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Note: Determination of temperature dependence of GaP bandgap energy from diode temperature response characteristics

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A simple method of $E_g(T)$ dependence determination for active areas of semiconductor devices based on wide bandgap semiconductors has been proposed and developed. Verification of the method has been carried out while determining $E_g(T)$ dependence in a base area of p$^+$-n-type GaP diodes in the temperature range 77–523 K. The method is based on *U-T* characterization of the diodes and calculation of $E_g(T)$ dependence according to the expression obtained within present study. Satisfactory agreement between experimental and theoretical results has been achieved including references available on gallium phosphide. The method proposed could be applied to experimental data processing in high-temperature thermometry. © *2011 American Institute of Physics*. [doi:10.1063/1.3626902]

Temperature dependence of bandgap energy (E_g) of semiconductors significantly affects temperature behavior of semiconductor device key parameters. The urgency of $E_g(T)$ dependence estimations is especially obvious due to multiple applications of semiconductor devices in high-temperature electronics. In physical researches to determine $E_g(T)$ dependence of bulk semiconductors or discrete layers of semiconductor structures, a semiconductor spectral absorption characterization as well as measurement of near-band-edge luminescence spectra are widely used. Disadvantages of the optical methods are limited applicability, complexity of usage, difficulty of $E_g(T)$ dependence estimation for indirect bandgap semiconductors as well as fundamental non-applicability of the methods for the majority of sealed semiconductor devices. For theoretical analysis of temperature dependencies $E_g(T)$, a well known Varshni formula[1] is used. However, the formula demands fitting two empirical constants at once, therefore it is rather suitable for approximation of experimental $E_g(T)$ data than for prediction of $E_g(T)$ dependence behavior of a certain semiconductor device in wide temperature range. In this paper, the method based on measurement and subsequent processing of GaP diode temperature response characteristics (*U* vs. *T*) is proposed to determine $E_g(T)$ dependence in the diode base area.

In a space-charge region of a p-n-junction based on wide bandgap semiconductor, recombination currents exceed diffusion currents considerably at low carrier injection level. Current-voltage (*I-U*) characteristic of asymmetric p$^+$-n (or n$^+$-p) junction (diode) depends on absolute temperature and is described by the following expression:

$$I = I_0 \exp \frac{qU}{nkT}, \quad I \gg I_0, \tag{1}$$

where I is a forward current of the p-n-junction; I_0 is a reverse current of the junction; q is the electron charge; U is a voltage applied to the p-n-junction; k is the Boltzmann constant; n is an ideality factor of the junction *I-U* characteristic that generally depends on the junction current and temperature; n possesses the values from 1 to 2 (for diffusion currents $n = 1$, for recombination currents $n = 2$); T is the absolute temperature.

Expression (1) is correct in condition that the voltage drop across the diode is approximately equal to the junction voltage drop, i.e., the voltage drop across n(n$^+$) and p(p$^+$) regions as well as across other elements of the diode structure is negligible in the temperature and current ranges investigated. Such an approximation is valid for diodes based on abrupt asymmetric junctions in GaP.[2]

In condition of generation-recombination current domination the reverse current of the p-n-junction is expressed by following formula:[3]

$$I_0 = K T^{5/2} \exp\left(-\frac{E_g}{nkT}\right), \tag{2}$$

where K is the constant depending on the material parameters and the junction geometry; E_g is the value of energy bandgap of the semiconductor material in the diode base area.

It should be noted that the value of ideality factor n of the diode depends on peculiarities of charge carrier generation and recombination processes within the junction space-charge region. The value of n and its temperature and current dependence behavior are determined by the diode fabrication conditions. It is one of the most important parameters characterizing the level of the technology reproducibility and being taken into account during development of quite a number of semiconductor devices operating in wide temperature range.

Inserting expression (2) in Eq. (1) and expressing it in terms of the diode forward voltage, one could obtain:

$$U = \frac{E_g}{q} - \frac{nkT}{q}\left[2.5 \ln T - \ln\left(\frac{I}{K}\right)\right]. \tag{3}$$

The expression in square brackets of formula (3) weakly changes with temperature change as it contains T in the logarithmic function. Therefore, dependence of the diode forward voltage from the diode forward current as well as from the temperature could be expressed by following quasi-linear

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dependence:

$$U = U_0 - m(I)T. \tag{4}$$

Here we assume that the value of n weakly depends on the temperature as well within the temperature and current ranges considered.

