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Semiconductors with Zero Ohmic Loss

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Abstract

Using the equations of thermodynamics, the universal principles of creating homogeneous solids of macroscopic dimensions are substantiated, with the polarization of which by an electric field their free energy decreases. The fundamental reasons for which ohmic loss in solids is zero have been established. The phenomena accompanying the anomalous polarization of solids are considered.

Keywords: ***Surface; Semiconductors; Electric field; Permittivity; Polarization; Electricity; Ohmic loss***

Introduction

According to the Kramers-Kronig dispersion relations, the static permittivity of any substance satisfies one of the following conditions: $\varepsilon \geq 1$ or $\varepsilon \leq 0$ [1]. For a long time, the possibility of creating substances that satisfy the condition $\varepsilon \leq 0$ was debatable [1-3]. Solids with a negative static permittivity can be high-temperature superconductors [2, 3].

According to experimental data, the conditions $\varepsilon \leq 0$ are satisfied in the case of finely dispersed semiconductors with ionized donor centers on the surface of powder particles and free electrons in the bulk [4, 5]. For example, when a layer of $KMnO_4$ or $KNaC_4H_4O_6 \times 4H_2O$ powder, consisting of microparticles, is polarized by an alternating electric field, the effect of field amplification and inversion occurs, while the ohmic loss is zero [4]. Composites and metamaterials with negative and zero values of the real part of ε are known. They differ from the powders that have studied by the frequency dispersion $\partial\varepsilon/\partial\omega$ and the absence of the effect of amplification and inversion of a zero or low-frequency field [4, 6-8].

The anomalous polarization of another dispersed system (fog) is the cause of atmospheric electricity phenomena: lightning in thunderclouds and ball lightning [5].

In the case of a constant electric current in powders consisting of spherical Al_2O_3 or NiO nanoparticles with interstitial hydrogen atoms on their surface, the ohmic loss is zero [9]. This effect is due to the polarization of the powder layer by the electric field of the current source [10]. The mechanism of electrical conductivity of powder nanoparticles and the state of free electrons in their volume differ from the electrical conductivity and state of electrons of homogeneous solids, macroscopic dimensions. The nanoparticle diameter $l \approx 10^{-7}$ m is comparable with the de Broglie wavelength of free electrons in semiconductors. The electrical conductivity of the powder is due to tunneling transitions of free electrons between polarized spherical particles in the region of

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their point contacts and is similar to the hopping conductivity of homogeneous semiconductors [11, 12]. The relatively low electrical conductivity of finely dispersed semiconductors hinders their practical use.

In this article the structure of a semiconductor is established, the polarization of which by an electric field is accompanied by a decrease in its free energy. The unique properties of such semiconductors due to a stable built-in electric field are substantiated. Analytical expressions describing the conditions of zero ohmic loss in the case of direct current in semiconductors having the form of a film, thread, ball or a chain of balls are obtained.

Free Energy of Polarized Semiconductors

Let us determine the conditions under which the polarization of a solid by an electric field is accompanied by a decrease in its free energy. Let's place a homogeneous dielectric in a homogeneous electric field. We use expressions describing the electronic polarization of a dielectric by a constant electric field under stationary isothermal conditions [13]:

$$\mathbf{P} = \left(\varepsilon_d - 1\right)\varepsilon_0\mathbf{E}\,, \tag{1}$$

$$F = \left(\mathbf{E}, \mathbf{P}\right)/2 + \varepsilon_0 E^2/2 \tag{2}$$

where **P** is the dielectric polarization due to the field-induced displacement of electrons bound in its atoms (dipole moment per unit volume); ε_d is the static permittivity of the dielectric; ε_0 - electrical constant; **E** is the electric field strength in the dielectric; F is the change in the free energy of a solid body polarized by an electric field. Substituting Eq. (1) into formula (2), we obtain:

$$F = \varepsilon_d \varepsilon_0 E^2/2. \tag{3}$$

Due to the condition $\varepsilon_d \geq 1$ we have: $F > 0$. The external electric field does the work of dielectric polarization. The polarization of a substance consists in the displacement of bound electrons relative to positively charged centers under the action of the forces of an external electric field.

