# ELECTRIC CONDUCTIVITY OF NITROGEN-DOPED DIAMOND-LIKE CARBON FILMS: POOL–FRENKEL AND FOWLER–NORDHEIM MECHANISMS

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The results of experimental investigations of the electric conductivity of diamond-like carbon (DLC) films on their doping level with nitrogen are presented. Two mechanisms of electron transport through DLC films in the region of high electric fields  $E \ge 1 \times 10^6 \text{ V/cm}$ , namely the Pool–Frenkel and Fowler–Nordheim mechanisms were revealed. The nonmonotonous dependence of the DLC (a-C:H) film conductivity on the nitrogen doping level was observed. The electric conductivity of films was in the range  $2 \times 10^{-15} - 2 \times 10^{-10}$  Ohm<sup>-1</sup>cm<sup>-1</sup>, and the maximal electric conductivity of films was realized at the nitrogen concentration  $N_2 = 10\%$  in a gas mixture during the deposition. A model is proposed to explain the nonmonotonous dependence of the electric conductivity of DLC films on the nitrogen doping level. According to this model, nitrogen at low concentrations builds in the structural net of a DLC film as a doping n-type impurity. This causes the creation of donor levels and a growth of the current. At the same time, nitrogen at high concentrations builds in as an undoping center and causes the creation of deep energy levels (electron traps) in the middle of the DLC film bandgap.

## 1. Introduction

The mechanism of current transport through insulator and semiconductor films is determined by their structure and content. The study of the current transport mechanism gives possibility for a better understanding of the physical processes in films and prospects of their use in various devices.

Three main mechanisms of the electric conductivity in amorphous materials in a definite temperature region are distinguished [1,2]: 1) – transport of excited electrons through energy electron states in the conduction or valence band; 2) – transport of excited carriers through states localized near the band edges ("tails" of bands)  $E_a$ and the hops at energies close to  $E_a$ ; 3) – conductivity through states near the Fermi level according to the mechanism of hops with variable length.

The general conductivity for all processes can be obtained by integration over all energy states

$$\sigma = e \int N(E)\mu(E)f(E,T)dE,$$
(1)

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where f(E,T) is the Fermi function, e is the electron charge,  $\mu$  is the mobility, and N(E) is the energy state density.

At low temperatures, there is the current transport according to mechanism (3). In the middle temperature range, process (2) dominates. At a subsequent growth of the temperature, process (1) begins to dominate. However, if the density of electron states in the Fermilevel region is high, process (2) can't be display, and the direct transition from process (3) to process (1) takes place.

#### 2. Experimental

To investigate the electric conductivity of DLC films (a-C:H), the metal-insulator-semiconductor (MIS) structures with a DLC film instead of an insulator were formed. The DLC film was deposited on a silicon wafer of the *n*- or *p*-type with the specific resistivity  $\rho_v = 4.5$  Ohm cm or  $\rho_v = 10$  Ohm cm, respectively. After the DLC film deposition, the aluminum electrodes with a thickness of 0.8–1.0  $\mu$ m were formed by the resistive deposition through a mask. The area of the separate upper electrode (capacitor) was of  $8 \times 10^{-3}$  cm<sup>2</sup>. To realize the reliable contact, the overall aluminum electrode was sputtered on the back side of a silicon wafer.

The current–voltage (I - V) characteristics in such structures were measured with an automatic setup Hewlett Packard Analyzer 4145A in the investigation of peculiarities of the current transport. To exclude the influence of a substrate on the I - V characteristics of DLC films, the voltage with polarity corresponding to the accumulation of majority carriers by the silicon substrate surface was applied. The dark current measurements were performed at room temperature (293 K).

