Chapter 28 The Electrostatic Discharge (ESD) Problem

Consider a chip which is packaged. There must be some lines emanating from the chip to the outside world. If any line is touched by a human being, some static electrical charges will be on this line. These charges may induce a huge voltage which will damage the circuits inside the chip.

In this chapter, we will introduce some mechanisms to neutralize the electrostatic discharge problem.

Section 28.1 A Simple Method to Solve the ESD Problem

Positive Charges

The static charges may be positive or negative. Positive charges will cause a positive high voltage. We first discuss how to solve the positive high voltage problem. To neutralize the high voltage serge, we may use a PMOS transistor which acts as a diode. Consider Fig. 28.1-1



Fig. 28.1-1 Using a PMOS transistor to prevent a positive high positive voltage serge

In Fig. 28.2-1, M2 is a PMOS transistor and M1 is a switch which allows a high voltage to come in. Because the drain of M2 is connected to its gate, it can be considered as a diode as shown in Fig. 28.1-2.



Fig. 28.1-2 The equivalent circuit of M1

VC1 and VC2 are two square waves and there must be a time lag between as shown in Fig. 28.1-3



Fig. 28.1-3 VC1 and VC2

The circuit in Fig. 28.1-1 demonstrates the principle of solving the ESD problem. The capacitor C1 represents the place where static electric charges may occur. If there is no static electricity, the voltage of C1 will be low; otherwise it will be high. If this high voltage is transmitted to Node 3. It will be a big disaster. Our job is to prevent this to happen.

VH is a voltage source which represents the static electric charges. If VH is low, it represents the fact that there is not much static electric charges; otherwise, there is a large amount of static electric charges. If VC1 is high, switch S1 is closed, and VH will charge the capacitor. There is a switch S2 controlled by VC2. If VC2 is high, the voltage of C1 will go through S2 to reach Node 3.

If the voltage of C1 is low, there will be no current flowing through M1 and V3 will be low which will not cause any damage to our circuit. If there are a large amount of static electric charges V3 will be temporarily high, but current will flow through M1. This means that all of the charges will be gone and V3 will go back to normal which is 0.

Experiment 28.1-1 The Circuit in Fig. 28.1-1 When VH is 2V

In this experiment, we test the ESD circuit in Fig. 28.1-1 by assuming VH is 2V. This indicates that there is not much static electric charge. The program is in Table 28.1-1 and the result is in Fig. 28.1-4.

Table 28.1-1	The program f	for Experiment	28.1-1
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esd	
protect	
lib "C:\mm0355v.l" TT	
unprotect	
option post	

```
.op
VDD
        VDD
               0
                    3.3V
VSS VSS 0
            0V
         VH
                 0
                         2V
VH
VC1VC10
            pulse 0V 3.3V 5u 100n 100n 1u 1000u
VC2VC20
            pulse 0V 3.3V 10u 100n 100n 1000u 1000u
G_S1
       VH
             1
               VCR pwl(1) VC1 0 0,10Meg 3.3v,1m
G_S2
       2
            3 VCR pwl(1) VC2 0 0,10Meg 3.3v,1m
C1
                0
                        100p
        1
R1
        1
                2
                        1.5K
M1 3
        VDD
                VDD
                        VDD
                               PCHW=20U L=1U
.ic V(1)=0 V(2)=0 V(3)=0
.tran 0.1u 20u
.probe I(M1)
.end
```



Fig. 28.1-4 The result of Experiment 28.1-1

From Fig. 28.1-4, we can see that VH is transmitted all the way to Node 3 when VH is low. Note that the current in M1 is very small.

Experiment 28.1-2 The Circuit in Fig. 28.1-1 When VH is 1000V

In this experiment, we set VH to be 1000V simulating a large amount of static electric charges appear. The program is Table 28.1-2 and the result is in Fig. 28.1-5.

