Facile Manufacturing of Sub-mm Thick CNT-Based RC Filters

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Abstract

CNT-Based RC networks are described with the purpose of showing empirical findings on the influence of the interdigitated electrodes (IDE) spacing, the dispersant compound and the number of deposited layers, on the impedance magnitude and phase of the CNTs. Additionally, we propose use-cases for these networks, applying them to the realization of filters of second order with easily tunable cut-off frequency, and with the inherent advantages of CNTs and printed technologies, rendering them a prime choice for applications where thin and flexible second order filters are necessary.

Keywords: spray deposition, single-walled carbon nanotubes, interdigitated electrodes, frequency response, filters

1. Introduction

Since their discovery, Carbon Nanotubes (CNTs) have being extensively studied for a broad spectrum of applications due to their unique characteristics in geometry, morphology and electrical properties [1]. Such applications include nanobalances, with a resolution up to 1.7 yoctogram [2]; composites as electrode material for rechargeable Li-ion batteries [3]; among others.

CNTs are nanometer-scale cylinders composed of rolled-up graphene sheets around a central hollow core and end caps with a hemisphere of fullerene structure [3]. They can be classified depending on their physical characteristics, like the thickness of the carbon atomic wall. It is then possible to distinguish between single-walled CNTs (SWCNTs), with a one-atom thick graphene layer and multiwalled CNTs (MWCNTs), consisting of two or more layers with van der Waals forces between adjacent layers [4].

For their fabrication, there are three main techniques: arc-discharge, which was the first technique to be used; laser ablation and chemical vapor deposition (CVD) [5]. While the first two are unsuitable for mass production, CVD can synthesize CNTs at relatively low temperature, being more efficient and allowing scaling up growth of both SWCNTs and MWCNTs. In all these growth methods, impurities in the fabrication may affect negatively the CNTs properties. For that reason, a purification process is important to obtain high-quality nanotubes.

Once the CNTs are grown, they need to be transferred to the target surface, which could be structured or flat, and can then be employed as conductors or semiconductors depending on their physical and chemical characteristics. Solution processing by means of spray deposition is one of the methods that showed the most reliable and significant results in the cost effective deposition of CNT networks [6].

The result ultimately is a material with outstanding properties that can be brought quickly into solution, which facilitates their use in processing techniques commonly employed in emerging technologies. Such techniques have inherent advantages in comparison to conventional silicon-based processes in terms of processing condition, resulting features and potential throughput [7].

Here, we demonstrate the feasibility of designing analog circuits and RC networks based on CNT devices by only tuning the spacing of interdigitated electrodes (IDE) or the number of spray-deposited layers. The facile realization of a higher resistivity conducting film (i.e., the CNT network) connecting “ideally conductive” lines (i.e., the Au fingers) is a peculiar characteristic, which allows the controlled production of capacitive-resistive structures. This structure, albeit very simple, is unique and difficult to implement with other techniques. In this framework, we study the influence of the dispersant employed for the CNT solution, the thickness of the connecting layer and the spacing among consecutive fingers of IDE layouts. Figure 1 shows the highlights of this technology: limited (and easily scalable) size, thickness dominated by the substrate (which, in case of plastic, can go down to tens of microns) and possibility to fine-tune the (R,C) pair, setting them to arbitrary values. These characteristics (thickness and R/C values) are remarkable as it is unachievable with external discrete components. The article is then completed with we show some applications where multiple RC elements are utilized.

