Flexible Laser-Reduced Graphene Oxide Thermistor for Ubiquitous Electronics

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Abstract—**This work presents a versatile sensing platform, intended for ubiquitous and flexible electronics based on a laser reduced-Graphene-Oxide thermistor. This technique enables the fast and ecological production of reduced Graphene Oxide without the need of masks or expensive lithography processes. The final transducer is fabricated on a flexible plastic substrate in order to use it as a superficial patch. Finally, a full demonstrator, which integrates this flexible thermistor with a low power System on Chip with wireless transmission, is presented.**

Keywords–Graphene; rGO; flexible; sensor; thermistor; SoC.

I. INTRODUCTION

After the Nobel Prize in Physics 2010 was awarded jointly to Andre Geim and Konstantin Novoselov for the isolation of single Graphene flakes, Graphene has become one of the most studied materials in all the fields of technology, in both theoretical and application lines. This interest is due to its unique spectrum of physical, chemical and electrical properties [1]. However, the expectations have not been yet materialized into end-user applications due to, among other reasons, the difficulty to obtain high quality samples with the current mass production techniques. The research activity related to Graphene has awaken the interest in other Graphene-like materials. One of them is the reduced-Graphene-Oxide (rGO) which, although it is far from achieving the unique properties of Graphene, capitalizes part of its unique features (e.g., flexibility, transparency or electrical and thermal conductivity) together with the great advantage of an easier and simpler synthesis process. Several works have demonstrated the potential of reduced-GO as a sensor [2][3]. In this work, the rGO's linear conductivity-temperature dependence is exploited to develop a flexible temperature transducer (thermistor). Finally, as a demonstrator of the potential of this technology, we present a complete ultra-low power temperature monitoring solution based on a reduced Graphene Oxide thermistor. After the introduction, the manuscript is divided in four sections Sections as follows: Section II introduces the process to obtain rGO from the GO colloid. Section III presents the design of a thermistor based on rGO as well as its electrothermal behavior. Sections IV exemplifies the use of rGO flexible sensors in end-applications. Finally, the main conclusions are drawn in Section V.

II. GRAPHENE OXIDE REDUCED BY LASER

The first step in the rGO-based thermistors fabrication process is to synthesize the Graphene Oxide colloid (GOc). This synthesis has been based on a fast and reliable production technique which is a modified version of the Hummers and Offeman method [4] which consists on the oxidation and sonic exfoliation of graphite powder. The GOc can be deposited as a thin and uniform film on any non-porous surface (structurally flexible or not) and turned into rGO through a reduction process. The alteration of the crystallographic network of carbon atoms after the oxidation process turns the GO into an electrical insulator. However, the GO reduction process removes the functional groups and restores partially the crystallographic structure [5], returning the electrical conductivity. The reduction procedure selected is the laser photothermal reduction [6], which offers the following advantages:

- Environmental friendly.
- High precision patterns without the use of mask.
- Conductivity control through the laser power control.

Based on this third point, we studied the sheet resistance of the lasered-rGO as a function of the laser photothermal power. First, the GO was deposited on a polyethylene terephthalate (PET) film in order to provide flexibility to the sample. After that, it was reduced at a wavelength of 550 nm, which as confirmed by Raman spectroscopy is capable to reduce the GO, using different values of the laser power. As seen in Figure 1, the results obtained show that an increase of the photothermal power implies a sheet resistance exponential decay. Therefore, once the power exceeds 90 mW, the sheet resistance remains almost constant.

According to these results, the selection of a laser photothermal power in the range [90, 115] mW would reduce the variability among different samples for power shifts due to the stability of the sheet resistance in this range.

III. FLEXIBLE TEMPERATURE SENSOR BASED ON REDUCED GRAPHENE OXIDE

There are a lot of works focused on the study of the conductivity of the rGO using different substrates and reduction methods. However, it is most difficult to find works about end-use applications based on this technology. Because of it, this

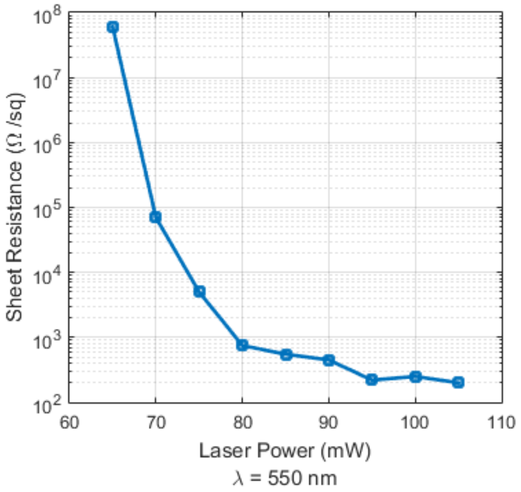

Figure 1. Lasered-rGO sheet resistance as a function of the laser power ($\lambda = 550\ nm$) for a GO concentration of 70 $\mu g/cm^2$.

paper presents a rGO flexible temperature sensor on the basis of its conductivity dependence with respect to the temperature.

