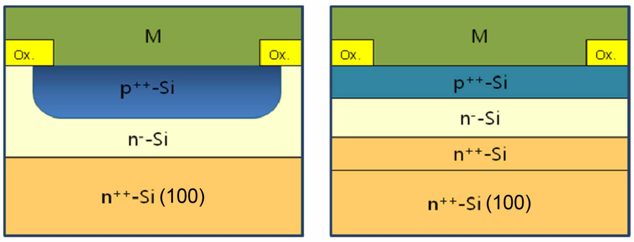

Fig. 1. Schematic cross-sectional view of Zener devices consisting of (a) junctions with a linearly-graded carrier concentration formed by a conventional diffusion process, and (b) abrupt junctions especially formed by epitaxial growth technology. Low-temperature processes along with epitaxial growth technology enables the precise manipulation of doping profiles at the nanoscale, so that the gradient of carriers may exceed 5×10^{25} cm^{-4} at the p-n junction interface.

3. RESULTS AND DISCUSSION

I-V characteristics of Zener diodes were obtained as shown in Figs. 2(a) and (b), where the conventional Zener device consists of linearly graded junctions formed by high-temperature diffusion processes. On the contrary, Fig. 2(b) exhibits the abrupt junctions formed by the epitaxial growth. Their corresponding insets are differential resistance values plotted as a function of reverse current. As noted in the reverse and forward I-V curves of Figs. 2(a) and (b), compared to the conventional Zener structure, the Zener TVS resulted in an enhanced conductance property in terms of differential resistance, reverse leakage current, and the degree of forward conductance. These enhanced properties observed from the Zener TVS device are predominantly attributed to the large gradient (> 5×10^{25} cm^{-4}) of dopant profile maintained across the p-n junction.

It is shown that the differential resistance ($R_Z = dV/dI$) in the breakdown region is one of the most important parameters of the Zener device. Figure 2(a) exhibits a differential resistance of 23 Ω at a reverse current of 10 mA, which corresponds to a current density of 69 A/cm^2 considering the effective area of 120 × 1 20 μm^2. On the contrary, the new Zener TVS as shown in Fig. 2(b) presents a differential resistance as low as 5 Ω at a reverse current of 10 mA, where the effective area is 100 × 100 μm^2. The standoff voltage (V_{so}, defined as 80% of the voltage at which the current density is 100 mA/cm^2) and the clamping voltage (V_{cp}, defined as the voltage at 500 A/cm^2) are important to clarify the leakage current and the accuracy of the voltage control when the device is used for voltage regulation.[3]

Figure 3 shows the forward-reverse *I-V* curves measured from three different types of Zener diode: two of the types

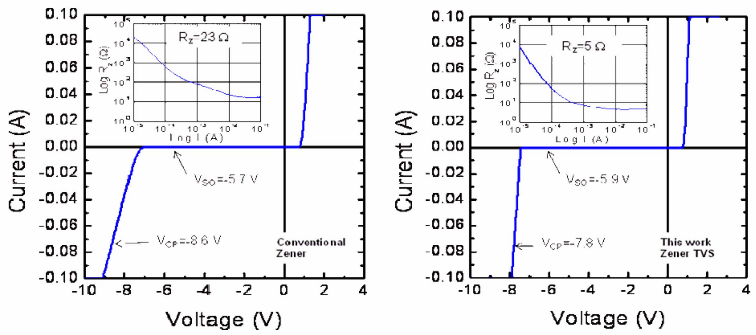

Fig. 2. Electrical properties of Zener diodes made of (a) conventional broad junctions formed by the diffusion process, and (b) abrupt junctions formed by epitaxial growth controlled at the nanoscale. Insets show differential resistance values plotted as a function of current flow.

are diffusion-controlled with high differential resistance (R_Z = 30 Ω and 23 Ω), and the third, showing low differential resistance (R_Z = 5 Ω), is made of epitaxial films. There is a remarkable difference in the level of leakage current flow. At first, the reverse-biased Zener TVS revealed the reverse leakage current at stand-off voltages of -5.7 V and -5.9 V, one to two orders of magnitude less than the conventional Zener devices. It is seen that both the leakage current and the differential resistance could be improved significantly by employing the abrupt junctions of epitaxial films. Accomplishing the lowest leakage current is very fundamental and important because it enables significant improvement in reliability performance with respect to EDS immunity.

