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Sublattice Reversal in GaAs/Ge/GaAs (113)B heterostructures and its application to THz emitting devices based on a coupled multilayer cavity

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Abstract

Sublattice reveral (SR) epitaxy on (113)B GaAs substrate is proposed as an versatile method for the $\chi^{(2)}$ (second-order nonlinear susceptibility) inversion in the coupled cavity structure for the THz device. SR in GaAs/Ge/GaAs heterostructrues grown by molecular beam epitaxy (MBE) were confirmed by comparison the anisotropic etching profile of epitaxial sample with that of reference (113)A and (113)B GaAs substrates. Then, a GaAs/AlAs coupled multilayer cavity structure with SR was grown on (113)B GaAs by MBE. Smooth GaAs/AlAs interfaces were formed over the entire region of the coupled multilayer cavity structure both below and above Ge layer. Two cavity modes with frequency difference of 2.9 THz were clearly observed.

1. Introduction

We have proposed planar-type and room-temperature-operable terahertz (THz) emission devices based on the difference-frequency generation (DFG) of two cavity modes in a GaAs/AlAs coupled multilayer cavity [1]. The second-order nonlinear polarization of DFG from two cavity mode is given by $\chi^{(2)}E^*(\lambda_1)E(\lambda_2)$, where $\chi^{(2)}$ is the second-order nonlinear susceptibility, and $E(\lambda_1)$ and $E(\lambda_2)$ are the electric fields of the two modes inside the coupled multilayer cavity. A high-index GaAs substrate is essential for THz emission based on DFG because the $\chi^{(2)}$ is zero on the (001) orientation due to crystal symmetry. In addition, the opposite signs of $\chi^{(2)}$ in the two cavity regions are necessary to realize stronger THz-DFG of two modes. The sign of $\chi^{(2)}$ can be inverted by introducing 180° rotation of the crystal around the appropriate axis. We have successfully demonstrate the $\chi^{(2)}$ inverted coupled cavity that was fabricated by face-to-face bonding of two epitaxial (113)B wafers [2]. However, it is difficult to achieve equivalent optical thickness of two cavity layers grown on two substrates separately. Moreover, one of the substrates has to be completely removed from the bonded wafer for the device processing.

In this study, sublattice reveral (SR) epitaxy on a high-index substrate is demonstrated as an novel method for the $\chi^{(2)}$ inversion in the coupled cavity structure of the THz device. Koh et al. have reported SR in GaAs/Ge/GaAs system on low-index (001) and (111) substrates [3]. We confirmed SR in GaAs/Ge/GaAs heterostructures grown on a high-index (113)B GaAs substrate grown by molecular beam epitaxy (MBE). Then, A GaAs/AlAs coupled multilayer cavity structure with SR was grown on (113)B GaAs by MBE. We investigated the epitaxial quality and reflection spectrum of the structure.

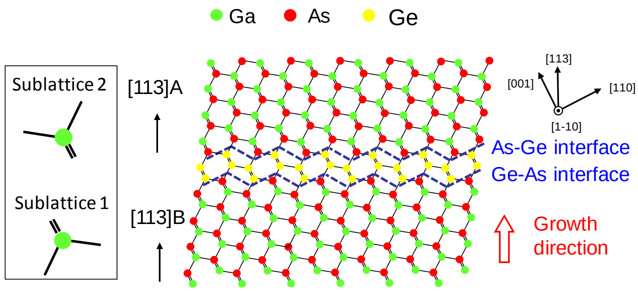

Fig. 1. Scheme of sublattice reversal in GaAs/Ge/GaAs heterostructures. By inserting a thin intermediate layer of group-IV atoms Ge, the sublattice occupation changed from sublattice 1 to 2, that is, from (113)B to (113)A.

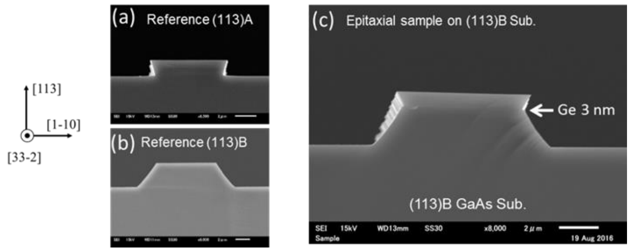

Fig. 2. SEM image of etching profile on the cross section cleaved along [33-2] direction. (a) Reference (113)A GaAs. (b) Reference (113)B GaAs. (c) Epitaxial sample on (113)B GaAs substrate.

2. SR in GaAs/Ge/GaAs heterostructures

Fig. 1 illustrates the basic scheme of the SR epitaxy on (113)B substrate for the ideal case. By inserting a thin intermediate layer of group-IV atoms Ge, we expected to reverse the sublattice occupation from sublattice 1 to 2, that is, from (113)B to (113)A. The epitaxial structure of the GaAs/Ge/GaAs heterostructures was grown on (113)B GaAs substrate. After thermal cleaning of the substrate at 610°C for 10 min, a 500 nm thick GaAs buffer layer was grown at 600°C. Then the As source shutter was closed and the substrate temperature was cooled to 450°C. Ge layer of nominal thickness of 3 nm was grown at 450°C with the As source shutter closed. After the Ge growth, the As shutter was opened to establish an As pre-layer and the substrate temperature was ramped up to 600°C for growth of 800 nm GaAs.

