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Application of resonant ultrasound spectroscopy to β-Ga_2O_3

β-Ga_2O_3に対する共振超音波スペクトロスコピーの適用

Kanta Adachi[1‡], Hirotsugu Ogi[2], Nobutomo Nakamura[1], Hideyuki Watanabe[3], Toshimitsu Ito[3], Yasuko Ozaki[3] ([1]Osaka Univ. Grad. Sch. of Engineering Science; [2]Osaka Univ. Grad. Sch. of Engineering; [3]National Institute of Advanced Industrial Science and Technology, Electronics and Photonics Research Institute, Correlated Electronics Group)
足立 寛太[1‡], 荻 博次[2], 中村 暢伴[1], 渡邊 幸志[3], 伊藤 利充[3], 尾崎 康子[3]
([1]阪大院 基礎工, [2]阪大院 工, [3]国立研究開発法人 産業技術総合研究所 電子光技術研究部門 強相関エレクトロニクスグループ)

1. Introduction

Beta-type gallium oxide (β-Ga_2O_3) attracts much attention because of its great potential to high-power electron devices. Its bandgap is second largest among semiconductors, which realizes extremely high breakdown electric field. This characteristic makes β-Ga_2O_3 suitable material for power devices such as transistors and diodes; the Baliga figure of merit, which shows suitability for power devices, is about four times larger than that of GaN [1]. β-Ga_2O_3 has an advantage also in commercialization. A β-Ga_2O_3 bulk monocrystal can be produced by the same method as Si at low cost [2]. By contrast, fabrication of a GaN or a SiC single-crystal substrate by vapor-phase epitaxial methods requires great cost and energy. For these reasons, β-Ga_2O_3 is much superior in terms of device application than other wide-bandgap semiconductors for power devices. Recently, Ga_2O_3-based transistors are actively studied and developed, where it is important to clarify material properties of β-Ga_2O_3. The elastic constants of β-Ga_2O_3 are necessary to estimate performance of the transistors because strain in Ga_2O_3 layer, which is induced by mismatch of lattice constants between the different materials or is artificially introduced to increase the electron mobility, affects the device performance. It is, however, difficult to accurately measure all the elastic constants, C_{ij} of β-Ga_2O_3 due to its low crystallographic symmetry, and no study exists providing all the elastic constants.

Monoclinic β-Ga_2O_3 exhibits thirteen independent elastic constants:

$$[C_{ij}] = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & C_{15} & 0 \\ C_{12} & C_{22} & C_{23} & 0 & C_{25} & 0 \\ C_{12} & C_{23} & C_{33} & 0 & C_{35} & 0 \\ 0 & 0 & 0 & C_{44} & 0 & C_{46} \\ C_{15} & C_{25} & C_{35} & 0 & C_{55} & 0 \\ 0 & 0 & 0 & C_{46} & 0 & C_{66} \end{bmatrix} \qquad (1)$$

Previously, all the 13 C_{ij} of a monoclinic single crystal have been determined using resonant ultrasound spectroscopy (RUS) [3]. The RUS method, however, requires unambiguous mode identification to obtain reliable results because it inversely deduces elastic constants by comparing the measured and calculated resonance frequencies. It is, therefore, necessary to know “good” initial guesses of the elastic constants for the correct mode identification; it is usually carried out by comparing measured resonance frequencies with those calculated from the initial guesses. Consequently, the standard RUS method is inapplicable to β-Ga_2O_3 because no reported values for elastic constants appear. Here, we apply the RUS/Laser technique [4], where it is possible to identify the resonant modes by measuring displacement distributions of a crystal surface through laser-Doppler interferometry and comparing them with computed distributions, to β-Ga_2O_3 in order to accurately determine elastic constants.

2. Experiment Procedure

We developed the tripod-type RUS with laser-Doppler interferometry as shown in Fig. 1 [5].

