UDC 621.315.592

A. Yu. Bak, Yu. N. Karakis, A. E. Stupak, M. I. Kutalova, A. P. Chebanenko

Odessa National University, 42, Pasteur St.;
e-mail: wadz@mail.ru

DETERMINATION OF BAND GAP OF SEMICONDUCTOR MATERIAL IN END PRODUCT

The paper puts forward a method for determination of semiconductor activation energy in end product. It is illustrated that band gap can be calculated at cutoffs on both axes of graphs *ln(I)÷U*, measured at different temperatures. Minimum temperature interval is determined depending on measuring accuracy. A new method for determination of value E_g without VAC (volt-ampere characteristics) extrapolation is put forward.

1. INTRODUCTION

Classic method for determination of band gap of semiconductor crystal is a study of temperature dependence of its conductivity [1,2]. Among optical methods the most widely used is determination of excitation light wavelength at maximum photosensitivity and extrapolation of spectral distribution of absorption coefficient [3,4].

However, in some cases, such as identification of semiconductor material, it is required to determine matter activation energy in end product. Simple thermal methods cannot be applied for this purpose, since crystal has already undergone a series of complementary technological operations, such as contact etching, annealing and oxide coating, etc.

Optical methods cannot be used for the same reason. In case of photoconverters measuring results are distorted due to protective coatings, transparent layers of SnO_2 applied as a front window, etc. Frequently photocells are fabricated on a hard opaque surface obstructing the passage of penetrating light. This excludes measurement of absorption coefficient.

In this case temperature variations of volt-ampere characteristics (VAC) are studied. There are two methods [5]. The first one implies study of temperature variations of saturation current I_s in VAC reverse-bias region. However, not to get into junction region, it is necessary to apply fairly large reverse voltages of tens of Volts. For many photocells this is beyond their operating parameters. And in that case rectification of VAC forward biases in semi-log plot is applied to operating region below open circuit voltage – usually a few tenths of a Volt (Fig. 1).

2. RESULTS, DISCUSSION

Photoconverters operate due to potential barrier between p- and n-semiconductors. Effect of relatively insignificant barriers on ohmic contacts in this case is negligible.

Here is the expression for photodiode VAC lines without photo-excited carriers [5]:

$$I = I_s\,[\exp(\frac{eU}{kT}) - 1] \qquad (1)$$

where I_s - reverse saturation current of p-n – junction, created by carriers flowing from the barrier. Its value is in proportion to concentration of minor carriers in p-region

$$n_p = N_c \exp(-\frac{E_g}{kT}) \qquad (2)$$

and n-region

$$p_n = P_v \exp(-\frac{E_g}{kT}) \qquad (3)$$

In case of fairly large forward bias, where

$$eU \gg kT \tag{4}$$

unit (1) can be disregarded. Then, taking into account (2) and (3), the expression (1) can be as follows:

$$I = A\exp\left(-\frac{E_g - eU}{kT}\right) \tag{5}$$

where A – weakly temperature-dependent coefficient. Taking logarithm (5), we obtain:

$$\ln I = \ln A - \frac{E_g - eU}{kT} \tag{6}$$

It follows that the set of characteristics lnI(U) at different temperatures is represented by temperature-dependent slope intercept form of a line

$$tg\,\alpha = \frac{\Delta \ln I}{\Delta U} = \frac{e}{kT}. \tag{7}$$

and meeting at some point with abscissa E_g/e. This enables to calculate band gap of material by measuring diode VAC lines at two different temperatures (Fig. 1).

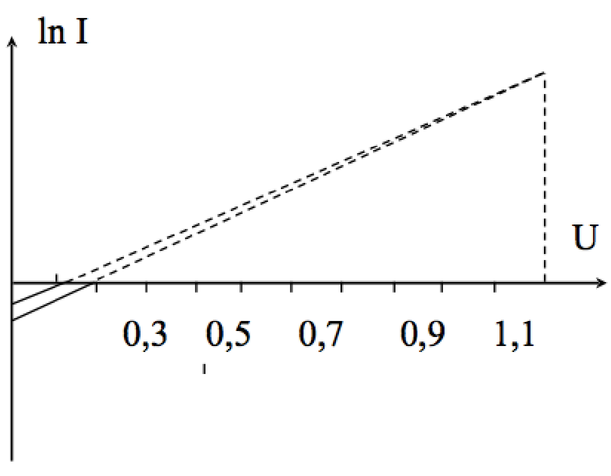

Fig.1. Standard direct current-voltage dependence for silicon diodes in semi-log plot.