Let's place substitute into Eq. (2) the expression [13]:

$$\mathbf{E} = \mathbf{E}_0 - \mathbf{P}/\varepsilon_0, \tag{4}$$

where $\mathbf{E}_0$ is the field strength in vacuum. We get:

$$F = \varepsilon_0(\mathbf{E}, \mathbf{E}_0)/2 = \varepsilon_0\left(E_0\right)^2/2 - (\mathbf{P}, \mathbf{E}_0)/2. \tag{5}$$

According to expressions (4) and (5) under the condition

$$P \geq \varepsilon_0 E_0 \tag{6}$$

we have:

$$F \leq 0. \tag{7}$$

Consequently, the condition $F \leq 0$ can be satisfied for solids with anomalously high polarization. In this case, the vectors **E** and $\mathbf{E}_0$ are antiparallel $(\mathbf{E}, \mathbf{E}_0) < 0$ or $(\mathbf{E}, \mathbf{E}_0) = 0$.

Using the formula $\mathbf{P} = (\varepsilon - 1)\varepsilon 0\mathbf{E}$ and Eq. (2), we find: $F = \varepsilon\varepsilon 0 E2/2$. Therefore, expression (7) corresponds to the value of the static permittivity of the semiconductor $\varepsilon \leq 0$. Hence, the inequalities $F \leq 0$ and $\varepsilon \leq 0$ are satisfied if condition (6) is satisfied.

In the case of dielectrics and conventional semiconductors conditions (6) and (7) are not fulfilled. Therefore, we will consider a semiconductor, on the entire surface of which ionized donor centers are uniformly distributed, and free electrons are located in the volume. According to the Gauss theorem, the strength of the field created in the bulk of the semiconductor by the positive surface charge of ionized donor centers is equal to zero. Inside the volume of a semiconductor there are no forces opposing the displacement of an electron. The electric potentials of all points in the volume of semiconductor are the same. The work of external forces on the displacement of free electrons in a semiconductor is zero. Therefore, in the process of isothermal polarization of a semiconductor, for the rate $\gamma = (\mathbf{j}, \mathbf{E})/T$ of the local occurrence of entropy in its volume, the following condition is satisfied [13]:

$$\gamma = \left(\mathbf{j}, \mathbf{E}\right) / T < 0, \tag{8}$$

where $\mathbf{j}$ is the instantaneous value of the current density in the semiconductor at time t; $\mathbf{E}$ is the strength of the field created by the emerging polarization charges at time t, $E > E_0$; $(\mathbf{j}, \mathbf{E}) < 0$; T is temperature. Condition (8) corresponds to a decrease in the entropy of the system due to its transition to an ordered state.

Let the semiconductor be in the form of a plane-parallel plate. Let us place the plate in a uniform electric field with lines of force perpendicular to it. Under the action of an electric field, free electrons experience a maximum displacement. On the opposite surfaces of the plate, positive $+\sigma$ and negative $-\sigma$ polarization charges appear equal in absolute value, formed by charged donor centers and free electrons, respectively. According to condition (5), the free energy of a polarized semiconductor has a minimum value when the polarization P and, accordingly, the value of σ have maximum values. In accordance with the Le Chatelier principle, the internal forces of the Coulomb interaction in a semiconductor counteract the decrease in the surface polarization charges $+\sigma$ and $-\sigma$, since it is accompanied by an increase in its free energy $F<0$ [13]. Therefore, the equality is fulfilled: $\sigma = \sigma_{max} \cong en_s$, where e is the absolute value of the electron charge; n_s is the concentration of ionized donor centers on two opposite surfaces of the plate. The polarization of a semiconductor due to the displacement of free electrons is:

$$P_c = \sigma \cong en_s.$$

The surface polarization charges $+\sigma$ and $-\sigma$ create in the volume of the plate a uniform electric field with strength $\mathbf{E} = -\boldsymbol{P}_c/\varepsilon_d\varepsilon_0)$. Due to the unstable state of the semiconductor electron gas, under the condition $\mathbf{E}_0 = 0$, the semiconductor can be in a stable state of spontaneous polarization with a negative value of its free energy F_0:

$$F_0 = \varepsilon\varepsilon_0 E^2 / 2 = \left(\mathbf{E}, \mathbf{P}_c\right) / 2 + \varepsilon_0 E^2 / 2 = -\left(\varepsilon_d - 1\right)\varepsilon_0 E^2 / 2, \tag{9}$$

where $\boldsymbol{P}_c = -\varepsilon_d\varepsilon_0\mathbf{E}$ is the polarization of the semiconductor in the form of a plate due to the displacement of free electrons and the formation of surface polarization charges $+\sigma$ and $-\sigma$; ε_d is the static permittivity of semiconductor atoms. Its static permittivity is a negative value: $\varepsilon = -(\varepsilon_d - 1) < 0$, where $\varepsilon_d > 1$.

