

OPTICAL PROPERTIES OF THE HYDROGENATED AMORPHOUS SILICON FROM POINT OF VIEW OF THE BARRIER-CLUSTER MODEL

I. BANIK

Department of Physics, Faculty of Civil Engineering, Slovak University of Technology, Radlinského 11, 813 68 Bratislava, Slovak Republic

Although hydrogenated amorphous silicon has its important practical application there still is not any generally accepted model explaining all the physical phenomena ongoing in this matter. The article shows the possibility to explain various important phenomena in hydrogenated amorphous silicon by using barrier-cluster model.

(Received May 19, 2010; accepted June 6, 2010)

Keywords: Amorphous silicon, Hydrogenated silicon, Barrier-cluster model, Photoconductivity, Photoluminescence

1. Introduction

Non-crystalline semiconductors are now applied as elements of optoelectronics (optical switches and so on), optical light-guides, memory elements, as xero-materials, solar cells, and others [1-9]. The situation still seems to be unsatisfactory if one wants to understand physical processes running in these materials.

In physics of non-crystalline materials, there are many unsolved problems yet [1-9]. Thousands works have been published in the field. Majority of those works were of experimental character and brought experimental results. The theory in this field lagged behind the experiments. No model has been suggested yet that could explain sufficiently the wide range of observed phenomena.

Research into amorphous silicon began, in England, nearly 35 years ago, but the major development, the demonstration of doping and the subsequent implementation of devices, was made in Scotland by Spear and LeComber [10]. The first report of amorphous silicon solar cells in 1976 [11] sparked worldwide interest because of their promise as an economically viable source of renewable energy.

Continuous progress has been made over the years not only in improving the initial properties of a-Si based materials but also in reducing their light induced degradation. This has been achieved by optimizing the growth conditions of the materials that improved the incorporation of hydrogen into the network and the corresponding microstructure. Presently, champion solar cells have stabilized efficiencies of 12% and champion modules have stabilized efficiencies of over 10% [12, 13].

In this article, some basic ideas of the barrier-cluster model [14-23] will be introduced, and then the arguments about its possible application in explaining physical properties of amorphous silicon will be given and discussed.

2. Barrier-cluster model

2.1 Barrier-cluster model – basic information

The barrier-cluster model assumes that an amorphous semiconductor consists of microscopic regions – perhaps clusters - separated from each other by potential barriers [14-22].

The barriers hamper the transfer of low energy conduction electrons from one region to the other. Such electrons behave between barriers in particular regions of the material in a similar way as electrons do in a crystal. The potential barriers can be depicted inside both the conduction and valence band of an amorphous material, separating individual localized energy states at the edges of the bands (Fig. 1). The electron levels between the barriers, due to the small dimensions of the microscopic regions, exhibit a distinct discrete character. At the lower margin of the conduction band, a sub-band with carriers of low average mobility is created. The states with energy above the peaks of barriers are delocalized. They create a sub-band with a high average mobility. Quite a similar situation occurs at the edge of the valence band.

2.2. Optical absorption

The potential barriers also influence significantly the optical absorption at the optical absorption edge. It is caused first of all by a strong electron-phonon interaction, which implies that an electron can also take the energy of a phonon at the optical transition and thus, the total energy taken by an electron equals the sum of the photon and phonon energies. This enables to explain existence of exponential tails at the optical absorption, which reach deeply inside the forbidden band of the semiconductor [14-23]. Another important factor - as far as the influence of barriers on optical phenomena is concerned - is that the absorption of light in the region of the absorption edge at low temperatures is usually connected with a tunneling of carriers through potential barriers. Thus, the absorption process is influenced by the barriers. These facts enable us to explain successfully not only the creation of exponential tails at the optical absorption edge, but also their temperature dependences both at high and at low temperatures [14-22].

