ISSN 0021-3640, JETP Letters, 2017, Vol. 105, No. 5, pp. 327–331. © Pleiades Publishing, Inc., 2017.
Original Russian Text © V.A. Volodin, V.A. Timofeev, A.R. Tuktamyshev, A.I. Nikiforov, 2017, published in Pis'ma v Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, 2017, Vol. 105, No. 5, pp. 305–310.

CONDENSED MATTER

Splitting of Frequencies of Optical Phonons in Tensile-Strained Germanium Layers

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Received January 16, 2017; in final form, January 30, 2017

Tensile-strained germanium films in Ge/GeSn/Si/GeSnSi multilayer heterostructures grown by molecular-beam epitaxy on Si(001) substrates are investigated by Raman spectroscopy. Biaxial tensile strains in the films reach 1.5%, which exceeds values previously obtained for this system. Splitting of frequencies of long-wavelength optical phonons is experimentally observed; i.e., the shift of the frequency of the singlet induced by biaxial tensile strains is larger than the shift of the frequency of the doublet in agreement with calculations. The strain-induced shift of Raman scattering peaks from two-phonon scattering in germanium is also detected.

DOI: 10.1134/S0021364017050137

Elastic deformation provides one of the methods for control of the band structure of semiconductors [1, 2]. Fischetti and Laux [3] theoretically showed that biaxial tensile strains in germanium increase the mobility of electrons and holes. A relatively small difference in energy (0.14 eV) between direct and indirect transitions in Ge gives hope to creating direct-gap strained germanium for the production of light-emitting structures with a high quantum efficiency. Theoretical calculations predict a decrease in the energy of the Γ valley in the conduction band and a transformation of Ge to a direct-gap material at its biaxial tension by ~2% [4–6]. The authors of [7] reported a superlinear pump-induced increase in the radiation power (laser effect) in tensile-strained *n*-type germanium films. The growth of films on an artificial substrate with a different crystal lattice parameter is one of the methods for obtaining strongly strained materials. The tensile strain in Ge films in InGaAs/Ge/InGaAs multilayer heterostructures in the growth plane reaches 2.33% [8–10]. In this case, if the lattice parameter of the substrate is larger than the lattice parameter of the strained material and the thickness of the grown layer is no more than the critical value, the film remains pseudomorphic and is biaxially tensile-strained. For the growth of tensile-strained Ge and GeSn layers, heterostructures in which relaxed Sn_xGe_{1-x} buffer layers were grown on the Si substrate were also used as artificial substrates [11–15]. However, because of a limited solvability of Sn in Ge, biaxial tensile strains of Ge in such a system are usually no more than 1.1%. The use of Sn_xGe_{1-x} buffer layers allows growth on a Si substrate. Therefore, this technology is compliant with traditional silicon technology, in contrast to the approach involving InGaAs buffer layers.

Changes in the optical properties of tensile-strained germanium films in such structures were analyzed from photoluminescence spectroscopy data [16–18]. A long-wavelength shift of the absorption edge of such films was detected in [19] by the light transmission spectroscopy method. The Raman scattering is an efficient tool for studying mechanical strains in semiconductor films and their solid solutions [20–22]. It is known that biaxial mechanical stresses result in the splitting of a triply degenerate long-wavelength optical phonon in Si or Ge into a singlet and doublet [20, 21]. According to the selection rules, the singlet and doublet are allowed for backscattering from the Si(111) surface; for this reason, their splitting can be observed experimentally [21]. It is difficult to experimentally study this splitting for films with the most widespread orientation (001) because a signal from the doublet is not observed at backscattering from the (001) surface since scattering in these modes is forbidden by the selection rules in symmetry.

The first attempt to detect the doublet was made with the use of a large-aperture objective to increase the angles of incidence and scattering [23]. In this work, we used the so-called "in-plane" scattering geometry with the possibility of detecting phonons with the wave vector directed along the layers of the heterostructure [24–26].

The sample with a 70-nm-thick strained Ge layer was grown on the $Ge_{0.88}Sn_{0.12}$ solid solution at a tem-