The developed transducer, shown in Figure 2, presents a total resistance which depends on both sheet resistance and pattern physical dimensions (width (W) and length (L)) as follows:

$$R_T = \rho_s \cdot (L/W) \tag{1}$$

where R_T is the total resistance of the sensor and ρ_s is the sheet resistance of the rGO.

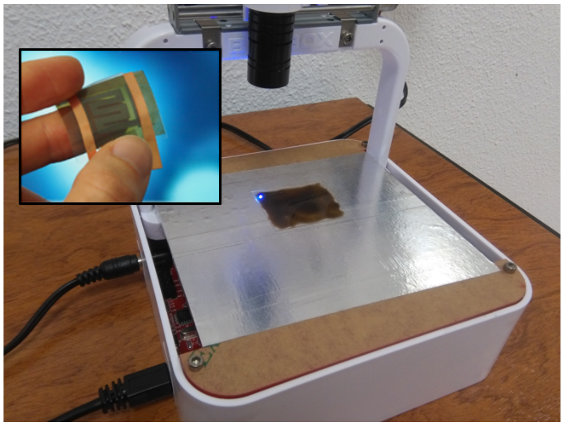

Figure 2. Image of laser reduction of GO deposited on PET film. Inset: Final flexible temperature sensor.

Once GO is deposited on the PET flexible film and patterned using the laser, a second PET film is used to seal the sensitive layer in order to avoid any undesired effect due to the contact with the the atmosphere. In the middle of this stack, two copper strips allow the access to the sensitive layer.

The dependency of the developed flexible transducer resistance with respect to the temperature is shown in Figure 3. As seen in this figure, the response is almost linear and does not present hysteresis. On the other hand, the sensitivity obtained in this prototype is $-77.43\Omega/^{o}C$ for the range of temperature studied.

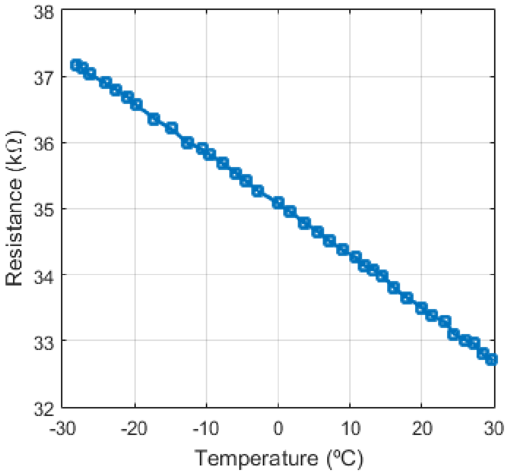

Figure 3. Representation of the flexible transducer resistance as a function of the temperature. Heating and cooling cycles are shown.

IV. A SIMPLE APPLICATION: ULTRA-LOW POWER SENSOR PLATFORM

As a demonstrator of the potential of this technology, a device to monitor the ambient temperature has been developed based on the rGO sensor previously detailed. This device, shown in Figure 4, combines the rGO sensing capabilities with the versatility that the System-on-Chip (SoC) devices offer. This prototype, whose controller is the low power version of the Programmable System-on-Chips (PSoCs) by Cypress [7], has also wireless data transmission capability. Then, the measured temperature can be sent by Bluetooth Low Energy (BLE, or Bluetooth 4.0) to a master device, e.g., a smartphone.

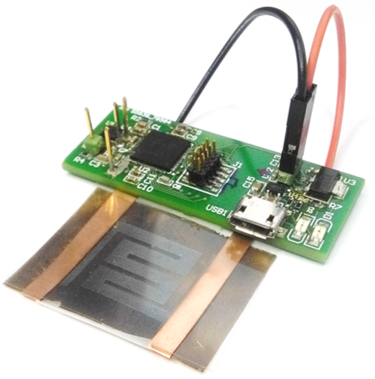

Figure 4. Prototype developed.

V. CONCLUSION

Graphene Oxide has been suited as a flexible sensing platform ready to be exported to certain end-user applications as it was shown in this work. Once the GO is deposited on a flexible substrate, a simple process of reduction based on laser gives to the GO the conductivity needed to constitute a thermal transducer whose conductivity is completely linear with respect to the temperature. Therefore, we advocate that once the SoC systems become available on flexible substrates, the rGO-based sensors will take a big step forward expanding to multiple ubiquitous applications.

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