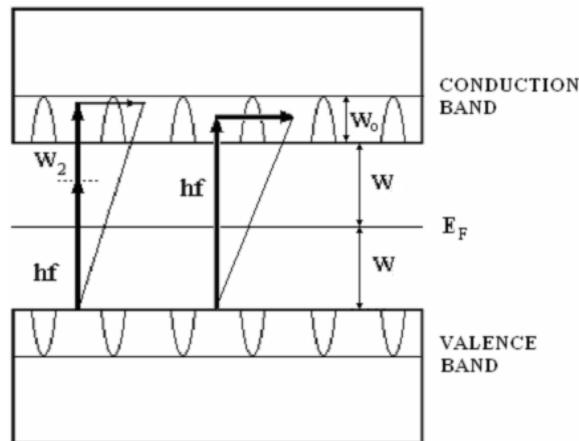


Fig. 1 Electronic spectrum of non-crystalline semiconductor and optical transition at higher (left) and at lower (right) temperature

The optical absorption in most crystalline solids is characterized by a sharp edge of the absorption band. The absorption band near its border in the case of non-crystalline semiconductors is smeared out and it creates a tail that extends deeply into the forbidden band. The profile of the tail is exponential as a rule. The exponential tails at higher temperatures tend to fit Urbach's formula. The slope of the tails changes with a further temperature decrease. At lower temperatures, the slope of the tails does not vary with a further temperature decrease. However, a certain parallel shift towards lower absorption is observed.

The exponential tail

Higher temperature range: The starting point in the following discussion is an assumption that the potential barriers in non-crystalline semiconductors under proper conditions enables to

explain a distinct absorption of light, with phonons participating in the energy exchange [14, 15]. We assume that an electron in the optical transition accepts not only the energy hf of a photon but also the phonon energy W_{phon} . Thus, the whole energy accepted is

$$hf + W_{\text{phon}} \quad (1)$$

where W_{phon} is the energy acquired from a phonon “field”. The quantity hf is given by the wavelength of the radiation, while W_{phon} has a statistical character.

In principle, a photon can be absorbed only when the energy of the electron is sufficient to cause a transition of the electron into the conduction band. However it should be taken into account, that optical transitions on the energy levels lying just below the tops of barriers will dominate at higher temperatures. In this case, the probability of transition within a single localized region is small. The levels in adjacent micro regions offer more possibilities of combination. However, they are connected with tunneling through barriers. Under these assumptions, the transitions on levels just below the barrier peaks will be more probable for two reasons. The transitions on lower levels will be restricted considerably by a small tunneling probability. The second reason consists in the strong electron-phonon interaction in the presence of the barriers. The number of electrons that can acquire such energy from a phonon field depends on the temperature. The number of electron transitions when irradiating the material by „low energy“ photons (and thus, also the coefficient of optical absorption α) is directly proportional to the phonon concentration corresponding to the minimal (least) energy needed for transition. For the absorption coefficient it can be written [14, 15].

$$\alpha \approx \exp(hf/2kT) \quad (2)$$

or, for a particular (constant) temperature

$$\ln \alpha = hf + \text{const} \quad (3)$$

which is a mathematical expression of an exponential tail of optical absorption [1,2]. However, the slope of the tails is also temperature dependent. Formula is of the same kind as the Urbach's formula.

Low temperature range: At low temperatures, only photons with sufficient energy can be absorbed by the material. There are not enough phonons with sufficiently high energies to realize the high-temperature mechanism of the absorption. The optical transition of an electron can be virtually divided into two parts [14-15]. The first part (Fig. 1) is a vertical transition onto an energy level inside its own localized region; the second part represents a horizontal tunneling transition onto a real level in an adjacent localized region. Thus, absorption of a photon in a low-temperature mechanism is connected with the tunneling of the electron through a potential barrier. The barrier model explains in this case the temperature dependence parallel shift of the exponential tails [14, 18].

2.3. Photoconductivity

2.3.1 Mechanism of free electrons origin – basic ideas

If we want to treat a problem of photoconductivity in chalcogenide glasses at first we have to answer the question in which way in a glass can be created free electron via optical method in a range of an exponential tail of optical absorption. Just free electrons are carriers of the photoelectric current. The photo absorption in a range of the exponential tail is connected – as it was already said – with electron tunneling through potential barriers. Majority of electrons in this transition pass through one barrier but a certain (comparatively small) part of electrons can pass through many barriers.

The source of free electrons in a non-crystalline matter during photo-irradiation at low temperatures is a multiple tunneling of a small electron fraction at the process of the optical

absorption connected with tunneling. For this mechanism, it is essential that the majority of electrons execute tunneling through one potential barrier at the optical transition. Some electrons drive a tunnel s - times across s barriers consecutively at the optical transition. In this manner, electrons overcome a long distance from their original region (together with a corresponding hole) and become free. An electron will no longer be bounded with a hole by the Coulomb force.