Let's consider the consequences of the results obtained.

The electrical capacitance of a semiconductor plate with ionized donor centers on its entire surface is:

$$C = \sigma S / u = \sigma S / \left(EL\right) = -\varepsilon_d \varepsilon_0 S / L,$$

where

$$u = EL = -\sigma L / \left(\varepsilon_d \varepsilon_0\right) \cong -en_s L / \left(\varepsilon_d \varepsilon_0\right), \tag{10}$$

u is the difference in electric potentials of opposite surfaces of a polarized semiconductor plate; L is its thickness; $E = -\sigma/(\varepsilon_d\varepsilon_0)$. Due to the inequalities $F < 0$ and $(\mathbf{E}, \mathbf{E}_0) < 0$ (see expression (5)) the electric capacitance of the semiconductor plate C and the corresponding static permittivity $\varepsilon = -\varepsilon_d$ are negative values.

Let a plane-parallel semiconductor plate and the same dielectric plate are between the plates of an electric capacitor. The electric capacitance of the capacitor is:

$$C_t = CC_1 / \left(C + C_1\right) = \varepsilon\varepsilon_1\varepsilon_0 S / (\varepsilon L_1 + \varepsilon_1 L),$$

where C and C_1 are the electrical capacitances of the semiconductor and dielectric plates, respectively; the subscript "$_1$" refers to the parameters of the dielectric plate; $\varepsilon = -\varepsilon_d$; $\varepsilon_1 > 1$. The capacitance C_t can be positive or negative. If the basis of the semiconductor and dielectric plates is the same material, then we have: $L_1 = L; \varepsilon_1 = \varepsilon_d = -\varepsilon; \varepsilon L_1 + \varepsilon_1 L \cong 0;$

$$1 / C_t \cong 0; u_t = LE + L_1 E_1 = D(L / \varepsilon + L_1 / \varepsilon_1) / \varepsilon_0 = D(L\varepsilon_1 + L_1\varepsilon) / (\varepsilon\varepsilon_1\varepsilon_0) \cong 0,$$

where u_t is the electrical voltage across the capacitor; D- electric field induction. In this case, $1/C_t$ and u_t are negligible values in the case of a constant field or a low frequency alternating field. In this case, the capacitance $1/(\omega C_t) \cong 0$ does not depend on ω.

A spontaneously polarized semiconductor in the form of a plate or film (see Eq. (9)) serves as a source of electromotive force. The electrical potentials of opposite surfaces of a semiconductor plate are different. Their closure by a conductor is accompanied by the appearance of an electric current in the circuit. The electrons move along a closed path. According to Coulomb's law, due to the condition $\varepsilon < 0$, electrons in a semiconductor move under the action of a force $\mathbf{f} = |e|\mathbf{E}$ from a positive surface charge $+\sigma$ to a negative surface charge $-\sigma$. The condition $(\mathbf{j}, \mathbf{E}) < 0$ is satisfied. The inequality $(\mathbf{j}, \mathbf{E})/T < 0$ correspond to the action of internal forces directing free electrons to an ordered state with a negative value of the free energy of the system. Due to this, positive $+\sigma$ and negative $-\sigma$ surface polarization charges are preserved. The energy of free electrons in metal electrodes and in a semiconductor does not match. An electric current through the interface of an electrode and a semiconductor with a positive surface charge is accompanied by heat absorption. In the stationary state, when the temperature of the metal-semiconductor-metal system does not change, it exchanges heat with the environment. In accordance with the law of conservation of energy, the following condition is fulfilled: $Q = uJ$, where Q is the heat flux coming from the environment into the volume of the system through its surface; u is the electrical potential difference between two metal electrodes; J is the current in the circuit. There is a conversion of heat into the work of an electric field with an efficiency of 100%. The entropy of an isolated system (a closed electrical circuit and the environment) increases. This effect was observed in experiments with a spontaneously polarized powder layer [14].

