A 200 GHz CVD Graphene FET Based Resistive Subharmonic Mixer

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Abstract—We report on the design and characterization of a 200 GHz resistive subharmonic mixer based on a single, multi-channel CVD graphene field effect transistor (G-FET). The device has gate length 0.5 μm and width 2x40 μm. The integrated circuit is implemented in coplanar waveguide (CPW) technology and realized on a 100 μm thick high resistive silicon substrate. The measured mixer conversion loss (CL) is 34 ± 3 dB across 190-210 GHz band with 10 dBm local oscillator (LO) pumping power and the overall minimum CL gives 31.5 dB at 190 GHz.

Index Terms—Graphene, FETs, subharmonic resistive mixers, millimeter wave integrated circuits, coplanar waveguide.

I. INTRODUCTION

Graphene, a two-dimensional monolayer of carbon atoms [1], currently draws great attention in nanotechnology research aiming at improved high frequency electronics. The high intrinsic carrier mobility as well as high carrier saturation velocity make it a promising candidate for high speed analog devices such as transistors operating in the millimeter wave and terahertz frequency bands [2]. Potential applications of such graphene based components and circuits are wireless high speed communication links [3], and security imaging [4].

However, with the exception of graphene millimeter wave [5], [6] and terahertz power detectors [7], [8], no graphene integrated circuits operating above 30 GHz [9], [10] have been demonstrated. To date, considerable efforts have been made to develop graphene field effect transistor (G-FET) based microwave devices [11], [12] and circuits with extensive focus on frequency translating devices. While fundamental single-ended [13] and double balanced [14] resistive mixers achieve conversion loss (CL) of 14 dB at 2 GHz and 33 dB at 3.6 GHz, the inherent symmetry of G-FET channel conductance was not utilized. For this purpose, subharmonic resistive G-FET mixers have been reported with 22 dB and 19 dB CL at 2-5 GHz and 24-31 GHz [10], [15], respectively. As can be seen, the operating frequency of the devices and circuits listed above are far below the anticipated values. Therefore, increasing the G-FET based integrated circuit operation frequency and performance are keys in order to satisfy the expectation of graphene.

In this paper, we demonstrate a subharmonic resistive mixer circuit operating at 190-210 GHz based on a single, multi-channel CVD graphene FET. The channel dimensions of the G-FET are designed to be 0.5 μm × 80 μm. The mixer circuit was designed in coplanar waveguide (CPW) technology due to its better performance at high frequency compared to microstrip [16] and was realized on a 100 μm thinned high resistive silicon substrate. The implementation uses a single G-FET and no balun is required, which makes the circuit topology more compact. Harmonic balance [17] and full wave EM simulation are applied for design and optimization of device and circuit, respectively. The measured CL is 34 ± 3 dB at 190-210 GHz with a minimum of 31.5 dB at 190 GHz. Albeit the performance of our proof-of-concept G-FET mixer on Si is inferior to CMOS [18], by transferring the process graphene has clear advantages for flexible electronics [19].

II. MIXER DESIGN AND FABRICATION

A. G-FET Design and Fabrication

In a resistive mixer, the drain-source channel is swept by a local oscillator (LO) on the gate as a time-varying resistor, \( R_{ds}(t) \), which contains different harmonic frequency components. The unique p-n channel duality of graphene, which gives a highly symmetrical transfer characteristic, is essential for mixing at the second harmonic of the LO. According to [20], at low RF frequency the conversion loss is determined by

\[
\text{CL} \propto \frac{1}{\Gamma_{\text{max}} - \Gamma_{\text{min}}}.
\]

In order to get lower CL, higher \( \Gamma_{\text{max}} \) as well as lower \( \Gamma_{\text{min}} \) are required, which translates to \( R_{\text{max}} \gg Z_0 \) and \( R_{\text{min}} \ll Z_0 \). This requires G-FET components with high current on-off ratio and preferably with impedance level \( Z_0 = \sqrt{R_{\text{max}}R_{\text{min}}} \approx 50 \Omega \).

Special care must be taken in designing G-FETs for resistive mixers, due to the lack of bandgap in graphene. The drain-source resistance is \( R_{\text{ds}} = R_{\text{channel}} + R_c \). Here, \( R_{\text{channel}} \) is the gate variable G-FET channel resistance which is essentially proportional to \( L_{\text{channel}}/W_{\text{channel}} \), and \( R_c \) is the contact resistance at the graphene-metal interface which scales with the gate width, \( W_{\text{gate}} \) [21]. For the purpose of getting a lower \( R_{\text{min}} \), a wide device is necessary. This simultaneously reduces \( R_{\text{max}} \) as G-FETs have no off-state. However, the gate capacitance limiting the high frequency mixer performance is determined by channel area, i.e. \( L_{\text{channel}} \times W_{\text{channel}} \). In a normal G-FET channel structure, \( L_{\text{channel}} = L_{\text{gate}} \) and
$W_{\text{channel}} = W_{\text{gate}}$, which limits the degrees of freedom in device design. A partial remedy was demonstrated in [22] and utilized in the mixer in [10]. Arrays of nanoconstrictions, i.e., bow-tie structured G-FET channels with $W_{\text{gate}} > W_{\text{channel}}$, are used to achieve higher current on-off ratio and proper impedance level. To optimize the device dimensions in the trade-off between impedance level and gate capacitance for CL at 200 GHz, the large-signal G-FET model proposed in [23] was set up in a standard circuit simulator (Agilent, ADS).