The relations similar to Eq. (4), i.e., $U(T, I)$ measured at different fixed values of the forward current I are referred to as diode temperature response characteristics. The slope of the U-T characteristic $m(I)$ depends on the current magnitude I. Such characteristics underlie diode thermometry technique.[4] Here the maximum length of the temperature response curve or, in other words, high-temperature limit of the characteristic is a function of $E_g(T)$.[5] So having measured the $U(T, I)$ [Eq. (4)] characteristic and having calculated the $n(T, I)$ dependence, one can plot $E_g(T)$ dependence for low-doped base area of wide bandgap diode in the temperature range selected.

The technique of gallium phosphide structures obtaining by liquid phase epitaxy as well as technological operations of sample diodes manufacturing were described in detail in works (Refs. 2 and 6). Figure 3 in Ref. 6 shows in semi-logarithmic scale a set of I-U curves of GaP diodes investigated in the temperature range of 77–463 K. Additionally, within the framework of this paper, we also measured I-U dependencies of the diodes in the temperature range 463–523 K.

The set of U-T curves (in the form of $U(T, I_i)$) of the diode have been plotted using constant current cross sections of the set of I-U curves, i.e., the cross sections at fixed values of $I_i = const$. Corresponding graphs are shown in Fig. 1. The U-T curves obtained are almost linear (quasi-linear). A certain loss of linearity is seen with I_i increase in the liquid nitrogen temperature range. Nevertheless in this range of temperatures and the diode forward currents, the deviation from linearity of the $U(T,I_i)$ dependencies is smooth which allows to consider them to be a part of the approximated U-T lines.

The $n(T, I)$ dependence was calculated for segments of the I-U curves (see Fig. 3 in Ref. 6) confined by constant current sections $I = 10^{-9}$ A and $I = 10^{-6}$ A. The segments represent straight lines in semi-logarithmic scale $\log I = f(U)$. It should be noted that within these segments, the value of n does not actually depend on the diode current. It has allowed us to pass from $n(T, I)$ dependence to $n(T)$ function. The graph of this function is shown in Fig. 2.

To obtain $E_g(T)$ dependence, we have transformed the expression (3) as follows:

$$E_g(T) = 2.3n(T)kT(2.5\log T - \log I + \log K) + qU(T, I). \tag{5}$$

To determine the constant K (or $\log K$) by formula (5), we have used a reference point of E_g which is chosen to be the value of energy bandgap of low-doped base of p$^+$-n GaP diode at 300 K. For the given base area doping level of the GaP diodes investigated ($n^- \leq 5 \times 10^{15}$ cm^{-3} (Ref. 6)) the value of $E_g(n^-)$ determined according to empirical dependence[8] makes 2.25 ± 0.005 eV at 300 K. The averaged value of $\log K$ calculated for the diode forward current range considered makes about -5.928.

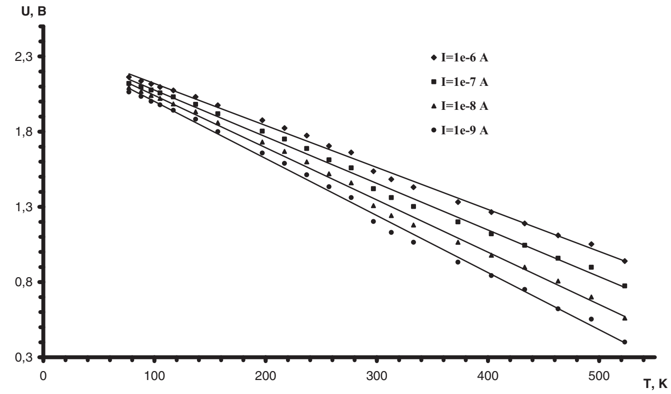

FIG. 1. $U(T, I)$ characteristics of the GaP diodes. Experimental data are shown as separate points and solid lines correspond to the results of approximation of $U(T, I)$ experimental data by the least-squares fit (Ref. 7).

Using dependence (5) and experimental values of $U(T, I)$ (Fig. 1), $n(T)$ (Fig. 2), the $E_g(T)$ dependence is determined for the temperatures at which the diode I-U data have been obtained. The graph of the $E_g(T)$ dependence is shown in Fig. 3.

As it has been previously mentioned, to approximate experimental data of the $E_g(T)$ dependence shown in Fig. 3, Varshni formula[1] is generally used in the following form:

$$E_g(T) = E_g(0) - \alpha\frac{T^2}{T + T_0}, \tag{6}$$

where $E_g(0)$ is a semiconductor material energy gap at 0 K; α and T_0 are empirical constants.

By varying the parameters of dependence (6), we have obtained the following values of the constants $E_g(0)$, α, and T_0 that ensure the best fit of the experimental data: $E_g(0) = 2.325$ eV, $\alpha = 5.1 \times 10^{-4}$ eV/K, $T_0 \approx 470$ K. The approximation curve in the form of Eq. (6) is shown in Fig. 3 as solid line.

