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Cavalheiro, D.; Moll, F.; Valtchev, S., "A battery-less, self-sustaining RF energy harvesting circuit with TFETs for μW power applications," in New Circuits and Systems Conference (NEWCAS), 2016 IEEE 14th International , vol., no., pp.1-4, 26-29 June 2015; doi: 10.1109/NEWCAS.2016.7604751

A Battery-Less, Self-Sustaining RF Energy Harvesting Circuit with TFETs for µW Power Applications

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***Abstract*—This paper proposes a Tunnel FET (TFET) power management circuit for RF energy harvesting applications. In contrast with conventional MOSFET technologies, the improved electrical characteristics of TFETs promise a better behavior in the process of rectification and conversion at ultra-low power (µW) and voltage (sub-0.25 V) levels. RF powered systems can not only benefit from TFETs in front-end rectifiers by harvesting the surrounding energy at levels where conventional technologies cannot operate but also in the minimization of energy required by the power management circuit. In this work we present an energy harvesting circuit for RF sources designed with TFETs. The TFET controller emulates an adequate impedance at the output of the rectifier in order to allow maximum transfer of power from the RF source to the input of the boost converter. The output load is activated once the output capacitor reaches a voltage value of 0.5 V. The results show an efficiency boost of 89 % for an output load consuming 1 µW with an available RF power of -25 dBm.**

Keywords—Energy Harvesting; Power Management; Radio-Frequency; Tunnel FET; Ultra-low Power

I. INTRODUCTION

Several low-power applications can benefit from the surrounding radiated energy in order to power their circuits. RFID tags and biomedical implants are examples of radio-frequency (RF) powered circuits that can be placed in areas of difficult access. As the constant replacement of their batteries is undesired the field of energy harvesting from ambient has gained importance as shown by recent works [1-3]. However, the low power conversion efficiency (PCE) demonstrated by battery-less circuits at low RF input power levels (below -20 dBm) along with the limited available RF power from the surrounding environment constrains the operation range of the electronic circuits.

Low power levels of electromagnetic radiation produce low output voltage values, thus requiring energy conversion circuits to increase the voltage for use by the electronic systems. Under extreme low voltage scenarios, conventional switches cannot perform efficiently in front-end rectifiers. The main drawback of such technologies is the large on-resistance at voltage levels close to those produced by the antenna.

The Tunnel Field-Effect Transistor (TFET) appear as an interesting device to be applied in RF powered circuits. In contrast to thermionic devices, the high energy filtering of the band-to-band tunneling (BTBT) carrier injection mechanism characterizes the TFET device with a sub-threshold slope (SS) below 60 mV/dec (at room temperature) and lower leakage current. These characteristics turn this technology attractive for front-end rectifiers and switched-capacitor converters performing at sub-0.25 V values [4-5]. The decrease of energy required per switch allows the design of more efficient digital cells compared to conventional CMOS [6-7]. These characteristics can enable the design of efficient power management circuits for energy harvesting applications, working at very low voltage and power levels as shown in this work.

This paper presents a power management circuit with TFETs for a RF source with impedance matching between the rectifier and the boost converter for maximum power transfer. A start-up circuit is proposed, which allows to avoid the use of any external electrical mechanism. The power management circuit controls the boost converter for a stable output voltage of 0.5 V and a load of 200 kΩ. All the simulations are performed with a III-V TFET model with a gate length of 40 nm. More information about the model can be found in [8]. In section II the electrical properties of the TFET and the proposed power management circuit are explained. Section III presents the simulated results and section IV concludes the work.

II. POWER MANAGEMENT CIRCUIT WITH TFETS

A. TFET structure and electrical characteristics

As presented in Fig 1 (a) and in contrast with thermionic devices the TFET is designed as a reverse biased *p-i-n* diode [5]. With a different structure, the carrier injection mechanism can be divided into two components: for forward bias conditions (V_{GS} and $V_{DS} > 0$ for n-TFET and < 0 for p-TFET) the current is mainly characterized by the band-to-band tunneling (BTBT) mechanism as shown in Fig. 1 (b). Under reverse bias conditions (V_{GS} and $V_{DS} < 0$ for n-TFET and > 0 for p-TFET) the carrier injection mechanism can be divided into two distinct regions.

