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Graphene-Based Ambipolar RF Mixers

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Abstract—The combination of the unique properties of graphene with new device concepts and nanotechnology can overcome some of the main limitations of traditional electronics in terms of maximum frequency, linearity, and power dissipation. In this letter, we demonstrate the use of the ambipolar-transport properties of graphene for the fabrication of a new kind of RF mixer device. Due to the symmetrical ambipolar conduction in graphene, graphene-based mixers can effectively suppress odd-order intermodulations and lead to lower spurious emissions in the circuit. The mixer operation was demonstrated at a frequency of 10 MHz using graphene grown by chemical vapor deposition on a Ni film and then transferred to an insulating substrate. The maximum operating frequency was limited by the device geometry and the measurement setup, and a high-quality factor was observed with a third-order intercept point of +13.8 dBm.

Index Terms—Ambipolar conduction, chemical vapor deposition (CVD) graphene, graphene field-effect transistors (GFET), mixers.

I. INTRODUCTION

GRAPHENE is a 2-D material that has attracted great interests for electronic devices since its discovery in 2004 [1]. The high intrinsic carrier mobility of graphene ($> 100\,000\text{ cm}^2/(\text{V}\cdot\text{s})$ in suspended graphene, and $> 10\,000\text{ cm}^2/(\text{V}\cdot\text{s})$ in graphene on a substrate at room temperature) [1], [2], combined with its high electron velocity and thermal conductivity, makes this carbon-based material an excellent candidate for high-frequency electronic applications. Meric *et al.* [3] demonstrated that graphene devices can exhibit current gain in the microwave frequency. Recently, IBM showed operation of transistors fabricated on epitaxial graphene with current-gain cut-off frequency f_T of 100 GHz [4].

Moreover, ambipolar transport in graphene offers great flexibility for novel device and circuit applications. Due to its ambipolar transport, the electrical conduction in a graphene field-effect transistor (GFET) can be dominated by either positive holes or negative electrons depending on the bias applied to the gate electrode, resulting in a “V”-shape drain current–gate voltage (I_D – V_{GS}) characteristic [1]. The unique ambipolar-transport properties of graphene, combined with its extremely high mobility allow for the development of a new form of nonlinear electronics for radio frequency (RF) and mixed-signal applications. As an example of these new nonlinear devices, [5] demonstrates that frequency doubling can be realized with a

single graphene transistor by biasing the gate to the minimum conduction point and superimposing a sinusoidal input signal to the gate. Electrons and holes conduct in alternating half-cycles to produce an output signal at the drain, whose fundamental frequency is twice that of the input.

In this letter, we demonstrate the use of the ambipolar property of graphene for the fabrication of a new kind of single-transistor RF mixer device, which can effectively suppress odd-order intermodulations. This device was fabricated on graphene grown by chemical vapor deposition (CVD) [6], which assures its scalability and low cost.

II. AMBIPOLAR-MIXER CONCEPT

The I_D – V_{GS} characteristics of an ambipolar GFET, which are symmetrical about a minimum conduction point, are shown in Fig. 2(a). The symmetrical GFET characteristics usually show a very significant quadratic component and hence, can be used as excellent RF mixers. Assuming that the transfer characteristics of the GFET are completely symmetric and infinitely differentiable, we can then describe the drain current as

$$I_D = a_0 + a_2(V_{GS} - V_{G,\min})^2 + a_4(V_{GS} - V_{G,\min})^4 + \dots \quad (1)$$

where $V_{G,\min}$ is the gate voltage at the minimum conduction point. a_0, a_2, a_4, \dots are constants. From this expression, for ideal GFETs with symmetric transfer characteristics and biased at the minimum conduction point, no odd-order intermodulation distortions should appear at the output, and all the output power is coupled to the difference and sum frequency and other even-order terms. Therefore, odd-order intermodulations, which are often present in conventional unipolar mixers [7], [8] and are harmful to circuit operations [8], can be significantly suppressed in GFET mixers while keeping a simple circuit. Matlab simulations show that, for given input signal power, the GFET mixer with transfer curve shown in Fig. 2(a) can generate 7 dB higher useful power while having a third-order intermodulation that is 8 dB lower than a single-transistor unipolar mixer with comparable ON/OFF current ratio and transconductance. This advantage can be increasingly more significant if the I – V of the GFET becomes more symmetrical. Conventional mixers with unipolar devices rely on more complicated circuits to achieve good intermodulation performance [9].

