The Influence of Crystalline Orientation on the Photoelastic Property of {100} Gallium Arsenide Wafer*

Kenji GOMI** and Yasushi NIITSU**

We developed an optical birefringence measurement method that uses a photoelastic modulator and a polarized laser. A He-Ne infrared laser was utilized as the light source for measuring the birefringence in gallium arsenide wafers. In this paper we will explain the theory behind this method and the process of measuring the stress in GaAs wafers. The magnitude of the principal stress difference as well as the directions of the principal stresses were obtained simultaneously and quantitatively by using equipment developed for this study. The optical birefringences of stressed GaAs specimens were measured. From the experimental results, it was found that the photoelastic constant depended upon the crystalline orientations. Furthermore, the birefringence direction did not always coincide with the principal stress direction. The relationship between the principal strain difference and the retardation was obtained by the stress-strain analysis of a single GaAs crystal. That relationship was almost independent of the crystalline orientations and the birefringence direction was almost equal to the principal strain direction.

Key Words: Experimental Stress Analysis, Nondestructive Inspection, Material Testing, Photoelastic Modulator, Laser Photoelasticity

1. Introduction

Recently, the production technology of small precision devices, for example, VLSIs and sensor devices, has advanced significantly. These devices have been widely employed in mechanical and electrical apparatus. They consist of many components bonded or molded with resins. These complex systems sometimes break due to thermal stresses induced by a mismatch of thermal expansions. Therefore, the development of evaluation technology for stress states in electrical devices is required in various fields. Several techniques have been developed to evaluate the stress states in complex small devices, for example, laser Raman microspectroscopy and ultrasonic microscopy. On the other hand, an optical stress analysis method like photoelasticity is useful for evaluating microscopic stress distribution.

Jasperson and Schnattely⁽¹⁾ found that the polarization modulation was applicable for the measurement of the optical anisotropy, and Modine, Major and Sonder⁽²⁾ studied the optical birefringence using the photoelastic modulation. Yamada⁽³⁾ applied the polarization modulation to the stress analysis. However, that method was not suitable for high-speed measurement. Dobrilla and Blakemore⁽⁴⁾ obtained the residual strain distribution of GaAs wafer. However, that method did not mention the effect of crystalline orientations on the photoelastic property of a single GaAs crystal. We have developed a new stress measurement method and equipment that was suitable for the single silicon crystal. The equipment was a type of circular polariscope utilizing a photoelastic modulator and polarized laser⁽⁵⁾⁻⁽¹¹⁾.

In this paper, the optical birefringences in the tensile specimens of the GaAs wafers are measured with the equipment. From the experimental results, the photoelastic constants seem to depend on the crystalline orientations. Furthermore, the birefringence direction does not always coincide with the principal stress direction. By the stress-strain analysis of a single GaAs crystal, it was found that the magnitude

* Received 29th September, 1997. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 63, No. 610, A (1997), p. 1294-1298 (Received 19th August, 1996)

** Department of Mechanical Engineering, Tokyo Denki Univ., 2-2 Kanda-Nishikicho, Chiyodaku, Tokyo 101-0054, Japan

and direction of birefringence of the {100} face GaAs wafer depends directly on the principal strain.

2. Measuring Equipment and Theory

2.1 Birefringence measurement equipment

Figure 1 shows the design of the birefringence measuring equipment. This equipment enables the simultaneous measurement of magnitude and direction of the birefringence without the specimen rotation. An 8 mW He-Ne laser beam ($\lambda=1150$ nm) passes through in sequence: a polarizer (Glan-Thompson Prism), a PEM (PhotoElastic Modulator), a quarter wave plate, a birefringent specimen (a stressed specimen), a quarter wave plate and an analyzer. After passing through the analyzer, the laser beam is measured by a photodetector. The PEM converts linearly polarized light into oscillating elliptic light at its 42 kHz resonant frequency. The direction of the birefringence axis of the PEM inclines 90° from the axis of the analyzer, and 45° from the axis of the polarizer. The directions of the fast axes of the quarter wave plates incline 45° from the axis of the analyzer, and 90° from the axis of the polarizer. It is important to differentiate between the applied stress direction θ_σ and the induced birefringence direction θ_{bir} as shown in Fig. 1. They do not always coincide and this matter will be mentioned later in the paper.

