Dual SCR With Low-and-Constant Parasitic Capacitance for ESD Protection in 5-GHz RF Integrated Circuits

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***Abstract* — Silicon-controlled rectifier (SCR) had been reported with good electrostatic discharge (ESD) robustness and low parasitic capacitance. In this work, SCR devices were investigated to have low and constant capacitance for on-chip ESD protection in RF ICs. The test devices had been verified in a 65-nm fully-silicided CMOS process. The SCR devices can pass 8-kV human-body-model (HBM) ESD tests, and the parasitic capacitance at 5 GHz kept at ~135 fF with only 3-fF variation as the input voltage swung from VSS to VDD. Thus, the ESD protection design with SCR devices is very suitable for RF ESD applications.**

***Index Terms* — Electrostatic discharges (ESD), radio-frequency integrated circuit (RF IC), silicon-controlled rectifier (SCR).**

I. Introduction

With the advantages of scaled-down feature size, improved high-frequency characteristics, low power consumption, high integration capability, and low cost for mass production, nanoscale CMOS technology has become suitable to implement RF circuits [1], [2]. However, the thinner and delicate gate oxide in advanced CMOS processes seriously degrades the electrostatic discharge (ESD) robustness of IC products [3]. Therefore, on-chip ESD protection devices are needed for all input/output (I/O) pads which are connected to the external of RF ICs. A general concept of on-chip ESD protection for RF ICs is illustrated in Fig. 1 [4]. The parasitic capacitance (C_{ESD}) of ESD protection device is one of the most important design considerations for RF ICs. The parasitic capacitance of ESD protection device inevitably contributes capacitive loading to the I/O port, which causes degradations on RF performances [5], [6]. For RF applications, the ESD protection device is required to have high enough ESD robustness, low parasitic capacitance, and constant capacitance.

Silicon-controlled rectifier (SCR) has been reported as the useful ESD protection device in RF ICs due to its high ESD robustness within a small layout area and low parasitic capacitance [7], [8]. To reduce the parasitic capacitance of SCR device, the waffle-structured SCR device has been studied [9]. When the input voltage (V_{in}) is swing from VSS to VDD, the junction capacitance in SCR device is varied, which leads to the parasitic capacitance variation. To study the parasitic capacitance of SCR device under different voltage bias conditions, some test devices have been fabricated in a 65-nm fully-silicided CMOS process. The parasitic capacitances of the waffle-structured SCR devices are investigated in this work.

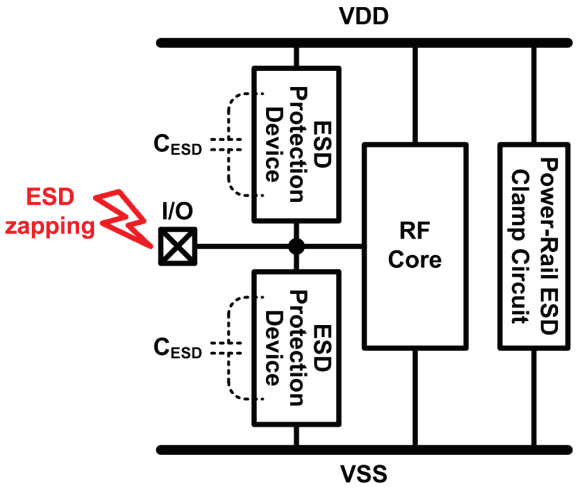

Fig. 1. RF ESD protection with ESD protection devices between I/O and VDD/VSS, and power-rail ESD clamp circuit between VDD and VSS.

II. ESD Protection SCR Devices

A. P-Type SCR

The p-type SCR is design to place between I/O and VDD. The device cross-sectional view and equivalent circuit of the p-type SCR is shown in Fig. 2(a). The SCR path exists among the P+ diffusion (VDD), N-well, P-well, and N+ diffusion (I/O). The deep N-well layer was used to isolated the P-well from the grounded P-substrate. The equivalent circuit of the p-type SCR consists of a parasitic vertical PNP BJT Q_{PNP} and a parasitic lateral NPN BJT Q_{NPN}. Q_{PNP} is formed by the P+ diffusion (VDD), N-well, and P-well. Q_{NPN} is formed by the N-well, P-well, and N+ diffusion (I/O). Under negative ESD stresses from I/O to VDD, the positive-feedback regenerative mechanism of Q_{NPN} and Q_{NPN} results in the SCR device highly conductive, and makes SCR very

