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**PLA conductive filament for 3D printed smart sensing applications**

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## PLA conductive filament for 3D printed smart sensing applications

### Abstract

*Purpose* - This paper presents a study on a commercial conductive PLA filament and its potential application in a 3D printed smart cap embedding a resistive temperature sensor made of this material. The final aim of this study is to add a fundamental block to the electrical characterization of printed conductive polymers, which are promising to mimic the electrical performance of metals and semiconductors. The studied PLA filament demonstrates not only to be suitable for a simple 3D printed concept, but also to show peculiar characteristics that can be exploited to fabricate freeform low cost temperature sensors.

*Design/methodology/approach* - The first part is focused on the conductive properties of the PLA filament and its temperature dependency. After obtaining a resistance vs temperature characteristic of this material, the same was used to fabricate a part of a 3D printed smart cap.

*Findings* - An approach to the characterization of the 3D printed conductive polymer has been presented. The major results are related to the **definition of** resistance vs temperature characteristic of the material. This model was then exploited to design a temperature sensor embedded in a 3D printed smart cap.

*Practical implications (if applicable)* - This study demonstrates that commercial conductive PLA filaments can be suitable materials **for** 3D printed low cost temperature sensors or constitutive parts of a 3D printed smart object.

*Originality/value* – A clear demonstration that a new generation of 3D printed smart objects can already be obtained employing low cost commercial materials.

### Keywords

Conductive polymers; PLA; FDM; smart objects

### Classification

Research paper;

### 1. Introduction

Three-dimensional (3D) printing has the potential to revolutionize science and technology in the field of mechanical, electronic and, in general, engineering systems usually **manufactured** with high-cost facilities, by employing low cost materials and processes and **thanks to an easy transfer approach** from the idea to the fabrication.

Additive manufacturing is a freeform, easy access bottom up technology and **a wide portfolio of** low cost printing **equipment is currently** available on the market, **above all** Fused Deposition

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3 Modeling (FDM) printers, which are typically applied to prototype fabrication as well as very low  
4 **volume** production (Tyson et al. 2015). This technology surpasses the **constraints** imposed by the  
5 traditional polymer replication (injection moulding and hot embossing) mainly **due** to the moulds  
6 fabrication, thus allowing new design strategies and innovative applications (Milani et al. 2015).  
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8 Moreover the affordable cost of the consumables brings to very low cost 3D prints. In this  
9 **framework**, the capability to use materials **with** conductive properties **may** lead to a new generation  
10 of 3D smart devices (Leigh et al. 2012; Lu et al. 2013; Vatani, Engeberg, et al. 2015; Vatani, Lu, et  
11 al. 2015; Zhang et al. 2015; Muth et al. 2014; Kong et al. 2014). Employing electrical conductive  
12 composites, it is possible to **print 3D** current **supply lines** for active or passive elements that are **on**  
13 **their own** printed by the same materials. This new approach, **indeed**, provides a novel devices  
14 architecture, which on one side surpasses the **intrinsic** planarity in conventional fabrication and, on  
15 the other side, automatically integrates the active components in the structure of the final object  
16 leading to a real smart **3D printed** system. In this view new commercial polylactic acid (PLA)  
17 filaments and FDM represent a benchmark to understand which are the real potentialities of smart  
18 objects 3D printing.

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20 The mentioned materials are carbon (Ning et al. 2015) or metal (Mostafa et al. 2009; Nikzad et al.  
21 2011) based composites, in which the polymer matrix is mixed with conductive powders to improve  
22 the quality of the printing in terms of mechanical behaviour. In fact, the major interest **in** these  
23 **classes** of composite is **usually about** the mechanical improvements as for tensile properties  
24 (including tensile strength, Young's modulus, toughness, yield strength, and ductility), flexural  
25 properties (including flexural stress, flexural modulus, flexural toughness, and flexural yield  
26 strength), fatigue behaviour and so on. A lot of works **about** the structural and mechanical  
27 characterizations can be found, while very few papers are related to the electrical behaviour of such  
28 materials (Leigh et al. 2012). In particular intrinsic characteristics, as the variations of electrical  
29 properties as a function of external environment, have not been investigated methodically yet.  
30 In this study a PLA conductive filament has been characterized in terms of resistivity versus  
31 temperature. Then a resistance vs temperature characteristic of this material was **attained** and, as a  
32 proof of concept, a 3D printed smart cap **integrating** an electrical contact and a temperature sensor  
33 was built.

