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OBTAINING CARBON NANOMATERIALS FROM SHUBARKOL COAL AND APPLICATION FOR HYDROGEN STORAGE

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This study presents a promising method for the synthesis of graphene - the electric arc discharge method. The synthesis of nanomaterials containing graphene was carried out based on carbonized coal ”Shubarkol” using the electric arc discharge method at a constant voltage of 75 V and a current of 100 A in a quartz reactor. Based on Raman scattering data and analysis of electrical properties (dielectric constant and electrical resistance), it was shown that the synthesized products have a high degree of graphitization and long-range structural order (2D peak), which indicates the formation of nanomaterials containing graphene. These results present a potential route for low-cost mass production of high-quality graphene samples. In addition, the electrical resistance (R), capacitance (C) and dielectric constant (ε), electrical resistivity (R) and electrical conductivity (χ) of nanomaterials containing graphene were determined for the first time in the temperature range 293-483 K. The highest a degree of graphitization of 80.7% is achieved with the formation of graphene-containing material on the walls of the reactor after an arc discharge. Since the resulting nanomaterial on the reactor walls showed better results in terms of physicochemical and electrophysical properties, the material was tested for hydrogen storage. The sorption capacity of the nanomaterial for hydrogen was 35.1516 cm^3/g (0.314%).

Keywords: coal, carbonized coal, carbon nanotubes, graphene, arc discharge, hydrogen, storage.

ШҰБАРКӨЛ КӨМІРІНЕН КӨМІРТЕК НАНОМАТЕРИАЛДАРЫН АЛУ ЖӘНЕ СУТЕКТІ САҚТАУҒА ҚОЛДАНУ

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Бұл зерттеуде графен синтезінің перспективті әдісі - электр доғалық разряд әдісі ұсынылды. Құрамында графен бар наноматериалдардың синтезі кварц реакторында 75 В тұрақты кернеуде және 100 А ток кезінде электр доғалық разряд әдісін қолдану арқылы «Шұбаркөл» көмірі негізінде жүзеге асырылды. Раман шашырау деректері және электрлік қасиеттерді талдау (диэлектрлік өтімділік және электр кедергісі) негізінде синтезделген өнімдерде графиттенудің жоғары дәрежесі және алыс-диапазондағы құрылымдық реті (2D шыңы) бар, бұл құрамында графен бар наноматериалдардың

түзілуін көрсетеді. Бұл нәтижелер жоғары сапалы графен үлгілерін арзан жаппай өндірудің әлеуетті бағытын көрсетеді. Сонымен қатар, құрамында графен бар наноматериалдардың электрлік кедергісі (R), сыйымдылығы (C) және диэлектрлік өтімділігі (ε), электрлік кедергісі (R) және электр өткізгіштігі (χ) 293-483 К температура диапазонында алғаш рет анықталды. Графиттенудің ең жоғары дәрежесі 80,7% доғалық разрядтан кейін реактордың қабырғаларында графен бар материалдың пайда болуымен қол жеткізіледі. Реактор қабырғаларында алынған наноматериал физика-химиялық және электрофизикалық қасиеттері бойынша жақсы нәтиже көрсеткендіктен, материал сутегі сақтау үшін сынақтан өтті. Наноматериалдың сутегі үшін сорбциялық қабілеті 35,1516 см^3/г (0,314%) құрады.

Түйін сөздер: көмір, көміртекті көмір, көміртекті нанотүтіктер, графен, доғалық разряд, сутегі, сақтау.

ПОЛУЧЕНИЕ УГЛЕРОДНЫХ НАНОМАТЕРИАЛОВ ИЗ ШУБАРКОЛЬСКОГО УГЛЯ И ПРИМЕНЕНИЕ ДЛЯ ХРАНЕНИЯ ВОДОРОДА

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В данном исследовании представлен перспективный метод синтеза графена - метод электродугового разряда. Был осуществлен синтез наноматериалов, содержащих графен, на основе карбонизованного угля «Шубарколь» с использованием метода электродугового разряда при постоянном напряжении 75 В и токе 100 А в кварцевом реакторе. На основе данных метода комбинационного рассеяния света и анализа электрофизических свойств (диэлектрической проницаемости и электрического сопротивления) было показано, что синтезированные продукты обладают высокой степенью графитизации и дальним порядком структуры (2D пик), что свидетельствует о формировании наноматериалов, содержащих графен. Эти результаты представляют потенциальный путь для дешевого массового производства высококачественных образцов графена. Кроме того, впервые были определены электрическое сопротивление (R), емкость (C) и диэлектрическая проницаемость (ε), удельное электрическое сопротивление (R) и удельная электропроводность (χ) наноматериалов, содержащих графен, в интервале температур 293-483 К. Самая высокая степень графитизации 80,7% достигается при образовании графенсодержащего материала на стенках реактора после дугового разряда. Поскольку полученный наноматериал на стенках реактора показал лучшие результаты по физико-химическим и электрофизическим свойствам, материал был протестирован на хранение водорода. Сорбционная емкость наноматриала по водороду составила - 35.1516 см^3/г (0.314%).

Ключевые слова: уголь, карбонизованный уголь, углеродные нанотрубки, графен, дуговой разряд, водород, хранение.

Introduction. Since Sumio Iijima reported it in 1991, carbon nanotubes (CNTs) have attracted much attention from researchers and industry. CNTs can be classified into single-walled CNTs (SWNTs), double-walled CNTs (DWNTs), and multi-walled CNTs (MWNTs) depending on the number of graphite layers. They consist of sp^2 bonded carbon atoms arranged in a cylindrical tube ranging in length from less than 100 nm to several centimeters. The diameter of SWCNTs is typically 0.4–2 nm,

while the diameter of MWCNTs ranges from *1.4 nm to nearly 100 nm, depending on the synthesis conditions. CNTs are well known for their unique physicochemical properties, including extremely high tensile strength, high electrical conductivity, high ductility, and relative chemical inactivity. All these properties make CNT-based products attractive. Moreover, due to their low dimensionality, CNTs are also preferred for use in the development of nanocomposites. In this context, CNTs open up a new direction in materials science and nanotechnology. CNTs can be found in a wide range of applications, such as electronics, polymer composites, energy storage materials, catalysis, gas storage materials and sensors [1].

There are many methods for synthesizing nanostructures. They are usually divided into two groups: «Top bottom» is a «top-down» technology, that is, the dispersion of macroscopic bodies into nanoscale sizes, and the second group «bottom-up» is a technology the assembly of nanoparticles from atoms. There are also various hybrid methods.

One of the first methods for producing carbon nanoparticles was laser evaporation of graphite or coal, arc evaporation of graphite in the presence of a metal catalyst, chemical vapor deposition, pyrolysis, and mechanical separation [2].

Arc discharge is the oldest and most common method for producing CNM. This also makes it possible to obtain carbon formed by fullerene and soot molecules. This method is based on the electrical destruction of gas to produce plasma. It uses high temperature (over 1700°C) to evaporate carbon atoms in plasma, allowing CNMs to grow with fewer structural defects than other methods.

