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NOISE PROPERTIES OF GRAPHENE-POLYMER THICK-FILM RESISTORS

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Abstract

Graphene is a very promising material for potential applications in many fields. Since manufacturing technologies of graphene are still at the developing stage, low-frequency noise measurements as a tool for evaluating their quality is proposed. In this work, noise properties of polymer thick-film resistors with graphene nano-platelets as a functional phase are reported. The measurements were carried out in room temperature. $1/f$ noise caused by resistance fluctuations has been found to be the main component in the specimens. The parameter values describing noise intensity of the polymer thick-film specimens have been calculated and compared with the values obtained for other thick-film resistors and layers used in microelectronics. The studied polymer thick-film specimens exhibit rather poor noise properties, especially for the layers with a low content of the functional phase.

Keywords: graphene, polymer thick-film resistor, low-frequency noise, noise measurements.

1. Introduction

Graphene is a very promising material for potential applications in many fields, especially in micro- and nano-electronics. Its outstanding properties make it an ideal material for various applications, *e.g.* optoelectronics [1], RF communications [2], strain and pressure sensors [3, 4]. Due to its very high thermal conductivity, graphene is also used in electronic devices as a heat dissipation material [5]. One more application of graphene is its use as a conducting material in polymer resistors. *Polymer thick-film resistors* (PTFRs) have many advantages, among others a wide resistivity range, low processing temperature, low cost. Although they have been used in electronics for many years, they are considered as good candidates for the next generation of functional electronic components, especially due to their flexibility [6, 7]. Manufacturing technologies of this material are still in the developing stage. Therefore, many works dealing with PTFRs are focused on their electrical properties [8–10]. It is also well known that low-frequency noise measurements can be used as a tool for evaluating material quality. In this work, noise properties of polymer thick-film resistors, made of polymer and graphene, are studied in order to evaluate quality of the studied material.

2. Experiment

2.1. Specimens

Specimens for the measurements were manufactured in the thick-film technology. A resistive layer in PTFR specimen contains graphene nanoparticles dispersed in a polymer vehicle. Graphene nanoparticles were prepared from graphite using a modified Hummer's

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method, acquired from Cheap Tubes Inc. Characteristic dimensions, estimated from *Scanning Electron Microscope* (SEM) observations, were 10 nm for average thickness and 15 µm for average particle diameter. The polymer vehicle selected to prepare the ink for printing was a solution of Mw 350 000 *poly-methyl metacrylate* (PMMA) in diethylene glycol butyl ether acetate (8 wt.%). Compositions of graphene nanoparticles in PMMA polymer vehicle were prepared with a modified mixing process used in thick-film material preparation. The main purpose of the mixing process is to prepare a well-dispersed paste without agglomerates. This was achieved by the sonication of carbon nanomaterials with dispersing agents in toluene for 60 minutes at room temperature. Malialim AKM-0531 dispersing agent provided by NOF Corporation was used for the surface treatment of carbon powders, to improve dispersion. Addition of 5 wt.% of the dispersing agent in respect to the weight of carbon fillers was sufficient to break agglomerates. After the partial evaporation of toluene, all specimens were mixed with PMMA vehicle in a mortar for 15 minutes. Afterwards, the pastes were homogenised on a three-roll mill with *silicon carbide* (SiC) rollers and a 5 µm gap. The specimens patterned into multi-terminal devices (see Fig. 2) of size 1 × 5 mm were printed with an AMI Presco 242 screen printer with 200 mesh stainless steel screens. Afterwards, the layers had been cured in 120ºC for one hour. Film thickness was estimated to be 10 µm. A SEM picture of cross-section of resistive layer after firing is shown in Fig. 1.

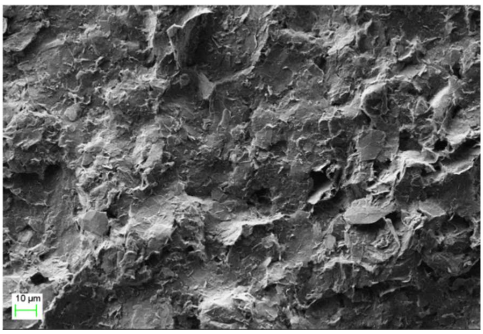

Fig. 1. A SEM picture of resistive layer.

