CMOS Schottky diode microwave power detector fabrication, Spice modeling, and applications

Woochul Jeon, John Melngailis, and Robert W. Newcomb
Institute for Research in Electronics and Applied Physics
University of Maryland, College Park, MD, USA
E-mail: wcjeon@glue.umd.edu

Abstract

CMOS Schottky diodes with various contact areas and geometries were fabricated through 0.35μ CMOS process. Fabricated diodes were tested under DC and RF direct injection. Based on the measured result, a CMOS Schotkty diode SPICE model is suggested and simulated. The suggested SPICE model is used for designing charge pump circuits and a low-voltage reference circuit.

1. Introduction

In passive microwave systems such as RFID the self-biasing circuit is a critical component and consists of broadband antennas and charge pump circuits. The DC operating voltage is generated by collecting, rectifying, and multiplying incident reading microwave signals. In addition, ambient signal harvesting has also been considered [1]. The charge pump consists of diodes and capacitors. Schottky diodes are the preferred candidates for better rectifying efficiency [2,3]. One of the main issues of these RF CMOS system designs is integrating all components onto one chip for more compact, low power, and high frequency operation. Thus Schottky diodes also need to be integrated on a chip through the CMOS process. However, most CMOS processes are not specified for Schottky contacts, and modifications of a process is required to fabricate Schottky diodes [4]. And, for more precise circuit simulation, a SPICE model of a CMOS Schottky diode is required. In this work we addressed the fabrication and Spice modeling of CMOS Schottky diodes.

2. CMOS Schottky diode fabrication

Schottky diodes with various contact areas and geometries were fabricated through a 0.35μ CMOS process and tested. To figure out the relationship between the IV curve and the contact area, Schottky diodes with various contact areas from 0.6μm x 0.6μm to 50μm x 50μm and different geometries were designed. DC measurements showed that the series

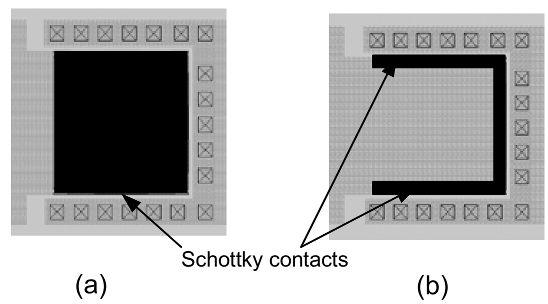

Figure 1. Layout of two Schottky diodes. Diode (b) has 18 times smaller contact area than diode (a). Contact area: (a) 2500μm^2, (b) 140μm^2

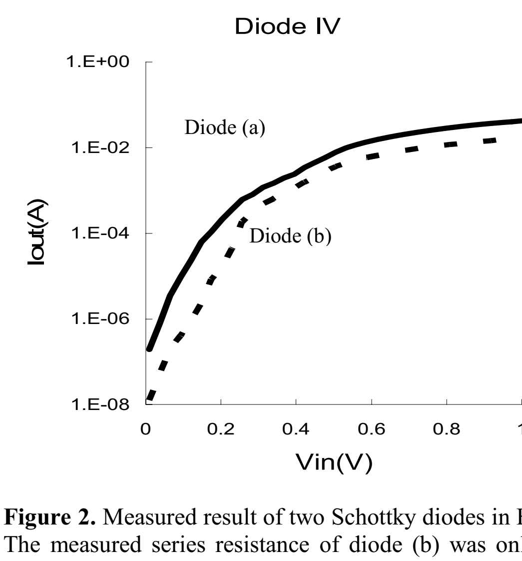

Figure 2. Measured result of two Schottky diodes in Fig. 1. The measured series resistance of diode (b) was only 2.6 times bigger than that of (a).

