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Carrier dynamics of hopping conduction in high-resistance GaN studied by resonant ultrasound spectroscopy

共振超音波法を用いた高抵抗 GaN のホッピング伝導におけるキャリアダイナミクスの研究

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1. Introduction

Gallium nitride (GaN) attracts attention because of its high breakdown electric field and high saturation electron velocity. These properties are particularly important for semiconductor power devices, and GaN is a key material in high-frequency transistors such as a high-electron-mobility transistor (HEMT). The device uses the two-dimensional electron gas as electron transport pathway, realizing high-frequency and high-power operation. However, the device performances deteriorate at high temperature due to leakage current resulting from the hopping conduction in GaN. [1] It is, therefore, important to understand the hopping behavior of trapped carriers in semi-insulating GaN.

The free-carrier flow is restricted by deep accepters in semi-insulating GaN, where the hopping of trapped carriers between the sites is main conduction mechanism. The phonon-assistant carrier hopping is a thermally activated phenomenon. The carrier movement is also provoked by periodic piezoelectric polarization originating from ultrasonic vibration. Therefore, the hopping conduction is efficiently enhanced when the site-to-site jump rate of carriers coincides with resonance frequencies, at which internal friction shows a peak because most of the vibration energy are spent on the carrier hopping. Furthermore, the frequency decrement occurs due to the disappearance of apparent piezoelectricity above the matching temperature, where the piezoelectric polarization is canceled by the carrier movement. Hence, it is considered that the resonance frequency change and the corresponding internal friction show the Debye-type relaxation behavior due to hopping conduction in piezoelectric semiconductors.[2] Nevertheless, we found that these changes could take non-Debye-type relaxation forms in Fe-doped GaN, depending on the resonant mode. The existing relaxation models can't consistently explain the non-Debye-type relaxation characterized by more than one relaxation time. Here, we study the relaxation mechanism by measuring resonance frequencies and internal friction of various resonant modes between room and high temperature, providing insight into carrier dynamics at elevated temperatures in semi-insulating GaN.

2. Experiment procedure

We used high-quality Fe-doped GaN and prepared a rectangular-parallelepiped specimen with dimensions of 3.5 × 3.0 × 0.4 mm^3 at room temperature. (The *c* axis is parallel to the 0.4-mm side.) The mass density determined by Archimedes' method is 6080 kg/m^3.

We utilized the tripod-type resonant ultrasound spectroscopy (RUS) measurement system to measure the resonance frequencies and internal friction of the small GaN specimen at high temperatures. [3] The specimen is put on a tripod, consisting of two needle-like fused silica rods and one exposed-type thermocouple. Rod transducers are attached to the silica buffer rods for excitation and detection of elastic vibration. The specimen is heated by a small electric furnace, and the specimen's temperature is directly measured by the thermocouple. The specimen placed on the tripod is subjected to only specimen weight, realizing the measurement of the resonance frequencies with high enough precision (～0.01%) to monitor their changes caused by the hopping conduction. The acoustically contactless situation also allows us to measure internal friction without extra energy leakage; conversely, in the conventional internal-friction measurement with a contacting transducer, the energy loss arises from the contact between the specimen and transducer.

3. Results and Discussion

Figure 1 (a) presents an example of temperature behavior of resonant spectrum of the Fe-doped GaN. The resonance sharpness reduces and then gains as temperature increases, suggesting that internal friction shows a peak in this temperature range. The value of internal friction obtained from the resonance peak width indeed represents maximum at about 130 ℃ as indicated in Fig. 1(b). The resonance frequencies of solid materials usually decrease linearly as temperature increases. Figure 1(b), however, shows that the drastic drop in the resonance frequency occurs in the vicinity of the internal-friction peak temperature, indicating the disappearance of the piezoelectric stiffening. These behaviors exactly represent the Debye-type relaxation phenomenon caused by the hopping conduction. Figure 1(c) shows the temperature dependences of resonance frequency and internal friction of another vibrational mode. The relaxation behaviors are obviously different from the Debye-type relaxation: Internal friction exhibits two peaks at about 110 ℃ and 150 ℃, and the rapid frequency drops arise at the peak temperatures. Similar anomalous behaviors appear at relatively high frequencies. These observations imply that Fe-doped GaN has multiple relaxation mechanism associated with the resonant mode.