The investigations of the level of the *in situ* doping of DLC films with nitrogen on the current transport through them in MIS structures were performed. The



Fig. 1. Current density on electric field dependences of Si–DLC–Al structure built on a semilogarithmic scale (a), Fowler–Nordheim coordinates (b), and Pool–Frenkel coordinates (c): 1 - 0% N<sub>2</sub>; 2 - 5% N<sub>2</sub>; 3 - 30% N<sub>2</sub>; 4 - 35% N<sub>2</sub>; 5 - 40% N<sub>2</sub> (N<sub>2</sub> is the nitrogen content in a gas mixture at the deposition, P=0.2 Torr)

doping is an efficient way to influence properties of a material. That is why the introduction of *n*-type impurities is very important for applications of diamond and diamond-like carbon films in electronics. A DLC film is one of the amorphous semiconductors that can be doped by elements of groups III and V of the Periodic table according to the substitution mechanism. However,

the investigation of the doping of a-C:H films showed that the doping efficiency is significantly lower than that for a-Si:H films [2]. The n-type impurities (P, As, Sb) traditional for semiconductors have a very low solubility in diamond. This is caused by a low value of the crystal lattice constant (3.7 Å) [4]. The most efficient n-type impurity for diamond and DLC films is nitrogen due to its low size. The efficiency of the a-C:H film doping with nitrogen is high enough, whereas nitrogen is an inefficient doping impurity for a-Si:H films in comparison with phosphorus. This is explained by a low size of nitrogen atoms to adjust four neighbor Si atoms in a structural net. In a-C:H films, nitrogen can substitute for carbon atoms and adjust four lower (in comparison with silicon) neighbor carbon atoms [5]. However, the lower efficiency of the doping of a-C:H films with nitrogen than the expected one is caused by the strong autocompensation. As this takes place, the doping is accompanied by the growth of the defect density. Nevertheless, the *in situ* doping of DLC films during the deposition with nitrogen is a perspective and efficient enough method to rule their properties.

During the plasma-enhanced chemical vapor deposition (PE CVD) of DLC films from the mixture of CH<sub>4</sub>, H<sub>2</sub>, and N<sub>2</sub>, the nitrogen content was changed from 0 to 45%. The gas mixture pressure in a vacuum chamber that had discrete values 0.2, 0.6, and 0.8 Torr was as a parameter. The analysis of the nitrogen influence was performed, by comparing the properties of the films doped with the above-mentioned mixture with those of DLC films deposited from the CH<sub>4</sub>:H<sub>2</sub> mixture. As the Auger electron spectroscopy results [6] show, there is a correlation between the nitrogen concentration in the gas mixture and its content in a DLC film.

# 3. Results and Discussion

The dependences of the current density on the applied electric field (E = V/d) built on a semilogarithmic scale are shown in Fig. 1, a [7,8]. The bend on the I - Vcharacteristics is observed (see Fig. 1, a, curves 2, 3). This fact indicates the existence of two current transport mechanisms in the dependence on the electric field. The rebuilding of the I - V characteristics in the Fowler– Nordheim coordinates  $\lg J/E^2 - 1/E$  (Fig. 1, b) shows that high voltage parts of the I - V characteristics are straight lines. In this case, the current transport is realized by tunneling through an energy barrier on the interface according to the Fowler–Nordheim mechanism (Fig. 2). In lower electric fields, the current is limited by the current transport mechanism through DLC films. To

clarify it, the I - V characteristics were rebuilt in the Pool–Frenkel coordinates  $\lg J - E^{1/2}$ . As can be seen from Fig. 1, c, the I - V characteristics are straightening in low electric fields. This evidences the realization of the Pool–Frenkel mechanism: the electric-field-enhanced thermal excitation of electrons from a donor level into the conduction band (Fig. 2). At the current transport according to the Pool–Frenkel mechanism, the current density is described by the relation [9]

$$J = \text{const}NT^m E^n \exp\left(-\frac{\Phi_t}{kT}\right) \exp\left(\frac{e\beta_{\text{FP}}E^{1/2}}{kT}\right), \quad (2)$$

where m and n are constants. Moreover, n = 1/2 in the case where  $l \sim E$ , and n = -1/2 for l = const; l is the length going by a carrier before its capture by an empty donor center.