## 51 52 53 **2. Experimental**

### 54 *2.1 Resistivity measurements approach*

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56 Cubic 10x10x10 mm<sup>3</sup> samples made of conductive 2.85 mm diameter PLA filament (Composite  
57 PLA - Electrically Conductive Graphite from Protoplant INC) were printed employing a Velleman  
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3 K8200 equipped with a 0.5 mm extruder nozzle and with the following settings: an infill density of  
4 60 % (honeycomb rectilinear), an extruder temperature of 225 °C, a bed temperature of 55 °C and  
5 an infill speed of 65 mm/s. A metallic Ti/Al thin layer (thickness: 100 nm for Ti and 700 nm for Al)  
6 was then deposited by sputtering (Kurt Lesker PVD 75) and a physical mask was employed to  
7 obtain circular patterns of 5 mm diameter. A physical shadow mask made of a 0.5 mm thick sheet  
8 of PolyMethylMethAcrylate (PMMA), adherent to the surface, was employed to obtain circular  
9 patterns on the samples. The metal deposition was repeated on the different sides of the samples.  
10 The deposited Ti/Al film provides the optimal electrical contact that is fundamental to **achieve**  
11 reproducible measurements, moreover the circular patterns are pads with an accurate and defined  
12 dimension **allowing** to calculate the resistivity of the printed samples. Electrical wires (1 mm  
13 diameter) were bonded on the Ti/Al pads by means of a silver paste (from RS Components). Two  
14 different resistivities ( $\rho$ ) have been **measured** (figure 1): the resistivity parallel to the printing table  
15 ( $\rho_{xy}$ ), and the resistivity along the z axis ( $\rho_z$ ).  $\rho$  was calculated by the following formula (1):  
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$$\rho = \frac{R \cdot S}{L} \quad (1)$$

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27 where R is the measured resistance, S is the area of the pad (19.6 mm<sup>2</sup>) and L the cube height (10  
28 mm). The resistivity measurements were acquired with the sample loaded in a climatic chamber  
29 (Angelantoni climatic system TY80) with a temperature range between 10°C and 70°C using an  
30 Agilent data logger model 34970A (equipped with the 34901A board). The conductive PLA  
31 filament has a declared resistivity of 115 Ω·cm for the  $\rho_z$  and 30 Ω·cm for the  $\rho_{xy}$ . During the  
32 measurements, the sample was **heated** to a specific temperature in the climatic chamber, with an  
33 accuracy of 1 °C ± 0.1 °C. The samples were tested by increasing and decreasing the temperature  
34 always **within** the range 10 °C-70 °C, with a step of 10 °C between successive measurements. To  
35 avoid any transitory effect due to material inertia during the experiment, a rest time of 10 min was  
36 imposed for each acquisition at a specific temperature and then the resistance values were acquired  
37 in a 10 minutes **window** with a sampling rate of 1 sample/minute. Six different samples were tested  
38 with the above mentioned conditions.  
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## 49 2.2 Smart cap design and fabrication

50 The smart cap was designed using Rhinoceros<sup>®</sup> 3D CAD software and then printed by Object 30  
51 (Stratasys) for the non-conductive parts and by Velleman K8200 for the electric contacts/sensor. As  
52 depicted in figure 2, the cap is composed by: an external cap that contains the contacts and allows  
53 for the sealing to the bottle; a spring that separates the contacts/sensor; the top and bottom  
54 contacts/sensor fixed by a seeger on the bottom of the spring and by a bolt on the top of the cap.  
55 The contacts/sensor were made by the same conductive PLA employed in the previous electrical  
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3 characterization, while the other parts were fabricated by VeroWhite Plus FullCure 835 (from  
4 Stratasys). The PLA parts were finished by fine abrasive paper, while Object printings were only  
5 finished by water jet to remove the supporting sacrificial material. The smart cap fabrication was  
6 achieved after several prints to obtain the best joints compromise among the different parts; at the  
7 end of this optimisation step the best fabricated smart cap was tested with the same equipment  
8 reported previously.  
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### 13 14 15 **3. Results and discussion**