Table 28.1-2 The program of Experiment 28.1-2

esd									
.protec	t								
.lib "C:\	,mm03	55v.	I" TT						
.unprot	ect								
.option	post								
.op									
VDD VD	DD 0	3.3	V						
VSS VS	S 0	0V							
VH	VH		0	1	1000V				
VC1 VC	21 0	pul	se 0V 3.3V	5u	100n	100	n 1u 1000u		
VC2 VC	2 0	pul	se 0V 3.3V	10	u 100	n 10	0n 1000u 1	000u	
G_\$1	VH	1	VCR pwl(1)	VC1	0	0,10Meg	3.3v,1m	
G_\$2	2	3	VCR pwl(1	L)	VC2	0	0,10Meg	3.3v,1m	
C1	1		0	1	00p				
R1	1		2	1	.5K				
M1 3	VDD	VD	D VDD PCH	I W	/=20U	L=	=1U		
.ic V(1):	=0 V(2)	=0 \	/(3)=0						
.tran 0.	1u 20u								
.probe	I(M1)								
.end									



Fig. 28.1-5 The result of Experiment 28.1-2

Fig. 28.1-5 shows that the circuit works because V3 recovers to 0 after V1 becomes extremely high. Note that the current in M1 is very high. This indicates that the static charges disappear as current in M1.

Negative Charges

If the static charges are negative ones, a negative high voltage occurs. In this case, we may use an NMOS transistor to neutralize this voltage. The circuit is as shown in Fig. 28.1-6.



Fig. 28.1-6 Using an NMOS transistor to prevent a negative high positive voltage serge

Experiment 28.1-3 The Circuit in Fig. 28.1-6 When VL is 2V

In this experiment, we tested the circuit in Fig. 28.1-6 by assuming that VL is 2V. This indicates that there is not much static electric charge. The program is in Table 28.1-3 and the result is in Fig. 28.1-7. As shown in Fig. 28.1-7, V3 reaches 2V and there is almost no current in M2 which is expected.

Table 28.1-3	The program	for Experiment	28.1-3
--------------	-------------	----------------	--------

Esd									
.protect	ī.								
.lib "C:\	mm03	55v.	I" TT						
.unprot	ect								
.option	post								
.op									
VDD VD	D 0	3.3	V						
VSS VS	S 0	0V							
VH	VH		0		2V				
VC1 VC	10	pul	se OV 3	3.3V 5ι	u 100n	100	n 1u 1000u		
VC2 VC	20	pul	se OV 3	3.3V 10)u 100	n 10	0n 1000u 1	000u	
G_\$1	VH	1	VCR p	owl(1)	VC1	0	0,10Meg	3.3v,1m	
G_\$2	2	3	VCR p	wl(1)	VC2	0	0,10Meg	3.3v,1m	
C1	1		0	1	.00p				
R1	1		2	1	5K				
M2 3	VSS	VSS	S VSS	NCH V	V=20U	L=	=1U		
.ic V(1)=	=0 V(2))=0 \	/(3)=0						
.tran 0.2	1u 20u	I							
.probe l	(M2)								
.end									



Fig. 28.1-7 The result of Experiment 28.1-3

Experiment 28.1-4 The Circuit in Fig. 28.1-6 When VL is -1000V

In this experiment, we set VL to be -1000V which means that there are a large amount of negative static electric charges. The program is in Table 28.1-4 and the result is in Fig. 28.1-8. As shown in Fig. 28.1-8, V3 goes back to 0V and there is a large current in M2 momentarily which means that the static electric charges have gone through M2 and their effect is neutralized.

Table 28.1-4	The program	of Experime	ent 28.1-4
--------------	-------------	-------------	------------

esd	
.protect	
.lib "C:\mm03	55v.l" TT
.unprotect	
.option post	
.op	
VDD VDD 0	3.3V
VSS VSS 0	0V
VH VH	0 -1000V
VC1 VC1 0	pulse 0V 3.3V 5u 100n 100n 1u 1000u
VC2 VC2 0	pulse 0V 3.3V 10u 100n 100n 1000u 1000u
G_S1 VH	1 VCR pwl(1) VC1 0 0,10Meg 3.3v,1m

```
G S2
            3 VCR pwl(1) VC2 0 0,10Meg 3.3v,1m
       2
C1
        1
                 0
                         100p
R1
        1
                 2
                         1.5K
        VSS VSS VSS NCH W=20U L=1U
M2 3
.ic V(1)=0 V(2)=0 V(3)=0
.tran 0.1u 20u
.probe I(M2)
.end
```



Fig. 28.1-8 The result of Experiment 28.1-4

Complete ESD circuit to Prevent Both Positive and Negative Charges with NMOS and PMOS

To prevent both positive and negative charges, we will use both PMOS and NMOS transistors as shown Fig 28.-9.