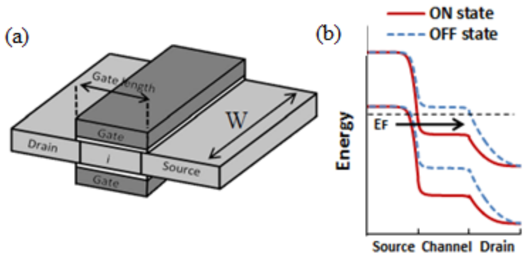

Fig. 1a) TFET structure; b) Energy Band Diagram for n-TFET

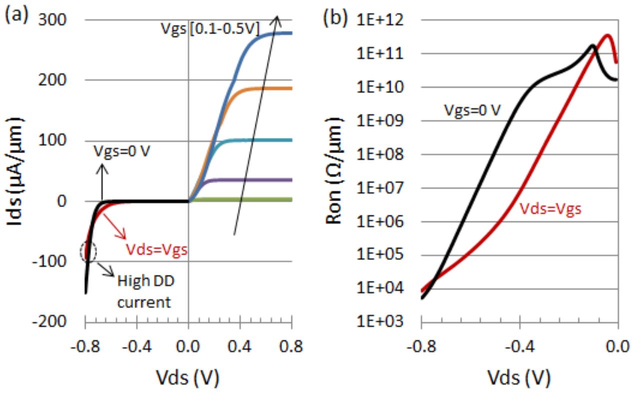

Fig. 2 a) I-V characteristic; b) Internal resistance under reverse bias

Under low reverse bias, the TFET current is characterized by a reverse BTBT injection mechanism. In contrast, at high reverse bias the BTBT mechanism is suppressed and the drift-diffusion (DD) mechanism characterizes the current as shown in Fig. 2 (a). This TFET characteristic requires different circuit topologies in order to avoid high reverse losses when the transistors are reverse biased, an effect not observed in MOSFETs. As shown in Fig. 2 (b), a solution to attenuate the reverse losses of circuits designed with TFET is to set the V_{GS} of reverse biased TFETs to 0 V.

B. *PMC structure and description*

The building blocks of the proposed power management circuit (PMC) with TFETs for RF sources are presented in Fig. 3 (a). The RF source is set to 915 MHz with an input power level of -25 dBm (3.16 μW). The PMC is required to boost the output of the rectifier (input of the boost converter) to 0.5 V. Once this value is achieved, a load of 200 kΩ is activated consuming an instantaneous power of 1.25 μW.

The TFET gate cross-coupled rectifier (GCCR) presented in Fig. 4 (a) presents a good conversion performance at μW power levels and very low-voltage values (sub-0.25 V) [5]. Fig. 4 (b) shows the performance of a three stage TFET-based GCCR matched with a power source of -20 dBm (modeled as a port with 50 Ω) and how the efficiency decrease with decreasing the available power. At an available power of -25 dBm, a rectification efficiency of 35 % is observed for an output load of 31.6 kΩ. For this value, the resultant output voltage is 190 mV. As shown in Fig. 4 (c), a power of 1.12 μW with an available RF power of -25 dBm can be delivered to the input of the boost converter if the proposed TFET PMC sets an average voltage value of 190 mV at the output of the rectifier.

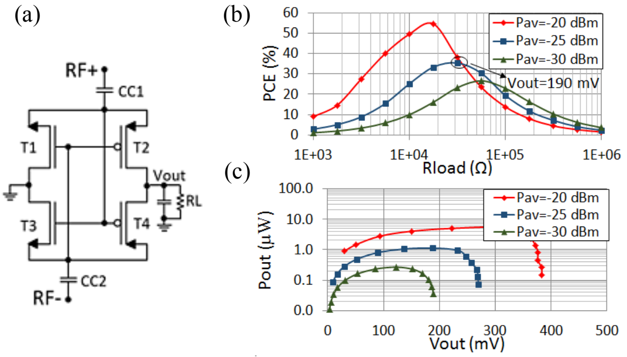

Fig. 4a) TFET GCCR topology; b) Performance of a three-stage GCCR; (c) Output power in function of available RF power

1) *Startup circuit*

The startup circuit of the PMC is responsible to avoid the use of any external battery for a proper boost operation. As shown in Fig. 3 (a), a ring oscillator followed by a non-overlapped (NO) phase circuit with drivers generates two clock signals with opposite phases. These signals are applied in a gate cross-coupled charge-pump (GCCCP). In [4] we have shown that a TFET-based GCCCP can operate with high efficiency values at sub-0.2 V and µW power levels. In the startup circuit, the charge-pump is required to charge the capacitor connected to node "Vddstartup". This capacitor is used as a power source for the the analog and digital circuitry of the startup. At the output of the charge-pump a voltage monitor is used to trigger the signal "setboost" once the capacitor is charged up to 200 mV. This signal is important to enable the boost converter. A voltage reference with TFETs provides a fixed 50 mV signal to the voltage monitor.