16 The conductive PLA cubic samples were tested as described in the experimental section and no  
17 statistical differences were found between the mean value for the ramp up and ramp down of the  
18 temperature. A good reproducibility of the measured values was registered and a statistical standard  
19 error of  $\pm 0.01 \Omega$  was found for  $R_{x,y}$  and of  $\pm 0.15 \Omega$  was found for  $R_z$ . The calculated  $\rho_z$  and  $\rho_{xy}$   
20 for each temperature (table 1-2) show a significant discrepancy from the nominal ones, in particular  
21 for the  $\rho_{xy}$  that is one order of magnitude smaller. On the contrary, the difference between  $\rho_z$  and  $\rho_{xy}$   
22 is still significant (about one order of magnitude) as declared by the supplier. Therefore, this  
23 difference should be related to how the filament has been fabricated by extruding the original  
24 powders; such extruding process probably leads to a filament with a core rich of conductive powder  
25 and a shell with a lower concentration of the same.  
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28 The most interesting result is the noteworthy variation of resistivity as a function of temperature:  
29  $0.1 - 0.85 \Omega/^\circ\text{C}$  for  $R_{x,y}$  and  $0.65 - 5.7 \Omega/^\circ\text{C}$  for  $R_z$ . It means that it is possible to appreciate a  
30 resistance variation as a function of temperature and vice versa to measure the temperature by  
31 resistance acquisition. Therefore, it is likely to fabricate a sensor with a sensitivity of about  $1 \Omega/^\circ\text{C}$   
32 or greater depending on the contacts configurations, along z axis or on the printed layer. The plots  
33 in figure 4 show that this dependency is not linear since at higher temperature the resistance  
34 variation increases. However it is possible to find the empirical model using a parabolic fit with a  
35  $R^2$  of 0.99:  
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$$46 R_z(T) = 0.0532 T^2 - 0.997 T + 199.95 \quad (2)$$

$$47 R_{x,y}(T) = 0.0071 T^2 - 0.2045 T + 29.447 \quad (3)$$

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53 If compared with other commercial thermistors or Pt100 probes, which are based on the well  
54 studied Temperature Coefficient of Resistance (TCR) of Pt (Tommasi et al. 2016), similar or higher  
55 sensitivity can be attained by choosing a z axis resistance configuration, especially for temperature  
56 above  $20^\circ\text{C}$ .  
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3 The practical consequence of this behaviour is the possibility to build a 3D printed object where the  
4 temperature sensor is not a separated **element** to be **assembled** in the structure, but a part of the  
5 object itself. To demonstrate this assertion a 3D smart cap has been fabricated. In this system the  
6 objective is to determinate the open or close position of the cap by a simple electrical contact, that is  
7 by closing the circuit between the 3D printed top and bottom contacts (figure 2 and 3). During the  
8 closing and opening of the bottle the resistance has been acquired thus providing both the status  
9 (open/close) and the temperature of the cap (figure 5). **Such a case study was selected since**  
10 **embodying a very common and critical component in several packaging solutions and commercial**  
11 **goods (food, chemicals, biology, drugs,...), often characterised by customised dimensions and**  
12 **shape depending on the specific use. No particular consideration for future upgrades of the**  
13 **production volume or current regulation (both strictly application dependent) has been taken into**  
14 **account.**

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23 This test confirms the hypothesis that a 3D printed object can acquire active features to become  
24 more than a simple mechanical **component**. This also demonstrates that the evolution of 3D printing  
25 techniques is closely correlated to the innovation on materials in order to add functionalities and to  
26 technologies in order to **achieve** better resolutions.