Proceedings of the Third IEEE International Workshop on Electronic Design, Test and Applications (DELTA'06)
0-7695-2500-8/05 $20.00 © 2005 IEEE

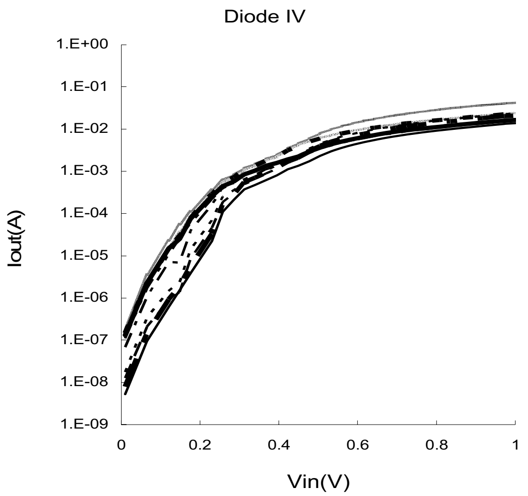

Figure 3. DC measured result of 10 Schottky diodes with different contact area with same conduction path geometry. The results were similar.

resistance of the diodes is decided by not only the Schottky contact area but also the geometry of the conduction path. Figure 1(a) and 1(b) show two different layouts of Schottky diodes. Even though the contact area of the horseshoe shape contact (Fig. 1(b)) is 18 times smaller that that of rectangular shape contact (Fig. 1(a)), the two diodes showed very similar IV curves as shown in Fig. 2. The series resistances were 14Ω for diode (a) and 43Ω for diode (b). By using horseshoe shape geometry, the contact capacitance reduced 18 times and the series resistance increased 3 times. As a result, we can assume that the

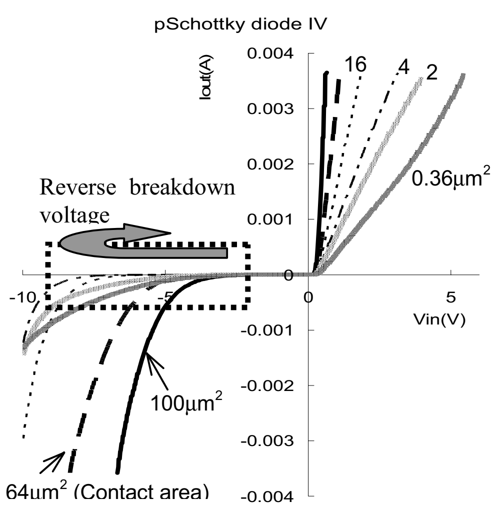

Figure 4. DC measured result of p-type Schottky diode with small contact area from 0.36μm^2 to 100μm^2. The series resistance varies from 74Ω to 1610Ω.

cut off frequency increases 6 times. In other words, since the contact area should be small for the high frequency operation, as far as the design rule allows, a horseshoe shape contact rather than a rectangular shape contact should be used. Figure 3 shows the DC measured result of 10 n-type Schottky diodes with different contact areas and similar conduction paths. The measured series resistances were almost identical. Figure 4 shows the DC measured result of p-type Schottky diode with small contact areas from 0.36μm^2 to 100μm^2 with shortest possible conduction paths. The series resistance was from 74Ω to 1610Ω. From the DC measured result in Fig. 4, the reverse breakdown voltage showed an interesting result. When the contact area decreases, the absolute value of the breakdown voltage increases due to high junction and series resistors. However, when the contact area decreases to smaller than 4μm^2, the absolute value of the reverse break down voltage decreases as shown in the dashed box in Fig. 4. This is because the tunneling current begins to dominate the reverse leakage current, when the contact area becomes small enough.

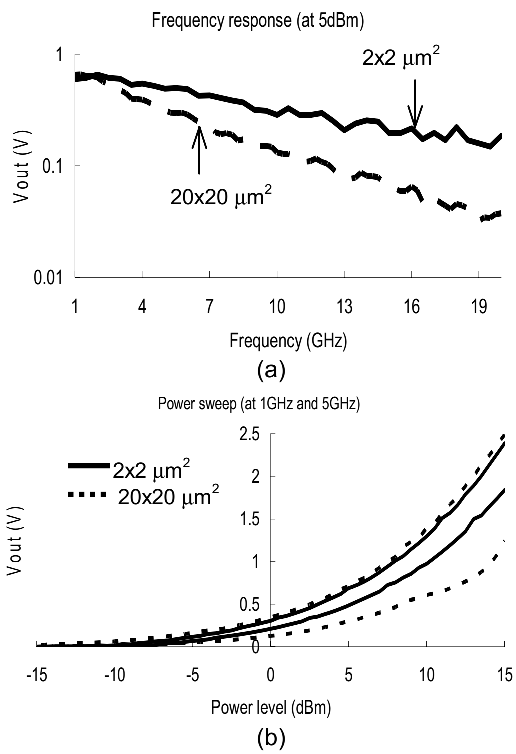

Figure 5. (a) Frequency sweep from 1GHz to 20GHz at 5dBm (b) Power sweep from –15dBm to 15dBm at 1GHz (upper set) and 5GHz (lower set) for two Schottky diode power detectors: the Schottky diode power detector with large contact area showed poor frequency response

