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# Tunnel FET device characteristics for RF energy harvesting passive rectifiers

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***Abstract*—The lack of high power conversion efficiency in RF passive rectifier circuits at sub-µW power levels with current MOSFET technologies is directly related with the difficulty of the transistors in conducting the required level of current at low voltage values. With a different carrier injection mechanism, the superior electrical characteristics of the Tunnel FET devices at low voltage values (sub-0.25 V) can outperform the process of energy conversion at ultra-low power, thus improving the operation range of RF energy harvesting circuits. In this work, a simulation study on the doping profile and material selection of Tunnel FET devices shows the impact of device properties in rectifier circuit efficiency.**

***Keywords—Doping; Energy Harvesting; Radio-Frequency; Rectifier; Tunnel FET; Ultra-Low Power.***

## I. Introduction

The search for high power conversion efficiency (PCE) at reduced power levels has been, over the last years, the main focus in the radio-frequency (RF) energy harvesting (EH) field [1-4]. The limitation of the available RF power from the surrounding environment constrains the operation range of batteryless circuits, and this way, it is of the major importance to improve the efficiency of RF powered circuits at a broader range of input power. As an example, the lack of power efficiency at the sub-mW range limits the operation distance of passive RFID tags to some meters and their computational capability [5].

Conventional MOSFET technologies applied in the front-end rectifiers of RF powered circuits are characterized by a minimum subthreshold-slope swing (SS) of 60 mV/ dec (at room temperature). This characteristic limits the current at low input voltage values in the front-end rectifier. Steep-slope transistors may overcome this drawback and thus take advantage of the available sub-mW RF input power range for RF powered circuits.

The Tunnel FET (TFET) device has been shown to present better electrical characteristics at low voltage levels compared to other electronic and spintronic devices [6]. With a sub-60 mV/dec of SS, this device is suitable in the EH field, both in the ultra-low power DC-DC conversion [7] and AC-DC rectification [5, 8]. For example, an RF passive rectifier circuit with TFETs can improve the PCE up to 70 % at -39 dBm [5]. However, when the *p-i-n* structure of the TFET device (Fig. 1) is largely reverse biased (both $V_{GS}$ and $V_{DS}$ negative for n-type TFET, and $V_{GS}$, $V_{DS}$ positive for p-type TFET), the reverse current of the transistors in the “off state” is important, thus limiting the PCE of the rectifier circuit. This undesired property can be alleviated by doping and material selection.

In this work, it is shown by means of simulations how a proper doping concentration and material selection in TFET devices can improve the efficiency of RF passive rectifiers for energy harvesting circuits. For the purpose, the dependence of the TFET internal resistance on these parameters is presented for both reverse and forward biasing conditions. The simulations are performed with Atlas device simulator [9].

Section II introduces the TFET carrier injection mechanism. Section III discusses the problems of applying TFET devices in passive rectifiers. Section IV presents the dependence of the TFET internal resistance on different channel materials and source/drain doping concentrations. Finally, the conclusions are presented.

## II. The Tunnel FET Device

### A. Physical Characteristics

Unlike the conventional MOSFET, the TFET device is designed as a reverse-biased gated *p-i-n* diode. For an n-type TFET (n-TFET) the source region is highly doped p-type and the drain a highly doped n-type semiconductor as shown in Fig. 1. For this configuration, the tunneling current is generated at the source-channel interface (Fig. 2 b). For the p-type TFET (p-TFET) the drain presents a p-type doped and the source an n-type doping semiconductor. In this work, a double-gate structure configuration is considered. All the simulations are performed considering a gate length of 20 nm, source and drain regions of 100 nm, relative dielectric constant of 22, dielectric thickness of 2.5 nm and a channel thickness of 5 nm.


