Engineering Research Express

PAPER

Printed resistors for flexible electronics—thermal variance mitigation and tolerance improvement via oxide-metal coatings

Ryan B Middlemiss, Jack R McGhee, Darren J Southee, Peter S A Evans and Upul K G Wijayantha

1 School of Design & Creative Arts, Loughborough University, Loughborough, United Kingdom
2 Department of Chemistry, Loughborough University, Loughborough, United Kingdom
3 Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough, United Kingdom

E-mail: r.middlemiss@lboro.ac.uk

Keywords: printed electronics, printed resistors, metal oxides, screen printing, ink formulation, heat sink, heat dissipation

Abstract

Manufactured resistors in conventional electronics are classified into tolerance groups ranging from <1% for high stability film types (E192) to 20% (E6) which are often carbon-based and utilised in less critical resistance value contexts such as current limiting or pull-up/down applications [IEC 60063:2015, Preferred number series for resistors and capacitors]. One of the major identified challenges in the printed electronics industry currently is the ability to match this manufacturing capability for printed resistors in terms of initial tolerance, stability over time and power capabilities.

In this work, a variety of screen-printed carbon resistors were designed and produced. The effects of utilising additional screen-printed ZnO and Ag layers as thermal variance management for the carbon resistors are investigated with the aim of improving the resistors power rating and stability. The introduction of ZnO or ZnO/Ag layers to carbon resistors saw notable improvements in the peak power capability, stability when sustaining 500 mW power dissipation, and stability in varying environmental conditions. Utilizing ZnO and Ag layers also notably improved the initial tolerance groupings when compared to basic uncoated carbon resistors.

1. Introduction

Printable electronics is quickly becoming a widely-established industry with sensors [1–4], conductive tracks [5, 6], and energy storage [7, 8], all experiencing significant interest in both academic and industrial research [9]. The promise of flexible, low-cost applications is of great interest for the growing ‘internet-of-things’ [10, 11]. However, one electronic component which has struggled to reach maturity in the field of printed electronics is the basic resistor. Research has shown that in industry, many devices which could be printed are not. This is due to it being difficult to fabricate reliable and stable resistors to an adequate power rating and tolerance for their needs. In conventional resistor manufacture, the initial tolerance depends to a large degree on the type of resistive element used. Carbon is a widely accessible and cheap resistor material, however, even conventionally manufactured carbon resistor tolerance values are usually limited to >5% and power ratings of <5 W. Conventional resistor manufacturing is widely standardised with regards to tolerance and power rating by standards such as IEC 60063:2015 in order to optimise economical production and accessibility for product design [12]. In printable, flexible electronics to date, however, neither the control to manufacture and resolve across this range of initial tolerances, nor comparable power dissipation and stability have been realised. Current research has largely relied on bulky, ceramic substrates [13, 14], non-scalable deposition techniques [15, 16], or lengthy post-processing involving high temperatures that limit substrate options [17]. Work carried out that avoids these pitfalls for high throughput printable resistors is somewhat lacking, and when available, fails to address the ambient stability or longevity [18]. Kumar et al presented a mass producible printed carbon resistor with seemingly good tolerance, however the use of a cryostat to enforce constant temperature during power studies casts doubt on the real applicability of the presented resistors. Therefore, printable resistors that can...
provide predictable initial tolerance and power ratings in line with standards set out for conventional resistors, while being easily scalable to mass-manufacture with flexible substrates, present much opportunity for printed electronics as an industry. If this industry demand can be met then more complex, composite circuits can be printed en masse in a roll-to-roll process, driving down costs and expanding the market.

