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적외선 영상기법에 의한 화합물 반도체 에너지갭의 온도계수 측정 방법

(A Method for Evaluating the Temperature Coefficient of a Compound Semiconductor Energy Gap by Infrared Imaging Technique)

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요 약

온도에 따른 반도체 에너지갭의 변화를 디지털 영상처리를 이용해 직접 측정하는 적외선 영상기법을 제안하고 있다. 본 방법은 반도체 에너지갭의 온도계수를 경제적이고 간단하게 평가할 수 있도록 한다. 본 기법의 핵심 구성 부품은 다색광원기(Polychromator), 프레임 그래버가 내장된 컴퓨터 및 가변 온도 저온유지장치(Cryostat)이다. 방법의 타당성을 검증하기 위해 LEC 방법으로 제조한 GaAs에 시험적으로 행한 실험은 온도 계수가 이론 모델에서 구한 값과 전반적으로 잘 일치함을 보여 주었다.

Abstract

An infrared imaging method in which direct measurement of energy gap variations can be achieved by digital image processing is proposed. This method allows economic and easy evaluation of the temperature coefficients of a semiconductor energy gap. The key components of the method are a polychromator, a computer equipped with a frame grabber and a variable temperature cryostat. Tentative experimentation conducted on LEC grown semi-insulating GaAs has resulted in a fairly good agreement with the theoretical model. This proposed method could be applicable for most compound semiconductors.

I. Introduction

There is now sufficient information in the literature to document the energy gap of GaAs point. At room temperature and under normal atmosphere, the value of the bandgap is about 1.43 for GaAs. This value is for high-purity material. For compound semiconductors from 0 K to the melting highly doped materials the bandgap becomes smaller. Experimental results show that the bandgap of most III-V semiconductors decreases with increasing temperature. The bandgap approaches 1.52 eV for the GaAs at 0 K. It is well known that the temperature dependance of GaAs bandgap can be expressed approximately by the formula known as the Thurmond equation[1] :

$$E_g(T) = 1.52 - \frac{5.4\times10^{-4}T^2}{T+204}\ \text{eV} \tag{1}$$

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The temperature coefficient dEg/dT is negative for GaAs, and it is similar to that for Si and Ge, being linear over a large range of temperatures, but it tends to be a constant value near 0 K. It should be noted that the values of band gap for II-VI compounds decrease as the temperature is lowered, in contrast to the behavior of Si and Ge and the III-V compound.

Equation(1) is based upon two assumptions that the energy gap should be proportional to T at high temperatures and to T^2 at low temperatures. Thurmond reported that the GaAs energy gap measurements at room temperature and above are satisfactorily represented by the equation. Although the equation is formulated by experimental data, there is some uncertainty about the value of the constants 5.4 and 204. Therefore, it is necessary to experiment further to find the exact temperature dependance behaviors of GaAs band gap in piecewise temperature ranges. The method of evaluating the equation used here leads to a direct imaged result for temperatures in the range from room temperature to 0 K.

The infrared transmission imaging technique(IRT) has been used to identify defects in semiconductors in two dimensional images[2,3]. IRT is especially known as a technique well adapted to the measurements of the energy gap of compound semiconductors[4]. IRT is not at all destructive, and it is simple to implement. This paper examines the applicability of the IRT technique slightly modified in evaluating the temperature dependance of the energy gap in GaAs semiconductors.

II. The theory of the method

The energy bands of solids have been studied theoretically using a variety of numerical methods. For semiconductors, the three methods most frequently used are the orthogonalized plane-wave method[5], the pseudopotential method[6], and the k·p method[7]. The simplified band picture is shown in Figure 1.

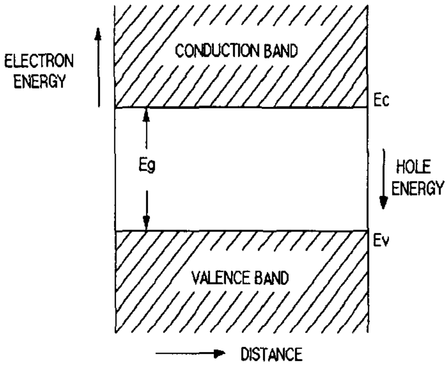


그림 1. 반도체의 에너지밴드 다이어그램
Fig. 1. Simplified band diagram of a semiconductor.

