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A subharmonic graphene FET mixer

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Abstract—**We demonstrate a subharmonic resistive graphene FET (G-FET) mixer utilizing the symmetrical channel resistance vs. gate voltage characteristic. A down-conversion loss of 24 dB is obtained with f_{RF}=2 GHz, f_{LO}=1.01 GHz and f_{IF}=20 MHz in a 50 Ω impedance system. Unlike the conventional subharmonic resistive FET mixers, this type of mixer operates with only one transistor and does not need any balun at the LO port which makes it more compact.**

***Index Terms*— Graphene, FETs, subharmonic resistive mixers.**

I. Introduction

Since the first production of graphene [1], considerable work has been performed to make use of its unique electronic properties [2-3]. Due to the inherent high intrinsic carrier mobility and speed, much of the research on graphene electronics has been focused on demonstrating transistors with high cut off frequencies (f_t) [4-5], and little work has been reported on circuit applications utilizing G-FETs. A frequency doubler to 20 kHz was shown in [6]. A fundamental mixer at 10 MHz with a 35 dB conversion loss (CL) was demonstrated in [7] and recently a fundamental mixer at 4 GHz with a 27 dB CL was presented [8]. So far, the demonstrated mixers do not take full advantage of the unique properties of graphene.

For the first time, we utilize the ability to switch between n- and p- channel in graphene and introduce a novel subharmonic resistive mixer based on a single G-FET. A subharmonic mixer only needs half the local oscillator (LO) frequency compared to a fundamental mixer. This property is attractive especially at millimeter and submillimeter wavelengths where there is a lack of compact sources providing sufficient power [9]. Moreover, subharmonic mixers suppress the LO noise [10], and the wide frequency gap between the RF and LO signals simplifies the LO and RF separation [11].

In this paper we demonstrate a subharmonic mixer at 2 GHz (RF). The G-FET subharmonic resistive mixer is implemented using only one transistor. Hence, no balun is required, which makes the mixer circuit more compact as opposed to conventional subharmonic resistive FET mixers, which require two FETs in a parallel configuration including a balun for feeding the two out of phase LO signals [12-14]. Finally, the mixer CL versus the LO power and the gate voltage as well as the 1 dB compression point of the mixer are characterized.

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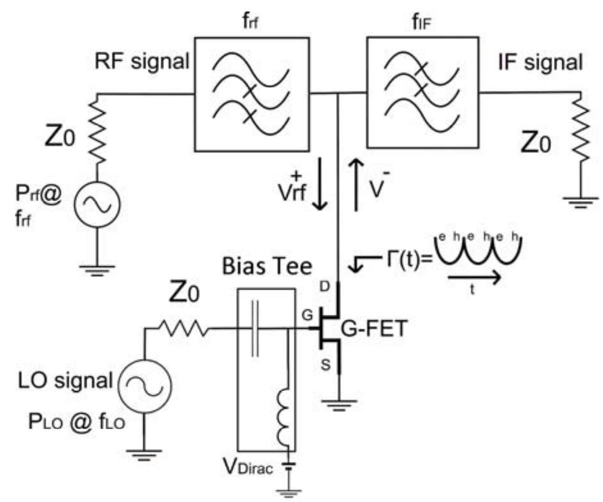

