

## ELECTRIC CHARGING AND CHARGE RELEASE IN HORNET SILK

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The present study deals with the electric properties of the silk caps produced by pupating larvae of the oriental hornet, *Vespa orientalis* (Hymenoptera, Vespinae). The released silk acts like an organic semiconductor endowed with thermophotovoltaic (TPV) properties, one that can be charged and discharged numerous times under suitable conditions of illumination, relative humidity and temperature. The charging can be achieved under warming, under illumination or by applying an electric potential, all combined or each separately. Upon charging of the silk for about 5-180 min., the discharging is almost instantaneous and complete, whereas upon continuous charging for 180-1080 min., the discharge is lengthy and can assume two forms of discharge, namely, a slow one and a rapid one.

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### 1. Introduction

The oriental hornet is a social insect which founds an annual nest whose population increases during the summer [1]. The development of the nest and population in this group of insects is similar to that described for other species who have rather been ubiquitously described [2, 3, 4, 5].

The hornet, in the course of its development from egg to imago undergoes a complete metamorphosis [6], that is the larva undergoes complete morphologic transformation on its way to imago and it therefore belongs to the *Holometabola*. To achieve this metamorphosis the mature larva spins a silk thread which she fashions around itself a coating whose bulk resides at the cell entrance in the shape of a silk cap, while the scantier remainder is utilized for making a 'shirt' around the body of the pupating larva in which she grows. The silk is released by the pupating larva from four labial glands [7]. Two are located on the ventral side of the body and the remaining two – on the dorsal side, close to the head region. The four glands unite into two and subsequently, just where the silk is being released, the two unite into a single labial gland which releases only a single fibre of silk. Yet the silk fibres are actually composed of two layers, having an outer layer composed of the protein *sericin*. The thin layer of sericin encloses the bulk of the silk fiber, which is made up of the protein called *fibroin*. The quantitative ratio between the two proteins is 4:1 in favour of the later [8]. It is still not clear whether the composition of the two mentioned proteins is uniform throughout. Benshalom-Shimony and Ishay [9] did observe that the luminescence under light of the pupating larval silk, is not the same if observed the outer and inner part. This suggests a different structure of the silk on outside part compared to the inside part of the nest. The difference here could stem from a different make up or arrangement of the amino acids (or from numerous other reasons). Conceivably, the silk produced by the pupating larva at the onset of pupation, when it focusses on the silk cap, is different than that at the terminal stages, when the inside coating of the cell or the pupal "shirt" is woven. In the summer, the nest of the hornet contains a number of brood combs and each of these contains concurrently tens to hundreds of silk-enwrapped pupae. The silk caps in the nest are not normally exposed to light, being constantly in the dark or in twilight. The silk exposed to light, shows photovoltaic properties [10]. In darkness, on the other hand, one can read off the silk cap an electrical current whose intensity

is dependent on the temperature, the relative humidity (RH) and the duration of the measuring [11, 12]. We have found that the vespan silk can be electrically charged by heat, electrical potential or light [13]. We are of the opinion that in the hornet nest, the ambient heat causes the silk to be charged electrically, provided the temperature in the nest exceeds the optimal value, which is  $29^{\circ}\text{C}$  for a hornet nest [14]. The electrical charge is probably stored during peak heat hours that is, between 10 am and 4 pm. Remember that in the dissemination area of the oriental hornet, the temperature at summer can attain  $31\text{--}41^{\circ}\text{C}$  on bodies situated in the shade. At night, when the ambient heat diminishes, the stored electric energy is utilized for purposes of thermoregulation inasmuch as the peak heat lasts 6-8 hours. The present study was set up to evaluate the effect of energy discharge from the silk following prolonged charging of 6-8 hours as compared to shorter periods of exposure to heat.

## 2. Materials and methods

Silk caps removed from queen puparia of oriental hornet were prepared for electrical measurement as previously described [11] while the method and instrumentation for these electrical measurements were described elsewhere [12]. In the present study, the measurements of electrical charging and discharge were carried out over varying time durations as specified in Table 1. The measurements for each time interval were repeated 3-9 times (see Table 1) under the same conditions, i. e., at a temperature of  $29^{\circ}\text{C}$  ( $\pm 0.5^{\circ}\text{C}$ ), which is optimal in the hornet nest [1], a RH of 90% and in total darkness.

Table 1. Summary of relaxation time and amplitude of first and second component obtained in the electrical measurements.

