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Wave velocity dispersion in GaN single crystal measured by Brillouin scattering method

Brillouin 散乱法を用いた GaN 単結晶の音速分散測定

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1. Introduction

In recent years, GaN resonators and SAW devices have attracted attention because they are compatible with GaN IC technology. Therefore, measurement of relaxation process due to piezoelectric (stiffening) effect and temperature dispersion of wave velocity are important for the device applications in GaN single crystal.

When stress is applied to a piezoelectric material, piezoelectric polarization is generated. The internal electric field due to piezoelectric polarization induces a strain in the reverse direction of applied stress. As a result, the apparent elasticity increases. This phenomenon is called "piezoelectric stiffening effect".[1)] However, in case of conductive piezoelectric material such as GaN and ZnO, charge carriers drift to prevent the piezoelectric stiffening effect. Therefore, apparent elasticity changes due to resistivity and frequency.[2)] Temperature also affects because the resistivity depends on temperature. Eventually, the relaxation process may be observed as temperature dispersion at high frequencies.

In this study, we estimated theoretical longitudinal wave velocity in GaN as functions of resistivity and frequency. Furthermore, we measured temperature dispersion of hypersonic wave velocity in a GaN single crystal by Brillouin scattering technique.

2. Theoretical estimation

Here, we estimated the dependence of longitudinal wave velocity on resistivity and frequency using Hutson and White's theory that includes the effects of carrier diffusion.[3)] **Fig. 1** shows the estimated results. Temperature was fixed at 27ºC and the piezoelectric coefficient used was e_{33}=0.63 C/m^2, which was obtained by first-principles calculation.[4)] In this estimation, black area shows high velocity limit $v^{D}_{//L}$ where GaN is stiffened by the piezoelectricity. On the other hand, white area shows low velocity limit $v^{E}_{//L}$ where GaN is not affected. According to this estimation, the relaxation process in GaN single crystal with low resistivity was located in GHz range.

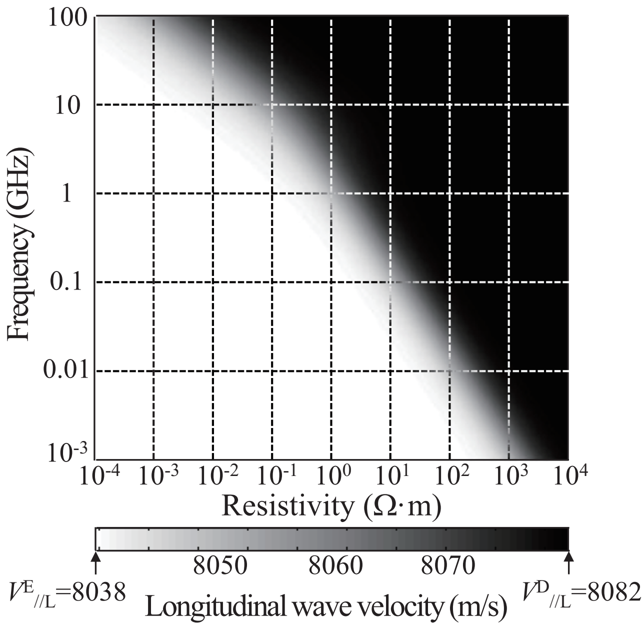

Fig. 1 Theoretical estimatation of longitudinal wave velocities propagating along c-axis in a GaN single crystal, as a function of resistivity and frequency at room temperature.[3-6)]

3. Sample

The measurement sample was a *m*-plane GaN single crystal (Kyma .Co). The sample size was 6×6×0.475 mm^3. The resistivity described in specification was in the range of 1-5×10^{-2} Ω·m.

4. Experiment

In our Brillouin measurement system, a six pass tandem Fabry-Perot interferometer (JRS scientific instrument) was used. In addition, Argon ion laser (Coherent, Innova-304, wavelength: 514.5nm, 40mw near the sample) and photomultiplier (Hamamatsu photonics, R464S) were used. The actual diameter of the focused laser beam was approximately 50 μm. The actual diameter means the measurement area and we measured the center of sample. The temperature of sample was controlled using a stage (LK-600PM, Linkam) during the experiment.

A measured wave vector $\boldsymbol{q}^{\Theta A}$ was in direction of c-axis, which was decided by the reflection induced ΘA (RIΘA) scattering geometry as shown in **Fig .2**.[7] The measured Brillouin spectra at 20ºC is shown in **Fig .3**. The wave velocities were determined from frequency shifts of these peaks, using the following equation:

$$v^{\Theta A} = f^{\Theta A} \frac{\lambda_i}{2\sin \Theta'/2} \tag{1}$$

where $f^{\Theta A}$ is the shift frequency, λ_i is the wave length of the laser, and Θ is the scattering angle.