Due to printed electronics typically favouring thin, plastic substrates, considerations must be made for heat generation. Inks are a mixture of electronically-active particles dispersed in resin binders [19, 20] which in drying inherently introduces porosity and amorphous macrostructure. Printed electronics will struggle at increased power dissipation as transfer of heat is inhibited with increased porosity without external convection [21]. Conventional electronics utilizes bulky, thermally conductive ceramics and mechanically induced air or liquid flow in order to maintain low operating temperatures when functioning at elevated power [22, 23], however, these solutions are not viable in a printed medium on thin, often flexible substrates. An alternative method of managing heat lies in utilizing metals that present high thermal conductivities due to their high electrical conductivity, such as silver. Silver is known to have a very high thermal conductivity and would be effective at dissipating heat from printed electronics provided there is an electrically non-conductive thermal transfer material between itself and the active area. Whilst the authors acknowledge the considerable cost of silver, the dimensions and therefore volume deposited in the designs proposed amount to a cost of less than $0.01 per resistor. Further, the designs explored in this work are created such that if the technology were to be adopted in an industrial setup, the silver could be replaced with another suitably thermally conductive material such as copper once copper inks begin to mature as a technology. It should also be considered that this approach removes the need for additional post-processing techniques (such as surface mount pick and place) that often cannot be simply carried out in a roll-to-roll process making the cost more comparable. The thermal transfer material works to prevent short circuit via the silver heatsink, as well as working to some degree of plugging some of the pores within the inks and thus making heat transfer more efficient. An effective material for this purpose would be zinc oxide (ZnO) due to it’s superior thermal conductivity compared to carbon black [24, 25], being electrically insulating in the undoped state, and being cheap and widely available.

Therefore, this study presents designs for printable carbon resistors with a predictable initial resistance within a tolerance comparable to conventional carbon resistors (20% for E6, and 10% for E12). Furthermore, it aims to present a possible solution to managing heat dissipation in printed resistors, improve resistor stability, and potentially be applied to other printed electronic components. All this can be achieved using readily available screen printing techniques and relatively low curing temperatures, making it suitable for thin plastic substrates and future application in high-throughput printed electronics.

2. Materials and methods

2.1. Ink formulation
The silver interconnects were printed using Flexible Silver Paste (C2131014D3, Gwent Electronic Materials) which was used as received. The carbon resistor was printed using Carbon Sensor Paste (C2030519P4, Gwent Electronic Materials), also used as received. Zinc Oxide (ZnO) (>99%, Z/1300/60, Fischer Scientific) powder was mixed with a nitrocellulose (NC)-based vehicle in a 7:3 weight ratio, and homogenised using a three-roll mill to produce a viscous, white ink. The silver heatsink was printed using an altered version of the commercial silver paste used to print the interconnects. The Flexible Silver Paste (as mentioned above) was mixed with fumed silica (7 nm, 1002399468, Sigma-Aldrich) and homogenised using a three-roll mill to produce a more viscous, less electrically conductive silver paste with reduced solvent content. This paste however exhibits good thermal conductivity, and is less likely to leach through the ZnO layer and short-circuit the resistor [26].

2.2. Device fabrication
All structures were printed on the untreated side of 5 cm × 5 cm samples of Melinex ST504 Heat-Stabilized polyethylene terephthalate (175 μm thickness) (PET) (Dupont Teijin Films), a clear, flexible plastic substrate. All prints were made using a DEK 1202 screen printer and stainless steel screens with 230 (75/36) meshes. The silver interconnect was printed using a screen producing a 13 μm wet film while all other prints used screens producing 50 μm wet films. After all printing steps, the samples were cured in a box oven for 30 min at 120 °C.

Silver interconnect was printed as two dumbbells as shown in figures 1(a), (b) and then dried in a box oven as described above. The carbon resistor strip was then printed to connect the two silver dumbbells before being cured. Control samples underwent no further print steps and henceforth are known as carbon resistors (CR). Carbon resisters using a heatsink would undergo one or two further print steps. ZnO ink was printed covering the carbon strip entirely leaving only the silver interconnect exposed before being dried in the oven. These samples are known further as CR/ZnO. Samples using a silver heatsink would have the same process as CR/ZnO followed by printing the altered silver paste over the ZnO layer such that it covers the center section of the carbon
(that isn’t overlapping the silver interconnect), known further as CR/ZnO/Ag. Further designs were produced with the same layout as the CR/ZnO/Ag design however consisted of two or three layers of ZnO which are known further as CR/ZnO$_2$/Ag and CR/ZnO$_3$/Ag respectively. A visual cross-section and image of the print design is seen in figure 1.

Further to these core designs, another control was made which consisted of the CR design with then only the NC vehicle of the ZnO ink printed on top before being dried as above (CR2).

