Towards Solution-Processed RF Rectennas: Experimental Characterization and Non-Linear Modelling based on ZnO Nanogap Diodes

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***Abstract*—The growing demands of the IoT market call for novel ultra-low-cost RF semiconductor devices. Using GHz-frequency Schottky diodes fabricated on a wafer-scale, low-cost natively flexible rectennas and RF energy harvesters can be realized. This paper will present, for the first time, the non-linear model followed by antenna-circuit co-design for solution-processed Zinc-Oxide (ZnO) Schottky diodes. The diode's equivalent circuit model is extracted and compared to experimental on-wafer characterization showing very good agreement up to 40 GHz. Using a complex-impedance source emulating a printable rectenna, the designed voltage doubler rectifier shows a power conversion efficiency up to 70% in the UHF RFID band (0.915 GHz). The optimum source and load impedance parameters for a single-series and voltage-doubler rectifier are finally presented, showing that ZnO nano-gap diodes can be adopted in future rectenna designs.**

***Index Terms*—energy harvesting, rectennas, rectifiers, Schottky diodes, wireless power transfer, adhesion lithography**

I. Introduction

With the growing Internet of Everything (IoE) vision, and predictions of over a trillion wireless connected devices, there is a need for microwave energy harvesting front-ends realized using inexpensive fabrication methods [1]. To realize a microwave-powered IoE using rectennas, both high-efficiency inexpensive passive components, such as antennas and matching networks, as well as semiconductor devices, such as diodes and transistors are required.

The transition to natively-flexible semiconductors, including machine learning accelerators [2] and microprocessors [1], implies that computing and intelligence could be ported to extremely high-volume and low-cost applications. To enable such flexible solution-processed IoE devices, there is renewed interest in all-flexible rectennas for RF energy harvesting and wireless power transfer (WPT) applications [3]. A plethora of flexible, printed, and textile-based rectennas has been developed recently. Beamforming "5G" rectennas [4], meshed optically-translucent antennas [5], and wearable textile-based antennas for Simultaneous Wireless Information and Power Transfer (SWIPT) applications are among the recent implementations [6]. Moreover, it has been widely observed that the use of inexpensive conductors and lossy substrates does not prevent rectennas from achieving a state-of-the-art Power Conversion Efficiency (PCE) in line with that achieved using bulk metals and low-loss RF laminates [7]. However, the aforementioned *high-efficiency* rectennas were based on commercial Schottky diodes, which require careful packaging and high-temperature complex nano-fabrication methods.

Schottky diodes processed from solution are among the emerging device topologies, which have been used to demonstrate the scalability of RF semiconductor devices. Recently, Zinc Oxide (ZnO) nano-gap Schottky diodes have been demonstrated with cut-off frequencies in excess of 100 GHz [8]. Furthermore, the ability of solution-processed Indium Gallium Zinc oxide (IGZO) diodes to function as rectifiers up to mmWave bands was experimentally demonstrated [9]. Nevertheless, there has been no detailed RF modelling of such devices in order to design optimized rectennas. Furthermore, the achievable RF-DC PCEs of ZnO-based rectennas remain unknown.

In this paper, we present the first non-linear SPICE circuit model based on the measured parameters of a solution-processed ZnO diode. Exhibiting a good agreement with the measured characteristics up to 40 GHz, in Section II, the proposed model is used to design and optimize two rectifiers yielding a state-of-the-art PCE exceeding 70%, matching the performance of silicon-based rectifiers.

II. ZnO Diode Characterization and Modelling

To enable the design of ZnO-based natively-flexible rectennas, an accurate SPICE model is required. To explain, non-linear circuit simulations using closed-form Harmonic Balance (HB) models are typically used to optimize the rectifier, before an antenna can be designed using full-wave electromagnetic simulation.