According to [16-20], the probability, p , of a single tunneling of such a particle is proportional to the expression

$$\begin{aligned} p &\approx \exp[-A(2W + W_0 - (hf + CT))] \\ p &\sim \exp(A(hf + CT)) \end{aligned} \quad (4)$$

For the probability p^s of the multiple-tunneling of the electron through s barriers, we can write

$$P^s \sim p^s \sim \exp[sA(hf + CT)] \quad (5)$$

The probability of the creation of a free electron is proportional to expression (5). Since the probability is small, the number of free electrons will slowly increase after the beginning of the illumination of the glass. The probability of a free electron appearance at the mechanism of multiple tunneling during absorption at the temperature T and energy of activating photon hf is given as follows

$$P^s = \exp(As.(hf + CT - \beta_0)) \quad (6)$$

where $\exp(-\beta_0)$ represents indeed the pre-factor in that relation.

2.3.2 Processes affecting free electron concentration

In our consideration we come out from an assumption that for photoconductivity are responsible free electrons created in a process of optical absorption by the mechanism of multiple electron tunneling through potential barriers which occurred at lower margin of the conduction band. Generation of those free electrons can be described in accord with the formula (6) as follows

$$G = \left\{ \frac{dn}{dt} \right\}_{GENER} = \exp[sA(hf + CT - \beta_1)] \quad (7)$$

where a generation factor G determines the number of free electrons created in unit time. That number is of course proportional to the probability P^s of multiple tunneling of an electron at optical absorption.

A reversal process to the electron generation is recombination which can be in general described by the relation

$$R = \left\{ \frac{dn}{dt} \right\}_{RECOMB} = K.n(n + n_t) \quad (8)$$

where R is the recombination factor. It represents the number of annihilated free electrons per unit time. Symbol n_t denotes concentration of hole (or free electrons) of thermal origin. Process of recombination is in general affected (at higher temperatures) also by holes created by means of thermal mechanism. It holds

$$n_t = F \exp\left(-\frac{W}{kT}\right) \quad (9)$$

where $2W$ is the width of forbidden gap of a non-crystalline semiconductor (chalcogenide glass) and F is a constant.

The change of free electron concentration with time is given by the relation.

$$\left\{ \frac{dn}{dt} \right\} = \left\{ \frac{dn}{dt} \right\}_{GENER} - \left\{ \frac{dn}{dt} \right\}_{RECOMB} \quad (10)$$

or

$$\left\{ \frac{dn}{dt} \right\} = G - R \quad (11)$$

In an equilibrium state it holds

$$\left\{ \frac{dn}{dt} \right\} = 0 \quad (12)$$

respectively

$$\left\{ \frac{dn}{dt} \right\}_{GENER} = \left\{ \frac{dn}{dt} \right\}_{RECOMB} \quad (13)$$

In a steady state $G = R$, so that $n(n + n_t) = G$, from which it follows

$$n^2 + n_t n - G = 0 \quad (14a)$$

In accordance with (7) we obtain

$$n^2 + n_t n - \exp [sA (hf + CT - \beta_2)] = 0 \quad (14b)$$

The change of the constant β_1 for the β_2 in (14b) in comparison with (7) is connected with existence of the constant K in (8).

The solution of this equation in an interval of positive values of n is

$$n = -\frac{n_t}{2} + \sqrt{\left(\frac{n_t}{2}\right)^2 + G} \quad (15)$$

This relation also automatically includes character of a recombination mechanism which one changes from one type to other one with increasing temperature. The change of the recombination mechanism type in significant manner influences the shape of a photoconductivity curve and it is a dominant reason (source) for existence of maximum that curve. In the case if $n_t \gg n$ it follows from the relations (7-9, 15) the approximate relation

$$n = \exp\left(\frac{W}{kT}\right) \exp [sA (hf + CT - \beta)] \quad (16a)$$

resp. if $n_t \ll n$

$$n = \exp [0.5 sA (hf + CT - \beta)] \quad (16b)$$

2.3.3 Two mobility sub-bands of free electrons

Next we want to point out one important feature: a level of photoconductivity is not determined by concentration n given by (15) only. Very important will be too, a distribution of the total number n of electrons into two mobility sub-bands. This distribution split is caused by the temperature. One fraction of concentration n_1 in a steady state will be in sub-band of high mobility μ_1 therefore, at energy levels above the peaks of potential barriers. The second fraction of concentration n_2 will be distributed in sub-band of low mobility μ_2 at energy levels below the peaks

