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APPLICATION OF THE CLOSED CURRENT IN POLARISAED MEDIA PHENOMEN FOR DEVELOPING OF INTEGRATED POWER SUPPLIES

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Abstract. The application of the steady-state closed electrical current arising in the polarized nonhomogeneous media phenomenon (SCECAP) for manufacturing of the integrated power supply is considered. SCECAP is proved theoretically via algebraization of a basic system of partial differential equations. The discrete model of the integrated power supply is constructed. The results of computer account of the power supply discrete model with use of the gallium arsenide monocrystalline electrical characteristics are given. The output about possibility of creation of the power supply designed on the basis of SCECAP is in summary intended for microelectronics applications.

1. Introduction

Well–known in classical physics thermoelectric phenomena are excited in nonhomogeneous media by the outer temperature field [1]. But as we have shown before, if the electrically nonhomogeneous media are polarized, there the macroscopic closed electric current and temperature field can be excited in media. Necessary condition of this phenomenon is noncollinearity of the polarizing field and the electric conductivity field [2], [3]. We have resumed that the thermoelectric phenomena possess the cause–consequence reversibility with respect to external temperature and electric fields.

In this paper we consider application of the closed current in polarized media phenomenon for developing of integrated power supplies. In section 2 of the paper the analytical proof of existence of the closed electric current

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in polarized media is developed. In section 3 we consider a discrete model of the integrated power supply. One can find easily the cause of the closed current arising in this model. Results of computing done for active medium with electric features of gallium arsenide are presented and speculated in section 4.

2. Analytical theory

We consider the closed reference system $\boldsymbol{F} = \{f(\boldsymbol{r}_f) \in \boldsymbol{F}\}$, where $\boldsymbol{r}_f$ is the cartesian coordinates of an element f from $\boldsymbol{F}$. Let the following properties characterize $\boldsymbol{F}$:

(α) $\boldsymbol{F}$ is electroneutral in whole, i.e. there are equal amounts of immovable positive charges (cations) and mobile negative charges (electrons) in $\boldsymbol{F}$;

(β) The density gradient of the mobile electric charge carriers $\nabla\rho$ takes place in $\boldsymbol{F}$. It may be caused for example, by variable donor doping of semiconductor medium. Therefore there is an electric conductivity nonhomogeneity in $\boldsymbol{F}$;

(γ) $\boldsymbol{F}$ is isotropic. In particular the dispersion law of free carriers is isotropic and square;

(δ) The electron mobility μ doesn't depend on space coordinates.

The properties (γ) and (δ) essentially simplify the next deduction. However the results to be obtained don't overlay anisotropic media. It's proper to notice also that phenomena developed here take place in $\boldsymbol{F}$ under any electric field above zero.

In view of the system $\boldsymbol{F}$ is an electrically nonhomogeneous one, there the internal electric field has been established. In spite of that $\boldsymbol{F}$ remains in the thermal equilibrium state. Let now $\boldsymbol{F}$ to be polarized by the outer electrostatic field. After the electrification process has been finished $\boldsymbol{F}$ passes into a new steady state. This state will be a subject of our analysis.

In general, we suppose that the electric current may flow in the polarized system $\boldsymbol{F}$. Therefore, a thermal equilibrium state of $\boldsymbol{F}$ is discarded in its final stage as some possible but unproved case. Starting from this describe a steady state of polarized $\boldsymbol{F}$ with the following system of partial differential equations

$$\varepsilon_0 \nabla\nabla\varphi = \rho - \rho^+ \tag{1}$$

$$\boldsymbol{J} = -\rho\mu\nabla\varphi + \frac{k\mu}{e}\nabla(\rho T), \tag{2}$$

where ε_0 - is the dielectric permittivity of vacuum, φ is the electric potential, ρ^+ is the immovable positive charges density responding to the condition of electrical neutrality of $\boldsymbol{F}$

$$\int_F \rho df = \int_F \rho^+ df, \tag{3}$$

$\boldsymbol{J}$ is the electric current density, k is Boltzmann's constant, and e is the elementary charge. Equation (1) is the Poisson equation, and equation (2) presents the formula of an electron current consisting of two parts: drift and thermodiffusion ones. The well–known Einstein equation

$$D = \frac{kT\mu}{e}$$

has been utilized in the right–hand side of equation (2) for the diffusion coefficient D to be uncovered. The electron gas temperature T equals to a temperature of the system $\boldsymbol{F}$, e.g. to the crystal lattice temperature at the thermal equilibrium state. And it takes on a value of the effective temperature of a non–equilibrium electron gas at the non–equilibrium process [4]. Finally, let us complete equations (1) and (2) with the polarization $\boldsymbol{P}$ vs electric field linear relation

$$\boldsymbol{P} = -\varepsilon_0 \chi \nabla\varphi, \tag{4}$$

where χ is the medium polarizability.