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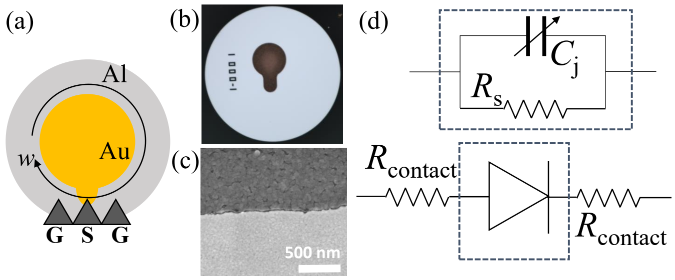

Fig. 1. The solution-processed ZnO diode and its SPICE model: (a) 2D diode layout showing its electrodes and nano-gap width w; (b) optical micrographs of the diode; (c) SEM micrograph of the nano-gap; (d) the non-linear SPICE diode model.

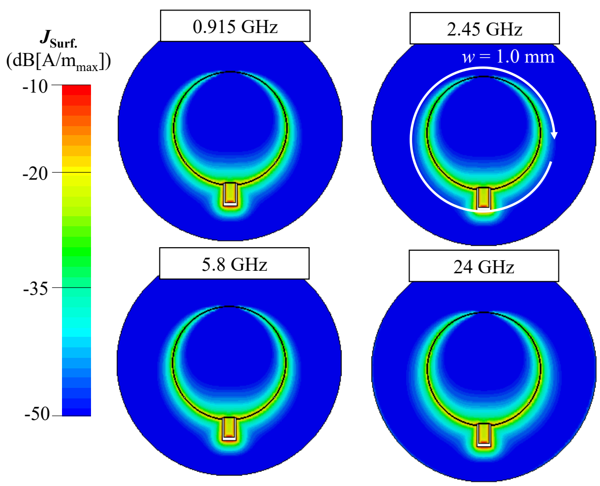

Fig. 2. Simulated surface current plot over the diode's electrodes at different frequencies below its intrinsic cut-off frequency.

Fig. 1 (a) shows the layout of the diode with its micrographs shown in Fig. 1(b) and (c). Prior to extracting a SPICE model, it is essential to verify that the diode's electrodes do not influence the electromagnetic waves at the input of the junction, illustrated by the ground-signal-ground (GSG) probes used for measurements. The diode's contacts were simulated in CST Microwave Studio to observed the surface current distribution $J_{\mathrm{surf.}}$ around the nano-gap junction. Fig. 2 shows the $J_{\mathrm{surf.}}$ at different frequencies, exhibiting minimal variations.

The diode's s-parameters were measured on-wafer using GSG probes, as in Fig. 1(a), with a TRL-calibrated E8361C Vector Network Analyzer (VNA), where the intrinsic cut-off frequencies were previously investigated in [8]. The measured S_{11} response was imported in Keysight ADS and a diode model was constructed based on the measured DC IV properties from [8], as well as the measured s-parameters. Fig. 3(a) and (b) show the complex impedance and magnitude S_{11} response of the diode, in good agreement, up to 40 GHz (the intrinsic cut-off frequency). The parameters used to simulate the diode's response are given in Table II.

TABLE I
SUMMARY OF THE w=1,000 µM DIODE'S SPICE PARAMETERS

I_S	R_S	B_V	C_{jo}	V_j	Tt	$R_{\mathrm{Cont.}}$
78 pA	9 Ω	4 Ω	0.35 pF	1.48 V	1 $\times 10^{-11}$	48 Ω

