UDC 621.315.592

N. S. Simanovych, Y. N. Karakis, M. I. Kutalova, A. P. Chebanenko, N. P. Zatovskaya

THE PROCESSES ASSOCIATED WITH THE BIFURCATION IN THE CURRENT-VOLTAGE CHARACTERISTICS

Odessa I. I. Mechnikov National University, Odessa, 42, Pastera str., tel. 765-32-16
e-mail: photoelectronics@onu.edu.ua.

The mechanisms leading to the intersection of the dark and light current-voltage characteristics and related phenomena has been considered. The possibility of participation in it as non-equilibrium carriers in the case of solar cells, and the contribution of the equilibrium charge when the temperature impact on the reference diode has been shown. A model explaining the observed features has been built

The intersection of the current-voltage characteristics (CVC) in the study of electrical characteristics of p-n-junctions suggests that in addition to the standard mechanisms of the CVC formation are present or additional process, depending on the applied voltage, or the formation of the diffusion and drift current differs from the "classic" model, or additional external exposure to radiation or temperature takes place. These reasons make the actual identification of additional mechanisms influencing the CVC formation.

1. The intersection of solar cells light and dark current-voltage characteristics

In the study of the solar cells based on CdS-Cu_2S heterojunctions [1] the crossing of the dark and light current-voltage characteristics under forward bias applied to the element (Fig.1) was observed. Similar was the appearance of the control volt-ampere characteristic of silicon solar cells FD6K of industrial manufacturing.

Crossing of the dark and light current-voltage characteristic of the photodiode seems quite paradoxical. It turns out that there is a bias voltage, where via structure the same current flows regardless of influence on it light or it is in the darkness. While it is known that irradiation creates new non-equilibrium carriers. Moreover, since for creation of the photodiodes are selected especially photosensitive materials, the concentration of nonequilibrium carriers Δn is much larger than the equilibrium concentration of carriers n_0, located in the semiconductor in the initial state before irradiation. At the same voltage light current must be much greater than the dark. Moreover, equilibrium carriers in the semiconductor before the lighting under the action of applied voltage are also involved in charge transfer and, accordingly, shall contribute to the light flowing current amount.

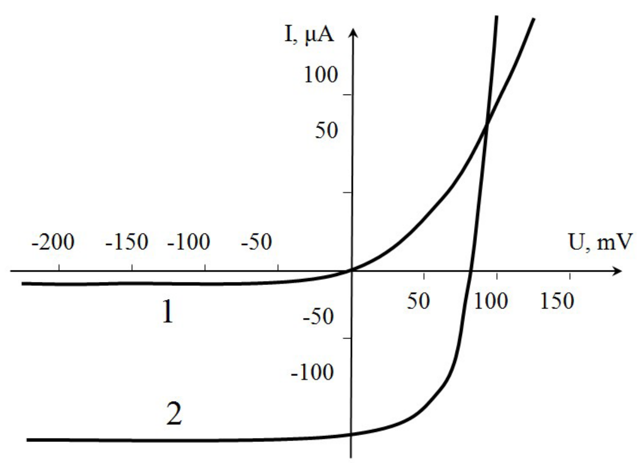

Fig. 1. Typical current-voltage characteristic in the dark (1) and under illumination (2) of investigated photodiode.

It should be noted that the effect of the current-voltage characteristic was observed only in the presence of a sufficiently large contact potential difference. The barrier height for the studied structures, defined as by the standard method from the capacitance-voltage characteristics [2], and by the cutoff of the straight section of direct branches of current-voltage characteristic at high voltages [3,4], was 0.6 eV for heterostructures and 0.4 eV in the case of silicon diodes. On the contrary, in the control experiments for germanium photocells FD-3 of the industrial manufacturing with a barrier height of 0.11 to 0.14 eV was not able to produce the intersection of light and dark current-voltage characteristics in the workspace of direct biases.

Thus, the model to explain the anomalous form of the CVC should be based on high altitude equilibrium barrier p-n junction.

At application of the reverse bias barrier height increases (Fig. 2, cipher 2) and current, as in the dark and at the light is formed by the drift of minority carriers, remaining essentially the same throughout the region of negative biases (left semi-axis, Fig.1). The effect of the light is reduced to the arise of additional nonequilibrium charge and a corresponding increase in the light-generated current. At the same time due to the spatially separated non-equilibrium carriers generates the additional internal field directed in accordance with the principle of Le Chatelier-Braun against the field barrier. As a result, the barrier height decreases slightly. In figure 2 this is shown by the dotted line. In order not to overload the zone diagram there shows only the changes of the bottom of the conduction band. Since the barrier height is significant, its small reduction has virtually no effect on the amount of the drift current.

