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Non-Linear Analysis of Self-Switching Diodes as Microwave Rectifiers

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Abstract: A planar device known as the Self-Switching Diode (SSD) has been demonstrated as a high-speed rectifier, up to terahertz frequencies. The rectifying properties of SSD are dependent on a nonlinear current-voltage characteristic of the device. In this research, the rectification of two SSD rectifiers has been reported and their performances were evaluated. The observed results showed a good agreement with the nonlinear theoretical analysis of both rectifiers by means of a Taylor series which can be utilized in improving the rectifying performance of any diode-based rectifier specifically for diodes with tunable threshold voltage such as SSDs.

Key words: Non-linear analysis, rectifier, evaluated, rectifying, voltage, SSDs, rectifies

INTRODUCTION

Recently, the development of rectifying devices that can operate at high frequencies (e.g., radio-frequency, microwave, terahertz and light) has become one of the major areas of research. These devices which include Schottky diodes, backward diodes and Self-Switching Diodes (SSDs) can be employed in many applications such as Radio-Frequency Identification (RFID) technology, Wi-Fi technology, energy harvesters and terahertz imaging systems (Hesler and Crowe, 2007; Jin *et al*., 2005; Vo and Hu 2006; Balocco *et al*., 2014). Hence, improving the rectifying performance of these devices is of paramount importance. As such in this report, the improvement has been performed and evaluated based on a nonlinear analysis of the devices.

In general a typical diode rectifier utilizes its non-linear characteristic to convert high-frequency signals into usable dc power. Although, the analysis of this behavior by means of Taylor series is very well-known (Pozar, 1998; Cowley and Sorensen, 1966) it is worth to include a brief review of the analysis in this report as presented in the next section. The outcomes of the analysis have identified the important parameters that can be used to improve the rectifying performance of the diodes which include the first and second order derivative of the current-voltage (i-v) function of the devices.

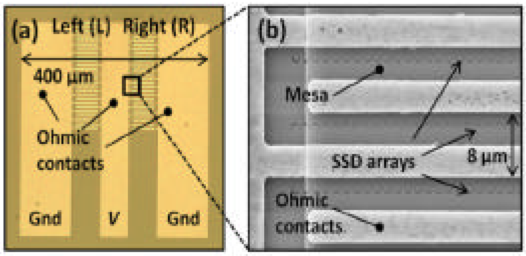

Fig. 1: a) Optical image of the interdigital structure where two SSD arrays (on the left and right-hand side of the structure) were positioned and b) Scanning electron microscope image of SSD array, fabricated within the fingers of an interdigital structure

This principle was applied on two SSD arrays fabricated within the fingers of an interdigital structure (i.e., on the left and right-hand side of the structure) as shown in Fig. 1a and b in which both arrays have different i-v characteristics (Fig. 2a and b) due to the difference in the geometry of the devices. The rectifying properties of these arrays have been characterized in our previous report where the details including the fabrication process, can be found by Kasjoo *et al*. (2015). The results from this report were used in this research for further evaluation based on the nonlinear device analysis as mentioned earlier. This evaluation is presented in results and discussion of this study.

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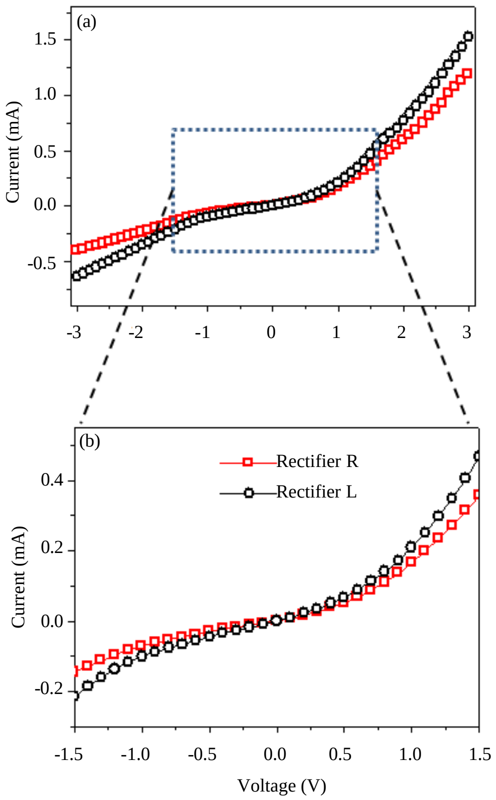

