ESD-Event Detector for ESD Control Applications in Semiconductor Manufacturing Factories

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Abstract—An electrostatic discharge (ESD)-event detector has been designed and fabricated in a single chip to detect and alarm the ESD events in semiconductor or integrated circuit (IC) manufacturing environments. The experiment measured results showed that the peak-to-peak voltage of the detected signal during an ESD event has a strong correlation with its ESD-stress voltage level. The proposed ESD-event detector can determine a detected signal to be an ESD pulse if its signal amplitude is higher than the settable threshold and its duration time is under 500 ns. The ESD-event detector circuit, including a 450 MHz logarithmic amplifier, a comparator, and a time discriminator, has been implemented in a single chip with a total silicon area of only $693 \times 563 \mu m^2$ and fabricated by 0.18-$\mu m$ CMOS process. The detector can detect high-frequency transient signals up to 450 MHz, which has been successfully verified in the field tests by detecting the signals generated from the ESD generators, the human-body model tester, and the field-induced charged-device model tester. The proposed ESD-event detector can efficiently perform the real-time ESD monitoring applications in the IC and semiconductor manufacturing factories.

Index Terms—Charged-device model (CDM), electrostatic discharge (ESD), ESD-event detector, ESD generator, ESD monitoring, human-body model (HBM), logarithmic amplifier.

I. INTRODUCTION

Electrostatic discharge (ESD) is a phenomenon that can cause serious damage to the microelectronics systems and integrated circuits (ICs). In recent years, more attention has been paid to the ESD static monitoring and control in the IC and semiconductor manufacturing factories. Thus, the monopole E-field probes and oscilloscopes have been commonly used to measure ESD events in the factory by detecting the radiated fields generated during ESD events. Several works describing the calculation and measurement of ESD radiated fields have been reported [1]–[4]. Those results motivate us to design the ESD-event detector which can quickly and accurately identify ESD events from the probe-detected transient voltage waveforms.

Various ESD detectors have been designed and reported in several previous articles [5]–[7]. In [5], sensors were designed for measuring the peak over or under voltage on a trace or pin during a transient electromagnetic event. The sensors wirelessly transmit the information to a remote receiver. In [6], an on-chip oscilloscope circuit was reported to monitor the system-level ESD noise at an IC’s power supply or signal line. In [7], the design of an on-chip circuit was presented, which can detect and store the occurrence of a fast transient stress event at the ESD protection structures in an input/output pad. In this article, an ESD-event detector is proposed to wirelessly detect the ESD radiated electromagnetic field for ESD control in the semiconductor manufacturing factories.

Previous articles have shown that the E-fields generated by charged-device model (CDM) ESD events can be caught and measured by a simple 6-mm monopole E-field probe, whose transfer function can be calculated from the probe dimensions. Those results showed that the probe-measured signal was close to the prediction from pulsed Hertzian dipole theory with the known parameters [8]–[10].

In this article, the measurements on the radiated E-fields by a similar monopole E-field probe among different types of ESD events were performed. One is generated by an ESD gun built following the International Electrotechnical Commission (IEC) 61000-4-2 specifications [11]. One is generated by a compact human-body model (HBM) tester built according to the JEDEC standard [12], and the other is generated by a field-induced CDM tester [13]. The probe-detected waveforms with discharging current during ESD events under different measurement conditions are investigated.

Once the probe-detected signals during ESD events are captured and analyzed, the ESD-event detector can be developed to catch particular transient pulses. The detector can detect ESD events with tunable thresholds for expected ESD intensity, which may cause IC and/or microelectronic equipment failures. When ESD event occurs, the detector can immediately send an alarm signal to us. With good sensitivity to detect ESD events, an ESD-event monitoring system comprised of multiple ESD-event detectors with RF communication modules placed in the manufacturing environments can be built. When an ESD event happens, the control center will receive the alarm with information of the scene of ESD event, which helps us to reach good and real-time ESD monitoring and ESD control in the IC and semiconductor manufacturing factories.
II. TRANSIENT WAVEFORMS OF ESD EVENTS

The monopole E-field probe applied in this article is from [2], which proposed the equivalent lumped circuits for simple sensors. This monopole E-field probe is made with an SMA cable. There is a 6-mm tip extension of the cable’s center conductor. The monopole E-field probe is illustrated in Fig. 1. A transient signal will be generated when ESD radiated field induces an electric dipole in the 6-mm tip.

