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Performance Comparison of Schottky Diode models for RF Energy Harvesting

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ABSTRACT
To convert radio frequency (RF) energy (freely available in the environment) into usable form, RF-DC rectifiers are used. The Schottky diodes are commonly considered for RF rectification purpose as they show the best performance at high frequency and low power levels. However, exact selection criteria for Schottky diode have not been reported yet. In this paper comparison of turn ON voltage ranges and characteristics of different commercially available Schottky diode models (HSMS2850, HSMS2860, HBAT5400, SMS7621) at low power levels has been carried out. The comparison has been done at 900 MHz and 2.45GHz frequency. HSMS2850 provided maximum output voltage among the selected diodes at low input power (less than -15 dBm). This work demonstrates the selection criteria of Schottky diode and will help designers in selecting the appropriate diode for rectification purpose at low power levels.
Keywords- Radio Frequency(RF),Wireless Sensor Network (WSN),Energy Harvesting, Schottky Diodes, Turn-on Voltages, Rectifiers.

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I. INTRODUCTION

Growing demand of wireless sensor network (WSN) in the field of medical [1], environment [2], military [3], transportation [4], petroleum industries[5], building monitoring [6] has attracted the attention of scientific community to improve the performance of these networks. Wireless sensor network contains large number of sensor nodes that are called motes. Working of these wireless sensor nodes mainly depend on the performance of the battery used in the node. With prolong usage, the batteries get discharge. If the batteries are chargeable, they need to be recharged or else they are needed to be replaced. Recharging or replacement of these batteries is very cumbersome task, notably at remote locations. Hence, for uninterrupted operation of the wireless sensor nodes, self-energized circuits employing capacitors should be used [7].

For self-energized WSN networks, energy harvesting is required. Energy harvesting is a method to extract freely available energy from environmental sources and convert it into usable form. Solar, wind, thermal, vibration, radio waves are the different sources of energy available in the environment for harvesting [8]. Fig. 1 shows that the performance of battery employed energy sources deteriorates with time, but lifetime of energy available from environmental sources remains constant [9].However, there are limitations associated with different sources of environmental energy. For instance, solar and wind provides energy at very large scale but intermittently. On the other hand, thermal and vibration sources do not provide consistent input.

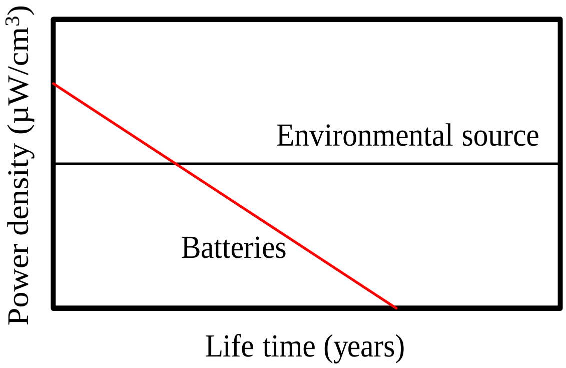


Fig. 1: Continuous power vs. Life for several power sources [9].

As number of cell towers, mobile base stations, FM/AM, Television broadcasting towers are increasing; RF energy seems to be a better option for energizing WSN networks. RF energy is easily available and does not depend on day and night frequency. But the only challenge in harvesting energy from RF sources is the low input power density. The power density of various RF sources ranges from 0.1 μW/cm^2 (ambient RF) to 1000 μW/cm^2 (dedicated RF) [10].There are two working regions for RF energy harvesters, low power region (-30 dBm to -15 dBm) and high power region (above -15 dBm). It is very challenging to harvest high amount of power with a single and high directive antenna in low power region. On the other hand, the circuit becomes enormously large while using multi-antenna system to capture this low input power. Hence, the efficiency of RF-energy harvesting circuit (with single operational antenna) should be adequately high to provide better performance in low power region.

To convert this RF energy into usable form, RF-DC rectifiers are needed. Diodes are used for the RF rectification. Schottky diodes are of particular interest for this purpose as they get turn on at very low voltage. Different types of Schottky diodes are commercially available. However, direct comparison of performance of different commercially available Schottky diodes is not available in the literature. This work, therefore, presents a detailed comparison of performance characteristics (like turn-on voltages, maximum diode current, and output voltage) of four commercially available and widely used Schottky diodes (HSMS2850, HSMS2860, HBAT5400 and SMS7621). Circuit design and Simulations have been carried out using LTSpiceIV software. The outcomes of this work may help designers in proper selection of the Schottky diodes for RF-DC rectification.