of potential barriers. The number n_1 of free photo-electrons in the sub-band of high mobility can be expressed as

$$n_1 = n \exp\left(-\frac{W_o}{2kT}\right) \quad (17)$$

Whereas, the number of free electrons in the sub-band of low mobility (with energy width W_o) will be determined by the difference $n - n_1 = n_2$, where

$$n_2 = n \left[1 - \exp\left(-\frac{W_o}{2kT}\right) \right] \quad (18)$$

2. 3.4 Photoelectric conductivity

The total photoconductivity will be determined as

$$\sigma \approx \mu_1 n_1 + \mu_2 n_2 \quad (19)$$

Apparently at the some time it holds $\mu_1 \gg \mu_2$. If one substitutes the concentrations accordingly to (17, 18) into the relation (19), then one obtains

$$\sigma \approx n \left\{ \mu_1 \exp\left(-\frac{W_o}{kT}\right) + \mu_2 \left[1 - \exp\left(-\frac{W_o}{kT}\right) \right] \right\} \quad (20)$$

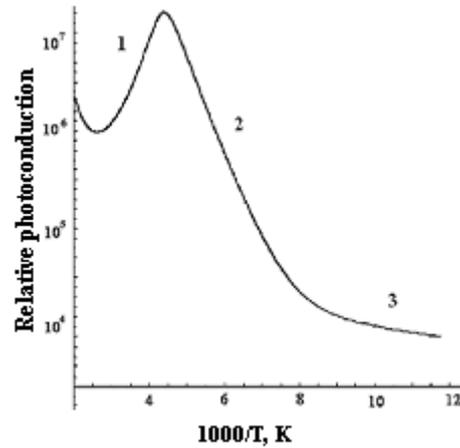


Fig. 2 The photoconductivity dependency on the temperature according to the theoretical formula (22).

In addition, if one expresses the concentration n in accord with (15) then (20) takes the form

$$\sigma \approx \left[-\frac{n_t}{2} + \sqrt{\left(\frac{n_t}{2}\right)^2 + G} \right] \left\{ \mu_1 \exp\left(-\frac{W_o}{kT}\right) + \mu_2 \left[1 - \exp\left(-\frac{W_o}{kT}\right) \right] \right\} \quad (21)$$

The result we have obtained can be expressed as follows

$$\ln\left(\frac{1}{T}\right) \approx \ln\left[-\frac{n_t}{2} + \sqrt{\left(\frac{n_t}{2}\right)^2 + G} \right] \left\{ \mu_1 \exp\left(-\frac{W_o}{kT}\right) + \mu_2 \left[1 - \exp\left(-\frac{W_o}{kT}\right) \right] \right\} \quad (22)$$

where G is determined by (7) and n_t by (9). Just in this form (that is, in a form of a graph of the type $\log \sigma(1/T)$) usually were published measured graphical dependences.

2.4 Photoluminescence

A possible concept of the physical nature of the photoluminescence in chalcogenide glasses at low temperatures, from the point of view of the barrier-cluster model, was analyzed in Refs [17, 19-22]. An electron during the optical transition connected with the tunneling, gets to an adjacent or a nearby region on an energy level, which is below the peak level of the potential barriers. At lower temperatures, the excited electron after an optical transition, will pass on the lowest energy levels of a given localization region. It will be free only within its own localization region. Its wave function would be localized practically in its own micro region between the neighboring barriers. Due to the Coulomb interaction a bound state of an $e-h$ couple arises. As a consequence, a new energy level is formed in the forbidden band. Let us assign this level formally to that localization region where the electron finds itself. This level will be below the bottom of the conduction band. Levels of this kind will arise not only in the neighboring micro region (cluster), but also in the more distant regions. The height of these levels will depend on the distance from the "mother" microregion (for the sake of simplification, we suppose that the hole did not move). With increasing distance, these levels will approach the bottom of the conduction band.

