Millimeter-Wave Graphene-based Varactor for Flexible Electronics

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Abstract—This paper presents the design, fabrication, and characterization of the first millimeter-wave Graphene-based varactor on flexible substrates. The varactor achieves quality factor of 20 at 20 GHz with variation of 5 — 10% for a bending radius down to 5 mm with pronounced varactor behavior measured up to at least 50 GHz. To prove the substrate independence of the proposed varactor, we fabricated it on high resistivity silicon (HRS) achieving quality factors of 6 at 20 GHz, and on Quartz substrate achieving quality factors of 15 at 20 GHz. Measurement results promote the proposed varactor for millimeter-Wave circuits and systems applications, especially on flexible substrates.

I. INTRODUCTION

Since the announcement of Graphene in 2004 [1] as a 2D material that has standing electrical and mechanical properties, its very high charge carrier mobility draws great attention for RF and millimeter-wave circuit applications. Nevertheless, the mechanical properties of Graphene especially its inherent strength in addition to its elastic properties which gives it the ability to retain its initial size after strain. Therefore, Graphene is considered a perfect candidate for millimeter-wave applications in flexible and wearable electronics.

However, due to process immaturity, the reported state-of-the-art Graphene transistors suffer from two main problems: The first is low cutoff frequency (\(f_T\)), and low maximum oscillation frequency (\(f_{\text{max}}\)) due to fabrication issues regarding the Graphene-gate metal contact resistance [2]. The second is the poor saturation of single-layer Graphene-based FETs which leads to poor dc gain. Using bilayer Graphene instead of single-layer improves saturation, but on the other hand it reduces the mobility. As a result, published circuits and systems based on Graphene operate only at relatively low frequencies and are not providing gain [3]-[5].

Quantum capacitance, which is another interesting property of Graphene, has drawn a lot of attention recently [6]. It originates from the low density of states in Graphene and represents a widely tunable capacitance [7], which can be observed up to very high frequencies. This, in combination with the high carrier mobility in Graphene, enables the design of millimeter-wave varactors. This work presents the first high frequency Graphene varactor on flexible substrate. The varactor combines the concept of quantum capacitance of Graphene together with our physical design considerations to produce wide tuning range with high quality factors up to 70 GHz.

II. THEORY OF OPERATION

The presented device is designed, optimized, and fabricated on a full-fledged in-house MMIC backend technology which can be processed on a variety of substrates, including flexible foil. The proposed device cross section, which was optimized...
to provide the highest possible quality factor and tuning range is shown in Fig. 1.

A. Quantum Capacitance

Quantum capacitance property of Graphene is exploited in this work to realize devices for micro- and millimeter-wave applications. The quantum capacitance in Graphene is a direct way to understand the density of states in Graphene as well as to explore the mechanism of Graphene-based transistors [8]. The quantum capacitance of Graphene can be extracted from the measured capacitance of a constructed Graphene-oxide-metal stack, providing the oxide linear geometrical capacitance is comparable to the quantum nonlinear capacitance. For this purpose, a thin layer of high-dielectric oxide is needed, otherwise the tuning of quantum capacitance with respect to the applied voltage, cannot be clearly obtained. Nevertheless, the observed tuning of the stack capacitance, which is due to the tunable quantum capacitance, is proposed to be used for varactors applications [9]. In combination with the high mobility and zero band gap of Graphene, varactors with high quality factor (Q) at high frequency can be expected. Recently, varactors fabricated on graphene with top oxide geometry have shown working capability up to 10 GHz, reporting a quality factor of 12 at 1 GHz [7].

B. Physical design considerations

The equivalent circuit of the stack mentioned previously results in a tunable non-linear quantum capacitance \( C_Q \) in series with the parallel plate geometrical capacitance \( C_G \) as shown in Fig. 2. The key to increase the tuning range is to physically design the linear parallel plate capacitance to be larger than \( C_Q \) such that the nonlinear quantum capacitance dominates in this series combination. This is achieved by using a 5 nm-thick layer of TiO\(_2\) as high-dielectric and an optimized physical design. Moreover, by embedding one electrode into the substrate, fringing capacitance \( C_F \) between the two terminals is reduced, which results in an improved tuning range of the varactor. In this way the quality factor and tuning range of the device could be maximized.

Also, increasing the thickness of electrodes would decrease losses and therefore lead to higher quality factors, but it would also reduce the capacitance tuning range. Decreasing the spacing between the electrodes also boosts the quality factor but at the expenses of increased leakage current. Hence, the presented physical design of the varactor is optimized to achieve the required compromise between quality factor, tuning range, and leakage current.