To fabricate the G-FET, a graphene sample was produced by chemical vapor deposition (CVD) process on copper film and transferred on a high resistive silicon substrate (10 kOhm bulk resistivity) covered by 90 nm SiO$_2$. For the fabrication procedure, e-beam lithography, metalization by e-gun evaporation, lift-off steps and an initial oxygen plasma etching step (at 50-mTorr pressure) are applied to define mesas and for the sake of patterning the channel structure. Fig. 1 demonstrates the final dimensions of the G-FET channel optimized for lowest CL at $f_{\text{RF}} = 200$ GHz and shows the image of G-FET device. The component has a gate length of 0.5 µm, where the gate-drain and the gate-source gaps are 0.1 µm. Gate width is set to be 80 µm (2 × 40 µm) and optimal channel width is given by 12 µm, i.e., ~120 constrictions each of width ~100 nm. Fig. 2 shows the resulting transfer characteristics, $R_{ds}$ versus $V_{gs}$, from simulation and measurement respectively. As can be seen, a current on-off ratio ~ 5 is achieved with $L_{\text{gate}} = 0.5$ µm.

### B. Circuit Design and Fabrication

The subharmonic resistive G-FET mixer circuit was designed with a center frequency of $f_{\text{RF}} = 200$ GHz to downconvert to an $f_{\text{IF}} = 1$ GHz. The corresponding LO frequency is centered around 150.5 GHz. The circuit was realized in coplanar waveguide technology. If properly designed, relatively lower risk of parasitic mode propagation as well as lower dispersion for a given substrate thickness [16] make CPW competitive to microstrip in millimeter wave circuit applications. Nevertheless, due to substrate mode propagation and radiation loss at high frequency range, circuit substrate need to be sufficiently thin. To ensure suppression of such effects and for layout dimensional optimization, full wave EM simulations (CST microwave studio, FDTD) are applied. The circuit topology of the proposed mixer is shown in Fig. 3a).

The IF signal readout is through a bandstop filter which consist of a quarter wavelength open stub and a quarter wavelength transmission line at RF frequency. Coupled line bandpass filters are utilized both at the LO port branch and the RF port branch in order to block the DC gate bias and the IF signal, respectively. The G-FET requires a bias of $V_{gs} = V_{\text{dirac}}$ for optimum subharmonic mixing performance. Instead of applying high order coupled line filters, since $f_{\text{LO}} \approx f_{\text{RF}}/2$, single order filters are preferred due to the requirement of circuit simplification and area limitation. However, because of the narrowband characteristics of the stub filter and the broadband property of the simple coupled line filter, neither IF- nor RF-filters are capable of completely attenuating the LO signal. Therefore an additional bandstop filter at the LO frequency can be added on the drain side to improve both the LO-RF and LO-IF rejection capability.

The circuit layer was overlaid to the G-FET by e-beam lithography and e-gun evaporation of Ti (20 nm)/Au (500 nm). Finally, the silicon substrate was thinned down from 280 µm to 100 µm by a lapping process. Fig. 3b) displays the mixer on-chip layout, with chip measure 0.7 × 1.4 mm$^2$.

### III. MIXER CHARACTERIZATION

#### A. Measurement Setup

The fabricated circuit was characterized on-wafer using waveguide interfaced GSG microprobes, as sketched in Fig. 4. The LO chain consists of an OML ×6 multiplied source followed by a W-band power amplifier. The RF power level is swept electronically and provided by a standard VDI-AMC-S120 ×18 multiplier module. The LO and RF powers are calibrated using an Agilent E4419B power meter together with a W8486A power sensor and an Erickson PM4 power meter, respectively. The IF signal power is monitored on a FSU26 spectrum analyzer.
This work presents a 200 GHz integrated subharmonic resistive mixer based on a G-FET, demonstrating a significant improvement in operating frequency compared to previous graphene implementations. The mixer was realized on a high resistive silicon substrate using CPW technology. The subharmonic mixer was biased at Dirac point $V_{\text{gs}} = V_{\text{dirac}}$ and $P_{\text{LO}} = 10 \text{ dBm}$, and $f_{\text{RF}} = 1 \text{ GHz}$. The conversion loss was measured to be 31.5 dB at 190 GHz and 10 dBm LO power. The mixer performance comparison among this work and previous graphene-based implementations is presented in Table I. As can be seen, our results represent a 7-fold improvement in operating frequency compared to previously reported G-FET integrated circuits and a significant (>30 dB) performance improvement to existing graphene based mixer in this frequency range [24]. This demonstrates the potential applicability of graphene in ubiquitous millimeter wave and even terahertz wave receivers.

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### REFERENCES