The SEM images of anisotropic etching profile on the cross section along [33-2] direction of (113)A and (113)B

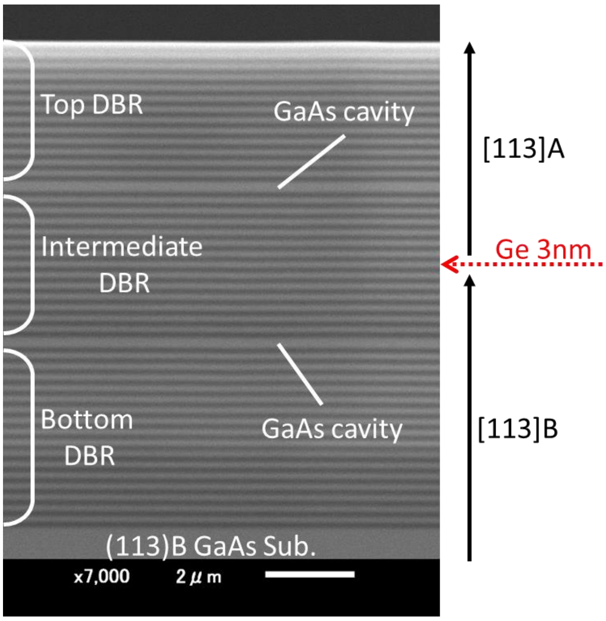

Fig. 3. Cross-sectional SEM image of GaAs/AlAs coupled multilayer cavity grown on (113)B GaAs with sublattice reversal.

substrates alone which have inverse and forward mesa shapes are shown as reference in Figs. 2(a) and 2(b), respectively. The SEM image of anisotropic etching profile on the cross section along [33-2] direction of GaAs/Ge/GaAs heterostructures grown on (113)B GaAs substrate is shown in Fig. 2(c). The mesa shape of GaAs grown below Ge layer was same with reference (113)B but that grown above on Ge layer was same with reference (113)A. The results indicate that SR was successfully confirmed in the GaAs/Ge/GaAs heterostructure on the (113)B GaAs substrate.

3. A GaAs/AlAs coupled multilayer cavity with SR

The GaAs/AlAs coupled multilayer cavity structure with SR was grown on (113)B GaAs by MBE after the confirmation of SR as stated above. Fig. 3 shows cross-sectional scanning electron microscopy (SEM) of the sample, which consists of two equivalent GaAs $\lambda/2$ cavity layers (222 nm) coupled with 13.5-period GaAs/AlAs (111 nm/130 nm) $\lambda/4$ distributed Bragg reflector (DBR) structures. 17- and 13-period DBRs were formed on bottom and top sides of the coupled cavity, respectively. The Ge layer of 3 nm was insert in GaAs layer in the middle of intermediate DBR for SR. As seen in Fig. 3, smooth GaAs/AlAs interfaces were formed over the entire region of the coupled multilayer cavity structure both below and above Ge layer.

The solid line in Fig. 4 shows the experiment reflection spectrum of the coupled cavity sample. The broken line shows the simulated reflection spectrum by a conventional transfer matrix method. The reflection spectrum was measured at room temperature using a white lamp and a monochrometer. The incident light was normal to the sample surface. Two cavity modes were clearly observed at wavelengths of 1492 and 1514 nm in the center of the high reflection band.

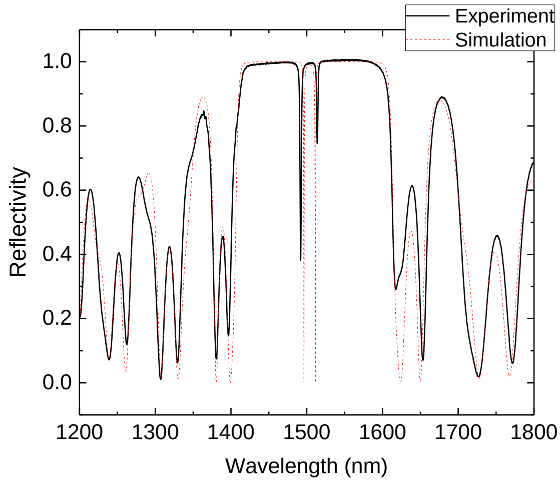

Fig. 4. Reflection spectra of GaAs/AlAs coupled multilayer cavity grown on (113)B GaAs with sublattice reversal.

The frequency difference between the two cavity modes corresponds 2.9 THz.

4. Summary

We grew GaAs/Ge/GaAs heterostructures on a high-index (113)B GaAs substrate by MBE. SR in GaAs/Ge/GaAs was confirmed by comparing the mesa shape of epitaxial sample with reference substrates. The mesa shape of GaAs grown below Ge layer was same with reference (113)B but that grown above on Ge layer was same with reference (113)A. A GaAs/AlAs coupled multilayer cavity structure with SR was grown on (113)B GaAs by MBE after the confirmation of SR. The Ge layer of 3 nm was insert in GaAs layer in the middle of intermediate DBR for SR. Smooth GaAs/AlAs interfaces were formed over the entire region of the coupled multilayer cavity structure both below and above Ge layer. Two cavity modes with frequency difference of 2.9 THz were clearly observed.

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