A Sensitivity Analysis of Power Conversion Efficiency of Rectifying Diodes on Their Device Parameters for Micro-watt RF Energy Harvesting

Yutaro Yamazaki and Toru Tanzawa
Shizuoka University

1. Introduction RF energy harvesting is considered as one of power sources for IoT devices in recent years [1]. Electromagnetic wave received by an antenna is rectified by a diode via a matching circuit. This system is called rectenna (Fig.1). Sensitivity analysis of the device parameters of the rectifying devices has been done to improve the rectification efficiency so far. In [2], it is shown that the parasitic capacitance *Cj* is the most important parameter for high rectification efficiency with Shottoky barrier diode (SBD) when the input power is in a range of 1 to 100 mW in 5.8GHz band. In [1], it is discussed that η at low power input can be improved by lowering the potential barrier using a tunnel diode. However, it is unclear which of the parasitic capacitance and the potential barrier can affect power conversion efficiency η at μW power level more. In this study, the potential barrier is included in device design parameters and the sensitivity of η at μW power level is analyzed.

2. Efficiency Analysis A diode I-V equation and power conversion efficiency η are defined by (1) and (2), respectively, where *Id* and *Vd* are the current and voltage applied to the rectifying portion of the diode, respectively. *Is* is a proportional coefficient, *Vth* is the potential barrier of the diode, and *Pav* is available power [4] expressed by (3)

$$\mathrm{I_d} = \mathrm{I_s}\{exp(V_d/V_{th}) - 1\} \cdots (1) \qquad \eta = \mathrm{P_{out}}/\mathrm{P_{av}} \cdots (2)$$

$$P_{av} = (V_{in}^2)/(8 \times R_{ant}), \quad (3)$$

where *Vin* and *Rant* are the input voltage amplitude and the internal resistance of the antenna (the real part of the antenna impedance). In [1], I-V of the tunnel diode was fitted by a 7th-order equation. In this work, the general formula (1) is used instead of the 7th order equation in [1]. As shown in Fig.2, with *Is*=1μA and *Vth*=20mV is well matched with the 7th -order fitting when the fitting range is -50 mV to 0.2 V. Note that the 7th-order equation has non-physical behavior when the input voltage range is expanded. This work assumes *Vdd*=0.5V [3], *Idd*=10μA for *Pout*=5μW with *Rant*=70Ω at 2.4GHz band at 25°C. The matching elements *Lm* and *Cm* are adjusted so that the input power becomes minimal for the above condition. Their values are limited to *Lm*≦40nH and *Cm*=0.1~33pF for 2.4GHz band. The sensitivity of η on *Rs*, *Cj*, *Is* and *Vth* was investigated. η had significant sensitivities on *Cj* and *Vth* among them. Therefore, only the sensitivity of η on *Cj* and *Vth* is reported in this paper with *Is*=5μA and *Rs*=20Ω [5]. *Cj* was varied to be 0.14pF [5], 0.018pF [1] and 0.42pF. *Vth* was swept from 5 mV to 45 mV where the thermal voltage of SBD is equivalent to *Vth*=25mV at room temperature. Harmonic balance simulation was used with ADS.

3. Simulation Results Fig.3 shows contour plots of η on *Cj*-*Vth*. η varies more significantly over *Cj* than over *Vth*. Fig.3 suggests that η can be improved with smaller *Cj* rather than with smaller *Vth*. Such a difference in the sensitivity of η on the diode device parameters may be because of the definition on power conversion. Fig.4 shows *Pav*-η for the three conditions A [5], B [1] and C (the highest η in Fig.3). The solid black symbols represent the condition of *Idd*=10μA at *Vdd*=0.5V. In this demonstration, *Pav* for the tunnel diode [1] is smaller by 3dBm than that for SBD [5]. Even if the potential barrier was reduced to 5mV with *Cj* unchanged, an expected improvement in *Pav* would be as small as 0.5dBm.

4. Conclusion Junction capacitance *Cj* is the most significant factor for high power efficiency among diode device parameters at μW level in 2.4GHz band. Rectifying diodes with a reduced potential barrier such as tunnel diodes can have higher power efficiency when their junction capacitance is smaller than that of Shottoky barrier diodes. Therefore, reduction in *Cj* should be prioritized to design rectifying diodes for micro-watt RF energy harvesting.

5. References

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6. Ackowlegement

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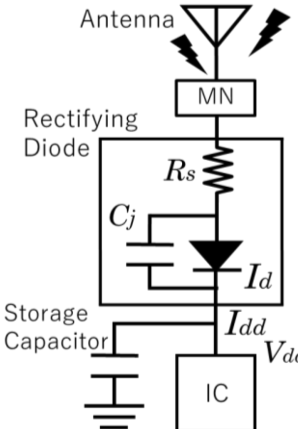

Fig.1 Rectenna

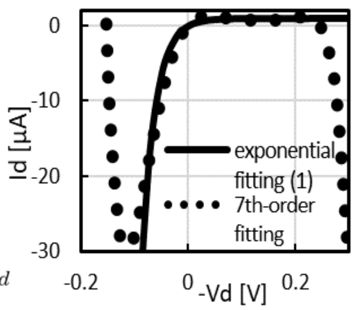

Fig.2 Fitting curves of the tunnel diode.

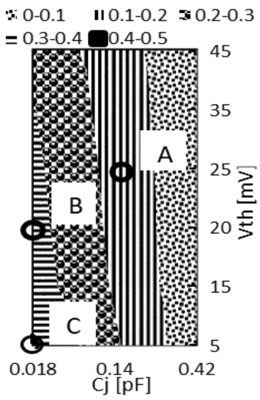

Fig.3 Contour plot of η on *Cj* and *Vth*.

	Cj, Vth
A	[5]
B	[1]
C	the highest η in Fig.3

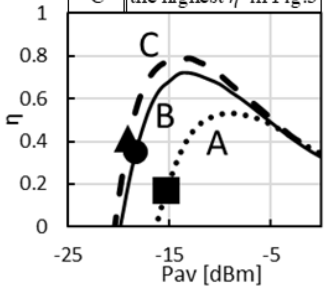

Fig.4 *Pav*-η.