CMOS & POST CMOS FABRICATION OF ON CHIP MICROWAVE PULSE POWER DETECTORS

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I. INTRODUCTION

Modern integrated circuits use lower and lower operating voltage. As a result, the circuits are increasingly vulnerable to malfunction due to incident electromagnetic radiation, whether from ambient sources or from electromagnetic weapons intended to disable an adversary's electronics. They have been called HPM (high power microwave) weapons on E-bombs. [1] Building on-chip detectors to measure the microwave power levels and the receiver antenna gains in various locations within chips or on various chips within an electronic system is the first step to investigating the microwave propagation and the vulnerable points in these systems and devising protective measures. We have fabricated numerous on-chip RF pulse power detectors by both a CMOS process and a post-CMOS, focused-ion-beam-based process. Standard CMOS processes (e.g. MOSIS) are not specified for the Schottky contacts. Although diodes have been made, [2][3] the operating frequency of both diodes were less than 1GHz and high frequency operation was not achieved due to the difficulty in fabricating small Schottky diodes. We have investigated various alternatives [4] and have concluded that a post-CMOS process may be the best approach for the passive power detector fabrication. As an alternative CMOS design to make a power detector without post processing, we have designed power detectors using diode connected MOSFET with a bias circuit instead of a Schottky diode.

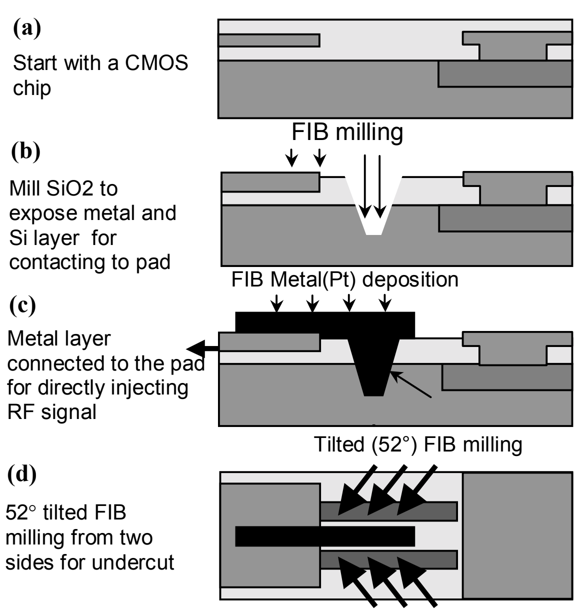

Fig. 1. FIB Schottky diode fabrication, (a),(b), and (c): cross-section view (d): top view

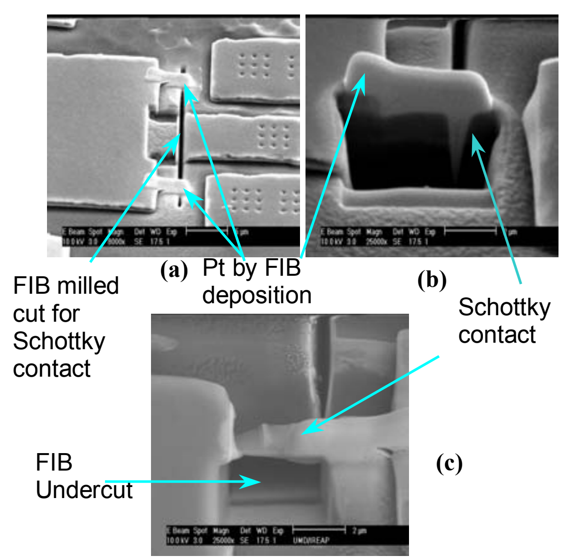

Fig. 2. SEM image of a FIB processed diode, (a) Grooving silicon and Platinum deposition, (b) Cross section of the fabricated device: refer Fig. 1(c), (c) Undercut by tilted FIB to minimize capacitance

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II. POWER DETECTORS BY FIB

Schottky diodes are known as fast rectifying devices and can be used as RF power detectors to convert AC signals to DC signals. Focused Ion Beam (FIB) milling and ion induced deposition were used as post-fabrication steps to build Schottky diodes in specially designed locations on the CMOS chips fabricated using MOSIS. We cross-sectioned the CMOS chip and found that the oxide and nitride layer was too thick(6.8μm) for FIB fabrication. Reactive Ion Etching(RIE) and chemical etching were used to remove the nitride and oxide layers. To make a Schottky contact, Platinum was deposited after opening a cut in SiO_2 and silicon by FIB ion induced milling.(Fig. 1(a)-(c)) Even though the Schottky contact was done in this step, to minimize the contact capacitance and the series resistance, we also made undercut triangular bridge shaped Schottky contacts by tilted FIB milling.(Fig. 1(d)) Fig. 2 shows the SEM pictures of cross section and fabricated Schottky diodes.

