
TABLE OF CONTENTS

GLOSSARY/DEFINITIONS.....	1
1.0 INTRODUCTION	5
2.0 BASIC ESD CONCEPTS	6
2.1 ESD DESIGN WINDOW.....	6
2.2 OVERVIEW OF ESD PROTECTION APPROACHES	7
3.0 ESD CHECKS THROUGHOUT THE IC DESIGN FLOW.....	11
3.1 FLOW PHASES	13
3.1.1 <i>Technology Enablement Phase</i>	13
3.1.2 <i>Product Definition Phase</i>	14
3.1.3 <i>Product Architecture Phase</i>	16
3.1.4 <i>Product Design Phase</i>	16
3.1.5 <i>Product Verification Sign-off Phase</i>	19
3.1.6 <i>Product Validation Phase</i>	21
3.2 ESD EDA CHECKS: AVAILABILITY, INPUT DATA, AND RUNTIME PERFORMANCES.....	23
3.2.1 <i>ESD Design Data for Product Specification</i>	24
3.2.2 <i>Complexity and Performance for ESD Checks</i>	30
4.0 SCHEMATIC-BASED STATIC TOPOLOGICAL ESD CHECKS	32
4.1 CONCEPT AND PURPOSE.....	32
4.2 DESIGN DATABASE AND INPUT INFORMATION	37
4.3 ESD RULES FILES AND TECHNOLOGY FILES	40
4.4 CHECKS OUTPUT	41
4.5 ESD TOPOLOGICAL CHECKS CASE STUDIES.....	42
4.5.1 <i>ESD Topological Verification of Protected Devices</i>	42
4.5.2 <i>Topological Verification of ESD Protection on Cell Level</i>	53
4.5.3 <i>Topological Verification of ESD Protection on IP (Block, Macro, Intra/Inter Power Domain) Level</i>	59
4.5.4 <i>Topological Verification of ESD Protection on an IC (SoC, Die, Top, Inter Power Domain) Level</i>	62
5.0 LAYOUT-BASED ESD CHECKS	62
5.1 METHODOLOGY AND FLOW DESCRIPTION OF THE LAYOUT-BASED CHECKS.....	65
5.2 DESIGN DATABASE	66
5.3 EDA ESD TOOL	66
5.4 ESD DEVICE AND TECHNOLOGY ASPECTS	67
5.5 INPUT/OUTPUT DATA	68
5.6 CASE STUDIES.....	69
5.6.1 <i>Low Impedance Parasitic ESD Paths</i>	69
5.6.2 <i>Protection of Gates Along Power Cross Domains Paths</i>	72