Fig. 1 Double-gate n-TFET structure

### *B. Band-to-Band Tunneling and Drift Diffusion*

In TFET devices, the carrier injection mechanism does not follow the laws of thermionic injection as in conventional MOSFET devices. In Fig. 2, the band-to-band tunneling (BTBT) injection mechanism and drift diffusion of a Si n-TFET device with the same source/drain doping concentration ($N_{A,D} = 1 \cdot 10^{20} cm^{-3}$) is presented:

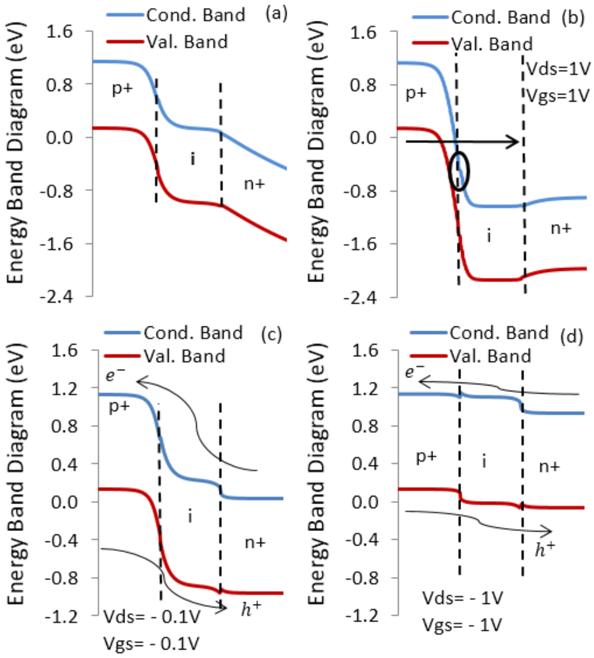


Fig. 2 Energy band diagram of a Si n-TFET, a) Equilibrium State; b) Forward biasing; c) Low reverse biasing; d) High reverse biasing

In the equilibrium state, the source and the drain in an n-TFET are doped such that the valence band in the p+ type region is located above the Fermi level and the conduction band in the n+ type region is located below the Fermi level. In the off state condition (Fig 2 a), the tunneling barrier between the source and the channel region is high. This will result in a low BTBT probability as expressed in (1) and consequently low tunneling generation rate (TGR) between the regions (2).

According to (1), materials with low relative mass *m* and low energy band gap $E_g$ can increase the tunneling probability and hence the tunneling current as expressed in (3). This characteristic will be discussed in section IV. More information about the presented equations can be found in [10].

$$\mathrm{T_{b2b}} = \exp\left(-\frac{4}{3}\cdot\frac{\sqrt{2\cdot \mathrm{m}\cdot \mathrm{m_0}}.\mathrm{E_g^{3/2}}}{\mathrm{q}\cdot \mathrm{h_{eff}}\cdot \mathrm{E_{(x,y)}}}\right) \qquad (1)$$

$$\mathrm{TGR} = \mathrm{T_{b2b}}.(\mathrm{f_c}-\mathrm{f_v}).\mathrm{E_{(x,y)}} \qquad (2)$$

$$\mathrm{I_{on}} = \frac{\mu_{\mathrm{tun}}\cdot \mathrm{N_C}\cdot \mathrm{q}^2}{\mathrm{k}\cdot \mathrm{T}}\int\int \mathrm{TGR}\cdot \mathrm{E_{(x,y)}}\mathrm{dxdy} \qquad (3)$$

In passive rectifiers it is assumed the same polarity of both gate and drain regions in the transistors. For the case of n-TFET devices, an increase of both gate and drain voltage will result in the decrease of the tunneling barrier in the source-channel interface as shown in Fig 2 b). The conduction and valence band in the channel region bend down, increasing this way the tunneling probability of carriers under the valence band of the $p^+$ region to tunnel through the channel to the empty states of the conduction band in the $n^+$ region giving rise in this way to tunneling current (normal on-state).

In TFET devices, the reverse biasing results in two different carrier injection mechanisms. With the increase of both energy band curves in the channel and drain regions produced by reverse biasing, drift diffusion of carriers can occur as shown in Fig. 2 c). At low reverse biasing, both tunneling and drift injection mechanisms may coexist. At large reverse biasing, the drift diffusion is the main injection mechanism as shown in Fig. 2 d). In this case, no tunneling current is presented. The transition between these two different injection mechanisms results in a negative differential resistance for large reverse bias voltages as shown in Fig. 4 and Fig. 5. Besides, unlike thermionic injection devices as conventional MOSFET technologies, the drift diffusion current of TFETs can result in high reverse losses in passive rectifiers.