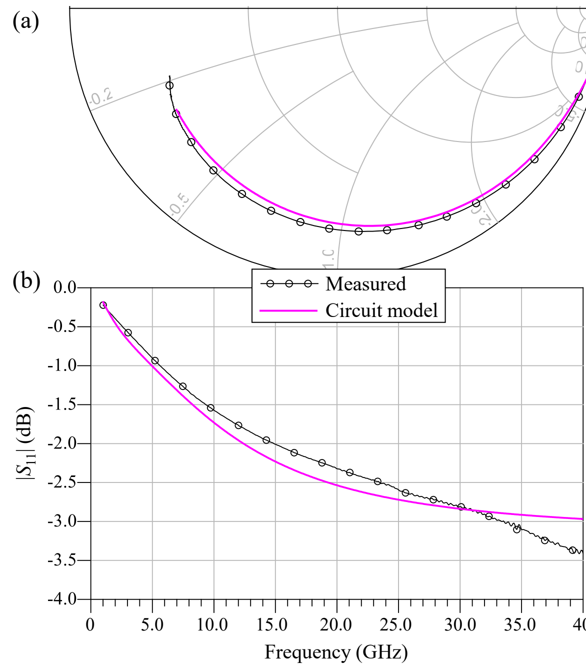

Fig. 3. Measured and calculated S_{11} response of the w=1 mm diode and its equivalent SPICE model using HB simulation.

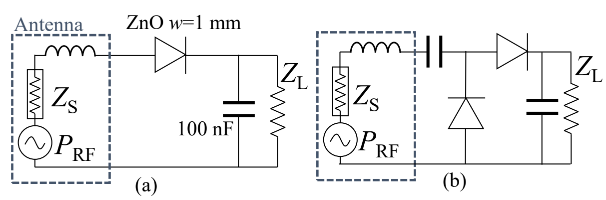

Fig. 4. HB rectenna models for the single-series (a) and voltage-doubler (b) rectifiers.

III. COMPLEX-Z RECTENNA DESIGN AND MODELLING

Observing the close agreement between the extracted SPICE model and the measured S_{11} response, the extracted model can be used in the design and simulation of a rectifier. Two rectifiers are included in the design and optimization: a single-series and a voltage doubler, both shown in Fig. 4. The complex source impedance, emulating the complex-conjugate antenna, has been optimized iteratively using the approach proposed in [10]. The rectifiers are designed to achieve the maximum PCE around 915 MHz, for RFID and license-free WPT applications.

A complex-conjugate rectenna could be modelled, at its frequency of operation, as a power source with a series resistive and inductive impedance [11]. Typically the packaging parasitic inductance (e.g. from wire-bonding) and capacitance

TABLE II
SUMMARY OF THE RECTENNA'S PARAMETERS

Rectifier	Peak PCE	PCE at -3 dBm	1 V sensitivity	Z_L	Z_S
Single-series	51%	33%	-1 dBm	4 kΩ	$130+ j\omega 91 \times 10^{-9}$
Voltage-doubler	71%	7%	-2 dBm	7 kΩ	$70+ j\omega 56.6 \times 10^{-9}$

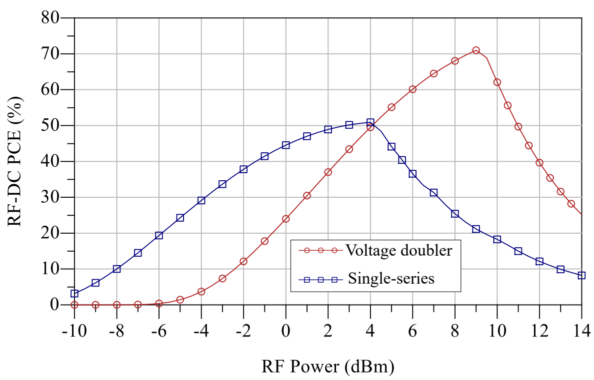

Fig. 5. Simulated RF-DC PCE of the complex-conjugate rectennas (single-series and voltage-doubling) based on the ZnO w=1.0 mm diode.

(from soldering pads) would be included in the modelling. However, a key advantage of large-area devices and rectennas is the potential for direct integration between the rectifying elements and the antenna's radiators. Both rectifiers were optimized to achieve the peak PCE, limited by both their reverse breakdown voltage V_B and forward voltage drop V_F. The optimal rectenna parameters are summarized in Table II. The contact resistance R_{Contact} of the diodes is excluded from the rectenna modelling, as such resistance would not be present in a monolithically-integrated rectenna.