At room temperature and under normal atmosphere, the values of the bandgap are 0.66 eV for Ge, 1.12 eV for Si, and 1.42 eV for GaAs. These values are for high-purity materials. For highly doped materials the bandgaps become smaller. Experimental results show that the bandgaps of most semiconductors decrease with increasing temperature. For GaAs, the variation of bandgaps with temperature can be expressed approximately by a function given in equation(1). The temperature coefficient dEg/dT is negative for the most important three semiconductors(Si, Ge, GaAs) and the temperature coefficient for the GaAs is given as follows :

$$\frac{dE_g}{dT} = -\frac{5.4\times10^{-4}T(T+408)}{(T+204)^2} \qquad (2)$$

The absorption coefficient α in a fundamental absorption edge (band to band transition) can be expressed in the following equation corresponding to direct transition(The major absorption mechanism in GaAs);

$$\begin{aligned} \alpha &= A(h\nu - E_g)^{1/2} \; ; \; h\nu > E_g \\ &= 0 \qquad h\nu \leq E_g \end{aligned} \qquad (3)$$

where $h\nu$: photon energy , E_g : energy gap.

The value α is zero for photon energy below the energy gap. Therefore, the transmission spectrum of a semiconductor material with no impurity can be depicted as in Figure 2, and the energy gap E_g can be determined from the spectrum at any given temperature. That is, the starting point of the transmission in Figure 2 indicates the energy gap Eg. This method can be applied to most types of compound semiconductors because they all generally have the direct energy gap characteristic.

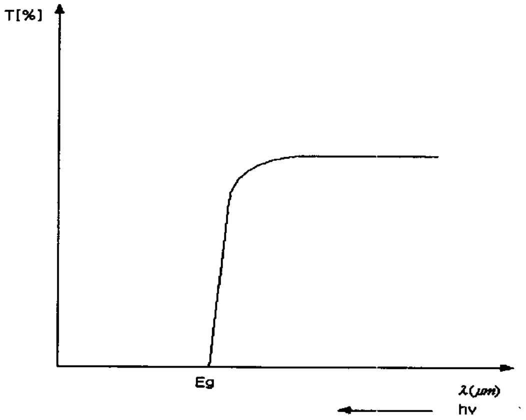


그림 2. 직접 에너지갭에 대한 광 투과 스펙트럼
Fig. 2. Characteristic diagram of a transmission spectrum of a direct energy gap.

The goal underlying the alternative method presented in this paper is to achieve a direct measurement of the energy gap variations using the infrared imaging technique. Accordingly, the present method provides both a technique and an apparatus for measuring the energy gap variations of a semiconductor, whereby a given band of light is irradiated onto a semiconductor sample under different temperature conditions. This produces images which are displayed on a monitor and applied to a digital image processing algorithm to derive the energy gap values at different temperatures. This method is based on our patents[4,8] and includes the following principal aspects:

- presetting an energy gap pixel value that is a gray level, corresponding to the energy in spectral image, at a given temperature, using a reference semiconductor sample;
- inducing a functional relationship between the X-coordinate values of pixels in the spectral image and the corresponding wavelengths of the pixels;
- storing the live image and scanning the pixel values along an X-axis of the image;
- comparing, in sequence, first the image's pixel values and the energy gap pixel value, then reading the X-coordinate of the pixel at which the values coincide, and finally converting the wavelength of this pixel into a unit of eV to find the energy gap E_g.

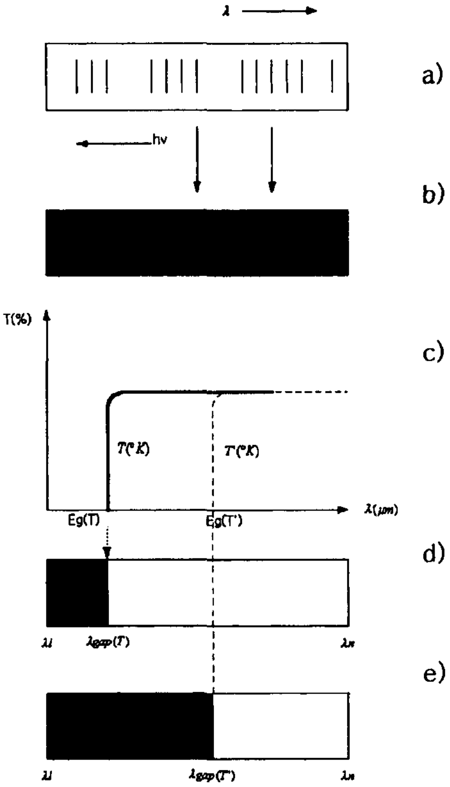
The key apparatuses to be used for measuring the energy gap of a semiconductor are :