Fig. 1. The circuit structure of the subharmonic resistive G-FET mixer

II. Subharmonic G-FET mixer

The circuit topology of the proposed mixer is shown in Fig. 1. The gate voltage is biased at the Dirac point and is modulated by the LO signal. The RF signal is applied to the drain of the G-FET through a highpass filter and the IF signal is extracted with a lowpass filter. The operation principle of the mixer is demonstrated in Fig. 2. We analyze the mixer according to the method described in [15]. The drain-source resistance (R_{ds}) of a typical G-FET versus its top-gate voltage V_G is shown in Fig. 2a. Modulating the gate voltage results in a time-varying channel resistance ($R_{ds}(t)$). Due to biasing at the Dirac point $R_{ds}(t)$ varies with twice f_{LO} (Fig. 2b). However, if the gate voltage is biased away from the Dirac point, $R_{ds}(t)$ will have the same frequency as the f_{LO} [8]. This is due to the G-FET's symmetrical transfer characteristic related to the ability to switch between n- and p-channel, during the first half period the current is carried by electrons and during the second half period it is carried by holes. The time-varying reflection coefficient $\Gamma(t) = (R_{ds}(t)- Z_o)/(R_{ds}(t)+Z_o)$, seen into the drain of the G-FET is depicted in Fig. 2c, where $Z_o = 50\ \Omega$ is the system impedance. In this work, the effect of the gate channel capacitors is negligible, i.e. $Z_{ds} \approx R_{ds}$. By feeding an RF signal, $V^+_{RF}(t)$ (Fig. 2c) to Γ(t), the reflected signal $V^-(t) = \Gamma(t)V^+_{RF}(t)$ is generated [15]. The reflected voltage has frequency components at $|f_{RF}\pm 2nf_{LO}|$ and the intermediate frequency (IF) component ($f_{IF} = |f_{RF}-2f_{LO}|$, $f_{LO}\approx f_{RF}/2$) is the desired one for the down-conversion mixer, Fig. 2d.

III. Device fabrication

To fabricate the mixer, a graphene sample was produced by micromechanical exfoliation of natural graphite and placed on

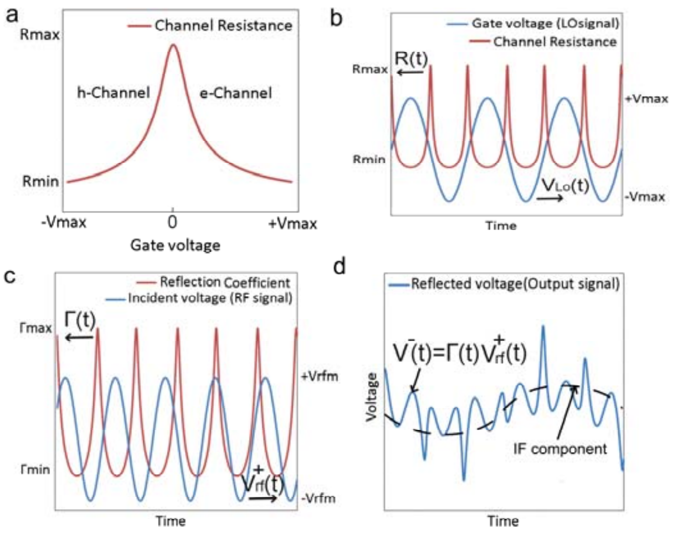

Fig. 2. (a) Drain-source resistance versus topgate voltage of a G-FET. (b) Time-varying gate voltage (LO signal) and the corresponding drain-source resistance. (c) Time-varying reflection coefficient and the incident voltage (RF). (d) Reflected voltage (mixing signal) including IF component.

a 300 nm silicon oxide film, thermally grown on a high resistive (ρ>10kΩ cm) silicon substrate. By measuring the changes in the reflectance of green light, it was confirmed that the exfoliated flake was a single layer of graphene [16]. Choosing a proper FET size (W_g, L_g gate width and length respectively) for a high performance mixer differs from a high f_t G-FET design. The CL of a resistive mixer is proportional to $1/(\Gamma_{max}-\Gamma_{min})^2$ [15] which is equivalent to a high on and off channel resistance ratio for a high performance mixer. The drain-source resistance, R_{ds} for the on and off state can be approximated as $R_{ds\text{-}on}=R_{min} \approx 2\rho_C/W_g$ and $R_{ds\text{-}off} =R_{max}\approx 2\rho_C/W_g + L_g/(W_g q\mu n_0)$, where μ, n_0 and ρ_C are the carrier mobility, the residual carrier density and the contact resistivity respectively [17]. Thus, for a high on-off ratio, a long gate length is preferred. However, for high frequency operations the gate length has to be short. As a result, the operating frequency puts an upper limit on the gate length. Finally, the gate width specifies the impedance level. For a given set of parameters (n_0, μ, L_g and ρ_C), the CL can be minimized by setting the gate width in a way so the large-signal device impedance becomes close to the circuit embedding impedance, i.e. $Z_o = \sqrt{R_{\max} R_{\min}}$ [15]. In this work a gate length of 1 µm and a gate width of 20 µm (2×10 µm) were selected due to the size limitation of our exfoliated graphene flake. The source to drain pad separation is 1.2 µm. The pads were defined by electron beam lithography and consist of Ti(1 nm)/Pd(30 nm)/Au(70 nm) metal layer stack. The top-gate dielectric was formed by natural oxidation of 2 nm thick Al followed by 25 nm Al_2O_3 deposited by e-gun evaporation. A top-gate electrode consisting of Ti(1 nm)/Pd(30 nm)/Au(60 nm) was patterned by electron beam lithography. Fig. 3a demonstrates the optical image of the fabricated mixer and the SEM image of the G-FET. The R_{ds} and the simulated reflection coefficient (with 50 Ω termination at the gate) seen at the drain of the G-FET versus gate voltage are also shown in Fig. 3b. As can be seen the device has an on-off ratio of 3.