Relation (2) was obtained in the frame of a model that the excitation probability of a carrier in any direction depends only on the barrier height in this direction. The slope of the I - V characteristic in the Pool–Frenkel coordinates gives possibility to determine the lowering of the energy barrier height due to the influence of the electric field. The energy barrier lowering according to the Pool–Frenkel mechanism is as follows:

$$\Delta\Phi_{\rm FP} = e\Delta\varphi_{\rm FP} = \left(\frac{e^3 E}{\pi\varepsilon_0\varepsilon_d}\right)^{1/2} = e\beta_{\rm FP} E^{1/2}.$$
 (3)

Here,  $\beta_{\rm FP} = (e/\pi\varepsilon_0\varepsilon_d)^{1/2}$  is the Pool–Frenkel constant.

By analyzing the current transport through insulators and amorphous semiconductors, it is important to distinguish the Pool–Frenkel and Schottky mechanisms [10–12]. The Pool–Frenkel mechanism is realized when the electric conductivity is determined by the volume of a material, whereas the electric conductivity at the Schottky mechanism is limited by electrodes (a barrier at the interface of materials). Both these effects are caused by the Coulomb interaction between the electron that is released and a positive charge. But they differ from each other. For the Pool-Frenkel mechanism, the positive charge is fixed. But, for the Schottky mechanism, it is the moving charge that determines the image force action. As a result, the barrier lowering in case of the Pool–Frenkel effect is twice more than that for the Schottky effect. The energy barrier lowering for the Schottky effect has the form

$$\Delta \Phi_{\rm S} = e \Delta \varphi_{\rm S} = \left(\frac{e^3 E}{4\pi\varepsilon_0 \varepsilon_d}\right)^{1/2} = e\beta_S E^{1/2},\tag{4}$$

where  $\beta_{\rm S} = (e/4\pi\varepsilon_0\varepsilon_d)^{1/2}$  is the Schottky constant.

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Fig. 2. Energy band diagram fragments of Si–DLC film structures and the current transport mechanisms in case of structures with a DLC film slightly doped with nitrogen: a – without electric field; b, c – at the action of the electric field; c – lowering of the barrier in the electric field (Pool–Frenkel effect). 1 – Fowler–Nordheim tunneling; 2 – Pool–Frenkel current transport mechanism

To prove the domination of the Pool–Frenkel mechanism in case of the current transport through DLC films in relatively low fields, we performed the comparison of theoretically calculated values of the Pool–Frenkel ( $\beta_{\rm FP}$ ) and Schottky ( $\beta_{\rm S}$ ) constants with experimental ones determined from the slope of I - V characteristics. It is possible to precisely calculate the values of  $\beta_{\rm FP}$  and  $\beta_S$  at the known high-frequency value of relative permittivity of the material [13–15]

$$\varepsilon_d = n^2 - k^2,\tag{5}$$

where n is the real part of the complex refraction coefficient of the material (refractive index), and k is the imaginary part (extinction coefficient). As a rule,  $n \gg k$ for DLC films [16]. Consequently, expression (5) with a high level of accuracy can be written as

$$\varepsilon_d \approx n^2.$$
 (6)

The dependences of the refractive index of DLC films on the nitrogen content in a gas mixture during PE CVD are shown in Fig. 3,*a*. The measurements of the refractive index were performed by laser ellipsometry at the wavelength  $\lambda = 632.8$  nm. As can be seen from Fig. 3,*a*, the growth of the nitrogen content in a gas mixture decreases the refractive index. The influence of the gas mixture pressure is also significant. The values of relative dielectric permittivity ( $\varepsilon_d$ ) of DLC films and its dependence on the nitrogen content are presented in

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Fig. 3. Refractive index (a) and relative permeability (b) of DLC films on the nitrogen content in a gas mixture at 1 P=0.2; 2 P=0.6; 3 P=0.8 Torr. (c) Energy barrier lowering constants versus the nitrogen content: 1 - Pool-Frenkel constant; 2 - Schottky constant; 3 - experimental points