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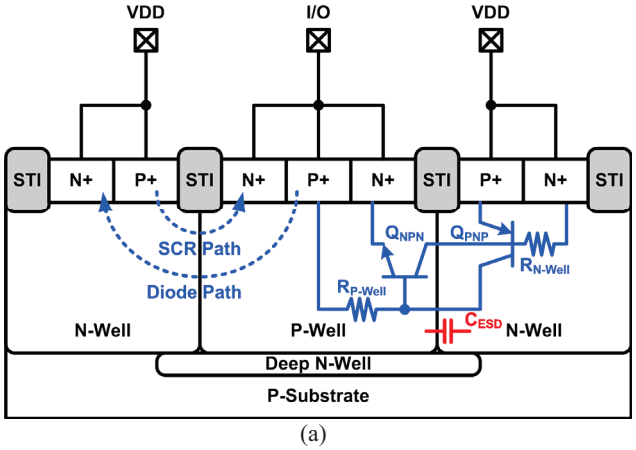
robust against ESD stresses. Under positive ESD stresses from I/O to VDD, the parasitic diode path exists among the P-well and N-well, which can quickly discharge ESD currents.

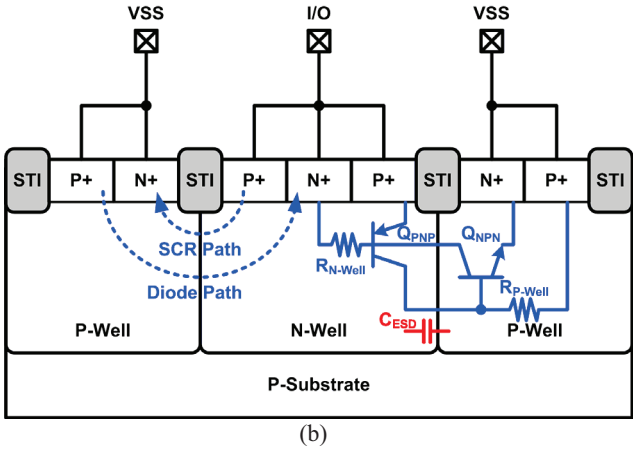
B. N-Type SCR

The n-type SCR is design to place between I/O and VSS. The cross-sectional view and equivalent circuit of the n-type SCR is shown in Fig. 2(b). The SCR path exists among the P+ (I/O), N-well, P-well, and N+ (VSS). Under positive ESD stresses from I/O to VSS, the n-type SCR device will turn on to bypass ESD currents. Under negative ESD stresses from I/O to VSS, the ESD currents will discharge along the path of P-well/N-well diode.

Both p-type and n-type SCR devices realized in waffle structure with 2x2 squares have been fabricated. The size of each SCR device in layout is ~23x23 μm^2.



(a)



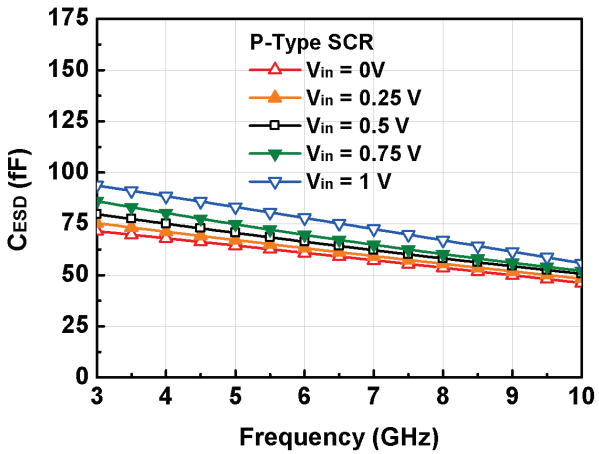
(b)

Fig. 2. Device cross-sectional view and equivalent circuit of (a) p-type SCR and (b) n-type SCR.

