Asymmetric Tunnel Field-Effect Transistors as Frequency Multipliers

Himanshu Madan, Student Member, IEEE, Vinay Saripalli, Huichu Liu, and Suman Datta, Senior Member, IEEE

Abstract—This letter proposes a novel application of asymmetric (double-gate) tunnel field-effect transistors (asymmetric TFETs) as a frequency multiplier. Work-function tuning of an asymmetric TFET was used to demonstrate symmetric ambipolar transfer characteristics by TCAD simulation. Unlike the conventional balanced FET-based multiplier, the asymmetric TFET design needs only one transistor for rejecting odd harmonics. Advanced design system simulations are used to compare the performance of an n-type FET and an asymmetric TFET frequency multiplier.

Index Terms—Ambipolar TFET, asymmetric TFET, band-to-band tunneling, frequency multiplier, mixer.

I. INTRODUCTION

The availability of a stable distortion-free RF local source is the inherent upper limit of operating frequency in microwave and millimeter-wave applications. The lack of high-power, high-frequency, and compact frequency sources makes a frequency multiplier in conjunction with reliable low-frequency crystal oscillators a potential candidate for the RF local source. Diodes, RF MOSFETs, and high-electron mobility transistors are the obvious choice for the design of a frequency multiplier circuit. However, the operation of these devices in the nonlinear regime not only gives the desired frequency multiplication but also results in high-order harmonic distortion to the system. These unwanted harmonics and their subsequent mixing are of great concern as the order of cascade stages in multipliers is increased. For a single-ended multiplier topology, a filtering and matching circuit is added to reject the unwanted harmonic components. This limits the multiplier to a narrow-band frequency operation. Traditionally, balanced multiplier designs are used to reject odd harmonics by mixing out-of-phase signals from two or more individual single-ended mixers. Recently, mixer applications of graphene-based FETs have generated a lot of interest due to their inherent ambipolar transfer characteristics [1]. Here, the ambipolar characteristics essentially eliminate the odd harmonic components in the output.

The sub-$K_B T/q$ switching slope makes TFETs an attractive design for low-voltage logic application. Recently, [2] has demonstrated record ON-current characteristics using vertical heterojunction TFETs. Here, we explore the analog application of a TFET. The drain-side doping in a TFET dictates the ambipolar leakage in its transfer characteristics [see Fig. 1(c)]. For logic application, the drain doping is limited to avoid and limit the ambipolar leakage current. By increasing the drain-side doping, one can essentially increase the reverse leakage and obtain near-symmetric transfer characteristics. However, for significant frequency multiplication, the turn-on voltage of the reverse ambipolar conduction branch and the forward current characteristics need to be independently tuned. Here, we propose a dual-work-function (WF) asymmetric TFET to obtain ideal ambipolar transfer characteristics for mixer application.

II. TCAD SIMULATION

In this letter, we have employed a Sentaurus TCAD simulator for the device simulation. Fig. 1(a) shows the schematic of an InAs homojunction dual-gate (DG) TFET. The DG TFET structure shown here is similar to that in [3], where the drain region is lightly doped with $1 \times 10^{17}$ cm$^{-3}$ n-dopants in order to reduce the strong leakage current resulting from drain-side tunneling at negative gate bias. Fig. 1(b) shows the electron and hole density profiles in the DG TFET obtained from TCAD simulations under neutral conditions (gate and drain biases of 0 V). The electrons and holes in this ultrathin-body DG TFET are heavily quantized, and quantum correction is applied in our TCAD simulations using the density-gradient correction model, as shown in Fig. 1(b). Fig. 1(c) shows the calibration of the DG
TFET TCAD model with the atomistic non-equilibrium Greens function (NEGF) simulations from [3]. The TCAD simulation uses a nonlocal band-to-band tunneling model based on Kane’s two-band dispersion (prefactor $A = 2 \times 10^{20}$ cm$^{-3}$ s$^{-1}$ and exponential factor $B = 2.24 \times 10^{6}$ V/cm) and shows good agreement with the atomistic NEGF simulation.

Fig. 2(a) shows the schematic of a dual-WF TFET. As compared with the design in Fig. 1(a), the WF of the two gates of the TFET is different, and the drain is heavily n-doped ($4 \times 10^{19}$ cm$^{-3}$) so that the drain-side tunneling current becomes significant. Fig. 2(b) compares the $I_d$-$V_g$ characteristics of dual- and single-WF TFETs (both with heavily doped drain regions) for an applied drain bias of 0.3 V. The use of dual-WF values causes the turned-on regions of the $I_d$-$V_g$ of the single-WF TFET to shift, as shown in Fig. 2(b), thereby causing the early onset of tunneling for both positive and negative $V_g$ in the dual-WF TFET. The parabolic shape of the $I_d$-$V_g$ resulting from the use of dual WFs can be used for analog mixer application as described later. Fig. 2(c) shows the band diagram of the TFET showing the source- and drain-side tunneling regions. Fig. 2(d) shows the onset of tunneling (band-to-band generation rate of holes) for positive and negative gate biases, respectively.

Fig. 2. (a) Schematic of a dual-WF InAs homojunction TFET. (b) Transfer characteristics showing ambipolar transfer characteristics by using a dual-WF TFET. (c) Band diagram across the channel showing the source- and drain-side tunneling regions. (d) Contour plots showing band-to-band tunneling at the source-channel and drain-channel junctions for positive and negative gate biases, respectively.

III. NONLINEAR DISTORTION

Fig. 3 shows the transfer characteristics for a 32-nm-gate-length ambipolar TFET and an nMOS transistor. For low frequencies, output current $i_D$ can be expressed by power-series expansion in terms of gate bias $v_G$ as

$$i_D = g_{m0} + g_{m1} v_G + g_{m2} v_G^2 + g_{m3} v_G^3 + g_{m4} v_G^4 + \cdots$$

The proportionality coefficient of the power series is

$$g_{mn} = \frac{1}{n!} \frac{d^n I_D}{dV_G^n}.$$
In summary, we have proposed an asymmetric TFET model with ambipolar transfer characteristics. Symmetric ambipolar $I_d-V_g$ transfer characteristics were obtained by tuning the WF of the two gates independently. The study of the nonlinear components shows the elimination of odd intermodulation terms in the output. Mixer simulation by ADS confirms the absence of odd harmonics in the output spectrum.

V. Conclusion

In summary, we have proposed an asymmetric TFET model with ambipolar transfer characteristics. Symmetric ambipolar $I_d-V_g$ transfer characteristics were obtained by tuning the WF of the two gates independently. The study of the nonlinear components shows the elimination of odd intermodulation terms in the output. Mixer simulation by ADS confirms the absence of odd harmonics in the output spectrum.

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