A TVS device is required to turn on at high current without snap-back and to provide excellent clamping at high currents.[8] In order to achieve strong behavior over electrical overstress (EOS), a Zener TVS needs to operate without considerable hard breakdown, even up to a sufficient current level in dc operation mode. European standard IEC61000-4-2 Level 4, although usually applied to end products, requires very strict endurance specifications for a TVS device: ±8 kV and a peak current of 30 A. For the Zener TVS (not shown here), reverse current kept flowing without failure to a maximum value of 230 mA (2.3 kA/cm^2), which clearly confirmed its excellent power handling capability. This property is closely related to the extremely low differential resistance of 5 Ω delivering smaller resistive heat, which becomes, generally, the major cause of degradation at the p-n junction region.

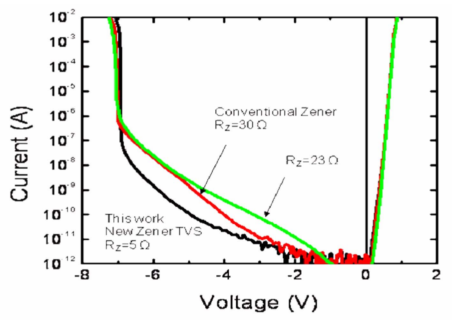

Fig. 3. Forward and reverse I-V curves measured from three types of Zener diode with critical differences in device structure and fabrication technology: two for the diffusion process (R_Z = 30, 23 Ω) and one for epitaxial film growth (R_Z = 5 Ω).

To determine the current drivability of a conventional Zener diode with R_Z = 30 Ω, I-V characteristics were sequentially measured as shown in Figs. 4(a) and (b). The conventional Zener diode with high differential resistance (R_Z = 23 Ω and 30 Ω) shows very unstable current drivability. For example, the discontinuity in Fig. 4(a) at 60 mA implies the possibility of irreversible hard breakdown, even below 100 mA.

We confirm from Fig. 4(b) that catastrophic degradation has occurred during the first measurement, as shown in Fig. 4(a). The complete destruction of the reverse current shown in Fig. 4(b) was frequently identified across a broad range of reverse current values, 60~140 mA (400~980 A/cm^2), for the conventional Zener devices. For those devices, the limited flow of the reverse current is probably due to the high level of differential resistance.

Figure 5(a) shows I-V curves of the Zener TVS at various temperatures. Figure 5(b) shows ESD test results carried out at an elevated temperature of 180°C. Because the carriers in the semiconductor follow Boltzmann statistics, the reverse leakage current is known to normally increase as the temperature is increased from 30°C to 180°C, as shown in Fig. 5(a). The temperature coefficients of the clamping voltage and the leakage current obtained from the Zener TVS reveal very reasonable values of +1.5 mV/°C and 67 pA/°C (at -4 V), respectively. These values are reasonable because the Zener voltage (above 7 V) corresponds to the switching region from tunneling mode to avalanche multiplication mode.

Figure 5(b), as previously mentioned, demonstrates the excellent hardness of the new Zener TVS against ESD as measured up to an elevated temperature of 180°C. Even after ten repetitions of an ESD pulse (HBM, 8 kV), the increase of leakage current looks negligible considering that leakage current is generally accepted up to 1 μA. Also, we observed that the mean time to failure (MTTF) was 2×10^{10} h while

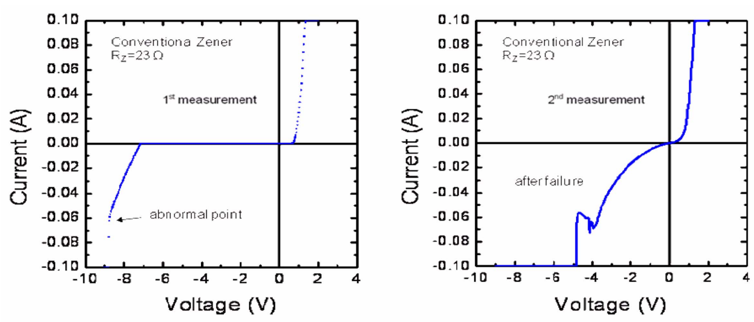

Fig. 4. Conventional Zener diode with R_Z = 30 Ω shows (a) 1st *I-V*, and (b) 2nd *I-V* from sequential measurements. After the hard breakdown occurred at around 60 mA as shown in (a), the irreversible, poor *I-V* curve measured as shown in (b) clearly illustrates that catastrophic failure occurred.