3. Microwave power injection

Microwave power detectors with fabricated Schottky diodes, resistors, and capacitors were tested under a microwave pulse direct injection. Figure 5 shows the measured frequency sweep and power sweep results for two Schottky diode power detectors fabricated and tested. The RF pulse was directly injected by using a Cascade Ground Signal Ground (GSG) probe. From the measured result, the Schottky diode power detector with small contact area showed flat frequency response, and the output voltage of the Schottky diode power detector with large contact area rolled off, when the frequency of the input signal increased.

4. CMOS Schottky diode SPICE model

Currently available SPICE CMOS Schottky diode models for circuit simulation were insufficient for the actual CMOS circuit simulations. In the current SPICE Schottky diode models, forward bias currents for the high voltage region can be similar to the measured result by simply changing the series resistance value of a Schottky diode model. However, for the low forward voltage region where the junction resistance is bigger than the series resistance, a more precise model is required to solve the mismatch between the measured data and the simulation results mainly due to the generation-recombination effect, which is given by the following equation. [5]

$$I_d = I_{te} + I_{rg} \tag{1}$$

$$= I_o\left[\exp(\frac{qV}{2kT}) - 1\right] + I_{Ro}\left[\exp(\frac{qV}{2kT}) - 1\right]$$

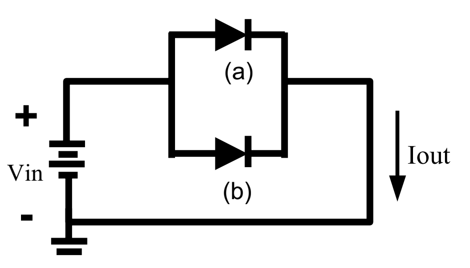

Figure 6. Schottky diode model for the Spice simulation: (a) is for high voltage range simulation, and (b) is low voltage region where the series resistance is smaller than the junction resistance. Parameters: (a) IS = 1E-14 RS = 40 N = 1 CJO = 160f XTI = 2 BV = 5.1 (b) IS = 5E-7 RS = 100 N = 1.5 CJO = 160f XTI = 2 BV = 45

Where I_{te} is the main diode current due to the thermionic emission and I_{rg} is the generation-recombination current. Since it was difficult to create a new level of a diode model for SPICE simulation, currently available diode models were used for the simulation as shown in Fig. 6. The first diode is for high voltage region and the second diode is for the low voltage region. A third diode can be added in the reverse direction for considering the tunneling effect when high reverse bias is applied. Figure 7 shows the comparison between the measured result and the simulated result. The dashed line shows the simulation result for one Schottky diode with the same series resistance. The solid line shows the measured result, and the gray line is the simulation result of the tow diode Spice model of eq. (1) and Fig. 6. Other two lines are the simulation result of each diode.

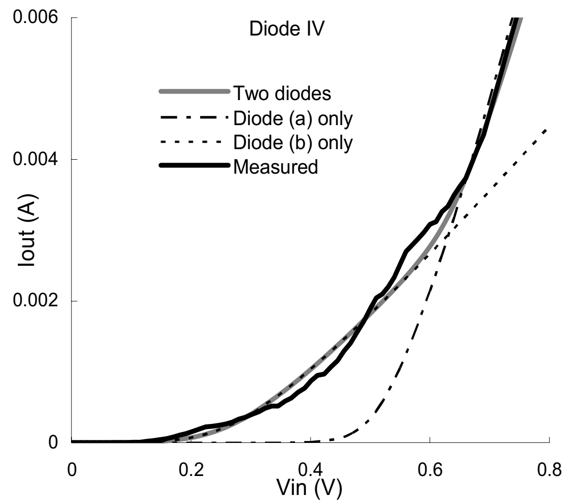

Figure 7. Measured and simulation result of the CMOS Schottky diode with 10x10µm^2 contact area. The simulation result of the modified diode model in Fig. 6 lays on the measured result