However, this method is difficult to apply in practice. Standard potential barrier height at p-n-junction for the most popular silicon diodes is 0.1-0.15 eV. At forward biasing the barrier reduces. That is why beyond the above voltage diode current loses its diode nature and is limited to series resistance only, whereas VA characteristics become linear. This means that experimentally measured points applicable for calculation in the given method, are located as shown in Fig. 1, in the lower quadrant outside voltage ~ 0.2 V (solid graphs).

One should note that ln I = 0 at amperage ~ 1 A. In real low-power diodes direct current is milliampere units or even fractions. Which is equivalent to ln I ~ - 5.0. All points on a graph above this value on current axis can be only extrapolation-based. In other words, a large number of points near both axes disappears, narrowing actual rectification region even more.

Silicon band gap is 1.1 eV. Thus, intersection of graphs should be expected at voltage bias ~ 1.1 V on voltage axis, i.e. extrapolation (dotted lines) is applied to 90-95% of graph length. Clearly, at this arm intersection of lines is extremely sensitive to two factors. Firstly, it is measuring accuracy, i.e. spread of points with confidence interval Δ. And secondly, temperature interval applied at measuring, i.e. difference in slopes of graphs. These values are interconnected. At a large value of confidence interval and insufficient temperature difference graphs may not intersect at all, as shown in Fig. 2 for lines CN and DG.

VAC measuring pattern is the following. Exact applied rectification is specified. Then error current flowing at a given voltage is measured. Value Δ means vertical spread of points on a graph lnI÷U.

Graphs lnI÷U are plotted within a few confidence bands, as shown in Fig. 2. In general, width of these bands differs. It is determined by band slope

$$\Delta_1 = 2\Delta \cdot \cos\alpha \tag{8}$$

Inclination angle according to (7) depends on measuring temperature.

However, in reality temperature difference is not too large. Lower limit is correlation (4). Naturally, it is assumed that room temperature is the lower. The upper limit is maximum rated temperature of the product (for silicon it is around +60 ^{0}C), when contribution of intrinsic carriers becomes more obvious due to region-region junction. At this temperature interval for the sake of simplicity we assume that confidence band width in both graphs is the same.

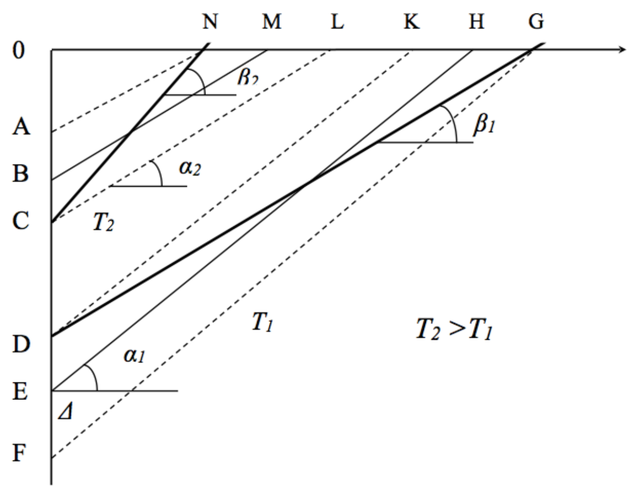

Fig. 2. Operating region for method of VAC intersecting lines.