#### 31 **4. Conclusion**

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35 The presented study **focuses** on the potentiality of 3D printed conductive polymers, which are a new  
36 **class** of low cost materials that promise to substitute metals and semiconductors, opening the way to  
37 a new generation of 3D printed smart objects. After **measuring** a resistance vs temperature  
38 characteristic of this material **and defining a simple thermo-electrical model**, the same **material** was  
39 used to fabricate a **component** of a 3D printed smart cap. The results of the conductive PLA **thermo-**  
40 **electrical characterization** indicate that this material is not only **exploitable** for its electrical  
41 conductivity, but also for its significant variation as a function of temperature. Finally it was  
42 demonstrated that it is possible to print a conductive **element** of a 3D object that is also a  
43 temperature sensor. **The proof of concept presented in this work has the aim to demonstrate the**  
44 **actual application of functional materials to 3D printing and to inspire new sensors integration**  
45 **solutions, or more generally, new electrical-based functionalities provided to structural components**  
46 **such as: antennas, identification codes, bolometers, UV sensors, magnetic field sensors etc. This**  
47 **opens a** new scenario, where for instance personal objects like smartphones, smartwatches, cars,  
48 computers, etcetera, but also disposable parts like food packages may be connected each other to  
49 provide the right information at right time: for instance by communicating to the shop assistant that  
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3 a food is expired or **contains allergens**, or to inform that the **package was exposed to an excess of**  
4 **radiation or, finally to detect any eventual electromagnetic interference between a commercial good**  
5 **and its potential user.**  
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8 Future investigations will be focused on more complex objects in which the PLA conductive 3D  
9 pattern may be employed for both temperature sensing and eventually heating (i.e. anemometric  
10 flow sensors) and the miniaturization of the same. Further evolution will cover the integration of the  
11 PLA 3D printable material with other Additive Manufacturing technologies to build temperature  
12 based sensing solutions integrating all the active features together with a customized 3D printed  
13 plastic package.  
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Table 1:  $R_{x,y}$  mean value obtained by the measurements and calculated  $\rho_{xy}$  values.

Temperature (°C)	$R_{x,y}$ ( $\Omega$ )	$\rho_{xy}$ ( $\Omega \cdot \text{cm}$ )
10	27.66	5.42
20	28.64	5.61
30	29.97	5.87
40	32.72	6.41
50	36.56	7.16
60	41.81	8.20
70	50.28	9.86

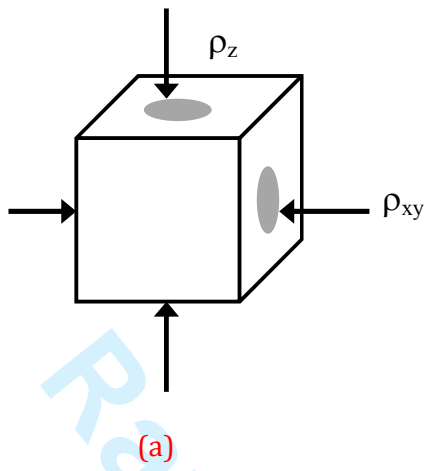
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Table 2:  $R_z$  mean value obtained by the measurements and calculated  $\rho_z$  values.

Temperature (°C)	$R_z$ ( $\Omega$ )	$\rho_z$ ( $\Omega \cdot \text{cm}$ )
10	195.23	38.26
20	201.77	39.55
30	217.33	42.60
40	245.46	48.11
50	281.87	55.25
60	333.33	65.33
70	389.99	76.44

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Figure 1: schematic of the measurement (a) and a 3D printed sample (b).