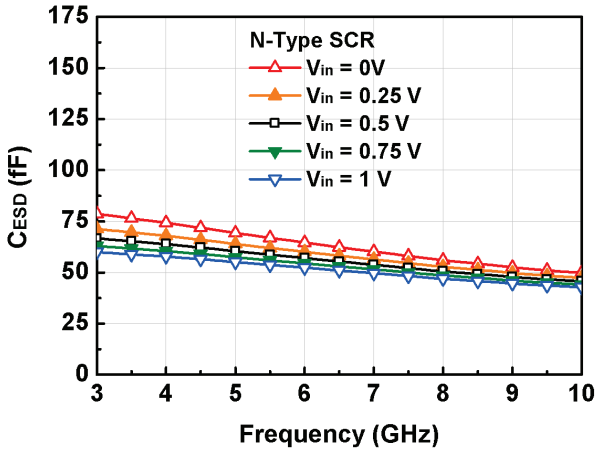
III. Experimental Results

A. Parasitic Capacitance

The extracted capacitances (C_{ESD}) within 3 ~ 10 GHz of the p-type and n-type SCR devices are shown in Figs. 3(a) and 3(b), respectively. Fig. 4 compares the extracted capacitances at 5 GHz. The parasitic capacitance of the p-type SCR was increasing as the input voltage raising. Contrarily, the parasitic capacitance of the n-type SCR was decreasing as the input voltage raising. With both SCR devices, i.e. the p-type SCR between I/O and VDD, and the n-type SCR between I/O and VSS, the total capacitance keeps at ~135 fF with only 3-fF variation when the input voltage swing is from VSS (0 V) to VDD (1 V).



(a)



(b)

Fig. 3. Parasitic capacitances from 3 to 10 GHz of (a) p-type SCR and (b) n-type SCR.

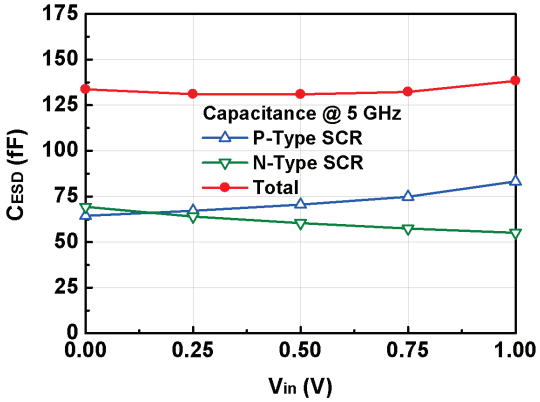


Fig. 4. Parasitic capacitances at 5 GHz as input voltage swing is from 0 to 1 V.

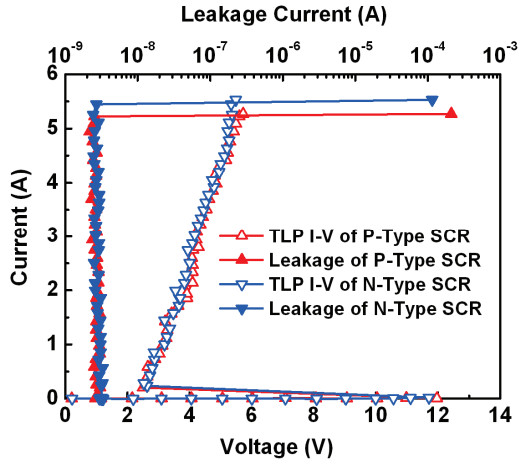


Fig. 5. TLP-measured I-V characteristics of p-type and n-type SCR.

Table 1
MEASURED CHARACTERISTICS OF FABRICATED SCR DEVICES

ESD Device	P-Type SCR	N-Type SCR
C_{ESD} @ 5 GHz	64.4 ~ 83.2 fF	55.1 ~ 69.3 fF
It_2	5.2 A	5.4 A
V_{HBM}	> 8 kV	> 8 kV

B. TLP I-V Characteristics and ESD Robustness

The secondary breakdown current (It_2) of the fabricated SCR devices in high-current regions were characterized by using the transmission line pulsing (TLP) system with 10-ns rise time and 100-ns pulse width. Fig. 5 shows the TLP measurement results of the p-type and n-type SCR devices. The secondary breakdown current of the p-type SCR is 5.2 A, and that of the n-type SCR is 5.4 A. The human-body-model (HBM) ESD robustness (V_{HBM}) have been evaluated by the ESD tester. Both these SCR devices pass the 8-kV HBM ESD tests. All measurement results of the fabricated SCR devices are listed in Table 1.

IV. CONCLUSION

The p-type SCR is design to place between I/O and VDD, and the n-type SCR is design to place between I/O and VSS. The RF characteristics and ESD robustness of both SCR devices are investigated in this work. With both SCR devices at I/O port, the total capacitance at 5 GHz keeps at ~135 fF with only 3-fF variation when the input voltage swing is from 0 to 1 V. Besides, both SCR devices pass 8-kV HBM ESD tests. Thus, the ESD protection design with SCR devices is very suitable for RF ESD applications.

ACKNOWLEDGEMENT

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