Fig. 5 and 6 show the PCE and DC voltage output, respectively, of the single-series and voltage-doubling rectifiers for varying RF input power levels. The single-series rectifier exhibits a higher PCE at lower inputs, which is attributed to the lower voltage drop across the fewer diodes' junctions compared to the voltage doubler [12]. On the other hand, the voltage doubler-based design achieves a higher peak PCE, which is in line with the theoretical PCE limits of different rectifier topologies [13].

Observing the DC voltage output in Fig. 6, the enhanced sensitivity of the single-series rectifier can be observed for the low inputs below -4 dBm. While the DC voltage output is as low as 100 mV, which is insufficient for powering a boost-converter or a low-voltage logic circuit, a series power-combining array configuration could be adopted to maximize the voltage output leading to improved sensitivity, longer range, and improved load impedance range [11]. Moreover, the scalability of the solution-processed diodes enables such large-area rectenna arrays to be realized at a lower cost and complexity compared to rectennas utilizing discrete parts.

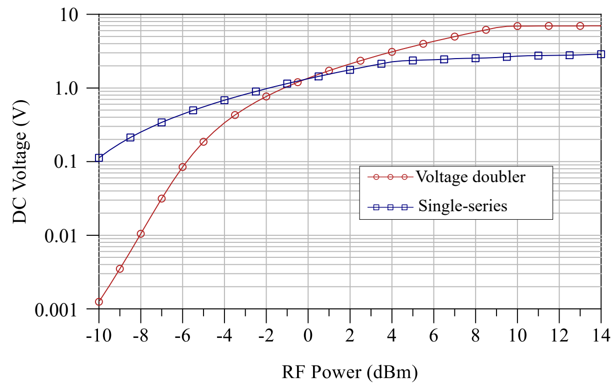

Fig. 6. Simulated DC voltage output of the complex-conjugate rectennas (single-series and voltage-doubling) based on the ZnO w=1.0 mm diode.

TABLE III
COMPARISON WITH RECENT SOLUTION-PROCESSED RECTIFIERS

	Peak PCE	Diode	Rectifier Topology	Frequency
This work	71%†	ZnO nano-gap	Voltage-doubler	0.915 GHz
[3]	40%	MoS_2	Single-series	2.4 GHz
[14]	<1%	Metal-Insulator-Graphene	Single-series	2.4 GHz
[15]	81%	Si, BAT15-04R	Voltage doubler	0.915 GHz

† simulated response using empirical SPICE model

Table III compares the simulated response of the ZnO-based rectifiers, under excitation with an optimal source and load impedance, to recent monolithic rectifiers and rectennas. The high peak-PCE is attributed to the optimal impedance matching [10], previously found to maximize the DC output of off-the-shelf devices, as well as the diodes' low parasitic capacitance and resistance. While the rectifier's performance was simulated using HB simulations and an ideal source impedance, the optimized Z_S values in Table II fall within the tuning range of multiple complex-conjugate rectenna designs [6], [10].

IV. CONCLUSION

As solution-processed semiconductors continue to advance reaching GHz frequencies of operation, future RF energy harvesting rectennas could be realized using monolithically-integrated all-flexible devices. Using one-port s-parameter and IV measurements, an accurate SPICE model of a Schottky diode was extracted showing good agreement up to 40 GHz. Based on the proposed model, two rectifiers were designed and optimized showing the potential for up to 70% RF-DC PCE for the optimum antenna and load impedances, which compares well to off-the-shelf silicon diodes. This work serves as the foundation for the design of future high-efficiency rectennas using large-area devices. Future work will include the realization of fully-integrated rectennas based on the extracted Z_S and the nano-gap diodes.

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