Before the boost conversion, the input and output capacitors shown in Fig. 5 are pre-charged to suitable values by the TFET devices controlled respectively by T3 and T4. Once charged, a signal "set_vout_vin" is triggered and the boost converter starts to operate. The TFET controlled by T1 is required to charge the input boost capacitor whenever the "setboost" signal is active. TFETs controlled by T5 and T7 are required to charge the capacitor at the node "Vddint" and to enable this capacitor as a power source for the controller circuit. Once the load of the boost converter is enabled for the first time, a signal SSM (Self-Sustaining Mode) is triggered and the charge-pump circuitry is deactivated by the TFET controlled by T2. Therefore, the power source capacitors for the startup and controller circuit are charged by the output of the boost converter. The TFET controlled by T6 is responsible for the SSM operation.

2) *Controller circuit*

The controller circuit is responsible for providing the control signals to the switches of the boost converter presented in Fig. 5. The operation sequence of the control signals is presented in Fig. 3 (b). During the time interval t0 to t1 the input capacitor at node "Vin" is charged by the rectifier up to a reference voltage of 200 mV. During this time interval, the transistor P1 is closed and a very small current flows in the inductor. The absence of body diode in reverse biased TFETs (due to a different doping

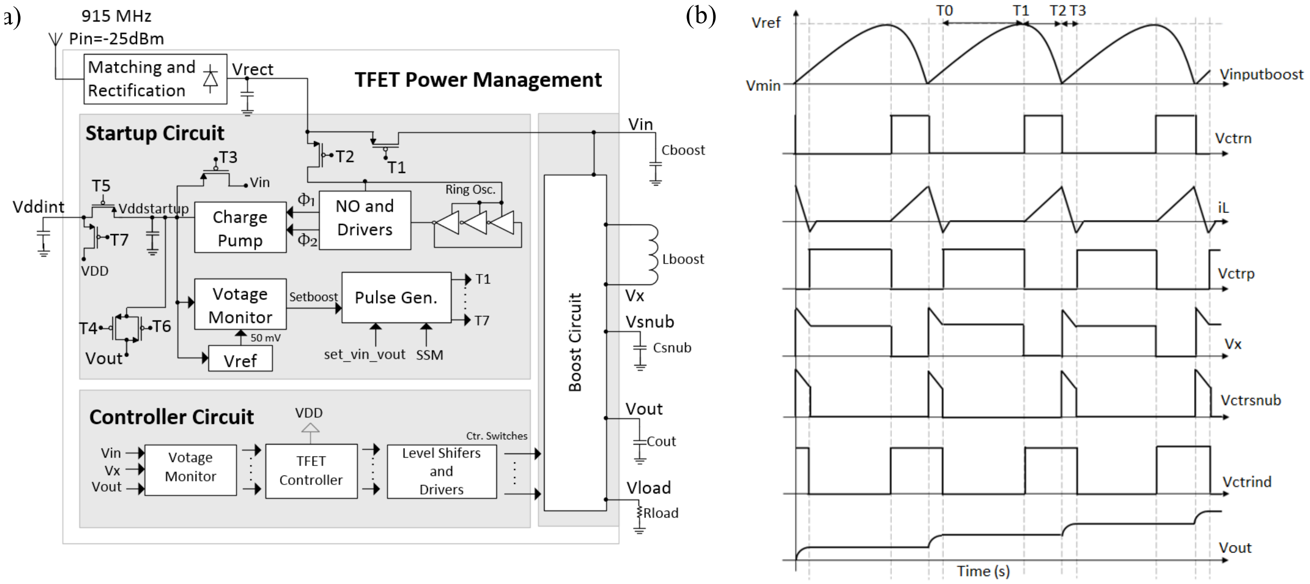

Fig. 3(a) Proposed RF Power Management Circuit with TFETs; (b) Operation sequence of main electrical signals structure than MOSFETs) requires a change in the conventional boost converter. A snubber circuit composed by the transistor P3 and a capacitor "C_{snub}" is proposed in order to provide a path for the inductor current when the output transistor P4 is open. During the time interval t1 to t2 the inductor is charged by the input boost capacitor until the latter reaches a minimum value of 180 mV.