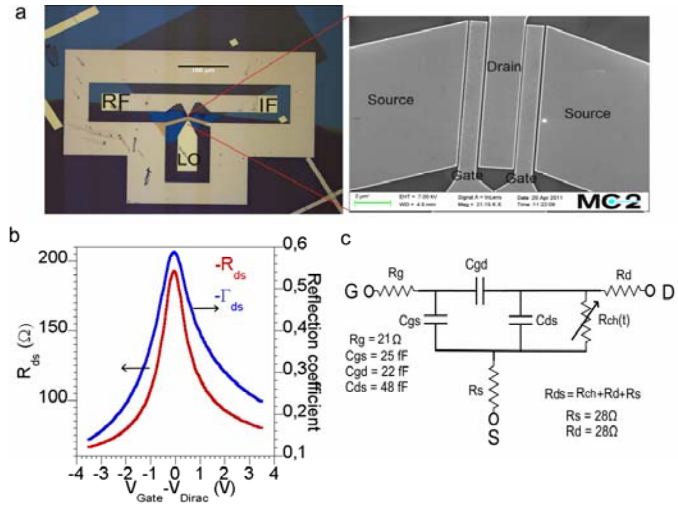

Fig. 3. (a) Optical image of the fabricated mixer (scale bar, 100 µm) and SEM image of the G-FET (scale bar, 2 µm). (b) R_{ds} versus gate voltage and the simulated reflection coefficient seen at the drain of the G-FET. (c) G-FET equivalent circuit ($R_{ds} = R_{ch} + R_d + R_s$).

The carrier mobility for electron and hole are about 2000 cm^2/Vs and 2400 cm^2/Vs respectively which are extracted by the method described in [17] and the device has a contact resistivity of $\rho_C \approx 560$ Ωµm and the residual carrier density of $n_0 \approx 10^{12} cm^2$. The device model is also depicted in Fig. 3c.

IV. Mixer measurement

For the mixer characterization, an external highpass SMA filter (1.3 GHz to 4 GHz) was used in the RF line and an external lowpass SMA filter (DC to 600 MHz) was used in the IF line. Measurement was performed by biasing the gate of the G-FET via a bias tee and applying RF and LO signals through microwave coplanar waveguide (CPW) probes to the mixer. The IF signal was measured with a spectrum analyzer. We selected f_{LO} = 1.01 GHz, f_{RF} = 2 GHz and thus f_{IF} = 20 MHz. Fig. 4a depicts the CL of the mixer versus LO power ($V_{gate} = V_{Dirac}$ = 1V). A CL of 24 dB was obtained at P_{LO}= 15 dBm (about 3.5 V gate voltage swing). We also simulated the mixer with the device model in Fig. 3c. As can be seen there is a discrepancy between the measurement and the simulation and it can be attributed to the losses in filters (0.7+0.2 dB), cables and probes (0.2 dB). The rest discrepancy may be due to the modeling errors and the measurement uncertainty. It should be noted that in this mixer the RF and IF embedding impedances are 50 Ω, while the optimum impedance level is around $\sqrt{R_{\max} R_{\min}} \approx 105\,\Omega$. Since the CL of the mixer is proportional to $1/(\Gamma_{max}-\Gamma_{min})^2$, it can be improved by fabricating a high quality device (lower n_0 [17-18] and ρ_C result in a higher on-off ratio) and by optimizing embedding impedances with load-pull analysis [19]. The required LO power can be reduced by reducing the gate dielectric thickness and selecting high-k materials for gate dielectric as well as having a device with a higher carrier mobility and optimizing the LO source impedance. Fig. 4b shows the CL of the mixer versus gate voltage bias for different LO power levels. As can be seen, a deviation from the Dirac point increases the mixer CL severely and the reason for this is that the channel resistance no longer is symmetric. This effect is more obvious at lower LO power levels where the gate voltage swing is small. Fig. 4c demonstrates the mixer IF output power versus the RF input power with a 1 dB compression point, P_{1dB} at -6 dBm RF power. Moreover the mixer CL versus the input RF frequency with $f_{IF} = 20$ MHz is plotted in Fig. 4d. Finally, in order to analyze the spectrum of the reflected signal, $V^{-}(t)$, a 10-dB directional coupler was used to separate $V^{-}(t)$ from the incident RF signal, $V^{+}_{RF}(t)$. Low levels of odd harmonics are observed as well, which are attributed to a non perfect symmetry of $R_{ds}(V_g)$ (Fig5).