5.6.3	<i>Influence of Bus Inductance on Intra-Domain CDM Robustness</i>	74
5.6.4	<i>Method for Removing Common I/O Resistance in Layout-Driven ESD Network Analysis</i>	77
5.7	SoC DESIGN LAYOUT ESD VERIFICATION.....	78
6.0	PACKAGE-LEVEL ESD CHECKS	81
6.1	PACKAGE EFFECTS AND IMPLICATIONS FOR ESD PROTECTION NETWORKS	81
6.2	EXTRACTION OF THE DIE AND PACKAGE PIN META DATA AND PACKAGE NETLIST	83
6.3	INTEGRITY OF THE OVERALL ESD PROTECTION NETWORK ACHIEVED AT THE DEVICE PACKAGE PIN LEVEL	83
6.4	PACKAGE R/L/C NETWORK COMPATIBILITY WITH OVERALL ESD PROTECTION SCHEME.....	86
6.5	INTEGRITY OF THE OVERALL ESD PROTECTION NETWORK ACHIEVED AT PACKAGE PIN LEVEL WHEN HAVING MULTI-DIE (SYSTEM IN A PACKAGE) DESIGNS	89
6.6	DEPENDENCE OF CDM PEAK CURRENT ON THE PACKAGE-DIE	90
6.7	ADVANCED PACKAGE: 2.5D/3D INTEGRATION AND CHIPLETS.....	95
7.0	SYSTEM LEVEL ESD CHECKS	100
7.1	SIMULATION MODELS REQUIRED FOR BOTH SEED AND FULL WAVE SYSTEM ESD CHECK. .	101
7.1.1	<i>Transient Voltage Suppressor (TVS) Simulation Models for System Level ESD Checks</i>	102
7.1.2	<i>Common Mode Choke (CMC) Simulation Model for System Level Checks</i>	104
7.1.3	<i>IC Model for System Level ESD Checks</i>	104
7.1.4	<i>PCB Model for System Level ESD Checks</i>	108
7.1.5	<i>ESD Pulse Model for System Level ESD Checks</i>	108
7.2	SYSTEM LEVEL ESD CHECKS CASE STUDIES.....	109
7.2.1	<i>Case Study 1: SEED Methods for System Level ESD Checks</i>	109
7.2.2	<i>Case Study 2: 3D Full Wave Dynamic Simulation System Level ESD Checks</i>	111
7.2.3	<i>Case Study 3: System Level ESD Checks With Near Field Scanning</i>	113
8.0	ESD CIRCUIT SIMULATION (SPICE)	115
8.1	MOTIVATION AND FLOW.....	115
8.2	COMPACT MODELING	118
8.3	ESD EVENT SIMULATION	120
8.4	FAILURE MODELING	122
8.5	TEST BENCH BUILDING.....	124
8.6	CASE STUDY: VERIFICATION OF TRIGGER CIRCUIT IMPLEMENTATION IN TRANSIENT-TRIGGERED DESIGNS.....	126
9.0	ESD TCAD SIMULATION	129
9.1	MOTIVATION AND FLOW	129
9.2	TCAD MIXED-MODE SIMULATION	132
9.3	CASE STUDY: TCAD MIXED-MODE ANALYSIS OF POST-LAYOUT ESD CIRCUIT PERFORMANCE.....	134
10.0	CONCLUSIONS	135
11.0	REFERENCES	135

Tables

Table 1: General Reference Table: ESD EDA Tools Availability	24
Table 2: General Reference Table: INPUT Data to ESD EDA Tools	25
Table 3: General Reference Table: ESD EDA Tools Runtime (Execution Time)	30
Table 4: System Level ESD Checks.....	101
Table 5: Simulation Models for SEED and Full Wave System Level ESD Checks.....	102
Table 6: Example of an RC-Triggered Clamp Design Specification	128

Figures

Figure 1: ESD EDA Tools and Methods Outlook	6
Figure 2: Generic ESD Design Window	7
Figure 3: ESD Elements With Various Triggering Mechanisms	8
Figure 4: Rail Clamp Versus Local Clamp Based Protection Approaches.....	9
Figure 5: Using Low Resistance Master VSS Bus Versus APD Connected Ground Domains ...	10
Figure 6: Simple ESD Verification Flow Mapped to Sample IC Design Flow	12
Figure 7: Technology Enablement Phase	14
Figure 8: Product Definition Phase.....	15
Figure 9: Product Architecture Phase	16
Figure 10: Product Design Phase.....	17
Figure 11: Product Verification Sign-off Phase	20
Figure 12: Concept of Sign-off System Verifying for Presence and Compliance of All Required ESD EDA Checks	21
Figure 13: Product Validation Phase	22
Figure 14: Interface Between Pre-Silicon and Post-Silicon Verifications.....	23
Figure 15: In-Design Specifications.....	28
Figure 16: Example of I/O Chiplet Specification Using CDXML Format With ESD Target	29
Figure 17: Utility Tools Needed to Translate Specifications to the Setup of Each EDA Tool	30
Figure 18: Extracted Netlist and Corresponding Schematic View.....	32
Figure 19: Schematic-Based Static Topological Checks Flow	33
Figure 20: Static Topological Checks: Verification of Devices to Be Protected from ESD	34
Figure 21: Static Topological Checks: Verification of ESD Protection Network.....	34
Figure 22: Protected Devices Check - Objective: Report ESD-Vulnerable Devices.....	35
Figure 23: ESD Network Checks - Report Missing ESD Diodes and Diodes With Insufficient Perimeter.....	36
Figure 24: ESD Network Checks - Objectives: Report Missing ESD Clamps and ESD Clamps With Insufficient Width.....	37
Figure 25: All Input Information Necessary to Perform a Complete and Correct Static Topological Verification	38
Figure 26: Example of a Graphical User Interface to List the Power and Ground Nets Before the Start of the Topological Check.....	38
Figure 27: Example of a Text File That is Read at the Start of the Check, Where the Technology, Path to the Netlist, Topcell Name, and List of I/O Ports are Given as Input	39
Figure 28: Initialization Methodology by Means of “Controller” Components	39
Figure 29: Extracted Netlist Line Containing Controller Component Information.	40
Figure 30: Technology-Independent Files and Technology-Dependent Files	41

