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MAGNETO-OPTICAL PROPERTIES OF THE ALLOY SYSTEM $In_{1-x}Ga_xP$

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The room-temperature dependence on composition of the energy gap is measured for the ternary alloy system $In_{1-x}Ga_xP$ semiconductors. The cross-over point from the direct to indirect optical transition energy gap is found at $x = 0.718$. An empirical relation for the alloy system energy-gap dependence is found for both direct and indirect transition regions. From the empirical relations belonging to the direct region transition, the values of the expected indirect energy transition at Γ_{c1} are calculated. The difference between these values and the corresponding indirect energy ($\Gamma_{c1} - X_{c1}$) are also calculated. The change of E_g due to the effects of magnetic field up to 1.6 T (Tesla) was also measured. The magnetic coefficient is found to be between 3.33×10^{-7} and 3.87×10^{-7} eV/T for $x = 0.31$ to $x = 1$. A clear deviation of the magnetic coefficient occurred for the change from the direct-region to that of the indirect-region transition.

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1. Introduction

Magneto-optical properties of semiconductors have been investigated since 1950's. In 1956, Burestein and Picus [1] investigated these effects on thin samples of InSb. In 1957, Zwedling et al. [2] investigated infrared magneto-absorption in thin samples of germanium, indium arsenide and indium antimonite in a magnetic field up to 3.7 Tesla (37 kilogauss). They found a considerable absorption below the energy gap, and they suggested that the large absorption was due to the transitions involving both photons and optical phonons. In 1958, Roth et al. [3]

developed a theory of the effect of a magnetic field on the optical absorption in semiconductors on the basis of the effective-mass approximation.

In 1976, Sari [4] investigated magneto-optical and Raman-scattering at the E_1 edge of InSb. He observed in good details the Landau-level structure in this compound as well as in the related semiconductors GaSb, Ge and HgTe.

In 1988, Lamari and Sham [5] reported a theoretical investigation of the magneto-optical properties of a narrow-gap semiconductor quantum well and emphasized the important differences brought about by the strong confinement.

In 2005, Abbas [6] investigated magneto-optical absorption on n-type single-crystal GaP by using the methods of both optical transitions and photoconductivity. The reduced effective mass was calculated and compared to that of the calculated values from the electrical and thermal measurements of the sample.

In the recent decades, $In_{1-x}Ga_xP$ alloy has attracted a great deal of interest for optoelectronic devices such as light emitting diodes, lasers and solar cells [7, 8]. Due to the lack of information on the magneto-optical properties for this alloy as a complete system, an attempt is made in this work to measure and investigate energy band diagram and the effects of magnetic field on the energy gap of six single-crystal samples of the alloy system $In_{1-x}Ga_xP$.

2. *Experimental technique*

Six samples of the ternary alloy system $In_{1-x}Ga_xP$ with a thickness of about 0.4 to 0.7 mm were used in the experiment. The samples were cut from a cylindrical wafer of a 2.5 cm diameter and 0.8 mm thick. These wafers were single crystals prepared by the method of solid-solid diffusion (the details of the preparation are given in Ref. [9]).

Optical measurements were carried out by using a spectrophotometer type CE 595. To make the system suitable for the magneto-optical experiments, the monocromator was separated from the detector. The output beam from the monocromator was focused on the polished samples and the transmitted beam from the sample to the optical detector through a 5 mm diameter copper tube. Such focusing system was found to transfer more than 90% of the input light intensity to the sample and from it to the detector. Further, the geometrical distribution, size and shape of the monochromator, cryostat, magnetic field and the detector do not affect the measurement. The optical detector unit produces a signal output of an amplitude proportional to the intensity of the incident light. By using the multimeter type (Agilent 34410A), this signal was transferred to a personal computer and read as a function of the wavelength.

Samples were mounted in a temperature-controlled cryostat (the details are given in Ref. [10]). The sample chamber was fixed between the two poles of a home-made d-c electromagnet which is capable to produce a magnetic field up to 1.8 Tesla [11]. The sample temperature was measured by using a cooper-constantan thermocouple. The sample thickness was measured by the optical interference technique by an air-wedge method. Details for these systems are given in Ref. [11].