The chamber consists of two electrodes, one of which is the anode and the other is the cathode. The anode is filled with a mixture of graphite powder and catalyst. The catalyst promotes the growth of SWCNTs rather than MWCNTs [3]. The cathode consists of a pure graphite rod. Initially, the electrodes are held independently of each other in a gas atmosphere (usually an argon/hydrogen mixture); then the distance between the electrodes is reduced, and an electric arc is applied with an intensity of 60-100 A or 50-150 A, which corresponds to a decrease in potential by 25 V [4, 5].

The inert gas flow is maintained at 50-600 Torr; the temperature in the interelectrode region ranges from 1700° to 4000 °C. The electrodes turn red and plasma is formed, so carbon sublimes from the positive anode, which is consumed and condenses as a filamentary carbon product at the cathode due to the temperature gradient.

Speaking about the physical and chemical properties of carbon nanotubes, CNTs are the strongest and hardest materials on earth in terms of tensile strength and elastic modulus. The planar cellular carbon atoms of graphene in CNTs are responsible for these high-strength fibers. Carbon nanotube is more rigid than steel and is very resistant to physical damage.

When you press on the end of the nanotube, it bends without damaging the tip, and when the force is removed, the tip returns to its original position. The reason they don't break is because the carbon rings of the walls change their structure when bent, but don't break. This is a unique result of sp2 C-C bond hybridization and bending overhybridization. The degree of change and s-p coefficients depend on how much the bonds bend. Due to this property, CNTs can be used as very high resolution probe tips for scanning probe microscopy [6].

In the metallic state, the conductivity of nanotubes is very high. They can transmit billions of amps per square centimeter. Copper wire fails when it transmits a million amps per square centimeter because the joules of heat cause the wire to melt. Theoretically, metal nanotubes can conduct an electric current density of 10-15 A/cm^2, which is 1000 times greater than that of metals such as copper [7]. One of the reasons for the high conductivity of carbon nanotubes is the very small number of defects that cause electron scattering and therefore low resistance [8].

Another carbon nanomaterial that can be synthesized by an arc discharge is graphene [9-10]. Graphene is a material that has a large specific surface area (2630 m2g-1), high internal mobility (200,000 cm^2 V^{-1}s^{-1}), high Young's modulus (~

1.0 TPa), thermal conductivity (~5000 $W*m^{-1}/K^{-1}$), optical transmittance (~ 97.7%) [11-12]. In addition to arc, there are methods of micromechanical cleavage, electrochemical exfoliation, solvent-based exfoliation [13], graphite oxide exfoliation [14] and laser evaporation. Among all these methods, arc discharge has many advantages such as low production cost, high efficiency, and the ability to be synthesized without using any catalysis [15].

In the research, multiple layers of graphene were synthesized using a homemade arc discharge chamber. Helium (He), nitrogen (N), and mixtures thereof have been used to understand the influence of the reactor atmosphere on graphene synthesis. The purity and number of graphene layers were determined using Raman spectroscopy. The purity of the synthesized graphene also depends on the diameter of the electrodes and the arc current. Thus, optimal synthesis conditions were obtained with an electrode diameter of 12 mm and an arc current of 150 A in a $He+N_2$ atmosphere. TEM studies revealed a crumpled texture of graphene [16].

Graphene can be doped with atoms of other elements, such as nitrogen, fluorine, hydrogen, oxygen, etc., changing its properties. All this makes it an interesting material for many applications. First of all, these are applications in opto- and nanoelectronics (touch screens, solar cells, flexible electronic devices, high-frequency transistors, logic transistors), photonics (photodetectors, optical modulators, mode-locked lasers, THz generators and optical polarizers), composite materials, paints and coatings. Graphene is seen as a promising candidate to replace transparent indium tin oxide (ITO) electrodes. Promising applications of graphene coating include transparent heating elements and thermoacoustic transducers.

Materials and methods. In this work, carbon nanomaterials obtained by the electric arc method were studied. Activated carbon «Shubarkol» is used as an electrode. The coal carbonization process includes an initial low-temperature (at 180°C, with a heating rate of 10°C/min) treatment of the raw material in the presence of air for 1 hour, followed by carbonization in an inert atmosphere at temperatures ranging from 180-900°C with a heating rate of 5°C/min, and steam activation at the maximum temperature for 1 hour. Process parameters: constant voltage - 75 V; current – 100 A; process time ~10 min, inert gas - N_2 with a purity of 99.99%. The reactor is transparent quartz glass that can withstand high temperatures. The chamber is placed inside the water used for cooling. The principle of this method is the evaporation of carbon under reduced pressure of an inert gas. According to the method scheme, a movable anode and a stationary cathode are used, as in Fig. 1.

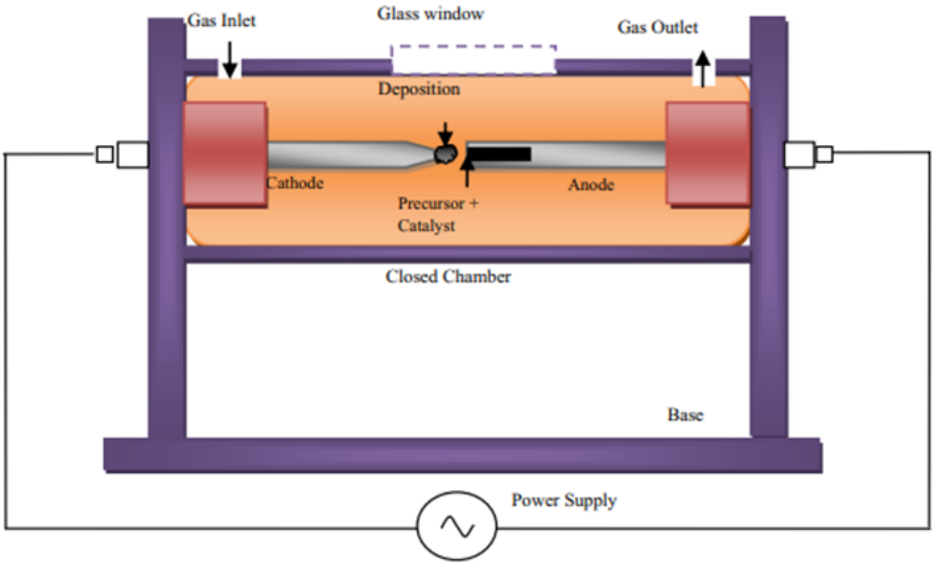

Figure 1 - Schematic diagram of an electric arc discharge

After the electric arc is ignited, the plasma ignites. Carbon nanomaterials condensed on the walls of the reactor and on the surface of the electrode. Activated carbon "Shubarkol" after an arc discharge was separated according to figure 2.

The resulting materials were tested for hydrogen storage at a high-performance automatic physiosorption and chemisorption station Micromeritics 3Flex Chemi&TCD (Made in the USA). This device is equipped with three ports, each of which has a 0.1 Torr sensor for analysis of micropores. Before measurement, all samples were preliminarily degassed using a SmartVacPrep unit (manufactured by Micromeritics, USA) equipped with a forevacuum pump.

