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SYNERGETICS OF THRESHOLD SWITCHING IN NON-CRYSTALLINE SEMICONDUCTORS

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On the basis of a simple model of electrical conductivity of non-crystalline semiconductors it is proved in the paper presented that the threshold switching effect in those materials is of the synergetic character, i.e. threshold switching is a rapid qualitative change of a system of free electrons from one stable state to another. The new result here is the fact that it is necessary neither to suppose the space self-organization of the system of electrons (the generation of a filament of high electrical conductivity), nor to postulate the inhomogeneities of the electric field intensity. Moreover, our model allows the explanation of the "pure" electronic mechanism of threshold switching and gives the fundamental qualitative and quantitative characteristics of this effect in very good agreement with observation.

СИНЕРГЕТИКА ПОРОГА ПЕРЕКЛЮЧЕНИЯ В НЕКРИСТАЛЛИЧЕСКИХ ПОЛУПРОВОДНИКАХ

В работе на основе простой модели электропроводности в некристаллических полупроводниках доказано, что порог эффекта переключения в этих материалах имеет синергетический характер, т.е. что порог переключения представляет собой быстрое качественное изменение системы свободных электронов из одного устойчивого состояния в другое. В данном случае новым результатом является тот факт, что нет необходимости ни предполагать пространственную самоорганизацию системы электронов (генерирование волокна высокой электропроводности), ни постулировать неоднородности напряженности электрического поля. Более того, данная модель позволяет объяснить порог переключения на основе чистого электронного механизма и дает основные качественные и количественные характеристики этого эффекта, которые очень хорошо согласуются с наблюдениями.

I. INTRODUCTION

The switching effect in non-crystalline semiconductors [1, 2] was discovered more than 25 years ago, but this phenomenon has been attracting the attention of experimental and theoretical physicists up to now. Electronic elements using this effect are examples of elements of a new generation, i.e. of elements working in

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a state very far from equilibrium. Practical applications (see, e.g. [3]) are based on the existence of the so-called memory switching, the mechanism of which is well understood [4, 5] or on the existence of threshold switching, which is still the subject of fundamental research. All models of threshold switching can be grouped into two categories: thermal or electro--thermal models [6—10] and electronic models [11—13].

Many years ago, practically in the time of the most intensive research into mechanisms of threshold switching, some papers appeared in which a uniform point of view on both types of the switching effect was proposed [14—16]. These theories were based on the assumption that some relatively small regions (microcrystallites) generated either due to the existence of the short range order only or due to some type of inhomogeneities are present in non-crystalline semiconductors. These regions are separated by some potential barriers, which represent the scattering centres for free electrons during their transport. The so-called theory of modified relaxation time was useful for understanding some peculiarities of transport effects in non--crystalline semiconductors including a general qualitative model of threshold switching, but the attempt of using a synergetic approach to this effect was not realised at that time.

Mattis [12] was the first who pointed out that threshold switching can be of a cooperative nature, but his assumption was not very realistic. In [17] it was pointed out that some unstabilities can arise on current--voltage characteristics of noncrystalline semiconductors due to Joule's heating and due to special conditions of heat transfer resulting in the jump from the state with a small electrical conductivity into the state with a greater conductivity. All theories of this type are of electrothermal character and they are not capable to explain pure electronic threshold switching. The most popular theories in this field were theories based on the process of a continuous filling of traps [11] or theories based on the supposition that the activation energy of electrons decreases with the concentration of electrons (see, e.g. [18]). Theories which took into consideration the influence of strong electric fields on the transport of electrons [19, 20] acquired great importance. Howefer, theories representing this influence using the factor exp (U/U_0), where U is the electric voltage and U_0 a characteristic constant, were not able to explain the presence of a discontinuous change in current-voltage characteristics of noncrystalline semiconductors. Marschall and Miller [22] came to the conclusion that the electrical conductivity stimulated by the electric field can be expressed by the relation

$$\sigma = \sigma_0 \exp\left(\frac{eLE}{kT}\right) \tag{1}$$

where L is the so-called "activation length" and E the electric field intensity. According to the measurements published in papers [23] and [24] the value of this activation length in chalcogenide glasses is approximately 5 nm, thus we can use the model of free electron transport in a good physical sense.