3. Results and analysis

The absorption coefficient α, which is related to the transmittance T and the reflectance R of a sample of thickness d, was calculated using the relation [12].

$$\alpha = -\frac{1}{d}\ln\left[\frac{T}{(1-R)^2}\right] \tag{1}$$

where R is given by

$$R = \frac{(1-n)^2}{(1+n)^2} \tag{2}$$

where the average value of refractive index $n_{\mathrm{av}} = 3.5$, reported for the system $\mathrm{In}_{1-x}\mathrm{Ga}_x\mathrm{P}$, is used in the calculation in Eq. (2) [13, 14].

Photon-energy dependence of the optical absorption coefficient near the direct and indirect absorption edges can be calculated assuming parabolic band edges: α^2 is linear in the energy region near the direct absorption and $\alpha^{1/2}$ is linear in the energy region near the indirect absorption. Hence, by plotting both α^2 and $\alpha^{1/2}$ as functions of photon energy, the gap type can be determined with the help of the best-fitting method.

The variation of the absorption coefficient α with photon energy $h\nu$ for indirect band to band allowed transitions is given by

$$\alpha(h\nu) = A_1(h\nu - E_g)^2 \tag{3}$$

while for direct transition, it is

$$\alpha(h\nu) = A_2(h\nu - E_g)^{1/2} \tag{4}$$

where A_1 and A_2 are energy independent constants.

The optical energy gap E_g was obtained by extrapolating the straight-line portion of $\big[\alpha(h\nu)\big]^2$ and $\big[\alpha(h\nu)\big]^{1/2}$ versus $h\nu$ to zero absorption for the case of indirect and direct transition, respectively.

The first three samples of the system $\mathrm{In}_{1-x}\mathrm{Ga}_x\mathrm{P}$ for $x = 0.31$, 0.48 and 0.68 were found to give a direct optical transition, while samples having $x = 0.75$, 0.80 and 1 have given indirect transition energy gaps. These results are in agreement with those reported in Ref. [15].

As a consequence of the positive identification of Γ and X valleys, it was possible to draw the energy band diagram as a function of ternary composition as shown in Fig. 1. The points related to the indirect transitions shown in this figure gave the following empirical relation

$$E_{X_c}(x) = 0.119x^2 + 0.0453x + 1.9725\,. \tag{5}$$

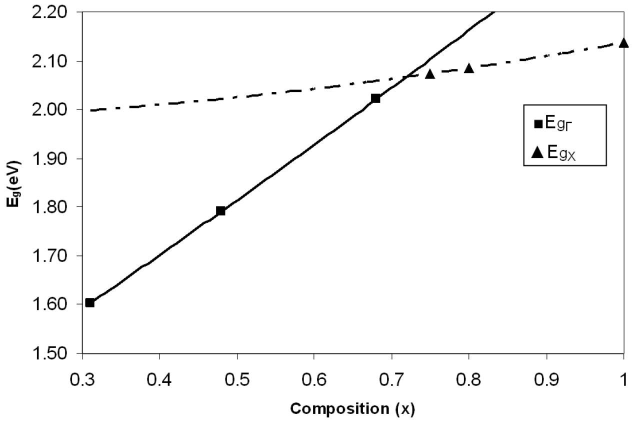

Fig. 1. Room-temperature dependence of energy gap of the alloy system $\mathrm{In}_{1-x}\mathrm{Ga}_x\mathrm{P}$ *on composition.*

From this quadratic relation of $E_X(x)$ dependence on composition, the position of X valley above the valence band in InP can be deduced. Eq. (5) gave 1.9725 eV as the value of $E_X(x)$ for InP. This value is near to that obtained by Hakke et al. [16], but it is lower than that obtained from calculations of the band structure of InP [17]. The differences in the values of E_g are due to the different concentration of carriers, impurities and the conditions of sample growth. The dependence of $E_\Gamma(x)$ on composition on the other hand, can be represented by a quadratic relation of the form

$$E_{\Gamma_c}(x) = 0.1055x^2 + 1.0255x + 1.275\,, \tag{6}$$

which is consistent with the general property of E_Γ in ternaries being a nonlinear function of composition. Equation 6 gives a value of 1.275 eV for the energy gap of InP which is in good agreement with that reported in Ref. [18], but it is smaller by about 0.05 eV than those reported in Refs. [19, 20].

In the case of GaP, its energy gap is in agreement with that reported in Ref. [21], while it is less by about 0.1 eV than that reported in Ref. [16]. Equations (5) and (6) give the direct-indirect conduction band crossover point at a composition of $x = 0.718$ in GaP which is in good agreement with those reported in Refs. [15, 22, 23, 24].