Fig. 2: a) Current-voltage characteristics of two SSD arrays fabricated on the right-hand side (rectifier R) and left-hand side (rectifier L) of an interdigital structure and b) The magnification of (a) whereby, the voltage range was captured from -1.5 to 1.5 V

The SSD, first introduced by Song *et al*. (2003) was chosen because its threshold voltage is easily tuned by modifying the dimensions of the device. Different i-v behaviors can therefore, be obtained and manipulated to improve the rectifying performance of the devices. In fact, a SSD-based rectifier with zero-bias operation can also be achieved whereby no external biasing is required and hence reducing the power consumption of the rectification system. More details on the working principles of SSDs can be found elsewhere by Song *et al*. (2003) and Aberg *et al*. (2004).

Nonlinear device analysis: The following analysis is based on references (Pozar, 1998; Cowley and Sorensen, 1966). The i-v function of a nonlinear device can be written as:

$$i = f(v) \tag{1}$$

Where:

i = The current flowing through the device
v = The voltage across the device

Microwave rectifiers are always operated with a dc bias. Therefore, in general, v can be described as the superposition of a dc bias voltage, V_0 and a high frequency signal voltage, $V_{rf} = A\cos(\omega t)$ where A is the amplitude of the signal ω is the angular frequency and t is the time. This can be written as:

$$v = v_0 + v_{rf} \tag{2}$$

By means of a Taylor series, evaluated at V_0 Eq. 1 can be expanded to:

$$i = I_0 + \frac{v_{rf}}{1!}f^{(1)} + \frac{v_{rf^2}}{2!}f^{(2)} + \frac{v_{rf^3}}{3!}f^{(3)} + \ldots + \frac{v_{rf^N}}{N!}f^{(N)} \tag{3}$$

Where:

f_N = The Nth order derivative of f (v) with respect to v
$I_0 = f(V_0)$ = The dc bias current

Replacing v_{rf} in Eq. 3 with A cos(ωt) yields,:

$$\begin{aligned} i = I_0 + \left[\frac{A^2}{4}f^{(2)} + \frac{A^4}{64}f^{(4)} + \ldots\right] + \\ \left[Af^{(1)} + \frac{A^3}{8}f^{(3)} + \ldots\right]\cos(\omega t) + \ldots \end{aligned} \tag{4}$$

Equation 4, the rectified dc current Δi can be extracted which equals to the first bracket term on the right-hand side of the equation, i.e.:

$$\Delta i = \frac{A^2}{4}f^{(2)} + \frac{A^4}{64}f^{(4)} + \ldots \tag{5}$$

At low-level input power of a microwave signal where by a small-signal approximation is still valid, the higher order terms of Eq. 5 become very insignificant, hence $\Delta i \sim A^2 f^{(2)}/4$. In an open-circuit configuration, the rectified dc voltage Δv can therefore be defined as:

$$\Delta v = R_D \Delta i = \frac{\Delta i}{f^{(1)}} = \frac{A^2 f^{(2)}}{4f^{(1)}} \tag{6}$$

Where:

$R_D = 1/f^{(1)}$ = The differential resistance of the nonlinear device
$f^{(2)}$ = The so-called bowing coefficient of the i-v function

As can be seen, Eq. 6 indicates that $\Delta v \alpha V_{rf}^2$ and this is usually referred to the square-law detection behavior of the device.

