Influence of the geometry of defects in textronic structures on their electrical properties

S Pawłowski¹, J Plewako² and E Korzeniewska³

¹ Department of Electrodynamics and Electrical Machine Systems, Rzeszow University of Technology, Rzeszow, Poland
² Department of Power Electronics and Power Engineering, Rzeszow University of Technology, Rzeszow, Poland
³ Institute of Electrical Engineering Systems, Lodz University of Technology, Lodz, Poland.

e-mail: spawlo@prz.edu.pl, jplewako@prz.edu.pl, ewakorz@matel.p.lodz.pl

Abstract. Continuity of the conductive path is a prerequisite for the phenomenon of electric current to exist in the structures of wearable electronics. The value of the current depends not only on the material properties of the structure but also on the geometrical dimensions of the defect of a thin electrically conductive layer. The article describes the analysis of the influence of the width and slope of the linear defect of a thin metallic layer on the value of the current. The conducted simulations show that when the width of the defect is smaller than 40% of the distance of the defect from the edge of the path, the current intensity depends on the ratio of the width to the length of the defect to a very small extent. The value of the current also depends on the slope of the defect to the path axis. In the case of a larger number of defects, their influence on the effective track resistance depends not only on their size but also on their location and distance from each other. The resistance of the entire electrically conductive layer is also influenced by the location of defects in relation to its edges.

1. Introduction

Thin metallic layers with good electrically conductive properties are used in many areas of science, including wearable electronics, textronics or thin-film sensors. They are created as a result of many technological processes, including chemical vacuum deposition [1], physical vacuum deposition [2,3], inkjet printing [4], magnetron sputtering [5,6], embroidery [7,8] etc. Each of the mentioned processes has advantages and disadvantages. Undoubtedly, the advantage of physical vacuum deposition is the lack of adverse environmental side effects.

Physical vapor deposition (PVD) is the deposition of atoms or particles of a material such as metals, alloys, metal oxides, and some composite materials, which, when applied with high energy, under high vacuum, are evaporated from a solid source and then deposited forming thin layers on the substrate. Coatings produced in the PVD technology show high hardness and durability, as well as wear resistance. A characteristic feature of such layers is high resistance to corrosion and abrasion. In these processes, the material can be deposited on various substrates, such as glass, silicon, aluminum oxide substrate or textiles. The latter-mentioned substrates deserve special attention in this case, due to the flexibility of the substrate as well as its three-dimensional structure. The production of thin electrically conductive layers in the PVD process requires special technological measures to adapt the substrate in order to enable the deposition of a metallic layer, most often with a thickness of several to several thousand Å.
Metallic structures created on flexible substrates of textile products can be used in textronics and other sensory applications [9, 10]. They are exposed to mechanical damage resulting from the stresses on these layers during use. The occurring damages and discontinuities affect the value of the layer resistance and the path of electric current flow. In the initial phase, single long defect appear, as shown in Figure 1. The image was taken with the Optical SZ 630-T optical microscope with a magnification of 60x. The figure shows a structure made of 99.99% pure silver on a textile composite substrate - the membrane.

![Fig. 1. A microscopic photo of the surface of a metallic layer produced in the PVD technology on a composite textile substrate after 100 bending cycles [11].](image)

The purpose of this article is to analyse the effect of the width and slope of a single defect as well as the impact of the location of two line defects on the value of the current intensity in the layer. The research was carried out with numerical simulations using the method of integral equations, described in detail in [12, 13].

2. **Formulation of the problem**

The subject of the problem is to search for the distribution of the vector field of current density $\mathbf{J}$ in a thin conducting path containing one or more defects. The model geometry is illustrated in Figure 2.

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![Fig. 2. The analyzed model of the conducting path with a defect](image)
1. The area of the conducting path is a uniform, isotropic and linear rectangular conductor.
2. The defect region and the path surroundings are homogeneous, isotropic and linear dielectrics with zero conductivity.
3. A constant voltage $u$ is applied between the ends of the path (lines $L_1$ and $L_2$ in Fig. 2).
4. All field functions are independent of the $z$ coordinate placed perpendicular to the surface of the path.
5. The stationary operating state of the system is analysed.
6. There are no unbalanced electric charges in the system.