Fig. 3,b. The theoretical values of  $\beta_{\rm FP}$  and  $\beta_{\rm S}$  were calculated using the experimental values of  $\varepsilon_d$ . The theoretical dependences of  $\beta_{FP}$  and  $\beta_{\rm S}$  on the nitrogen content are shown in Fig. 3,c (curves 1, 2). The experimental values of  $\beta_{\rm FP}$  (curve 3) obtained from I-Vcharacteristics rebuilt in the Pool–Frenkel coordinates are also presented in Fig. 3,c. As can be seen, there is a good agreement of theoretical and experimental values of  $\beta_{\rm FP}$ , while the theoretical values of  $\beta_{\rm S}$  are significantly differ from the experimental ones. This proves the realization of the electron transport according to the Pool–Frenkel mechanism in case of the current flow through DLC films in lower electric fields (Fig. 2).

It is possible to determine the influence of the nitrogen doping level on the trap depth  $(\Phi_t)$  in the forbidden band of DLC films from experimental I - V characteristics built in the Pool–Frenkel coordinates. For this purpose, we insert the experimental values of J and E taken from the I-V characteristics in Eq. (2) and

determine the relations for undoped and nitrogen-doped DLC films. This allows us, according to the equation

$$\Delta \Phi_t = \Phi_t - \Phi_{t0} = -kT \ln \frac{\beta_1 E_1^{1/2}}{\beta_0 E_0^{1/2}} + \beta_0 E_0^{1/2} - \beta_1 E_1^{1/2},$$
(7)

to determine a change of the depth of traps that take part in the current transport in doped DLC films in relation to that in undoped ones. The dependence of the donor center (trap) depth changing  $(\Phi_t - \Phi_{t0})$  on the nitrogen content in a gas mixture is shown in Fig. 4,*a*. The significant lowering (a decrease relative to the bottom of the conduction band) of the trap depth  $(\Phi_t)$  at the nitrogen doping is observed, especially at the initial period with a small doping level (5 and 10% N<sub>2</sub> in the gas mixture). At high doping levels, the opposite shift of  $\Phi_t$  to values corresponding to a nitrogen-undoped DLC film is observed.

The investigation of the electron transport through DLC films in the region of lower fields gives possibility to estimate the greatest level of the donor center concentration in DLC films. The Pool–Frenkel theory assumes the existence of insulated impurity centers with a Coulomb energy barrier. The assumption about insulated centers (non-interactive donors) becomes uncorrected if the density of insulated donor centers is high enough and such that the visible overlapping of potential wells is realized. Let us assume that insulated donors with the density  $N_d$  are distributed in a regular cubic sublattice with the cell size equal to  $2a = N_d^{-1/3}$ . We determine the critical overlapping as  $\varphi(a) = 4kT$ . Then the value of  $N_{dc} \approx 4 \times 10^{18}$  cm<sup>-3</sup> was found from the expression for the Coulomb potential of an electron in the field of positive charged donor centers:

$$\varphi(r) = -e^2/4\pi\varepsilon_0\varepsilon_d r. \tag{8}$$

If the local center density exceeds this value, the lowering of the barrier in the electric field is described by the formula

$$\Delta \Phi = -eaE,\tag{9}$$

rather than by relation (3) with the dependence  $E^{1/2}$ . As can be seen from Fig. 2, b, the electron transport proceeds according to the Pool–Frenkel mechanism with the field lowering of the barrier as  $E^{1/2}$ , rather than as E (Pool law). The concentration of donor centers in a DLC film is less than the critical one:

$$N_t < N_{dc} \approx 4 \times 10^{18} \text{ sm}^{-3}.$$
 (10)