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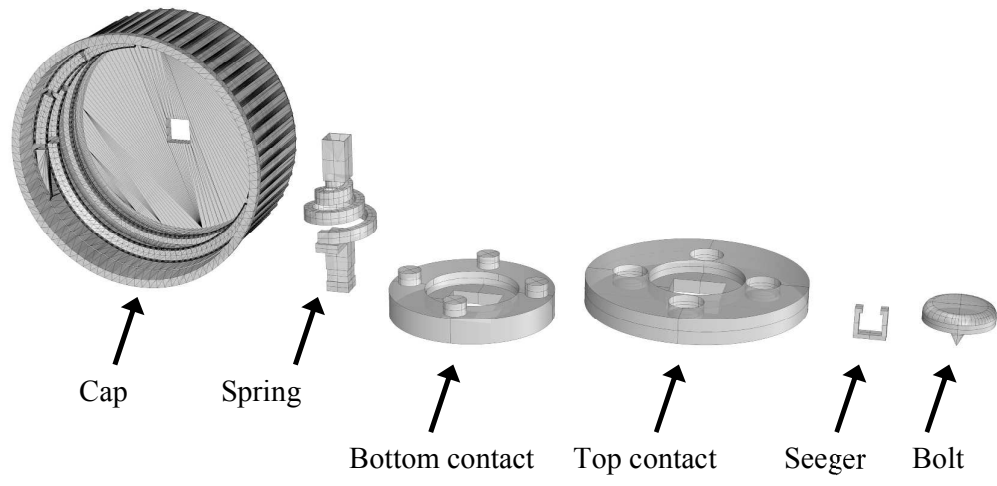


Figure 2: components of the smart cap

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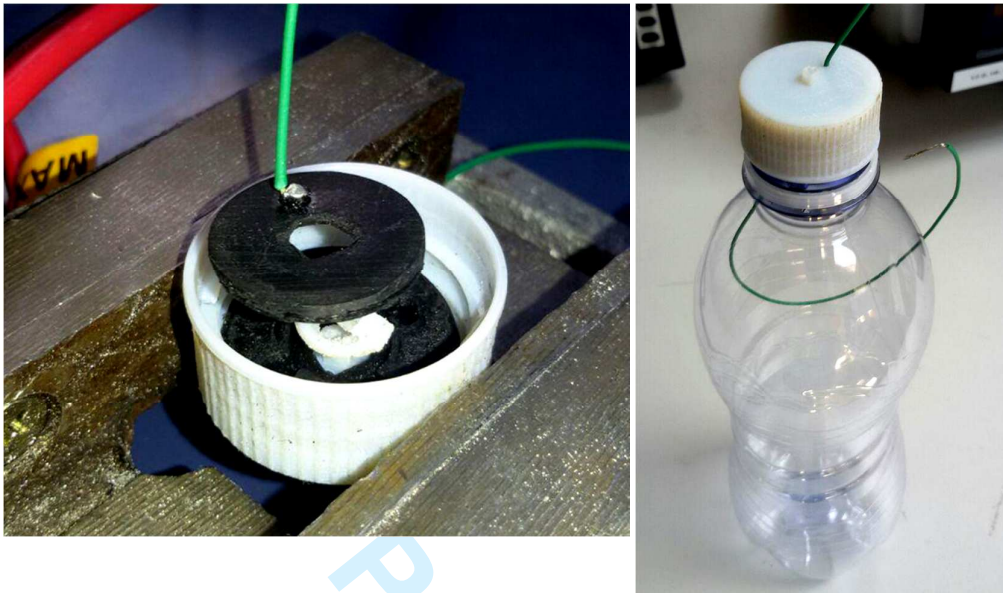


Figure 3: Assembled (on the left) and screwed on a bottle (on the right) smart cap.