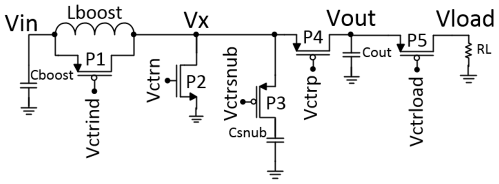

Fig. 5 Proposed boost converter topology with TFET devices

The average voltage of 190 mV at the input of the boost converter emulates an impedance value at the output of the rectifier that maximizes its efficiency as shown in Fig. 4 (b). During this time interval the transistor P2 is closed and the remaining transistors are open. During the time interval t2 to t3 the inductor acts as a power source and its current charges the output capacitor. During this time interval, the output transistor P4 is conducting the current while the remaining transistors are open. When the output of the boost converter achieves a value of 510 mV the TFET transistor P5 is closed until the output capacitor is discharged to 490 mV.

In order to reduce the reverse losses, the controller circuit presented in Fig. 6 characterizes the TFET transistors operating in the off-state with a V_{GS} of 0 V. The first comparator controls "Vctrn" by maintaining the input voltage of the boost converter between a reference voltage of 200 mV and a minimum voltage of 180 mV.

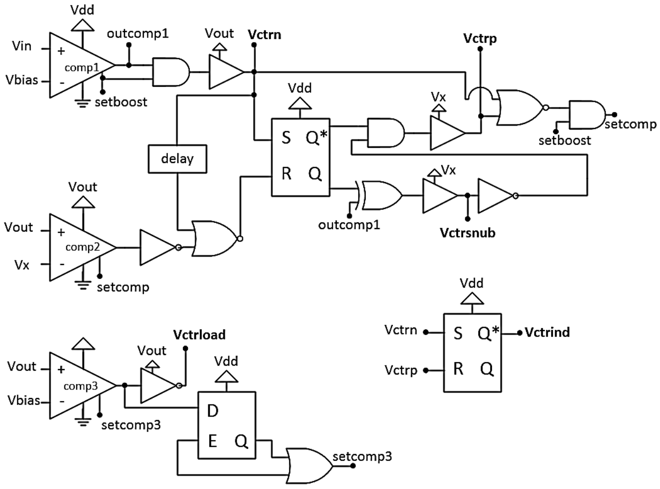

Fig. 6 Proposed controller circuit with TFET devices

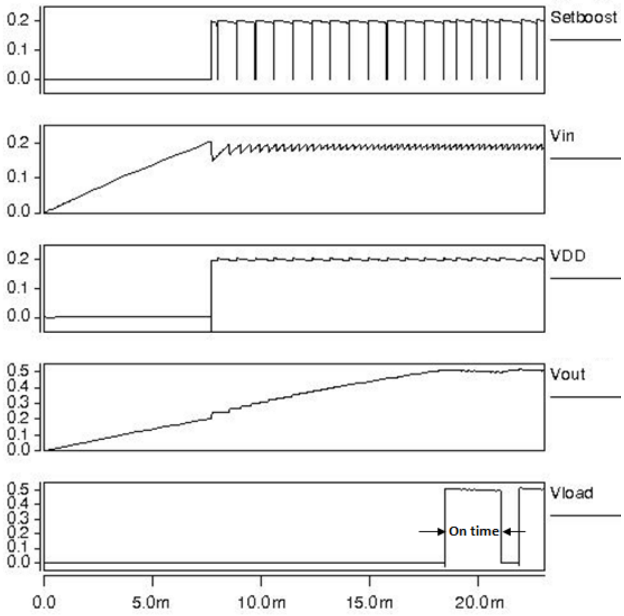

Fig. 7 Simulation results of the proposed TFET PMC for L1=10 mH, Cboost=0.1 µF, Cout=0.1 µF, Csnub=2 nF, Rload=200 kΩ, WP1=10 µm, WP2=500 µm, WP3,5=100 µm, WP4=50 µm.

