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Anelastic properties of gallium nitride studied by resonant ultrasound spectroscopy at elevated temperatures

高温共鳴超音波スペクトロスコピーを用いた窒化ガリウムの擬弾性特性の研究

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1. Introduction

Gallium nitride (GaN) is an attractive material for next-generation semiconductor power devices, because it exhibits the breakdown electric field and the saturation electron velocity higher than Si. In addition, high thermal conductivity enhances heat dissipation of devices. Nevertheless, the device performance deteriorates as the operating temperature increase[1]. For example, in semi-insulating GaN used in a high-electron-mobility transistor (HEMT), impurity atoms such as Fe are doped to trap carriers. Trapped carriers can be thermally activated and cause hopping conduction, leading to an additional carrier pass. We previously found characteristic anelastic properties of GaN resulting from hopping conduction of thermally activated carriers using resonant ultrasound spectroscopy (RUS)[2], and they were simply explained with the Debye-type relaxation. However, the trapping energy levels are complicated, and a physical model including a multi-level hopping process should be considered. Therefore, to clarify the interaction between phonon and carrier movement, it is needed to investigate the relaxation process in more detail for various resonant modes in a wider temperature range.

In this paper, we study the anelastic properties in Fe-doped GaN by measuring the internal friction of various resonance modes at elevated temperatures. We also study the temperature and time dependent the ultrasonic attenuation caused by diffusion of defects and carriers in GaN.

2. Experiment

2.1) Specimen

We used semi-insulating wurtzite GaN, where ~80 ppm Fe are doped to trap the carriers. A rectangular-parallelepiped specimen was cut out from the GaN wafer for the RUS measurement, measuring 3.5 × 3.0 × 0.4 mm^3, and the mass density is 6053 kg/m^3.

2.2) Experimental Setup

To study the anelastic properties of Fe-doped GaN, we developed the tripod-type RUS system[3]. **Figure 1** shows the measurement setup consisting of synthesizer, two rod-type ultrasonic transducers, needle-like thermocouple, amplifier, digitizer, heater, and PC for controlling the system. The needle-like silica rods were attached to the transducers for supporting the specimen, which was put on the two transducers and the thermocouple. We input sinusoidal signals generated by the synthesizer to one of the transducers to vibrate the specimen, and the other transducer detected the vibration. Then, we amplified the detected signal by the amplifier and converted it to digital data by the 8-bit digitizer with a 20 MHz sampling rate. Finally, we imported it to the PC and applied Fourier transform to obtain the signal amplitude of the frequency component of the driving signal. By sweeping the input frequency of the driving signal and measuring corresponding signal amplitude, we obtain the resonant spectrum. In the tripod-type

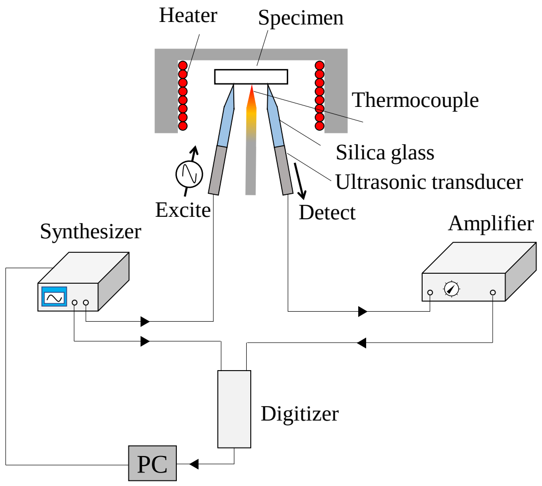

Fig. 1 Measurement system of the tripod-type RUS method.