- a computer for executing all operations and control functions associated with the measurement of the energy gap;
- a polychromator for irradiating a specific spectrum band of the light beam to the sample.
- optical filters for scaling the polychromator's spectrum band into corresponding wavelength values;
- an image signal processor for manipulating digital images;
- a variable temperature cryostat for making measurements over the range 4-300 K.
- an energy gap detecting and displaying algorithm for defining the functional relationship between the coordinate value and wavelength of the pixel.

With the present method, a specified band of light is irradiated onto the semiconductor sample, which is cooling down. The responses are recorded by the digital image processing system, which permits direct measuring of the energy gap.

Ⅲ. Detailed Description of the Method

Figure 3 illustrates the energy gap measuring principle used in the present method. A light source, such as, infrared rays having a wavelength band of 0.8~0.9 ㎛ around the energy gap, is irradiated onto a semiconductor sample[Fig. 3(a),(b)]. Figure 3(c) shows the transmission spectrum of a semiconductor at different temperatures. The resulting spectral characteristic of the light band transmitted through the sample can be depicted as in Figure 3(d),(e). By sliding the transmission spectrum of the Figure 3(c) while continuously varying the temperature, we can obtain many images like Figure 3(d). By applying a digital image processing algorithm to those images, we finally get a direct reading of the value of the energy gap. In reality, the absorption coefficient α increases as photon energy increases, so the real image will appear like the one in Figure 4. That is, as more light is absorbed, the color of the image deepens. The λ_l side of the image exhibits a darker color.



(a) 0.8-0.9μm band infared rays
(b) sample
(c) Transmission spectrum of a sample at different temperature(T : lower temperature, T' : Higher temperature)
(d),(e) Resultant images at different transmission spectra.

그림 3. 본 방법에 적용한 원리에 대한 도식적 설명

Fig. 3. Diagramatic construction of the principle employed in the present method.

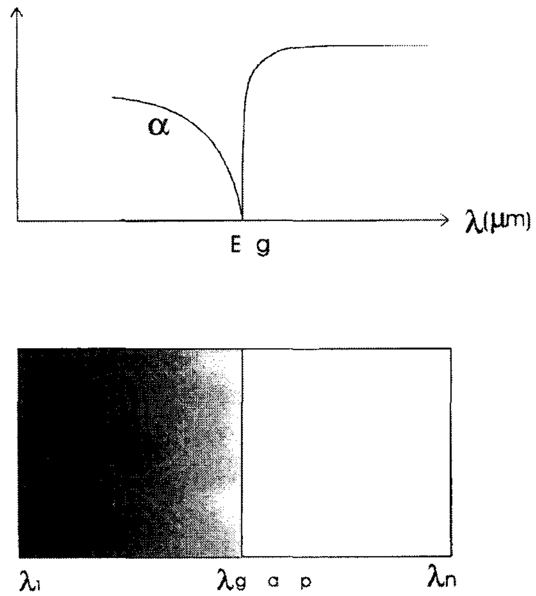


그림 4. (a) 시편의 흡수/투과 스펙트럼
(b) 흡수 계수의 크기에 따라 생성된 영상

Fig. 4. (a) Absorption/transmission spectrum of a sample
(b) Resultant image according to the absorption coefficients