Section 2 highlights block diagram of energy harvester. The SPICE model of Schottky diode is explained in section 3. Discussion on the results of performance characteristics of different Schottky diodes is presented in section 4. Conclusions of the present work are listed in section 5.

II. BLOCK DIAGRAM OF RF ENERGY HARVESTER

An RF energy harvester consists of the following blocks: antenna, matching network to match the input impedance of the RF-DC converter with the antenna impedance, RF-DC converter (for rectification), and storage unit (Fig. 2).

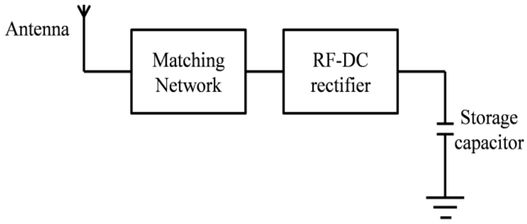


Fig. 2: Block diagram of RF Energy Harvester.

Antenna is used to receive RF energy at specified frequency. Antenna can be designed at one frequency or multiple frequencies. The expression for received power from free space is given by Eq. (1) [11].

$$P_r = \frac{P_t \; G_t G_r \lambda^2}{(4\pi R)^2 L} \quad (1)$$

where, P_r is the received power by receiving antenna with gain G_r , P_t is the transmitted power by transmitted antenna with gain G_t located at distance R from a receiving antenna. L is the system loss factor and λ is wavelength.

The most popular application of diodes is rectification, which converts alternating current to direct current. Received RF signal from antenna also has a sinusoidal waveform. Hence, diode is used for rectification in RF energy harvesters. In most of the literatures, Schottky diodes have been used for rectification purpose in RF-DC converters as they offer high switching speed, low forward voltage drop, which are the requirements of RF-DC rectifier design [12-16].

III. SPICE MODEL OF SCHOTTKY DIODE

A metal semiconductor junction is present in the Schottky diode. The metal side behaves as the anode and n-type semiconductor behaves as the cathode of the Schottky diode. Spice model of Schottky diode is shown in Fig. 3.

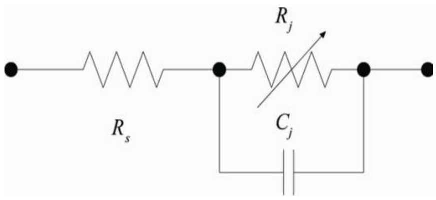


Fig. 3: SPICE model of Schottky Diode [11].

In the model (Fig. 3), R_s is the diode parasitic series resistance(the sum of the lead-frame, bond-wire, silicon bulk layer resistance).The RF energy is lost as heat through R_s. Thus R_s does not contribute to the rectification process of the diode. The C_j is the parasitic junction capacitance whose value is controlled by the epitaxial layer thickness.Diodecurrent passes through the resistance R_j, and there is a voltage drop across its two ends.

Schottky diode with metal-semiconductor junction has the following characteristics [17]:

- Fast Switching time
- Low reverse recovery time
- Low forward voltage drop
- Low junction capacitances
- Well suited at high frequency.
- High Reverse Blocking voltage (good for high power applications)