III. MOSFET POWER DETECTORS

To fabricate a power detector without using a post process, a diode connected (gate connected to drain) MOSFET with bias circuit was designed. A simple diode connected MOSFET can be used as a rectifier. However, its turn on voltage, usually 1V, is too high for small signal detection and a bias circuit required to improve the sensitivity. Fig. 3 shows the proposed circuit. M3 is diode connected nMOSFET and M1 supplies the bias current I_1. When the input voltage Vi is not bigger than 0, and I_1 is equal to I_2, V_{xo} (V_x when V_i is equal to 0V) can be calculated and I_3 is small enough to be neglected by the following equations.

$$I_1 = K\frac{w_1}{l_1}(V_{dd} - V_{xo} - V_T)^2 \qquad I_2 = K\frac{w_2}{l_2}(V_x - V_T)^2$$

$$V_{xo} = \left(\frac{\sqrt{l_2 w_1}}{\sqrt{l_2 w_1} + \sqrt{l_1 w_2}}\right)V_{dd} + \left(\frac{\sqrt{l_2 w_1} - \sqrt{l_1 w_2}}{\sqrt{l_2 w_1} + \sqrt{l_1 w_2}}\right)V_T \tag{1}$$

$$V_o = I_{o3}\left(e^{\frac{q}{kT}(V_{xo} - V_o)} - 1\right)R \tag{2}$$

Where, K = $\mu C_{ox} q/2kT$, w is the width and *l* is the length of the channel. When Vi becomes bigger than 0V and I_3 is not negligible and the output voltage V_o begins to rise by the following equations.

$$I_2 = K\frac{w_2}{l_2}(V_x - V_i - V_T)^2 \tag{3}$$

$$I_3 = K\frac{w_3}{l_3}(V_x - V_o - V_T)^2 \tag{4}$$

$$I_1 = K\frac{w_1}{l_1}(V_{dd} - V_x - V_T)^2 = K\frac{w_2}{l_2}(V_x - V_i - V_T)^2 + K\frac{w_3}{l_3}(V_x - V_o - V_T)^2 \tag{5}$$

$$V_o = I_3 R \tag{6}$$

By solving (3)-(6), Vi and Vo are square functions of V_x.

$$V_o = aV_x^2 + bV_x + c \tag{7}$$

$$V_i = a'V_x^2 + b'V_x + c' \tag{8}$$

Where a,b,c,a',b', and c' are constants. As a result, the output voltage Vo has a linear dependence on the input voltage Vi by the following equation.

$$V_o = AV_i + B \tag{9}$$

Where A is a positive constant and B is a constant and near to 0 when Vi is equal to 0. When Vi is much bigger than 0V and all of the bias current flows to M3 and I_1 is equal to I_3 and the output voltage becomes constant, I_3R. Fig. 4 shows the simulation result and the measured result of the proposed MOSFET power detector. For the low input region, Vi is less than 0.7V, the subthreshold operation applied and smooth curve between Vi and Vo was observed.

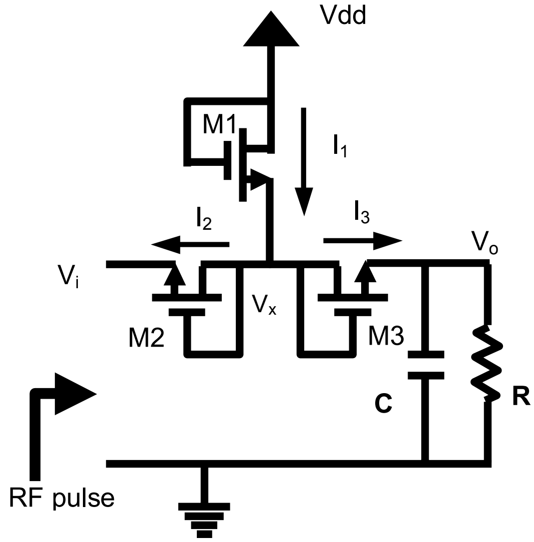

Fig. 3. MOSFET power detector circuit: depends on the polarity of RF input, bias current I_1 flows to one of

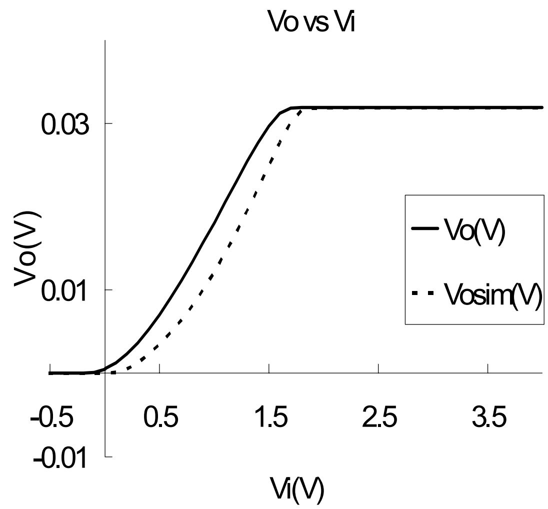

Fig. 4. Simulated (Vosim) and measured (Vo) dc curve of a MOSFET power detector. Measured result showed turn on voltage shift to –0.1V.