The lowering of the energy barrier for the carrier hopping according to the Pool–Frenkel mechanism by relation (3) is realized at the electric field growth. At the same time, the lowering of the energy barrier for electrons at the Si-DLC film interface due to the action of image forces proceeds. As can be see from Eqs. (3) and (4), the lowering of the barrier at the current transport according to the Pool–Frenkel mechanism is significantly faster. With increase in the electric field strength, the corresponding point on the I - V characteristic approaches the region, where the governing mechanism of the current transport is changed from the Pool-Frenkel to Fowler–Nordheim mechanism (Fig. 2). The current flowing though the structures containing DLC films at low fields is determined by the carrier transport through of the film volume (the Pool–Frenkel volume limiting mechanism). But, at high electric fields, the





Fig. 4. Shift of the electron trap depth in the forbidden band of DLC films (a), the energy barrier height for electrons at the Si–DLC film interface (b) (1 – without taking the image forces into account; 2 – with taking the image forces into account; 3 – data obtained by the internal photoemission method) and the Fermi level calculated from the conduction band bottom  $E_c$  (c) versus the nitrogen content (P = 0.2 Torr)

transport is limited by the flow through the Si–DLC film interface (the Fowler–Nordheim interface or contact limiting mechanism).



Fig. 5. Dependences of the dark electric conductivity of DLC films on the nitrogen content (a) and on the energy bandgap of a-C:H films (b) (P = 0.2 Torr)

It is possible to determine the energy barrier height at the Si–DLC film interface  $(\Phi_b)$  from the slope of the high-voltage part of the I - V characteristic in the Fowler–Nordheim coordinates. The dependence of  $\Phi_b$  on the nitrogen content is shown in Fig. 4,b; it is seen that this dependence is nonmonotonous.

Under conditions of the thermodynamic equilibrium, the Fermi level positions in Si and a DLC film coincide. It is possible to determine the Fermi level position in the DLC film, by using the known energy barrier height for electrons at the Si–DLC film interface and the calculated value of the Fermi level in silicon according to the relation [17]

 $E_f = E_c - kT \ln N_c / N_d. \tag{11}$ 

In case of *n*-type silicon with the doping level of phosphorous  $N_d = 10^{15} \text{ cm}^{-3}$ , the Fermi level position is  $E_f = -0.28 \text{ eV}$ .

The dependence of the Fermi level position in a DLC film calculated on the basis of experimental data on the nitrogen content in a gas mixture at the deposition,

$$E_f = \Phi_b + E_{fSi},\tag{12}$$

is shown in Fig. 4, c. The Fermi level position in undoped amorphous semiconductors and insulators is related, as a rule, to the middle of the bandgap [1,18]. This is caused by the presence of a large number of traps in the bandgap. This fact causes the difficulties at the doping of such materials. The influence of an *n*- or *p*-type impurity on the Fermi level position is not so significant as that for crystalline materials. As can be seen from Fig. 4, c, the Fermi level for small nitrogen doping doses is located above the bandgap middle. That is, DLC films after the introduction of nitrogen became a material with the *n*-type conductivity. However, with growth of the doping dose, the Fermi level falls lower than the bandgap middle. At this, as can be seen in Fig. 1, the conductivity of DLC films decreases to values close to those of nitrogen-undoped DLC films.

The dependence of the electric conductivity of DLC films on the nitrogen content in a gas mixture at the PE CVD deposition is presented in Fig. 5, a. The electric conductivity was determined at the electric field strength in films  $E = 1 \times 10^6 \text{ V/cm}$  at room temperature. No monotonous dependence of the electric conductivity  $\sigma$  on the nitrogen content is observed. The electric conductivity increases sharply at low N<sub>2</sub> concentrations (5, 10%). But the gradual falling to values close to those for nitrogen-undoped DLC films is observed with the following growth of  $N_2$ . The electric conductivity of the investigated DLC films was in the range of  $(2 \times 10^{-15} 2 \times 10^{-10}$ ) Ohm<sup>-1</sup>cm<sup>-1</sup>. It is in good agreement with values of  $\sigma$  for a-C:H films from the literature [19]. The low electric conductivity of a-C:H films is caused by a high content of hydrogen that blocks broken bonds and decreases, in such a manner, the concentration of traps in the forbidden band taking part in the current transport. At the same time, it is known that the electric conductivity of a-C films (without hydrogen) is significantly higher  $\sigma = 1 \times 10^{-4}$  Ohm<sup>-1</sup>cm<sup>-1</sup> [20].