Fig. 28.1-9 An ESD Circuit to Prevent Both Positive and Negative Static Electric Charges.

In Fig. 28.1-9, there is a voltage source VH which provides a high positive voltage. This is used for simulating positive static electric charges. If VH is replaced by VL, the circuit can be used to simulate negative static electric charges.

Experiment 28.1-5 The Circuit in Fig. 28.1-9 When VH is 2V

In this experiment, we

esd	
.protect	
.lib "C:\mm03	55v.I" TT
.unprotect	
.option post	
.op	
VDD VDD 0	3.3V
VSS VSS 0	0V
VH VH	0 2V
VC1 VC1 0	pulse 0V 3.3V 5u 100n 100n 1u 1000u
VC2 VC2 0	pulse 0V 3.3V 10u 100n 100n 1000u 1000u
G_S1 VH	1 VCR pwl(1) VC1 0 0,10Meg 3.3v,1m

G_S2 2 3 VCR pwl(1) VC2 0 0,10Meg 3.3v,1m C1 1 0 100p R1 1 2 1.5K VDD VDD VDD PCH W=20U L=1U M1 3 M2 3 VSS VSS VSS NCH W=20U L=1U .ic V(1)=0 V(2)=0 V(3)=0 .tran 0.1u 20u .probe I(M1) I(M2) .end



VH=1000V

esd		
.protect		
.lib "C:\mm03)355v.l" TT	
.unprotect		
.option post		
.op		
VDD VDD 0	3.3V	
VSS VSS 0	0V	