Number of recordings	Charging time (min)	1-st component	2-nd component	1-st component	2-nd component
		Relaxation time (min)		Log-amplitude	
5	5.00	1.36	112.40	-11.57	-14.62
5	60.00	3.42	19.75	-9.72	-11.65
5	120.00	38.00	83.19	-13.00	-14.78
6	180.00	6.37	28.46	53.21	0.11
5	210.00	108.74	259.16	-12.56	-14.31
9	240.00	101.24	242.24	-11.01	-11.96
3	300.00	73.91	203.04	-13.82	-14.47
7	360.00	108.02	206.29	-9.52	-9.52
5	480.00	107.97	261.51	-13.50	-14.05
3	720.00	126.00	337.67	-14.48	-14.30
6	1080.00	217.89	650.76	-13.28	-14.91

### 3. Data analysis

In order to test the dependence of the parameters of the discharging process on the duration of charging we analyzed the experimental recordings of discharge current obtained for different charging of the samples. The duration of charging has been varied from five minutes to eighteen hours. Typical recording consists of the values of current sampled at an interval of one minute. In most cases the current slowly drops to the background noise level after a very fast increase. The time interval of single recordings has been varied from one to twenty hours in correspondence with the duration of former charging (i.e. short measurements after long ones and vice versa). Commonly used parameters of relaxation have been the relaxation time (i.e. the time of e-fold decrease of a signal) and amplitude (i.e. the maximal expected value of a signal). By extracting these parameters from recordings with different charging time one can assess the afore-mentioned dependence.

### 4. Results

Instances of typical discharge dynamics for varying charging times are presented in Figs. 1 and 2. As can be seen in all the graphs, immediately upon onset of discharge there is a drop in the current level. The maximal current in diverse caps attained several microamperes ( $\mu\text{A}$ ). The slope of the discharge curve differs in different specimens. For example, after prolonged charges there is firstly a rise in the current level and only later on is there a drop recorded. We should point out that the silk caps are capable of storing the electrical charge for at least several days after the charging, provided that the specimen is maintained at a low temperature (around  $4\text{ }^\circ\text{C}$ ).

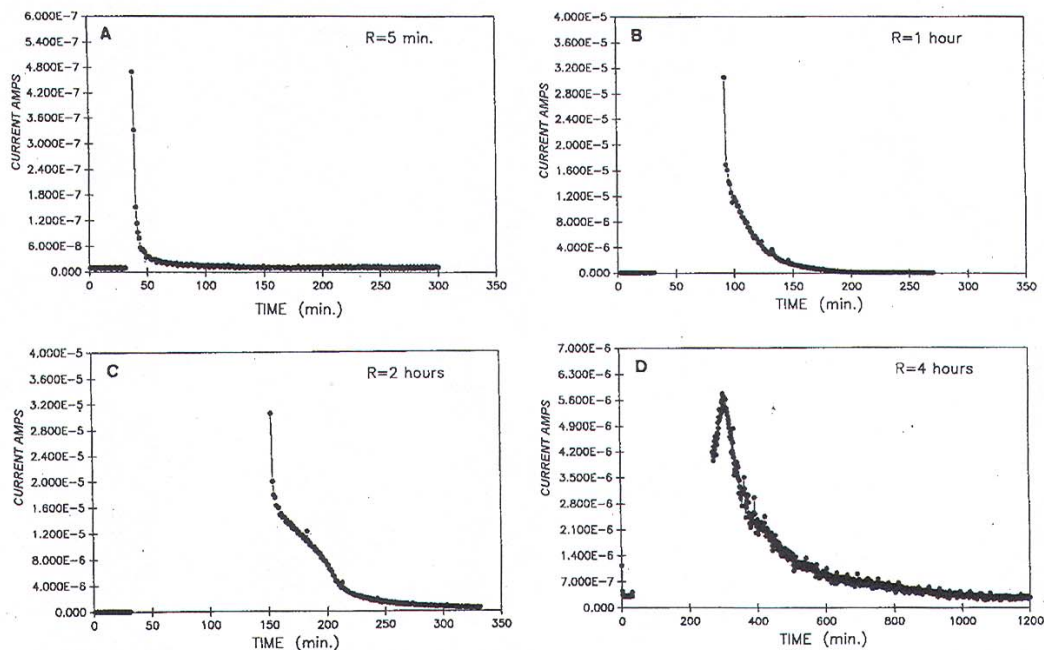


Fig. 1. Cycles of charging and discharging for short periods of 5 min. (A), 1 hr. (B), 2 hrs. (C), and 4 hrs. (D).