However, discrete levels of excited states in given region also belong to each level of the tunnel, as the lowest energy level of the given localization region. At low temperatures, an optically excited electron will, with a high probability, gradually get back to the mother region of the hole. Such an approach is connected to gradual tunneling and diffusion. The approaching jumps "region-by-region", are connected to an interaction with phonons. Without phonons, such a process would not be possible. These approaching processes are in principle not radiant. An electron loses gradually a considerable part of its energy in them. In the last phase of approach, a non-radiant transition occurs to its own localization region. In this region, radiant optical recombination of the $e-h$ pair occurs, connected with emission of a luminescence photon, whose energy is considerably lower than that of photons of the exciting radiation. A distinct Stokesian shift will occur. If there were no other disturbing processes, a stationary state with a relatively high level of luminescence would establish quickly within the material. In fact, this corresponds rather well to a real situation in the first phase of irradiation. However, the state of a high luminescence begins to impair and weaken rather quickly.

2.4.1 Free electrons as stimulators of non-radiant recombination

After irradiating a non-crystalline semiconductor by a flux of photons at low temperatures under conditions described above, free electrons are practically formed in materials only by a multi-tunneling of a little part of electrons, which took part in the optical transition. The slow rise of concentration of free electrons is caused by the relatively low probability of multi-tunneling processes. The concentration of free electrons in the semiconductor becomes stable only after a long time, when a dynamical equilibrium of two mutually opposing effects establishes. This means the process of arising free electrons and the process of their annihilation by joining with holes, so that new bound $e-h$ pairs are created. When explaining the laws of photoluminescence on the basis of the barrier-cluster model, an assumption is extremely important in our considerations, namely that free electrons, by their effect, stimulate the non-radiant recombination of bound $e-h$ pairs (as a kind of a catalyst), and thus, they reduce the number of radiant transitions. So, ultimately, free electrons markedly influence the luminescence process. The free electron remains free after such individual catalyst process and continues triggering non-optical transitions, acting as a catalyst.

2.4.2 Influence of temperature

It was already said that a source of free electrons in a non-crystalline matter during photo-irradiation at low temperatures is a manifold tunneling of a small electron fraction during the optical absorption connected with tunneling. For this mechanism it is essential that the majority of electrons execute a tunneling through one potential barrier at the optical transition. Some electrons exhibit the tunneling s -times (i.e. across s -barriers) consecutively at the optical transition. In this manner electrons travel a long distance from their original region (together with corresponding holes) and become free. The electron no longer will be bounded with a hole by the Coulomb force. In our model it is assumed that free electrons then activate non-radiate transitions of bounded pairs e - h . These pairs will not contribute to the luminescence. This is why the process of stabilization of luminescence will be relative slow. In [19, 20, 22], the Street's formula

$$I \approx \exp(-T/T_0) \quad (23)$$

was derived to give the dependence of photoluminescence on the temperature. It is based on the concept that the photoluminescence process in a non-crystalline matter is strongly influenced by free electrons.

2.4.3 Influence of the absorbed energy quanta

In [19, 20] the first attempt was done to describe quantitatively the dependence of efficiency of an excitation radiation on the energy of stimulated photons in the region of the exponential tail. At lower energies of the exciting photons in the region of the exponential absorption tail, the photoluminescence intensity increases with the increase of the photon energy hf , together with the absorption α . The photoluminescence I in this region copies the course of the absorption α . We can speak of a good correlation). Strictly speaking, in this range of photon energies practically all generated e - h couples recombine radiantly. There is a negligibly small number of free electrons in the solid and therefore the non-radiant recombination practically do not occur. At higher energies of the exciting photons in the region of the exponential tail, the absorption will continue to increase exponentially but photoluminescence passes through the maximum and will decrease with a further increase of photons energy.

This experimental fact is due - as we believe - standing on the basis of the barrier-cluster model - to the fact that at higher photon energies, the tunneling of electrons through barriers runs on higher energy levels. This circumstance strongly increases the probability of the s -fold tunneling of some electrons to larger distances. In this way the production of free electrons increases considerably with the increase of energy of the exciting photons and consequently, also with the amount of the non-radiant recombination. The number of radiant transitions decrease, and thus also of the photoluminescence level.

At higher photon energies, a tunneling of electrons through barriers will run on higher energy levels. This increases the probability of the tunneling. The probability of the s -multiple tunneling of electrons reaching long distances will rise much faster. Therefore, with an energy increase of the activating photons a free electron production will increase essentially and thus also the number of the non-radiate e - h pair recombination. The number of radiating transitions as well as the luminescence "niveau", will no longer be proportional to the number of absorbed photons and consequently to the number of generated e - h pairs. With increasing the photon energy, the luminescence increase first slows down, and then stops and finally the luminescence decreases.