In the last few years, especially in connection with amorphous silicon, the "crystallite" model became topical again., (see [25] and [26]). That is the reason why we tried to make use of some interesting results of crystallite theories and with regard to the expression of field activated electrical conductivity of type (1) to work out a uniform theory of threshold switching based on the synergetic method as used, for instance, in the cases of the laser, of Gunn's diode, etc. (see e.g. [27—29]). We shall show that it is the mean free path which can be used as an order parameter of the system.

II. MODEL

It is clear that we can write today for electrical conductivity of non-crystalline semiconductors the formula

$$\sigma = \sigma_0 \exp\left(-\frac{W}{kT}\right) \tag{2}$$

where σ_0 is the pre-exponential factor, W the activation energy, T absolute temperature. It is known that the activation energy of non-crystalline semiconductors is always greater than that in the same material in the crystalline state

$$W = W_c + \delta W\,. \tag{3}$$

The aditive activation energy δW is connected in crystallite theories with the height of potential barriers existing at the boundaries of crystallites. A formal combination of relations (1—3) gives the relation

$$\sigma = \sigma_c \exp\left(-\frac{\delta W}{kT} + \frac{eLE}{kT}\right) \tag{4}$$

where σ_c stands for $\sigma_0 \exp(-W_c/kT)$ and represents the electrical conductivity of the semiconductor in the crystalline state. (In fact, it need not be always correct, since it was shown that the pre--exponential factor σ_0 in (2) depends in general on the technology of the sample and on some other factors and therefore it is not identical with the pre--exponential factor corresponding to the crystalline state; however, this fact will not be essential for our consideration).

It seems that the formula (4) is not very "natural", because its physical interpretation is not in accord with general physical mechanisms. We can show very easily that this relation represents a limit case of a more general formula resulting from a more realistic physical model.

We can start with the expression

$$\sigma=\sigma_0 \exp\left(-\frac{\delta W}{kT^x}\right) \tag{5}$$

where T^x is the temperature of the electron gas, which may substantially differ from the temperature T of the lattice, due to a relatively high electric field intensity used in the region of threshold switching. According to the known simple formula $T^x=2W/3k$, where W is the total energy of electrons, i.e. $W=W_T+eEq'$, W_T being the thermal energy corresponding to the lattice temperature and q' the real mean free path of electrons, it is possible to express the formula (5) in the form

$$\sigma=\sigma_c \exp\left(-\frac{\delta W}{kT+eEq}\right)$$

with a modified mean free path $q=2q'/3$. For $kT>eEq$ this relation transforms into formula (4) where we denote

$$L=\frac{2}{3}\frac{\delta W}{kT}q' . \tag{6}$$

This is the relation between the activation length L and the real mean free path of electrons q'. It follows from this relation that for room temperatures and for the most probable value of δW (0.2 eV) the real mean free path corresponding to the measured values $L\approx 5$ nm in chalcogenide glasses is about 1.2 nm, which is a very realistic value. Using the clasical formula for electrical conductivity in the crystalline state $\sigma_c=e^2 n_c q_c'/mv$, where n_c is the concentration of electrons, m the mass of electrons and v thermal velocity and using an analogous formula for the non-crystalline state $\sigma=e^2nq'/mv$, we get the following result for the modified mean free path of electrons

$$q=q_0 \exp\left(-\frac{\delta W}{kT+eEq}\right) \tag{7}$$

where q_0 is the preexponential factor proportional to the mean free path of electrons in crystalline semiconductors. The relation (7) is a fundamental one and it expresses a very simple physical reality: electrons can use the thermal energy as well as the energy gained due to the electric field on the mean free path for the crossing of potential barriers of the height δW.