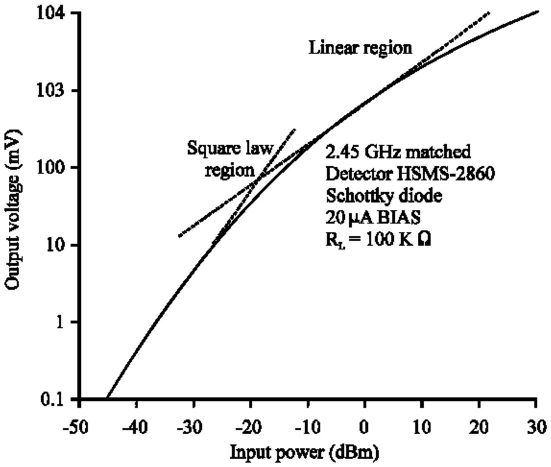

Fig. 3: Detected output voltage of HSMS-2860 schottky diode from Agilent Technologies with respect to the input power

However, at high-level input power, the second and higher order terms of Eq. 5 become significant. In this case, the small-signal approximation is no longer valid, hence the rectification behavior deviates from the square-law operation region into a quasi-linear detection region (i.e., $\Delta v \alpha v_{rf}$). On the other hand, at a very low-level input power, the microwave signal is lost into the noise floor of the device. Example of such detection behavior at different levels of input power is shown in Fig. 3 in which HSMS-2860 Schottky diode has been utilized.

Equation 6 also shows that $\Delta v \alpha$ $(f^{(2)}/f^{(1)})$. In other words, the rectified dc voltage is dependent on the ratio of the bowing coefficient to the differential resistance of the rectifier. In fact, this is the main focus of this report in which the highest value of $(f^{(2)}/f^{(1)})$ at certain biasing point can be utilized to improve the amount of rectified dc voltage. As a result, the voltage responsivity which is one of the important parameters to evaluate the diode rectifier's performance can also be improved.

RESULTS AND DISCUSSION

Figure 4a shows the rectified dc voltage, V_{out} as a function of input power (in a log scale) for two different SSD-based rectifiers (rectifier R and rectifier L) measured at 100 MHz at zero bias. As mentioned earlier, this result was taken from Kasjoo *et al.* (2015) where the experiments including the co-planar measurement set up have been reported in details. The result exhibited a typical rectification behavior as discussed in the previous study.

A square-law detection characteristic was also observed at input power lower than 0.1 mW for both rectifiers as shown in Fig. 4b. As can be seen, rectifier R has bigger value of V_{out} when compared to rectifier L.