We can obtain criterion for minimum temperature interval at a given spread of points Δ, subject to parallelism of CN and DG (Fig. 2). Line equation EH $y = a_1x + b_1$, where according to (6)

$$a_1 = \frac{e}{k}\frac{1}{T_1} \qquad b_1 = \ln A - \frac{E_g}{k}\frac{1}{T_1} \tag{9}$$

Value b is negative, since operating region of flowing current is I < 1A. Thus, both summands for a constant term are less than zero.

Then FG line equation is given by $y = a_1x - (/b_1/ + \Delta)$, remembering that values b_1 are negative and F point ordinate increases in comparison with point E. It follows that G point coordinate at y=0 is $x_G = \frac{|b_1| + \Delta}{a_1}$. D point coordinate decreases by confidence interval value: $- y_D = - (/b_1/ - \Delta)$. It gives the lowest possible slope for DG graph within confidence band:

$$tg\,\beta_1 = \frac{|b_1| - \Delta}{|b_1| + \Delta} a_1 \tag{10}$$

Note that numerator modulo is less than denominator, so $tg\,\beta_1 < a_1$, i.e. angle β_1 is less than angle α_1.

For similar reasons, at elevated temperature T_2 for BM line $y = a_2x + b_2$, where

$$a_2 = \frac{e}{k}\frac{1}{T_2} \qquad b_2 = \ln A - \frac{E_g}{k}\frac{1}{T_2} \tag{11}$$

we obtain equation for AN $y = a_2x - (/b_2/ - \Delta)$.

Thus, N point coordinate will be $x_N = \frac{|b_2| - \Delta}{a_2}$. C point coordinate – $y_c = - (/b_2/ + \Delta)$. Thus, maximum slope within this band for CN is given by equation

$$tg\,\beta_2 = \frac{|b_2| + \Delta}{|b_2| - \Delta} a_2 \tag{12}$$

while $tg\,\beta_2 > tg\,\alpha_2$.

Intersection point will be surely obtained once the condition is met

$$\frac{|b_1| - \Delta}{|b_1| + \Delta} a_1 = \frac{|b_2| + \Delta}{|b_2| - \Delta} a_2$$

or

$$\Delta^2 (a_1 - a_2) - \Delta (a_1 + a_2)(|b_1| + |b_2|) + b_1 b_2 (a_1 - a_2) = 0 \tag{13}$$

Here Δ – confidence interval, and the rest are temperature dependent parameters.

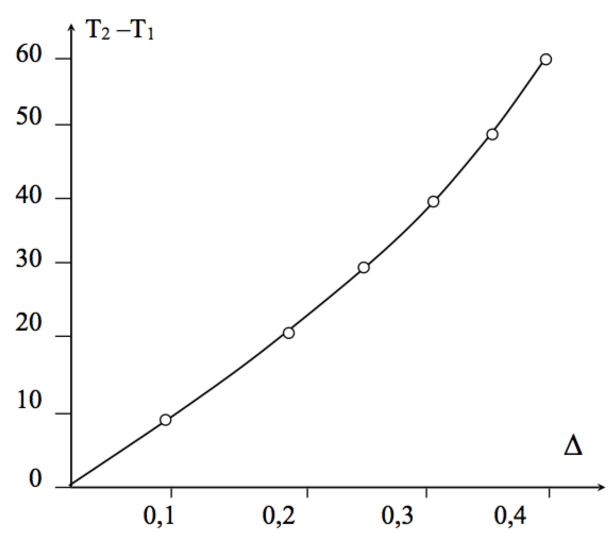

Fig. 3. Lowest possible temperature interval for determination of band gap.

Equation (13) was solved numerically. Parameter value lnA=29.77 is taken from experimental measurement for a sample of one of Si-diodes. a_1 and a_2 slope values were determined from the formulae (9) and (11) at given temperatures. Room temperature was used as reference temperature T_1. Point of graph intersection occurred at $x_0 = \frac{E_g}{e}$ [See dependence (6), silicon band gap 1.1 eV]. Then cutoffs b_i were determined from the equation of the pencil of lines, going through that point

$$\ln A = a_i\left(T\right)\left(\frac{E_g}{e}\right) + b_i\left(T\right).$$

By solving equation (13) two roots were obtained, different by a large ratio – either tenths or hundreds of units. Here b_i values fell in the interval of 12 - 25 units. For the sake of rationality the larger value Δ was discarded as having no physical content. Calculation result is shown in Fig. 3.