The room-temperature energy gap for this crossover point composition is 2.066 eV which is less than the energy gap values reported by other researchers [16]. From Eq. (6), the expected direct transition for compositions $x = 0.75, 0.8$ and 1 were calculated. Then the energy difference $[E_{g\Gamma} - E_{gX}]$ for these alloys were obtained. However, in general, the energy values for X_{c1} have a very small dependence on Ga concentration [24]. Such an energy deviation would be expected only due to the energy values. According to Eqs. (5) and (6), the values of $(\Gamma_{c1} - X_{c1})$ are 0.27 eV and 0.7 eV for InP and GaP, respectively. These values are smaller than 0.54 eV and 0.9 eV which have been reported for the two compounds in Refs. [24, 25], respectively, where the differences may be due to the methods of calculation. However, transitions at Γ_{c1} and X_{c1} regions for all alloy samples considered in this work are comparable to the results of those reported in Refs. [15, 26, 27].

The effect of magnetic field on E_g at room temperature is also investigated for all alloy samples. The experimental results, for the field up to 1.6 Tesla, gives a linear dependence for all six alloy samples under investigation. Figure 2, shows this dependence for the composition $\mathrm{In}_{0.66}\mathrm{Ga}_{0.34}\mathrm{P}$ as an example. The magnetic coefficient of energy gap ξ was calculated from the slope of this dependence for all alloys interested in this work and the results are shown versus their related composition in Fig. 3.

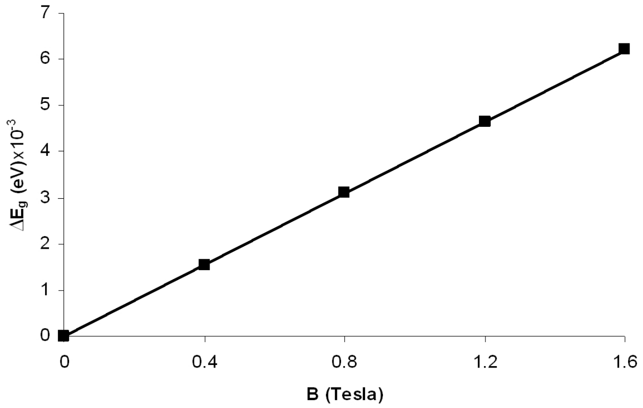

Fig. 2. Room-temperature dependence of the energy gap as a function of magnetic field for the alloy system $\mathrm{In}_{0.31}\mathrm{Ga}_{0.69}\mathrm{P}$.

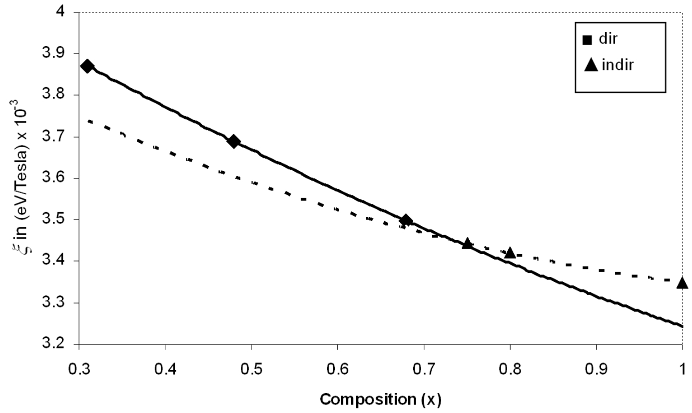

Fig. 3. Room-temperature magnetic field coefficient of the energy gap ξ *as a function of the alloy composition of* $\mathrm{In}_{1-x}\mathrm{Ga}_x\mathrm{P}$.

We know that for the indirect energy transition, phonon emission or absorption is sharing the process of optical transition with that of the photon absorption.