The boundary conditions are defined in the form of an electric potential distribution $\varphi(S)$ at the external surface S of $\boldsymbol{F}$. With the help of this distribution one can specify the outer electrostatic field. On the other hand, the $\varphi(S)$ distribution takes constants of integration of equation (1). Now we'll show that equation (2) when its left-hand side equals zero, is integrable with the only constant of integration. One can transform the right–hand side of equation (2) into the Pfaff $-\rho d\varphi + \frac{kT}{e} d\rho$ form of two independent variables and then dividing by ρ, into a total differential. Hence the only constant of integration is required for resolving of the appropriate pfaffian equation [5]. This constant can be defined with the help of the electroneutrality condition (3).

The goal of our analysis is to detect the conditions of flowing of the macroscopic electric current $\boldsymbol{J}$ in the polarized system $\boldsymbol{F}$. For this goal to be reached it is not obligatory to solve jointly the set of equations (1) – (4) in $\boldsymbol{F}$. Our simple method is as follows. Let as reason *ex adverso*. One can assume that when a polarizing process is completed the system $\boldsymbol{F}$ returns back to thermal equilibrium with $\boldsymbol{J}= 0$. Then from equation (2), bearing in mind the property (γ), one can output

$$\forall f \in \boldsymbol{F} \Rightarrow \nabla\varphi(f) \times \nabla\rho(f) = 0. \tag{5}$$

Further consider equation (4). The polarization means sharing of opposite electric charges. The vector $\boldsymbol{P}$ is situated along the direction of charge's shift [6]. Therefore, $\boldsymbol{P}$ is collinear to the vector $\nabla(\rho - \rho^+)$. From this and equation (4) one can formulate the second condition likely (5), as follows:

$$\forall f \in \boldsymbol{F} \Rightarrow \nabla\varphi(f) \times [\nabla\rho(f) - \nabla\rho^+(f)] = 0. \tag{6}$$

Compare (5) and (6), one can resume that collinearity of all the vectorial fields $-\nabla\varphi$, $\nabla\rho$ and $\nabla\rho^+$ gives a necessary condition of the electric current in polarized system $\boldsymbol{F}$ to be absent. And *vice versa,* non-collinearity of any two vectors from above mentioned ones yields an electric current in the system. It is rather not obvious that above vectors can be non-collinear because the fields $-\nabla\varphi$ and $\nabla\rho$ are in linear dependence to one another when $\boldsymbol{F}$ is at thermal equilibrium. One can find the only possibility to ensure non-collinearity of the mentioned vectors. This possibility is to set such a distribution of $\varphi(S)$ that $-\nabla\varphi$ and $\nabla\rho^+$ should be mutually non-collinear on S. For example, let S and S^+ are mutually intersect, where S^+ is the boundary surface of two subsystems in $\boldsymbol{F}$ with different quantities of ρ^+. Then it is sufficient that in vicinities of the line $S \cap S^+$ should be $\varphi(S) = const$. Then a macroscopic electric current $\boldsymbol{J}$ should flow in $\boldsymbol{F}$. Moreover, $\boldsymbol{J}$ is closed as $\boldsymbol{F}$ is a closed system. One can see making use of the common theory of autonomic systems that if an electric current arises in any part of the system $\boldsymbol{F}$, then all the system $\boldsymbol{F}$ will be finally filled with lines of an electric current with the exception of singular points [7].

The physical interpretation of the arising closed electric current in $\boldsymbol{F}$ is as follows [2], [3]. When the system $\boldsymbol{F}$ is brought to the thermal equilibrium state both drift and thermodiffusion components of $\boldsymbol{J}$ are mutually compensated. In the developed case the detail balance postulate [8] is broken with two mutually crossed potential thermodynamic powers $-\nabla\varphi$ and $\nabla(\rho T)$ (see equation (2)). In consequence of this the drift and thermodiffusion components of $\boldsymbol{J}$ are spatially separated and form an electric current

loop. It is evident that a quantity of $\boldsymbol{J}$ depends on a depth of penetration of the outer electric field into $\boldsymbol{F}$. This depth increases as an electric conductivity of $\boldsymbol{F}$ decreases. In addition, an electric conductivity of $\boldsymbol{F}$ is included into equation (2) via ρ. Therefore, one can resume that the phenomenon being investigated depends on an electric conductivity of $\boldsymbol{F}$ in a complicated way.