In order to remove the possibility of changes in performance due to curing effects, or a calendaring effect from the print process, samples with less printing steps than the maximum would have faux-prints done with no ink present and then placed in the oven as described above. For example, CR samples would have 2 print steps, while CR/ZnO/Ag samples would have 4 print steps, and so CR samples would undergo 2 faux-print steps so that in total the samples and consequently the carbon strips have undergone the same amount of compression from printing and the same amount of time in the oven. All samples had the outer squares of the interconnect covered in a small strip of copper tape in order to reduce damage to the films from electrical contacts.

### 2.3. Data collection

#### 2.3.1. Tolerance and critical power

Prior to testing, the cold resistance was measured for each sample using a Fluke 189 True RMS Multimeter as an ohmmeter while the samples were fixed in place to a 5 cm $\times$ 5 cm Teflon sheet square with the values used for the evaluation of tolerance. It was found in testing that printing the silver heatsink layer was short circuiting some of the samples and so the designs using 2 and 3 layers of ZnO were introduced to determine at what point the leaching issue ceased. The CR/ZnO/Ag design was kept due to the simpler and cheaper production process, as well so that it could be seen whether additional layers of ZnO hindered the tolerance and stability of the resistors. Tolerance measurements found that two layers of ZnO prevented device failure by silver leaching within the sample size while three layers of ZnO introduced a new method of failure in that the samples began to crack. Therefore, the CR/ZnO$_2$/Ag design was used for further testing, and the CR/ZnO$_3$/Ag design was removed.
Samples were clipped onto a hollow Teflon square (5 cm × 5 cm, 4 cm × 4 cm hole in centre) to ensure they remained flat. Samples were then connected to a Aim-TTi PL601 Power Supply in series with a Fluke 189 True RMS Multimeter as an ammeter and a Fluke 179 True RMS Multimeter as a voltmeter in parallel. Samples were then suspended in a blacked-out Faraday cage with a thermodiager TIM 400 thermal camera fixed in place above the sample to monitor the surface temperature. Thermal imaging data was collected using the TIM Connect thermal imaging software. Power was supplied to the samples in 0.5 V steps every 30 s with no current limiter in effect up to 15 V where it was held for 1 min before power supply was turned off. If the sample had catastrophically failed in the form of burning before reaching 15 V then the data collection would be stopped early.

2.3.2. Resistor stability
Device stability was measured in two ways. Method one was to expose the samples to varying environments of temperature and relative humidity (RH) using a Rotronic HygroGen for 100 h, measuring the resistance regularly. Tests were carried out at 50 °C/20%RH, 20 °C/50%RH, 50 °C/50%RH.

Method two was a sustained power dissipation study which used the same experimental setup as used for the critical power measurements. However, in this method the sample was stabilised at 1 V for 20 min, before using the calculated resistance from the applied voltage and measured current flow to determine the voltage required to dissipate 500 mW according to Ohm’s power law. From here the sample is kept at this applied voltage for up to 100 h or until the sample fails, with any changes in current flow and hence power dissipation measured. It should be noted that to prevent a fire risk, the top of the Faraday cage had two small holes with one where the wires were fed in, and the other where a Nederman extraction trunk was facing in order to remove any smoke from catastrophically failing samples. A diagram of the experimental setup used can be seen in figure 2. The convection introduced by the extraction trunk was measured by feeding a KIMO hotwire thermo-anemometer VT-115 through the air and wire inlet, and measuring the air flow rate. The flow rate in the position of the samples was found to be 0.09 m s⁻¹. This setup refers to the critical power study and the sustained power dissipation study.

3. Results and discussion

3.1. Tolerance
The CR, CR/ZnO, and CR/ZnO₂/Ag designs did not show any significant outliers in resistance values however the CR/ZnO/Ag design experienced some samples for which the resistance value was significantly lower than expected. This is due to leaching of the silver heatsink ink through the ZnO layer, shown in figures 3(a), (b), creating a lower resistance path than through the carbon, resulting in resistance values of 30–40 Ω. The samples
which were serious outliers in their resistance value were considered to be failures and are thus reflected in the failure rate in table 1. Failed samples were ignored in other calculations used in table 1 and instead each design was produced until there was a sample size of 10 ‘working’ devices.