Semiconductor Ohmic Loss

Let us place a semiconductor plate with ionized donor centers on the entire surface in a closed electric circuit with a constant electric current generated by an electromotive force source. We assume that the condition $en_s > \varepsilon_0 E_0$ is satisfied, where E_0 is the electric field strength in the bulk of the semiconductor generated by the current source. The field E_0 causes polarization of the semiconductor. Due to the electric current in the semiconductor, the field E_0 cannot cause its polarization corresponding to the inequality $F < 0$. In the case of a closed circuit, the magnitude of the emerging surface polarization charges of the semiconductor is limited, since its opposite surfaces are connected by a circuit section external to the semiconductor. Therefore, an intermediate metastable polarization state of the semiconductor arises with the maximum possible value of P:$P_{max} = \varepsilon_0 E_0$. The following conditions are met:

$$E = E_0 - P_{max} / \varepsilon_0 = 0;\ F = \varepsilon\varepsilon_0 E^2 / 2 = 0;\ \left(\mathbf{j}, \mathbf{E}\right) = 0.$$

Semiconductor ohmic loss $(\mathbf{j}, \mathbf{E})$ is zero. The current in the semiconductor is due to the contact differences of potentials of the electrodes with a polarized semiconductor (10). The probability of a semiconductor transition from a metastable state F=0 to a polarized state corresponding to condition $F < 0$ is small, since polarization charges are limited and the forces acting on electrons are equal to zero: $\mathbf{f} = e\mathbf{E} = 0$.

Below, we will consider polarized semiconductors for which condition $F < 0$ is satisfied.

Let, under the action of a constant electric field, the semiconductor plate is transferred to a polarized state with free energy $F < 0$ (see expressions (5) - (7)). Let us bring the capacitor plates connected to the source of Electromotive Force (EMF) into contacts with the plate of a semiconductor. The EMF source creates a constant electric current in the circuit, which reduces the polarization charges $+\sigma$ and $-\sigma$. According to Le Chatelier's principle [13], internal forces in a semiconductor oppose an increase in its free energy $F < 0$. Substituting the expression $E = \sigma/(\varepsilon_d\varepsilon_0)$ into the formula $F = -|\varepsilon|\varepsilon_0 E^2/2$, we find that the value of F has a minimum value at the maximum value $\sigma \cong en_s$. The stable polarization state of the semiconductor with free energy $F < 0$ and built-in electric field with intensity $\mathbf{E}$ is preserved.

The electric potentials of points in the volume of a polarized semiconductor ($\varepsilon < 0$) and in metal electrodes ($\varepsilon_m > 1$) adjacent to it have different signs. The EMF source moves the charges in the wires of the circuit and creates a difference in electrochemical potentials between two metal electrodes *I* and *II* connected to a semiconductor **(FIG. 1)**. According to Coulomb's law, due to the condition $\varepsilon < 0$, electrons in a semiconductor move under the action of a force $\mathbf{f} = |e|\mathbf{E}$ from a positive surface charge $+\sigma$ to a negative surface charge $-\sigma$. The current density vector $\mathbf{j}$ and the built-in field strength vector $\mathbf{E}$ are directed in opposite directions: $(\mathbf{j}, \mathbf{E}) < 0$. The condition $(\mathbf{j}, \mathbf{E})/T < 0$ correspond to the action of internal forces directing free electrons to an ordered state with a negative free energy of the system. The movement of electrons in a semiconductor is accompanied by a decrease in their potential energy. The current source does not do work to move electrons in the semiconductor. The Ohmic loss becomes impossible.