In this study, longitudinal wave propagating along c-axis of GaN single crystal was measured in the region from -190ºC to 470ºC. Measurement errors of wave velocities were about ±4 m/s. We also measured Full Width at Half Maximum (FWHM) of the peaks.

5. Result and discussion

Fig. 4 shows measured longitudinal wave velocity and FWHM as a function of temperature. Two velocity kinks at around 30ºC and 300ºC were observed. The temperature dependence of wave velocity was non-linear in this sample. In Fig. 1, the sample with resistivity of $1\text{-}5\times10^{-2}\ \Omega\cdot$m is expected to show a relaxation around 15 GHz. Therefore the non-linear behavior of wave velocity seems to come from the relaxation. However, the measured values of wave velocities at low temparatures were lower than the estimated high velocity limit $v^{D}_{//L}$ by about 40 m/s. In addition, an increase of FWHM due to attenuation in relaxation process was not observed. One important point is that temperature dependence of shear wave velocity showed similar tendency with longitudinal wave velocity. Therefore, the existence of relaxation process should be discussed more carefully.

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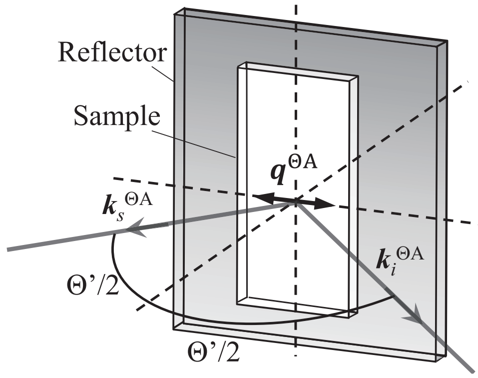

Fig. 2 RIΘA scattering geometry: $\boldsymbol{k}_i^{\Theta A}$ is the wave vector of incident light, $\boldsymbol{k}_s^{\Theta A}$ is the wave vector of scattered light, $\boldsymbol{q}^{\Theta A}$ is the wave vector of the measured acoustic wave, Θ is the scattering angle.

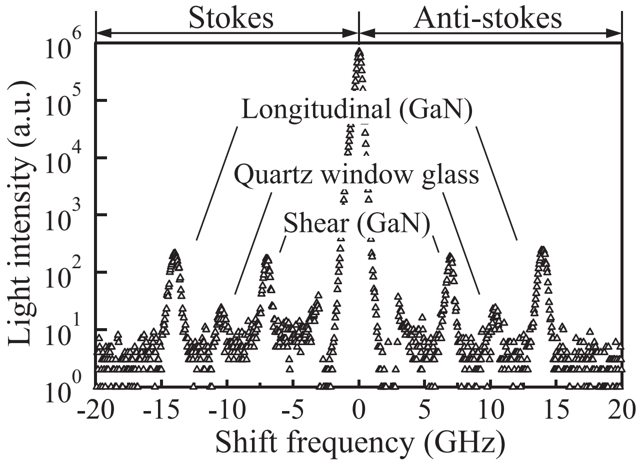

Fig. 3 The observed Brillouin spectrum in GaN single crystal at 20ºC. The peaks between longitudinal and shear wave peaks were due to a quartz window glass in front of the sample.

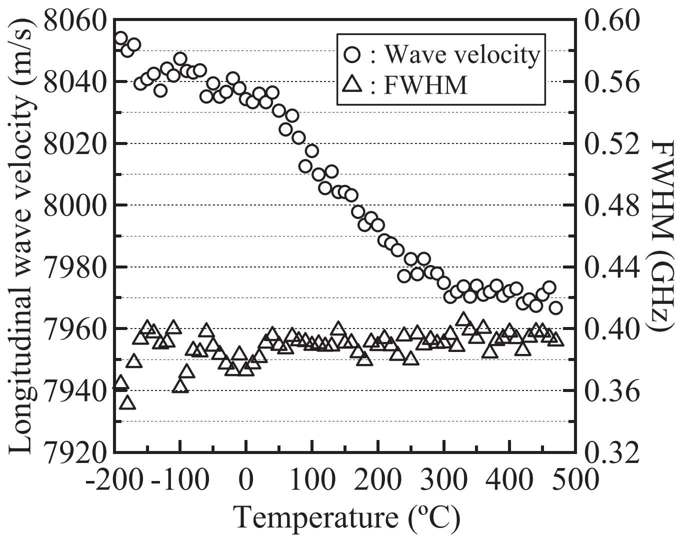

Fig. 4 Measured longitudinal wave velocity and FWHM as a function of temperature in a GaN single crystal.