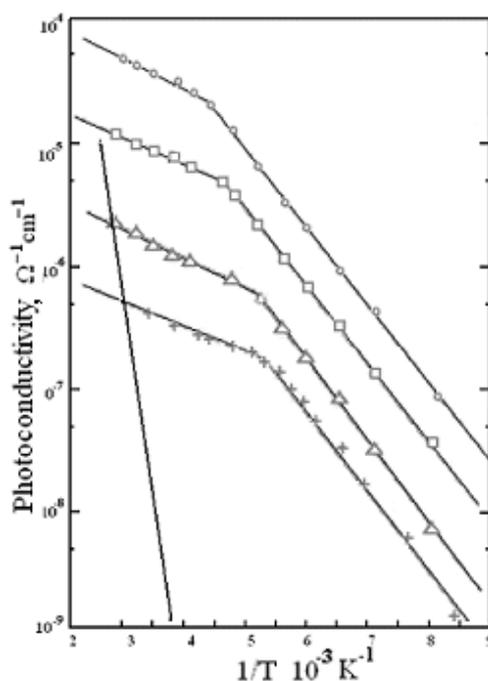


Fig. 3. Dependence of photoconductivity of doped *a*-Si:H at various light flows on $1/T$.

Based on this concept, a law was derived, determining the luminescence intensity dependence on the temperature (in a region of low temperatures) as well as on the photon energy in an energy region of the upper part of the exponential tail. The attempt to express the dependence of the photoluminescence affectivity on the photon energy of the primary radiation from the whole region of the exponential tail will be presented in [20, 21].

3. Barrier-cluster model and amorphous silicon

In this chapter we will answer the question whether and to which measure is the barrier-cluster model capable of giving a true picture of the physical processes accomplishing in both amorphous hydrogenated and doped silicon. Understanding the core of these processes could probably enable the purposeful efficiency improving of *a*-Si solar cells.

We will show that many important results of optical experiments on amorphous silicon can be explained on the barrier-cluster model base. The barrier-cluster model is well applicable for the chalcogenide glasses. However, there is a question: to which measure must this well-developed model be modified in order to give a true picture of physical processes in amorphous silicon. Specifically the photoconductivity and the photoluminescence in non-crystalline silicon will be discussed.

3.1 Photoconductivity in *a*-Si:H in a steady state

The curves in Fig. 2 show the typical photoconductivity behavior in chalcogenide glasses as it depends on the reciprocal temperature $1/T$. The same behavior demonstrates also the theoretical curve following from the barrier-cluster model under appropriate input model parameters. However, the input parameters affect the theoretical curve behavior. It is important for our exploration that the curves shape in Fig. 2 can under other input parameters values change into the shape shown in Fig. 4. This shape is in accordance with experimental shape of curves as measured on both, *a*-Si:H and doped Si, as shown in Fig. 3. The curves show the dependence of photoconductivity on sample illumination. The photocurrent values increase with increasing of

illumination. We can also see some change of the curves slope at elevated temperatures. The slope increases / decreases with increasing of illumination.

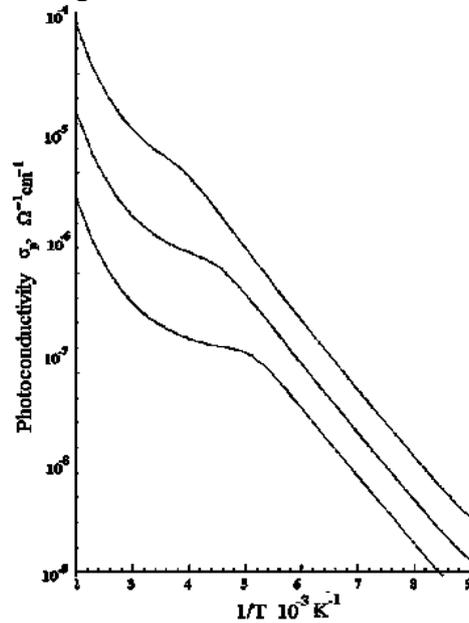


Fig. 4 The photoconductivity dependency on the temperature according to the theoretical formula (22).

Thus, the barrier-cluster model can explain the photoconductivity processes occurring in both a-Si:H and doped silicon. Next, we will discuss the photoluminescence.