## III. TFET IN ENERGY HARVESTING PASSIVE RECTIFIERS

In order to evaluate the application impact of Tunnel FET devices in RF energy harvesting passive rectifiers, it is important to understand the limitation of this technology in the different regions of operation of the circuit. The RF passive rectifier presented in Fig. 3 a) will be the subject of study. This rectifier has been presented as a viable solution for RF energy harvesting at low power levels (~mW range) with conventional transistors [1, 3].

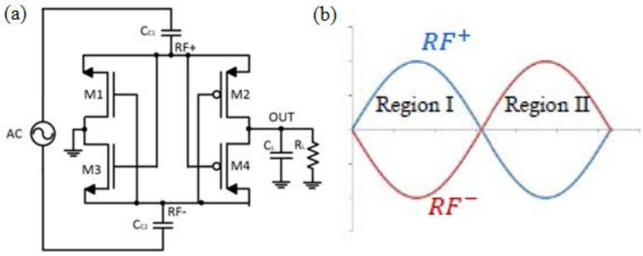


Fig. 3 a) Differential-drive passive rectifier topology; b) Regions of operation

The transistors in this topology are characterized by a $V_{GS}$=2 $V_{DS}$ during both regions of operation of Fig. 3 b) (at least in the initial condition: $V_{OUT}$ = 0 V). As the output voltage increases, and during the first region of operation, the transistors M2 and M3 are "on", while the transistors M1 and M4 are in the "off" state. In the second region of operation both M1 and M4 are "on" while M2 and M3 are "off".

These biasing conditions considers that the transistors in the "off" state are reverse biased with a voltage in the gate that is twice the voltage in the drain. For the TFET technology, and considering the simulations in section II B, this biasing condition can result in a high drift diffusion current, and consequently high reverse losses in the rectifier. In fact, the application of TFET devices in this passive rectifier topology was already investigated in [5, 8]. The authors have shown by simulations higher power efficiency at low RF AC magnitude voltage values (sub-0.35 VAC) compared to the use of the FinFET technology. However, and as expected, at higher AC magnitude values the power conversion efficiency of the circuit is degraded due to the increase of the reverse current suffered by the TFET transistors in the "off" state during both regions of operation (negative $V_{GS}$ and $V_{DS}$ values for
n-TFETs and positive $V_{GS}$ and $V_{DS}$ for p-TFETs). This cause of PCE loss is evident with the previous discussion in Section II and was not explicitly identified in previous works.

As the unwanted drift diffusion current of reverse biased TFETs is dependent on the level of energies shown in Fig. 2, the next section will present the variation of the TFET internal resistance for different materials and doping concentrations on both source and drain regions.

## IV. INTERNAL RESISTANCE AND PHYSICAL PARAMETERS

### A. *Source Doping Dependence*

In order to improve the power conversion efficiency of RF passive rectifiers, low forward and reverse losses in the applied transistors must be verified. According to (1), the decrease of the first can be accomplished with low energy band gap and mass materials. Fig. 4 a) presents the current-voltage characteristic of an n-TFET device with different materials, biased with the specific conditions of the passive rectifier of Fig. 3 a): $V_{GS}$=2 $V_{DS}$. The simulated n-TFET presents a drain doping concentration of $\mathrm{N_D} = 1 \cdot 10^{18}\mathrm{cm}^{-3}$ and source doping concentration of $\mathrm{N_A} = 1 \cdot 10^{20}\mathrm{cm}^{-3}$. It is observed that III-V materials as InGaAs with an energy band gap of 0.571 eV (room temp.) can conduct the same amount of current ($I_{DS}$=10µA/µm) at a lower voltage value compared to Germanium TFET (0.66 eV) and Silicon TFET (1.12 eV). It is evident from the graph that the inclusion of III-V TFET materials in passive rectifiers can reduce the forward losses, compared to the use of Si or Ge materials.

With the drain doping concentration fixed, the increase in the source doping results in the decrease of the internal resistance of both n-TFET devices and consequently lower forward losses can be expected. This can be seen in Fig. 4 b), c) and d). The increase of the source concentration results in an increase of the energy curves in the $p^+$ region of Fig. 2 b), decreasing this way the tunneling barrier between the source-channel interface. This barrier decrease results, however, in an increase of the reverse current at very low reverse biasing (while the BTBT is still the main injection mechanism). This behavior is observed with the decrease of the internal resistance at low reverse biasing. At high reverse biasing, the increase of the reverse current is mainly due to the increase of the drift diffusion carrier mechanism. Therefore, increasing the source doping concentration can reduce the forward losses of a passive rectifier but consequently increases the reverse losses.