One cannot avoid taking into account dissipation processes when macroscopic fluxes of charged particles are considered. Various possible compensating processes are concluded in [3] which put down to zero either locally or integrally the energy dissipation as a result of an electron flow interaction with an outer electric field as well as because of the internal friction in the flow itself. It was shown there that the total compensation can be achieved in a *closed* electric current only.

Finally, focus our attention to the following special case. Let the $\varphi(S)$ distribution to be such that the condition (5) is valid. Then the final state of $\boldsymbol{F}$ will be a thermal equilibrium one in which the macroscopic electric current is absent. That case is commonly cited as the one-dimensional one.

3. Digital model

Our goal now is to deduce the same results as above with the help of a discrete model of the system $\boldsymbol{F}$. We shall compose this model making use of the finite differences approximation method. Let us consider a three–dimensional electroconductive system $\boldsymbol{F}$, having form of cube with the edge length L, the nodes number of 3D rectangular proportional grid N^3, and the spacing between neighboring nodes along an edge l. We again use the method of deduction *ex adverso*. Let the left-hand side of equation (2) is zeroth, that is a feature of the thermal equilibrium state. Then replace equation (1) and simplified as above equation (2), with the following system of algebraic equations:

$$\varphi_{i-1,j,k} + \varphi_{i+1,j,k} + \varphi_{i,j-1,k} + \varphi_{i,j+1,k} + \varphi_{i,j,k-1} + \varphi_{i,j,k+1} - 6\varphi_{i,j,k} = \frac{l^2}{\varepsilon_0}(\rho_{i,j,k} - \rho^+_{i,j,k}), \tag{7}$$

$$(\rho_{i,j,k} + \rho_{i+1,j,k})(\varphi_{i,j,k} - \varphi_{i+1,j,k}) = 2t(\rho_{i,j,k} - \rho_{i+1,j,k}), \tag{8}$$

$$(\rho_{i,j,k} + \rho_{i,j+1,k})(\varphi_{i,j,k} - \varphi_{i,j+1,k}) = 2t(\rho_{i,j,k} - \rho_{i,j+1,k}), \tag{9}$$

$$(\rho_{i,j,k} + \rho_{i,j,k+1})(\varphi_{i,j,k} - \varphi_{i,j,k+1}) = 2t(\rho_{i,j,k} - \rho_{i,j,k+1}), \tag{10}$$

where the node indices i, j, k are numbered as $1, \ldots, N$; $t = kT/e$. First derivatives of $-\nabla\varphi$ and $\nabla\rho$ in equations (8)-(10) are approximated by the right difference derivatives. We don't use central difference derivatives because they doesn't permit to define currents flowing across border nodes of

the grid. Let us also define border conditions as the set of electric potentials $\varphi_{0,j,k}$, $\varphi_{N+1,j,k}$, *etc.*

The system (7)-(10) consists of $N^3 + 3N^2(N-1)$ equations. Electric potentials and mobile negative charge densities in nodes play a role of unknowns in this equations. Transferring all the members of equations (7)-(10) into their left-hand sides, we obtain the set of functions $F_i (i = 1, ..., N^3 + 3N^2(N-1))$, each of them being equal to zero after roots substituting. It follows from equations (7)-(10) that functions F_i are differentiable with respect to every of $2N^3$ independent variables in $\boldsymbol{F}$. Therefore, one can analyze Jacobian of any subset of $2N^3$ functions from the total set of F_i. It is found that every Jacobian belonging to any subset from F_i doesn't equal to zero. (Because of space deficit we don't present here the proof of this statement, which is however elementary.) This yields that the total set of F_i forms a system of $N^3 + 3N^2(N-1)$ independent functions. Hence all equations (7)-(10) are mutually independent. When N is a great enough value, the number of equations is twice as great as the number of independent variables. It follows now that the system of equations (7)-(10) is a noncompatible one and therefore, it cannot specify the thermal equilibrium state of $\boldsymbol{F}$.

Let now the condition (5) is fulfilled in $\boldsymbol{F}$. Then equations (8)-(10) are identical when relative to the same triple of indices. But the following stipulation should be taken into account. The number N must be great enough for difference between densities $\rho_{i,j,k}$ on the one hand, and $\rho_{i+1,j,k}$, $\rho_{i,j+1,k}$, $\rho_{i,j,k+1}$ on the other hand, to be disregard. This stipulation is not required if the central difference derivative approximation is used. So, if equations (8)-(10) are identical, the full system of equations (7)-(10) is resolvable. Then the final state of the polarized system $\boldsymbol{F}$ is the thermal equilibrium state. Mutual collinearity of the vector fields $-\nabla\varphi$ and $\nabla\rho^+$ in $\boldsymbol{F}$ yields the same result when combined with the condition (6).