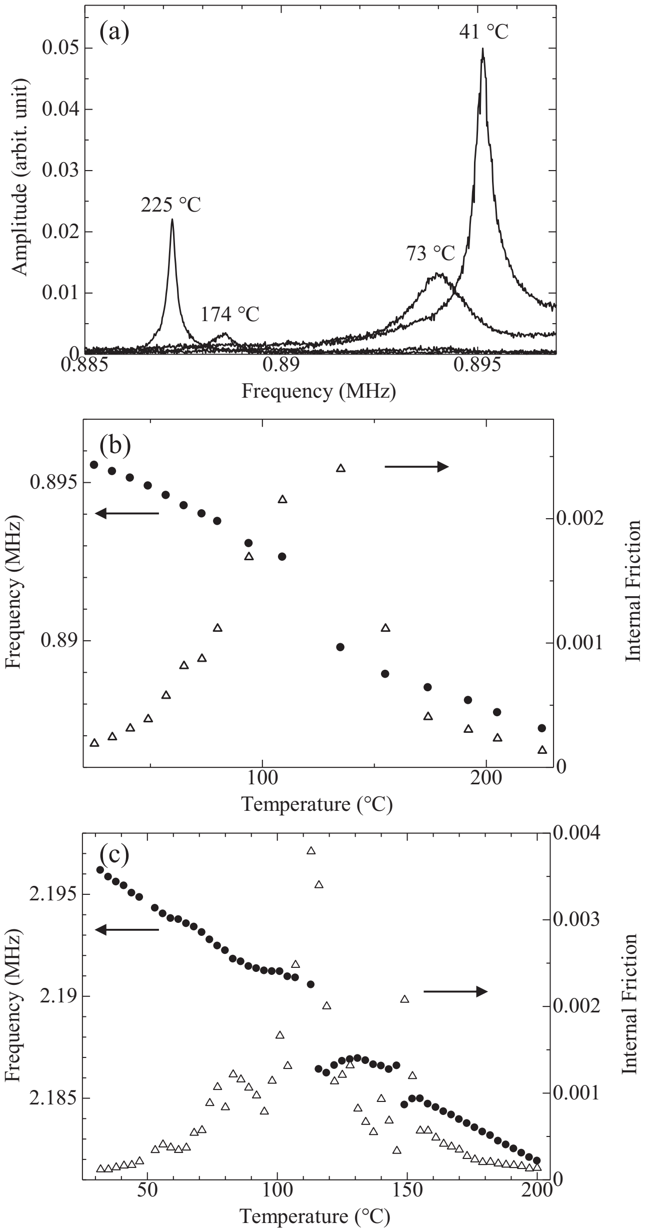

Fig. 1 (a) Resonant spectra of a resonant mode at several temperatures and (b) the temperature dependence of the corresponding resonance frequency and internal friction. (c) An example of non-Debye-type relaxation behavior in Fe-doped GaN.

4. Conclusion

We monitored the resonance-frequency and internal-friction behaviors of a Fe-doped GaN specimen at high temperatures using the tripod-type RUS. We succeeded in precisely observing the relaxation phenomenon caused by the hopping conduction for various vibrational modes. Although the changes of resonance frequency and internal friction take the Debye-type relaxation forms basically, some resonant modes in the high frequency region show the unusual relaxation behaviors. These measurements suggest that the carrier dynamics in Fe-doped GaN is characterized by the resonant modes, and its relaxation phenomenon due to the hopping conduction has an undiscovered mechanism.

References

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