2.2. Measurement setup

Low-frequency noise measurements have been performed in the dc Wheatstone bridge configuration. To dump fluctuations of the bias source voltage, a low-pass filter with a large time constant was placed between the dc source and the bridge. In the upper arms of the bridge, wire-wound resistors with a resistance much higher than that of specimens have been placed. The specimens were placed in the bottom arms of the bridge (Fig. 2). As thick-film resistors have been printed in pairs (on one substrate), two PTFR specimens of nearly the same resistance have been used. A noiseless wire-wound variable resistor has been connected in series with one of the PTFRs to enable balancing of the bridge. The amplified voltage signal from the bridge diagonal has been low-pass filtered and converted to digital samples in the *data acquisition* (DAQ) board. Then *power spectral densities* (PSDs) of voltage fluctuations S_{Vs} have been calculated.

The specimens have been mounted on a heat plate which temperature can be precisely controlled by an external temperature controller. The measurements were performed as a function of bias at room temperature.

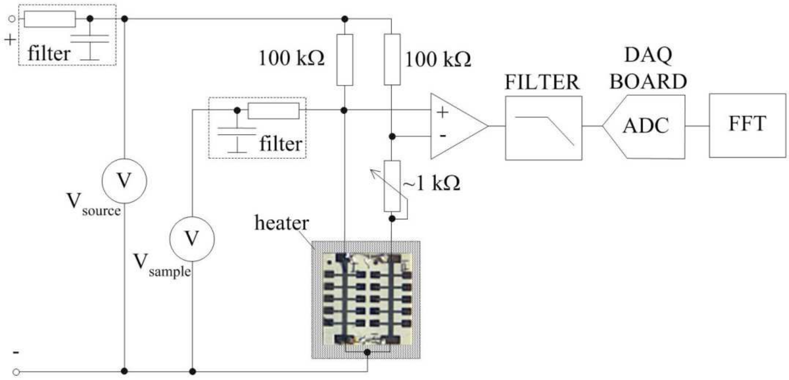

Fig. 2. The measurement setup.

3. Results

3.1. Noise intensity

In order to identify noise components, PSDs (S_{Vs}) of voltage fluctuations have been measured for several sample voltages, V_s. Then excess noise spectra have been calculated as $S_{Vex} = S_{Vs} - S_{Vs=0}$, where $S_{Vs=0}$ is the background noise, *i.e.* a PSD measured at $V_s = 0$. The resulted excess noise spectra measured at room temperature are plotted in Fig. 3.

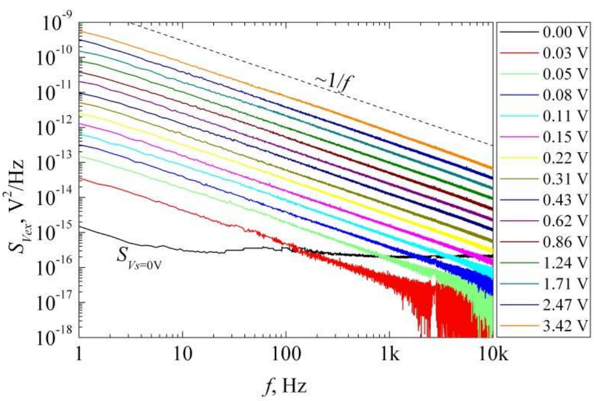

Fig. 3. The excess noise spectra, S_{Vex}, measured at room temperature for different bias voltages together with the background noise spectra, $S_{Vs=0}$.

Since the observed spectra $S_{Vex}(f)$ exhibit $1/f$ dependence, the product fS_{Vex} is frequency-independent. After averaging in some frequency band, Δf, it can be used as a reasonable measure of noise intensity. The data in Fig. 4 reveal that the noise intensity, $\langle fS_{Vex}\rangle_{\Delta f}$, scales linearly with the sample voltage squared. Usually, such a behaviour is interpreted as the evidence that $1/f$ noise is caused by the resistance fluctuations [11].

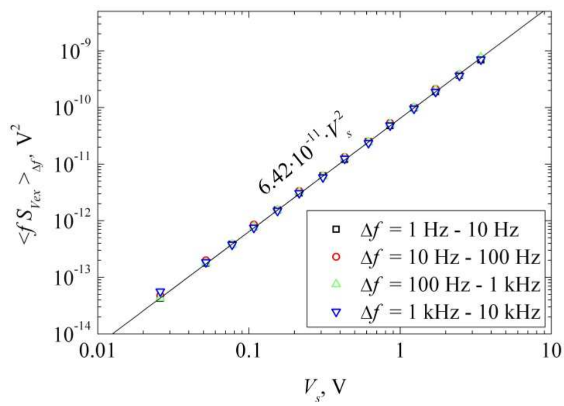

Fig. 4. The noise intensity, $\langle f S_{Vex} \rangle_{\Delta f}$, vs. sample voltage, V_s, for a PTFR specimen calculated for different frequency bands (points). The approximating line has a slope of 2.
The measurements were carried out at room temperature.