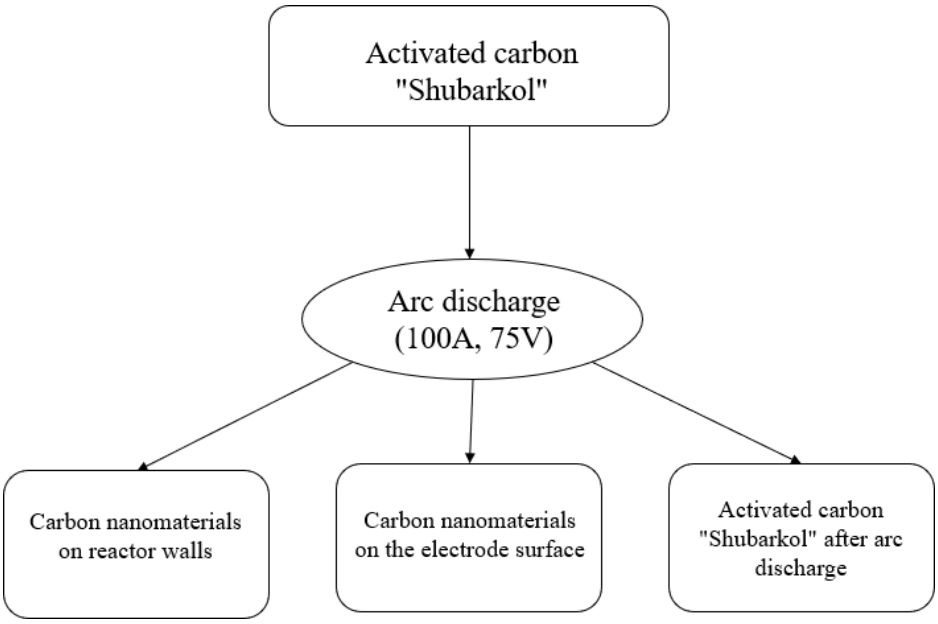

Figure 2 - Schematic diagram for producing nanomaterials using the electric arc discharge method

Adsorbate gas - hydrogen, measurement temperature - 77 K, p_0 values for all points were considered the same and equal to 760 Torr, A Peak Scientific hydrogen generator with a maximum productivity of 500 cm^3/min was used as a source of hydrogen, Water in the hydrogen generator was used from a Thermo Scientific deionizer, Readout points started from a value of 0.0001 p/p_0 to 0.995 p/p_0. The measurement of free space or void volume was carried out after analysis with helium in order to avoid premature filling of micropores with helium.

Due to the smaller radius and transverse radius of the hydrogen molecule, the specific surface area and porosity values will be higher compared to nitrogen sorption. Classical BET methods in the case of H_2 will be incorrect since the saturation pressure value was used as a constant (760 Torr). To calculate the pore distribution, the theoretical hydrogen sorption model DFT HS H_2 Carbon, heterogeneous, taking into account the heterogeneity of the carbon surface. For most samples, this model showed good consistency. The limitation of nitrogen to fill pores with a radius of less than 0.35 nm was also taken into account.

Results and discussion. The obtained materials were studied by SEM and Raman spectroscopy. As a result, the original «Shubarkol» coal contained different agglomerates ranging from 719 nm to 231.97 μm, as shown in Fig. 3. The degree of graphitization is G_f = 29.6% and peaks at 1258.3 are noticeable; 1374.9; 1535.1; 1594.3; 2704.9; 2928.6 cm^{-1}. I(D)/I(G)=0.6 I(G)/I(2D)=12.2. The intensity of peak D at 1374.9 cm^{-1} is lower than peak G at 1594.3 cm^{-1}, and peak G at 1594.3 cm^{-1} is much higher than peak 2D at 2704.9 cm^{-1} (Figure 4), this explains that the material is amorphous carbon. There may be polymer chains or other impurities, as indicated by the luminescent trend.

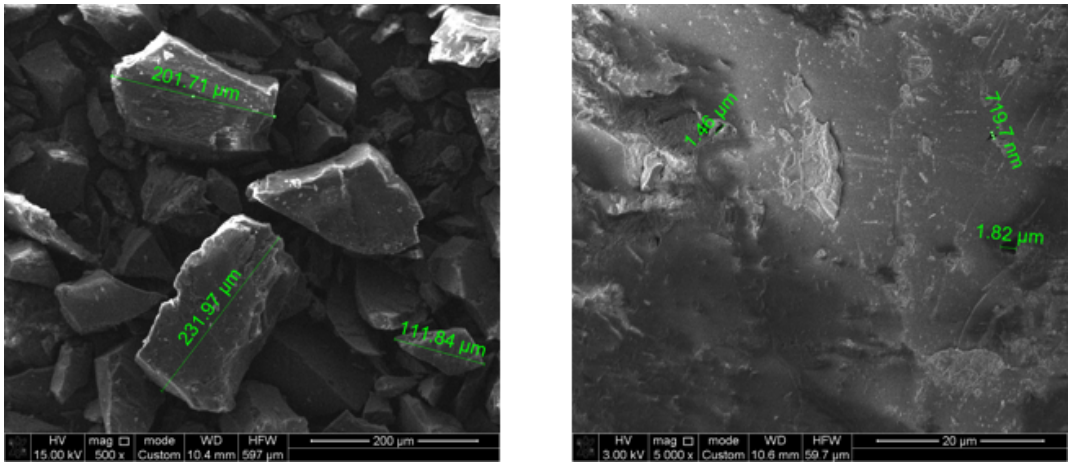

Figure 3 - SEM of the original coal «Shubarkol»