The CR design showed a much greater standard error and mean absolute deviation than all other designs indicating it is less predictable than the other designs explored in this work with the worst tolerance of close to 20%. This is comparable to basic conventional carbon resistors [27]. This suggests that application of the ZnO layer can improve the tolerance of the carbon resistor. The ZnO layer however does not directly affect the current flow in the resistor as the CR2 control design displayed resistances considerably lower than any of the other core designs which when considered with the controls on print process involving ‘faux-prints’ means that the presence of ink vehicle on the surface on the carbon is what brings about the reduction in nominal resistance. This is likely a surface reorganisation effect to produce a more favourable structure for current flow. This effect could also be extended to explain the reduction in nominal resistance between the CR/ZnO/Ag and CR/ZnO2/Ag designs via partial leaching of the second ZnO layer through the first to initiate a second surface reorganisation effect.

Table 1. Mean resistance, standard error (STE) and mean absolute deviation (MAD) are calculated using a sample size of 10 working samples while failure rate was calculated from the total number of devices produced.

| Design       | Mean resistance/Ω | STE  | Fail rate/% | MAD  | Resistance for 10% tolerance/Ω |
|--------------|-------------------|------|-------------|------|-------------------------------|
| CR           | 186               | 3.99 | 0           | 9.6  | N/A                           |
| CR/ZnO       | 157.9             | 2.51 | 0           | 6.3  | 160                           |
| CR/ZnO/Ag    | 149.8             | 3.08 | 33          | 7.4  | N/A                           |
| CR/ZnO2/Ag   | 141.8             | 2.45 | 0           | 6    | 145                           |

Figure 3. Cross-sectional SEM (a) and SEM/EDX (b) displaying the leaching of silver through the zinc oxide layer to create lower resistance pathways in the resistor. Images (c) displays a cross sectional SEM with image (d) showing a cross sectional SEM/EDX demonstrating the lack of silver leaching through the zinc oxide layer. The fragments of Ag and ZnO in the carbon region are artefacts from the cutting process.
The leaching of silver through the ZnO layer was averted in the CR/ZnO/Ag design with no significant outliers in resistance as shown in figures 3(c), (d). A second layer of ZnO appears to be beneficial for both failure rate and tolerance, though the tolerance is likely affected by the CR/ZnO/Ag designs all experiencing varying degrees of leaching.

All designs tested above show tolerances that fit comfortably within the 20% tolerance often seen in conventional carbon resistors and the CR/ZnO and CR/ZnO2/Ag designs both present a resistance value around which all devices in the sample sit within a 10% tolerance enabling the resistors to be rated within the E6 and E12 tolerance categories respectively. Further, 70% of the CR/ZnO design samples, and 50% of the CR/ZnO2/Ag design samples were within 5% tolerance of the quoted 10% tolerance value (160Ω for CR/ZnO, and 145Ω for CR/ZnO2/Ag). This suggests that these designs could be utilised in a manufacturing process for resistors specified to a 5% tolerance.

3.2. Critical power

According to Ohm’s law, at a fixed resistance value, current flow increases linearly with applied voltage. This is an ideality and of course many factors affect the resistance of an electrical component such as the temperature of the surroundings, the applied voltage and subsequent power dissipated, and the thermal conductivity of the material. The temperature coefficient of a material dictates how the resistance will change with temperature. Most metals will present a positive temperature coefficient, meaning an increase in temperature results in an increase in resistance. Non-metallic materials such as semiconductors and carbon allotropes often have a negative temperature coefficient of resistance\[^{28, 29}\]. In order to limit this effect in electronics, heat management is utilised which extends their functional range by moving thermal energy away from the resistive element to a heatsink. This means that while a given level of power dissipation should correspond to a temperature rise in the component, it is instead acting as if it is effectively at ambient temperature. This concept is utilised to characterise the resistors studied in this research. As the resistor is fabricated using carbon, the resistance is expected to decrease due to its negative temperature coefficient. If the printed heat management is working as intended, then the resistors should be able to achieve a higher power dissipation before experiencing a deviation from the linear current-voltage relationship.