If no other processes have not occurred, as the result of lighting the entire dark current-voltage characteristic must shift down the same distance at all points, and no intersection of the graphs could not happen. However, for direct branch (right semi-axis, Fig.1) it is not so.

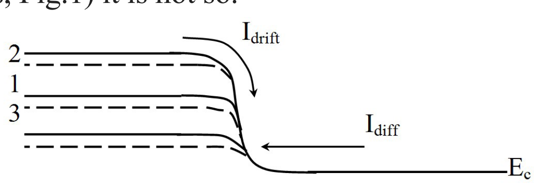

Fig. 2. The change of the barrier profile from the initial state (1) at the reverse (2) and direct (3) biases

At forward bias occurs two processes. First, the external voltage is now directed against the field barrier and, consequently, lowers its (in Fig. 2, cipher 3). Secondly the current transport mechanism changes. Now the current is formed due to diffusion of majority carriers from right to left, as shown in figure 2.

For a much lower barrier additional its reducing at light exposure is much more sensitive. Moreover, note that into the transfer process involves electrons with lower, much more populated levels.

At the same time due to the barrier height decrease the field electric intensity in junction decreases and competing drift current occurs less. These reasons lead to an additional increase in current at the light, and as a result, its value is more than dark one. Light current-voltage characteristic at the curtain biases lies above the dark.

At the same time at small direct biases, as seen in Fig. 1, at voltages that are lower than open-circuit voltage, the current remains negative. This is transfer region when the barrier is not enough strong lowered and current formation is carried predominantly by the same mechanisms as for backward branch. Plot of the light current-voltage characteristic lies below the plot of the dark current-voltage characteristic.

If at the beginning of the straight branch of the light current-voltage characteristic curve is below the dark current-voltage characteristic curve, and at the end of the straight branch the light current-voltage characteristic curve lies above the curve of the dark current-voltage characteristic, in accordance with the theorem of Bolzano-Cauchy necessarily exist a point of their intersection. From the above it is also clear that this can occur only for positive currents, that is, when voltages are greater than the open-circuit voltage.

Thus, the proposed model is based on the reducing of the barrier height at light and a corresponding diffusion current increase in the formed gap. This helps to explain the currents balance at the bifurcation point. Under illumination field patterns of the barrier, now at this point unchanged, the spatial parts of the nonequilibrium carriers. Drift current occurs(figure 2) from left to right. But this process includes feedback – at the expense of the field of free carriers, the barrier is reduced and the additional diffusion currier stream forms – (figure 2) from right to left. At some forward bias, so the original height of the barrier in the dark, these two additional competing flux at light compensate each other. So for this voltage at the point of current-voltage characteristic intersection total current across the junction when the light is on not changed.

It becomes also clear why for photodiodes with a small initial barrier it is difficult to achieve the current-voltage characteristic crossing. Diffusion current even before lighting is too large. So the lightning may not considerably change its value.

The proposed model allows us to explain the bifurcation point coordinate dependence on the light intensity. If the luminous flux increases, a number of carriers separated by a barrier grow. It requires larger forward bias, the barrier height occurs less and its sagging at the light effect were more efficiently. Indeed, such behaviour has been identified for the CdS-Cu_2S heterostructure (Fig.3).

On the plot, are clearly seen two regions. So, the view according to Fig. 3 indicates the existence of two mechanisms of the volt-luxury characteristic formation at high and low light intensities.

It should be noted that the point of intersection always observed on the transitional region of schedule current-voltage characteristic between the exponential part, when works normal diode mechanisms and a linear ohmic region for large direct biases when the barrier is already compensated by the external field and the current is limited only by the diode base series resistance. This requires additional considerations.

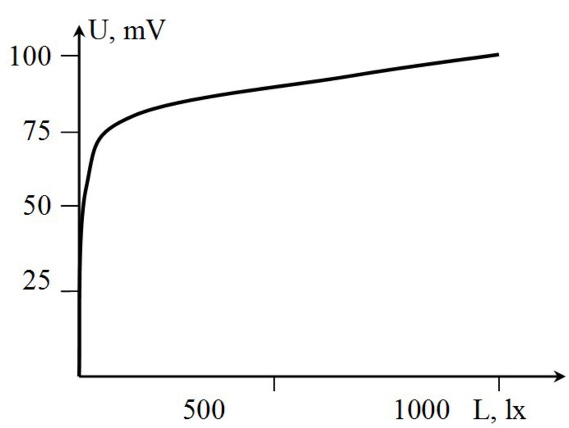

Fig. 3. The dependence of the coordinates of the current-voltage characteristics crossing point on light intensity.

If the diode series resistance in the dark and at the light has not changed, the ends of current-voltage characteristic plots would be parallel. However, the photocells consciously made of very sensitive materials. At lightning, the series resistance decreases. The slope of the linear part of the plot at limiting direct biases at the light increases. The curves intersect.