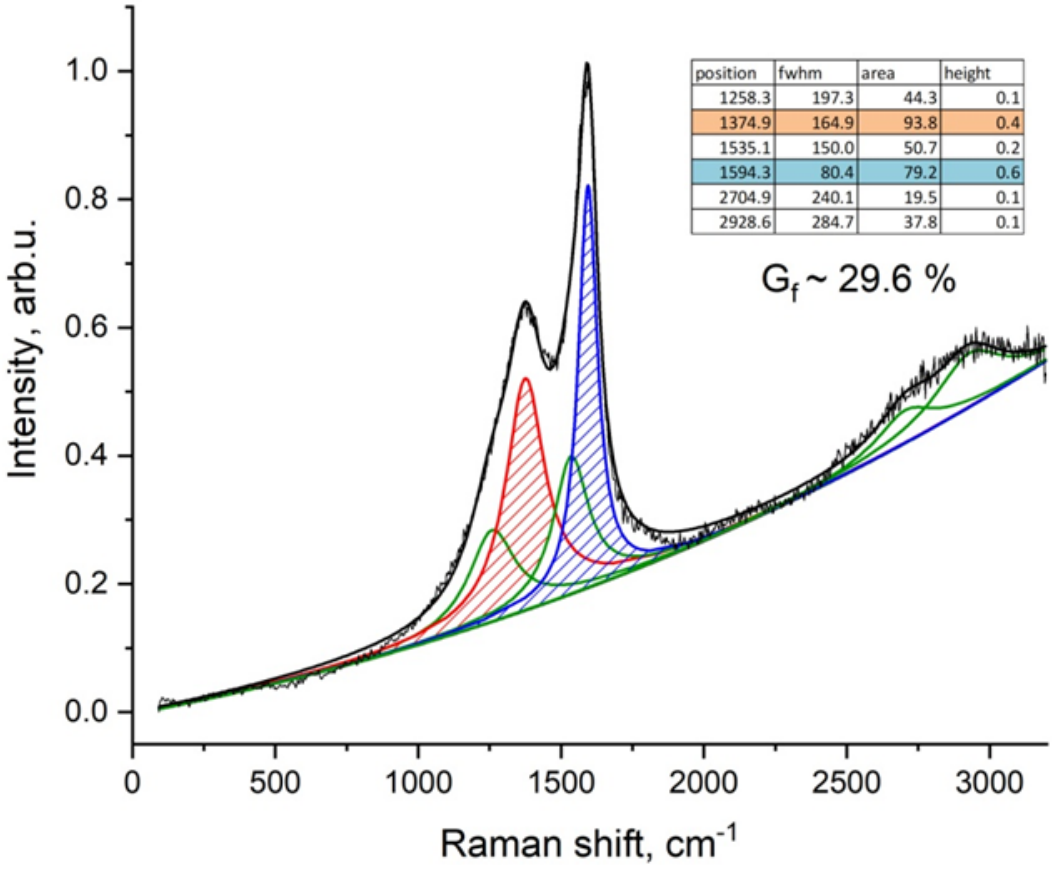

Figure 4 - Raman spectroscopy of the original coal «Shubarkol»

After activation of Shubarkol coal, SEM images show that agglomerates of different elements were removed. Pores are noticeable, with sizes ranging from 155 nm to 33.08 µm. During the carbonization process, mineral agglomerates opened, as shown in Fig. 5 by white spots. Peaks at 1194.4 are visible in the Raman spectrum; 1347.9; 1517.1; 1595.4; 2700.7; 2914.0 cm^{-1}. The degree of graphitization after the activation process dropped to G_f=24%, this is explained by the fact that peak D 1347.9 cm^{-1} increased its intensity (Figure 6). I(D)/I(G)=0.9 I(G)/I(2D)=13.1. Amorphous carbon with signs of graphitization - a narrow peak G, as well as a weak manifestation of a second-order peak - 2D.

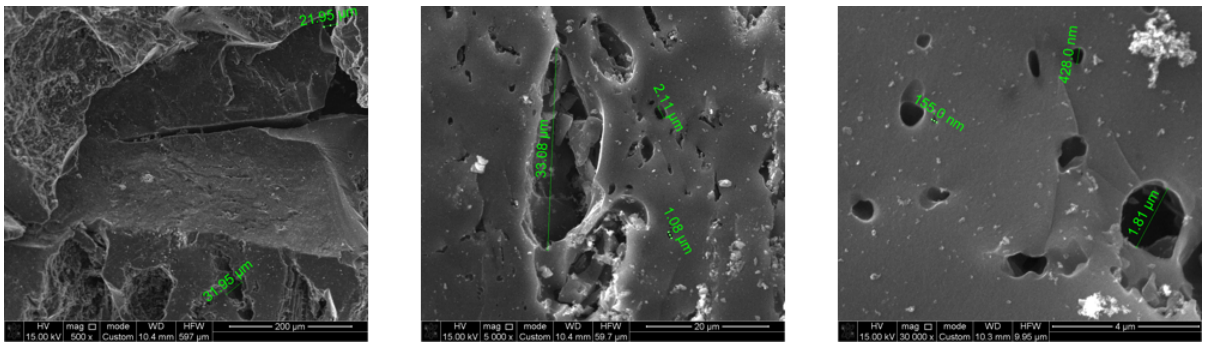

Figure 5 - SEM image of activated carbon «Shubarkol»

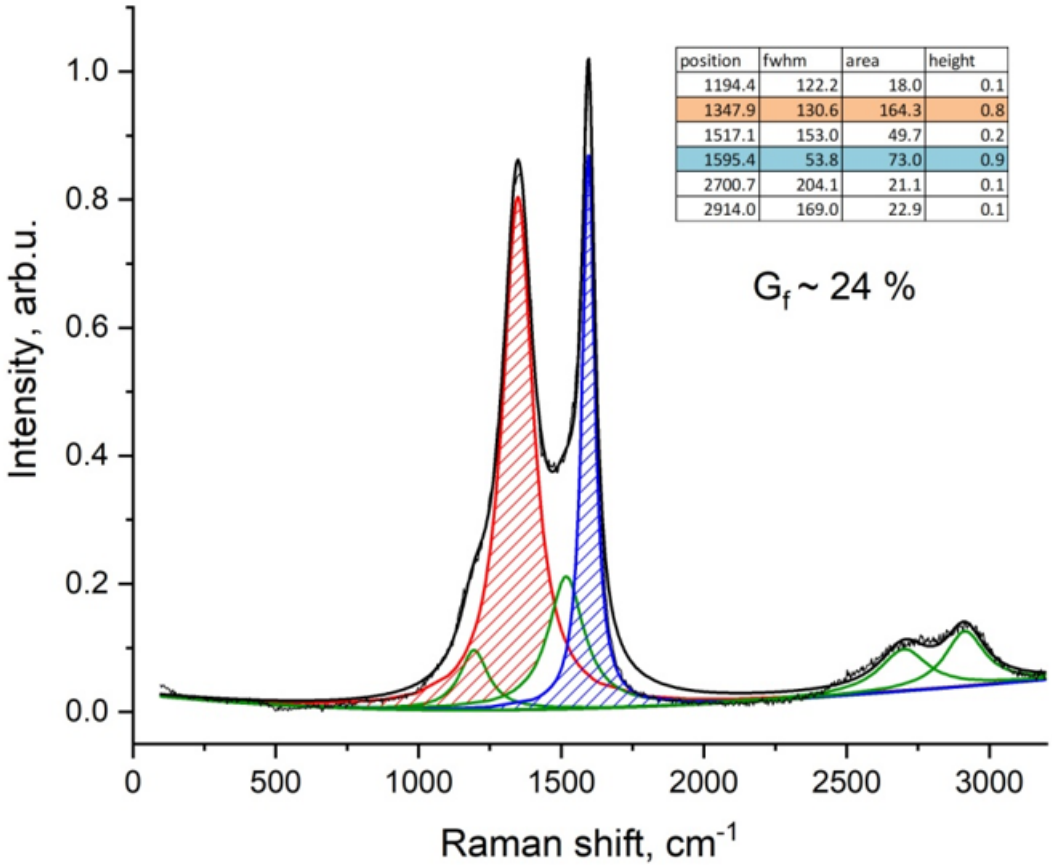

Figure 6 - Raman spectroscopy of activated carbon «Shubarkol»

After the arc discharge, we see deformation of the pores in SEM images. The pores have become smaller and range from 159.9 nm to 1.83 μm. The formation of micro- and mesopores is assumed. White flake-like spots are visible on the surface (Figure 7). As you can see in Fig. 8 there are peaks at 1363.7(D); 1465; 1582.5(G); 2448.5; 2725.9(2D); 2959 cm^{-1} According to the Raman spectroscopy data, the «Shubarkol» activated carbon after an arc discharge on the reactor walls has a high degree of graphitization G_f = 80.7%. Compared with activated carbon, peak D shows a weaker intensity, and peak 2D shows a more prominent intensity. I(D)/I(G)=0.1, I(G)/I(2D)=2.9. As a result, it can be said from the surface of the «Shubarkol» activated carbon that after an arc discharge, graphene structures of high quality and small thickness were formed on the walls of the reactor.