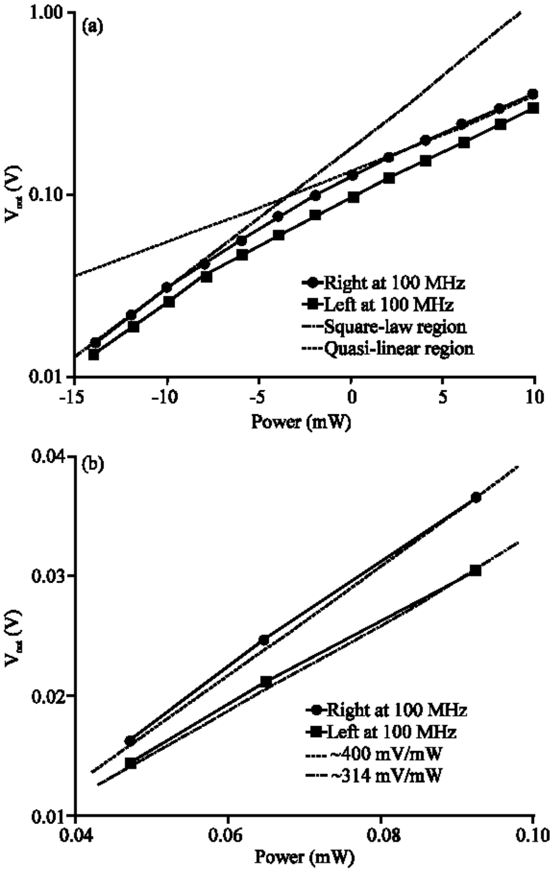

Fig. 4: a) V_{out} as a fuction of input power (in log scale) for rectifier R and rectifier L, measured at zero bias at 100 MHz and b) V_{out} as a fuction of input power (in linear scale) for rectifier R and rectifier L measured at zero bias at 100 MHz with input power <0.1 mW (in the square-law region) (Kasjoo *et al.*, 2015)

Hence, rectifier R has higher voltage responsivity (~400V/W) than rectifier L (~314V/W). Here, voltage responsivity is defined as rectified dc voltage divided by total input power. This result can be explained using the nonlinear theoretical analysis of both rectifiers which involves parameters $f^{(1)}$ and $f^{(2)}$ as discussed earlier.

Figure 5 shows the value of $(f^{(2)}/f^{(1)})$ as a function of the applied voltage. At zero bias, the amount of $(f^{(2)}/f^{(1)})$ whereby, Δv or V_{out} is proportional to $(f^{(2)}/f^{(1)})$ was higher for rectifier R than rectifier L. This prediction was in a good agreement with the experimental results obtained as shown in Fig. 4. Moreover, in forward bias, the rectifying performance of rectifier L can be further improved by biasing the device at ~70 μA, corresponded to 0.5 V which has the maximum value of $(f^{(2)}/f^{(1)})$.

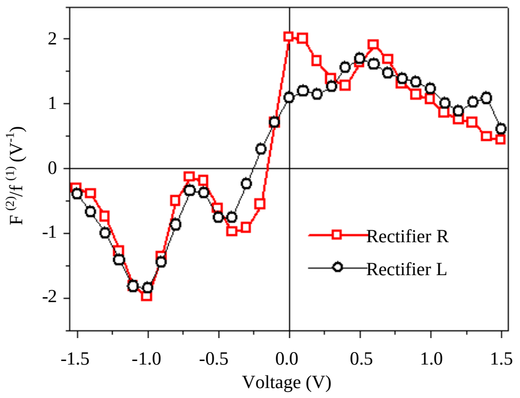

Fig. 5: ($f^{(2)}/f^{(1)}$) as a function of voltage. At zero bias, rectifier R was predicted to have higher Δv compared to rectifier L [since $\Delta v \alpha (f^{(2)}/f^{(1)})$]. This prediction was supported by the experimental results obtained

For rectifier R, the highest value of ($f^{(2)}/f^{(1)}$) can be obtained at zero bias. Since, no external biasing is required, a zero-bias rectifier (such as rectifier R) not only offers low dc power consumption but also simplifies the detector design. Furthermore, it exhibits lower flicker noise when compared with a biased rectifier which helps to increase its signal-to-noise ratio performance. Hence, this nonlinear analysis has suggested that the design of SSD array in rectifier R can be further utilized in order to attain zero-bias microwave rectifiers with the optimum performance.

CONCLUSION

In summary, it has been shown that the non-linear analysis, based on the i-v characteristics of SSD rectifiers and by means of a Taylor series can be used to improve the rectifying performance of any diode rectifier. The important parameter was the ratio of the second order derivative to the first order derivative of the diode's i-v characteristic, i.e. ($f^{(2)}/f^{(1)}$). In the case of SSD, the improvement can be performed by modifying the dimension of this device to obtain the optimum i-v behavior with respect to ($f^{(2)}/f^{(1)}$).

Moreover, an optimized biasing value in the operation of rectifying diodes can be predicted by using this nonlinear analysis in order to improve the voltage responsivity as previously reported by Balocco *et al*. (2011), Kasjoo and Song (2013).

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