3.2 Photoluminescence in a-Si:H in a steady state

We must underline that the a-Si:H photoluminescence characteristics shown in Fig. 5 are similar to those of chalcogenide glasses. In this paragraph we will show that the barrier-cluster model gives true picture of several photoluminescence processes in a-Si and we present several facts which support the concept of the role of free electrons in photoluminescence processes in amorphous silicon.

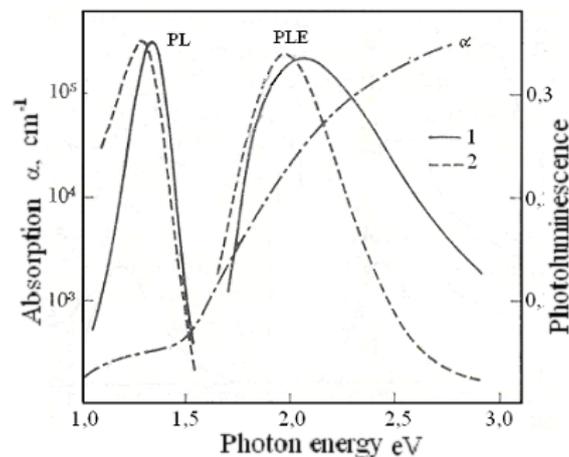


Fig. 5. Photoluminescence spectra (PL) and photoluminescence excitations (PLE) curves of undoped (curves 1) and n-doped (curves 2) a-Si:H at 10 K. The curve α describes behaviour of photoabsorption in the (PLE) excitation region.

Supposing that there are conditions in a non-crystalline solid when free electrons practically do not emerge via optical process (i. e. through the above described mechanism of s -fold tunnelling). It would happen, for example, if tunnelling through barriers occurs on low energy levels. In such case the probability of s -fold tunnelling would be minor. Free electrons of optical origin would have practically zero concentration. However, it does not mean that free electrons of other origin, e. g. electrons produced via temperature mechanism cannot exist in such a solid. In case the electrons are of thermal origin, then for their concentration is valid the relation [17, 20, 22].

$$n \approx \exp\left(-\frac{W}{kT}\right) \quad (24)$$

In a special case, if $nC_4 > C_2$, it follows from

$$I \approx \frac{C_1}{C_2 + C_4 n} \quad (25)$$

[14] and (24) for the luminescence intensity

$$I \approx \exp\left(\frac{W}{kT}\right) \quad (26)$$

However, this is quite different relationship than that, which is represented by the Street's luminescence law. The dependence (26) expressed in the form

$$\ln I\left(\frac{I}{T}\right) \quad (27)$$

represents a straight line with a positive directive. Thus, photoluminescence rapidly decreases with increasing temperature owing to the growth of concentration n of free thermal electrons. The concentration of optically excited free electrons (via mechanism of s -fold tunneling) is unimportant in this case.

3.3 Confrontation of two dependencies

It is possible in this way also to explain e. g. the experimentally observed temperature dependence of photoluminescence for amorphous silicon Si as described in [2].

Let us stop for a while over the presented picture in [2]. Apart from a straight line dependence of photoluminescence on the argument $(1/T)$, also a graph is depicted that displays the dependence of concentration of photoelectrons (photoconductivity) on the argument $(1/T)$. It might seem at first sight that these two dependences contradict to our described concept about the role of free electrons.

It can be clearly seen from the graph that photoluminescence rapidly decreases with increasing temperature right in the place where the concentration of free electrons n is constant, i. e. stable. It is in direct contrast with our concept of the role of free electrons. We will demonstrate however, that this is only a seeming discrepancy. But a clarification of this dilemma needs a little more detailed consideration of photoconductivity. It is well known from the photoconductivity in non-crystalline semiconductors that in the low temperature region it increases with increasing temperature. With further increase in temperature it reaches the maximum and then it falls down.