Assume now that local currents flow through nodes of the grid in $\boldsymbol{F}$. We'll denote this current by $J_{i,j,k,t}$, where t takes values 1, 2, 3 in accordance with a dimensionality of the model. Apply the finite differences approximation method to the total equation (2), with non-zeroth left-hand side. Here we must make some clarifications.

(ε) Now T in equation (2) is the effective temperature, that depends on the space coordinates in general. Leading T from under the operator "nabla" out, we state temperature to be constant in $\boldsymbol{F}$ and therefore, simplify the model. This simplification is not essential in thin films structures because of good heat transfer.

(ζ) The Einstein relation used in equation (2) takes place both in the hydrodynamic and quasi–hydrodynamic approximations [4]. So application of equation (2) to a non–equilibrium process is reasonable.

(η) We have assumed that mobility of charge carriers is not depend on an electric field value. This simplification can be violated closely to external surface of $\boldsymbol{F}$ only.

(θ) A constant of integration of equation (2) must be defined now in another way as compared with it under equilibrium conditions because the statistics of non-equilibrium electron gas can deviate essentially from the Fermi statistics.

The above mentioned restrictions are not of importance in our deduction but simplify matter essentially.

Taking into account the above remarks write the following equations instead of equations (8)–(10):

$$2t(\rho_{i,j,k} - \rho_{i+1,j,k}) - (\rho_{i,j,k} + \rho_{i+1,j,k})(\varphi_{i,j,k} - \varphi_{i+1,j,k}) = \frac{J_{i,j,k,1}}{\mu}, \quad (11)$$

$$2t(\rho_{i,j,k} - \rho_{i,j+1,k}) - (\rho_{i,j,k} + \rho_{i,j+1,k})(\varphi_{i,j,k} - \varphi_{i,j+1,k}) = \frac{J_{i,j,k,2}}{\mu}, \quad (12)$$

$$2t(\rho_{i,j,k} - \rho_{i,j,k+1}) - (\rho_{i,j,k} + \rho_{i,j,k+1})(\varphi_{i,j,k} - \varphi_{i,j,k+1}) = \frac{J_{i,j,k,3}}{\mu}. \quad (13)$$

The set of equations (7), (11)-(13) of the total number $N^3 + 3N^2(N - 1)$ includes $2N^3 + 3N^2(N - 1)$ unknowns. It can be shown that this set of equations is compatible and indeterminate. For avoiding of the infinite solutions number of equations being investigated, we shall add to equations (7), (11)–(13) one more, namely the continuity equation $\nabla \cdot J = 0$. In a discrete model the last formula is converted into N^3 equations as follows:

$$J_{i,j,k,1} + J_{i,j,k,2} + J_{i,j,k,3} + J_{i-1,j,k,1} + J_{i,j-1,k,2} + J_{i,j,k-1,3} = 0. \quad (14)$$

The set of equations (7), (11)–(14) is compatible and determinate. It means that the final state of the polarized system $\boldsymbol{F}$, when any two vector fields of $-\nabla\varphi$, $\nabla\rho$ and $\nabla\rho^+$ are mutually non–collinear, is a steady state. Its main feature as for our research consists of the closed electric current flowing.

4. Digital computation

The above results were used in digital computation of an active device possessing electrical features of monocrystalline gallium arsenide. We were

based in our choice on the following. The well-known field-effect transistor on $GaAs$ presents a ready integrated device possessing the set of initial features relevant for solution of our task. Those are: *(i)* The electrical conductivity of $GaAs$ varies within wide limits with using of appropriate doping technology; *(ii)* An electric field formed by a transistor gate is sufficient for to overlay its conducting channel; *(iii)* $GaAs$ crystallizes in the cubic syngony; therefore, its features are isotropic in a high degree. Hence above results are applicable to the model based on $GaAs$ features.