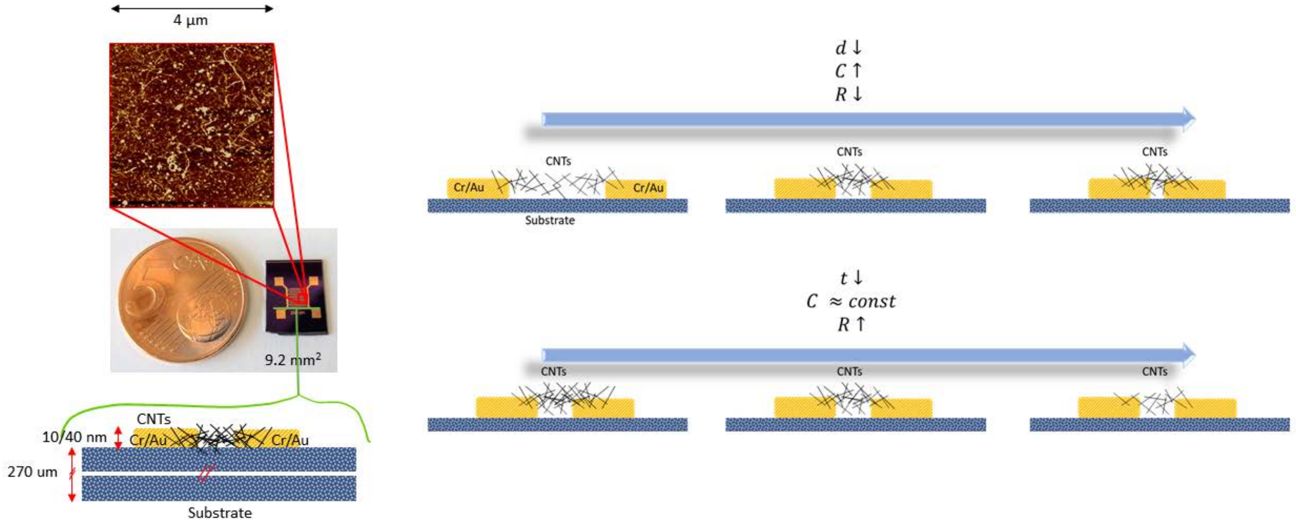


Figure 1. Left: picture of the fabricated device, AFM scan (inset) of the CNT network and cross-sectional view with relevant dimensions. Right: concept of the hybrid RC IDES: with a tentative CNT thickness (t), it is possible to set the capacitance by changing the finger distance. Subsequently, the resistance (and the cut-off frequency) can be fine-tuned by changing the thickness or dispersion of the CNT film.