Table I Comparison with RF power management circuits in state-of-the-art

	[1]	[2]	[3]	This work
RF freq.	1.93	2.45	0.95	0.915
Tech.	350 nm	-	180 nm	40nm TFET
Startup	Ext. battery	Electrical	Electrical	Electrical
Vout/Pout	1.4 V/ 0.52 µW	1 V/ 5 µW	1 V /13.1 µW	0.5V/0.997µW
PCE DC-DC	35.13 % @ 1.48 µW (measured)	50 % @ 10µW (measured)	80% @ 16.33µW (simulated)	89 % @ 1.12 µW (simulated)
PCE RF-DC	0.87 % @ -13.16 dBm (measured)	50 % @ -15d Bm (measured)	13% @ -10 dBm (simulated)	32 % @ -25 dBm (simulated)

The second comparator detects when the inductor current is negative, triggering a Reset signal in a RS latch. Depending on the state of “Vctrn” the output transistor P4 is activated or deactivated. In order to maximize the PCE of the PMC the comparators only operate during a fraction of time when both “Vctrn” and “Vctrp” signals are 0 V (time of the inductor to discharge). The third comparator is required to control the transistor P5 when “Vout” is between the range 510-490 mV. The control signal “Vctrind” is triggered when both input (P2) and output (P4) transistors are operating in the off-state.

III. SIMULATION RESULTS

In Fig. 7, the simulation results of the proposed TFET power management circuit are presented. It is shown that before the boost operation, the input and output nodes are charged to 0.2 V. After this charging time, the “V_{DD}” node is activated (power supply node of the controller) and the boost converter enters into a synchronous mode of operation. C_{boost} is charged and discharged with an average value of 190 mV.

The performance of the DC-DC conversion is presented in Fig. 8. For both simulations, the consumption of the startup and controller circuits are respectively 7.5 nW and 12 nW. DC-DC efficiency values close to 90 % are achieved for an inductor value of 10 mH and an input boost capacitor of 0.05 µF as shown in Fig. 8 (a). According to [3], the inductor current and boosting frequency are directly proportional to the size of the input boost capacitor. Larger peak current values with larger capacitors require larger transistors to reduce the conduction losses and increase the PCE as shown in Fig. 8 (b). Larger transistors also come at the expense of larger switching losses. As shown in Fig. 8 (c) larger capacitor values increase the on-time of the load.

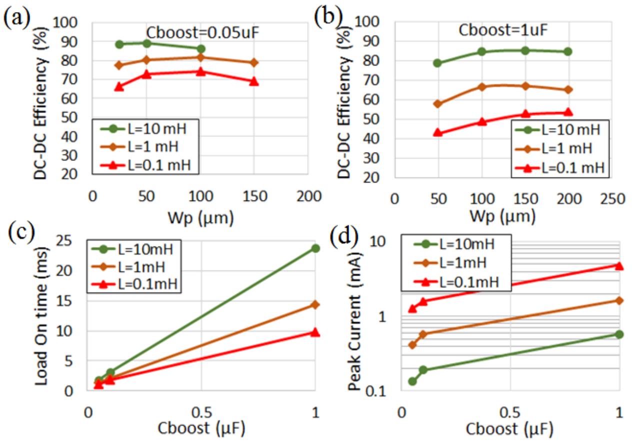

Fig. 8 Performance of the TFET boost converter for Cout=Cboost, Csnub=2 nF, Rload=200kΩ, W1=10µm, W2=500µm, W3, 5=100µm

An increase of the inductor size at the expense of a larger circuit die area is an efficient way to reduce the losses of the boost converter by decreasing the peak inductor current as shown in Fig. 8 (d) and consequent conduction losses of the transistors. In Table I, the proposed TFET RF PMC shows advantages in terms of efficiency at sub-µW power levels in comparison with recent works.

IV. CONCLUSIONS

A TFET-based RF power management circuit is presented, showing higher power efficiencies than those of the state-of-the-art at µW power levels. A startup circuit (consuming 7.5 nW) and a controller (consuming 12 nW) designed with TFETs are proposed showing promising results for the RF energy harvesting field for µW power applications. Simulation results show a DC-DC conversion efficiency of 89 % for an input power level of 1.12 µW and a RF-DC efficiency of 32 % for a RF power level of -25 dBm.

ACKNOWLEDGMENT

The authors wish to acknowledge the support for this research, coming from the Portuguese funding institution FCT (Fundação para a Ciência e a Tecnologia) and Spanish Ministry of Economy (MINECO) and ERDF funds through project TEC2013-45638-C3-2-R (Maragda).

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