On the Kinetic Inductance of Graphene Devices

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Abstract

Introduction: Graphene interconnects are predicted to show an additional inductance term, the kinetic inductance, which sums up with the magnetic one, originated by the geometry of the strip. The effect of this term is twofold. It introduces a delay in the signal propagation, which is generally unwanted in both digital and analog electronic circuits. On the other hand, it introduces a slow-wave effect when coupled with another semiconductor parasitic, the quantum capacitance. This should allow for more compact resonating microwave structures, like antennas and filters, up to 2 times smaller for microwave frequencies [1], [2]. However, the presence of the kinetic inductance is strongly dependent on sample quality and high momentum relaxation times for quasi-ballistic carriers. In this work, graphene interconnects deposited on Au CPW access lines are analyzed in both DC and RF up to 67 GHz. An equivalent circuit for graphene has been extracted, composed by frequency-independent parameters, finding the sheet and contact impedance of each graphene strip.

Method: Supporting Au CPW lines have been embedded within the surface of a flexible Polyimide substrate (ε_r=3.3) in order to offer a flat surface for the deposition of graphene (Fig. 1). The geometrical parameters of the line are signal width S=22 μm, signal-ground spacing G=1.5 μm and Au thickness t=300 nm. Probe landing pads with 150 μm of pitch have been connected to the narrower central line with 45° tapers. CVD monolayer graphene provided by Graphene Supermarket® has been deposited and then patterned with optical lithography. Two topologies of electrical connections were fabricated: Series, defining the graphene strip between the signal lines of ports 1 and 2; and Shunt, defining the strip symmetrically between signal and ground (Fig. 2). The size of the strips is of width W=20 μm and lengths L=1, 2 and 20 μm for Series devices, and W=2 x 10 μm and length L=2.5 μm for the Shunt device. All graphene strips are electrically short at all tested frequencies. The lines have been measured with an Agilent PNA-X up to 67 GHz calibrated at -20dBm of power, so that graphene is in linear regime [3]. Reference lines and de-embedding standards have been measured too, and the Open-Thru [4] and Open-Short [5] de-embedding algorithms have been used respectively for Series and Shunt devices to remove the effects of access lines. The resulting data have been matched with the lumped element circuit shown in Fig 3, composed by the sheet resistance $R_{\square}$, the contact resistance R_C and the contact capacitance C_C. The values of the component have been fitted with an RF circuit simulator (Agilent ADS) and the matched S-parameters are shown in Fig 4 for the Shunt device and in Fig 5 for Series devices, showing excellent agreement between simulations and measurements. The extracted values are shown in Table 1, with a strong similarity of the calculated R_C among devices. The differences in $R_{\square}$ and C_C are instead explainable with non-idealities in the metal/graphene contact extension. No evidence of the presence of the kinetic inductance L_k, which should be connected in series with $R_{\square}$, has been found as the quality of the fitting didn't improve or even deteriorated with L_k values greater than zero. This is also consistent with the results of a previous in-house experiment based a CPW line deposited on exfoliated graphene, where L_k was not necessary to fit graphene's S-parameters up to 110 GHz [6]. The measured devices are larger than the expected mean-free-path (hundreds of nm or less), thus the conduction regime is mostly diffusive and ballistic effects as the kinetic inductance are expected to be very limited. L_k has also been found in other experimental studies, in which graphene is not in contact with metal (a more pristine condition)[7] or the equivalent circuit does not use frequency-independent elements.

In conclusion, this result does not directly contradict theoretical predictions, that are computed mostly for nearly ideal graphene with low scattering and high carrier mobilities [1]. However, the importance given to kinetic inductance and slow-wave effect in graphene interconnects by theoretical results must be reconsidered for realistic devices and/or commercially available graphene samples.