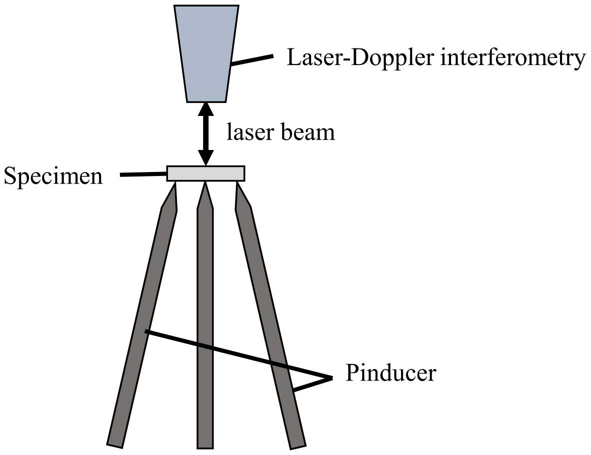


Fig. 1 Schematic of the RUS/Laser measurement system.

Free vibrations of the specimen can be excited and

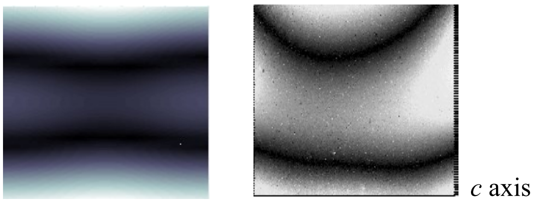
E-mail:ogi@me.es.osaka-u.ac.jp

detected by the needle piezoelectric transducers constituting a tripod. A laser beam was focused on the surface of the resonating specimen. A Doppler interferometry detects the frequency shift of the reflected beam and measures vertical component of velocity at the focal point. Vertical-velocity distributions are obtainable by scanning the whole surface of the specimen. The velocity distribution can be converted into the normal-displacement distribution due to harmonic oscillation, where there is a proportional relationship between maximum velocity and displacement. The mode identification is achieved by comparing measured and calculated displacement distribution because each resonant mode shows unique distribution.

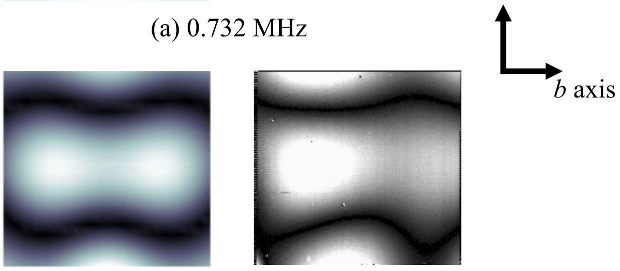
We used high-quality β-Ga_2O_3 monocrystal, and three rectangular-parallelepiped specimens were prepared. The typical dimensions are 3.4 mm, 4.9 mm, and 3.6 mm. (The *b* and *c* axes are parallel to the 4.9-mm and 3.6-mm sides, respectively.) The measured mass density is 5.709 g/cm^3. We deposited 100-nm Al on the specimen to reflect the laser beam.

3. Result and Discussion

We estimated the elastic constants of β-Ga_2O_3 through *ab-initio* calculation, which provided theoretical displacement distributions. Figure 2 compares calculated and measured displacement distributions on a resonating crystal surface. The agreement between them is enough to unambiguously identify the resonant modes. Similar consistency appears for many other modes, which realizes the complete mode identification for β-Ga_2O_3. Hence, the RUS/Laser technique allows us to accurately determine elastic constants of β-Ga_2O_3 via the inverse calculation; the differences between the resultant and first-principle values of elastic constants are less than 3.2 %, including the off-diagonal components.



(a) 0.732 MHz



(b) 1.143 MHz

Fig. 2 Examples of calculated (left) and measured (right) displacement distributions for the β-Ga_2O_3 specimen. The bright and dark zones represent antinode and node, respectively. The values below the drawings indicate measured resonance frequencies.

4. Conclusion

We measured elastic constants of β-Ga_2O_3, which doesn't have any reported values of them, by performing the unambiguous resonant-mode identification via the RUS/Laser technique. The measurements indicate that it is possible to observe the displacement distribution on a surface of the monoclinic material and precisely determine all the independent elastic constants using the technique.

References

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