3.1. COMMERCIALLY AVAILABLE SCHOTTKY DIODE MODELS

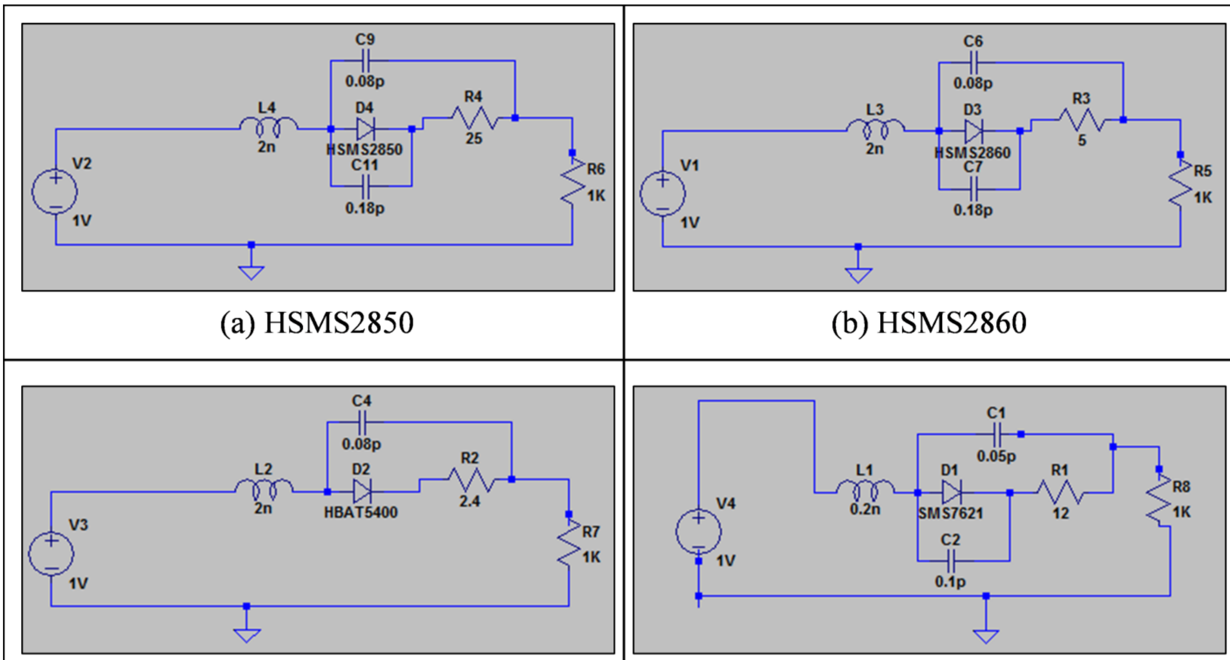
Schottky diodes turn on easily at low input power levels due to their low voltage drop. This property of Schottky diodes provides them an edge over other types of diodes (p-n junction diode)in various applications. Additionally, they have less noise and better performance.

In the present work, four widely researched Schottky diodes from three different manufacturers were selected. The selected diodes are HSMS2850(Avago Technologies), HSMS2860(Avago Technologies), HBAT5400 (Agilent Technologies) and SMS7621(SKYWORKS). Spice parameters of these diodes are provided in Table1and are reported in Refs. [17, 19, 20].

Table 1: SPICE parameter of Schottky Diodes [17, 19, 20]

Parameter	**HSMS2850**	**HSMS2860**	**HBAT5400**	**SMS7621**
BV	3.8 V	7 V	40 V	3 V
C_{j0}	0.18p	0.18p	3p	0.1p
EG	0.69 eV	0.69 eV	0.55 eV	0.69 eV
IBV	300 µA	100 µA	1000 µA	10 µA
IS	3 µA	0.05 µA	0.1 µA	0.04 µA
N	1.06	1.08	1	1.05
R_s	25 Ω	5 Ω	2.4 Ω	12 Ω
PB (VJ)	0.35 V	0.65 V	0.6 V	0.51 V
PT(XTI)	2	2	2	2
M	0.5	0.5	0.5	0.35

Fig. 4 shows the model of HSMS2850, HSMS2860, HBAT5400, SMS7621 Schottky diodes designed in LTSpiceIV software.Different parameters like series resistance (R_s), Junction capacitance (C_{j0}) at zero bias provided in Table 1 are used for the modeling of Schottky diodes. Series resistance for HSMS2850 is denoted as R4 (Fig. 4a), for HSMS2860 as R3 (Fig. 4b), for HBAT5400 as R2 (Fig. 4c), for SMS7621 as R1 (Fig. 4d). Other capacitors and inductors are parasitic elements, whose values have been taken from Technical manuals of AVAGO Technologies Agilent Technologies and SKYWORKS [17,19,20]. To obtain DC characteristics, variable input voltage is applied with maximum 1 V and output is received at 1 KΩ resistance.



(a) HSMS2850 (b) HSMS2860 (c) HBAT5400 (d) SMS7621

Fig. 4: Models of selected Schottky diode in LTSpiceIV.

IV. CHARACTERISTICS & PERFORMANCE COMPARISON OF SCHOTTKY DIODES

SPICE model of Schottky diode hasalready been explained in section III. In the model of Schottky diode, two important parameters are there, viz. junction resistance $R_j$and the junction capacitor C_j . The performance of Schottky diodes mainly depends on these two elements. The junction resistance $R_j$is inversely proportional to the sum of diode current and reverse saturation current [17]. Junction capacitance is parallel to junction resistance. Impedance of this parallel combination decides the value of DC output during rectification. Thus, low value of junction capacitance provides maximum output [18].