A. ESD Generator

The ESD generator used in the experiment is built according to IEC 61000-4-2 specifications [11]. The measurement setup is shown in Fig. 2. The bandwidth of the digital oscilloscope is 1 GHz, and the monopole E-field probe is connected to a 50-Ω terminal load with a 50-Ω coaxial cable. A 50-Ω resistance was under test in this experiment, while the ESD generator was applied in the contact mode. To catch the radiated fields of ESD events under different stress levels, the probe was placed 15-cm away from the zapping point.

The ESD generator was able to create ESD events by zapping the same point on the 50-Ω resistance. The detected ESD-event waveform and discharge current measured at a distance of 15 cm from the zapping point under the stress voltage of 500 V is shown in Fig. 3. The maximum peak-to-peak voltage ($V_{pp}$) is used to define the intensity of the detected transient pulse.

When adjusting the ESD voltage polarities and voltage levels from the ESD generator, the dependence of $V_{pp}$ and peak current measured by the monopole E-field probe on the ESD voltage of ESD generator is summarized in Fig. 4. The $V_{pp}$ has a positive relation to the amount of the charge [1]. The ESD generator’s charge accumulation can be considered the product of the equivalent capacitance and stress voltage. The charge is proportional to the stress level with fixed capacitance. This measurement finding enables us to examine the ESD level according to the detected $V_{pp}$. Moreover, this concept will be used to design the ESD-event detector.

B. HBM Tester

The HBM is a simulation of the discharge that occurs when a device is touched by a human. HANWA HCE-5000 Compact ESD Simulator built according to JEDEC standard JS-001 specifications [12] was used to reproduce HBM ESD event in the experiment. Fig. 5 shows the measurement setup to capture the ESD-induced transient voltage waveform by the monopole E-field probe. A 50-Ω resistance was under test in this experiment and placed at a distance of 15 cm away from the probe. Moreover, a current probe was used to measure the HBM current in the experiment. When the HBM tester zapped on the DUT, ESD charges were discharged from the positive terminal.
Meanwhile, the HBM discharging current flowing to the ground was observed by the oscilloscope.

The radiated field of the HBM event was caught by the monopole E-field probe while the current probe observed the transient current. Fig. 6 shows the measured discharging current waveform and the probe-detected signal under the ESD voltage of 500 V. The discharge current waveform conformed to the standard characteristics of the HBM current. The maximum $V_{pp}$ for the HBM tester zap of 500 V was 37 mV with a discharging peak current of 0.322 A. Thus, the intensity of HBM ESD event can be estimated by measuring the $V_{pp}$ and the discharging peak current.

The dependences of discharging peak current and the $V_{pp}$ of the probe-detected signals on the voltage levels of the HBM ESD tester are shown in Fig. 7. Both $V_{pp}$ and discharging peak current almost linearly correlate to the ESD voltage level of HBM ESD events. HBM has a similar standard, IEC 61000-4-2, used for system-level testing and measured in this article with the ESD generator. As comparing the $V_{pp}$ values between Figs. 4 and 7, the $V_{pp}$ induced by the ESD generator is bigger than that by HBM ESD tester under the same ESD voltage level. The reason can be found in their equivalent circuit models. HBM has a larger series resistance with a smaller capacitance, as comparing to that of ESD generator (IEC 61000-4-2). The maximum $V_{pp}$ of ESD event has a large range from dozens to hundreds of millivolts; therefore, the ESD-event detector must be designed with a large input dynamic range to detect the transient peak voltage from the monopole E-field probe.