Figure 31: As the Parasitic Resistance From the Primary ESD Protection Element to VSS Pad Exceeds a Critical Value, the Need for a Secondary ESD Protection Element to the Input Arises	43
Figure 32: Example of a Rail Clamp Network for a Domain Containing Decoupling Caps.....	44
Figure 33: Cross-Domain Level Shifter - Gate at Node 1 Could be Overstressed During an ESD Event.....	45
Figure 34: Screenshot of the Results of the Cross-Domain Schematic Checking Tool, Highlighting an NFET Device (N10) at Risk When ESD Currents Pass Between the VA/GNDR and VA/GA Domain.	46
Figure 35: Input File With Pin-Pair Names and Associated ESD Voltage Drop.....	46
Figure 36: Some Examples of MSV _{tot} Calculation – Couple of Terminals in “Series” for Protected Circuitry.....	47
Figure 37: An Illustration of MSV Violation Condition in Protected Path Parallel to a Main ESD Current Path.....	48
Figure 38: Product A – Red Box Failing for V _{DR} Overstress	48
Figure 39: Product B – Red Elements Failing for V _{DR} Overstress.....	49
Figure 40: ESD Verification Flow.....	49
Figure 41: Circuit With Negative Supply Rail in Different Hierarchy	50
Figure 42: Instruction Set Example in a Commercial Tool to Screen Out Big-Buffer Topology in a Design Netlist.....	51
Figure 43: IC Schematic With Protection Circuits to be Extracted	52
Figure 44: Identified Possible ESD Active Devices in the ESD ‘Critical’ Path for the Circuit in Figure 43, and Devices ESD I-V Parameters	52
Figure 45: Example Case for Flip-Chip ESD Protection in I/O	53
Figure 46: Optimization of ESD Protection Elements.....	54
Figure 47: A Cross-Domain Layout Example	54
Figure 48: A Cross-Domain Circuit Schematic Example.....	55
Figure 49: Illustrative Example of “Controller” Placement.....	56
Figure 50: Check Flow for Top-Level Verification	57
Figure 51: Example of I/O Controller Component	58
Figure 52: Improperly Connected Gates and Power Domains in a Digital Circuit	59
Figure 53: ESD Verification Flow and Circuit Topology Used to Check Gate Oxide Protection Crossing Power Domains	59
Figure 54: ESD Checker Tool Verification Flow	60
Figure 55: ESD Checker Tool Error Viewer GUI.....	60
Figure 56: Lacking Both a Supply Clamp Cell and a Supply Controller Highlighting Rule Violation	61
Figure 57: Layout-Based ESD Checks Flow	64
Figure 58: Simplified Interconnect Robustness Flow for ESD CD, P2P, LDL, and DRC-Checks	65
Figure 59: Typical I-V Curve of a Snapback ESD Device and a Diode.....	68
Figure 60: A Cross-Section Image of the Parasitic Bipolar Formed When an N-well is Connected to an I/O Pad Too Close to Another N-well Connected to a Different Pad.....	69
Figure 61: Screenshot of the DRC Tool Results Showing Error Regions Where an N-well Resistor is Placed Too Close to a PFET.....	70
Figure 62: Hot Transistor, Source Connected to Signal Pin (I/O), and Drain Connected to Ground Pin (VSS)	71