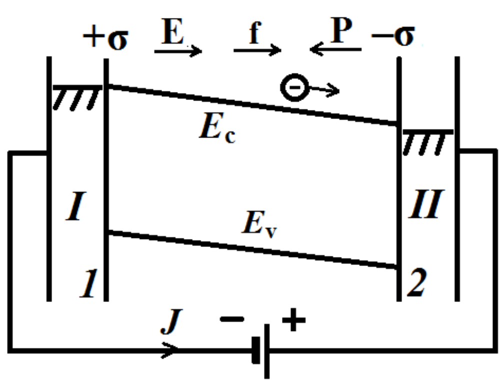

FIG. 1 **The metal-semiconductor-metal system energy levels of electrons. *I* and *II* are metal electrodes; $+\sigma$ and $-\sigma$ are the densities of polarization charges at the boundaries *1* and *2* of the semiconductor; E_c is the bottom of the conduction band of the semiconductor; E_v is the ceiling of the valence band; P is the polarization of the semiconductor; E is the intensity of the built-in electric field in the semiconductor; *J* is the current strength in a closed circuit.**

According to Eq. (10), due to the condition $u(J)$=const, the differential resistance of the semiconductor r is equal to zero, regardless of the current strength J in the circuit: $r = \mathrm{d}u/\mathrm{d}J = 0$, where $J \geq 0$. Using the expressions $u = RJ$, $du/dJ = 0$, we obtain: R=0.

The ohmic resistance of the semiconductor R and ohmic loss RJ^2 are equal to zero, regardless of the temperature (T =290 K-500 K) and the current strength in the circuit. The flow of electrons in a semiconductor is similar to the flow of a superfluid liquid with a source (electrode *I*) and a drain (electrode *II*) (see **FIG. 1**). Because of the inequality $\varepsilon<0$, the states of electrons moving in the flow are self-consistent.

Thus, in a polarized semiconductor included in a closed electric circuit with a direct current created by an EMF source, the ohmic loss is zero (the condition $(\mathbf{j}, \mathbf{E})<0$ is satisfied).

We apply the results obtained above. Consider a semiconductor or dielectric thread in the form of a cylinder with a diameter d≈0.1-1 mm. Let the ends and the cylindrical surface of the thread contain uniformly distributed ionized donor centers. Let us place the thread in a uniform electric field, directing its lines of force along the thread. Under the influence of electric field forces, free electrons will be displaced along the thread. It will pass into a stable polarized state with a negative value of free energy. One end of it will acquire $+q$ charge, and the other end will acquire $–q$ charge. The $+q$ charge is formed by surface ionized donor centers, and the $–q$ charge is formed by free electrons. The $+q$ and $–q$ charges create a stable built-in electric field in the thread. Let us place a semiconductor thread in a closed electrical circuit with a constant electric current generated by an EMF source. The ohmic loss in the thread is zero. Therefore, the strength of the current in the thread determines by the EMF of the current source and the resistance of the wires of a closed circuit. For the maximum current density in the semiconductor thread, we have: $j_{max} = E_m/\rho$, where E_m is the electric field strength of the EMF source in the wires of the circuit; ρ is specific resistance of metal wires. Let's take:

$$E_m = 10^4 V/m;\ \rho = 10^{-8}\,\Omega \bullet m,\ we\ get:\ j_{max} = 10^{12}\,A/m^2.$$

Let us estimate the induction of the magnetic field of a solenoid made of a thread with zero resistance: $B = \mu_0 s j_{max} N$, where μ_0 is the magnetic constant; s is the cross section of the thread; N is the number of turns of the solenoid per unit length. We use the estimate $j_{max} = 10^{12}$ A/м^2 and the values: $s=10^{-6}$ m^2; $N=10^3$ m^{-1}. We get: $B=10^3$ T.

If the above assumptions are fulfilled, a semiconductor thread in the form of a solenoid with zero ohmic losses can be used to obtain a strong magnetic field.

Consider a spherical semiconductor with ionized donor centers uniformly distributed over its surface. The electric field of a polarized glob is uniform in its volume. At $E_0 = 0$, the following conditions are satisfied [5]: $E = -P_c/(3\varepsilon_d\varepsilon_0)$; $P_c \cong en_s$, where E is the field strength in the volume of the ball; P_c is the ball polarization due to the displacement of free electrons. The free energy per unit volume of a polarized ball is:

$$F = \varepsilon\varepsilon_0 E^2/2 = (\mathbf{E}, \mathbf{P}_c)/2 + \varepsilon_0 E^2/2 = -(3\varepsilon_d - 1)\varepsilon_0 E^2/2. \tag{11}$$