2.2 Relation between stress and transmitted light intensity

Jones' calculus computation gives the light intensity I that comes through the analyzer as follows,

$$I = \frac{aI_0}{4} \{1 + \sin \gamma (\cos \delta \cdot \sin 2\theta_{bir} - \sin \delta \cdot \cos 2\theta_{bir})\} \quad (1)$$

where a is the transparency of the specimen, I_0 is the light intensity before transmission by the polarizer, θ_{bir} is the angle between the specimen birefringence axis and the fast axes of the quarter wave plates as shown in Fig. 1. If the specimen is an isotropic material, the birefringence direction of the specimen

Fig. 1 Schematic figure of birefringence measurement system

coincides with the principal stress direction. The notations γ and δ show the retardations of the specimen and the PEM, respectively. If the specimen is optically isotropic, the retardation γ is proportional to the principal stress difference $(\sigma_1 - \sigma_2)$ according to Brewster's law. Therefore, the principal stress difference and its direction can be obtained by calculating γ and θ in Eq. (1). The retardation δ of the PEM can be expressed as the sinusoidal change of the 42 kHz resonant frequency. These retardations are written as follows,

$$\gamma = 2\pi C(\sigma_1 - \sigma_2) \frac{d}{\lambda} \quad (2)$$

$$\delta = \delta_0 \cdot \sin \omega t \quad (3)$$

where C is the stress-optical coefficient (Brewster's constant). The notation d is the thickness of the specimen (the pass way length of the laser beam in the specimen), λ is the wavelength of the He-Ne laser beam (1150 nm), δ_0 is the amplitude of the modulator retardation which is proportional to the applied oscillation of the PEM voltage, and ω is the resonant angular frequency of the PEM. Substituting Eq. (3) into Eq. (1) and rearranging, the following Fourier expansion is obtained,

$$I = I_{DC} + I_{AC1} \sin \omega t + I_{AC2} \cos 2\omega t + I_{AC3} \sin 3\omega t + \dots \quad (4)$$

$$I_{DC} = \frac{aI_0}{4} \{1 + J_0(\delta_0) \cdot \sin \gamma \cdot \sin 2\theta_{bir}\} \quad (5)$$

$$I_{AC1} = -\frac{aI_0}{2} J_1(\delta_0) \cdot \sin \gamma \cdot \cos 2\theta_{bir} \quad (6)$$

$$I_{AC2} = \frac{aI_0}{2} J_2(\delta_0) \cdot \sin \gamma \cdot \sin 2\theta_{bir} \quad (7)$$

where I_{AC1} and I_{AC2} are the alternating light intensities of the resonance frequency and its double frequency, and I_{DC} is the direct component of the light intensity. Both I_{AC1} and I_{AC2} are measured by lock-in amplifiers. The direct component I_{DC} is measured by a voltmeter. $J_0(\delta_0) \sim J_2(\delta_0)$ are Bessel's functions. The second term of Eq. (5) can be eliminated by adjusting the PEM voltage, so that I_{DC} becomes constant,

$$I_{DC} = \frac{aI_0}{4} \quad (8)$$

The direct component, I_{DC} , is independent of both θ_{bir} and γ of the specimen. Dividing Eqs. (6) and (7) by Eq. (8), we can obtain,

$$\frac{I_{AC1}}{I_{DC}} = A_1 \cdot \sin \gamma \cdot \cos 2\theta_{bir} \quad (9)$$

$$\frac{I_{AC2}}{I_{DC}} = A_2 \cdot \sin \gamma \cdot \sin 2\theta_{bir} \quad (10)$$

where, A_1 and A_2 are constants which are independent of both the transparency and stress state of the specimen. They are determined by the experimental results of the quarter wave plate as a specimen. They were $A_1 = -0.111$ and $A_2 = 0.0167$. The values of γ and θ_{bir} of the specimen are obtained from Eqs. (9)

and (10),

$$\gamma = \sin^{-1} \left[\sqrt{\left(\frac{I_{AC1}}{I_{DC} \cdot A_1} \right)^2 + \left(\frac{I_{AC2}}{I_{DC} \cdot A_2} \right)^2} \right] \quad (11)$$

$$\theta_{bir} = \frac{1}{2} \tan^{-1} \left[\frac{A_1 \cdot I_{AC2}}{A_2 \cdot I_{AC1}} \right] \quad (12)$$

where γ is the absolute value of γ in Eq. (2). If the photoelastic constant, C , of a specimen is positive, the first principal stress direction corresponds with the birefringence direction, θ_{bir} . On the other hand, if the constant C is negative, the second principal stress direction corresponds with θ_{bir} .