5. Applications

5.1 Charge pump circuit

By using the suggested SPICE model, a charge pump circuit was fabricated and tested (Fig. 8). Schottky diodes with 10x10µm^2 contact areas were chosen for the proper current flow to charge up the load capacitors. The number of the stages, which consists of two Schottky diodes and two capacitors shown in Fig. 8, can be decided to meet the required efficiency and the required operating voltage. After

0-7695-2500-8/05 $20.00 © 2005 IEEE

simulating a 4-stage charge pump circuit with 2pF capacitors shown in Fig. 8, a CMOS circuit was fabricated and tested. The measured and simulated results in Fig. 9 are seen to agree. A 4-stage charge pump with diode connected MOSFET's as well as 2-stage and 13-stage charge pump circuits with Schottky diodes were also fabricated for comparison. From the measured results, lower stage charge pump circuits showed a better performance to a low power input, and higher stage charge pump circuits showed better performance for high power input. This result shows that 6-stage or 7-stage charge pump circuits or a 4-stage charge pump circuit with larger contact area Schottky diodes may be useful for RFID applications and ambient microwave signal harvesting, though the number of stages strongly depends on the required operating voltage.

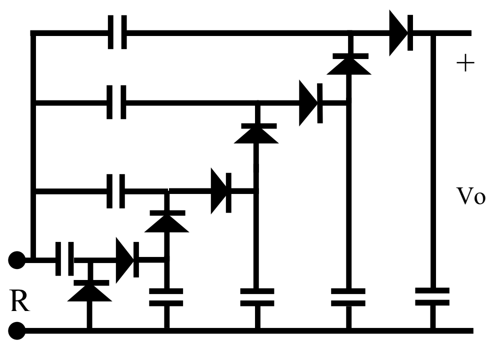

Figure 8. Fabricated 4-stage charge pump circuit with Schottky diodes. For simulation, two Schottky diode model in Fig. 5 was used for each diode.

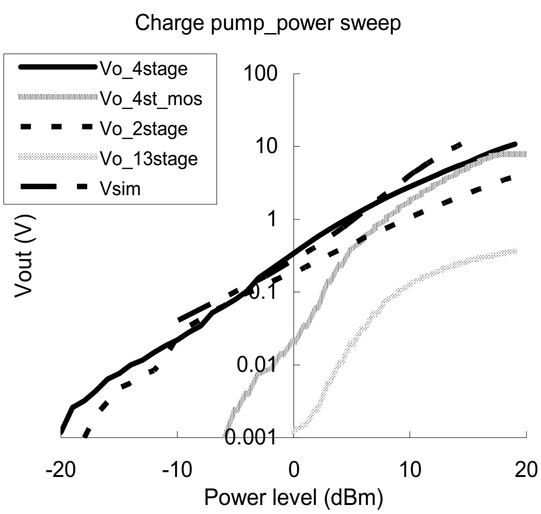

Figure 9. Measured and simulation result of the fabricated charge pump in Fig. 8 at 2.45GHz. The simulation result was similar to the measured result. Diode connected MOSFET showed less sensitive result as expected.

5.2. Low-Voltage reference circuit

The operating voltage of a passive circuit using collected ambient signals should be constant and low, such as 1V or less. Since the operating voltage generated by a charge pump circuit is not a constant, a voltage regulator circuit is required. The voltage regulator circuit consists of a voltage reference circuit, which generates a supply independent reference voltage. The reference voltage usually refers to the turn-on voltage of a pn junction diode. However, pn-junction diodes have high turn-on voltage, 0.8V or more; a lower voltage reference is impossible to be generated by referring the turn-on voltage of a pn junction diode. For more advanced CMOS technology, the operating voltage would be around 0.5V. Since we have developed a method of fabricating a Schottky diode for any CMOS process, a Schottky diode can be used in a voltage reference circuit. By referring to the turn-on voltage of a Schottky diode in a voltage reference circuit, a lower reference voltage, such as 0.2V, can be achieved. By adding one more Schottky diode in series, the reference voltage can be 0.4V. Figure 10 shows the suggested voltage reference circuit, which is a well-known circuit [6], except for using two Schottky diodes. By using a feedback between two current mirrors, the output voltage becomes the turn-on voltage of the Schottky diode. Figure 11 shows the DC simulation result for Fig. 10. The operating voltage is almost independent of the change of the supply

