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Point-contact sensory nanostructure modeling

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The mechanism of synthesis of copper dendritic point contacts for sensory analysis was studied for the first time. Experiments were performed using elongated element utilized as model for metallic point-contact nanostructure. We have shown that contactless magnetic method can be applied when investigating current distribution along the elongated linear conductor's main axis. It was revealed that the local minimum of magnetic field strength matches with the point separating conjugate electro-chemical processes. The new method was proposed for determination of ionic charge fracture versus point-contact voltage. This method opens up possibilities in targeted synthesis of nanostructures for new generation of sensory devices.

Впервые изучен механизм синтеза медных дендритных точечных контактов для сенсорного анализа. Эксперименты выполнены с использованием протяженного элемента, моделирующего металлическую точечно-контактную наноструктуру. Показано, что распределение токов вдоль главной оси линейного протяженного элемента можно исследовать бесконтактным магнитным методом. Обнаружено, что локальный минимум напряженности магнитного поля соответствует точке, пространственно разделяющей сопряженные электрохимические процессы. Предложен новый метод определения зависимости доли заряда, переносимого ионами, от напряжения на точечном контакте. Метод позволяет целенаправленно синтезировать наноструктуры для создания сенсорных устройств нового поколения.

1. Introduction

Point-contacts are among the most promising high-tech nanoobjects and can become the basis of highly sensitive sensory devices [1, 2] and spin electronics equipment [3]. Utilization of point-contacts fundamental properties allows of addition of new functional properties to standard materials as well as creation of new objects with unique technical features [4]. Transition from fundamental research to the applied point-contact-based technological objects is associated with necessity to create new methods for synthesizing nanostructures mentioned above. Application of electrochemical method provides the significant advances in solution of the described problem [5–8]. Therefore, naturally, established mechanical methods for point-contact production [9] were recently augmented by electrochemical method that allows to produce nanostructures in the touching point of highly ordered metal dendrite and counter electrode [10]. Such objects have size that is comparable with electron mean free path for the given metal [9] whereas the technical task of direct photographic recording is difficult enough, and is not accomplished yet because of shielding of point-contact conductivity channel by the current-feeding conductors. Thus need for large-scale modeling arises. In the fundamental low-temperature experiments point-contacts are created and operated in non-conductive environment. In the meantime, electro-chemical synthesis of this nanoobject is performed in the ion conductor environment, that calls for development of a new model.

Every metallic conductor that is immersed in electrolytic environment and placed in electric field constitutes an elongated element that can be considered as multielectrode system with monotonic distributed potential [11, 12]. Investigation on this model was shown that voltage applied to the electrochemically synthesized dendritic point contact caused parallel electronic and ionic currents in the system.

In this paper an elongated element as a model of point contact in the ion-conducting environment was studied in order to determine current distribution for the sake of developing methods for electro-chemical synthesis of dendritic point-contact sensory nanostructures. Methodological approach and methodic steps for research in point-contact field that are presented in this paper can be applied for all groups of homogenous and composite conductive materials.

2. Experimental

Experiments were performed at room temperature in atmospheric environment. *U*-or *I*-shaped metallic conductor was placed in the rectangular organic glass cell (Fig. 1). As a conductor a copper wire with diameter of 0.2 mm was used. Electrolyte solution was 0.5 M $CuSO_4 \cdot 5H_2O$ solution prepared with chemically pure salt and redistilled water. Electric influence on the system was performed using PINTEK PW-3032R stabilized power supply. M2038 ampere meters were used to detect and register current distribution. Keithley-2000 multimeters were used to measure voltage and potential distribution along the elongated conductor in electrolyte solution. Special structure flux-gate magnetometer was used in such experiments for the first time [13].