3. Specimens

Three kinds of rectangular specimens shown in Fig. 2 were cut from the $\{100\}$ face wafers of GaAs in order to investigate the influence of crystalline orientations on their photoelastic properties. The retardations of the three specimens were measured using the birefringence measurement equipment. Uniaxial tension was applied to the specimens during the measurement to investigate the relationship between the applied stress and the induced retardation. Figure 2 shows the tensile specimens and the relationship between the crystal systems and the longitudinal directions of the specimens. The rectangular specimens were reinforced at both ends with PMMA plates.

4. Photoelastic Constant of Gallium Arsenide

The relationships between the tensile stress and induced retardation of the GaAs specimens were measured to investigate the photoelastic constant of the $\{100\}$ GaAs wafer. The applied stress levels were 0, 1.64, 3.27, 4.91 and 6.54 MPa. The tensile loads were applied in a longitudinal direction with a screw-type loading equipment. The measurements were collected at every 5° interval during the rotation of the specimen from 0° to 180° . During this phase, the axis of rotation coincided with the optical axis. The

Fig. 2 Schematic figures of GaAs wafer and specimens

birefringence measurement equipment did not require any sample rotation. In this paper, the specimens were rotated to investigate the relationship between the applied stress direction, θ_σ , and induced birefringence direction, θ_{bir} .

The experimental values of $(I_{AC1}/(I_{DC} \cdot A_1))$ and $(I_{AC2}/(I_{DC} \cdot A_2))$ are shown in Fig. 3(a), (b) and (c). For example, Fig. 3(a) shows the measurement

(a) At $\langle 110 \rangle$ direction in $\{100\}$ face, the birefringence direction coincides with the principal stress direction

(b) At an angle of 22.5° from the $\langle 110 \rangle$ direction in $\{100\}$ face, the birefringence direction does not coincide with the principal stress direction

(c) At $\langle 100 \rangle$ direction in $\{100\}$ face, the birefringence direction coincides with the principal stress direction

Fig. 3 The trajectories of $I_{AC1}/(I_{DC} \cdot A_1)$ and $I_{AC2}/(I_{DC} \cdot A_2)$ for three $\{100\}$ face specimens that are tensed at; (a): $\langle 110 \rangle$, (b): 22.5° from $\langle 110 \rangle$ and (c): $\langle 100 \rangle$ directions

results of the specimen that has a {100} crystal face and a <110> crystal direction that were coincident with the longitudinal direction. The cubes and its cross sections in the Fig. 3 show this {100} crystal face. The cross sections show the relationship between the longitudinal directions of the cut specimens and the <110> crystal direction. Equations (9) and (10) formulate the circle and the parameter is 2θ . Therefore, the radius and argument of the measured point in Fig. 3(a), (b) and (c) correspond to the magnitude and the direction of birefringence. The induced birefringence in the <100> direction is much larger than that of the <110> direction as shown in Fig. 3. The photoelastic constants of a single GaAs crystal depend on the crystalline orientations, just as in the single Si crystal⁽¹¹⁾. The white points in each of the graphs show the experimental results at $\theta_\sigma = 0^\circ$. If the value of θ_{bir} is equal to θ_σ , then the white points should be located on straight horizontal lines. The values of θ_{bir} coincide with θ_σ for the <110> (Fig.(a)) and the <100> (Fig.(c)) specimens, but θ_{bir} is not equal to θ_σ for the other specimen as shown in Fig. 3(b). The divided circular arcs in Fig. 3 show the applied stress direction, θ_σ , on the graphs. The relationship between θ_σ and the induced birefringence direction, θ_{bir} , can be seen on the graph. The relationship of the direction between θ_{bir} and θ_σ are shown at the lower right of each Fig. 3(a), (b) and (c).

Figure 4 shows the linear relationships between the load per unit width and the retardation for the three specimens. Each experimental point is the average of thirty-six measurements. Each mean square error shift is smaller than the size of each point. The three lines show the regression lines for each set of experimental points. The retardation of a single GaAs crystal is proportional to the principal stress difference. The photoelastic constants depend on the crystalline orientations.

