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Introductory Invited Paper

Design and characterization of ESD solutions with EMC robustness for automotive applications

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ABSTRACT

Electrostatic discharge (ESD) protection design and characterization with consideration of harmful electromagnetic compatibility (EMC) events for automotive interface networks are presented. The EMC events discussed in this paper include: electrostatic discharge (ESD), electrical fast transient (EFT), surge and automotive environment transients. Key electrical parameters defined in those standards are extracted and compared. To provide efficient protection against these EMC requirements, two major automotive process technologies namely, full-dielectric isolation or silicon on insulator (SOI) and junction isolation (JI), are compared with respect to the leakage current, latch-up immunity, design complexity, EMC handling capability and cost. Protection solutions for EMC-compliance issues are reviewed at both the off-chip and on-chip levels. Trade-offs among several off- and on-chip protection devices with varying degrees of area efficiency and robustness are analyzed.

1. Introduction

Electromagnetic compatibility (EMC) is defined as the ability of an electronic system to function satisfactorily in its intended electromagnetic environment. Electromagnetic environment is composed of radiated and conducted energies. Conducted energy stemming from large transient voltages is a major consideration in the EMC design, as it may cause permanent damages. In automotive applications, most permanent damages are caused by power induction, power source fluctuation, inductive switching, and electrostatic discharge. In this sense, circuit designers need to ensure that the key automotive electronic components, such as LIN (local interconnect network), CAN (controller area network) and FlexRay, can survive under the stress conditions obtained in these harsh environments. LIN, CAN and FlexRay are the most commonly used as communication protocols in automotive applications. LIN is used for low data-rate operations with the advantage of cost-efficiency. CAN handles medium-speed communication, and FlexRay is suitable for higher speed data rates and safety-critical applications [1–3].

Various industry and government agencies have developed EMC standards describing the high voltage transients induced by these harsh environments and operating conditions, including the electrostatic discharge (ESD), electrical fast transient (EFT), surge, and automotive fast transients. These transient disturbances have a wide spectrum of frequencies and energies. The durations of ESD pulses range from a few nanoseconds (i.e., charged device model (CDM) ESD events) to hundreds of nanoseconds (i.e., human body model (HBM) ESD events). On the other hand, pulses associated with the standard ISO 7637-2 can range from 50 μs up to 2 ms. Due to the high energy in the long duration EMC pulses, the protection strategy has to be different from traditional ESD protection. To protect IC against those high energy pulses, large area is needed to improve the heat dissipation ability. On-chip protection is not suitable for diverting the high energy transients because of area and cost constraints. Thus, off-chip protection is commonly co-designed along with the on-chip protection to achieve the target electronic system robustness levels.

Design, implementation, and characterization of ESD and transient protection of these automotive electronics are increasingly challenging due to the process, packaging and cost constraints. Minimizing the protection components while providing the required protection capability is always a key objective. Off- and on-chip ESD protection designs for the industrial and automotive applications have been reported in the literature [4–9]. Protection architectures against EFT with considerations for latch-up immunity are described in [7,10–11]. Power line surge and their impact on industrial facilities are discussed in [12–14]. Comparisons of ISO 7637 transient waveforms to real world automotive transient phenomena are described in [15]. Automotive transient

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control and protection are studied in [16–18]. However, the previous work has been fragmented, covering narrow aspects of the EMC problem in ICs design. An overview is thus needed to provide the details of ESD solutions with EMC robustness consideration.

This paper provides a comprehensive overview of the EMC robust protection for automotive applications, covering standards, technologies, and device physics considerations. The EMC stresses considered include ESD, EFT, surge, and automotive transient. In Section 2, various EMC standards are compared with respect to the specifications of voltage, current and intended applications. In Section 3, ESD design window and two major automotive electronic isolation technologies are discussed, including the silicon on insulator (SOI) and junction isolation (JI). In Section 4, design considerations for off-chip protection on a communication interface are presented. In Section 5, off-chip and on-chip protection co-designs are demonstrated. In Section 6, on-chip automotive interface network protection structures are introduced. In Section 7, transient voltage suppression elements are included as the off-chip protection devices. Finally, in Section 8, on-chip ESD protection devices (diodes, LDMOS, PNP and SCR) with different real-estate area and ESD protection capabilities are compared.

2. Standards and test methods

2.1. Electrostatic discharge

Electrostatic discharge (ESD) is a sudden transfer of electrostatic charge between bodies at different potentials caused by a direct or proximity contact. It has the characteristics of a high current within a short time period. Different ESD models with corresponding parameters are summarized in Table 1. Nowadays, the major component-level ESD standards required in the industry include Human Body Model (HBM) and Charge Device Model (CDM). IEC 61000-4-2 and ISO 10605 are widely required for system-level ESD protections.