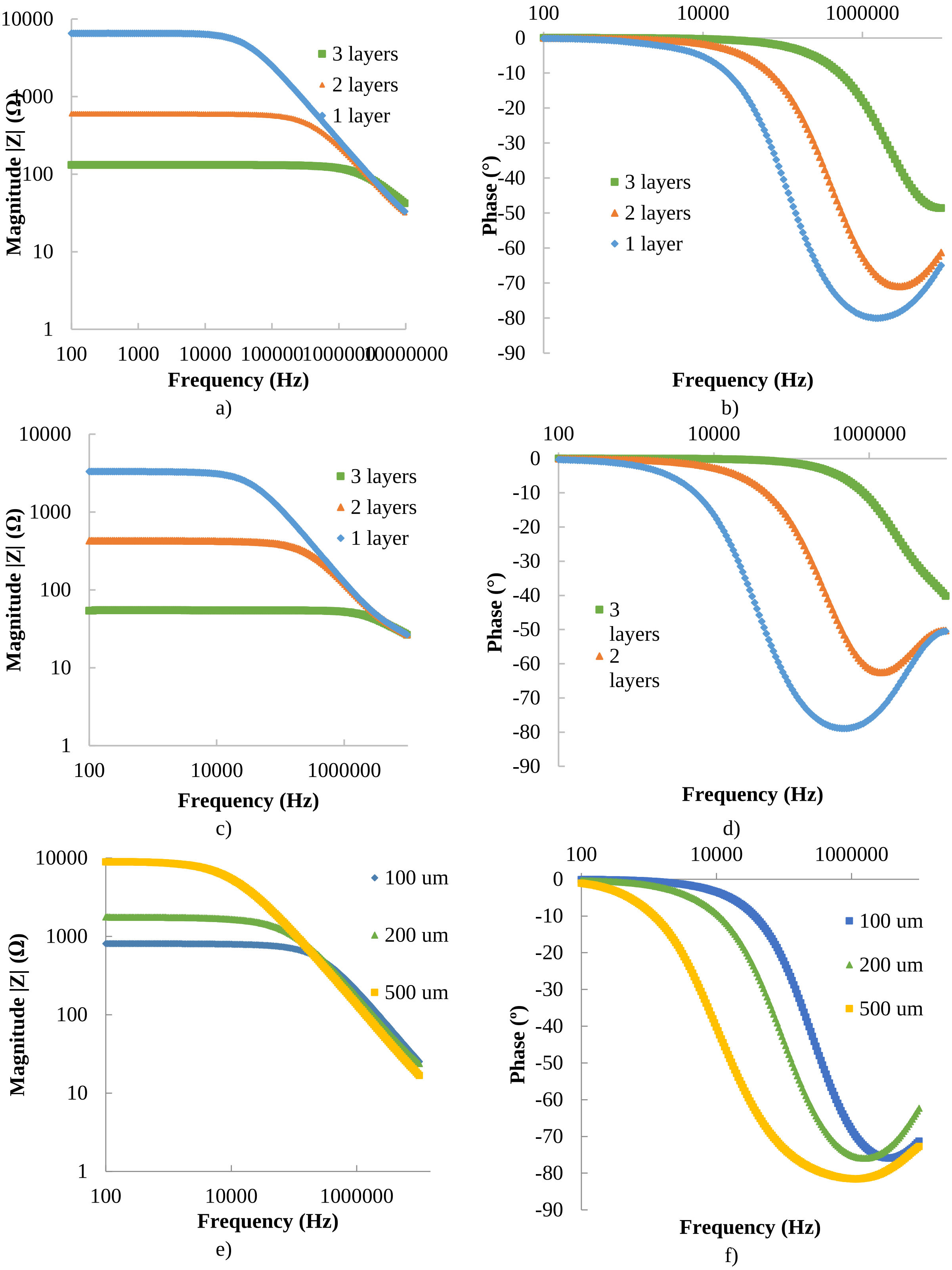
2. Materials and Methods

For the device fabrication, Si wafers with a 200 nm thermally grown oxide were used as substrates. IDE structures were photolithographically patterned with a subsequent physical vapour deposition of Cr/Au as contacts. Commercially available CNTs (Carbon Solution Inc.) (0.03 wt%) were dispersed in deionized water (DI H_2O) with the aid of a dispersant. Two solutions were prepared, one based on sodium carboxymethyl cellulose (CMC) and one on sodium dodectyl sulfate (SDS). The corresponding weight percentage of dispersants were 0.5 wt% for CMC and 1% for SDS. The solutions were spray deposited on the substrate. For CMC, the substrates were placed in dilute nitric acid while the SDS samples were placed in DI H_2O. The impedance response of the fabricated devices was measured with a Keysight E4990A Impedance Analyzer. Further details of the experimental part can be found in the supplementary information.

3. Results and Discussion

3.1 Number of Layers

The successive deposition of multiple CNT layers proves how the impedance response in the frequency domain of CNT-baseddevices is directly influenced by the thickness of the CNT film (see Figure 2a-d). For higher number of layers, i.e., higher thickness, the impedance magnitude decreases at low frequencies, converging later on the same values. In the same way, higher number of layers means more stable phase along the frequency axis, following all the same pattern, and with less pronounced lobes.



a)

b)

c)

d)

e)

f)

Figure 2. Magnitude and Phase for different number of layers with CMC dispersant (a) and (b); with SDS dispersant (c) and (d). IDEs spacing: 200µm. Magnitude (e) and phase (f) for different IDE finger spacing values with 1 CNT layer with CMC dispersant.

From these results, we can also deduce how the cut-off frequency shifts to higher values as the number of layers increase. Table 1 presents our measurements,, including the measurement of the DC resistance, which is higher for the least number of layers, as there is less material for the current to flow.

Table I. Cut-Off Frequency and DC Resistance

Number sprayed layers	CNT-type	Cut-off Frequency (kHz)	DC Resistance (Ω)
1	CMC	72.8 ± 0.8	6539 ± 53
2		653 ± 27	600 ± 43
3		4430 ± 89	131 ± 20
1	SDS	59.5 ± 1.2	3330 ± 47
2		461 ± 23	428 ± 42
3		1230 ± 45	54.2 ± 24

These trends, as well as the dispersion amongst samples, are consistent with both CNT dispersants employed and simply provides more flexibility to achieve the desired impedance range. The choice on which dispersant to employ can clearly be based on a few parameters: the process needs (CMC is more cumbersome to remove, although it gives better results in terms of transmittance to impedance ratio [8]) andthe exact values needed in each application, as well as by the well-known inherent advantages of each one. Notice how the impedance phase starts rising again from frequencies above 0.5 MHz. This is due to the metallic contacts used for connecting the CNT network to the experimental setup, which introduce inherit parasitic components.