III. GROWTH OF GRAPHENE AND DEVICE FABRICATION

The graphene samples used in this work were grown by CVD on thin-film Ni and then transferred to an Si/SiO₂ substrate [6]. Fig. 1(a) shows a top-view optical micrograph of one of the graphene sheets used in this work. Arrows indicate regions of few-layer graphene, which can be up to 20 μm in lateral size as characterized by Raman spectroscopy [6]. Hall

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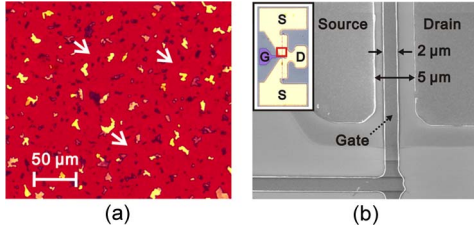


Fig. 1 (a) Micrograph of CVD-grown graphene. The arrows indicate regions of few-layer graphene. Regions with a mix of single-layer and bilayer graphene can be up to $20 \mu\text{m}$ in lateral size. (b) SEM image of a fabricated GFET with $L_G = 2 \mu\text{m}$ and $L_{DS} = 5 \mu\text{m}$. The inset shows a micrograph of the device where the square indicates area of the SEM image.

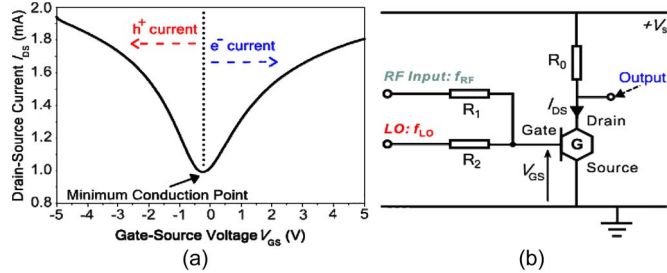


Fig. 2 (a) I_D - V_{GS} characteristics of the fabricated GFETs with $L_G = 2 \mu\text{m}$, $W_G = 2 \times 75 \mu\text{m}$, and $L_{DS} = 5 \mu\text{m}$. The minimum conduction point is very close to 0 V. (b) Proposed circuit for graphene ambipolar RF mixers. Note: no dc bias is needed at the input due to minimum conduction point being close to 0 V.

measurements show mobility greater than $1200 \text{ cm}^2/(\text{V} \cdot \text{s})$ at room temperature.

The fabrication of the GFETs starts with the source and drain contacts Cr (5 nm)/Au (90 nm). To promote the adhesion of the gate dielectric on graphene, a 5-nm layer of SiO_2 is first deposited by electron-beam evaporation as a seed layer for the subsequent deposition of 25-nm high- k Al_2O_3 using atomic layer deposition. Mesa isolation is then done using reactive ion etching CF_4 , which etches away both the dielectrics and the graphene itself. Finally, the gate Ni (30 nm)/Au (200 nm)/Ni (50 nm) is formed. The fabricated GFETs have gate length $L_G = 2 \mu\text{m}$, gate width $W_G = 2 \times 75 \mu\text{m}$ and drain-to-source distance $L_{DS} = 5 \mu\text{m}$. Fig. 1(b) shows a scanning electron microscope (SEM) image showing a fabricated GFET. Fig. 2(a) shows the I_D - V_{GS} transfer characteristics measured with an Agilent 4155 Parameter Analyzer. More than 50 devices on ten different samples have been fabricated. The contact resistances of all the devices are between 2 and $5 \text{ k}\Omega \cdot \mu\text{m}$.

IV. GRAPHENE AMBIPOLAR MIXERS

Fig. 2(b) shows the proposed circuit for GFET mixers. Since the fabricated GFETs have a minimum conduction point close to zero, no dc bias is needed at the gate. This greatly simplifies the circuit and improves energy efficiency. Fig. 3 shows the experimental demonstration of ambipolar GFET mixers. If a single RF input signal $f_{RF} = 10.5 \text{ MHz}$ is applied to the gate, the device works as a frequency doubler. The output spectrum [Fig. 3(a)] shows a dominant peak at $2f_{RF} = 21 \text{ MHz}$.