IV. MEASURED RESULT

For the better comparison, a pn-junction diode, FIB Schottky diodes without undercut, and a diode connected MOSFET without a bias circuit were also fabricated and tested. A 10μs of pulse width and 1ms of period microwave pulse was directly injected by using Cascade Ground Signal Ground(GSG) probe. The input frequency range was 1GHz to 10GHz. The input power level was swept up to 15dBm. Fig. 5 shows the measured result for all detectors fabricated and tested. From the measured result, all detectors showed square responses to the input power level and the MOSFET power detector circuit with 150kΩ load was saturated due to the limited bias voltage. MOSFET power detectors with a 1kΩ load resistor

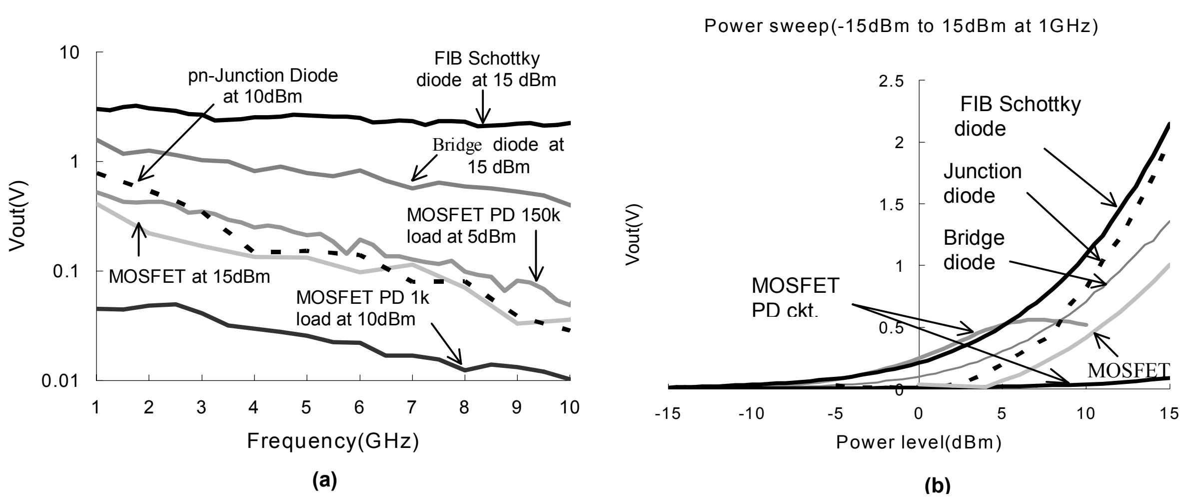

Fig. 5. Measured result of four power detectors: (a) Frequency sweep, (b) Power sweep

made small output voltage and began to detect –9dBm of power level. However, it had the shortest pulse response time, 56 ns. The bridge shaped FIB fabricated Schottky diode power detectors had 72ns of pulse response time, 25dBm or more of dynamic range, and began to detect 0dBm of power level. The large contact area, 15μm^2, FIB Schottky diode detector, which has the same structure as Fig. 1(c), had 6us of pulse response time, 25dBm or more of dynamic range, and began to detect -10dBm of power level. Due to the high junction resistance in the bridge shaped diode, the frequency response showed less flat than that of the large FIB Shottky diode. However, its pulse response time was much faster and showed better pulse detection than the FIB Schottky diodes, which has 4μm^2 of contact area. And both the diode connected MOSFET without a bias circuit and the pn-junction diode showed poor detection in terms of the sensitivity and the frequency response. (Table 1) From table I, a detector can be chosen depending on the injected rf pulse type. If the pulse width is less than 1μs, MOSFET detectors can be used and if the flat frequency response and the wide dynamic range are the main concern, FIB Schottky diodes can be the best choice.

Table I. Comparison of microwave pulse power detectors:
FIB diodes, MOSFET with and without bias circuit, and pn-junction diode

	FIB diode			**MOSFET detector**		**MOSFET**	**Junction diode**
	N-type 15μm^2	P-type 4μm^2	Bridge 1μm^2	150kΩ Load	1kΩ Load		
Pulse response time (nsec)	6000	100	72	200	**56**	1200	16000
Frequency response (Vout at 1GHz / Vout at 10GHz)	**1.34**	2.38	3.97	9.59	4.43	11.33	14.4
Dynamic range (dBm)	**> 25**	> 15	**> 25**	15	**>25**	> 10	> 10
Sensitivity (dBm) (smallest possible detection)	-10	0	-10	**-12**	-9	4	7

V. CONCLUSION

MOSFET and Schottky diode microwave pulse power detectors were fabricated by the CMOS and a post-CMOS process, respectably, and compared. FIB fabricated Schottky diode power detectors were the best choice for long and high power pulse detection and MOSFET power detectors were good for short and low power pulse detection.

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