### C. Field-Induced CDM Tester

The Orion3 CDM tester was used in this article to create CDM ESD events with a field-induced method. The measurement setup with the monopole E-field probe to detect CDM induced transient voltage waveform is shown in Fig. 8, where the distance of 15 cm between the probe and DUT is still kept. The JEDEC calibrating coin of the standard module (capacitance of 6.8 pF) is used to simulate the CDM discharging events. The same 6-mm monopole E-field probe connected to the oscilloscope was placed 15 cm nearby the DUT. When the experiment started, the field plate charged the coin (DUT). Charges were discharged when the pogo pin extended to the coin. When the CDM current passing through the pogo pin to ground, the CDM induced transient voltage waveform detected by the monopole E-field probe can be observed on the oscilloscope.

The probe-detected signal at a distance of 15 cm from the DUT under the stress voltage of 50 V, and the corresponding CDM discharging current waveform, are shown in Fig. 9(a) and 9(b), respectively. The measured $V_{pp}$ under the field-induced CDM tester zap of 50 V was 45 mV with a corresponding CDM peak current of 0.699 A. The CDM current has the feature of a
Fig. 9. (a) Measured transient waveform ($X$: 50 ns/div.; $Y$: 10 mV/div.) for the CDM tester with a zap of 50 V to get a $V_{pp}$ of 45 mV. (b) Measured current waveform ($X$: 1 ns/div.; $Y$: 0.075 A/div.) for the CDM tester zap of 50 V with a peak current of 0.699 A.

Fig. 10. Dependence of peak-to-peak voltage ($V_{pp}$) detected by the monopole E-field probe and the CDM-discharging peak current on the voltage level of field-induced CDM tester.

huge peak current and a short duration time of 1–2 ns. However, the probe-detected signal lasted 50–75 ns, much longer than that of the CDM current. The reason was that the radiated field is oscillatory because of the oscillations of the ground plate [1].

The dependence of $V_{pp}$ detected by the monopole E-field probe and the CDM-discharging peak current on the voltage level of field-induced CDM tester are shown in Fig. 10. Under the same capacitance (6.8 pF) of DUT, both CDM peak current and $V_{pp}$ have a strong correlation with stress voltage level, since a higher stress level has more charges stored in the capacitance.

Fig. 11. Block diagram of the proposed ESD-event detector.

After the aforementioned experimental measurement with the 6-mm monopole E-field probe under the ESD events generated by ESD generator, HBM ESD tester, and field-induced CDM tester, the ESD transient signal signature has been characterized. The probe-detected sinusoid transient voltage waveform has a fast rise time, a high damping ratio, ringing in the hundreds of MHz, and a decay of 40–100 ns. Moreover, the $V_{pp}$ has an almost linear correlation with the ESD stress voltage level, so that we can estimate the intensity of ESD events from the probe-detected transient voltage pulses.

III. CIRCUIT DESIGN OF ESD-EVENT DETECTOR

The ESD-event detector is used to discriminate among different types of EMI signals detecting by the monopole E-field probe. In this article, this ESD-event detector can determine whether the probe-detected signal falls within the ESD pulse by detecting both of signal amplitude and its duration time [14].

The block diagram of the proposed ESD-event detector is shown in Fig. 11, which includes the main circuit blocks of the logarithmic amplifier, comparator, and time discriminator. All circuits are operating with the voltage supply of 1.8 V. The input signal of ESD event and output waveforms of each circuit block in the ESD-event detector are illustrated in Fig. 12. The ESD-event detector demodulates the ESD-event signal, which meets the aforementioned ESD characteristics, and then it will deliver an alarm signal to warn the occurrence of an ESD event.
A. Logarithmic Amplifier

To measure the strength of the ESD-event signal, an amplifier is needed in the ESD-event detector. In this article, a logarithmic amplifier is designed to operate at dc $\sim 450$ MHz to match the duration time of the ESD-event pulses [15], [16]. The logarithmic amplifier is often used as a power detector to measure the RF power of the antenna signal during transmission, and produces a voltage that has logarithmic relation with the input power. Because of the large voltage range of the ESD-event signals, the logarithmic amplifier has a higher gain with small $V_{pp}$ input and a lower gain with high $V_{pp}$ input, which meets the function we needed. The logarithmic amplifier developed in this article has a negative log slope. The stronger the ESD event signal strength, the lower the output voltage level of the log amplifier. Therefore, the output voltage has a logarithm relationship with the transient $V_{pp}$ input, which helps us to distinguish whether the signal is an ESD event or not.