According to the above assumptions, the sought function of the current density field $J$ can be related to the electric field strength $E$ by the relationship (local Ohm's law):

$$ J = \gamma E $$  \hspace{1cm} (1) $$

where $\gamma$ is the conductivity of the layer.

From assumption 5 and Faraday's law it follows that the electric field is a non-vortex field ($\text{rot} E = 0$), which allows it to be expressed by the scalar potential $\phi$:

$$ E = -\nabla \phi $$  \hspace{1cm} (2) $$

On the basis of Gauss's law and assumption 6 we have:

$$ \nabla \cdot E = 0 $$

which in connection with the equation (2) means that the potential $\phi$ satisfies the Laplace equation

$$ \Delta \phi = 0 $$  \hspace{1cm} (3) $$

According to assumptions 4 and 5 we have: $\phi = \phi(x, y)$. The boundary conditions for the potential $\phi$ at the edges of the path and the defect are given by:

$$ \phi(0, y) = u, \quad \phi(l, y) = 0 $$  \hspace{1cm} (4) $$

$$ \left. \frac{\partial \phi}{\partial n} \right|_{y=0} = \left. \frac{\partial \phi}{\partial n} \right|_{y=L} = 0 $$  \hspace{1cm} (5) $$

where the symbol $\Gamma^\pm$ denotes the boundary surface of the defect on the side of the conductive area.

The problem comes down to the search for a solution to equation (3) with mixed boundary conditions (4), (5). In order to solve it, the method of integral equations was used. Its detailed description and algorithm is presented in [12, 13]. The numerical application was implemented in the Microsoft Visual Studio 2010 environment in Fortran 77 language. It enables the calculation of the flow field distribution and the current intensity in a path containing any number of defects of any given shape.

### 3. Simulation results

#### 3.1 Influence of the defect width

Defects in textronic layers usually have the shape of scratches (cracks), the width of which is much smaller than their length (see Fig. 1). It suggests that they can be modeled as infinitely thin, i.e. with lines on which the potential meets the condition (5). Such idealization significantly simplifies and accelerates the simulation; its correctness, however, may raise some doubts due to the singularities that appear at the end points of the defect line. As it results from the precise analytical solution for a defect with the shape of a rectilinear segment presented in [12], the current density at its ends assumes infinite values (despite the continuity of the potential). Therefore a problem appears how this effect may affect the accuracy of the calculation of the total current in the conductive path.
In order to investigate this issue, a series of simulations was carried out for rectangular defects with one side lying on one edge of the path and compared with the case of an infinitely thin defect of the same length.

Figure 3 shows the analyzed system and an example of the vector field distribution of current density and potential. The presented simulations concern the path with the ratio $l/H = 10$ and defects of various dimensions located in its central part (for better visualization, the area of the path was limited to the vicinity of the defect in the charts).

![Fig. 3. Calculated distributions of the current density (a) and potential (b) fields in the analysed system with a rectangular defect](image)

It should be expected that in such a system, the dimensions of the "conductive channel", i.e. the area between the defect and the edge of the path, marked with symbols in Figure 3, have the most significant impact on the total current flow. The plots in Figure 4 show the results of the current in the path as a function of the $w/c$ ratio.
The current values are related to the current $i_0$, it means the current flowing in the same defect-free path. Different curves correspond to defects with different heights $h$ related to the track width $H$.

![Fig. 4. The dependence of the current in the defective structure on the width of the defect and its distance from the edge of the conductive path](image)

These results indicate that for conductive channels with the ratio $w/c < 0.4$, the current intensity depends on the mentioned ratio to a very small extent and the error does not exceed 1%. The error can be caused by modelling defects in such cases considered as infinitely thin ($w = 0$).