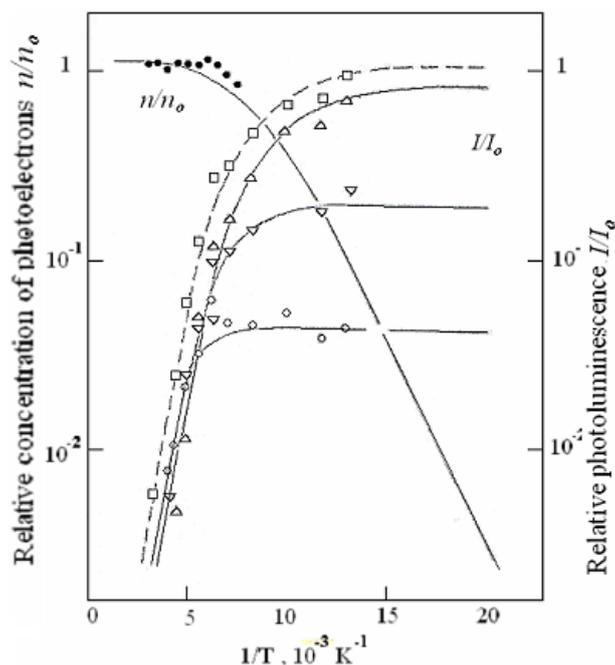


Fig. 6: The temperature dependence of: a) photoluminescence intensity I (for three wave-lengths), b) photo-carrier concentration n in $a\text{-Si:H}$ [3].

This type of dependence occurs really in $a\text{-Si}$ at elevated temperatures - see Fig. 6, 7, which will be discussed in the next part.

Obviously, the same will apply for the concentration of photoelectrons in dependence on temperature, but in connection with the depicted graph - its last phase (i. e. decrease of photoconductivity with increasing temperature in the high temperature region) is missing.

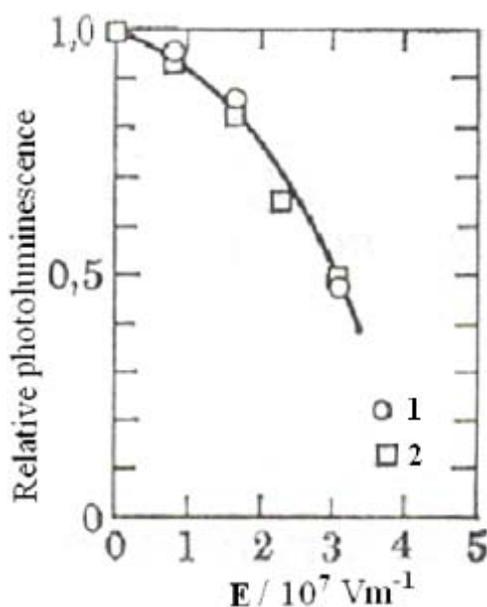


Fig. 7. The influence of electric field E on the photoluminescence of $a\text{-Si:H}$

Here we can observe that in the high temperature region the photoconductivity curve begins to decrease because the mechanism of recombination is changing. This change is a consequence

of thermal carriers, that begin to dominate over the photo carriers. Therefore, it is no surprising that photoconductivity electrons will not run any longer, but the predominating thermal electrons. So, suppression of photoluminescence with increasing temperature in the picture does not relate to the stabilized concentration of photoconductivity electrons, but to a rapid growth of concentration of free thermal electrons. Thus, these two graphs do not represent any dilemma as far as the role of free electrons in a photoluminescence process is concerned.

3.4. Influence of a strong electric field on photoluminescence in a-Si:H

Strong electric field E – as it is known from experimental observations – depresses the level of the photoluminescence I in amorphous silicon. From the barrier-cluster model viewpoint this effect is accompanied with the influence of the electric field which increases number of free electrons. During the process of the optical absorption those electrons become free due to the multiple tunneling across the barriers. The increased number of free electrons (stimulating the non-radiative recombination) implicates a lowering of the radiative recombination number and simultaneously the lowering level of the luminescence.

Effect of the field on a process of the multiple tunneling is the consequence of the strong electric field affects on the electron energy during of the tunneling through the potential barriers. The energy of a moving electron in the direction of the acting electric force increases, in the opposite direction decreases. Theoretical analyses [23] give the result

$$I(E) = I(0) \sqrt{\frac{1}{1 + 0,5 B_3^2 E^2}} \quad (28)$$

or approximately

$$I(E) = I(0)(1 - 0,25 B_3^2 E^2) \quad (29)$$

where B_3 is constant. The intensity of the photoluminescence decreases quadratic with the electric field intensity E . The relations (28) and (29) are but more general.

4. Conclusion

The offered arguments show that the barrier-cluster model can be a good starting point for the interpretation of the physical (first of all optical) processes in both hydrogenated amorphous silicon and doped silicon.

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