Figure 5,b shows the dependence of the dark electric conductivity of DLC films on the optical bandgap. The bandgap was determined by the spectral ellipsometry

method [6]. A decrease of  $\sigma$  with growth of  $E_g$  is observed. The diminution is small at relatively low values of  $E_g$ , but it increases with the following growth of  $E_g$  (Fig. 5,b). The given results for a-C:H films are in good agreement with the dependence of  $\sigma$  on  $E_g$  for other amorphous semiconductors, namely, a-Si<sub>1-x</sub>C<sub>x</sub>:H and a-Si<sub>1-x</sub>N<sub>x</sub>:H [2]. In case of a-Si<sub>1-x</sub>C<sub>x</sub>:H films, the value of  $\sigma$  decreases at the bandgap growth from  $\sigma = 10^{-11}$  Ohm<sup>-1</sup>cm<sup>-1</sup> ( $E_g = 1.9$  eV) to  $\sigma =$  $10^{-16}$  Ohm<sup>-1</sup>cm<sup>-1</sup> ( $E_g = 2.43$  eV) [21]. For Si<sub>1-x</sub>N<sub>x</sub>:H films, a decrease of the electric conductivity from  $\sigma =$  $10^{-8}$  Ohm<sup>-1</sup>cm<sup>-1</sup> ( $E_g = 1.9$  eV) to  $\sigma = 10^{-14} 10^{-15}$  Ohm<sup>-1</sup>cm<sup>-1</sup> ( $E_g > 2.4$  eV) is observed [22].

The analysis of the dependence of the electric conductivity on the nitrogen doping level (Fig. 5, a) shows no monotonous behavior. At the introduction of a low amount of nitrogen (5, 10% in a gas mixture), the sharp growth of the electric conductivity is observed. The following increase of the nitrogen content causes a gradual falling of  $\sigma$ . As a result, there is the maximum at  $N_2 = 10\%$  on the  $\sigma = f(N_2)$  dependence. It is possible to explain this dependence by peculiarities of the building of nitrogen into an a-C:H film. Nitrogen has good solubility in diamond and DLC films in contrast to other n-type impurities (for example, phosphorus) [23]. But not all nitrogen atoms are ionized and play the role of donor centers. Moreover, nitrogen can create various bond configurations with carbon [24]. At low concentrations of nitrogen in the film, it substitutes for a carbon atom in a six-membered ring (Fig. 6). As a result, three  $\sigma$  bonds with three neighbor carbon atoms are created. Such nitrogen has one  $\pi$  electron and one electron that can be ionized. That is, nitrogen in such a state dopes the solid state. This causes the appearance of a donor center and a shift of the Fermi level to the edge of the conduction band, as shown in Fig. 4, c. At the following increase of the amount of nitrogen, its building occurs in other configurations with carbon (Fig. 6). First of all, it can be a configuration similar to pyridine  $(C_5H_5N)$ . Nitrogen in it has only two  $\sigma$  bonds with two neighbor carbon atoms. Two electrons are positioned on the anti-bonding  $\pi$  orbital, and one electron is on the delocalized  $\pi_z$  orbital [24,25]. Nitrogen in such bond configuration is an undopping impurity. It is also possible to find nitrogen in the five-membered ring configuration likely to pyrrole  $(C_4H_5N)$ . In it, nitrogen has three  $\sigma$  bonds with three neighbor carbon atoms, and two electrons are on delocalized  $\pi_z$  orbitals [25]. Nitrogen in such bond configuration is also an undopping impurity.