Under the effect of magnetic field, the energy gap will have the form

$$(E_g)_B = E_g \pm k\theta + (\Delta E_g)_B \,. \tag{7}$$

Hence, $k\theta$ is the phonon energy and $(\Delta E_g)_B$ is the energy rise due to the applied magnetic field. Higher-energy gap samples will have lower values for $(\Delta E_g)_B$ and that is the case for the alloy system $In_{1-x}Ga_xP$ with higher x values as shown in Fig. 3. In general, values of $(\Delta E_g)_B$ obtained in this work are higher than those obtained for InP [28] and $InGaP_2$ [29]. For values of $x > 0.718$ (the indirect transition region), $(\Delta E_g)_B$ will have a smaller dependence on x values which accordingly is the dependence on the values of E_g in this region. The effective mass is a function of X_{c1} curvature rather than Γ_{c1}. When E_g increases (x increases), X_{c1} will deviate more from Γ_{c1} level. That results in a higher X_{c1} curvature, what causes a reduction of m^* in comparison with the expected effective mass values obtained if it were a direct band transition. Such a deviation in m^* will create a smaller dependence on the effects of magnetic field in the range of x from 0.718 to 1. This can be clarified as follows.

From the empirical relation related to the transition region (Fig. 3), the values of $\xi_{\Gamma_{c1}}$ for $x > 0.718$ were calculated. Then the values of $(\xi_{\Gamma_{c1}} - \xi_{X_{c1}})$ in this range were drawn as a function of $[E_{g\Gamma} - E_{gX}]$ as shown in Fig. 4. The dependence gave the following empirical relation

$$(\xi_{\Gamma_{c1}} - \xi_{X_{c1}}) = 42.578 \times 10^{-4}[E_{g\Gamma} - E_{gX}]^2 + 33.131 \times 10^{-4}[E_{g\Gamma} - E_{gX}] \,. \tag{8}$$

This equation indicates how magnetic field interaction with an electron transition increases according to the energy difference between Γ_{c1} and X_{c1} in the indirect region, which supports the decrease of m^* as a function of x for $x > 0.718$.

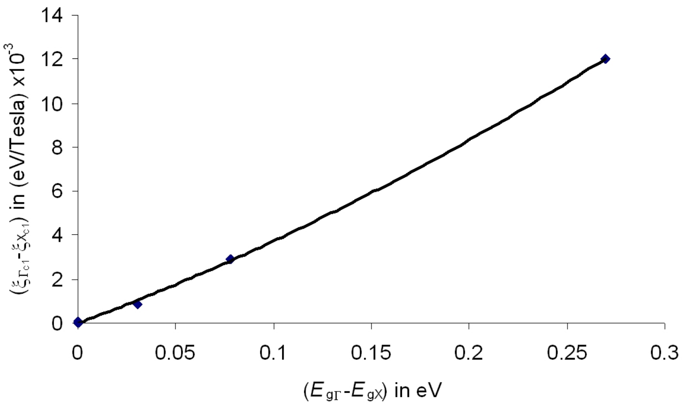

Fig. 4. Difference between the expected magnetic coefficient calculated for the direct transition in the indirect-region composition and that of the indirect transition $(\xi_{\Gamma_{c1}} - \xi_{X_{c1}})$ versus the difference between the expected direct energy gap calculated for the indirect region ($x \geq 0.718$) and that of the indirect energy gap $[E_{g\Gamma} - E_{gX}]$.

4. Conclusion

The alloy system $In_{1-x}Ga_xP$ has a direct energy gap transition in the InP side and indirect in the GaP side. The quadratic dependence of Γ_{c1} is higher than that for X_{c1} energy level for the alloy system. Magneto-optical effect has a higher effect on the direct transition energy gap compared to that of the indirect transition. In general, the effect of magnetic field decreases with increasing the samples energy gap.

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MAGNETSKO-OPTIČKA SVOJSTVA LEGURE $In_{1-x}Ga_xP$

Mjerili smo ovisnost energijskog procijepa u trojnom sustavu poluvodičke legure $In_{1-x}Ga_xP$ na sobnoj temperaturi. Našli smo prijelaznu točku od izravnih k neizravnim optičkim prijelazima za $x = 0.718$. Izveli smo iskustvenu ovisnost energijske ovisnosti energijskog procijepa tog sustava za izravne i neizravne prijelaze. Na osnovi iskustvene ovisnosti za područje izravnih prijelaza izračunali smo energiju neizravnih prijelaza za Γ_{c1}. Izračunali smo također razlike tih vrijednosti koje odgovaraju energiji neizravnih prijelaza $(\Gamma_{c1} - X_{c1})$. Promjene E_g zbog učinaka magnetskog polja mjerili smo do 1.6 T. Našli smo magnetski koeficijent između 3.33×10^{-7} i 3.87×10^{-7} eV/T za $x = 0.31$ do $x = 1$. Opaža se jasan otklon magnetskog koeficijenta pri prijelazu od izravnih k neizravnim prijelazima.