28-12

esd .protect .lib "C:\mm0355v.I" TT .unprotect .option post

١ /١	1_	10	00	
VI	H=-	τu	υυ	v

												ead											
Wave Last	1.21						_					-				1	±						
D0:A0:v(vc1) ^	121				+	M						+	<u>†</u>	+	÷	+	÷						
4	5002					- ¥ 🔨	┙╇										+						
			*									+	·····		+								
< >	-	1u -	0 1	u	20.	3u	4u.	5u	60.	7u	8u	9u Time (li	0u a) (TIME)	11u	120 :	13u :	14u	15u	16u	170	18u	19u	20u
	14											eod											
-Wave List.	1 .1		L		+							+	1				+						
D0:A0:v(vc2)	13		1/1		10	AA	\/				IC)		+			÷						
	500m		V	—	LU	υυ	V				ソレム		1			+	+						
	4 H						····.	····															
	-	1u	J 1	u	20	3u	40.	50.	60	70	80	9u Time (li	Uu a) (TIME)	11u	120 :	130. 3	14u	15u	1bu	170	180	190	20a
Ways List	11											esd											
.move Lost													Ν				1						
DU:RU:V(1)	§ 500 -				+		\/1					+	+	+	+	+	+						
4							A T																
	- 16						4			7	0	0	0		10	12	4	15	16-	17	10-	10.	
	-	1u '			20	20	40.	20	00	14	04	Time (li) (TIME)				.40	120	100	110	100	190	2010
Wave List				_								ead											
	< X00 HF		b																				
D0.40.v(3)	400											1	N	1	1		1						
D0:A0:v(3)	400 - 200 -										V	2	\setminus										
DO:A0.v(3)	400 - 200 -										V	3	$\left \right\rangle$										
■D0:A0.v(3) ▲	400 - 200 - 0 -	4		u	20	3u	4u		бu	7u	V	3	0u		12u	3u	L4u	15u	16u	17u	180		20u
■D0:A0:v(3) ▲	400 -	1u	0 1	u	2u	3u	4u		бu	7u	V	3 ^{9u} Time (li	Ou a) (TIME)	1u	12u	Ju :	14u	15u	16u	17u	18u	19u	20u
More Litt.	400	1u		u	2u	3u	4u	5u	бu	711	8u	3 ^{9u} Time (li est	Ou (IIME)	 u	12u	13u	4u	15u	16u	17u	18u	19a	20u
D0:A0:v(3)	400	1u		u	2u	311	4u	5u	би.	7u	У ⁹⁴	3 9u Time (li est	Ou) (TIME)		12u	(3u	14u	15u	160	170	180.	19u	20u
IDO:A0v(3)	400	1u		u	2u	30.	40	5u	6u	7u	• •	3 ^{9u} Time (li est	0u .) (TIME)	llu	12u :	3u	4u	15u	16u	17a	18u	19a	20u
■ ■ ■ ■ ■ ■ ■ ■ ■ ■ ■ ■ ■ ■ ■ ■ ■ ■ ■	400	1u		u	2u	3u.	40	5a	6u	7u	• • •	3 ^{9u} Time (li est	0u L) (TIME)	IIu	12u	3u.	4u	15u	160.	170	180	190	204
100 40 v(3) A	400	iu		u 2	2u	3u 3u 3u	4u 4u	5u 5u	6u.	7u	вч Вч	9 ⁹ u Time (li ext L)	ou a) (TIME)	11u	12u	3u 3u 3u 1	4u 4u	15u.	16u 16u	17u	18u 18u	19a 19a 19a	20u 20u 20u
Wave List	400 + 400 +	1u		u 2	2u	3u 3u	4u 4u 4u	Su Su Su	6u 6u	7u 7u	8u (M:	9 ⁹⁰ Time (li ext L)	Du a) (TIME) bu (TIME)	liu lu	12u 1	3u 1	4u 4u	15u	16u 16u	17u 17u	18u 18u	19a 19a	20u 20u
Wave Litt V UD 4.0 vr (3) A V V	400 + 400 +	iu iu		u 2	2u	3u 3u	4u 4u	5u	6u	7u 7u	вч (МЗ	9 ⁹ Time (li ext L) ^{Pu} 1 Time (lin ext	Du) (TIME) Du (TIME)	liu iu j	12u	30 1	4u.	15u	16u	17u	18u 18u	19u 19u	20u
100 A0 v (3) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1	400 + + + + + + + + + + + + + + + + + +	iu iu		u. 2	2u	3u 3u	4u 4u 4u	Su Su	6u	7u	8u (M:	3 ⁹ u Time (li ext 1 Time (in ext	Du) (TIME) Du (TIME)	11u	12u 1	3u 1	4	15u	16u	17u	18u 18u	19u 19u	20u
IDO 4.0×(5) I IDO 4.0×(5) I	400 + 400 +	iu i		2	2u	3u 3u	40.	Su Su	6u	7u	вч (M: ^{ри}	3 ^{9u} Time (li ext 1 Time (in ext	Ou (TIME)	lu lu	2u 1	3u 1	4u.	15u	16u 16u	17u	18u 18u	19u 19u	20u
CO 4.0 v(5) A V	400 + 400 +	iu '		2	20	3u 3u	40.	Su Su Su	6u	7u	ου δu (Μ2	9 ⁹⁰ Time (li ext L) ¹⁰ Time (lin ext	Ou () (TIME) (TIME)	liu lu	12u	3u 1	4u	15u	16u 16u	17u	18u 18u	19u 19u	20u
E 0 40 40 1 4 1 4 1 4 1 4 1 4 1 4 1 4 1 4	400 + 400 +	ju , , , , , , , , , , , , , , , , , , ,		2	20	3u 3u 3u	40	Su Su Su	6u	7u	вч (М: вч (М2 вч	B 9 ¹⁰ Time (li est L) ⁹¹⁰ Time (lin est 2)	Du a) (TIME) (TIME)	lu lu lu lu	12a 1 2a 1	3u 1	4u. 4u.	15u	16u 16u	17u 17u	18u 18u 18u	19a 19a 19a 19a	20u 20u 20u 20u

VH	VH	0	1	1000V					
VC1 VC1 0 pulse 0V 3.3V 5u 100n 100n 1u 1000u									
VC2 VC2 0 pulse 0V 3.3V 10u 100n 100n 1000u 1000u									
G_\$1	VH	1 VCR	pwl(1)	VC1	0	0,10Meg	3.3v,1m		
G_S2	2	3 VCR	owl(1)	VC2	0	0,10Meg	3.3v,1m		
C1	1	0	10	00p					
R1	1	2	1	.5K					
M1 3	VDD		PCH W	/=20U	L=	:1U			
M2 3	VSS	VSS VSS	NCH W	/=20U	L=	:1U			
.ic V(1)=	=0 V(2)	=0 V(3)=0							
.tran 0.2	1u 20u								
.probe l	(M1) I	(M2)							
.end									

```
.op
VDD VDD 0
           3.3V
VSS VSS 0
           0V
VH
       VH
              0 -1000V
VC1 VC1 0 pulse 0V 3.3V 5u 100n 100n 1u 1000u
VC2 VC2 0
           pulse 0V 3.3V 10u 100n 100n 1000u 1000u
G_$1
      VH
          1 VCR pwl(1) VC1 0 0,10Meg 3.3v,1m
G_S2
      2
          3 VCR pwl(1) VC2 0 0,10Meg 3.3v,1m
C1
       1
              0
                      100p
R1
       1
              2
                      1.5K
M1 3 VDD VDD VDD PCH W=20U L=1U
M2 3 VSS VSS VSS NCH W=20U L=1U
.ic V(1)=0 V(2)=0 V(3)=0
.tran 0.1u 20u
.probe I(M1) I(M2)
.end
```