III. THEORY

Let us have a sample of the form of a planparallel plate with the cross-section S and of the thickness h_0. Supposing that the thickness of the sample is sufficiently small we can write the equation of thermal balance in the form

$$\frac{dT}{dt}=\frac{\sigma E^2}{sc}-\frac{2\alpha}{sch_0}(T-T_0) \tag{8}$$

where E is the electric field intensity, s specific mass, c specific heat, α the coefficient of heat transfer from the surface of the sample, T the lattice temperature of the sample and T_0 the temperature of the environment.

After the derivation of equation (7) we get with regard to relation (8) the "evolution" equation of the system in the form

$$\frac{dq}{dt}=\frac{G(q)}{scH(q)}q=F(q) \tag{9}$$

where

$$H(q)=\delta W \ln^{-2}\frac{q}{q_0}-eEq$$

$$G(q)=Aq+B\ln^{-1}\frac{q}{q_0}+C$$

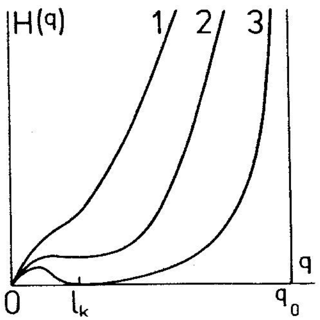
$$A=\frac{ke^2n}{mv}E^2+\frac{2\alpha e}{h_0}E$$

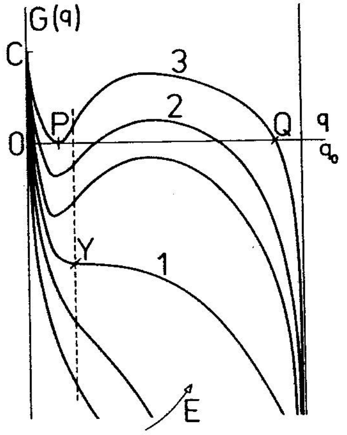
$$B=\frac{2\alpha\delta W}{h_0}, \qquad C=\frac{2\alpha kT_0}{h_0}.$$

First we shall try to analyse the equation (9) qualitatively. The dependence of the function $y=H(q)$ on the mean free path is illustrated in Fig. 1. At sufficiently small values of the electric field intensity this function is a monotonously increasing one (curve 1). At higher values of the electric field intensity a characteristic fold can arise (curve 2), which touches the axis q at a critical value of the intensity E^x. This critical value results from the condition $dH(q)/dq=0$ and is determined by the formula $E^x=\delta W/4eq_0$, which (at standart values $\delta W\approx 0.2$ eV and $q_0\approx 10$ nm) gives $E^x\approx 3\times 10^7$ V/m. Threshold switching takes place at lower values of the electric field intensity. Thus we can suppose that in all practically important cases the function $H(q)$ is a non--negative and monotonous one and therefore it can influence neither the sign of the function $F(q)$ nor the stability of stationary states.

One of most fundamental functions (from the point of view of the possibility of generating threshold switching) is also the function $G(q)$. Its dependence on the electric field intensity is illustrated in Fig. 2. It is seen that under the condition $dG(q)/dq<0$ only one stationary and stable state exists (corresponding to the equation $dq/dt\approx G(q)=0$). At high values of the electric field intensity the dependence $y=G(q)$ has the form of the curve 2 in Fig. 2. At that moment two other stationary states are produced. However, the lowest is stable ($dG(q)/dt<0$), and so the element remains in the first stationary state and the electrical conductivity of the sample changes very little.

There is a rapid change when the lowest part of the fold losses the contact with the axis q (curve 3). The originally stable state becomes unstable, the system of electrons jumps from the point P in the state characterized by the point Q and the electrical conductivity discontinuously increases. That is a qualitative explanation of threshold switching in non--crystalline semiconductors.