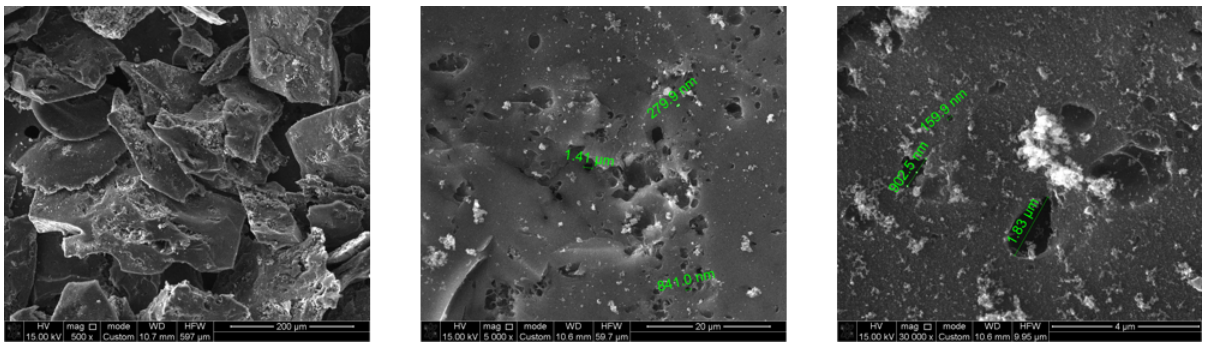

Figure 7 - SEM image of «Shubarkol» activated carbon after an arc discharge on the walls of the reactor (100A, 75B)

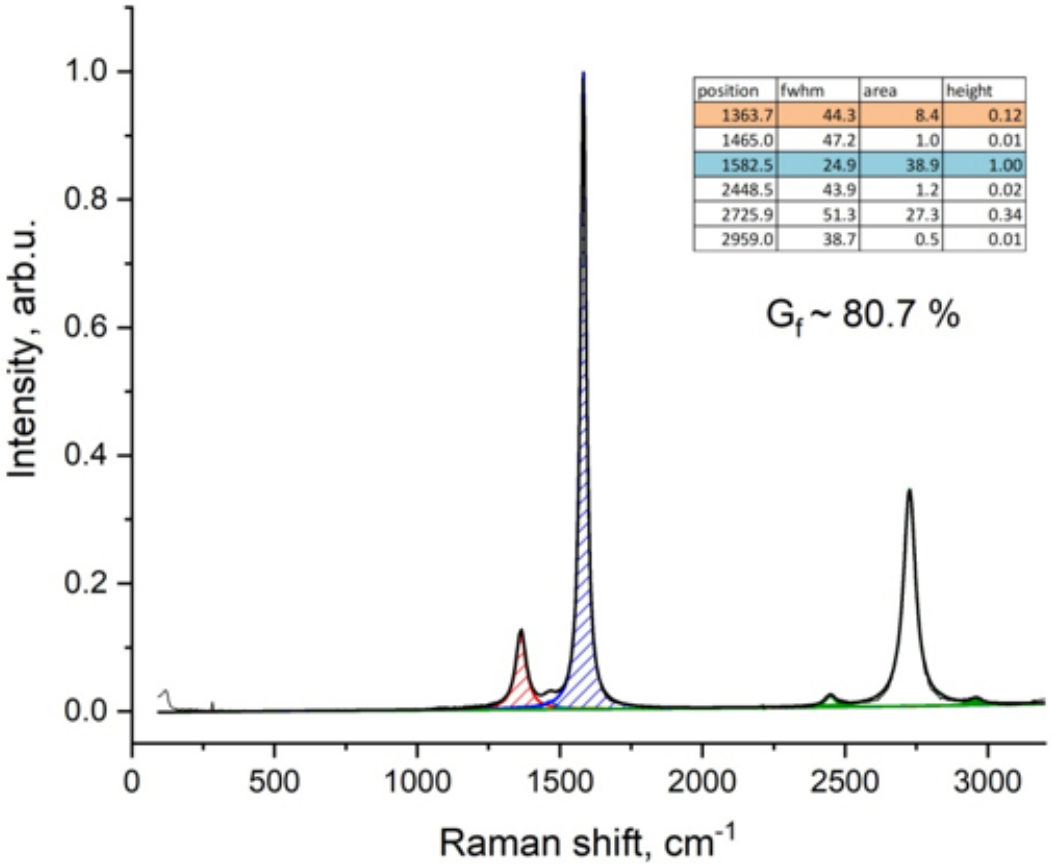

Figure 8 - Raman spectroscopy of «Shubarkol» activated carbon after an arc discharge on the walls of the reactor (100A, 75B)

After an arc discharge, layers of graphene are visible on the surface of the Shubarkol coal, according to the SEM image. Nanomaterials ranging in size from 67.3 nm to 467.9 nm were formed. Pore deformations are noticeable (Fig. 9). It is assumed that layers of graphene have grown together on the surface of the pores. In the Raman peaks at 1228.8 are noticeable; 1355.3(D); 1476.6; 1577.4(G); 2435.4; 2714.5(2D); 2935 cm^{-1}. I(D)/I(G)=0.3 I(G)/I(2D)=2.8 From these data we can say that on the surface of the Shubarkol activated carbon after an arc discharge on the surface of the electrode there are graphene-like structures of varying degrees of defects (Fig. 10).

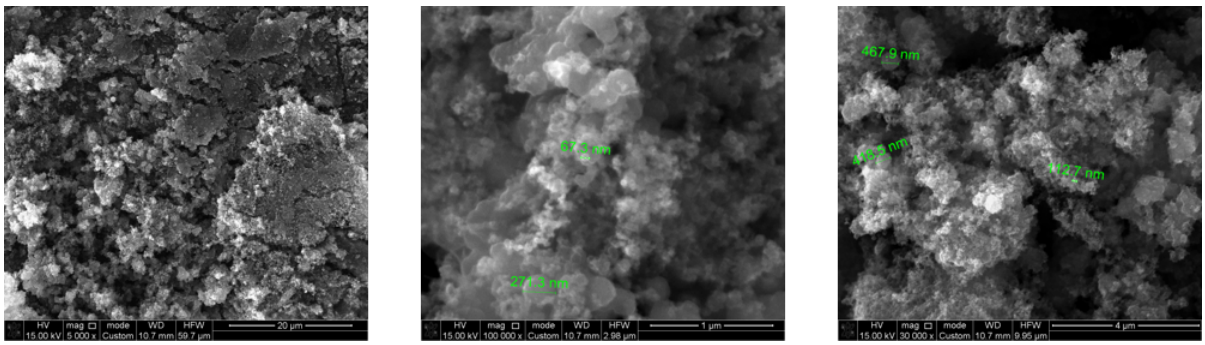

Figure 9 - SEM image of activated carbon «Shubarkol» after an arc discharge on the surface of the electrode (100A, 75B)