If two signals, an RF input signal and a local oscillator (LO) signal with frequencies $f_{RF} = 10.5 \text{ MHz}$ and $f_{LO} = 10 \text{ MHz}$ are introduced to the gate, the GFET mixes them to generate output signals with a frequency equal to the sum ($f_{RF} + f_{LO} = 20.5 \text{ MHz}$) and difference ($f_{RF} - f_{LO} = 500 \text{ kHz}$), as shown in the output power spectrum in Fig. 3(b). It is also

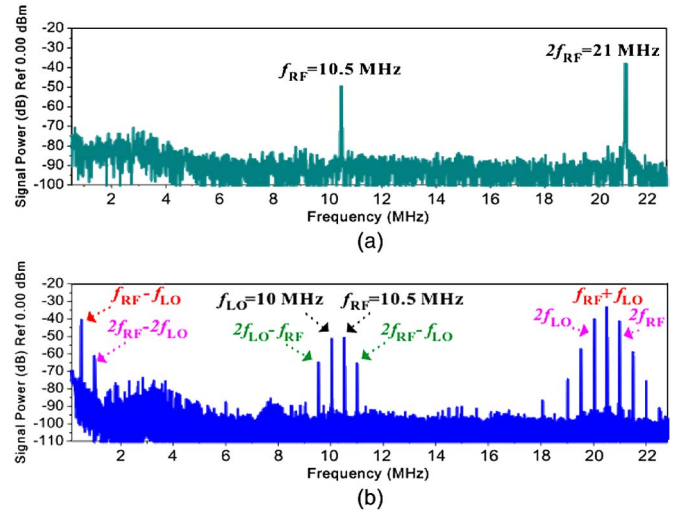


Fig. 3 Spectrum analysis. (a) Output spectrum with single RF input $f_{RF} = 10.5 \text{ MHz}$ without LO signal. The frequency doubling is clearly visible. The signal power at $2f_{RF} = 21 \text{ MHz}$ is about 10 dB higher than the signal power at $f_{RF} = 10.5 \text{ MHz}$ without filtering. (b) Output spectrum with RF input $f_{RF} = 10.5 \text{ MHz}$ and LO $f_{LO} = 10 \text{ MHz}$ at equal power. The presence of strong signal power at $f_{RF} - f_{LO} = 500 \text{ kHz}$ and $f_{RF} + f_{LO} = 21.5 \text{ MHz}$ clearly demonstrates mixing operations. All data are obtained using Agilent N9010A spectrum analyzer, and the measurements were done at room temperature in air.

interesting to note that the power at second-order frequencies, $f_{RF} - f_{LO}$ and $f_{LO} + f_{RF}$, is more than 10 dB higher than the power at fundamental frequencies f_{RF} and f_{LO} ; the power at the fourth-order frequencies, $3f_{RF} - f_{LO}$ and $3f_{LO} - f_{RF}$, is 8 dB higher than the power at the third order frequencies, $2f_{LO} - f_{RF}$ and $2f_{RF} - f_{LO}$ [Fig. 3(b)]. Similar trend is also observed for higher order even and odd frequencies. This is in strong contrast to the mixing operation in unipolar devices [10], where odd-order frequencies are often much higher in power than the corresponding even-order frequencies. Hence, in GFET mixers, a larger proportion of the output power is at the sum and difference of the RF input frequencies, as well as other useful even-order harmonics. The power at odd-order frequencies, particularly third-order frequencies like $2f_{LO} - f_{RF}$ and $2f_{RF} - f_{LO}$ that are usually too close to the fundamental signals to be filtered out and are harmful to circuit operations, is significantly suppressed due to the symmetrical character of the GFET transfer characteristics. In addition, these devices have the potential to operate at very high frequencies due to the high electron mobility in graphene.

Fig. 4(a) shows the dependence of the signal power at intermediate frequency (IF) $f_{IF} = f_{RF} - f_{LO} = 500 \text{ kHz}$ on the RF input power with $f_{RF} = 10.5 \text{ MHz}$ and $f_{LO} = 10 \text{ MHz}$. The fabricated GFET mixer shows good linearity. The conversion loss of the mixer is between -30 and -40 dB . The conversion gain can be increased by improving the device transconductance. As a first-order estimate, a 0-dB gain can be achieved if the transconductance g_m can improve from 5.5 mS/mm of the device shown in Fig. 2 to 181 mS/mm, which can be achieved through using thinner gate dielectrics and material with higher mobility [11].