The power \(W\) can be calculated using Ohm’s law.

\[
\text{Power (W)} = \text{Voltage (V)} \times \text{Current (A)}
\]

By plotting the applied voltage against the measured current from the critical power measurements (figure 4(a)) the working regions of the resistors were examined. A linear relationship shows that the resistance is constant and therefore the resistor is behaving as it should. As the power being dissipated increases, and the resistor is no longer capable of sustaining a fixed resistance due to the heat generation, the current-voltage relationship will become non-linear. Resistor materials with a negative temperature coefficient of resistance (NTC), such as carbon, will show an increase in current flow that is non-linear with applied voltage, while resistor materials with a positive temperature coefficient of resistance (PTC) will show a decrease in current flow. Figure 4(a) shows examples of the current-voltage relationships with the data clipped just after the lines become non-linear. From the point of deviation the power can be calculated using Ohm’s law and is seen as the critical
power of the resistor, beyond which it no longer acts ideally. The steepness of the I–V relationships dictates the resistance of the resistors, with a steeper line corresponding to a lower resistance value—the trend in resistance values seen from the different designs is in-line with the changes seen and discussed in section 3.1. All designs deviate from linear in the 10–12 V region. The designs utilising ZnO and Ag layers are dissipating significantly higher power in this voltage region given their lower nominal resistance which will contribute to such deviations for those structures.

Figure 4(b) shows the comparison of critical powers achieved by the different resistor designs. The CR/ZnO design showed a 6.4% increase in critical power compared to the CR design, calculated from the means. The CR/ZnO/Ag and CR/ZnO₂/Ag designs then showed increases of 22.0% and 52.1% respectively, relative to the CR design. It is clear that the incorporation of ZnO coating with Ag heatsink dramatically improves the critical power of the carbon resistor. However, although this improvement in the critical power of the resistors with a printed heatsink is clear, the true cause of this needed to be determined. The printing of additional layers on top of the carbon resistors resulted in a lower resistance value. It needed to be shown whether the improvement in critical power was independent of the overall change in resistance caused by the second printed layer. It also needed to be determined what is actually causing this decrease in resistance. Control samples of the CR2 type resistors were printed with with the pure vehicle of the ZnO ink. This was performed in order to determine whether the effect could be achieved with any ink using this vehicle or whether the effect was actually from the heat dissipating properties of ZnO.

The CR2 samples having the vehicle of the ZnO ink printed on top of the carbon resistor showed much lower resistance values than any other samples. With the controls placed on sample production in the form of ‘faux-prints’ and secondary drying steps suggests that the improvement in resistance is due to the NC vehicle. This is either due to it’s contracting nature in the drying process or partial resolvation of the surface of the carbon particles into a more favourable alignment for conducting electricity. There is a possibility this could also be due to some sort of secondary curing effect of the initial layer but is unlikely as the curing of the inks are performed 10 °C higher and for 20 min longer than the specifications for this particular vehicle. For the manufactured inks. However, the CR2 design, while displaying the same change to resistance, also displayed a significantly lower critical power. This demonstrates that the improvement to the critical power does not come from favourable surface restructuring or contraction, but instead from the improved heat management properties offered by the ZnO and Ag layers.

While the range of critical power values was wider for the CR/ZnO/Ag design, it is still consistently better than the CR design. Most of the samples in this test ultimately ‘burnt out’ at a higher power dissipation. It was noted that for the CR and CR/ZnO designs, the position of burning of the resistor happened in the centre of the resistor. This means that the centre of the carbon strip is the position of the highest resistance resulting in a greater voltage drop in this region, equating to a higher power dissipation and thus a higher temperature resulting in burning. The resistor designs CR/ZnO/Ag and CR/ZnO₂/Ag, however, burnt at the junction between the carbon and Ag interconnect (examples of the burn positions can be seen in figures 5(a) and (b)). This means that the heat generated at the centre of the strip was being adequately managed by the coatings, but it could not manage the heat generated at the junction. This was expected as the Ag heatsink layer did not cover the junction and electrical junctions are well-known for introducing resistance to circuits. This does not mean that the junction resistance is significant—theoretical resistance calculations for the resistors roughly matched those of the CR design—it means that because the heat generated by the carbon strip is being adequately managed, the next most-resistive region, outside of the coverage of the thermal management will be the failure point.