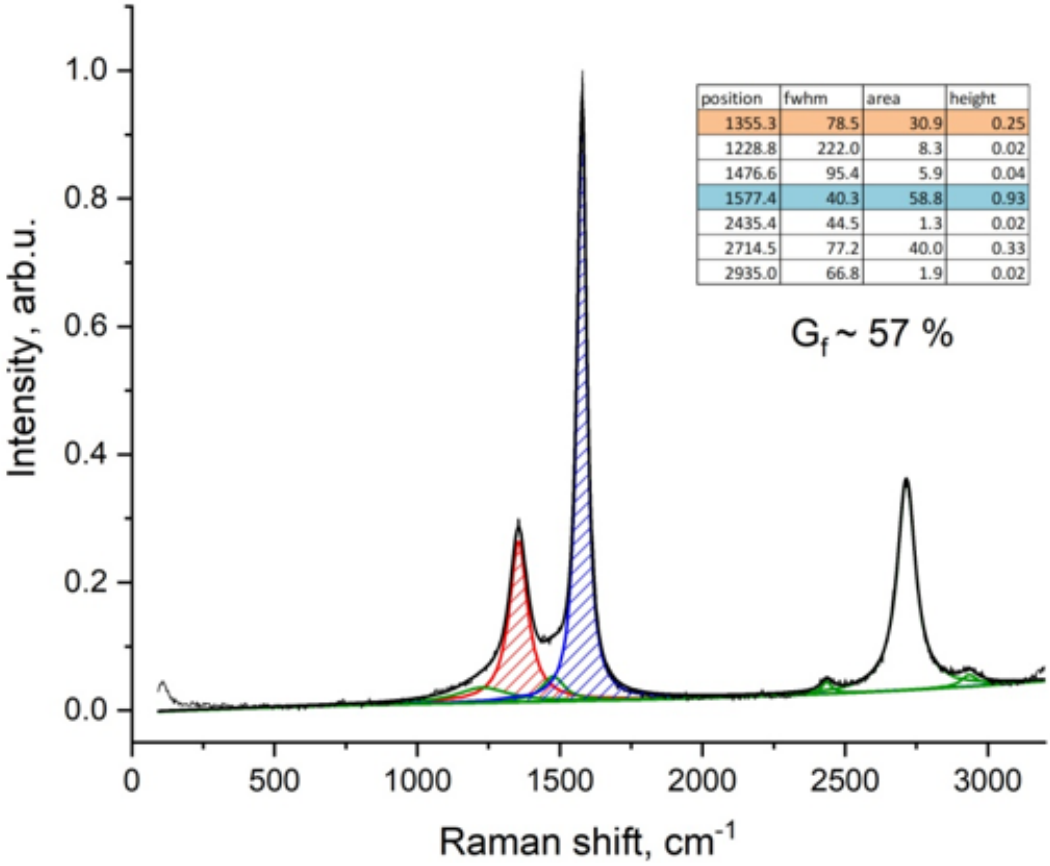

Figure 10 - Raman spectroscopy of activated carbon «Shubarkol» after an arc discharge on the surface of the electrode (100A, 75B)

SEM images (Figure 11) of crushed Shubarkol coal used as an electrode show nanodots of different diameters. The dots start from 29.5 nm to 8.95 μm. Peaks at 1249.1 are visible in the Raman distribution; 1357.4(D); 1472.6; 1584.6(G); 2459.1; 2725.3(D); 2937.4 cm^{-1}. I(D)/I(G)=0.4 I(G)/I(2D)=1.8. Graphene-like structures of varying degrees of defects and thickness.

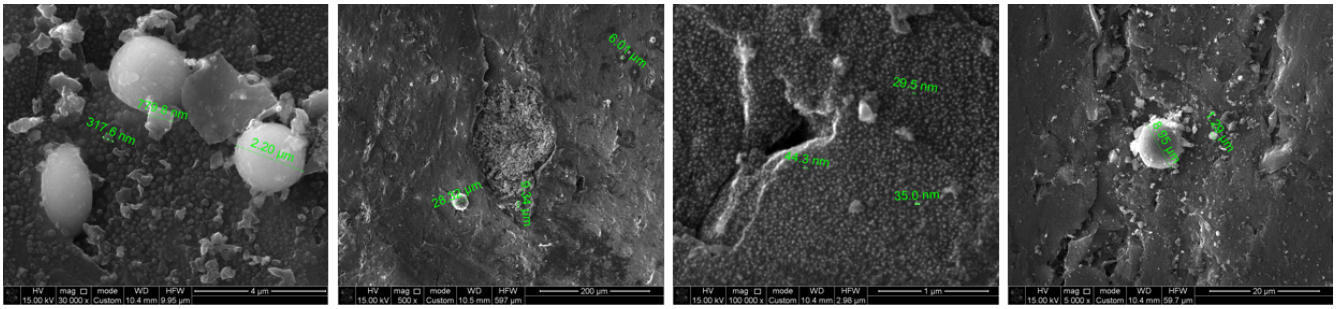

Figure 11 - SEM image of «Shubarkol» activated carbon after an arc discharge (100A, 75B)

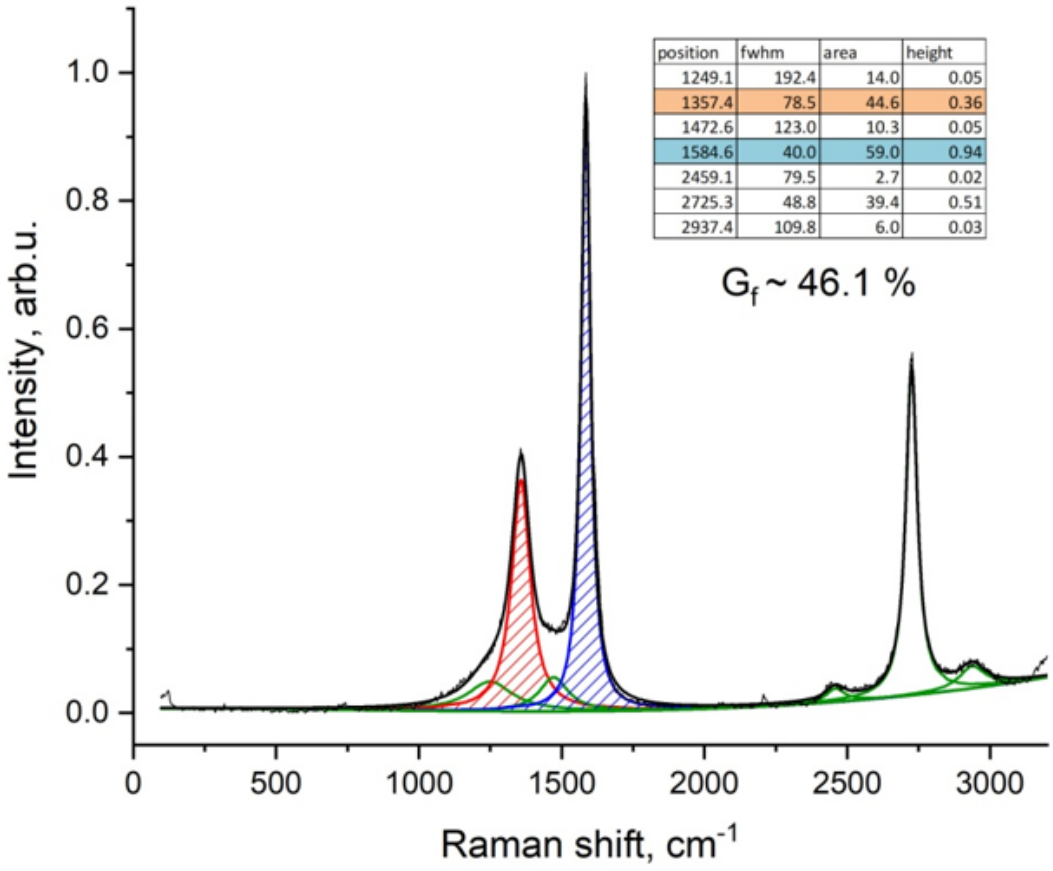

Figure 12 - Raman spectroscopy of «Shubarkol» activated carbon after an arc discharge (100A, 75B)