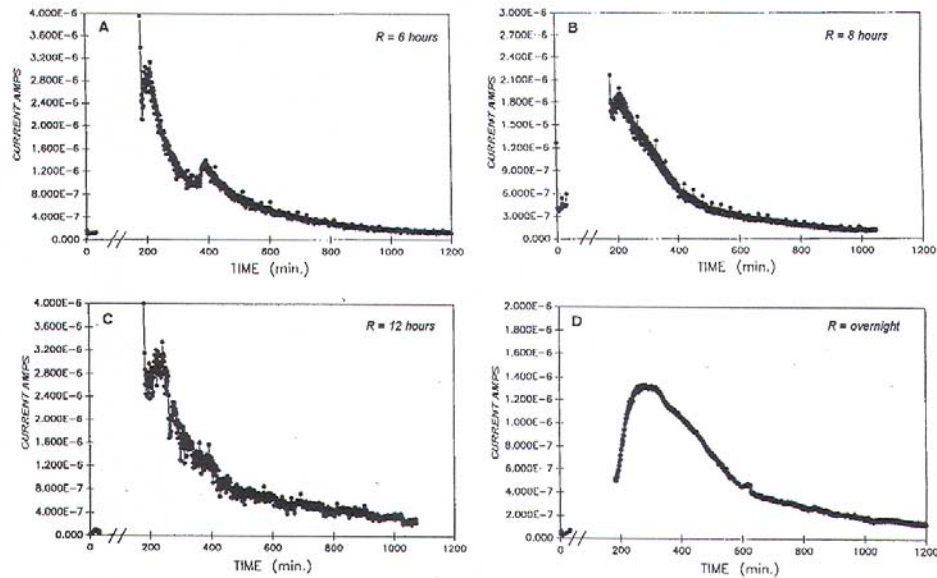


Fig 2. Cycles of charging and discharging during periods of 6 hrs. (A), 8 hrs. (B), 12 hrs. (C) and overnight (D).

The characteristics of the discharging process were obtained by fitting of a certain theoretical expression, including unknown (free) parameters, to each experimental recording. Following a simple model, we expected the drop of current with time to be amenable to a single exponent treatment, but our attempts to a single exponent expression fit the experimental curves were not very successful, yielding at best only a rough approximation. Consequently, we resorted to a two-exponent procedure as follows:

$$I = a_1 \exp(-t/\tau_1) + a_2 \exp(-t/\tau_2) \quad (1)$$

where  $a_1$ ,  $a_2$  are the amplitudes of the first and second component respectively;  $\tau_1$ ,  $\tau_2$  are the relaxation times of the first and second component, respectively. This approximation offered more reliable results, wherein the fitting relied on minimum squared deviations of the theoretical function (see above) from the experimental one. For this purpose we used an original computer programme which solves non-linear least-square problems with an objective function including a two-exponent approximation and parameters  $a_1, a_2, \tau_1$  and  $\tau_2$  as the variables. The value of termination tolerance for the objective functions was chosen to equal 0.01 and so also the values of termination tolerance for the variables.

The obtained values of free parameters were averaged for all recordings with the same charging time. Thus, we averaged the results for the above mentioned four parameters, namely the amplitudes of the two components and the corresponding relaxation times, as presented in Table 1 and in Figs. 3-4. Owing to a significant disparity in the values of the current amplitudes of about three orders of magnitude there was need to calculate the logarithms of these values.

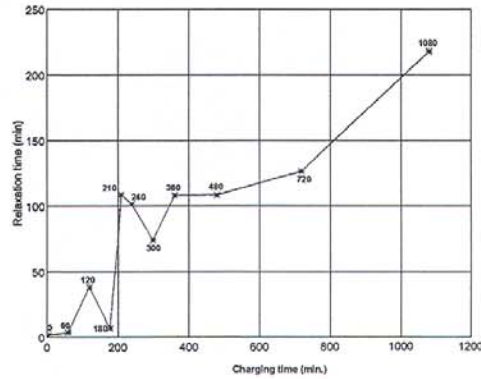


Fig. 3a. The relaxation time of the first component as a function of the charging time. The duration of charging minutes is noted above every point. The relaxation time of the first discharge component is presented on axis y. One notices the evident peak corresponding to the four hours charging, which gradually falls with an increase in charging time. Further increase in the charging time values yields a gradual increase of the first component relaxation times, too.