The more operating temperatures T_1 and T_2 are different, the more accurate the results are. However, there is a limit for lower temperature. At large errors Δ confidence bands are too wide, and it is necessary to increase minimum temperature interval for graphs to intersect ln I ÷ U.

As shown in Fig. 3, the more spread points are obtained at current measurement, i.e. the larger value Δ is and the wider confidence bands are, the more temperature interval should be applied to measurement of graphs. Here high-temperature band is more sloped, which compensates divergence of lines. However, the problem of determination accuracy of intersection coordinate persists.

To determine diode band gap, there is no need to extrapolate VAC lines at a huge arm till their intersection, as it is recommended in the classic method. This parameter can be obtained with more accuracy at cutoffs on axes.

For current axis those are values $\ln I_1$ and $\ln I_2$, i.e. values b_1 and b_2 from the formulae (9) and (11). As shown in Fig. 4, length of the respective interval is

$$\ln I_1 - \ln I_2 = \frac{E_g}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \quad (14)$$

Since temperatures T_1 and T_2 applied for measurement are given, and values on the left are determined directly on the graph, formula (14) enables to calculate value E_g.

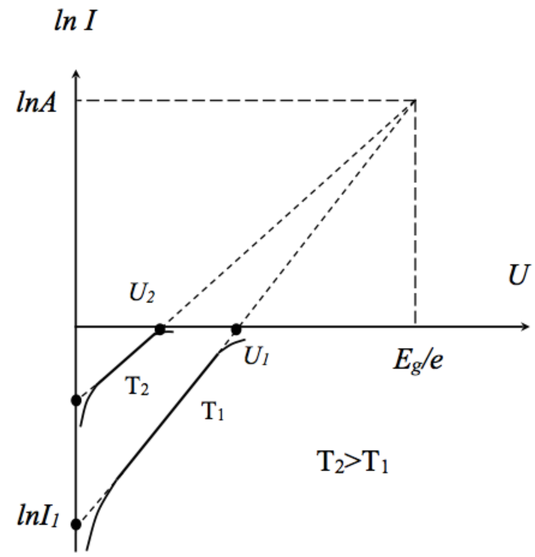

Fig. 4. VAC lines at different temperatures.

Similarly, for voltage axis intersection points (Fig. 4) from equation (6) it is true that

$$-\ln A = -\frac{E_g}{kT_1} + \frac{eU_1}{kT_1} = -\frac{E_g}{kT_2} + \frac{eU_2}{kT_2}$$

from which

$$\frac{E_g}{e}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) = \frac{U_1}{T_1} - \frac{U_2}{T_2} \quad (15)$$

which also enables to determine parameter E_g, given values U_1 and U_2 from the graph.

Compare accuracy of two offered options with the classic method (Fig. 5). Obviously, for current axis parameter spread is

$$\pm 2\Delta \quad (16)$$

To determine spread of axis intersection points, it is necessary to determine band width projection from (8) on X-axis:

$$\pm \Delta \cdot \left(ctg\,\alpha_1 + ctg\,\alpha_2\right) = \pm \Delta \cdot \left(\frac{1}{a_1} + \frac{1}{a_2}\right) \quad (17)$$

Formula (17) gives general change of confidence interval when determining coordinates U_1

and U_2 on voltage axis (Fig. 4), i.e. for the right member of dependence (15). However, extension of this interval is not symmetrical, since now it depends on angles α_1 and α_2, which are different for temperatures T_1 and T_2. According to (7), for higher temperature T_2 slope α_2 is lower. Segment U_1 - U_2 spreads more to the right (See Table).