Different characteristics like turn-on voltage and maximum output diode current have been simulated on LTSpiceIV software for analyzing the performance of the selected diodes at low input power levels. Fig. 5 shows the variation of output voltages with respect to given input voltages for selected diodes. In expanded part of this figure, the turn-on voltage range for different diodes has been showed. The HSMS2850 has turn on voltage value in between 60 mV to 100 mV, and for other diodes it is more than 100 mV. This may be attributed to the material of the metal used in HSMS2850 Schottky diode [21].

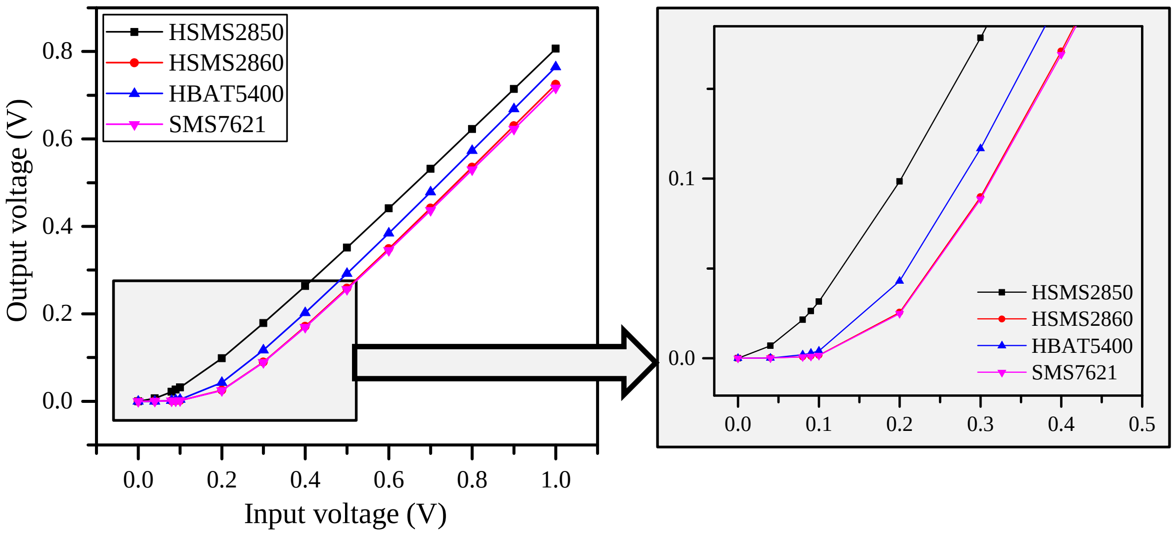


Fig. 5: Comparison ofturn-on voltage characteristics for selected Schottky diodes.

Due to low turn-on voltage, HSMS2850 diode is providing maximum diode current as shown in Fig. 6. From Table 1, it can be observed that HSMS2850 has higher reverse saturation current as well. Hence, the value of junction resistance happens to be low, which provides maximum output voltage.

