08

Inductive properties of disordered carbon of shungite

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Impedance measurements in the frequency range 0.1−15 MHz for samples of natural disordered carbon (shungite) made it possible to establish the dependence of active resistance and inductance on carbon content. If the resistance drops sharply with increasing C content, reaching a plateau at C of about 50%, then the inductance L has a pronounced power-law dependence $L \sim \mathrm{C}^{-0.7}$. The frequency at which inductance begins to affect impedance increases successively with increasing carbon content in the samples.

Keywords: natural disordered carbon, impedance, resistance, inductance.

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Glass carbon is a solid and isotropic material with low density contrary to graphite material. Good gas impermeability, chemical stability and thermal resistance, high electroconductivity [1–6] make it possible to successfully use synthetic and natural glass carbon materials in various technological processes. The reference glass-like material of natural origin contains shungite rocks of Karelia, which are a carbon-mineral composite with carbon content from 2 to 97 at.%. [7,8]. The shungite structure is based on local ordering of carbon atoms into honeycomb structures with covalent bonds (graphene layers with the size of several nanometers) and forming various turbostratic aggregates (stacks, tapes, globules) with Van der Waals bonds between the layers. Electron and X-ray amorphism prevent building a statistically unambiguous picture of these structures distribution in the specimens. Study of electrophysical properties of both shungite carbon and mixed material, where the substantial part belongs to poorly conducting or non-conducting mineral inclusions, made it possible to detect some interesting features of dynamic conductivity and microwave properties related to the presence of various nanoscale carbon structures and their interaction with minerals [9–12]. This paper will present the results of the study of shungite impedance and inductive properties depending on carbon content in the range of 0.1−15 MHz.

Shungite specimens were selected for the study with successively growing content of carbon 5, 17, 25, 49, 53, 54, 55, 73, 95 and 97 at.%. from Shunga (5, 73, 95 at.%), Maksovo (17, 25, 53, 55, 97 at.%), Tetyugino (54 at.%) and Lebeschina (49 at.%) deposits. Specimens were carved from solid pieces of the rock in the form of a square pellet with dimensions of $6.0 \times 6.0 \times 1.5$ mm. The opposite faces of the plates were coated with a thin layer of gold using magnetron sputtering in a vacuum. The impedance Z and inductance L were studied using an LCR meter E7-29 according to the four-wire circuit.

Using impedance measurement, the resistance of R shungite specimens was estimated, which drops dramatically as the content of carbon C grows up to ~ 50 at.%, with subsequent attainment of saturation (Figure 1, *a*). Besides, the paper also measured and analyzed the dependence of inductance value in shungites on C. It was shown that this nature was of marked power-mode (Figure 1, *b*), and inductance grows sharply with reduction of C. The growth is especially significant at C < 25 at.%. The assessment of the inductance curve L shows the following dependence on C:

$$L = 45 \cdot \mathrm{C}^{-0.7} \tag{1}$$

Besides, the property of inductance will not manifest itself immediately with frequency growth. In Hz and kHz ranges the impedance behavior for the specimens will not change with the frequency change, and its value only depends on C. Inductance „is included“ already in MHz area, where impedance starts increasing sharply. Obvious dependence of impedance „inclusion“ frequency on C (Figure 2) was found. If for high-carbon specimens (C > 70 at.%) inductance manifests itself already from frequency 0.7−1 MHz, then for medium-carbon ones (70 > C > 25 at.%) the inductance is included gradually in the range of 2−5 MHz, and in low-carbon (C < 25 at.%) shungites the inductance starts influencing the impedance only in the range of 7−10 MHz.

If we substitute formula (1) in the expression for full impedance:

$$Z = \sqrt{R^2 + (2\pi f L)^2}, \tag{2}$$

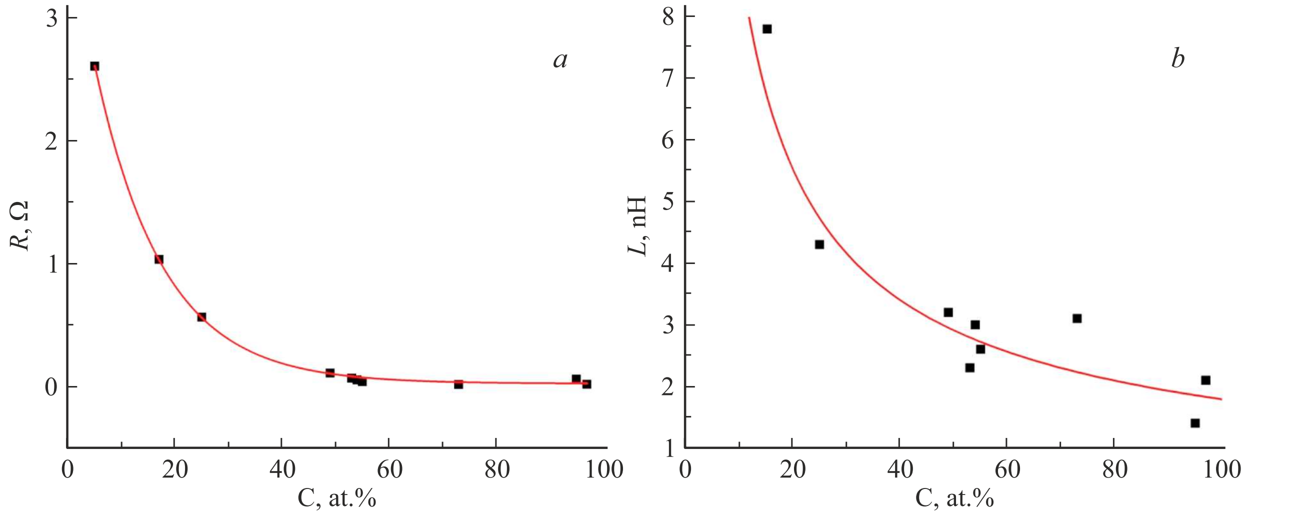

Figure 1. Dependence of resistance (*a*) and inductance (*b*) on carbon content in shungite specimens. The inductance curve lacks the point of the specimen with C = 5%, since its inductance value is more than 100 nH, and it complicates the clear presentation of dependence.

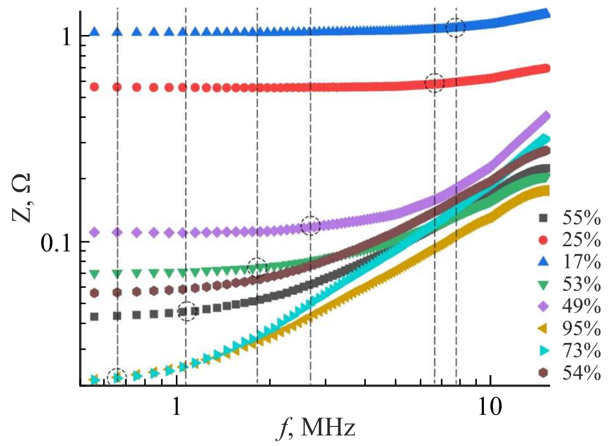

Figure 2. Impedance dependences on frequency for specimens with various carbon content. Areas of impedance „inclusion“ are marked with dotted circles.

we get the dependence of impedance Z on resistance R, frequency f and content of carbon C for shungites:

$$Z = \sqrt{R^2 + (90 \cdot \pi \cdot f)^2 \cdot \mathrm{C}^{-1.4}} \tag{3}$$

Taking into account the dependence of resistance R on carbon content (from Figure 1, *a*):

$$R = 3.8e^{-0.1\mathrm{C}}, \tag{4}$$

one may empirically assess the impedance dependence on f and C:

$$Z = \sqrt{14.4 \cdot e^{-0.2\mathrm{C}} + (90\pi f)^2 \cdot \mathrm{C}^{-1.4}}. \tag{5}$$

Inductive type of resistance in shungites is related to two types of carbon structures found in these materials [11,12]. The first type includes tapes of graphene layers (from three to a dozen in the tape) with length of dozens of nanometers forming a tanged felt-like microstructure in a carbon matrix, the second type — multi-layer graphite-like films with thickness of up to 30 nm, coating mineral crystals with size 1–5 μm, which are evenly distributed in a shungite carbon matrix. The last structures may serve as inductance coils. If the carbon content is low (and the quantity of minerals is high, accordingly), especially as the frequency increases, the conductivity prevails through the graphite-like films around the mineral crystals, since the distances between mineral inclusions are reduced. Accordingly, the

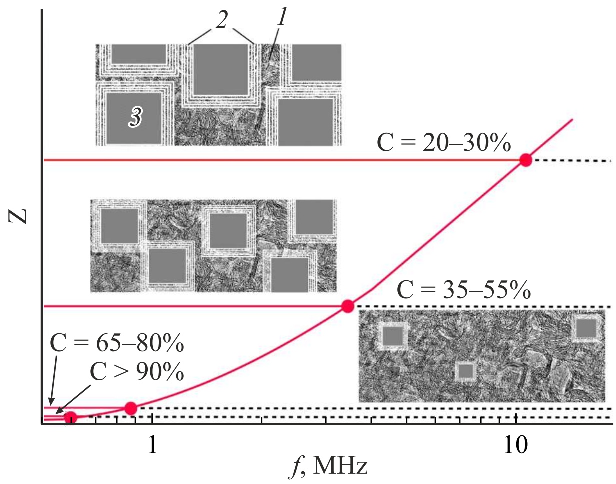

Figure 3. Conventional diagram of interaction between active and reactive components of shungite resistance. A curve is impedance of pure shungite carbon, horizontal lines — averaged active resistance of shungites in the specified ranges of carbon content. *1* — disordered carbon of shungites; *2* — graphite-like films; *3* — inclusions of minerals.

contribution of these specific „inductance coils" to the total resistance prevails. If the carbon content is high, and the conductivity is high, accordingly, for the current there is always the shortest path through the matrix, which may cause reduction of specimen inductance. Displacement of inductance „inclusion" frequency towards higher frequencies may be related to the difference in the inductance value caused by graphene tapes, and inductance related to multi-layer graphite-like films-coatings of mineral crystals. The alternative explanation of the observed frequency displacement may serve as the influence of specimen resistance related to C (Figure 3). Therefore, by changing C one can control the start frequency of conductivity drop using materials from shungites or synthesized carbon-containing composites with similar microstructure (glass-carbon conducting matrix/dielectric), for example, heat-resistant frequency filters.

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Conflict of interest

The authors declare that they have no conflict of interest.

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