Figure 63: Hot NPN Parasitic Formed With Emitter (Drain of NMOS(1)) Connected to Signal Pin (I/O), Collector (Drain of NMOS (2)) Connected to Ground Pin (VSS), and Base (Substrate) Connected to Ground Pin (VSSE)	71
Figure 64: Typical ESD Snap-Back I-V and its Parameters	72
Figure 65: An ESD Network Graph, Representing the ESD Elements Through the Parameters of ESD IVs and Connectivity	72
Figure 66: Layout-Specific Checks in a Context-Aware Flow Greatly Simplify Identification of ESD Protection Elements for a CDM Event.....	73
Figure 67: Simplified Cross-Domain Resistive ESD Network Model	74
Figure 68: Full-Chip Cross-Domain Voltage Map for Stress Between Domain 3 and Domain 1, With Indication of Over-Voltage Situation at the I/O Interface of Domain 1.....	74
Figure 69: Scanning Electron Microscopy (SEM) Picture Showing the Thin Gate Oxide Damage of a Victim Transistor in the Core Due to CDM Stress.....	75
Figure 70: Simplified Schematic and Layout Representations of the Test Case	76
Figure 71: CDM Layout Simulations Including the Impedance of the Self-Inductance	77
Figure 72: Expanded P2P Extraction of the Common Resistance, the ESD Device Resistance, and the Victim Device Resistance	78
Figure 73: Failure Analysis Results From Product Showing Oxide Damage at Core Devices Inside the Same Power/Ground Domain After CDM Stress	79
Figure 74: Full Chip CDM Verification Flow	80
Figure 75: Package-Level ESD Check Flow	82
Figure 76: Sample Structure for Package Level ESD Meta-Data	83
Figure 77: Package Level ESD Network Verification	84
Figure 78: Package Level ESD Network Verification	85
Figure 79: CDM Waveforms for Different Package Trace Time Delays.....	85
Figure 80: CDM Current Through ESD Element at the Far End of the Transmission Line on Different Chip Pads.....	86
Figure 81: Schematic for SPICE Simulation of CDM Waveforms	86
Figure 82: The Presence of the Package R/L/C Parasitics Could Lead to an Increase in the ESD Stress Levels V_{dev} at the Internal Circuit Nodes	87
Figure 83: Importance of Die-to-Package Connectivity and Inductances	88
Figure 84: Chip-Level CDF Model Extraction and Simulation Process Flow	89
Figure 85: A Macro Model for Each Subsystem in a Chip, and Equivalent Circuits Driven by Protection Circuits, Input Buffer, and Output Buffer.....	89
Figure 86: Example of Cross-Die ESD Path in a Multi-Die (System in a Package Design).....	90
Figure 87: CDM Peak Current Dependence on Package Size and Type	91
Figure 88: CDM Peak Current Variation for the Same Die in Different Packages	91
Figure 89: CDM Peak Current Distribution for Different Packages	92
Figure 90: Flip-Chip Package Cross-Section; C_{DUT} Is Between the Silicon Die/Package and Metal Lid That is Separated by Thermal Interface Material.....	93
Figure 91: Two Paths of CDM Peak Current - DUT (+) Both I_{local} and I_{global} Are Through ESD Protection Element (n+ diode) and DUT (-) I_{local} is Through the Vertical Parasitic p+n-p Bipolar and I_{global} is Through p+diode	93
Figure 92: A Package with a Three-Layer Substrate Placed on the Field Plate of the FICDM Tester	94
Figure 93: Data Flow Diagram of the Automated Peak Current Estimation Tool.....	94
Figure 94: Representative 2.5D and 3D Package Systems	95
Figure 95: Definition of Die-to-Die (Internal) and Die-to-Package (External) I/Os	96