3. Results and discussion

Voltage V applied to homogeneous cross section elongated conductor is distributed along the longitudinal axis of that conductor. Maximum voltage drop is observed between the waterlines of the opposite ends of this conductor. When decomposition voltage of given electrode system is achieved [14], ionic current arises in the parallel electrochemical arm along with the electronic current that runs along the conductor. Some electrons that move from the negative terminal of the power supply along the main axis of the elongated conductor cross the boundary line between the conductor and electrolyte solution thus taking part in electrochemical reduction reactions. Electronic density within the metal conductor decreases and runs into the minimum in the inversion point. In this point negative and positive potentials are mutually compensated and electrochemical reactions velocities equal to zero regardless of any voltages applied to the ends of the conductor [12]. Transition through the point is accompanied by continuous growth of conductivity electrons density in the metal. If the metal conductor is homogeneous, it is possible to consider inversion point of electrode as its geometric center in the beginning stage of electrolysis when assuming symmetry of anodic and cathodic arms of polarization pattern. Electronic density comes up to initial value on the waterline adjacent to the positive terminal of the power supply. Therefore, electron flows differ at the entrance and inversion points of the elongated conductive element. This difference is caused by participation of some conductive elec-

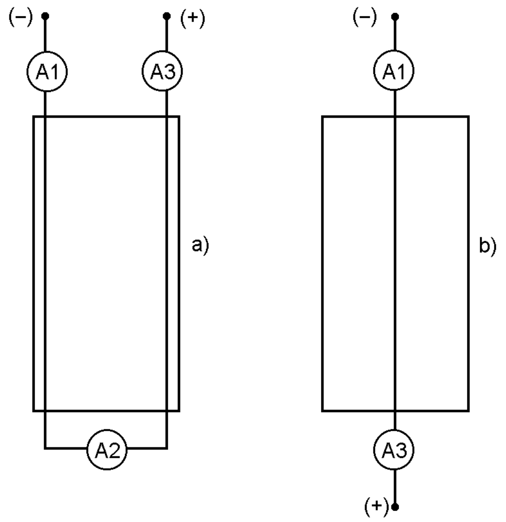


Fig. 1. Schematic representation of electrochemical cell: a — with *U*-shaped elongated conductive element; b — with *I*-shaped elongated conductive element. A1, A3 — ampere meters at the entry and exit points of an elongated element, respectively, A2 — inversion point ampere meter.

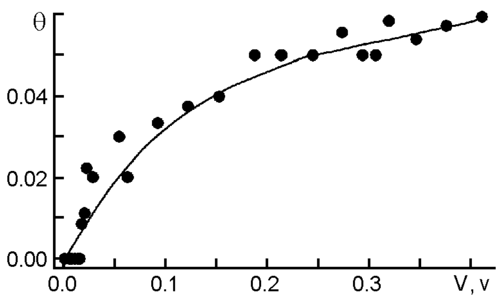
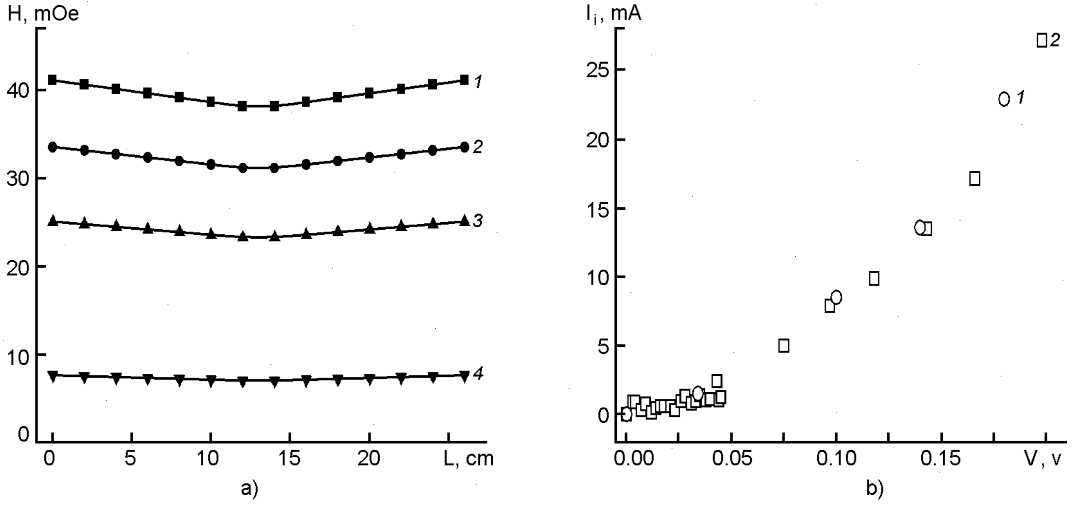