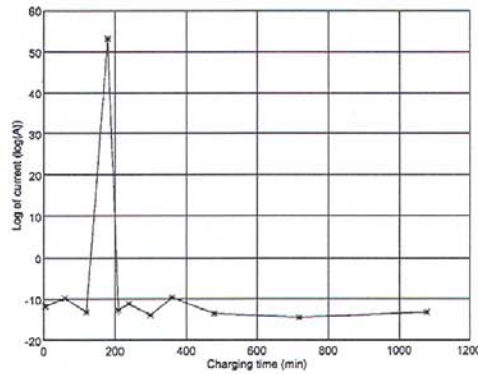


Fig. 3b. The amplitude of the current corresponding to the first component as a function of charging time. The values of charging time are depicted on axis x (as in Fig. 3a). The logarithmic values of the current amplitude of the first component are depicted on axis y. These values vary from about 100 microamperes ( $\mu\text{A}$ ) (for short charging times) to about several hundred nanoamperes (nA) for long charging times. One notices a significant peak, corresponding to 120 min. time of charging, with a strong drop of the values of the first component amplitude.

## 5. Discussion

In a previous study [12] we ascertained that electrical charging of the silk caps in the dark is by 3-5 orders of magnitude more efficient than charging under illumination. It is important to remember that darkness normally prevails in the nest of the oriental hornet. All effort was devoted to understand the phenomenon of charging silk caps with electricity. Our working hypothesis has been that the manner whereby we charge the pupal silk caps with electricity is analogous to what takes place in nature. Thus, when the dark nest is exposed to heat during most hours of the sun insolation – this is the time the charging takes place. Subsequently, from sunset until dawn, the stored electric charge disappears by an electric discharge giving rise to heat, in accordance with the needs of the nest. In order to ascertain the optimal time for charging, we exposed various specimens to charging for various time intervals and there after we have assessed, the optimal time for charging. Judging the shape of the curves obtained upon charging (Figs. 1, 2) it is clear that there are different discharging

levels. For a more precise evaluation of the dynamics of current discharge in dependence of the charging, the results were subjected to further processing. Indeed, the painstaking results presented in Table 1 and Figs. 3 and 4 reveal several significant features. To begin with, all these results prove the existence of two components of the cocoon's electrical conductance.

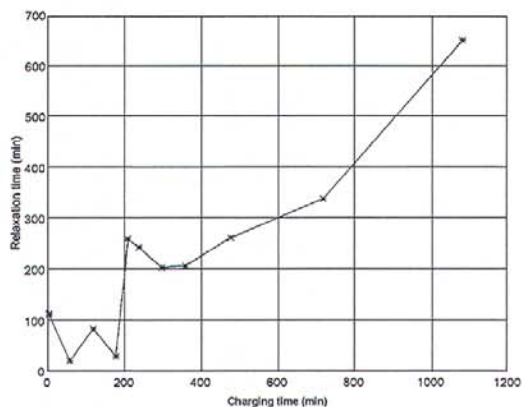


Fig. 4a. The relaxation time of the second component as a function of the charging time. The charging time is represented on abscissa (see Fig. 3a). The charging durations were as already mentioned above in Fig. 3a. The relaxation time of the second component is presented on axis y. It vary from several scores of minutes (for the short charging times) to about eleven hours (for the overnight charging). Note that the same peak corresponds to 4 hours charging but whereas the first component relaxation time depends on the charging duration (see Fig. 3a) this peak declines much more gradually in the direction of large charging times or even remains approximately near maximal value. Further increase of the charging time values yields a gradual increase in the second component relaxation times. Note that the values of the second component relaxation times are 2 - 3 times larger than those of the first component relaxation times for equal charging times.