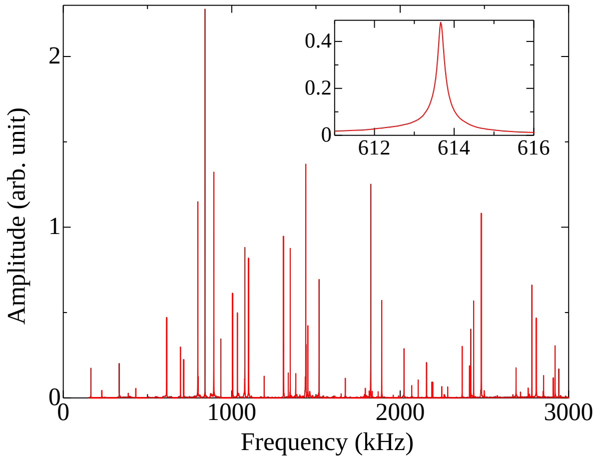

Fig. 2 Measured spectrum of an Fe-doped GaN at room temperature.

measurement system, the ideal vibration is measurable, because no external force, except for gravity, is applied to the specimen, allowing to measure the free-vibration resonance frequencies accurately. We covered the specimen with the heater to increase the temperature, where the thermocouple directly measured the specimen's temperature.

3. Results and Discussions

Figure 2 shows the measured spectrum at room temperature. The resonance frequency depends on specimen's size, mass density, and the elastic constants. We observed about 80 resonance peaks up to 3 MHz. **Figure 3 (a)** shows the temperature dependence of the B_{2g}-2 resonance mode as an example, and **Fig. 3 (b)** shows the calculated displacement distribution. The amplitude, quality factor Q, and the resonance frequency dramatically decrease around 100 °C, which is attributed to the hopping conduction[2]. Carriers trapped by Fe sites get the thermal energy and jump to other sites at a temperature-dependent hopping rate. Ultrasonic vibration also leads to carrier movement. Therefore, hopping conduction is efficiently enhanced when the hopping rate matches the ultrasonic frequency, resulting in increase in internal friction Q^{-1} because the acoustic energy is spent in the carrier movement. Thus, the Q value decreases at the specific temperature. This relaxation process will principally obey the Debye-type relaxation:

$$\frac{1}{Q} = \Delta_M \frac{\omega\tau}{1+(\omega\tau)^2}, \qquad (1)$$

where, Δ_M, ω, and τ denote relaxation strength, resonance frequency, and relaxation time,

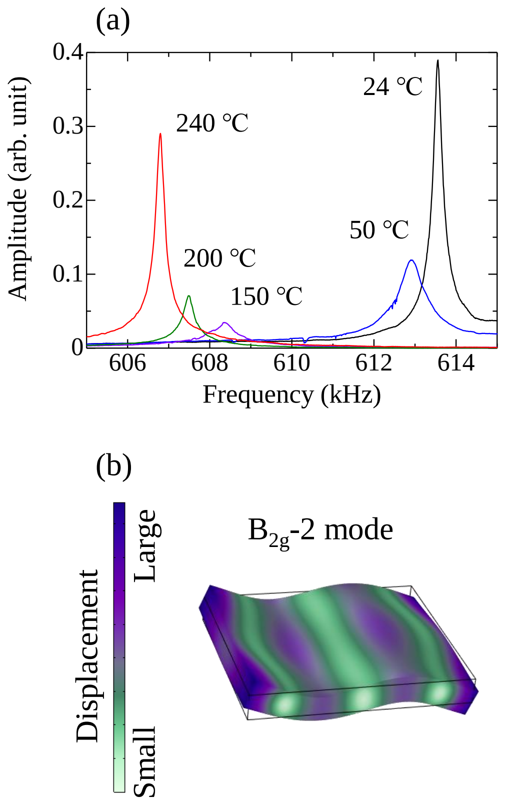

Fig. 3 (a) The temperature dependence of the B_{2g}-2-mode resonance spectrum and (b) corresponding displacement distribution figure.

respectively. We also study the aging effects of the internal friction when the specimen temperature is rapidly or gradually changed.

4. Conclusion

We measured the resonance peaks and internal friction of Fe-doped GaN using the laboratory-built RUS method at elevated temperatures. We observed the Debye-type relaxation processes caused by hopping conduction. We further investigate relaxation processes at higher temperatures in a wider frequency range, and study the aging effects of internal friction to understand the anelastic properties of GaN in more detail.

References

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