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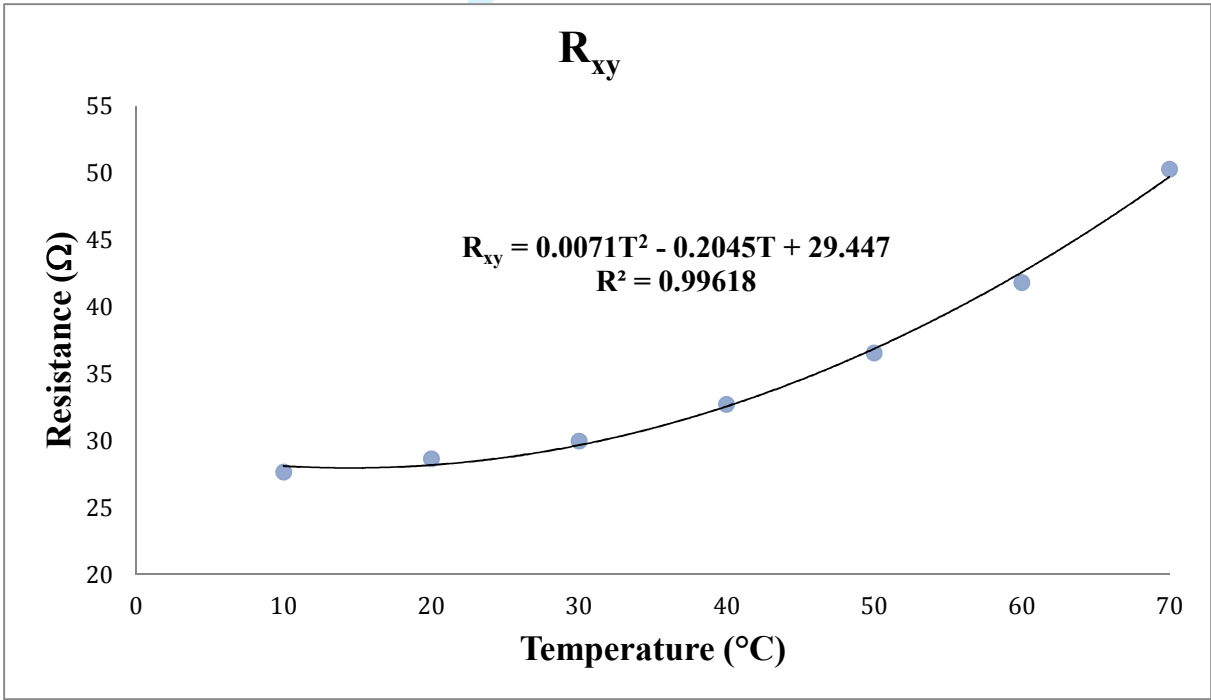
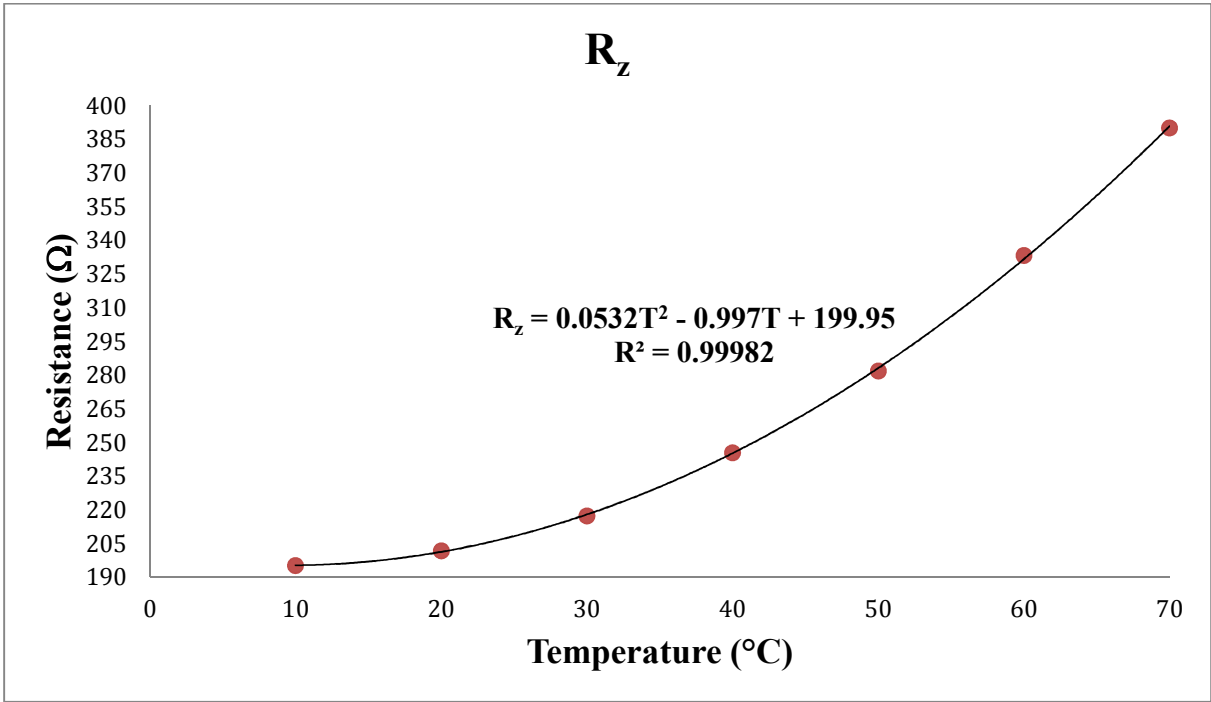


