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Coherent Guided Acoustic Phonons in GaN/AlN Nanowire Superlattices.

GaN/AlN ナノワイヤー超格子におけるコヒーレント音響フォノン

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1. Introduction

Advances in fabrication methods enable realization of various nanowire (NW) structures, such as nanowire superlattices (NWSLs). The NWSLs offer unique features in their electronic and optical properties [1, 2], which lead to a variety of possible applications.

NWSLs constructed from III-V semiconductors are also attractive for semiconductor devices. To improve electronic devices, understanding the acoustic phonons in the NWSLs is important. In addition, these structures yield interesting physical effects on phonon properties.

Mante et al. carried out the generation and observation of guided acoustic phonons in the GHz range in a GaN/AlN SL grown on a GaN NW [3]. They analyzed the generation and assigned the observed frequencies. Furthermore, they showed the potential of the NWSLs for small lateral size acoustic transducer and a new way to investigate phonon transport and thermal properties of NWs.

In their paper, the results were interpreted with the simple model, in which the dispersion relations for the single mode in a planer superlattice (i.e. Rytov's equation or Kronig-Penney's equation) was used. In general, phonon modes in a NWSL depend on the shape of the cross-section of the wire. Thus, we need to study the influence of the cross-section shape on the vibrational modes qualitatively.

In the present work, we calculate the acoustic phonon modes in the NWSLs with circular cross-section and analize the results of observation of guided acoustic phonons.

2. Method of Calculation and Dispersion Relations of GaN NW

The method we used is based on the *xyz* algorithm [4, 5]. The equation giving the eigenfrequencies of phonon modes in a freestanding NWSL composed of anisotropic crystals are presented in Ref. [6].

The phonon modes we are interested in the present study is dilatational modes. As in Ref. [4-5], the lattice displacement vector components for these modes are constructed with the use of the symmetry-adapted basis function. Here, we show the displacement components for the plain NW:

$$\begin{aligned} u_x(k,\mathbf{r}) &= \sum_{s,t} \frac{1}{\sqrt{S}} A_{x,s,t}(k) \left(\frac{x}{R}\right)^{2s+1} \left(\frac{y}{R}\right)^{2t} e^{ikz}, \\ u_y(k,\mathbf{r}) &= \sum_{s,t} \frac{1}{\sqrt{S}} A_{y,s,t}(k) \left(\frac{x}{R}\right)^{2s} \left(\frac{y}{R}\right)^{2t+1} e^{ikz}, \quad (1) \\ u_z(k,\mathbf{r}) &= \sum_{s,t} \frac{1}{\sqrt{S}} A_{z,s,t}(k) \left(\frac{x}{R}\right)^{2s} \left(\frac{y}{R}\right)^{2t} e^{ikz}, \end{aligned}$$

where S is the cross-section of the wire and R is the radius.

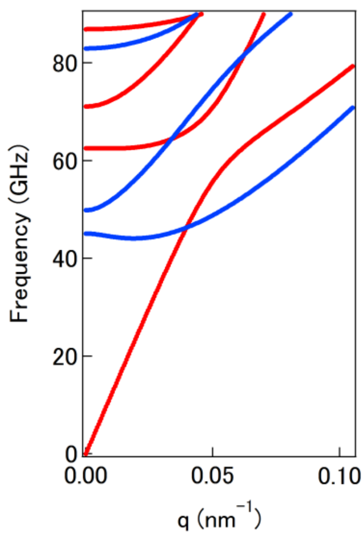

Fig. 1 Dispersion relation of dilatational phonon modes of a circular-cross-section GaN nanowire superlattice with wurtzite structure. All modes are named A_1 modes in C_{2v} symmetry. Only the modes shown by red lines have dilatational characteristics in the present structure.

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As a first step, we show in Fig. 1 the dispersion relations calculated for a circular cross-section GaN nanowire with wurtzite structure. These curves are in good agreement with those presented in Ref. [3]. The lowest two curves were used to obtain the approximated dispersion relations for a GaN/AlN NWSL.

Exactly speaking, two symmetrically different modes are included in these dispersion relations. Although the expressions (1) are exact ones for the materials with C_{2v} symmetry, the basis functions expressed in (1) are further classified into two different subspace for the circular cross-section NW with the wurtzite structure. Thus, we utilized group theory [7] and classified these modes in two groups. The red lines in Fig. 1 correspond to the dilatational modes in the present symmetry. In the experiments, it is expected to observe the phonon modes drawn by red lines.

3. Dilatational Phonon Modes in a GaN/AlN NWSL

Figure 2 shows the dispersion relations calculated for the dilatational modes in a GaN/AlN NWSL. The parameters in the present work correspond to those in the experiment [3]. That is, the radius of the NWSL is 75 nm, the thicknesses of the GaN and AlN layers are 56 nm and 42 nm, respectively, and the number of periods is 5.

Comparing the result by using Kronig-Penney's model with numerical one, we find that only the first dispersion curve and lower part of the second one is reproduced with this model.

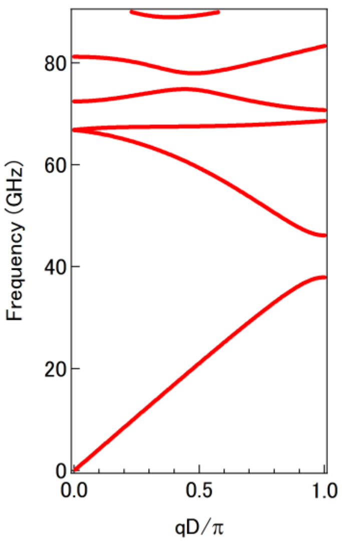

Fig. 2 Dispersion relations of dilatational phonon modes of a circular-cross-section GaN/AlN nanowire superlattice with wurtzite structure.

The time frequency analysis of the transient reflectivity in Ref. [3] shows the detection of the 25 and 60 GHz phonons, which are attributed to the paths illustrated in Fig. 3. Paths A and B correspond to 25GHz phonons and Path C to 60 GHz phonons.

Based on our numerical results, we can assign the observed phonons and give an alternative explanation for the dynamical process of the 25GHz phonons in this NWSL. The phonons generated at the tip travel toward the interface between the NWSL and substrate NW, then are reflected by this interface. In addition, phonons reach the end of the NW substrate, and then go back to the tip.

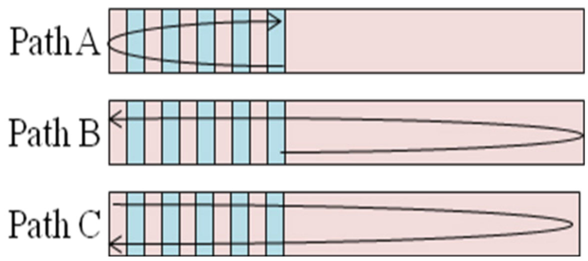

Fig. 3 Schematic representation for the dynamical process of the 25 GHz and 60 GHz phonons, which is given in Ref. [3].

4. Conclusions

Calculating the dispersion relations of the acoustic phonons with the *xyz* algorithm, we discussed guided acoustic phonons in a GaN/AlN NWSL. Our results show that only the lowest dispersion curve in the dispersion relations is well reproduced with the use of a simple Kronig-Penney's equation. Our calculational method is useful for the qualitative discussions of higher-frequency acoustic phonons in NWSLs.

Acknowledgment

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