3.3. Resistor stability
In general the stability of all resistor designs was acceptable at 50 °C and 20%RH with the CR and CR/ZnO designs showing the only appreciable level of variation as seen in figure 6(a). The CR/ZnO/Ag and CR/ZnO₂/Ag designs are again very stable at 20 °C and 50%RH while the CR/ZnO design appears to suffer
from hydration of the ZnO layer. It was observed in the process of testing that resistance values of the design using ZnO layers would appear to be far greater than expected (>1 kΩ). This effect was more pronounced in the CR/ZnO design than in the CR/ZnO/Ag or CR/ZnO₂/Ag designs, and was not present at all in the CR design. As the ZnO layer becomes hydrated in humid conditions (>50% RH) it begins to exhibit changing resistance once a multimeter is applied for measurement. The water drawn into the device by the hygroscopic ZnO could be responsible for the observed effect through either its high dielectric permittivity or through ionic conductivity, forming an electric double layer and adding parasitic capacitance to the circuit. This capacitive behaviour creates an issue with ohmeters resulting in displayed resistance values much greater than the reality. To bypass this problem, prior to taking resistance measurements the leads were held together for 20 s in order to discharge the ‘capacitor’. This explains why the CR/ZnO readings are unexpectedly high in figure 6(b) as the ‘capacitor’ could not be completely discharged. With the CR/ZnO/Ag and CR/ZnO₂/Ag designs both having the ZnO layer partially covered by silver suggests that it was harder for the ZnO layer to become fully hydrated, and therefore the effect was less pronounced. In manufacturing, this issue can be overcome through the same encapsulation techniques typically used for thermistors and printed sensors. An environment of 50 °C and 50%RH created the most variance with the CR/ZnO/Ag and CR/ZnO₂/Ag both remaining the most stable across 100 h (6000 min). The CR/ZnO design was more stable however than it was in the 20 °C and 50%RH environment. This could be due to an increased temperature therefore a greater mobility of the water. A greater mobility would allow for easier discharge of the effect noted above. Aside from the CR/ZnO design in the 20 °C/50%RH environment, only the CR design saw dramatic variation in resistance within the environments tested. This suggests that as well as improving the tolerance and critical power, the introduction of ZnO and Ag layers can also improve carbon resistor stability in difficult environmental conditions. Sustained power dissipation tests showed a marked improvement of all designs compared to the simple CR design as seen in figure 7. The CR design (figure 7(a)) catastrophically failed somewhere between 3 and 24 h (180–1440 min) of sustained power dissipation while all other designs lasted a full 100 h (6000 min) without visible damage to the samples. The CR/ZnO design (figure 7(b)) gradually became more conductive over time.

Figure 6. Effect of controlled environments on the stability of different resistor designs. (a) 50 °C and 20% relative humidity, (b) 20 °C and 50% relative humidity, (c) 50 °C and 50% relative humidity.

![Figure 6](image_url)
until reaching a power of 716 mW at the 100 h endpoint, equating to a 43.2% increase in power dissipation and 30.2% decrease in resistance. The CR/ZnO/Ag design (figure 7(c)) was more stable showing less signs of significant changes in conductivity until between 73 and 100 h (4380–6000 min) where it finished at 627 mW, showing a 25.4% increase in power dissipation and 20.3% decrease in resistance. Finally, the CR/ZnO2/Ag design (figure 7(d)) was the most stable, only breifly reaching 570 mW and overall showing no signs of steady increase in conductivity within the 100 h test. The peak power dissipation of 570 mW shows a 14.0% increase in power dissipation and 12.3% decrease in resistance. However, the final value at 100 h was 517 mW giving a 3.4% increase in power dissipation and 3.3% decrease in resistance.