Most likely, both considered mechanism – the light barrier height reducing and series resistance decrease is carried out at the same time, ensuring by their mutual action the occurrence of the plot current-voltage characteristic intersection effect.

However, for the volt-luminous characteristic (Fig. 3) two presented mechanisms are competitors. As shown above, the barrier height reduction at lightening should lead to an increase the voltage in the point of branching. Bifurcation coordinate needs to shift to the right. If the slope of the linear part of the current-voltage characteristic with the light intensity increases, the bifurcation point should to shift to the left (Fig. 1), towards the smaller voltage values. The presence of such competition creates rather complicated, nonlinear type of plot (Fig. 3). At low light intensities the first mechanism prevails. Coordinate of the bifurcation point increases relatively quickly. At high light intensities contribution of the second, competing, mechanism increases. The voltage at the point of branching is increased more flat.

2. The intersection of the dark current-voltage characteristics

For standard reference diode D814G of industrial manufacturing in the area of stabilization, we observed the intersection of current-voltage characteristics measured at different temperatures (Fig. 4). Further raising the temperature above 60 ^{0}C led to the current-voltage characteristic formation mechanism change as far as in this temperature region in Germanium already is noticeable number of area-zone and above-barrier transitions carriers.

The intersection of the current-voltage characteristics creates a paradoxical situation. Before the diode bifurcation point the reverse current increases with temperature due to the saturation current I_s increase (in the figure arrow “down”).

In the case of stabilitrons, one of this condition is in principle enough in order to from geometrical considerations formed the intersection point. If the basic proportions of the current-voltage characteristic plot are stored, including the section of stabilization, when the current graph grows downwards at an angle, a simple it lowering with temperature must inevitably create the intersection. This requires that for high temperatures the transition on the section of stabilization was carried out at higher voltages, i.e., the standard horizontal "shelf" on the reverse branches of current-voltage characteristic was delayed.

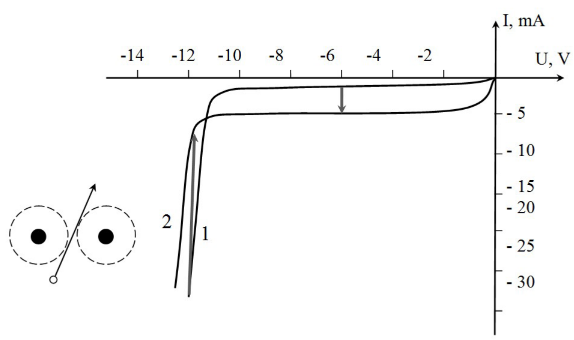

Fig. 4. Reverse current-voltage characteristics of the stabilitron, measured at different temperatures: (1) – 17 ^{0}C, (2) – 56 ^{0}C.

From a physical point of view it requires the construction of an adequate model, as the current formed after the bifurcation point in the diode at the same voltage decreases sharply. Moreover, this decrease was several times greater than the increase in the current at voltages before the bifurcation. This unusual manifestation is even more paradoxical if take into account that the processes leading to an increase in current I_s with temperature, of course, continue to be performed for the entire region of the applied voltage change.

Thus, it is necessary to fined the mechanism that is more powerful than the exponential increase with temperature in the carrier number and is able to imbibe this process. In addition, this model would explain the observed bifurcation point removal, during heating to the left in the region of higher biases. Or, what is the same, why with the temperature increasing increases the length of horizontal section of the current-voltage characteristic before the breakdown region.

To clarify this processes peculiarity lets consider influence of the temperature on the diode material crystal lattice. The usual carrier concentration in a semiconductor is of the order of 10^{16} – 10^{17} cm^{-3}, whereas the density of lattice sites ~ 10^{21} cm^{-3}. I.e. cell crystal lattice density is about 10^{20} cm^{-3}. This means that during the current formation carriers are not the total substance. Each one is in its crystalline cell and from each other they are separated by several orders of cells. The lattice points are charged relative to the electron by equal in magnitude but opposite in sign charge. Such points are much closer to each carrier. In other words, the current formation in the crystal structure mainly influences the individual interaction of the electron with the lattice points.

In the case of the reference diodes this mechanism is enhanced. One of the main processes of stabilization section formation, when the diode current is rising rapidly and the voltage remains practically unchanged, is the formation of carrier number avalanche multiplication. At the same time on one or more of the free path lengths, the carrier must pick up the energy in an external field equal or greater than the width of the forbidden zone. This allows it in the impact with another lattice point to knock out an additional electron. Therefore, the semiconductor material for the stabilitrone manufacture is chosen in such way as to ensure sufficient free carriers and the crystal structure points interaction - grid transition must be relatively small, and the capture cross section high [5].