V. Conclusions

A novel subharmonically pumped resistive mixer based on a G-FET has been fabricated and demonstrated at microwave frequencies. The performance of the mixer follows the theory and can be improved by further optimizing embedding impedances as well as designing a G-FET device with a higher on-off ratio. The contact resistances degrade the mixer performance, especially, for short gate lengths. Therefore, reducing the contact and access resistances is important for realizing high performance and high frequency G-FET subharmonic mixers.

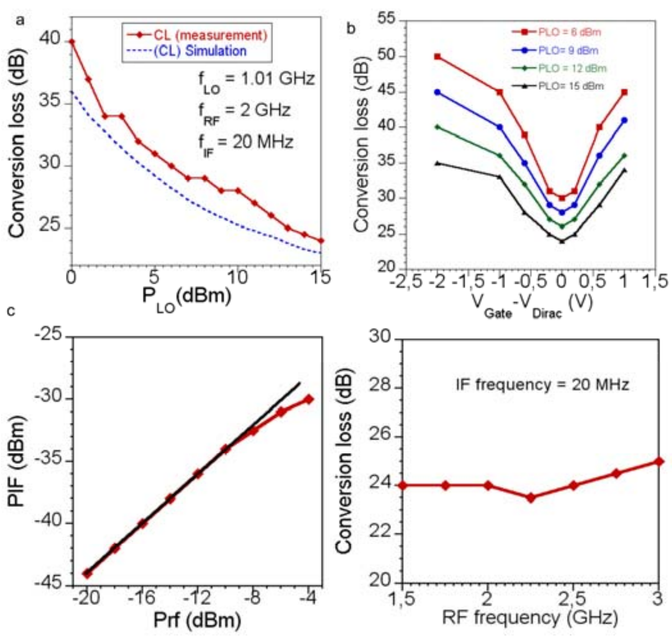

Fig. 4. (a) Mixer CL for different LO power, biased at $V_g = V_{Dirac}$ and simulation (dash line bottom) of the mixer CL, (b) Mixer CL for different gate voltage bias at P_{LO}= 6, 9, 12, 15 dBm (from top to bottom). (c) IF output power for different RF input power biased at $V_g = V_{Dirac}$, P_{LO}= 15 dBm. (d) Mixer CL versus RF frequency (P_{LO} = 15 dBm, P_{RF} = -20 dBm).

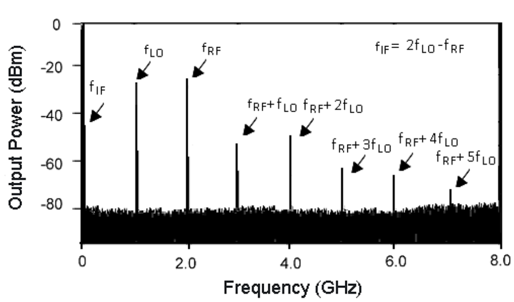

Fig. 5. Spectrum of the reflected signal, $V^{-}(t)$ and the LO leakage (P_{LO} = 15 dBm, P_{RF} = -20 dBm, f_{RF} = 2 GHz, f_{LO} = 1.01 GHz).

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