Fig. 4 The relationship between the retardation and applied stress for three specimens

5. Discussions

5.1 Stress-strain analysis of GaAs

Optical birefringence is due to the anisotropy of the dielectric constant. We assume that the deviation of the dielectric tensor depends upon the deviatoric strain tensor because the strain tensor corresponds to the anisotropy of density. If a theory is developed from this assumption, then retardation will depend upon the principal strain difference and the birefringence direction will depend upon the principal strain direction. By using the stress-strain relationships of a single GaAs crystal, the stress-retardation relationships can be calculated into the strain-retardation relationships. The stress-strain relationships of a single GaAs crystal are written as follows,

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{12} \\ \tau_{23} \\ \tau_{31} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix} \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{12} \\ 2\varepsilon_{23} \\ 2\varepsilon_{31} \end{bmatrix} \quad (13)$$

$$C_{11}=118.8 \text{ GPa}, C_{12}=53.8 \text{ GPa}, C_{44}=59.4 \text{ GPa}$$

where, σ_{ij} 's and τ_{ij} 's are the stress tensor components, ε_{ij} 's are the strain tensor components, and C_{ij} 's are the elastic constants of a single GaAs crystal⁽¹²⁾. The theoretical relationships between the principal stress and the principal strain are obtained by using the Eq.(13),

$$\varepsilon_1 - \varepsilon_2 = \sqrt{\frac{\cos^2 2\theta'_\sigma}{4C_{44}^2} + \frac{\sin^2 2\theta'_\sigma}{(C_{11} - C_{12})^2}} (\sigma_1 - \sigma_2) \quad (14)$$

$$\tan 2\theta_\varepsilon = \frac{2C_{44}}{C_{11} - C_{12}} \tan 2\theta'_\sigma \quad (15)$$

where θ'_σ shows the angle between the applied uniaxial stress direction and the <110> crystalline orientation in the {100} crystal face wafer. In the experiment, the tensile load is applied to the longitudinal direction of the rectangular specimen. Therefore, θ'_σ refers to the angle between the longitudinal direction of the rectangular specimen and the <110> crystalline orientation. This matter is discussed later. The notation θ_ε shows the angle between the induced first principal strain direction and the <110> crystalline orientation. The theoretical compliance $(\varepsilon_1 - \varepsilon_2)/(\sigma_1 - \sigma_2)$ is shown in Fig. 5 by using polar coordinates. This figure shows the results on the upper half of the wafer because of the crystal symmetry. The radii of the concentric semicircles correspond to the amount of the compliance that is present. Radial lines from the origin show the crystalline orientations of the {100} face wafer. The solid curved line shows the results of the theoretical calculations.

5.2 Strain-retardation relations of GaAs

This paragraph will elaborate on the assumption

Fig. 5 The theoretical ratio of compliance for the {100} GaAs crystal face using polar coordinates

Fig. 6 The relationship between the retardation and the principal strain difference for the three specimens

that retardation will depend on the principal strain difference. Figure 6 shows the relationship between the principal strain difference and the retardation for the three specimens. The solid line shows the regression line for the experimental data. The retardation of a single GaAs crystal is almost proportional to the principal strain difference, and the strain-retardation coefficient is almost independent of the crystalline orientation on the {100} wafer. Therefore, the retardation depends upon the principal strain difference, not the principal stress difference. Table 1 shows the experimental results of the photoelastic constants and the strain-retardation coefficients.

5.3 The relationship between the directions of principal strain and birefringence in GaAs

From the result of Fig. 6, it will be assumed that the birefringence direction depends upon the principal strain direction. Figure 7 shows the theoretical curve of the principal strain direction and the experimental points of the birefringence direction. The horizontal axis, θ_σ , refers to the angle between the uniaxial stress direction and the <110> crystalline orientation. The left vertical axis ($\theta_\epsilon - \theta_\sigma$) and the solid curve, which is calculated by Eq. (15), show the angle between the induced first principal strain direction and the applied stress direction. The right vertical axis ($\theta_{bir} - \theta_\sigma$) and the three points show the angle between the induced birefringence direction and the applied uniaxial stress direction. The points are experimental results. Each

Table 1 Photoelastic constants and strain-retardation coefficients of experimental results

Crystal face of GaAs	Applied stress direction	Photoelastic constant [$\times 10^{-5}$ 1/MPa]	Strain-retardation coefficient [m/m]
{100}	<110>	1.02	1.21
	22.5deg from <110>	1.52	1.22
	<100>	2.02	1.31

Fig. 7 The relationship between the strain direction and the birefringence direction

experimental point is the average of thirty-six measurements. Each mean square error shift is smaller than the size of each point. If the points are plotted on the curved line, the birefringence direction coincides with the principal strain direction. Therefore, the birefringence direction coincides with the first principal strain direction.