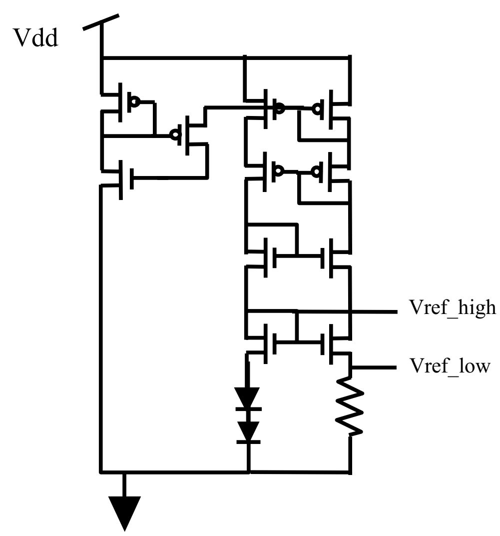

Figure 10. Voltage regulator circuit with two Schottky diodes, Vref_high = 1.05V, Vref_low = 0.42V

0-7695-2500-8/05 $20.00 © 2005 IEEE

voltage, Vdd. By referring to the Vref_high voltage, 1V of the reference voltage can be also generated.

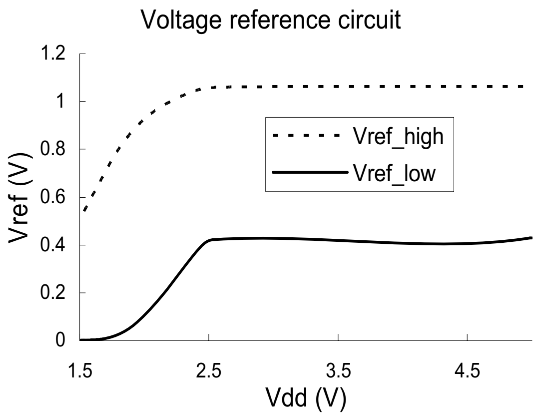

Figure 11 Simulation result of the voltage regulator circuit in Fig. 10.

6. Conclusions

CMOS Schottky diodes with various contact areas were fabricated through a MOSIS AMI 0.35μ CMOS process and tested under DC and RF direct injection. To meet the measured DC voltage IV curve, a SPICE model for a fabricated CMOS Schottky diode was suggested and simulated. As an application, several charge pump circuits with CMOS Schottky diodes were fabricated and tested. A low-voltage reference circuit was also designed and simulated. The suggested Schottky diode model and the measured data can be useful for battery-less RF circuit applications.

7. Acknowledgment

This work was supported by the Department of Defense MURI Program under AFSOR Grant F496 200 110 374. We wish to thank our colleagues for useful discussions, particularly, Victor Granatstein, at UMD. In addition we are grateful to Todd Firestone and John Rodgers for help with RF injection measurements.

Appendix

Charge pump design

In the charge pump circuit design, the power conversion efficiency and the required operating voltage are the most important design specifications. The adjustable parameters for designing a charge pump are the number of stages, the contact areas of the Schottky diodes, and the capacitors. To maximize the power efficiency, each Schottky diode should have low turn-on voltage and high current flow. Because a CMOS process has a specific metal, such as tungsten, to be contacted to the silicon surface, the turn-on voltage cannot be changed. The contact area is the only adjustable parameter and needs to be large to increase the diode current. However, the contact area of the Schottky diodes used in the charge pump should be limited to make the cut-off frequency to be higher than the frequency of the applied RF signal. Since each Schottky diode consumes the incident power, a smaller number of stages shows the better power efficiency. However, to generate a higher operating voltage with small RF signal input, the charge pump with more than one stage is required.