*B. Drain Doping Dependence*

In order to keep the low internal resistance at forward biasing conditions, and attenuate the reverse losses by increasing the internal resistance of the n-TFET device, a study of the variation of the drain doping concentration is performed and presented in Fig. 5. The simulated n-TFET present a source doping concentration of $N_A = 1 \cdot 10^{20} cm^{-3}$.

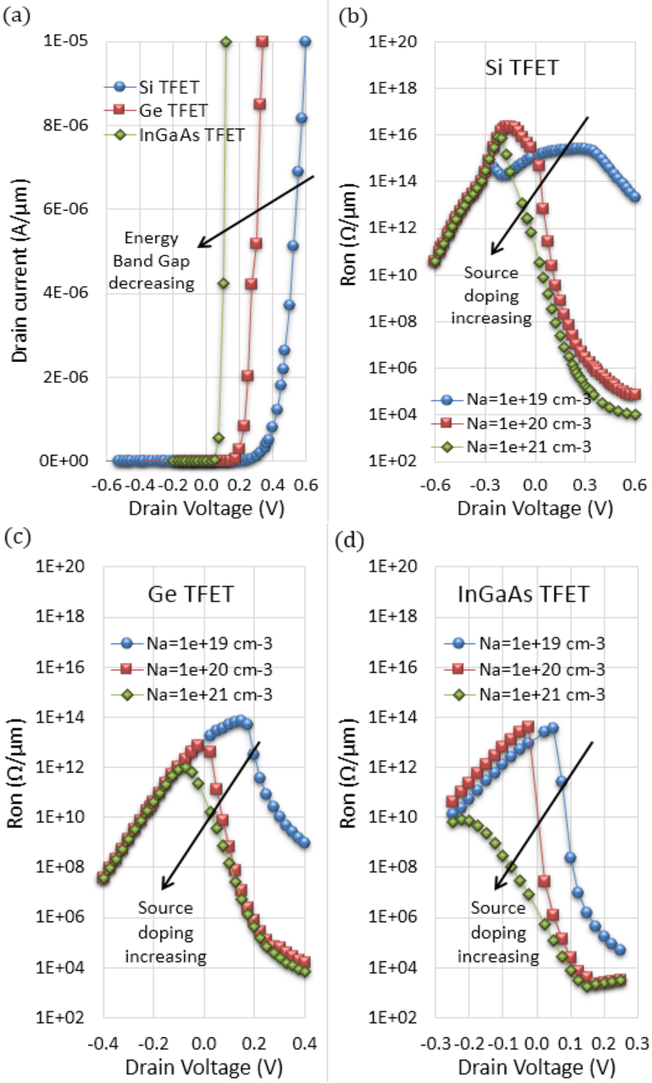


Fig. 4 a) Current-voltage characteristic of n-TFET with different materials; b) Dependence of TFET internal resistance on source doping concentration for: b) Silicon, c) Germanium and d) InGaAs materials.

With the highest energy band gap material in study ($E_g$=1.12 eV) the reverse current of the Si TFET does not change with the variation of the drain doping concentration as shown in Fig. 5 a). For the Ge TFET (Fig. 5 b), the increase in the drain doping concentration increases the internal resistance in the reverse region and this way, less reverse losses can be expected in a RF passive rectifier. In this case, an increase in the doping concentration is increasing the energy levels of the $n^+$ region in Fig. 2 c), decreasing this way the probability of BTBT.

In contrast, as the InGaAs TFET (Fig 5 c) presents a lower energy band gap ($E_g$=0.575 eV) and consequently a lower potential between regions, the increase of the drain doping concentration is not only attenuating the BTBT mechanism, but increasing the drift diffusion current (Fig. 5 d). This way, for low energy band gap materials as InGaAs TFETs, the increase on the n-TFET doping concentration can result in high reverse losses of passive rectifiers compared to the use of Si or Ge TFETs.