Fig. 2. Charge fraction Θ transferred by ions through the surface of the elongated copper conductor versus applied voltage V. Conductor length is 0.5 m.

trons in the electrochemical conversion reactions on the borderline, which allows estimating charge carriers' distribution along the elongated element, i.e. electrochemical conversion current determination. To determine integrated velocity of electrochemical reactions it is enough to determine currents difference between the starting part and inversion point of the elongated conductor. This measurement is easiest to perform using U-shaped elongated conductive element (Fig. 1). To perform this measurement one can move geometric center (i.e. inversion point) of the conductor out of the cell and measure current strength in that point. Charge fraction Θ that is transferred by ions can be calculated as ratio of ionic current value I_i and total current value I in the entrance point of the elongated conductor. When the voltage bias is low, electronic current changes in a linear fashion according to the Ohm's law, and ionic current changes exponentially depending on voltage [14], which proves formula $d^2\Theta/dV^2 > 0$ is correct. In the meantime the experiment had shown that correlation $\Theta(V)$ has arched shape within the range of $V = 0{-}400$ mV and is described by the equation $y = ax^b$, where $a = 0.12$; $b = 0.6$ (Fig. 2). This redistribution of electronic and ionic currents is characteristic for elongated conductive element where conjugation of electron transfer resistance and polarization resistance of border between metal and electrolyte phases is implemented based on mutual correlation.

It is well to bear in mind that point contact conductivity channel is a linear conductor [9, 12]. Therefore it will be most reasonable to model point contact as I-shaped elongated conductive element. Conventional galvanometric measurement of electrochemical current is complicated this way since inversion point (i.e. electronic current measurement point) of the conductor is immersed into the electrolyte solution. Contactless current detection via flux-gate sensor could be the most appropriate method of measurement in such system [13]. Measurements performed with flux-gate magnetometer have shown that inversion point is characterized with minimum magnetic field strength (Fig. 3a). Notably, this minimum becomes more evident with increase in current intensity through the elongated conductive element. The minimum in magnetic field strength distribution is in good corre-



a) b)

Fig. 3. a — Magnetic field strength H along the I-shaped elongated copper conductive element. Current intensity in the conductor, mA: 1000 (*1*), 800(*2*), 600(*3*), 200(*4*). L — length of the elongated conductive element; b — electrochemical current measured via flux-gate sensor (*1*) and galvanometric method (*2*) versus voltage applied to the ends of the elongated I-shaped conductive element.

lation with a minimal electronic current in that point obtained via short-circuit effect of electrochemical processes. This turns up as an experimental evidence of existence of inversion point in the elongated conductive element. It is obvious that inversion point-separated anode- and cathode-polarized zones will be created on the borderline between metal and electrolyte phases when the electric current flows through the conductivity channel of the point-contact immersed in electrolyte solution. Electrochemical current intensity values measured with flux-gate sensor correspond to values measured via galvanometric method (Fig. 3b).

4. Conclusions

Thus possibility for determination of fine morphologic features of nanoobject under study is shown using identified inversion point as an example. It was revealed that ionic share of integrated current depends significantly on intensity of electrical action applied to the given system. Based on the proposed method of correlation $\Theta(V)$ determination the possibility opens up for precision analogue control of point-contact nanostructure resistance characteristics, that is important for creation of new generation sensory devices [1].

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Моделювання точково-контактної наноструктури з сенсорними властивостями

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Вперше досліджено механізм синтезу мідних дендритних точкових контактів для сенсорного аналізу. Експерименти виконані з використанням протяжного елементу, якій моделює металеву точково-контактну наноструктуру. Показано, що розподіл струмів вздовж головної осі лінійного протяжного елемента можна дослідити безконтактним магнітним методом. Встановлено, що локальний мінімум напруженості магнітного поля відповідає точці, яка просторово розділяє спряжені електрохімічні процеси. Запропоновано новий метод визначення частки заряду, що переноситься іонами, від напруги на точковому контакті. Метод дозволяє цілеспрямовано синтезувати наноструктури для створення сенсорних пристроїв нового покоління.