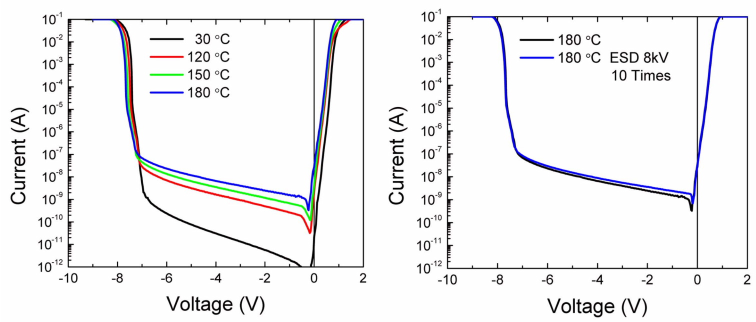

Fig. 5. Forward and reverse *I-V* curves measured from the Zener TVS device at (a) temperatures of 30°C, 120°C, 150°C, 180°C, and (b) the reliability test results of a HBM electrostatic discharge test performed at an elevated temperature of 180°C.

the Zener voltage was applied (the data are not included in this paper). Our experimental results illustrate that the new Zener TVS possesses remarkable strength against electrical shocks such as ESD and lightning surge.

A new technique for the fabrication of the Zener TVS was developed which has the following advantages over the conventional techniques. First, it is more economical and reproducible compared to high-temperature alloying or diffusion processes. Second, the maximum reverse current can be increased up to 230 mA, which is due to the significant reduction of differential resistance in the breakdown region. Also, the enhanced electrical property of the Zener TVS leads to very strong immunity against ESD shock. The non-uniform distribution of an electric field that is inappropriately focused around the corner of the diffusion front and edges can be the principal cause of ESD failures in conventional Zener diodes.

As discussed above, the stability of our new Zener TVS was confirmed by experimental data from devices that were still functioning after ten sequential trials of EDS shocks (HBM, 8 kV) at an elevated temperature of 180 °C. Endurance at an elevated temperature is important, particularly when the TVS device is used to protect group III-nitride light-emitting diodes. The weakness of these light-emitting diodes originates from unavoidable crystalline defects present in III-nitride epitaxial film. Unfortunately, their ESD strength is limited to a very low level-a few hundreds or thousands of volts at most. Conventional Zener diodes, which were developed for voltage regulation, are not sufficient to appropriately protect III-nitride light-emitting diodes (LEDs) for long periods. The electrical properties discussed above are essential for the Zener TVS device in order to provide proper reliability under the harsh environment of exposure to heat and light from LEDs.

4. CONCLUSIONS

We presented a new Zener TVS which has superior performance over a conventional Zener device in terms of differential resistance, current drivability, and ESD protection capability. The reverse leakage current can be suppressed one to two orders of magnitude lower than a conventional Zener diode. The advantages of the new Zener TVS are primarily attributed to the planar junction formed with abrupt distribution of dopant elements. Therefore, the remarkable performance of the new device can be achieved using low-temperature processes following the epitaxial growth technology.

ACKNOWLEDGMENTS

This work was supported by the IT R&D program of MKE/IITA [2008-F-023-01], and partly by a Korea Research Foundation Grant funded by the Korean Government (KRF-2008-005-J00302).

REFERENCES

1. Y.-C. King, B. Yu, J. Pohlman, and C. Hu, *IEEE Electr. Device Lett.* **16**, 303 (1995).
2. S. Mahajan, *Electron. Mater. Lett.* **2**, 59 (2006).
3. R. B. Fair and H. W. Wivell, *IEEE T. Electron Dev.* **ED-23**, 512 (1976).
4. O. M. Clark, *IEEE T. Power Electr.* **5**, 20 (1990).
5. J. Graffeuil, L. Bary, J. Rayssac, J. G. Tartarin, and L. Lopez, *IEEE Trans. Device Mater. Reliab.* **7**, 468 (2007).
6. S.-H. Dai, C.-J. Lin, and Y.-C. King, *IEEE CFP08RPS-CDR 46th Annual International Reliability Physics Symposium*, pp. 278-282, Phoenix (2008).
7. K. H. Shim, H. S. Kim, J. Y. Lee, J. Y. Kang, and M. K. Song, *Thin Solid Films* **369**, 185 (2000).
8. M. Bobde, S. Mallikarjunaswamy, M. Ho, and F. Hebert, "A novel ESD super-clamp structure for TVS applications," Applied Power Electronics Conference and Exposition, 2008. APEC 2008. Twenty-Third Annual IEEE, Feb. pp. 897-900, 2008.