An N-stage charge pump circuit consists of Schottky diodes and capacitors. To decide the contact area of a Schottky diode and the number of stages, a sinusoidal voltage V_i, which has a frequency f_i and an amplitude V_a, is assumed as an RF input. ($v_i = V_a \cos(2\pi f_i t)$) The required operating charge pump output voltage is V_{dd}. For a DC equivalent circuit, all capacitors are assumed to be open, and the voltage drop across each diode is V_{dd}/N. For an AC equivalent circuit, all capacitors are assumed to be short, and all diodes appear to be in parallel or anti-parallel to the input. As a result, the voltage drop across each diode is given by the following equation.

$$V_d = \pm V_0 \cos(\omega_o t) - \frac{V_{dd}}{2N} \qquad (2)$$

If the incident RF signal is small enough that the series resistances of Schottky diodes is much smaller than the junction resistance, the series resistance can be neglected, and the junction capacitance is small enough to be ignored. The diode current is given by the following equation.

$$I_d = I_S \left[\exp\left(\pm \frac{V_a}{V_T} \cos(\omega_0 t) \right) \exp\left(- \frac{V_{dd}}{2NV_T} \right) - 1 \right] \qquad (3)$$

By using the modified Bessel function series expansion, the exponential of a cosinusoidal function can be expressed by the following equation. [7,8]

$$\exp(\pm x \cos(\omega t)) = B_o(\pm x) + 2\sum_{n=1}^{\infty} B_n(\pm x)\cos(n\omega t) \qquad (4)$$

The DC operating current I_{dd} is therefore given by

0-7695-2500-8/05 $20.00 © 2005 IEEE

$$I_{dd} = I_s\left[B_o\left(\frac{V_a}{V_T}\right)\exp\left(-\frac{V_{dd}}{2NV_T}\right)-1\right] \quad (5)$$

The diode reverse leakage current depends on the contact area. From equation (5), the DC operating current can be adjustable by changing the contact area and the number of stages (N). From the measured results, the Schottky diodes with the contact area of up to 20x20μm^2 can be used for UHF (910MHz) or microwave (2.45GHz or 5.8GHz) applications. A 5-stage or 6-stage charge pump with 10x10μm^2 or a 4-stage charge pump with 20x20μm^2 would be the best choice for generating 1V of DC operating voltage.

8. References

[1] J. A. Hagerty, F. B. Helmbrecht, W. H. McCalpin, R. Zane, and Z. B. Popovic, "Recycling ambient microwave energy with broad band rectenna arrays.", IEEE Trans. Microwave theory and tech., vol.52, No 3, pp 1014-1024, March 2004

[2] U. Karthaus and M. Fisher, "Fully integrated passive UHF RFID Transponder IC with 16.7-μW Minimum RF input power," IEEE Trans. Solid State Circuits, vol. 38, no. 108, October, 2003, pp. 1602-160

[3] W. Jeon, J. Melngailis, and R. W. Newcomb, "CMOS passive RFID transponder with read-only memory for low cost fabrication", Proceedings, IEEE SOCC 2005, Washington DC, Sept. 2005, pp. 181-184.

[4] V. Milanovic, M. Gaitan, J.C. Marshall, and M. E. Zaghloul, "CMOS foundry implementation of Schottky diodes for RF detection," IEEE Trans. Electron Dev. Vol. 43 No. 12, Dec. 1996, pp. 2210-2214

[5] B.L. Sharma, "Metal-semiconductor Schottky Barrier Junctions and their applications", Plenum press, New York and London, 1984

[6] G.C.M. Meijer, J.B. Verhoeff, "An integrated bandgap reference," IEEE J. Solid State Circuits, Vol. 11, No. 3, June 1976, pp. 403-406

[7] G. De Vita and G. Iannaccone, "Design criteria for the RF section of UHF and Microwave Passive RFID Transponders,", IEEE Trans. Microwave and Tech., Vol. 53, Iss. 9, Sept. 2005 pp. 2978 - 2990

[8] M. Abramowitz and I.A. Stegun, "Handbook of Mathematical Functions with Formulas, Graphs and Mathematical Tables, 9th ed.," New York, Dover, 1972, pp. 358-364

Proceedings of the Third IEEE International Workshop on Electronic Design, Test and Applications (DELTA'06)
0-7695-2500-8/05 $20.00 © 2005 IEEE