Figure 5 is a schematic diagram of an energy gap variation measuring system that uses the present method. The illumination is provided by a halogen light source(12V/50W) through a polychromator (constructed by removing the output slit of a general-purpose monochromator). The semiconductor sample, both surfaces of which have been mirror-polished by mechano-chemical polishing, is illuminated with a light having a spectral band of 0.8~0.9 ㎛. The sample is held in a cryostat[Oxford Instrument CF204]. The spectral scaling is achieved with optical filter which allow only light of its own specific wavelength λ_p to pass through. The spectral images at a given temperature are observed with an image reading unit, such as a silicon vidicon [Sofretec] or a charge coupled device[SFA-410ED]. These images are then processed with a digital image processor, such as an image processing board [PCVISION Frame Grabber, Imaging Technology]. The energy gap detecting and displaying unit defines the functional relationship between the X-coordinate of the image and the wavelength λ of the light beam. A personal computer is used for executing operation and control functions associated with measuring the energy gap. Both the image processing unit and the energy gap detecting and displaying unit may be built into the computer.

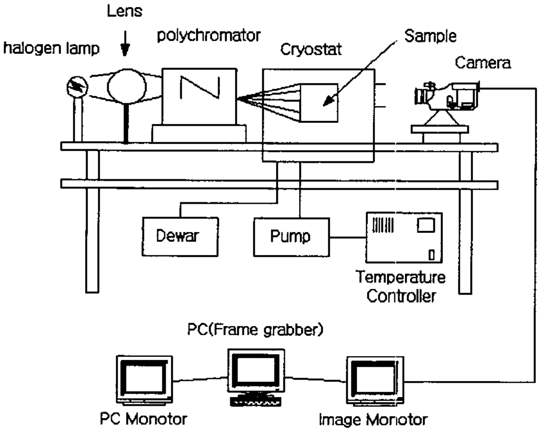


그림 5. 본 방법에서 이용한 실험장치

Fig. 5. Schematic diagram of equipment used in the present method.

The method used for determining an X-coordinate value λ of the image is as follows. First, a light beam having a wavelength band of λ around the energy gap E_g is used to irradiate the sample. The spectrum of the light beam transmitted through the sample is then imaged in order to determine the actual wavelength value of the beam band. More specifically, the relationship between the wavelength λ and the coordinate value X (i.e. $\lambda = f(x)$) should be derived from the image on the display monitor connected to the image processing unit. The value λ can be determined by obtaining the pixel coordinates X_{p1}, X_{p2}, ..., X_{pn} with several optical filters each having specified wavelengths of λ_{p1}, λ_{p2}, ..., λ_{pn} positioned after the sample, as in Figure 5. The optical filters allow only the light rays having a specific wavelength of λ_p to pass through, and only their spectrum images will be displayed on the monitor. The X-coordinates of the images displayed on the monitor indicate the wavelength λ_p. Referring to Figure 3, the sample is irradiated with an infrared ray of a continuous band (preferably with wavelengths of 0.7~1.5 ㎛) of the spectrum. Optical filters are employed to select specific wavelength values of the spectrum. Accordingly, as the optical filters are positioned between the sample and the image reading unit, an image of the wavelength of the light corresponding to any given color is displayed in a specific location on the monitor: The X-coordinate value of the image displayed on the monitor corresponds to the wavelength of any given color. Therefore, the optical; filters are used for inducing the relation $\lambda = f(x)$.

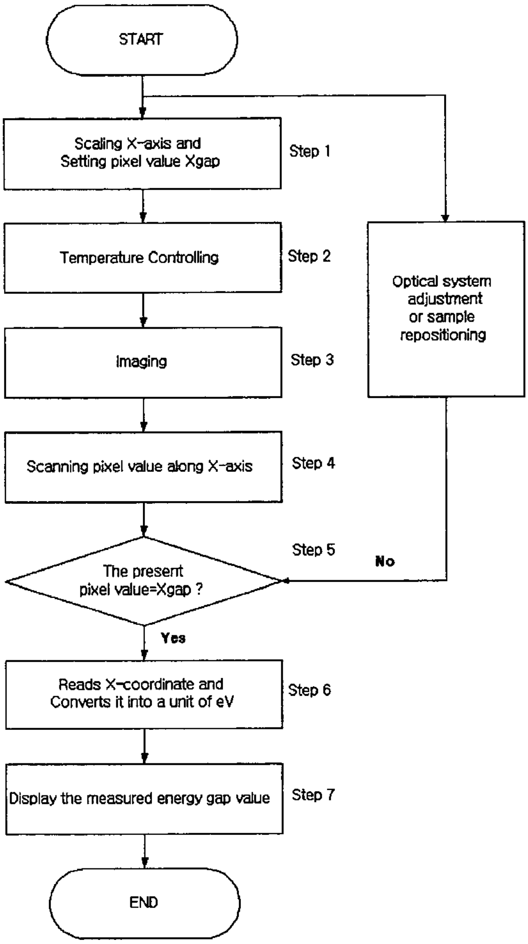


그림 6. 에너지갭 측정 단계별 흐름도

Fig. 6. Flowchart illustrating the step by step procedure of measuring the energy gap according to the present method.