B. Comparator

The strength of the ESD events caused by the IC components in the manufacturing environment depends on variable factors, including the failure threshold, the path from the pin to the ground, the mechanism, etc. Moreover, the distance between the monopole E-field probe and the ESD source also affects the ESD event signal. Therefore, we designed a pin, reference voltage, to modify the threshold of the detector for applications in different situations.

The output signal of logarithmic amplifier is then compared to the reference voltage by a fast differential-ends comparator. The output signal of logarithmic amplifier is on the positive input node of the comparator, whereas the reference voltage is on its negative input node. When the comparator receives the output signal from logarithmic amplifier that is lower than the reference voltage, a negative pulse is immediately delivered on the noninverting output of the comparator, and a positive pulse is delivered on the inverting output. Moreover, the reference voltage level is controlled by an off-chip voltage divider circuit that can be adjusted by a variable resistance. When the output of the logarithmic amplifier is a downward pulse demodulated from the probe-detected $V_{pp}$, the comparator can determine the ESD-event signal by setting the reference level.

C. Time Discriminator

The output of the comparator is then passed to a time discriminator, which is built of logic circuits. The time constant of 500 ns is produced by the RC time constant. If the pulse time is longer than the time constant, this pulse will be considered a non-ESD event. Therefore, the discriminator generated an alarm signal only when the duration time of a pulse has been determined to be an ESD event of interest. Alarm units, for example, red LED and sirens alarms, are triggered by the alarm signal.

The proposed ESD-event detector has been realized in a 0.18-$\mu$m CMOS process with the whole circuit in a single chip, as shown in Fig. 13. The off-chip monopole E-field probe is the same as the probe in [3] and connected with the high-pass filter, which attenuates the signals of low frequencies. In addition, some discrete $L$ and $C$ are used for impedance matching in PCB. The signal detected by the monopole E-field probe is processed by a high-pass filter used to pass the true ESD event signal and reject low-frequency signals. The filtered signal is passed to the designed logarithmic amplifier afterward.

A sine wave with a fast rise time, high damping ratio, and attenuation in 40–100 ns is used in the SPICE simulation to meet the real probe-detected signals generated by ESD events. The simulation waveforms of the ESD-event detector are shown in Fig. 14. When the detector received the probe-detected signal generated by the ESD event, the output of the log amplifier was lower than the set reference voltage, which was equal to 0.8 V in this case. Moreover, the duration time of the pulse is shorter than 500 ns. It implied that the probe-detected signal is the ESD event we expected. Therefore, the detector delivered an alarm signal.
On the contrary, if the strength of the probe-detected signal is weak, the output of the logarithmic amplifier will be higher than the threshold voltage level. In such a condition, the detector will not generate the alarm signal.

Fig. 15 shows an input signal with high amplitude and long continuous time, which was not the ESD-event signal. Although the strength of this signal was strong enough, which made the output of the logarithmic amplifier lower than the reference voltage, the time discriminator detected the long duration time of the signal. Therefore, the detector did not deliver the alarm signal.

IV. SILICON CHIP RESULTS

Fig. 16 reveals the die photograph of the fabricated ESD-event detector with a die size of $693 \times 563 \mu m^2$. The core circuit size (without I/O pads) is only $334 \times 203 \mu m^2$, which is operated with dc power supply of 1.8 V.