It is known that the 2D band of Raman spectra is more sensitive to the overlay of graphene sheets. From the Raman scattering data (Raman effect), the intensities of the D, G and 2D peaks were calculated. It is immediately noticeable that after activation the G peak increased its intensity from 0.6 to 0.9. After the arc discharge, peak D loses its intensity, and peak 2D increased its intensity from 0.1 to 0.51. The intensity ratios I2D/IG for one-, two-, three- and multilayer (> 4) in these materials were shown to vary from 0.11 to 0.54. And the ratio of IG/I2D peaks after arc treatment is from 1.84 to 2.94, which confirms the formation of two to three layer graphene (for single-layer graphene the ratio is 0.6-1). The Raman spectrum of the material with the lowest degree of crystallization contains a strong D-band and a broad and weak G-band, and their high

Table 1 - Ratio of D G and 2D peaks in materials obtained from Shubarkol coal

intensity ratio (ID/IG) confirms the strong disorder of the structure. Based on the intensity ratio of the ID/IG bands after an arc discharge, which ranges from 0.12 to 0.38, it can be argued that there are a small number of material defects. Based on these data, we can say that we have obtained modern carbon materials of very good quality.

Elements	Source coal «Shubarkol»		Activated carbon «Shubarkol»		Activated carbon «Shubarkol» After arcing (on the walls of the reactor)		Activated carbon «Shubarkol» after arc discharge (on the surface of the electrode)		Activated carbon «Shubarkol» after an arc discharge (crushed electrode)	
	Wt%	At%	Wt%	At%	Wt%	At%	Wt%	At%	Wt%	At%
C	77,15	82	90,35	92,92	87,21	90,40	71,70	85,89	83,49	90,83
O	22,24	17,74	8,57	6,62	11,75	9,15	6,51	5,86	7,84	6,40
Al	0,4	0,19	0,35	0,16	0,36	0,16	2,04	1,09	0,6	0,29
Si	0,07	0,03	0,11	0,05	0,19	0,08	7,68	3,94	0,44	0,21
Ca	-	-	0,29	0,09	0,25	0,08	0,25	0,09	1,41	0,46
Mg	-	-	0,11	0,05	-	-	0,18	0,11	0,49	0,26
Na	-	-	0,12	0,06	0,25	0,13	-	-	0,40	0,22
S	-	-	0,11	0,04	-	-	0,20	0,09	0,46	0,19
Fe	0,15	0,03	-	-	-	-	11,42	2,94	4,87	1,14

Table 2 - Elemental composition of the initial, activated and after arc discharge of Shubarkol coal

Name	I(D)	I(G)	I(2D)	I(D)/I(G)	I(G)/I(D)	I(G)/I(2D)	I(2D)/I(G)
Source coal ”Shubarkol”	0,4	0,6	0,1	0,67	1,5	6	0,17
Activated carbon ”Shubarkol”	0,8	0,9	0,1	0,89	1,12	9	0,11
After an arc discharge (on the reactor walls)	0,12	1	0,34	0,12	8,33	2,94	0,34
After an arc discharge (on the surface of the electrode)	0,25	0,93	0,33	0,27	3,72	2,8	0,35
After an arc discharge (crushed electrode)	0,36	0,94	0,51	0,38	2,61	1,84	0,54

Based on the elemental composition, we can say that the original Shubarkol coal contains 77.15% carbon; this figure increased to 90.35% after the activation process. In addition, the oxygen concentration decreased from 22.24% to 8.57% and minerals such as calcium and magnesium

were discovered and accounted for Ca-0.29% and Mg-0.11% of the total mass. Also noticeable is the low concentration of sodium and sulfur after the activation process (Na-0.12%, S-0.11%). Some elements, such as aluminum and silicon, did not change much after activation (Al-0.35%, Si-0.11%), and iron completely disappeared from the surface of Shubarkol coal during activation. Analysis of the elemental composition shows that activated carbon after electric arc contains 71.70-87.21% C 6.51-11.75% O. In addition to carbon and oxygen, CNM on the reactor walls contains small amounts of aluminum, silicon, calcium and sodium (Al-0.36% , Si-0.19%, Ca-0.25%, Na-0.25%). On the surface of the electrode there are elements such as aluminum, silicon, calcium, magnesium, sulfur and iron (Al-2.04%, Si-7.68%, Ca-0.25%, Mg-0.18%, S-0 .2%, Fe-11.42%). The crushed electrode has different concentrations of aluminum, silicon, calcium, magnesium, sodium, sulfur and iron (Al-0.6%, Si-0.44%, Ca-1.41%, Mg-0.49%, Na- 0.4%, S-0.46%, Fe-4.87%. The highest indicator of aluminum, silicon, and iron was shown by activated carbon after an arc discharge on the walls of the reactor, and for magnesium, calcium, sodium and sulfur, the highest concentration was activated carbon after an arc discharge, crushed electrode.

As can be seen in Fig. 13 The original Shubarkol coal does not exhibit semiconductor properties, the dielectric constant over the entire temperature range under study is very low and this material is not of electrical interest.