Figure 6 shows a flowchart illustrating the energy gap measuring process. In step 1 an energy gap pixel value X_{gap} is previously set in the energy gap measuring program. A semiconductor generally contains impurities, which result in an impurity level in the energy gap band, in that an impurity absorption takes place by photon energy below the energy gap Eg before fundamental absorption begins. For this reason, in step 1, the gray level value X_{gap} corresponding to the energy gap Eg is preset using a reference sample. This reference sample is one which has already been analyzed in terms of both its impurity-induced absorption and the gray level of its background image according to the strength of the lighting source used in the optical system.

In step 2, the ambient temperature is controlled by using a cryostat. Initially, the sample is at room temperature, and then it cools down to 4 K. Next, in step 3, the functional relation of λ=f(x) in the optical system set up for step 1 is determined by optical filters. The sample to be measured is positioned, and then an imaging is carried out by means of the digital image processor. A live image obtained by the image capture unit is stored in a frame memory of the image processor. Then, in step 4, the pixel values of the image on the monitor are scanned from left to right (or vice versa) on the monitor. In step 5, the pixel value X is then compared with the energy gap pixel value X_{gap}. If the values coincide, then the X-coordinate of the corresponding pixel is read to determine the value λ gap by means of the algorithm λ= f(x). However, if the values do not coincide, then either the optical system is adjusted, or the sample is repositioned to obtain an analyzable image. Next, in step 6, the value 'λ_{gap}' is converted into units of electron volts 'eV' by the equation gap(eV)=1.239/λ_{gap}(㎛). Finally the eV value of the energy gap Eg at a given temperature is displayed on the monitor, and the energy gap measuring procedure is repeated for different sample temperatures.

Ⅳ. Experimental Design

The experimental equipment is set as follows. Illumination is provided by a halogen lamp. In order to obtain a spectral quasilinear distribution band covering the 0.8~0.9 ㎛ domain, a monochromator whose output slit has been removed is placed at the back of the halogen lamp. Polychromatic light passes through the sample, and the vidicon camera, positioned after the sample, captures the resulting images. These images are displayed on the image monitor and stored on a digital image storage system. In order to validate the method and derive the temperature coefficient of the band gap, this experiment was performed on LEC grown semi-insulating GaAs. The resulting spectral image at room temperature is shown in Figure 7. This image is exactly the same as that described in the theory(Fig. 3a). After changing the sample temperature, the imaging process above is repeated. Figure 8 shows representative images at the temperatures of 10 K, 100 K, 150 K respectively. Observed infrared inhomogeneities have been attributed to fluctuations in the concentration of deep defects such as EL2[9].