Figure 96: 3D Interconnect Technology Landscape.....	96
Figure 97: Roadmap for Number of Die-to-Die Interfaces per Package	97
Figure 98: Top-Level Flow for Assembly 2.5D/3D ESD Verification	98
Figure 99: Extraction of Assembly-Level Data for ESD Verification.....	98
Figure 100: Verification of Complete 2.5D/3D Design Level	99
Figure 101: Simplified Schematic for a PCB Analysis with TVS and IC; Simplified Schematic of the IC ESD Signal Path Used in Some of the Analyses	101
Figure 102: Dynamic Voltage/Time Characteristic of a TVS and Idealized TVS I-V Curve	102
Figure 103: Response of a Low-Capacitance TVS to a 28-Ampere VF-TLP Pulse.....	103
Figure 104: Bidirectional TVS ESD 300-B1_02 LRH: Schematic for Quasi-Static Analysis; Schematic for LTSPICE Simulation; Transient Voltage/Time Simulation Results .	103
Figure 105: Bidirectional TVS PTVS5V5D1BL With Clamping Voltage of ~10 Volts: SPICE Circuit Schematic; Dynamic Simulation Results	104
Figure 106: WE-CNSW Common Mode Line Filter: LTSPICE Representation; PCB Placement Strategy	104
Figure 107: IC ESD Pin Model Development, Validation, and First Use Through IC Development Phases	105
Figure 108: ESD System Checks Flow	106
Figure 109: IC HDMI Differential Port: TLP I-V Characteristics; SPICE Circuit for V-T Simulation; (c) Quasi-Static SPICE Simulation Results	107
Figure 110: Off-Chip Diode Versus On-Chip Diode Characteristics: IC Is Not Powered; IC Is Powered	107
Figure 111: Internal (IC ESD Diode) and External (TVS) Protection Turn-On Scenarios.....	108
Figure 112: Example of Two ESD Pulse Models for IEC 61000-4-2 8 Kilovolts	109
Figure 113: An Example of Transient Behavioral Models (TBM) for SEED Simulations: ESD Protection Elements Mode; Combined Model with the Elements-To-Be-Protected from ESD	110
Figure 114: An Example of Typical SEED Analyses for 100-Volt TLP Pulse: Unpowered IC, VDD=0 Volts; Powered IC, VDD=3.3 Volts	111
Figure 115: Full Wave Dynamic ESD Simulation Analysis Flow.....	112
Figure 116: 6-Layer DDR Memory PCB; System ESD Pulse Waveform as Applied to Memory PCB at Point for an I/O Pin; Waveforms With and Without TVS Placed on PCB I/O (Plot Made at the PCB IC Pin)	113
Figure 117: Near Field Scanning Injection Methods Using Different Probes: Horizontal Loop; Vertical Loop; E-Field; and Direct Capacitive Injection	114
Figure 118: Typical Near Field 5-mm Probe Scan Colormap Without and With an RC Filter Inserted Into the Trace	114
Figure 119: Illustration of the FICDM Test System, Which Needs to be Modeled.....	116
Figure 120: Conceptual Flow Figure of ESD Circuit Simulation (SPICE) Tasks at Different Stages of the Product Design Cycle.....	117
Figure 121: Example HBM Simulation Schematic Diagram, With an I/O-to-I/O Stress	120
Figure 122: Cross-Section of Flip-Chip BGA Package Placed on the FI-CDM Tester Field Plate Showing Components of C _{DUT}	122
Figure 123: Cross-Section of FI-CDM Tester With Large Coin Placed on Field Plate Showing Components of the Relevant Capacitors to Predict the CDM Discharge Waveform	122
Figure 124: Example Output Driver Circuit Diagram to Illustrate the Difficulties Involved With Determining Bias Voltages Under ESD Conditions.....	126

Figure 125: Typical RC-Triggered Clamp Schematic.....	127
Figure 126: Conceptual Flow Figure of ESD TCAD Simulation Tasks at Various Stages of the Product Design Cycle.....	131
Figure 127: Conventional and Parameterized Mixed-Mode Simulation Flows	132
Figure 128: Illustration of the Automatic FEM Structure Generation and View of the Layout Interface.....	133
Figure 129: Device and Layout Aware TCAD Design Flow and Example of the Analysis.....	134