While no samples stayed within 10% variance in resistance during the 100 h tests, the CR/ZnO2/Ag design displayed no consistant upwards trend in power dissipation at the end of the test suggesting that while the CR/ZnO and CR/ZnO/Ag designs were deteriorating and heading towards failure, the CR/ZnO2/Ag design was not. It should also be stated that whilst less than 10% variance under load was not achieved over the course of 100 h, both the CR/ZnO/Ag and CR/ZnO2/Ag design would likely achieve this in applications that do not require constant power. Further, the CR/ZnO2/Ag design stayed comfortably below 20% variance which is a significant step forward compared to the basic CR design.

While it cannot be claimed that any designs could indefinitely dissipate 500 mW, it is clear that the designs incorporating ZnO and Ag films are far more stable and could feasibly do so in systems not requiring constant power. Alternatively, designs utilising ZnO and Ag films would likely become indefinitely stable at a power below 500 mW at which the CR designs would not such as 250 mW, a power rating commonly assigned to conventional carbon resistors.

4. Conclusions

The introduction of either a single ZnO layer or two ZnO layers and one Ag has been shown to display a notable improvement in initial tolerance such that within a sample size of 10 devices, all were within 10% of the resistance of a particular value. The ZnO and Ag layers also provided sufficient thermal variance mitigation such that critical power was improved by up to 52.1%, and 500 mW sustained power dissipation was possible without
significant deviation from the initial resistance value. Resistors utilising ZnO and Ag layers also displayed greater stability in varying environmental conditions compared to basic carbon resistors.

The findings presented here indicate that carbon resistors can be printed on flexible substrates while adhering to standardised tolerances with power ratings comparable to conventional resistors. The findings also present economical options for product design in that low-power applications (<500 mW) can utilise the design using only the ZnO layer for improved tolerance without the costly Ag layer that improves power stability.

Proposed further research should focus on three identified areas. Firstly, modification of the carbon stip width and shape (i.e. ‘zig-zag’) to control the nominal resistance and thus create resistors that more closely represent the decade values outlined in conventional resistor standards such as IEC 60063. Second, the demand for printable resistors to meet conventional resistor standards whilst also being suitable for flexible applications cannot be ignored. Therefore, adopting the concepts presented here whilst accounting for flex-induced resistance changes to produce resistors with flex-invariant resistance with tolerance and power ratings in-line with conventional standards is of great interest. Finally, exploration of either encapsulation methods to prevent moisture effects seen in the stability tests, or utilisation of different thermal transfer materials that are water resistant to remove the capacitor-like behaviour seen from the ZnO.

Acknowledgments

The authors greatly appreciate the help of industrial and academic partners. Help was received from Professor. Bill MacDonald of DuPont Teijin Films who has supplied the PET films used. The authors acknowledge use of facilities within the Loughborough Materials Characterization Centre. The research was funded by the EPSRC Doctoral Training Programme (DTP) at Loughborough University.

ORCID iDs

Ryan B Middlemiss https://orcid.org/0000-0003-3316-4813
Jack R McGhee https://orcid.org/0000-0001-7372-1966
Darren J Southee https://orcid.org/0000-0001-5428-8300
Upul K G Wijayantha https://orcid.org/0000-0003-0258-2385