Fig. 1 illustrates schematically a cross-section of the developed device discrete model. The working domain represents a right angled parallelepiped with dimensions $14.14\times3.535\times0.1\mu\mathrm{m}^3$ or $1.414\times0.3535\times0.1\mu\mathrm{m}^3$. The bold line on Fig. 1 shows a cut of the working domain. The electric current doesn't flow through this cut. This element of design weakens local closed currents, so that the total current flows around the above cut. The electron mobility is taken to be equal $8500\,cm^2/V\cdot s$, as in $GaAs$ [10]. Broken lines on Fig. 1 mark the four cross–sections *A, B, C, D,* which the computed current crosses through. Two one–halfs of domain ordered at difference sides of the cut are doped in a different degree from 10^{13} to 10^{19} $1/cm^3$. The gray region of the domain (Fig. 1a) is always doped more heavily. Two polarizing electrodes are situated upon the working domain along its opposite sides so that they overlay the cross–sections B and D (Fig. 1b). The constant potential of 10 V is applied onto this electrodes, plus being on left. We have defined that in the described structure the computed closed current always flows clockwise around the cut.

We have used a two–dimensional grid of 100×100 nodes for modeling the working domain. The electric properties of working domain are described by equations (7), (11)–(13), reduced to the two-dimensional forms. Equations (14) is disregarded. Nevertheless, the result is spontaneously a steady state. The Newton process of lower relaxations was used in the iterative process. The time interval τ per one iteration step is dynamically changed for the following condition to be fulfilled: the largest relative reduction of free negative carrier density in any node is established as great as 1% per one iteration step. So it is found that the product of τ and coefficient of lower relaxations α is weakly dependent on α. We have taken from this $\alpha \ll 1$. For $\alpha = 0.001\tau$ results $10^{-14} - 10^{-15}s$. Such short real time intervals increase essentially the total time of an iterative process. So $1.2\cdot10^8$ iteration steps are required for modeling $5\cdot10^{-7}s$ of real transient process when strong doping has been assumed. Iterative process is to be ended when the total currents through cross–sections *A, B, C* and *D* become identical.

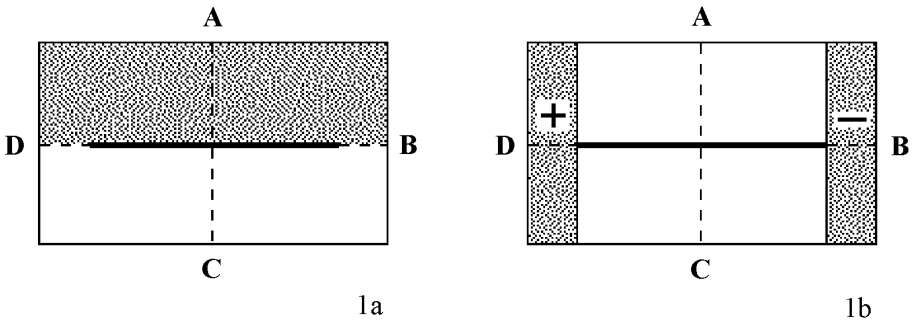

Fig. 1. The view from above on the discrete model of the working domain. Fig. 1a illustrates two regions of domain denoted as white and gray, with various doping densities. Placement of the polarizing electrodes is shown in Fig. 1b, in gray.

Some results of computing are presented in the Table below. The doping densities are equal to 10^{19} and 10^{15} $1/cm^3$. The length and the width specify dimensions of the working domain. The current density is measured in the cross–section A.

Table 1

Length, μm	Width, μm	Closed Current, A	Current Density, A/cm^2	Max.Electric Field, V/cm
14.14	3.535	$2.1 \cdot 10^{-5}$	$1.16 \cdot 10^{4}$	$7.74 \cdot 10^{5}$
1.414	0.3535	$9.5 \cdot 10^{-7}$	$5.37 \cdot 10^{3}$	$1.29 \cdot 10^{6}$
14.14	3.535	$9.2 \cdot 10^{-6}$	$5.21 \cdot 10^{3}$	$1.10 \cdot 10^{6}$
3.535	14.14	$2.2 \cdot 10^{-4}$	$3.14 \cdot 10^{4}$	$2.43 \cdot 10^{5}$
3.535	14.14	$1.6 \cdot 10^{-4}$	$2.25 \cdot 10^{4}$	$4.60 \cdot 10^{5}$

One of results of produced numerical treatment is a great density of the electric current in the device model. One can explain it by the imperfect discrete model. The main imperfection as we can assume, is that there is not taken into account concentration of the electric field lines at sharp angles of polarizing electrodes. So we don't consider obtained results as terminal.

5. Conclusion

In spite of the noted deficiency of the discrete model and some simplifications used in section 3 we assume that the theoretical consideration as far as the discrete modeling confirm existence of the above investigated phenomenon. So we resume that the phenomenon of arising of the macroscopic closed electric current in polarized nonhomogeneous electroconductive media can be used for integrated power supply development.

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