Fig. 4(b) shows the characterization of the third-order intermodulation product using two-tone measurements ($f_{RF,1} = 10.5 \text{ MHz}$ and $f_{RF,2} = 10.6 \text{ MHz}$). The LO frequency f_{LO} is 10 MHz, while the IFs are at 500 and 600 kHz. The third-order intermodulation frequencies are at 400 and 700 kHz. The output

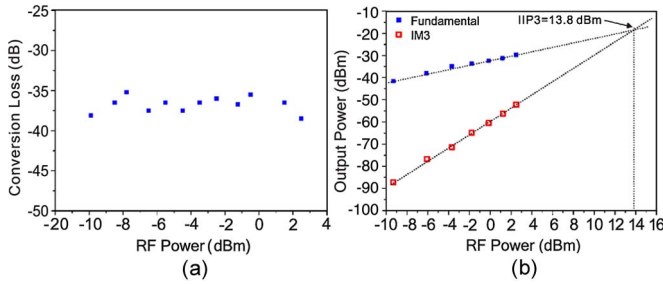


Fig. 4 (a) Signal power at IF versus the RF input power at room temperature, with $f_{RF} = 10.5$ MHz and $f_{LO} = 10$ MHz. GFET mixer shows good linearity. (b) Two-tone test in vacuum: $f_{RF,1} = 10.5$ MHz, $f_{RF,2} = 10.6$ MHz, and $f_{LO} = 10$ MHz. The IFs are $f_{IF,1} = 500$ kHz and $f_{IF,2} = 600$ kHz. The third-order intermodulations are $f_{IM3,1} = 400$ kHz and $f_{IM3,2} = 700$ kHz. LO input power is 0 dBm. DC supply voltage applied is 1 V, and R_0 is 1 k Ω .

power at IFs and third-order intermodulation frequencies follow the theoretical 10- and 30-dB/dec dependences, respectively. A third-order intermodulation intercept (IIP3) of 13.8 dBm is achieved in these devices with an LO input power (P_{LO}) of 0 dBm, resulting in a quality factor of $Q_{IIP3} = IIP3/P_{LO} = 13.8$ dB. Conventional diode or single-transistor mixers often have quality factor between 5 and 30 dB at GHz [12], [13].

V. DISCUSSION

A. Frequency Performance

The frequency performance of graphene mixers is primarily limited by the speed of the device themselves, which is limited to tens of megahertz in this experiment due to the device dimensions. f_T can be calculated by using the expression $f_T = g_m/2\pi C_G$. In our device, $g_m = 5.5$ mS/mm, as obtained from the slope of the $I_{DS}-V_{GS}$ curve. Capacitance-voltage ($C-V$) measurements show a gate capacitance of 4.5 pF/mm in this device. This leads to a calculated f_T of about 190 MHz for these devices. At these frequencies, the mobility of the material [~ 1000 cm²/(V \cdot s)] should not be the limiting factor for speed. If we estimate the RC time constant of the device, we obtain a 3-dB cutoff frequency $f_c = (2\pi RC)^{-1} = 99$ MHz, where we used $R = 2.38$ k Ω for the ON-state resistance and $Cg = 4.5$ pF/mm \cdot 150 μ m = 675 fF. The ON-state resistance is derived from dc measurements, and the gate capacitance is obtained from $C-V$ measurements.

The key limitation to f_T is the device gate length and gate capacitance. Higher frequency performance can be achieved by shrinking the gate length and gate-oxide thickness. As a first-order estimation using the $1/L_G^2$ dependence [14], these devices from CVD graphene will have f_T in the gigahertz range with gate length of less than 1 μ m and have f_T exceeding 100 GHz with gate length of 60 nm. Much higher frequencies would be possible for devices with mobilities above 1000 cm²/(V \cdot s). The contact resistance and the degradation of mobility due to top gate dielectric also affect frequency performance.

B. Symmetry in Transfer Characteristics

The asymmetry in the transfer characteristics shown in Fig. 2(a) may be attributed to chemical doping by adsorbants during processing and handling of the sample [15]. This asymmetry affects mixing by introducing more significant odd-order intermodulations. However, the asymmetry is not significant for gate voltage within ± 1 V of the minimum conduction point. Hence, for small-signal mixer applications where the

input signal is usually less than a couple of volt peak-to-peak, the asymmetry is not of major concern to mixer performance.

Furthermore, the concept described in this letter can also be realized in other materials that exhibit ambipolar conduction properties, such as some carbon nanotube transistors (CNTs) [16]. However, the ambipolar $I_{DS}-V_{GS}$ characteristics of GFETs are often more linear than CNT FET's, leading to a less distortion and higher efficiency.

In conclusion, this letter has demonstrated the use of the ambipolar-transport properties of graphene in the fabrication of nonlinear electronics for RF signal mixers. Given the extremely high carrier mobility in graphene, these nonlinear circuits have great potential for applications as transparent and flexible electronics, high-speed transmitters and receivers in sensor network, satellite communications, and radar systems. GFET mixers show effective suppression of third-order intermodulations. In addition, large-area CVD graphene and potentially CMOS-compatible fabrication technology can allow integration of these devices with Si-based circuits in the future.

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