For comparison, the parameters of Varshni formula in the form of Eq. (6) for GaP samples given in Ref. 9: $E_g(0) = 2.34$ eV, $\alpha = 6.2 \times 10^{-4}$ eV/K, T_0

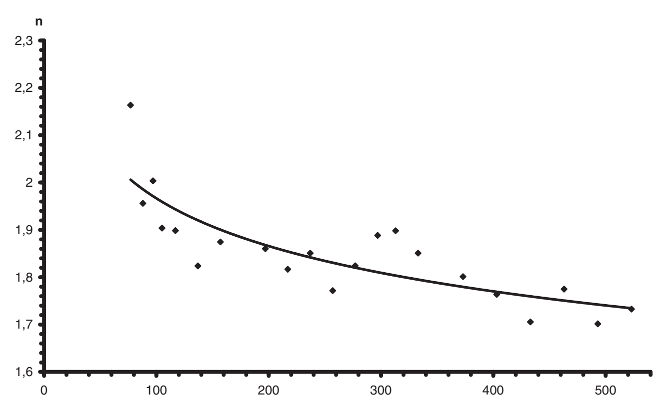

FIG. 2. $n(T)$ dependence of the GaP diodes: separate points represent averaged values of n obtained by the I-U characteristics processing; the solid curve is the power-law fitting (Ref. 7) of the form $y = ax^b$, where $a = 2.79$ and $b = -0.076$.

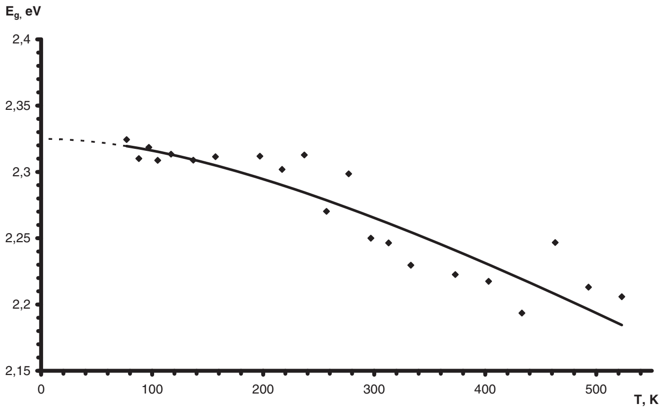

FIG. 3. $E_g(T)$ dependence of p$^+$-n GaP diode: the values of $E_g(T)$ calculated using Eq. (5) are shown as separate points; the solid curve is the approximation by dependence: $E_g(T) = 2.325 - 5.1 \times 10^{-4}(T^2/(T + 470))$.

≈ 460 K; given in Ref. 10: $E_g(0) = 2.34$ eV, $\alpha = 6.0 \times 10^{-4}$ eV/K, $T_0 \approx 460$ K. The difference observed between parameters obtained in the present study and those mentioned in the literature, particularly $E_g(0)$ value, could be explained both by a higher level of permanent mechanical stress in epitaxial layers as compared to bulk single crystals[11] as well as by a higher doping level of epitaxial layers[8] in our case. It would be interesting to note that E_g value given in Ref. 12 for GaP at the temperature of 545 K makes ~2.15 eV and the E_g value for GaP determined by our analytic $E_g(T)$ dependence at T = 523 K makes ~2.185 eV (Fig. 3). These values are close enough.

As it follows from the analysis of Fig. 3, the analytic dependence $E_g(T)$ in the temperature range of ~220–523 K could be approximated to a high accuracy by the following linear dependence:

$$E_g(T) = E_{g0} - \alpha' T, \tag{7}$$

where E_{g0} is the extrapolated GaP energy bandgap at 0 K, E_{g0} = 2.376 eV, $\alpha' = |\frac{dE_g}{dT}| \approx const. \approx 3.65 \times 10^{-4}$ eV/K.

The α' value of GaP devices given in Ref. 13 makes $\sim 3.57 \times 10^{-4}$ eV/K in a narrow temperature range and the α' value estimated according to Ref. 14 in the temperature range of 300–533 K makes $\sim 5.19 \times 10^{-4}$ eV/K. It should be noted that both α' values are in good agreement with our results.

Thus in this work the method based on measurement and processing of temperature response curves of the wide bandgap diodes has been described. The fundamental aspect of the method consists in a possibility to obtain more accurate $E_g(T)$ dependencies in wide temperature range for specific areas of semiconductor devices exposed to different factors and influence of manufacturing technology. Practical aspect of the method is particularly connected to its application in high-temperature diode thermometry. Such investigations are urgent for multiple applications in high-temperature electronics as well.

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