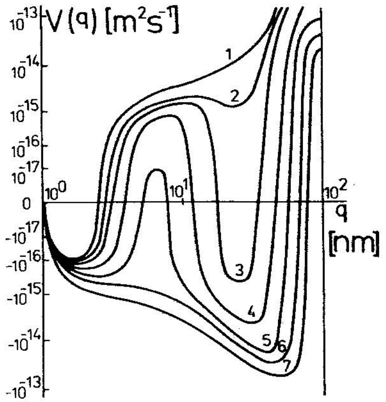


Fig. 1. Dependence of the function $y = H(q)$ for three various values of the electric field intensity.

Fig. 2. Dependence of the function $y = G(q)$ for various values of the electric field intensity.

Fig. 3. "Synergetic" curves of threshold switching: dependences of the potential function $V(q)$ on the electric field intensity.

Let us consider now the mechanism of threshold switching without the above approximations. As usual in synergetics, we introduce a potential function $V(q)$ by the definition

$$V(q) = -\int_0^q F(q)\,\mathrm{d}q\,.$$

It is very well known that the extremes of this function represent stationary states. The states corresponding to the valleys are stable and the states corresponding to the peaks are unstable. The dependences $V(q)$ for various values of the electric field intensities (calculated by computer) are illustrated in Fig. 3. It is seen that in agreement with the qualitative analysis made above only one stationary and stable state exists at small field intensities (curve 1). At given values of this intensities (curves 2—5) a second stationary and stable state arises, but due to the stability of the lower state resulting from the presence of some "barrier", threshold switching does not start yet. This effect realises exactly when a critical value of the electric field intensity is reached (curve 6) at which the first stationary state becomes unstable. On the contrary, the second state remains stable at the decrease of the electric field intensity exactly when the state corresponding to the curve 1 is reached. At this moment a reverse threshold switching takes place. As a result a hysteresis (observed in praxis) arises.

When the sample is connected with the current source with a given value of the current intensity I the equation (8) transforms into the form

$$\frac{\mathrm{d}I}{\mathrm{d}t} = \frac{I^2}{\sigma sc} - \frac{2\alpha}{sch_0}(T - T_0)\,. \tag{11}$$

The evolution equation is of the form

$$\frac{\mathrm{d}q}{\mathrm{d}t} = \frac{1}{sc}\ln^2\frac{q}{q_0}\,G(q) \tag{12}$$

where

$$G(q) = Aq\ln^{-1}\frac{q}{q_0} + Bq + C$$

$$A = \frac{2\alpha}{q_0}$$

$$B = \frac{2\alpha mv}{enq_0\delta W}\,I + \frac{2\alpha kT_0}{\delta W}\,;$$

$$C = \frac{kmv}{e^2 n\delta W}\,I^2\,.$$

With regard to the inequality $q < q_0$ the function $G(q)$ is a monotonous one (Fig. 4). As a result, only one stationary and stable state exists under all circumstances. The sample of non-crystalline semiconductor controlled by electrical current cannot switch.

It is not very difficult to demonstrate that our model permits a pure electronic threshold switching, which is not stimulated by heating. Supposing that the temperature is constant, we get from equation (7) for the electric field intensity the relation

$$E = -\frac{1}{eq}\left(\delta W\ln^{-1}\frac{q}{q_0} + kT\right). \tag{13}$$

Graphs of this function are illustrated in Fig. 5. The temperature of the sample (identical with the temperature of the environment) is here as a parameter. The function (13) has the form of a monotonously increasing curve (curve 4), therefore no switching at high temperatures occurs. At lower temperatures there exist two stationary states of electrons (curve 3 and 4) characterized by two different values of the mean free path of electrons. Once the value E_A of the electric field intensity (point A) is reached, the system of electrons suddenly changes jumping in the point B (Fig. 5). At the decrease of the electric field intensity at the value E_C the system of electrons jumps spontaneously into the state defined by the point D in Fig. 5, and so the hysteresis also takes place.

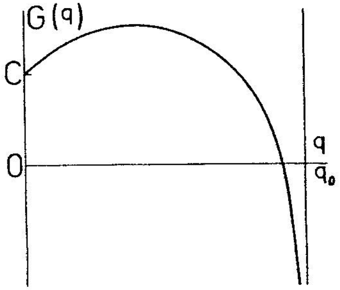


Fig. 4. Illustration of the function $y = G(q)$ for current controlled regime.