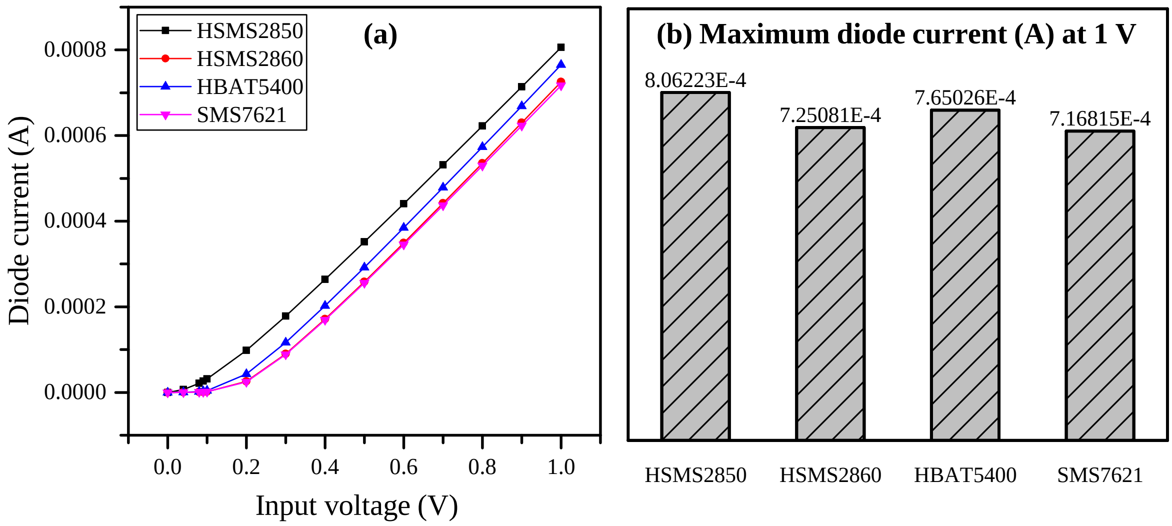


Fig. 6: (a) I-V characteristics of diodes, (b) Maximum diode current at 1 V input voltage.

So far, DC characteristics of the selected Schottky diodes have been examined. Further, to simulate the actual operation of the selected diodes in RF-DC rectifiers, the output voltage characteristics of the diodes at low input power levels and two different frequencies (900 MHz and 2.45 GHz) were investigated. The selected frequencies are widely used in transmission of RF signals. The output voltage characteristics were obtained at 1 KΩ resistance by applying -30 dBm to -15 dBm input power (at two selected frequencies of 900 MHz and 2.45 GHz) in the same circuits of diode model shown in Fig. 4. The obtained output voltage characteristics are presented in Fig. 7. It can be observed from the figure that at low input power levels, HSMS2850 provided better performance compared to other diodes. This is primarily ascribed to its low turn-on voltage and low value of junction resistance as explained earlier in section.

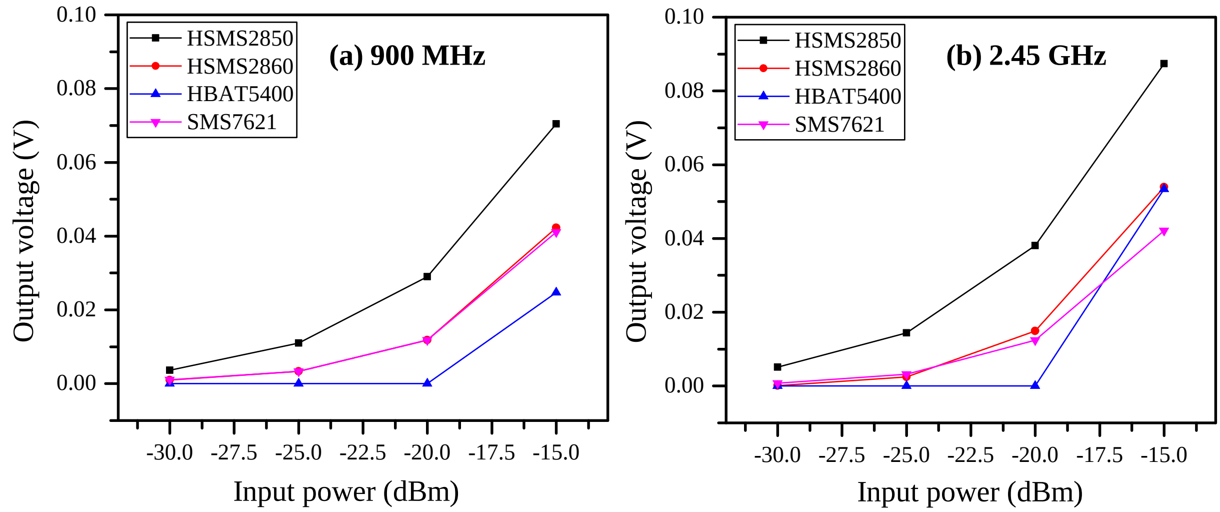


Fig. 7: Output voltage characteristics of the selected Schottky diodes at low input power levels - (a) Output voltage of diodes at 900 MHz frequency, (b) Output voltage of diodes at 2.45 GHz frequency.

V. CONCLUSION

This paper reportsthe performance comparison of four commercially available Schottky diodes HSMS2850, HSMS2860, HBAT5400 and SMS7621 carried out usingLTSpiceIV software. These diodes are widely used as RF-DC rectifiers.Based on DC characteristics, HSMS2850 diode showed low turn-on voltage between 60 mV to 100 mV and maximum output current of 806.22 µA at 1 V input. HSMS2850 also provided maximum output voltage at low input power levels while simulating the actual operation as RF-DC rectifier and found to be the most efficient Schottky diode for RF-DC rectification.

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