A. Logarithmic Amplifier

The measured input range of the ESD-event detector over which the logarithmic detector achieves less than $+/-1$ dB of error at the temperature 27 °C is $-25$ to $+5$ dBm. The measured transfer characteristic and error of the logarithmic amplifier at 150, 450, and 600 MHz are shown in Fig. 17. The nominal slope is $-19$ mV/dB at 450 MHz. The measurement result is shown that the logarithmic amplifier has an adequate function to detect ESD events.

B. Comparator

To measure the function of the comparator and the time discriminator, the pulses with different duration times and amplitudes were generated by the function generator to simulate the output of the logarithmic amplifier that delivered to the comparator. Fig. 18(a) and (b) shows the comparison with two different amplitudes but the same duration time to check the function of the comparator. The duration time equaled 300 ns which was short enough to be considered as an ESD event. Therefore, when the input signal with the voltage level of 0.3 V was lower than the 0.5-V reference voltage, the detector output delivered an alarm signal. On the contrary, the detector did not deliver an alarm signal when the input signal with the voltage level of 0.6 V which was higher than the threshold (reference) voltage (0.5 V). The threshold (reference) voltage level can be adjusted to meet the detection applications.

C. Time Discriminator

If the duration time of the pulse were too long, the time discriminator would determine the pulse as not an ESD event. Fig. 19(a) and (b) shows the measured pulses under the same amplitude but different duration times to check the function of the time discriminator. When the duration time of the pulse was 300 ns, the time discriminator discriminated the pulse as an ESD event and delivered an alarm signal. On the contrary, the duration time of the pulse was 600 ns, which was not an ESD event, and the ESD-event detector did not deliver an alarm signal. The measurement result also showed the response time of the detector was 430 ns.
V. FIELD TEST RESULTS

After measuring the function of each block circuit, the proposed ESD-event detector was used to detect the real-world ESD events. In the field tests, the detector was placed nearby the different sources of ESD events. The experiment setups are similar to Figs. 2, 5, and 8, in which the same DUT was placed 15 cm away from the zapping point. Meanwhile, the monopole E-field probe was connected to the oscilloscope and the detector to observe the transient signal and output waveforms of the detector simultaneously. Furthermore, the ESD-event detector was shielded by the metal box during the ESD zapping to prevent electromagnetic interference during ESD events, which may cause the failure in the circuit operation.

A. ESD Generator

The output waveforms of the ESD detector under different stress levels from the ESD generator are shown in Fig. 20(a)–(c). The standby output voltage of the logarithmic amplifier was 1.1 V originally. When the ESD-event signal came in, the output of the logarithmic amplifier was lower than the reference voltage (which was equal to 850 mV), the time discriminator detected the duration of the input waveform matched the characteristic of an ESD-event signal. Therefore, the detector delivered an alarm signal, as the measured waveforms shown in Fig. 20(a) with ESD stress voltage of 1.5 kV. The response time is less than 500 ns, from ESD event to the alarm signal. Under the ESD stress level of 1 kV, the strength of the probe-detected signal was weak, and the output of the logarithmic amplifier was higher than the reference voltage (850 mV). Thus, the detector did not deliver an alarm signal, as the measured waveforms shown in Fig. 20(b). In the field test, the output of the logarithmic amplifier was passed to both the oscilloscope and the input gate of the comparator, which made the capacitive load of the logarithmic amplifier much larger than that in the circuit simulation. Therefore, the rise and fall time of the logarithmic amplifier measurement is larger than the simulation result.

Furthermore, the reference voltage is adjustable for different sensitivities to detect the ESD event, as shown in Fig. 20(c). The reference voltage was reset to 950 mV. Under the same ESD stress level of 1 kV, the detector delivered an alarm signal because the output of the logarithmic amplifier was lower than the reference voltage in this condition.