It stems from the observed scaling that the quantity $\langle f S_{Vex} \rangle_{\Delta f}/(V_s)^2$, which can be termed *relative noise intensity*, is voltage-independent and can be used to compare noise properties of different specimens, however of the same volume. This conditioning arises from the Hooge's phenomenological formula [12]:

$$S_V \sim \frac{V^2}{Nf}, \tag{1}$$

where N is the total number of carriers in a specimen which is proportional to the specimen volume.

3.2. Noise of resistive layer

In order to compare noise properties of different materials, a parameter $C \equiv \text{volume} \cdot \langle f S_{Vex} \rangle_{\Delta f} V_s^{-2}$, independent of the specimen volume, should be used. The values of this parameter, evaluated for the studied PTFR specimen, are gathered in Table 1 and plotted in Fig. 5 as a function of specimen's resistivity. Another parameter, which is considered as a figure of merit in respect to $1/f$ noise and quality of the technology, is a ratio $K \equiv C/\rho$, where ρ is resistivity [13]. The parameter K is also independent of specimen's size and dimensions. The values of this parameter are also provided in Table 1 as well as in Fig. 5.

Table 1. The parameter values of the studied PTFR specimens.

Graphene content, wt %	ρ, Ω cm	K, μm²/Ω	C, m³
24	$2.43 \cdot 10^{-3}$	$3.13 \cdot 10^{-8}$	$7.61 \cdot 10^{-25}$
5	0.488	$2.87 \cdot 10^{-6}$	$1.40 \cdot 10^{-20}$
4	0.736	$1.39 \cdot 10^{-6}$	$1.02 \cdot 10^{-20}$

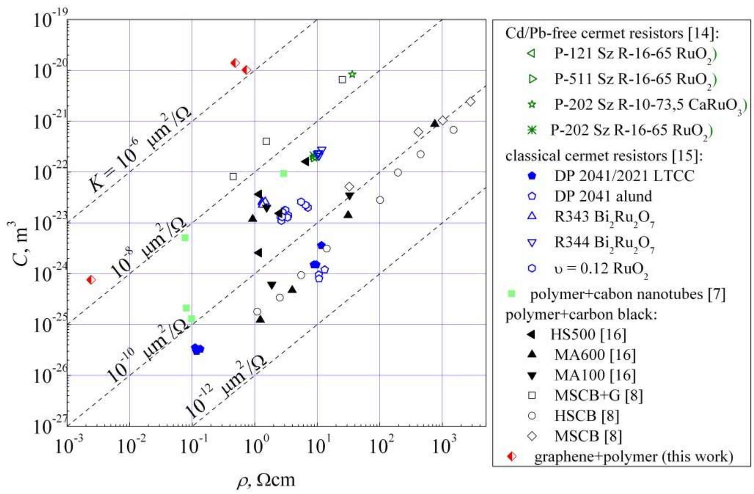

Fig. 5. The values of C and K parameters for different graphene-polymer thick-film resistors compared with those of other types of TFRs.

The values of C and K obtained for the studied PTFRs are compared with the values for other thick-film resistors used in microelectronics, especially those that use a polymer matrix. These values are presented in Table 2 and in Fig. 5. All of them are considerably lower. So one can conclude that noise properties of the studied specimens are rather poor and therefore the technology should be further improved, especially for the layers with a low content of the functional phase.

Table 2. The values of parameter K for various thick-film resistors (CNT – carbon nanotubes, MSCB – medium structure carbon black, HSCB – high structure carbon black).

Thick-film resistor type	K, μm^2/Ω
RuO_2 on LTCC substrate [17]	$2.5 \cdot 10^{-11}$
RuO_2 on alumina substrate [17]	$4 \cdot 10^{-10}$
$Bi_2Ru_2O_7$ [17]	$2 \cdot 10^{-9}$
$CaRuO_3$ [15]	$2 \cdot 10^{-8}$
poly/CNT [7]	$3.3 \cdot 10^{-9}$
polymer+carbon black: MSCB, graphite+MSCB, HSCB [8]	$4.3 \cdot 10^{-11}$, $4 \cdot 10^{-8}$, $2.7 \cdot 10^{-11}$

4. Summary

1/*f* noise caused by resistance fluctuations has been found to be the main noise component in the studied specimens of polymer thick-film resistors. The values of noise parameter, either K or C, for PTFRs are substantially higher than those for other thick-film resistors used in microelectronics, especially for a low content of the functional phase. These observations might be helpful in further optimization of the technology process in order to gain a technological advantage.

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