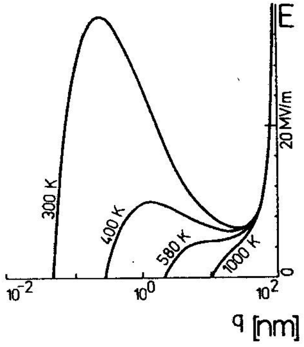


Fig. 5. Dependence of the function $y = E(q)$ for various values of temperature.

IV. DISCUSSION

Curves illustrated in Fig. 3 show clearly that threshold switching can occur in non- -crystalline semiconductors connected with a voltage source under special circumstances. It is not very difficult to specify the necessary conditions. We can deduce from the form of curves in Fig. 2 that two conditions "sine qua non" of threshold switching are

$$\frac{\mathrm{d}G(q)}{\mathrm{d}q} = A - \frac{Be_0^2}{4q_0} \geqslant 0; \qquad e_0 = 2.71\ \dots \tag{14}$$

$$G(q)_{E=E_0} = C - \frac{B}{4} < 0 \tag{15}$$

where the value of E_0 is defined in Fig. 2. Two very important conclusions can be derived from these inequalities:

1. There exist a critical value of the electric field intensity determined by the relation

$$E_c = \frac{amv}{kenh_0}\left[\left(1 + \frac{e_0^2 k\delta Wnh_0}{2amvq_0}\right)^{1/2} - 1\right] \tag{16}$$

below which threshold switching cannot take place and

2. there exist a critical value of the temperature given by the relation

$$T_c = \frac{\delta W}{4k} \tag{17}$$

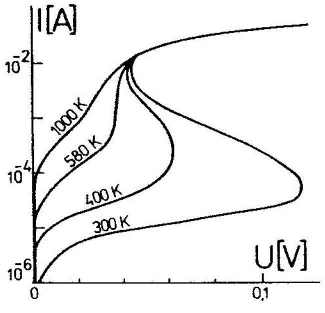


Fig. 6. Current-voltage characteristics with negative dynamic resistivity in current controlled regime of non-crystalline semiconductors.

above which threshold switching is impossible. The calculation using standart characteristic values of unknown parameters gives an approximate result: $E_c \approx 10^3$ V/m, $T_c \approx 500$ K. The existence of the critical field intensity and the critical temperature for threshold switching was experimentally well verified.

Equation (9) permits the calculation of time constants by the integral

$$\tau = \int_{(1)}^{(2)} \frac{1}{F(q)}\,\mathrm{d}q \tag{18}$$

where (1) stands for the initial and (2) for the final state of threshold switching. Numerical calculations (at $\delta W \approx 0.2$ eV, $h_0 \approx 0.5$ µm, $n \approx 10^{25}$ m^{-3}, $q_0 \approx 10$ nm, $v \approx 10^5$ m/s and sc 10^6 JK^{-1} m^{-3}) give the values $\tau \approx 10$ µs in good agreement with measurements. The values of decay times for pure electronic threshold switching are limited only by the time which is necessary for passing the distance q_0 by electrons, i.e. by the time $t \approx q_0/uE$, u being the mobility of electrons. With regard to the fact that $u \approx 10^{-4}$ m^2/Vs, $E \approx 10^6$ V/m and q_0 (10—10^2) nm we can deduce that the decay time in pure electronic threshold is of the order 10^{-9} s in good agreement with measured values.

It was pointed out by the analysis of the evolution equation (12) that no threshold switching can occur in the current controlled regime of semiconductor samples. It is easy to find that the current voltage characteristic is expressed in this case by the relation

$$U = AI \exp\left(\frac{\delta W}{kT + BI}\right) \tag{19}$$

where A and B are constants. The graphical illustration of this dependence (Fig. 6) shows that current-voltage characteristics with negative dynamic resistivity (the termistor type VA characteristics) are generated in this case. This behaviour of non-crystalline semiconductors is very well known.