With temperature increasing diode reverse current and the breakdown voltage increases. This is connected with the fact that the thermal scattering increases, the carrier free path reduces and to p-n-junction need to put more voltage for the charge carriers on a smaller path (equal to the length of free path) pick up kinetic energy sufficient for ionization [6]. Thus, with increasing temperature the length of the stationary section of the current-voltage characteristic ("shelves" on the current-voltage dependence) increases.

Simultaneously there is another process. With the temperature increasing the crystal lattice vibrations increases. As a result, their capture cross-sections increase. In conventional diodes it does not lead to any noticeable changes in current. However, in the reference diodes it is not so, because the semiconductor material is chosen so that the magnitude of the capture cross section is comparable with the distance between the lattice points. In these conditions, even small changes in the capture cross-section diameters can significantly narrow "corridor" for flying carries (see inset in fig. 4). The frequency of interactions with the lattice points is greatly increased. This leads to a strong additional scattering of picked up in a field the carrier energy. The formation of avalanches becomes more difficult, the current on the stabilization section decreases (see Fig. 4). Moreover, because the interaction with the lattice for each carrier is individually, the total increase in the equilibrium charge concentration with temperatures increasing influence on this effect slightly. If the capture cross-section will increase so that will be closed down, avalanche generation, and hence the stabilization section will be impossible for any charge amount.

Thus, all the observed features of the reference diodes current-voltage characteristic due to the specific character of the material used have the same nature, determined by the increase lattice points fluctuatings with the temperature, and consequently increase in currier scattering.

Literature

1. Karakis Yu.N., Kutalava M.I., Zatovskaya N.P. "Optimization in conditions for CdS-Cu_2S heterophotocell shaping" // "Photoelectronics", № 21. Odessa, "Одеський національний університет" 2012. – P. 86 – 89.
2. Берман Л.С., Лебедев А.А. – Емкостная спектроскопия глубоких центров в полупроводниках // Ленинград, "Наука", 1981. – 176 с.
3. Лебедев А.И. Физика полупроводниковых приборов // М. Физматлит., 2008 .
4. Чебаненко А.П., Зубрицкий С.В., Каракис Ю.Н. – Методические указания к специальному практикуму "Физика полупроводниковых приборов Часть I. Полупроводниковые диоды". // Издательство Одесского национального университета. г. Одесса. 2015. – С. 1 – 62.
5. Горелик С.С., Дашевский М.Я. Материаловедение полупроводников и диэлектриков//М., "Мисис" 2003, 481 с.
6. Викулин И.М., Стафеев В.И. – Физика полупроводниковых диодов // М. "Радио и связь" 1990, 264 с.

This article has been received within 2015

UDC 621.315.592

N. S. Simanovych, Y. N. Karakis, M. I. Kutalova, A. P. Chebanenko, N. P. Zatovskaya

THE PROCESSES ASSOCIATED WITH THE BIFURCATION IN THE CURRENT-VOLTAGE CHARACTERISTICS

Resume

The mechanisms leading to the intersection of the dark and light current-voltage characteristics and related phenomena has been considered. The possibility of participation in it as non-equilibrium carriers in the case of solar cells, and the contribution of the equilibrium charge when the temperature impact on the reference diode has been shown. Models explaining the observed features has been built

Key words: bifurcation, process, characteristic.

УДК 621.315.592

Н. С. Симанович, Ю. М. Каракис, М. И. Куталова, А. П. Чебаненко, Н. П. Затовская

ПРОЦЕССЫ, СВЯЗАННЫЕ С БИФУРКАЦИЕЙ ВОЛЬТ-АМПЕРНЫХ ХАРАКТЕРИСТИК

Резюме.

Рассмотрены механизмы, приводящие к пересечению вольт-амперных характеристик и сопутствующие явления. Показана возможность участия при этом как неравновесных носителей в случае фотоэлементов, так и вклад равновесного заряда при температурном воздействии на опорные диоды. Построены модели, объясняющие наблюдаемые особенности.

Ключевые слова: бифуркация, процессы, характеристика.

УДК 621.315.592

Н. С. Сіманович, Ю. М. Каракіс, М. І. Куталова, А. П. Чебаненко, Н. П. Затовська

ПРОЦЕСИ, ЩО ПОВ’ЯЗАНІ З БІФУРКАЦІЄЮ ВОЛЬТ – АМПЕРНИХ ХАРАКТЕРИСТИК

Резюме.

Розглянуто механізми, що приводять до перетину вольт-амперних характеристик та явища, що їх супроводжують. Показано можливість участі при цьому як нерівноважних носіїв у випадку фотоелементів, так і внесок рівноважного заряду при температурному впливі на опорні діоди. Побудовано моделі, які пояснюють особливості що спостерігаються.

Ключові слова: бифуркація, процес, характеристика.