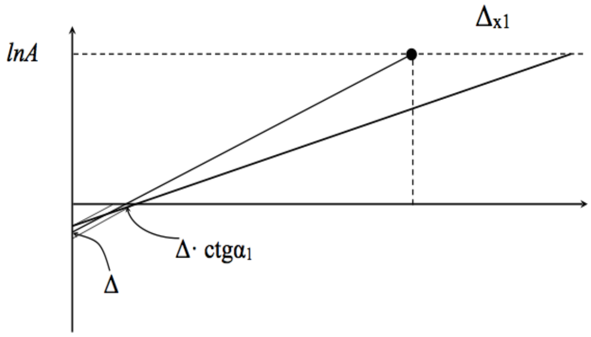

Fig. 5. In the same ratio, as in Fig. 1. Error for axis intersection points and graph convergence point (illustrated by one of dependences in the same ratio as in Fig.1).

It is well to bear in mind that, though absolute error at determining cutoffs U_1 and U_2 on voltage axis is much lower (See Table), absolute magnitude of these values is also an order less than cutoffs b_1 and b_2 for current axis. So it is not possible to say, which method is more accurate.

Define error in the coordinate of VAC graph convergence point. If temperature interval is set correctly based on dependence (13), abscissa of intersection point of lines DM and EH (See Fig. 1-2) shall be $\frac{E_g}{e}$. Then its ordinate from the equation (6) shall be y=lnA (horizontal line in Fig. 5).

Maximum deviation from it to the right can be determined as intersection point of line DG with highest possible slope to the right within confidence interval at temperature T_1 (See Fig. 2). Taking into account (10), we obtain

$$\ln A = \frac{|b_1| - \Delta}{|b_1| + \Delta} a_1 x - \left(|b_1| - \Delta\right).$$

from here

$$\Delta x_1 = \frac{\left[\ln A + \left(|b_1| - \Delta\right)\right] \cdot \left(|b_1| + \Delta\right)}{\left(|b_1| - \Delta\right) \cdot a_1} - \frac{E_g}{e} \qquad (18)$$

Highest possible deviation to the left can be obtained by extending line CN to intersection. According to (12), we obtain

$$\ln A = \frac{|b_2| + \Delta}{|b_2| - \Delta} a_2 x - \left(|b_2| + \Delta\right),$$

from which

$$\Delta x_2 = \frac{E_g}{e} - \frac{\left[\ln A + \left(|b_2| + \Delta\right)\right] \cdot \left(|b_2| - \Delta\right)}{\left(|b_2| + \Delta\right) \cdot a_2} \qquad (19)$$

Numerical values of parameter spread are given in the Table. Values used for calculation: T_1 = 300 K, T_2 = 360 K, Δ = 0.2 (mid segment Fig. 3). Other parameters are the same as for equation calculation (13).

	Inward departure	Outward departure
Determination of E_g at cutoff on Y-axis	0.2	0.2
Determination of E_g at cutoff on X-axis	0.04	0.031
Classic method of graph intersection	0.39	0.96

As shown in Fig. 5, classic method error is a few times higher, which is accounted for by extremely large extrapolation arm.

Suggested methods enable to obtain band gap of material without VAC graph extrapolation. Based on formula (6), distance between VAC lines /ln I_{01} – ln I_{02}/ in operating region at some fixed voltage U_0 will be:

$$-\left|\ln I_{01} - \ln I_{02}\right| = \frac{E_g}{k}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) + \frac{eU_0}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right).$$

from here

$$E_g = eU_0 + \frac{k\left|\ln I_{01} - \ln I_{02}\right|}{\left(\frac{1}{T_1} - \frac{1}{T_2}\right)} \qquad (20)$$

By contrast, for a section of horizontal graph system for a certain value ln I_0 in operating region the following is true:

$$\ln I_0 - \ln A = -\frac{E_g}{kT_1} + \frac{eU_{01}}{kT_1} = -\frac{E_g}{kT_2} + \frac{eU_{02}}{kT_2}.$$

from here

$$E_g\left(\frac{1}{T_1} - \frac{1}{T_2}\right) = \frac{eU_{01}}{T_1} - \frac{eU_{02}}{T_2}.$$

or

$$E_g = \frac{\frac{eU_{01}}{T_1} - \frac{eU_{02}}{T_2}}{\frac{1}{T_1} - \frac{1}{T_2}} \qquad (21)$$

where $T_1 < T_2$ – temperatures, at which graphs were measured, and $U_{01} > U_{02}$ are abscissas of section points.