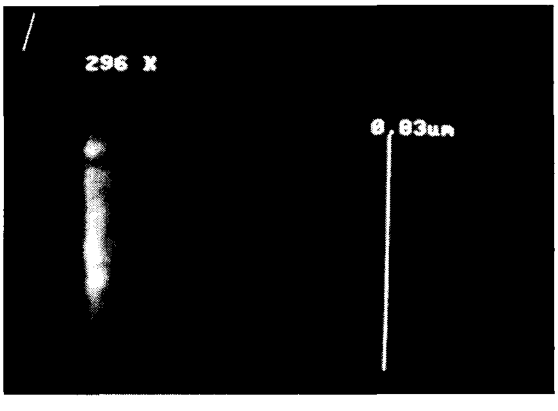
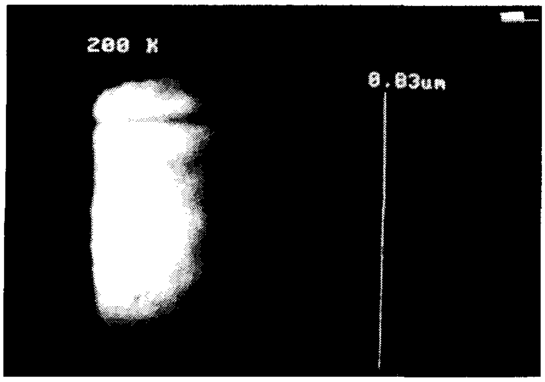
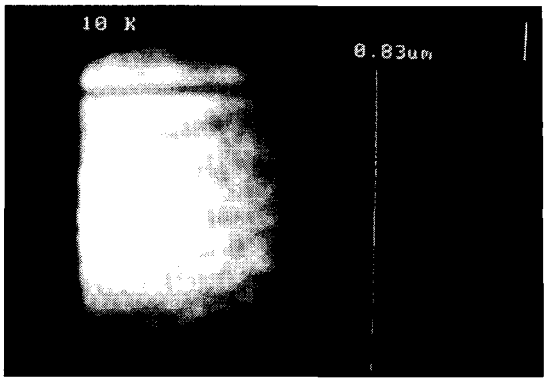


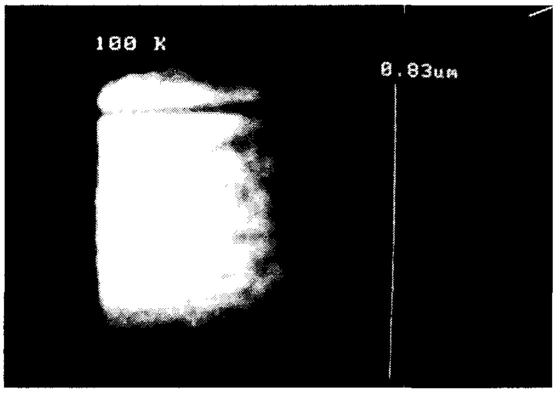
그림 7. 296 K에서의 GaAs에 대한 스펙트럴 영상
Fig. 7. Spectral images of a thick slab of GaAs at 296K.



(a)



(c)



(b)

그림 8. 시편 온도 하강에 따른 스펙트럴 영상
(a) 200 K (b) 100 K (c) 10 K

Fig. 8. Spectral images of decreasing sample temperatures
(a) at 200K (b) at 100K (c) at 10K

Figure 9 presents the actual energy gap values in function of temperatures from this experiment, and also the curve proposed by Thurmond is compared. From this figure, the Thurmond's curve is well fitted with the experimental one, except at the temperature range 60 K - 160 K. Particularly noticeable differences arose between 90 K and 130 K. Interestingly, this temperature range coincided with the specific EL2 thermal relaxation temperature[10]. Figure 9 also shows that the energy gap is