HBM is a common ESD event that directly transfers electrostatic charge from the human body via a series resistor to an object. It can be modeled with a 100 pF capacitor discharged through a switching component and a 1.5 kΩ series resistor into the component [19]. CDM, on the other hand, is the transfer of charge from a charged device to the ground. Although the duration of such a discharge is very short, the peak current can reach several tens of amperes [20].

IEC 61000-4-2 is a system-level ESD standard that replicates a charged person holding a metallic object and discharging to a system. The purpose of the system-level test is to ensure that finished products can survive such type of stress during different operating conditions. Contact discharge involves discharging an ESD pulse directly from the tester that is touching the device under test. This is the preferred method of testing. However, the standard provides for an alternate test methodology known as the air discharge for cases in which the contact discharge is not possible. In the case of air discharge test, the ESD test gun is brought close to the device under test until a discharge arc occurs. The two standards have been correlated in the literature. For example, a level 4 contact discharge of ~8 kV is considered equivalent to a ~15 kV air discharge [21].

The ISO 10605 is defined based on the IEC 61000-4-2 and describes vehicle-specific requirements. It includes test procedures for evaluating electronic modules on the bench and in the vehicle. It also describes a test procedure that classifies the ESD sensitivity of modules for packaging and handling. It applies to all types of road vehicles regardless of the propulsion system (e.g. spark-ignition engine, diesel engine, or electric motor) [22].

2.2. Electrical fast transient

EFT is applied via the lines connected to both the power and I/O ports of automotive parts [23]. It involves a burst of very fast pulses, and these pulses are usually generated from circuit switching. For example, when a circuit is switched off, the current flowing through the switch is interrupted instantaneously. The EFT test simulates the noise created by the arcs related to the switching phenomena. The purpose of the EFT testing is to ensure that equipment will operate reliably during the switching operations. The International Electrotechnical Commission (IEC) has created a document, IEC 61000-4-4, that describes the generator, setup and procedure for conducting EFT immunity tests.

Fig. 1 shows the EFT voltage waveforms with a 50 Ω load. The output waveform consists of a burst of high frequency and high voltage transients repeated at a 300 ms interval. Each individual pulse has a rise time of 5 ns and pulse duration of 50 ns, measured between the 50% point on the rising and falling edges of the waveform. As such, the EFT pulse has the characteristics of a fast rise time and a short pulse width. The total energy associated with a single EFT pulse is similar to that of an ESD pulse. IEC 61000-4-4 specifies different voltage test levels under different environmental conditions. From level 1 to level 4, the voltage peaks of the pulses are 0.25 kV, 0.5 kV, 1 kV and 2 kV, respectively.

2.3. Surge

Surge transients are caused by over-voltages resulting from switching or lightning transients. Switching transients can result from power system switching, load change in a power distribution system, or system faults, such as short circuits or arching to the grounding system of the installation. IEC 61000-4-5 defines waveforms, test methods, and test levels for evaluating the immunity of electrical and electronic equipments when they are subjected to these surges [24].

Two types of combination wave generator are used. Each has its own particular applications, depending on the type of port to be tested. The 10 μs rise time and 700 μs half to half combination wave generator is used to test ports intended for connection to symmetrical communication lines. The 1.2 μs rise time and 50 μs half to half combination wave generator is used in all other cases, and in particular, for ports intended for power lines and short distance signal connections. Fig. 2 shows the 1.2 μs/50 μs surge transient waveform. The surge pulse energy can have energy levels that are three to four orders of magnitude larger than that of an ESD or EFT pulse. Due to its high energy level, the design of protection against such a surge must be addressed differently.

Table 1
Electrostatic discharge ratings.

Standard	Application	V [V]	Duration (10–90%)	Pulses	Ri [Ω]	C [pF]	Ipeak [A]
AEC-Q100: JS-001-2012: HBM	Component	2 k	~150 ns	1	1.5 k	100	~1.5
AEC-Q100: JESD22-101: FICDM	Component	750	~0.7 ns	1	1	Packaged-dependent	~5–20
ISO 10605/IEC 61000-4-2	System	~ 8 k — contact discharge	120 ns	10	330	150	~30
ISO 10605/IEC 61000-4-2	System	~ 15 k — air discharge	120 ns	10	330	150	~30
ISO 10605	System	~ 8 k — contact discharge	150 ns	10	330	330	~30
ISO 10605	System	~ 15 k — air discharge	150 ns	10	330	330	~30
ISO 10605	System	~ 8 k — contact discharge	360 ns	10	2 k	150	~30
ISO 10605	System	~ 8 k — contact discharge	1 μs	10	2 k	330	~30