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Fig. 6. Schematic image of energy band diagrams of DLC films low-doped (a) and high-doped (b) with nitrogen. 1-3 – possible configurations of atomic bonds at the nitrogen building in a DLC film: 1 – nitrogen in six-membered ring; 2 – pyridine-type structure (C<sub>5</sub>H<sub>5</sub>N); 3 – pyrrole-type structure (C<sub>4</sub>H<sub>5</sub>N)

As can be seen in Fig. 6, a, the efficiency of nitrogen as a donor impurity in a-C:H films is small enough at relatively high doping levels. This allows us to suggest that the states of defects near the bandgap middle are mainly introduced instead of the entry of the donor levels (Fig. 6). As a result, the compensation of the material conductivity is realized similarly to the compensation mechanism described in work [26]. Similar peculiarities of the influence of the nitrogen doping were observed for a-C films [24]. The autocompensation mechanism in amorphous semiconductors is developed similarly to that in crystalline ones [27,28]. The doping causes the growth of the defect density. In *n*-type samples, the electrons of a donor level are captured by defects with lower energy levels in the bandgap. For example, it is known that a-Si:H is a compensated material with 90% of carriers captured on levels caused by defects [29].

### 4. Conclusion

Two mechanisms of electron transport through DLC films in the region of high electric fields  $E \geq 1 \times 10^6$  V/cm, namely the Pool–Frenkel mechanism characteristic of the electron transport through the film volume at lower electric fields ( $E = (1-2) \times 10^6$  V/cm) and the Fowler–Nordheim mechanism in the region of higher electric fields ( $E > 2 \times 10^6$  V/cm) limited by the electron transport through energy barriers at the Si/DLC film interface, are revealed.

The nonmonotonous dependence of the DLC (a-C:H) film conductivity on the nitrogen doping level is observed. The electric conductivity of the films was in the range  $(2 \times 10^{-15} - 2 \times 10^{-10})$  Ohm<sup>-1</sup>cm<sup>-1</sup>. The maximal electric conductivity of the films is realized at the N<sub>2</sub> = 10% nitrogen concentration in a gas mixture during the deposition.

A model clarifying the nonmonotonous dependence of the electric conductivity of DLC films on the nitrogen doping level is developed. According to this model, nitrogen at low concentrations builds in the structural net of a DLC film as a doping n-type impurity. It causes the creation of donor levels and the growth of the current. At the same time, nitrogen at high concentrations builds in as an undoping center and causes the creation of deep energy levels (electron traps) in the region of the bandgap middle of a DLC film.

- 1. N.F. Mott and E.A. Davis, *Electron Processes in Non-Crystalline Materials* (Clarendon Press, Oxford, 1979).
- T. Stapinski, Amorphous and microcrystalline silicon-based alloys for device applications (WND, Krakow, 1999).
- 3. D.I. Jones and A.D. Stewart, Phil. Mag. B B46, 423 (1982).
- N.W. Ashcroft and N.D. Mermin, Solid State Physics (Holt, Rinehart, and Winston, New York, 1976).
- B. Dunnett, D.I. Jones, and A.D. Stewart, Phil. Mag. B 53, 159 (1986).
- A.A. Evtukh, V.G. Litovchenko, N.I. Klyui, R.I. Marchenko, and S.Yu. Kudzinovski, J. Vac. Sci. Technol. B17, 679 (1999).
- V.G. Litovchenko, A.A. Evtukh, Yu.M. Litvin, S.Yu. Kudzinovski, N.M. Goncharuk, and V.E. Chayka, in Proceeding of the 2nd International Workshop on Vacuum Microelectronics (Wroclaw, Poland, July 11–13, 1999), p.123.
- N.L. Dmitruk, A.A. Evtukh, V.G. Litovchenko, and S.V. Mamykin, in *Proceeding of the 14th International* Conference on Vacuum Microelectronics (Davis, California, USA, August 12–16, 2001), p. 293.
- A.K. Jonscher and R.M. Hill, in *Physics of Thin Films*, edited by G. Hass, M.H. Francombe, and R.W. Hoffman (Academic Press, New York, 1975), Vol.8.
- S.M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1981).
- K.C. Kao and W. Hwang, *Electric Transport in Solids* (Pergamon, Oxford, 1979).
- E.H. Rhoderick, *Metal-Semiconductor Contacts* (Clarendon Press, Oxford, 1978).
- 13. N. Savvides, J. Appl. Phys. 59, 4133 (1986).
- 14. E.A. Irene, Thin Solid Films 233, 96 (1993).
- 15. V. Litovchenko, Ukr. Fiz. Zh. 42, 228 (1997).