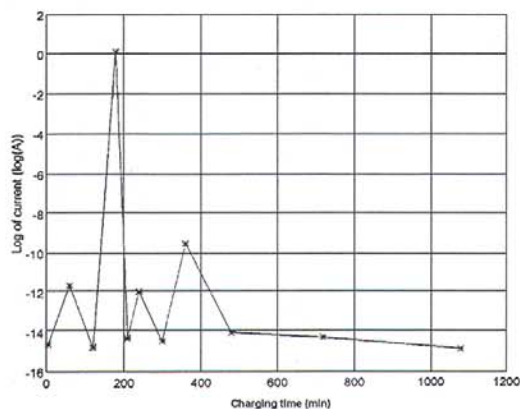


Fig. 4b. The amplitude of the second component current as a function of charging time. The charging times are depicted of axis x (see Fig. 3a). Second component current amplitude values are depicted logarithmically on axis y, varying from a few ( $\mu\text{A}$ ) (for short charging times) to about several hundred (nA) (for long charging times). Here one notes the same peak as in the first component amplitude (see Fig. 3b), namely, at 180 min. and three small peaks at 60 min., 240 min. and at 300 min. It is worth mentioning that these peaks were already present in Fig. 3B but the drop from the one peak to the other is sharper. This is unlike the first component amplitude upon charging, where the difference between the current amplitude peaks was about one order of magnitude (see Fig. 3b).

This outcome was somewhat unexpected and prompted us to ascertain that each of these two components represented a separate mechanism of conductance. Secondly, our results evidence the existence of peaks on the diagrams of both first and second component of the relaxation time as a function of the duration of charging. The general meaning is that the silk cap is capable of releasing a stored charge for an unexpectedly long time following certain charging conditions, e. g., a charging duration of about 4-6 hours or more. Again, under the same charging (4-6 hours) the silk cap unexpectedly produces a strong peak of current amplitude with both the first and second component. Thus, both the current amplitudes and the relaxation times increase upon a charging duration of about 4-6 hours, which leads us to suspect that the total released charge is greater here than under any other conditions. We therefore conjecture that a charging for about 6 hours is optimal for the pupal cocoon thus serving as a prolonged and strong source of energy. The real reason for the presence of two components of charging and discharging is not understood. While various speculations may be expressed it seems more plausible that they represent two mechanisms: a fast and a slow mode of charging and discharging in accordance with the climatic conditions prevalent in the specific area of the nest in nature. The different electrical properties are probably due to the complex properties of the silk fibres that behave in this and other respects as organic semiconductor materials [15, 16, 17].

It should be mentioned that the heterogeneity of the results as seen in Table 1 reflects the differences of the measured samples. Referring to the formula  $R = \rho \ell / S$ , where  $R$  is the electrical resistance,  $\rho$  is the resistivity of the material,  $\ell$  = the distance between the measuring electrodes and  $S$  is the contact area of the electrodes, it is worth mentioning that all these parameters are variable. As the measured specimens are a natural product the resistivity is not constant due to biological variability and since all the measured preparations were hand made (and not a machinery product) the degree of heterogeneity increases.

The above results clearly indicate that the silk present in the silk cap of the puparium is capable to serve as an instrument for electrical charging and discharging, apart from its ability to estimate the amount of electric charge stored in it and to react accordingly. It is noteworthy that charge durations of 4-6 hours were associated with considerable efficiency of the system. Perhaps this is a reflection on the actual state of affairs in the natural nest during the summer. At that time, the daily period during which the temperature in the shade exceeds the optimum of 29 °C lasts a few hours before and after noon. Conceivably, this is the period during which the silk caps absorb the excess heat and store it as an electric charge that is readily convertible back to heat for such occasions when the ambient nest temperature is below optimum.

We focussed on the electric properties of the silk cap produced by pupating vespan larvae. Yet, we need to remember that each of these larvae spins an entire coat around its body. This coat or envelope is composed both of silk cap, which seals the cell entrance as well as of a very thin "shirt" which enwraps the entire larva. As the pupating larva spins her silk it fastens it, whereas feasible, to the inner cell walls which have served it as abode since it was a mere egg. The brood comb, which is composed of numerous cells, is an electric appliance. It stores electrical energy from the heat prevailing in the nest, where the optimal temperature is 29 °C, and the comb cell walls actually act as a thermophotovoltaic (TPV) element [18], in that the level of the current in them is dependent on temperature, rising with the increase in temperature and dropping upon cooling (in accordance with the temperature range extent in the hornet nest). Furthermore, in the dark the comb may still support a current, while in light it accumulates electrical charge. Remember that the comb (and the contained silk) are naturally constantly in the dark (or at least not exposed to direct illumination). An analogy between a vespan comb and what we know about human enterprise and activity leads us to regard the comb both as a miniature power station and a power generator [19]. If this is so, then a pupating larva spinning a silk thread from its labial glands and fastening the silk to the inner cell walls is actually linking up to a power station via contact surfaces (the silk fibers and flats). Thereafter her receives on a regular basis she need of energy from the nest generator, ensuring to store any temporary excess energy formed during the peak hours in the heat. The main consumer of the energy formed within the silk weave is the pupating larva itself and since throughout its life as a pupa (about two weeks), it cannot receive food, its thermoregulatory needs are dependent on the energy which it can receive from the silk outside (via the silk cap) or from their proper comb (via the cell walls).