III. Device Fabrication

The device fabrication process is shown in Fig. 3. Trenches for the embedded electrode are patterned with photolithography and followed by reactive ion etching (RIE) of the substrate. After a depth of 190 nm is reached, the trenches are filled by e-beam evaporation with a metal stack of 180 nm Al and 25 nm of Ti. A 5 nm-thick layer of TiO\(_2\) is deposited as barrier material by atomic layer deposition (ALD) using an oxygen plasma enhanced process with titanium tetrachloride as precursor. Vias on the embedded electrodes are patterned by photolithography and a reverse sputtering step is employed to remove the TiO\(_2\). Then, vias are filled with 20 nm of Ni. The commercially available CVD Graphene grown on copper foil (Graphenea) is transferred onto the sample using PMMA as a supporting layer. After patterning the Graphene with oxygen plasma etching, metal contacts of 20 nm Ni and 100 nm Al are fabricated by sputtering deposition and lift-off. To prove the substrate independence of the proposed varactor operation devices have been fabricated on three different substrates: High resistivity silicon (HRS), Quartz, and kapton flexible foil.
IV. DEVICE CHARACTERIZATION

The fabricated devices were characterized using a precision impedance analyzer (HP 4294A) from 40 Hz to 110 MHz in air to measure the voltage dependency of the capacitance. Fig. 4(b) shows the CV measurements for devices fabricated on high resistivity silicon which is shown in Fig. 4(a). The pronounced voltage dependency of the capacitance on the applied bias proves the concept of quantum capacitance and that it dominates over the other linear capacitances. 

$C - V$ curves show a hysteresis because of charges accumulating just below the $SiO_2$ in the case that high resistivity silicon is used as substrate. The current flowing through the Graphene can be tuned with a ratio of 4.2 by applying a tuning voltage on the embedded electrode. A similar hysteresis is also observed for the current-voltage dependency. Dirac points, located at 0.48V and 0.62V for a forward- and backward-voltage scan direction, respectively, coincide with the ones measured for minimum capacitance.

The devices are also characterized to determine the self-resonance frequency, as well as capacitance and quality factor variation as function of frequency with different bias voltages. Using Keysight N5245A PNA-X microwave network analyzer to measure the varactors on the three substrates up to 70 GHz, and to characterize the effect of bending for the case of the flexible substrate. In the measurement setup the internal bias-T at port 1 is used to apply different voltages while port 2 is set to dc 0 volts. Measured capacitance with different biases in Fig. 5(b) shows clearly the pronounced varactor operation up to 70 GHz. Also it is important to mention that the varactors on rigid substrate are mainly designed for a higher quality factor by reducing the dc resistance, which in turn increases the leakage current of the device as shown in the extracted quality factor for different bias voltages in Fig. 5(c). The high quality factor at low frequencies is coming from the increased leakage and the embedded electrode as mentioned before, on the other hand, the measured leakage current is in the order of tens of milliamperes. Fig. 5(d) shows the varactor operation of proposed device at 50 GHz as a show case. The wide tuning range of the capacitance is demonstrated which proves the concept of quantum capacitance.

For the devices on flexible foil; RF measurements are done for two cases: on a flat metal chuck, and on a curved surface with 5 mm radius as shown in Fig. 6(a). Fig. 6(b) presents the extracted quality factor for the zero-strain measurements with different bias voltages over the frequency range from 100 MHz to 50 GHz. The low quality factor at low frequencies comes from the physical design, which is optimized for low leakage current and, hence, leads to high dc resistance. Extended frequency measurements up to 70 GHz are carried out to measure the bending effect with different radius values on the varactor parameters at higher frequencies. Extracted capacitance and resistance at 60 GHz for the two measurement scenarios are presented in Fig. 7. The change of extracted capacitance value between the two scenarios is less than $1-2\%$ while the strain in the bended case increases the lengths of the electrodes leading to slight increase in resistance. As a result, the extracted quality factor for the two measurements is reduced by $5-10\%$. 

Fig. 4. Device on HRS: (a) Chip micrograph, and (b) Measured C-V.

Fig. 5. Varactor on Quartz substrate characterization: (a) Device micrograph, (b) Measured capacitance up to 70 GHz for different bias voltages, (c) Measured Quality factor up to 70 GHz for different bias voltages, and (d) Measured Capacitance at 50 GHz as a function of bias voltages.

Fig. 6. Varactor on flexible substrate characterization: (a) DUT bending test on 5 mm radius surface, (b) Measured Quality factor as function of frequency for different bias voltages.
Fig. 7. Varactor on flexible substrate characterization: Measured Capacitance and Resistance at 60 GHz with flat and bended surfaces.

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<thead>
<tr>
<th>Ref.</th>
<th>Substrate</th>
<th>Configuration</th>
<th>Quality factor</th>
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<tbody>
<tr>
<td>[6]</td>
<td>Glass</td>
<td>Top-Gate</td>
<td>NA</td>
</tr>
<tr>
<td>[7]</td>
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<td>Top-Gate</td>
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V. CONCLUSION

Table I compares between the proposed varactors and other variable capacitors based on the graphene quantum capacitance. To the best knowledge of the authors, our proposed substrate-independent varactor is the first ever reported Graphene-based varactor device on flexible, and the first reported for any other substrate for frequencies higher than 10 GHz. In addition, quality factors higher than state-of-the-art Graphene varactors on rigid substrates are reported, with a clear understanding of the tradeoffs for further improvements depending on the application. The demonstrated high frequency varactor behavior of the presented devices on flexible substrates will be a key enabler for high performance flexible and wearable electronics for medical and communication applications.

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