Energy accuracy E_g obtained remains ± 2Δ for a section along voltage axis by the formula (20) and error (17) for the expression (21).

Note that there is no value ln A in the above dependences (20), (21), i.e. it is not required for determination of value E_g by given method.

3. CONCLUSION

Thus, determination of band gap based on volt-ampere characteristics becomes simpler and more accurate, using cutoffs on current and voltage axes or vertical or horizontal sections of VAC graphs instead of extrapolation. It is necessary to bear in mind dependence of required temperature interval on amperage measurement error.

REFERENCES

1. Tereshchenko O.E., Kostyurina A.G. - Opredeleniye shiriny zapreshchennoy zony poluprovodnikov // Novosibirsk, 2004.
2. Pavlov L.P. - Metody izmereniya parametrov poluprovodnikovykh materialov // M., Vysshaya shkola, 1997.
3. Vladimirova L.N., Bormontov Ye.N., Berlo Ye.N. – Vnutrenniy fotoeffekt v poluprovodnikakh // Izdatelsko-poligraficheskiy tsentr Voronezhskogo gosudarstvennogo universiteta, 2009.
4. Andreyev A.N., Gavrilov Ye.V., Ishanin G.G. – Opticheskiye izmereniya // M., Logos, 2012.
5. Lebedev A.I. - Fizika poluprovodnikovykh priborov // M. Fizmatlit., P 2008 .

This article has been received within 2014

UDC 621.315.592

A. Yu. Bak, Yu. N. Karakis A. E. Stupak, M. I. Kutalova, A. P. Chebanenko

DETERMINATION OF BAND GAP OF SEMICONDUCTOR MATERIAL IN END PRODUCT

Abstract

The paper puts forward a method for determination of semiconductor activation energy in end product. It is illustrated that band gap can be calculated at cutoffs on both axes of graphs *ln(I)÷U*, measured at different temperatures. Minimum temperature interval is determined depending on measuring accuracy. A new method for determination of value E_g without VAC extrapolation is put forward.

Key words: determination of band gap, semiconductor material, activation energy.

УДК 621.315.592

А. Ю. Бак., Ю. М. Каракіс.О. Е. Ступак, М. І. Куталова, А. П. Чебаненко

ВИЗНАЧЕННЯ ШИРИНИ ЗАБАРОНЕНОЇ ЗОНИ НАПІВПРОВІДНИКОВОГО МАТЕРІАЛУ В ГОТОВОМУ ВИРОБІ

Резюме

Запропоновано метод визначення енергії активації напівпровідника в готовому виробі. Показано, що ширину забороненої зони можливо розрахувати по відсічкам на обох осях графіків *ln(I)÷U*, виміряних при різних температурах. Визначений мінімальний температурний інтервал в залежності від точності вимірювань. Вказано новий засіб визначення E_g без екстраполяції ВАХ.

Ключові слова: ширина забороненої зони, енергія активації, напівпровідник.

УДК 621.315.592

.

А. Ю.Бак, Ю. М. Каракис, О. Е. Ступак, М. И. Куталова, А. П. Чебаненко

ОПРЕДЕЛЕНИЕ ШИРИНЫ ЗАПРЕЩЁННОЙ ЗОНЫ ПОЛУПРОВОДНИКОВОГО МАТЕРИАЛА В ГОТОВОМ ИЗДЕЛИИ

Резюме

Предложен метод определения энергии активации полупроводника в готовом изделии. Показано, что ширину запрещённой зоны можно рассчитать по отсечкам на обеих осях графиков *ln(I)÷U*, измеренных при разных температурах. Определён минимальный температурный интервал в зависимости от точности измерений. Указан новый способ определения величины E_g без экстраполяции ВАХ.

Ключевые слова: ширина запрещенной зоны, энергия активации, полупроводник.