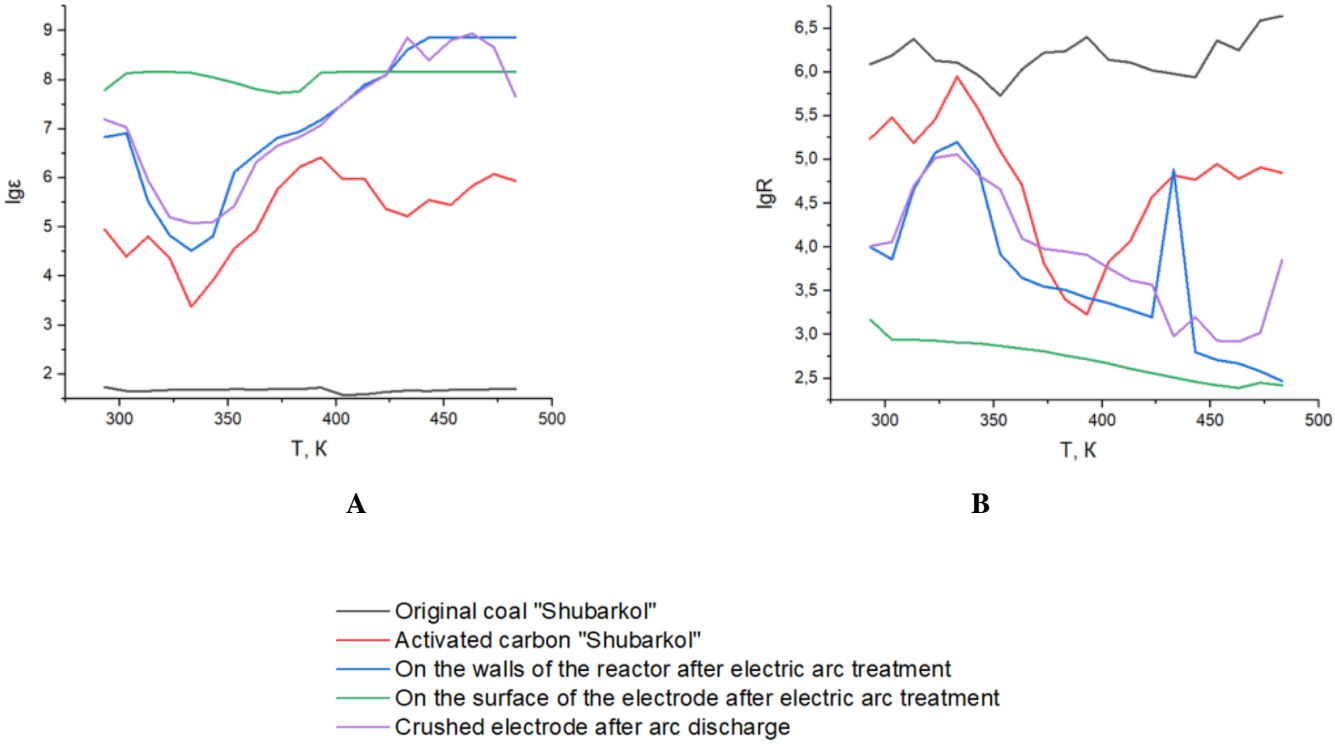

Figure 13 - Dependence of dielectric constant (A) and electrical resistance (B) on temperature at a frequency of 1 kHz

Activated carbon «Shubarkol» shows that the dielectric constant of this material has mainly average values. The maximum value of ε is achieved at 393 K – $2.62 \cdot 10^6$ (1 kHz), $7.23 \cdot 10^5$ (5 kHz) and $3.73 \cdot 10^5$ (10 kHz). A study of the temperature dependence of electrical resistance shows that activated carbon exhibits variable conductivity in the range of 293-333 K, semiconductor conductivity at 333-393 K, metallic conductivity at 393-453 K, and variable conductivity at 453-483 K.

Activated carbon ”Shubarkol” after an arc discharge obtained on the walls of the reactor at 293 K exhibits a high value of ε ($6.77 \cdot 10^6$) - 1 kHz, $3.72 \cdot 10^5$ - 5 kHz and $1.08 \cdot 10^5$ - 10 kHz and reaches colossal values at 443 - 483 K $7.20 \cdot 10^8$ and more (1 kHz), $2.50 \cdot 10^8$ (5 kHz and 483 K) and $8.41 \cdot 10^7$ (10 kHz and 483 K). A study of the temperature dependence of the electrical resistance of material III shows variable conductivity in the range of 293-333 K, semiconductor conductivity at 333-423 K, and semiconductor conductivity again at 433-483 K.

Activated carbon «Shubarkol» after an arc discharge obtained on the surface of the electrode already at lower temperatures of 293 and 343 shows gigantic values of dielectric constant $6.16 \cdot 10^7$ (1 kHz), $2.90 \cdot 10^6$ (5 kHz) and $2.45 \cdot 10^6$ (10 kHz) at 313 K and starting from 403 K at 1 kHz is also ε greater than $1.44 \cdot 10^8$ and colossal values of ε are maintained (albeit with a decrease) at frequencies of 5 and 10 kHz. Activated carbon «Shubarkol» after an arc discharge (on the surface of the electrode) in the range of 293-463 K exhibits semiconductor conductivity, and at 463-483 K – mixed conductivity.

According to the temperature dependence of the dielectric constant of Activated carbon «Shubarkol» after an arc discharge, the crushed electrode shows that already at 293 K it shows a gigantic value at a frequency of 1 kHz and at frequencies of 5 and 10 kHz high values of dielectric constant: $1.56 \cdot 10^7$ (1 kHz), $9.83 \cdot 10^5$ (5 kHz) and $2.78 \cdot 10^5$ (10 kHz). The colossal value of ε is achieved at 463 K and 1 kHz ($8.63 \cdot 10^8$). The temperature dependence of electrical resistance in the range of 293-333 K exhibits metallic conductivity, at 333-433 K - semiconductor conductivity, and at 433-483 K - variable conductivity.

Table 3 - Dependence of dielectric constant (ε) on temperature at different frequencies

Name of material	The dielectric constant (ε)					
	at 1 kHz		at 5 kHz		at 10 kHz	
	293	483	293	483	293	483
BaTiO3	1296	2159	1220	2102	561	2100
Graphite	6,07*	7,19*<	4,04*	2,56*	1,15*	8,70*
On the walls of the reactor	6770953	719702040<	371895	249796682	107561	84141207
On the surface of the electrode	61630141	143940408<	2898125	69699521	2453921	22287956
Crushed electrode	15614812	45948829	982576	2055749	277845	601308

As shown in Table 3, dielectric constant is inversely proportional to frequency. Materials after an arc discharge increased their dielectric constant. The most optimal indicator for activated carbon after an arc discharge is obtained on the walls of the reactor. For comparison, we gave the example of graphite and the resulting materials have a similar dielectric constant. The band gap of the resulting materials can be classified as narrow-gap semiconductors. Activated carbons after arc processing are of interest for semiconductor and microcapacitor technology.

Since the nanomaterial obtained on the walls of the reactor showed the best results in terms of physicochemical and electrophysical properties, the material was tested for hydrogen storage. The specific surface area according to Langmuir theory is 112.27 m^2/g, and according to BET - 104,08 m^2/g. For the case of 77 K, it is also possible to determine the specific surface area and pore distribution using DFT methods for carbon materials: total area in pores (>= 2,91 Å) - 1 099,971 m^2/g (H_2). Based on these data, the percentage of absorbed hydrogen on the adsorbent was calculated. Nonmaterial on

the walls of the reactor absorbed 0.314% (35.1516 cm^3/g) of the total mass.

Conclusions. When conducting an experiment using an electric arc discharge at a high current of 100 amperes, graphene and materials containing graphene are formed both on the walls of the reactor and in the electrode itself. The optimal degree of graphitization of 80.7% is achieved when graphene-containing material is formed on the walls of the reactor after an arc discharge. The method of producing graphene through electric arc discharge is promising and provides high purity and a minimum number of defects in the product. It has many advantages such as low cost, high efficiency and catalyst-free synthesis. This method is easily scalable from laboratory conditions to industrial processes.

The use of graphene in various industries such as batteries, capacitors and composite materials will help solve environmental problems. Graphene has unique physical properties that make it attractive to researchers and engineers. Some experts believe that graphene could replace silicon transistors in the future due to its cost-effectiveness and speed.

The environmental aspect of the method lies in the ability to use coal and carbon products to produce graphene, which will avoid the use of chemical compounds and reagents. Thanks to this, environmentally friendly technology with high added value of products is created.

Thus, the study made it possible to obtain important data on the dynamics of the process of hydrogen adsorption on a porous carbon material, its speed and efficiency. These results can be useful in the development and optimization of hydrogen adsorption processes for various industrial and scientific applications.

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