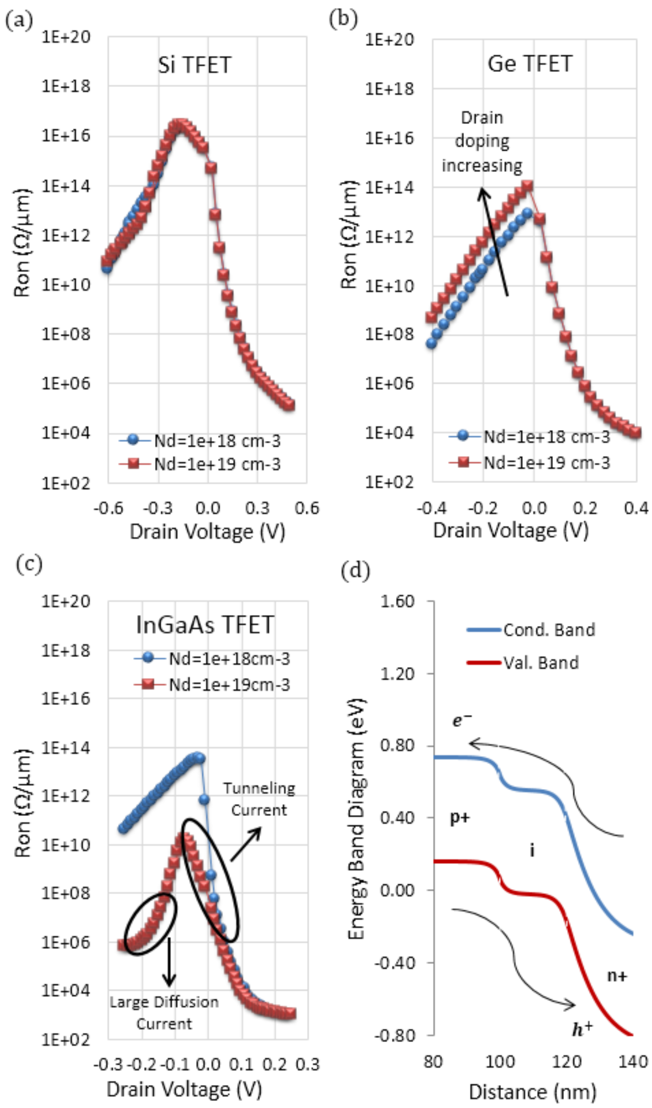


Fig. 5 Internal resistance of the n-Tunnel FET device for different drain doping concentrations. a) Silicon, b) Germanium, c) InGaAs. d) Drift diffusion current of InGaAs TFET at Vds= -0.25 V.

## V. Conclusions

This work discusses the perspectives of using TFET devices in RF passive rectifier circuits, taking into account the design with low energy band gap materials and different doping concentrations on both the drain and source regions.

Compared to Si and Ge materials, the design of TFET devices with III-V materials as InGaAs can reduce the forward losses of passive rectifiers due to the possibility of conducting more current at considerable less voltage. The increase of the source doping concentration is also expected to reduce the forward losses due to the increase of the tunneling probability at the source-channel interface. However, this same increase can also raise the reverse losses of the rectifier at low reverse biasing. At high reverse biasing, high reverse losses of the passive rectifier are produced due to the dominance of the drift diffusion carrier mechanism.

A method to attenuate the reverse losses at a low reverse biasing is increasing the drain doping concentration. This behavior is shown for the Ge TFET. However, for the InGaAs TFET, such increase in the doping concentration results in the dominance of the drift diffusion current (instead of the BTBT current) at similar reverse biasing conditions.

In summary, the inclusion of TFET devices in passive rectifier circuits can be a viable solution in terms of power conversion efficiency at low RF AC magnitudes (where conventional technologies presents difficulties in conducting the same amount of current than TFETs). However, at large RF AC magnitudes, the high reverse current due to the drift diffusion mechanism, inherent of TFET devices is expected to degrade the power efficiency of rectifier circuits.

A solution to solve this problem would be a different rectifier topology that forces the $V_{GS}$ to less negative values in the TFET transistors during their "off" state (instead of $V_{GS} = 2V_{DS}$), in order to mitigate the drift diffusion mechanism at high RF AC magnitudes.

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