V. CONCLUSION

It seems that many interesting peculiarities of threshold switching in non-crystalline semiconductors can be understood on the basis of a synergetic conception of this phenomenon. The most interesting result of this consideration is the knowledge that threshold switching can start without the electro-thermal initiation and without the formation of a specific filament. The accurate measurement of the temperature field at switching showed that there was observed in reality neither the gradient of temperature nor a significant increase of temperature of the sample, which was in the form of a thin film. It seems that in the case of a bulk material thermal processes are of fundamental importance.

It was demonstrated in this paper that Ovshinsky's threshold switching diode is an element analogous to Gunn's diode, or to the laser: in the state far from equilibrium an instability of the system of electrons takes place and physical parameters discontinuously change.

REFERENCES

[1] Ovshinsky, R. S.: Electronics *32* (1959), 76.
[2] Lebedev, A.: ŽTF *26* (1956), 2131.
[3] Ovshinsky, S. R., Fritzsche, H.: IEEE Transactions *20* (1973), 91.
[4] Fritzsche, H., Ovshinsky, S. R.: J. Non-Cryst. Solids *2* (1970), 393.
[5] Cohen, M. H., Neale, R. C., Paskin, A.: J. Non-Cryst. Sol. (1972), 885.
[6] Böer, K. W., Ovshinsky, S. R.: J. Appl. Phys. *41* (1970), 6.
[7] Warren, K.: Electronics Letters *5* (1969), 563.
[8] Böer, K. W., Döhler, G., Ovshinsky, S. R.: J. Non-Cryst. Sol. *4* (1970), 573.
[9] Böer, K. W., Döhler, G.: Phys. Stat. Sol. *36* (1969), 679.
[10] Böer, K. W.: Phys. Stat. Sol. (a) *2* (1970), 817.
[11] Henisch, H. K.: Sci. American *221* (1969), 30.
[12] Mattis, D. C.: Phys. Rev. Letters *22* (1969), 30.
[13] Owen, A. E., Robertson, J. M.: IEEE Transactions *20* (1973), 365.
[14] Krempaský, J., Dieška, P.: Phys. Stat. Sol. (b) *56* (1973), 365.

[15] Barančok, D., Dieška, P., Krempaský, J.: Phys. Stat. Sol. *16* (1973), 253.
[16] Krempaský, J., Barančok, D.: Phys. Stat. Sol. *74* (1976), 741.
[17] Barančok, D., Krempaský, J.: J. Non-Cryst. Sol. *16* (1974), 299.
[18] Hrivnák, L.: Acta Phys. Slov.
[19] Böer, K. W., Haislip, R.: Phys. Rev. Lett. *24* (1970), 230.
[20] Shousa, A. H. M.: J. Appl. Phys. *42* (1971), 5132.
[21] Kroll, D. M., Cohen, M. H.: J. Non-Cryst. Sol. *8—10* (1972), 544.
[22] Marschall, J. M., Miller, G. R.: Phil, Mag. *27* (1973), 1151.
[23] Kolomiec, B. T. et al.: *Proc. Conf. Amorph. Semiconductors.* Reinhardsbrunn 1974.
[24] Schauer, F.: *Proc. Conf. Amorph. Semiconductors.* Reinhardsbrunn 1974.
[25] Brodsky, M. H.: in: *Fundamental Physics of Amorphous Semiconductors,* Ed. Yonezawa, Springer-Verlag, Berlin — Heidelberg — New York, 1981.
[26] Fritzsche, H.: Solar Energy Materials *3* (1980), 447.
[27] Haken, H.: *Symergetics: An Introduction.* Springer-Verlag, Berlin — Heidelberg — New york, 1980.
[28] Nicolis, G., Prigogine, I.: *Self-Organization in Nonequilibrium Systems.* J. Wiley, New York — London — Sydney — Toronto, 1977.
[29] Ebeling, W. E.: *Strukturbildung bei irreversiblen Prozessen.* Leipzig, 1976.

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