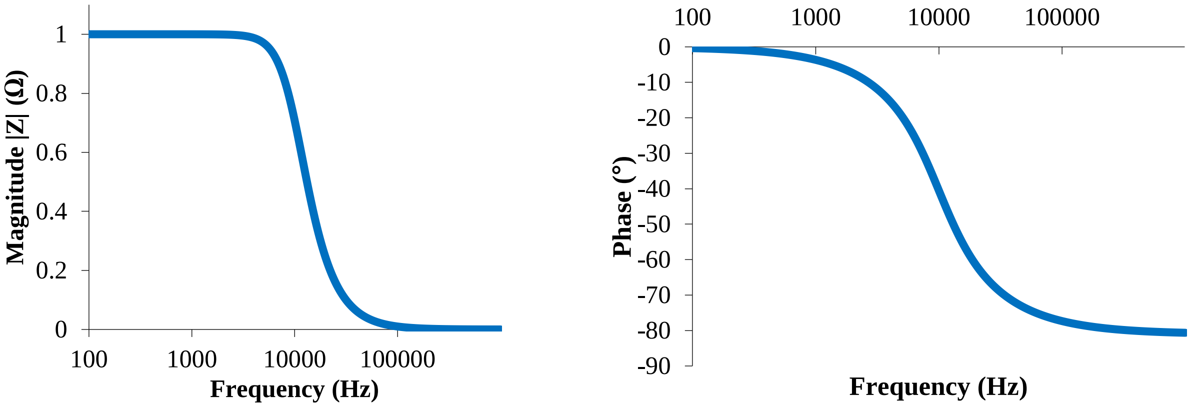
3.2 Spacing

After the analysis of the influence of the film thickness on the impedance, we carried out a similar experiment with the spacing between electrodes. In particular, as Figures 2e and 2f depict, the higher the separation between the IDE fingers, the higher the impedanceat low frequencies. This has a twofold explanation: expanding the distance between the electrodes, will at the same time increase the resistive path, and reduce the capacitance value ($R = \frac{\rho d}{t}$ and $C = \frac{\epsilon A}{d}$, respectively). While the modification of the CNT film primarily affects the resistance, the finger distance influences both degrees of freedom.. The results go along with what weexpected, nonetheless, and allows for a more precise tuning of the hybrid RC structure. Similarly to the thickness variation, the phase presents more stable values for the narrower structure at low frequencies, although in this case, the lobes also have a bigger slope.

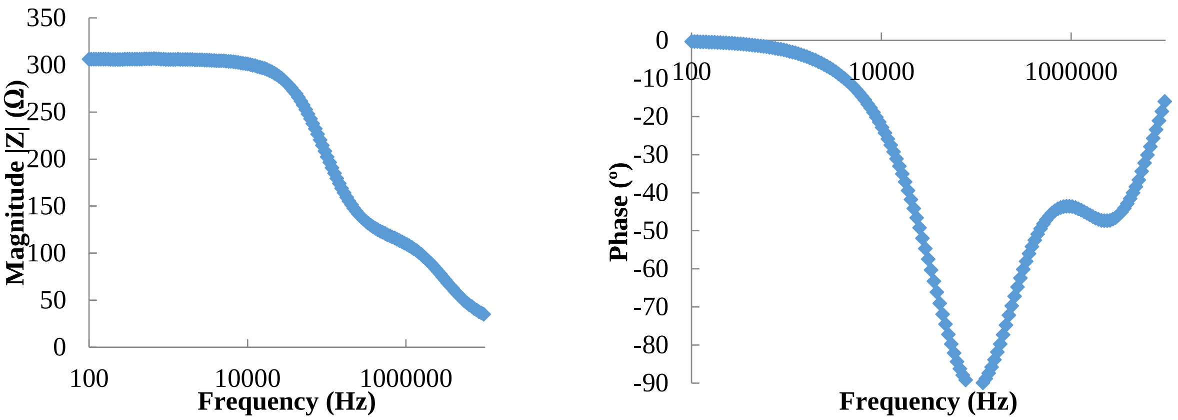
Resultantly, the three parameters we considered so far can be used to vary the resistance, the capacitance and, hence, the overall frequency behavior of the RC hybrid structure. By following this process, they can be employed as standalone components, or combined as multiple IDEs capacitors to be used as load circuit or as filtering network. These degrees of freedom allow to easily find the best trade-off in terms of employable space, processing constraints and costs.

3.3 Filters

As remarkable practical example, a second order low pass filter can be easily designed by connecting two structures with different cut-off frequencies. As seen in Figure 3, the impedance magnitude remains remarkably stable up to the new cut-off frequency, where a steep drop follows, coinciding with the model.



a)   b)



c) d)

Figure 3. Model (a) Magnitude and (b) Phase of a second order low pass filter. Magnitude (c) and Phase (d) of a CNT second order filter implemented with one IDE structure with 1 layer and another connected in series with 3 layers (with CMC dispersant and spacing.

This opens a wide new variety of possibilities related to their use. A filter out of this technology can be completely personalized and fine tuned on each situation, without the necessity of sitting between commercial values of discrete components or integrated filters. Likewise, for applications where the thickness of the whole device matters (e.g., wearables, stickers), CNT filters stand up, since integrated filters such as multilayer, ceramic monoblocks or even discrete components get substantially bulkier in comparison. In addition to this, the well-known properties of transparency of CNTs might allow for the realization of semi-transparent filters integrated in glass or plastic surfaces.

4. Conclusions

We describe experimental results on how different parameters affect the impedance of IDEs realized with conducting fingers and a random CNT network. The parameters we consider are the finger spacing, the CNT thickness and the dispersant employed. Understanding their effects allows for fine-tuning of the cut-off frequency and impedance magnitude, which is a distinguishing sign with respect to conventional discrete components. This approach paves the way to the creation of customizable, flexible and cost-effective passive components and filters. Particularly, given the observed behavior, the most immediate application is the development of second order low pass filters with customizable cut-off frequency. Such filters could be integrated in applications where the thickness is a critical constraint or in the domain of transparent electronics.

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