B. HBM ESD Tester

The output waveform of the ESD-event detector under the HBM tester with an ESD zapping voltage of 1500 V is shown in Fig. 21. In the field test with the HBM tester, we found that the probe-detected signals generated by the HBM event have lower amplitude and faster decay speed than that of the ESD generator and CDM tester. The reason is that HBM ESD events have a smaller discharge current and less oscillations of the radiated field in the experimental space. Therefore, we move the distance between the monopole E-field probe and zapping point closer to 7.5 cm in order to observe the higher intensity of the probe-detected signal. Under the stress level of 1500 V at a distance
of 7.5 cm, the strength of the probe-detected signal was strong enough so that the output of the logarithmic amplifier was lower than the reference voltage (950 mV). Thus, the detector delivered an alarm signal, as the measured waveforms shown in Fig. 21.

C. Field-Induced CDM Tester

The output waveforms of detecting CDM ESD event is shown in Fig. 22. Under the CDM level of 1000 V at the distance of 15 cm, the detector delivered an alarm signal because the output voltage level of the logarithmic amplifier with a short duration time was lower than the reference voltage (950 mV). Both CDM peak current and $V_{pp}$ have a significantly positive relationship with stress levels under the same capacitance (6.8 pF) because greater stress levels have more charges stored in the capacitance. The measurement demonstrates that with a known capacitance and distance, the proposed ESD-event detector can discriminate the severity of the ESD events by demodulating $V_{pp}$ from the monopole E-field probe.

VI. APPLICATION FOR ESD CONTROL

The ESD-event detector has been verified to detect different types of ESD events in field tests. However, the detector detects the input signals by amplitude and duration. The proposed ESD-event detector cannot distinguish whether the alarm signal is triggered by an ESD generator, an HBM, or a CDM. The field test results also showed that one detector could not detect both HBM and CDM events simultaneously, if we used a fixed distance to DUT and a fixed reference voltage. Future article should be devoted for improving the ESD-event detector with the ability to distinguish different types of ESD events simultaneously.

The field test results showed that the proposed ESD-event detector can detect the ESD events accurately. Therefore, we designed an ESD-event detection system to achieve ESD monitoring for ESD control in the factories. The whole ESD-event detection system, including the developed ESD-event detector and an RF data communication module, is shown in Fig. 23. It can be a suitable ESD-event monitor for placing in the semiconductor manufacturing environments. A number of such ESD-event detectors can be placed around the manufacturing factories, and all of the detection outputs can be collected wirelessly by the control center. The computer in the central control room communicates with each RF module, which will be triggered by the alarm signal from the ESD-event detector, to collect the ESD data at each detection site in the manufacturing factories.

Fig. 24(a) and (b) shows the scenario of the ESD-event detection system in the manufacturing field. (a) Time and the location of the ESD events are recorded in the central control computer.

Fig. 24(b) Setup of the ESD-event detection system in the manufacturing field. (b) Time and the location of the ESD events are recorded in the central control computer.
the high risk of ESD damage is equipped with the ESD-event detector with an RF communication module to real-time monitor the occurrences of ESD events. When an ESD event happens at some of the workplaces, as shown in Fig. 24(a), the equipped ESD-event detector sends an alarm signal and delivers the data to the central control room by the RF module. The transmitted data recorded in the computer include the ESD-event alarm and the time and location of the event, as that shown in Fig. 24(b). Workers in the factory can analyze these data for precise ESD control to avoid the yield loss of production due to ESD events.

VII. CONCLUSION

A single chip of the ESD-event detector, which can identify ESD events quickly and accurately from the probe-detected transient voltage waveforms, has been developed and verified in this article. The proposed ESD-event detector, including a logarithmic amplifier, a comparator, and a time discriminator, has been designed and fabricated in a 0.18-μm CMOS process with power supply of 1.8 V. The measurement result has shown that the high-frequency transient V_{ep} during the ESD event significantly correlates with its ESD stress voltage level under the same DUT and distance. Moreover, the probe-detected signal showed the distinct characteristics of the ESD event signal. The developed ESD-event detection system can be used to monitor and identify ESD events happening in the manufacturing field. Therefore, ESD control can be well and precisely executed by this ESD-event detector in manufacturing factories.

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REFERENCES


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