Another type of consumer are the adult hornets which fly out of the nest in the sun (or exposed to light) and become charged with electric energy [20] which subsequently serves as a source for light

and heat energy [21] which they discharge upon return to the nest within the comb. The very same adults also pick up energy (heat) from the comb at night or on rainy days. In many respects, the entire structure is reminiscent of an electric company which has a power station (the comb) that contains immobile elements for producing electric energy – the cell walls serving as a power generator – and also mobile elements (the adult hornets in their electric – storing cuticle). Add to all this a high electric capacitance, new consumers (hornets from the egg stage to the post pupal stage) and also consumers which in part are contributors as well (the adult hornets). Viewed in this fashion, the vespan silk enables “connecting” the single entity in the vespan colony to an electric supply for the limited period required for its maturation.

## 6. Conclusions

The silk present in the silk cap of the puparium is able to serve as an instrument for electrical charging and discharging and can control the electrical charge accumulation. It acts as an organic semiconductor and exhibit thermo-photovoltaic properties, useful for the energy supply of the hornet.

## References

- [1] J. S. Ishay, H. Bytinski Salz, A. Shulov, *Israel J. Entomol.*, **II**, 45 (1967).
- [2] E. O. Wilson, *The Insect Societies*. Belknap, Harvard Univ., Mass. (1971).
- [3] J. P. Spradbery, *Wasps*, Sidgwick & Jackson, London (1973).
- [4] R. Edwards, *Social Wasps. Their Biology and Control*. Rentokil Libr. East Grinstead (1980).
- [5] M. Matsuura, S. Yamane, *Biology of the Vespine Wasps.*, Springer Verlag, Berlin (1990).
- [6] A. D. Imms, *Entomology*, Methuen, London. 1960.
- [7] S. Kirshboim, J. S. Ishay, *J. Electr. Microscopy*, **47**(5), 505 (1998).
- [8] S. Ochiai, *Bull. Fac. Agric. Tamagawa Univ.*, **1**, 13 (1960).
- [9] T. Benshalom-Shimony, J. S. Ishay, *Comp. Biochem. Physiol.*, **97**, 555 (1990).
- [10] J. S. Ishay, T. Benshalom-Shimony, A. Ben-Shalom, N. J. Kristianpoller, *Insect Physiol.*, **38** (1), 37 (1992).
- [11] J. S. Ishay, V. J. Barenholz – Paniry, *Insect Physiol.*, **41**(9), 753(1995).
- [12] J. S. Ishay, V.J. Barenholz – Paniry, A. Bitler, *Phys. Chem. Physics and Med. NMR*, **29**, 95 (1997).
- [13] L. Litinetsky, H. Steinovitz, J. S. Ishay, *Phys. Chem. Physics. Med. NMR.*, **30**(1), 129 (1998).
- [14] J. S. Ishay, F. Z. Ruttner, *Physiol.*, **72**, 423 (1971).
- [15] F. Gutmann, L. E. Lyons, *Organic Semiconductors Part A*. R. E. Krieger Pub. Co., Malabar, Florida, 1981.
- [16] F. Gutmann, H. Keyzer, L. E. Lyons, R. B. Somoano, *Organic Semiconductors, Part B*, R. E. Krieger Pub. Co., Malabar, Florida, 1983.
- [17] H. Ybach, H. S. Lüth, *Solid State Physics* Springer Verlag, Berlin (1991).
- [18] T. J. Coutts, J. P. Benner, C. S. Allman, (eds), *Fourth MREL Conf.*, Denver, Colorado, USA, 1998.
- [19] J. S. Ishay, M. Shmuelson, *Phys. Chem. Physics and Med. NMR.*, **28**, 41(1996).
- [20] N. Croitoru, J. S. Ishay, L. Arcan, B. Perna, *Photochem. Photobiol.*, **28**(2), 265 (1978).
- [21] J. S. Ishay, T. Shimony (Benshalom), E. Rosenzweig, M. Avidar, A. Afek, *Biosystems*, **15**(2), 133 (1982).