Figure 4: Resistance versus temperature plots. The continuous black curve represents the cubic curve that fits the experimental data



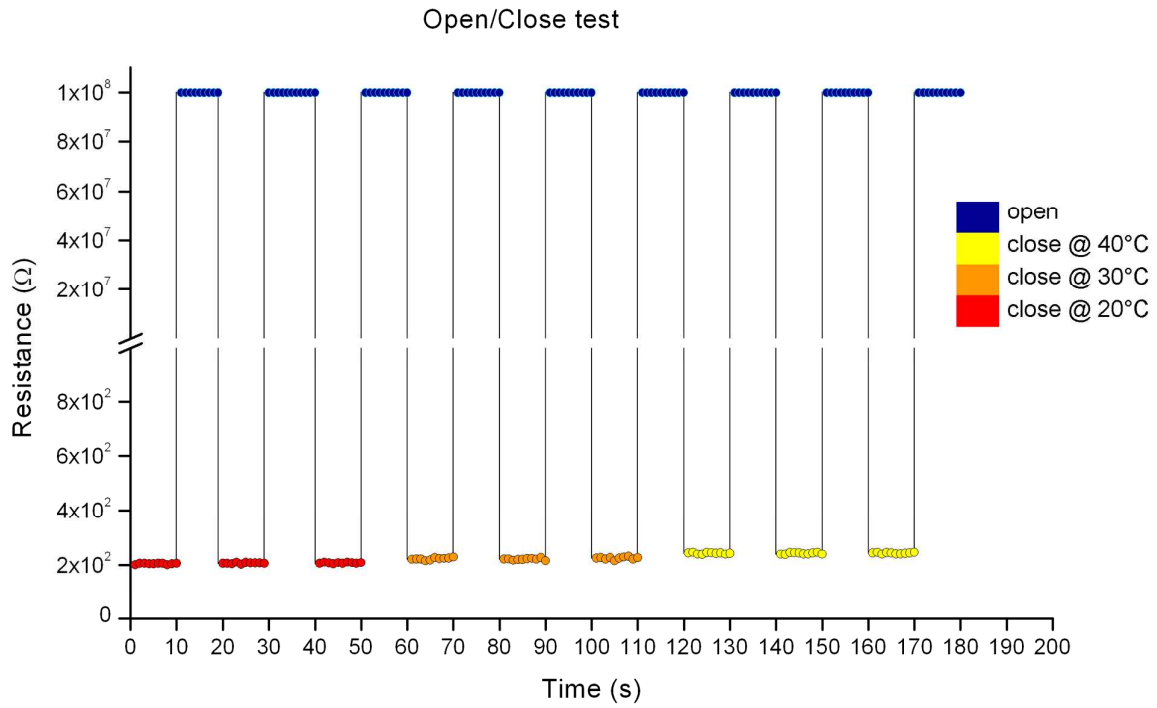


Figure 5: open/close test at different temperatures.

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