In the range $0.4 < w/c < 1.0$, the error caused by such idealization is in the range of 5% and in the most practical applications it can also be considered as acceptable. With regard to the typical crack sizes of textronic layers, this means that only in very special cases, i.e. when the width $c$ of the conductive channel is comparable with the crack width $w$, such idealization can lead to more significant errors.

3.2. Influence of defect slope

![Fig. 5. Calculated current density field distribution in the case of a defect tilted to the path axis and a direct contact of the defect with one of its edges.](image)
Simulations of current flow in paths with an infinitely thin defect indicate that in addition to the width of the conducting channel, the slope of the defect may also have a significant impact on the total value of the current. Two types of systems were analysed - with one and two conducting channels (Fig. 5 and 6).

![Fig. 6](image1.png)

Fig. 6. Calculated current density field distribution in the case of a defect tilted to the path axis and placed away from both its edges.

The results of the simulations are presented in the diagrams in Figure 7.

![Fig. 7](image2.png)

Fig. 7. The dependence of the current flowing in the path on the defect inclination angle to its axis. The continuous lines correspond to the system with one conducting channel (Fig. 5), and the dashed lines - with two channels (Fig. 6). The curves corresponding to the same total width of the conductive channels \( c \) are marked with the same colours.

The course of these curves indicates that the sharper the defect's inclination angle to the path axis, the greater its resistance at the same width of the conducting channel. This effect is clearly stronger when one of the ends of the defect meets one of the path edges (i.e. there is only one conductive channel with width \( c \)) than when both ends are distant from these edges (two conductive channels with width \( c/2 \)). This effect can be explained by the fact that in the first of the above-mentioned cases between the defect line and the path edge there is a "dead" area in which the current practically does not flow (cf. Fig. 5).
This area is larger, the sharper the angle of the defect is. The ability to flow around the defect from both sides eliminates the dead area, but the dependence on the defect angle also occurs. The dependence is the stronger, the narrower the conductive channel is.

The comparison of the plots which correspond to the systems with one and two conducting channels also shows that in the second case the resistance is clearly lower, despite the same total width of the channels. This effect can be explained by the fact that, near the ends of the defect, the current density increases strongly. It means that two conductive channels allow for more current value in comparison to one channel.

3.3. Two parallel linear defects

In the case of more defects, their influence on the effective track resistance depends not only on their size and shape, but also on their location in relation to each other. The graphs in Figures 8 and 9 show the results of the simulation of the flow field in a path with two parallel line defects of equal lengths in two different configurations.

In the case of configuration I (Fig. 8), there is a dead zone between the defects, which additionally increases the resistance of the track.

The continuous lines in Figure 10 show the dependence of the current intensity in the path as a function of the ratio of the distance $s$ between the defects to the path width $H$. When the distance between the defects increases, the area of the dead zone increases and the current intensity decreases to a certain limit value.
Fig. 10. The dependence of the current intensity on the distance between defects in the configuration from Figure 8 (solid lines) and the configuration from Figure 9 (dashed lines) for different channel widths $c$.

In the configuration II, shown in Figure 9, there is no dead zone, but the influence of the proximity of defects on the path resistance is even stronger (dashed lines in Figure 10). It is caused by the elongation of the effective current path and the reduction of the effective cross-section of the current path in the section between the defects. When the distance between the defects increases, the current intensity increases to the same limit value as in configuration I.

4. Summary

During the use of flexible conductive layers, defects appear. Their shape, size and number depend on the method and time of their use. The influence of these defects on the conductive properties of the layer depends on many factors. This paper focuses on defects in the form of long and thin cracks, which usually occur when the conductive path is subjected to bending stresses. The results of simulation tests concerning the dependence of the current intensity in the conducting path on the geometry (length to width ratio) of the defect, the angle of its inclination to the path axis as well the configuration of two linear defects and the distance between them are presented. The results of the conducted research are presented in plots (Fig. 4, Fig. 7, Fig. 10). Detailed qualitative and quantitative analyzes of the impact of defects on current conduction in a thin conducting layer and their interpretations are described in the paper.

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