References

[1] McGhee J R, Sinclair M, Southee D J and Wijayantha K G U 2018 Strain sensing characteristics of 3D-printed conductive plastics Electron. Lett. 54 570–2
[2] Chu Z, Peng J and Jin W 2017 Advanced nanomaterial inks for screen-printed chemical sensors Sensors and Actuators, B: Chemical 243 Elsevier 919–26
[3] Hayat A and Marty J 2014 Disposable screen printed electrochemical sensors: tools for environmental monitoring Sensors 14 10432–53
[4] McGhee J R, Middlemiss R B, Southee D J, Wijayantha K G U and Evans P S A 2018 Flexible, all metal-oxide capacitors for printed electronics 2018 IEEE 13th Nanotechnology Materials and Devices Conf. (NMDC) 1–4
[5] Kwon Y-T, Lee Y-L, Kim S, Lee K-J and Choa Y-H 2017 Full densification of inkjet-printed copper track on a flexible substrate utilizing a hydrogen plasma sintering Appl. Surf. Sci. 396 1239–44
[6] Ryu B-H et al 2005 Synthesis of highly concentrated silver nanosol and its application to inkjet printing Colloids Surfaces A Physicochem. Eng. Asp. 270–271 345–51
[7] Somalu M R, Muchtar A, Daud W R W and Brandon N P 2017 Screen-printing inks for the fabrication of solid oxide fuel cell films: a review Renew. Sustain. Energy Rev. 75 Pergamon 426–39
[8] Gonzalez-Guerrero M and Gomez F A 2019 An all-printed 3D-Zn/Fe3O4 paper battery Sensors Actuators B Chem. 289 226–33
[9] Khan S, Lorenzelli L and Dahyia R S 2015 Technologies for printing sensors and electronics over large flexible substrates: a review IEEE Sens. J. 15 3164–85
[10] Qian C et al 2019 All-printed 3D hierarchically structured cellulose aerogel based triboelectric nanogenerator for multi-functional sensors Nano Energy 63 103885
[11] Bao Z and Chen X 2016 Flexible and stretchable devices Adv. Mater. 28 4177–9
[12] International Electrotechnical Commission 2015 IEC 60063:2015, Preferred number series for resistors and capacitors
[13] Tian H, Liu H and Cheng H 2015 Microstructural and electrical properties of thick film resistors on oxide/oxide ceramic-matrix composites Ceram. Int. 41 3214–9
[14] Hlima J, Reboun J, Johan J, Simonovsky M and Hamacek A 2019 Reliability of printed power resistor with thick-film copper terminals Microelectron. Eng. 216 111095
[15] Jiang X et al 2016 Foldable and electrically stable graphene film resistors prepared by vacuum filtration for flexible electronics Surf. Coatings Technol. 299 22–8
[16] Santiago M et al 2017 Flexible and foldable fully-printed carbon black conductive nanostructures on paper for high-performance electronic, electrochemical, and wearable devices ACS Appl. Mater. Interfaces 9 24365–72
[17] Michel M et al 2017 A thermally-invariant, additively manufactured, high-power graphene resistor for flexible electronics 2D Mater. 4 025076
[18] Kumar S, Bhattacharjee K, Kumar P, Sharma S, Kumar A and Tripathi C C 2019 Laser patterned, high-power graphene paper resistor with dual temperature coefficient of resistance RSC Adv. 9 8262–70
[19] Perelaer J et al 2010 Printed electronics: the challenges involved in printing devices, interconnects, and contacts based on inorganic materials J. Mater. Chem. 20 8446

[20] Scarisbrick R M 1973 Electrically conducting mixtures J. Phys. D: Appl. Phys. 6 2098–110

[21] Lai Z, Hu H and Ding G 2018 Effect of porosity on heat transfer and pressure drop characteristics of wet air in hydrophobic metal foam under dehumidifying conditions Exp. Therm Fluid Sci. 96 90–100

[22] Kumar S, Sarkar M, Singh P K and Lee P S 2019 Study of thermal and hydraulic performance of air cooled minichannel heatsink with novel geometries Int. Commun. Heat Mass Transf. 103 31–42

[23] Yamada Y, Yanase M, Miura D and Chikuba K 2016 Novel heatsink for power semiconductor module using high thermal conductivity graphite Microelectron. Reliab. 64 184–8

[24] Olorunyolemi T et al 2004 Thermal conductivity of zinc oxide: from green to sintered state J. Am. Ceram. Soc. 85 1249–53

[25] Agari Y and Uno T 1985 Thermal conductivity of polymer filled with carbon materials: effect of conductive particle chains on thermal conductivity J. Appl. Polym. Sci. 30 2225–35

[26] Wilson S et al 1996 Void elimination in screen printed thick film dielectric pastes. European Study Group with Industry (ESGI 29)

[27] Bardsley M and Dyson A F 1974 Carbon composition, cracked carbon, metal film and metal oxide resistsors Radio Electron. Eng. 44 188

[28] Lee S-E et al 2016 Suppression of negative temperature coefficient of resistance of multiwalled nanotube/silicone rubber composite through segregated conductive network and its application to laser-printing fusing element Org. Electron. 37 371–8

[29] Di Bartolomeo A et al 2009 Multiwalled carbon nanotube films as small-sized temperature sensors J. Appl. Phys. 105 64518