References

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Figures

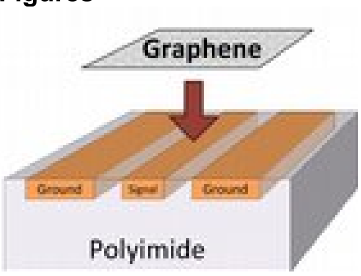

Fig. 1 - Graphene deposition on flat plastic substrate

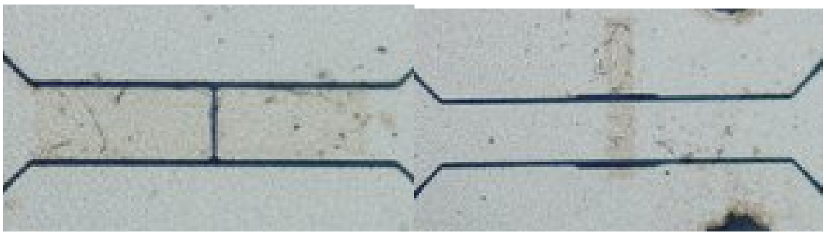

Fig. 2 - Series (left) and Shunt (right) graphene interconnects.

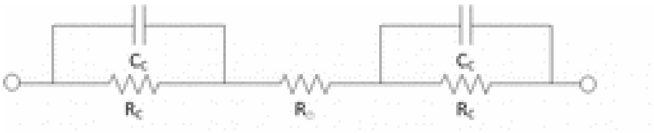

Fig. 3- Graphene equivalent circuit.

Device	R_{dc} [Ω]	$R_\square$[Ω]	R_C [Ω.mm]	C_C [pF.mm]
Series 1 µm	273	2933	1.70	3.73
Series 2 µm	240	1021	1.64	6.40
Series 20 µm	421	251	2.02	0.78
Shunt 2,5 µm	231	116	2.17	1.5

Table I - Extracted values.

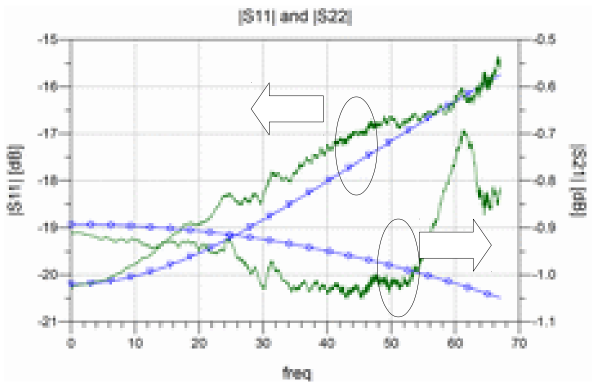

Fig. 4 - Shunt S-parameters magnitude, measurements (solid green) and simulations (symbols).

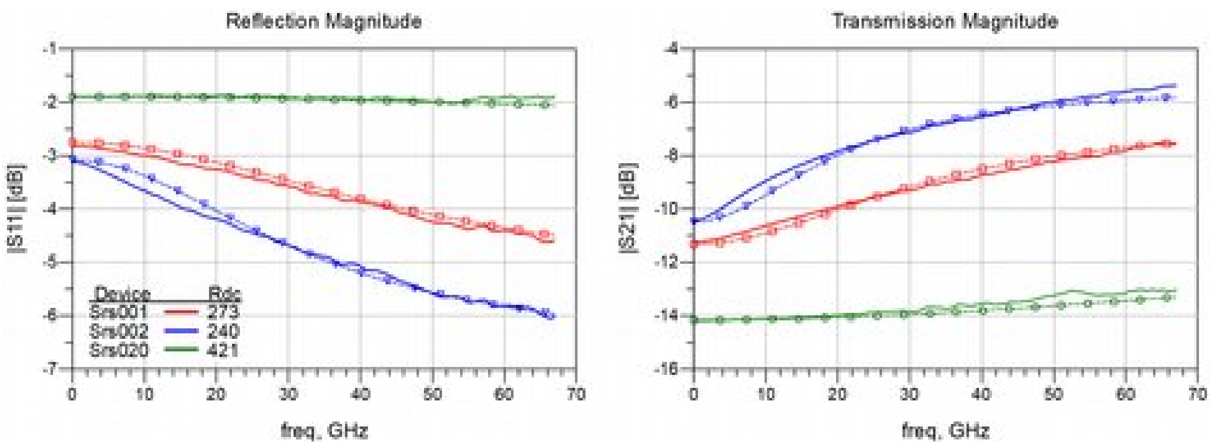

Fig. 3 - Series S-parameters