Wave Last	3	. 3 1															+			+				
D0:A0:v(vc1) ^	18	23 40					110										+			+				
	1 20	15 1					Vt.								÷				÷				1	
	Nol.	00m					· · ·										+	+		+				
¥	11	- <u>- 16</u>				· . · · · · · · · · · ·											·····							
		-11	, O) 1	u	2u	3u	4u	5u	6u	7u	8u 9	u 10 Time (lin)	(TIME)	1u 1:	2u 1	.3u :	4u :	15u	16u	170.	180 1	.90	200
													ead											
Wave List	a i	3 - 16-			ļ	-+											+						+	
D0:A0:v(vc2)	13	25 10					A A	^ 1 7				ica												-
	2	15 11-			in a second						V				+		+		+	+			+	-+
	Nob	00m		V 1	_			U V									+		+	+				
v	11.	· -16	*******											*******	·		1	1		·····			·····	
< ▶	1	-11	, 0	1 1	u	2u	3u	4u	5u	бu	7u	8u 9	hu 10	hu 1	lu 13	2a 1	3u :	4u :	15u	16u	170.	180. 1	.9u	20u
	inne (m) (iNR)																_							
Wave List		U 16-		<	-	-					p			~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~		-	1	1	1	1	1	1	1	
D0-40(0)	9																1		1	1		1	1	
D0:80:9(1)	Ë,	-500				+	- \	1									+	+		+	-+		+	
	췽					1	- V	1		1				/	1		1	1	1	1	1	1	1	
	>	-1k				<u></u>		····						J	į									
	1			1	u	2u	3u	4u	5u	6u	7u	8u 9	hu 10	hu 1	lu 1:	2u 1	3u.	4u.	15u	16u	17u :	18u 1	9u	20u
		-10	1										Time (lin)	(TIME)										
Wene List		V											ead											
	. â		1																1					
D0:A0:v(3)	1 E	-200				+						1/2		/			+	+		+				
	4	-400 1										V D		17	1		1	1						
	Å					1				-				V			1	1	1	1			1	1
	1					2	2	4	5	6	2.	Pu (. 10	in 1	1	2	2	4	5	16	17.	Pm 1	0	20
		-11	1 0	· ·	a	20	34	40.	54	ou	70	5u 3	Time (lin)	(TIME)	10 1.	20 1	.50.	40.	150	100	170 .		.50	200
													ead											
Wave List	<u> 3</u> -	5m 1	*								1			1								1	1	
D0:A0:i(m1) ^	T	0m :										11)		4										
	1 a -1	5m					+	-+				/ + + +		J					÷	+	+		+	
	8.2	5m 11					1												1		1	1		
Ψ.		10																	+	· · · · · · · · · · ·	· · · · · · · · · · · · · · · · · · ·	+	[++++++
< ▶		-1u	0	10	. 2	u :	3u	4u	5u	бu	7u	8u 9	1 101 Time (lin)	1 11	u 12	tu 13	3u 1	4u 1	Su I	161 1	17u 1	.8u 1	.9u	20u
													(uu) onu i	(111015)										
Wave List		· -18			_		-	-	-			-	000		_	_	-	-		1	1	-		
D0.40.000	7 년.2	10m 11				1	1		1									1		1	1		1	
LO:N03(m2)	- ' ' '	1										777		r							1			
	ĝ-4	00m				+	-+					v i Z J		·	·			·	+	-+			+	-+
	10	16				1			1			-		I				1	1	1	1	1	1	1
	1	-1u	0	1	u :	2u	3u	4u	5u	би.	7u	8u 9	u 10 Time (lin)	u 1 (TIME)	iu fi	lu 1.	3u 1	4u 1	5u	16u	17u	18u 1	9u	20u