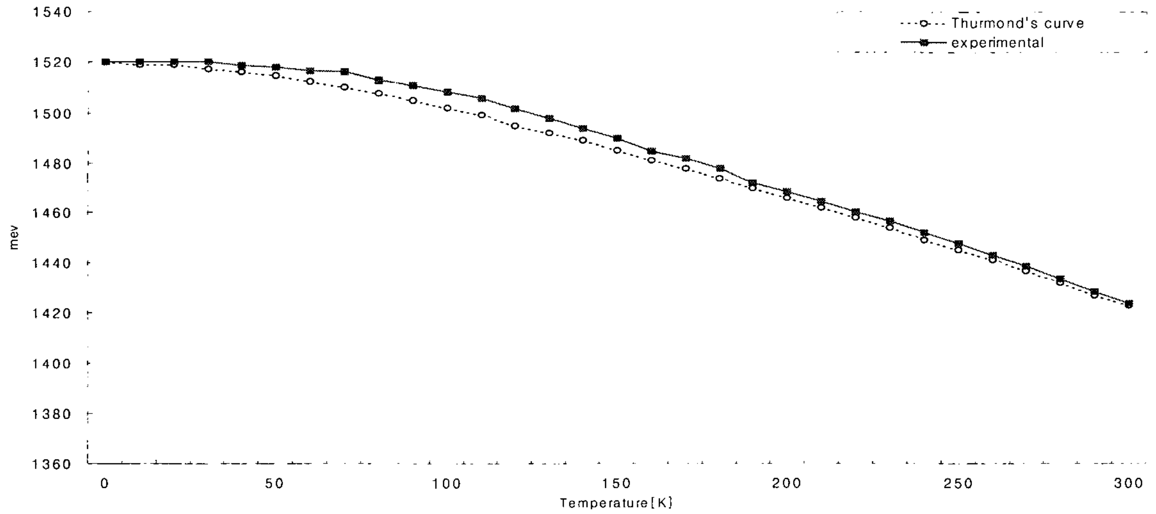


그림 9. 온도에 따른 에너지 갭

Fig. 9. Energy gap as a function of temperature

표 1. GaAs 에너지갭 온도계수에 대한 본 실험결과와 기존 데이터의 비교.
Table 1. Comparison of GaAs energy gap temperature coefficients between Thurmond's result and our result.

T[K]	10	30	50	70	90	110	130	150	170	190	210	230	250	270	290
Thurmond [meV/K]	0.05	0.13	0.19	0.24	0.28	0.31	0.34	0.36	0.38	0.40	0.41	0.42	0.43	0.44	0.45
Experimental result	0	0.08	0.1	0.19	0.22	0.33	0.40	0.46	0.34	0.55	0.45	0.35	0.45	0.50	0.50

(Temperature coefficients are all negative values)

proportional to T^2 until about 120 K and T above 120 K.

The temperature coefficients of GaAs energy gap is obtained from Figure 9, and these experimentally obtained values are compared with the values derived from equation (2) in Table 1. This table shows a relatively good agreement between the data excepting certain temperatures.

V. Conclusion

This method shows the possibility of successfully measuring the temperature coefficients of a semiconductor energy gap. The experiment tentatively performed for the LEC grown semi-insulating GaAs demonstrates that experimental and theoretical data agree to a great extent. Even though there are some differences in certain temperature ranges, it is not certain at the moment that these differences are caused from an oversimplified theoretical model or the sample-specific properties. Also, this experiment clarifies the temperature bound between the region which is proportional to T and the region which is proportional to T^2. This is an interesting finding in the sense that the theoretical model was based upon ambiguous assumptions of energy gap temperature dependance on T^2 at low temperatures and T at high temperatures.

It is expected that the proposed method could be applicable for most compound semiconductors in evaluating the temperature coefficients of energy gap easily and economically.

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REFERENCES

[1] C.D. Thurmond, "The standard thermodynamic functions for the formation of electrons and holes in Ge, Si, GaAs, and GaP", J. Electrochem. Soc., Vol. 122. No. 8, pp. 1133~1141, 1975.

[2] J.P. Fillard, "Infrared imaging and EL2", Revue Phys. Appl. Vol. 23, pp. 756~777 May, 1988.

[3] S.J. Kang, "Contribution to the study of EL2 centre in semi-insulating GaAs by photoquenching of infrared transmission images" Thèse de Doctorat(Ph.D. dissertation), U.S.T.L., Montpellier, France, Mar. 1990.

[4] S.J. Kang, B.W. Kim, Y.S. Bae, "Method of and apparatus for measuring energy gap of semiconductor", United States Patent, Patent No. 5,406,505, Apr. 11, 1995.

[5] L.C. Allen, "Interpolation scheme for energy bands in solids", Phys. Rev. 98, pp. 993~1005, 1955.

[6] J.C. Phillips, "Energy band interpolation scheme based on a pseudopotential". Phys. Rev., 112, pp. 685~697, 1958.

[7] R.A. Smith, "Semiconductors", 2nd ed., Cambridge University Press, London, 1979.

[8] S.J. Kang, "Method of and apparatus for evaluating the temperature coefficient of a semiconductor energy gap" Korean Patent, Patent No. 0219761, June 16, 1999.

[9] M.S. Skolnick, M.R. Brozel, "Distinction between near infrared optical absorption and light scattering in semi-insulating GaAs", Appl. Phys. Lett., Vol. 48, No. 5, pp. 341~343 Feb., 1986.

[10] J.P. Fillard, P. Montgomery, P. Gall, J. Bonnafé, "The role of EL2 centres in infrared images of defects in GaAs materials", Jpn. J. Appl. Phys., Vol 27, No. 3, pp. 384-388 Mar. 1988.

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