- 16. V.A. Semenovich and N.I. Klyui, Journal of CVD 4, 29 (1995).
- K.V. Shalimova, *Physics of Semiconductors* (Energiya, Moscow, 1976) (in Russian).
- Amorphous Semiconductors, edited by M.H. Brodsky (Springer, Berlin, 1979).
- 19. T. Mori and Y. Namba, J. Vac. Sci. Technol. A 1, 23 (1983).
- 20. H. Tsai and D.B. Bogy, J. Vac. Sci. Technol. A 5, 3287 (1987).
- F. Giorgis, F. Giuliani, C.F. Pirri, E. Tresso, C. Summonte, R. Galloni, A. Desalvo, and P. Rava, Phil. Mag. B 77, 925 (1998).
- A. Desalvo, F. Giorgis, C.F. Pirri, E. Tresso, P. Rava, R. Galloni, R. Rizzoli, and C. Summonte, J. Appl. Phys. 81, 7973 (1997).
- 23. J. Robertson and E.P. O'Reilly, Phys. Rev. B. 35, 2946 (1987).
- S. Waidmann, M. Knupfer, J. Fink, B. Kleinsorge, and J. Robertson, J. Appl. Phys. 89, 3783 (2001).
- 25. L. Pauling and P. Pauling, *Chemistry* (Freeman, San Francisco, 1975).
- 26. R.A. Street, Phys. Rev. Lett. 49, 1187 (1982).
- 27. V.L. Bonch-Bruevich and S.G. Kalashnikov, *Physics of Semiconductors* (Nauka, Moscow, 1977) (in Russian).
- B.I. Boltaks, M.K. Bakhadyrkhanov, S.M. Gorodetsky, and G.S. Kulikov, *Compensated Silicon* (Nauka, Moscow, 1972) (in Russian).
- M. Stutzmann and R.A. Street, Phys. Rev. Lett. 54, 1836 (1985).

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ЕЛЕКТРОННА ПРОВІДНІСТЬ ЛЕГОВАНИХ АЗОТОМ АЛМАЗОПОДІБНИХ ВУГЛЕЦЕВИХ ПЛІВОК: МЕХАНІЗМИ ПУЛА-ФРЕНКЕЛЯ ТА ФАУЛЕРА-НОРДГЕЙМА

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Резюме

Наведено результати експериментальних досліджень електропровідності адмазополібних вугленевих (АПВ) плівок в залежності від рівня їх легування азотом. Виявлено два механізми проходження електронів через АПВ-плівки у сильних електричних полях ( $E \ge 1 \cdot 10^6 \text{ B/cm}$ ), а саме механізм Френкеля-Пула та механізм Фаулера-Нордгейма. Встановлено немонотонну залежність електропровідності АПВ-плівок від рівня їх легування азотом. Електропровідність плівок лежала у діапазоні  $2 \cdot 10^{-15} - 2 \times 10^{-10}$  Ом $^{-1}$ см $^{-1}$ . Максимальну електропровідність плівки мали при концентрації [N<sub>2</sub>] = 10% в газовій суміші при осадженні. Запропоновано модель, що пояснює немонотонну залежність електропровідності АПВ-плівок від рівня легування азотом. Згідно з цією моделлю при низьких концентраціях азот вбудовується в структурну сітку АПВ-плівки у вигляді легуючої домішки *n*-типу, що приводить до утворення донорних рівнів і супроводжується зростанням струму. В той же час при великих концентраціях азот вбудовується у нелегуючому вигляді, що приводить до утворення глибоких енергетичних рівнів (електронних пасток) поблизу середини забороненої зони АПВ-плівки.