5.4 The accuracy of the measurement equipment and the reliability of experimental results

A quarter wave plate is used for the calibration of

our birefringence measurement equipment. The error for the retardation in the plate is less than 2.3 nm. Therefore, that is not a significant problem. The initial unbalance of the retardation changes with time. The change of the retardation is less than 1.7 nm (less than 0.5 nm with 1997 technical level). The quarter wave plate is used to examine the measuring accuracy of the birefringence direction. The birefringence direction is measured at every 5° interval during the rotation of the quarter wave plate from 0° to 360°. The experimental errors in the birefringence directions are less than 0.5°. The errors in the cut angle for the rectangular specimens shown in Fig. 2 are less than 0.5°. The cutting angle is determined by means of the orientation flat of the wafer. The error in the angle between the flat and the $\langle 100 \rangle$ crystalline orientation is less than 0.5°. These errors are insignificantly small when compared with the measured values.

6. Conclusions

The effects of the crystalline orientations on the photoelastic constant of a single GaAs crystal are as follows:

- i. The photoelastic constants of a single GaAs crystal depend upon the crystalline orientations. However, the strain-retardation coefficients are almost independent of the crystalline orientations and are essentially constant.
- ii. The birefringence direction depends upon the principal strain direction.

Acknowledgments

This study was partly supported by the Scientific Research Grant from Japanese Ministry of Education.

References

- (1) Jaspersen, S.N. and Schnatterly, S.E., An Improved Method for High Reflectivity Ellipsometry Based on a New Polarization Modulation Technique, *Rev. Sci. Instrum.*, Vol. 40, No. 6 (1969), p. 761.
- (2) Modine, F.A., Major, R.W. and Sonder, E., High Frequency Polarization Modulation Method for Measuring Birefringence, *J. Appl. Opt.*, Vol. 14, No. 3 (1975), p. 757.
- (3) Yamada, M., Quantitative Photoelastic Measurement of Residual Strains in Undoped Semi-Insulating Gallium Arsenide, *Appl. Phys. Lett.*, Vol. 47, No. 4 (1985), p. 365.
- (4) Dobrilla, P. and Blakemore, J.S., Optical Mapping of Residual Stress in Czochralski Grown GaAs, *Appl. Phys. Lett.*, Vol. 48, No. 19 (1986), p. 1303.
- (5) Ichinose, K., Niitsu, Y. and Ikegami, K., Residual Stress Measurement of Adhesive Layer by Polarized Laser, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 58, No. 554, A (1992), p. 1900.
- (6) Niitsu, Y., Ichinose, K. and Ikegami, K., Stress Measurement of Transparent Materials by Polarized Laser, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 59, No. 559, A (1993), p. 600.
- (7) Niitsu, Y., Ichinose, K. and Ikegami, K., A Stress Measuring Method by Polarized Laser and Photo-Elastic Modulator, *Proc. of Int. Elec. Pack. Conf.*, Vol. 1 (1993), p. 157.
- (8) Ichinose, K. and Niitsu, Y., Scanning Stress Measurement Method by Laser Photoelasticity (1st Report, Stress Measurement by Synthesis Method), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 60, No. 572, A (1994), p. 1114.
- (9) Niitsu, Y., Gomi, K. and Ichinose, K., Development of Scanning Stress Measurement Method Using Laser Photoelasticity, *JSME Int. J., Ser. A*, Vol. 40, No. 2 (1997), p. 143.
- (10) Niitsu, Y. and Gomi, K., Influence of Crystal Orientation on Photoelastic Property of Silicon Single Crystal, *Proc. of Advanced in Electronic Packaging ASME, EEP-Vol. 10-2* (1995), p. 1239.
- (11) Gomi, K. and Niitsu, Y., Influence of Crystalline Orientation on Photoelastic Property of Si Single Crystal, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 62, No. 604, A (1996), p. 2651.
- (12) Bateman, T.B., McSkimin, H.J. and Whelan, J.M., Elastic Moduli of Single-Crystal Gallium Arsenide, *J. Appl. Phys.*, Vol. 30, No. 4 (1959), p. 544.