Due to the condition $F < 0$, the ball is in a stable state of polarization. Outside of a polarized ball, its electric field is analogous to that of a dipole. Near the surface of the ball (in air), the maximum strength of its electric field is: $E_z = 8\pi P/(3\varepsilon_d\varepsilon_0)$ [15]. Using the values: $P_c \cong en_s$; $n_s = 10^{16} m^{-2}$, we get: $E_z \approx 10^9$ V/m. The strength of the external field of a polarized ball near its surface $E_z \approx 10^9$ V/m exceeds the field strength at which field electron emission occurs. The electron emission current from the surface of solids is observed at the field strength of $E_0 \approx 10^7$ V/m. Surface micro protrusions increase the field strength: $E_z \approx kE_0$, where k is the coefficient, k≈100. The emission current density increases with E_z according to the Fowler-Nordheim formula [16]:

$$j_e = BE_z{}^2 exp(b/E_z).$$

where B and b are coefficients depending on the state of the surface.

Let in a chain consisting of identical balls of a semiconductor with a diameter of 0.1mm - 10 mm polarized in one direction, electric current be created. Due to the condition $\varepsilon < 0$ (see Eq. (11)) in the volume of each ball electrons move under the action of the built-in field from its positive surface charge to its negative surface charge. In the area of point contacts between each two balls, the electric current is due to tunneling transitions of electrons through the gaps between them (from the negative surface charge of one ball to the positive surface charge of the other ball) [11]. In these gaps, the field strength is: $E_z \approx k \times 16\pi e n_s/(3\varepsilon_d \varepsilon_0)$, where $k \approx 100$. The electrical conductivity of the chain consists in the self-consistent movement of electrons between the balls, similar to the hopping conductivity of semiconductors. It can be assumed that the ohmic loss in the chain of balls is equal to zero.

The following system is of interest. Let a closed chain of polarized globs form a circle. Let us place the chain in a magnetic field with the field induction vector perpendicular to the plane of the circle. After turning off the magnetic field due to electromagnetic induction, an induction current will occur in the circuit. In a chain of polarized balls, the built-in electric field of the balls ensures that the electrons move in one direction along a closed path. The unique electric field of the chain ensures the self-consistent movement of electrons between balls. The inductive current creates a magnetic field, the change of which affects the strength of the current in the circuit. Due to the mutual dependence of the current strength and the induction of the magnetic field, the current in the circuit, apparently, does not decay, remains constant, since a decrease in the induction of the magnetic field created by the current of the circuit is impossible due to Lenz's rule.

Conclusion

The polarization by the electric field of a homogeneous semiconductor, on the entire surface of which the ionized donor centers are uniformly distributed and free electrons are located in the volume, is accompanied by a decrease in its free energy ($F < 0$). In a polarized semiconductor included in a closed electric circuit with a constant current created by an EMF source, ohmic loss is zero. The EMF source moves charges in the wires of the circuit. In the volume of a semiconductor the movement of charge carriers ensures its stable built-in electric field. The movement of electrons in a semiconductor is accompanied by a decrease in their potential energy. The current density vector **j** and the built-in field strength vector **E** are directed in opposite directions: $(\mathbf{j}, \mathbf{E}) < 0$. The condition $(\mathbf{j}, \mathbf{E})/T < 0$ correspond to the action of internal forces directing free electrons to an ordered state with a negative value of the free energy of the system. The current source does not perform the work of moving electrons in a semiconductor, which corresponds to zero ohmic loss.

For the maximum current density in a semiconductor, the following is obtained: $j_{max} \approx 10^{12}$ A/m^2. A semiconductor thread in the form of a solenoid with zero ohmic loss can be used to obtain a strong magnetic field with an induction of $B \approx 10^3$ T. A polarized semiconductor included in a closed electrical circuit can serve as a source of electromotive force. In this case, the heat is converted into the operation of an electric field with an efficiency of 100%. The description of an electric capacitor with zero capacitive reactance is given.

Outside the polarized ball of a semiconductor, its electric field is similar to that of a dipole. Near the surface of the ball (in the air) the maximum intensity of its electric field is equal to: $E_z \approx 10^9$ V/m. A unique built-in electric field can be created in a chain of identical balls of a semiconductor polarized in the same direction. The built-in electric field provides self-consistent movement of electrons in a chain of balls with zero ohmic loss.

Conflict of interest

Not conflict of interest, financial or otherwise.

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