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Phonon interference control of atomic-scale metamirrors, meta-absorbers, and heat transfer through crystal interfaces

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Аннотация:

The paper theoretically studies the possibility of using the effects of phonon interference between paths through different interatomic bonds for the control of phonon heat transfer through internal crystal interfaces and for the design of phonon metamirrors and meta-absorbers. These metamirrors and meta-absorbers are considered to be defect nanolayers of atomic-scale thicknesses embedded in a crystal. Several analytically solvable three-dimensional lattice-dynamics models of the phonon metamirrors and meta-absorbers at the internal crystal planes are described. It is shown that due to destructive interference in the two or more phonon paths, the internal crystal planes, fully or partially filled with weakly bound or heavy-isotope defect atoms, can completely reflect or completely absorb phonons at the transmission antiresonances, whose wavelengths are larger than the effective thickness of the metamirror or meta-absorber. Due to cooperative superradiant effect, the spectral widths of the two-path interference antiresonances for the plane waves are given by the square of partial filling fraction in the defect crystal plane. Our analysis reveals that the presence of two or more phonon paths plays the dominant role in the emergence of the transmission antiresonances in phonon scattering at the defect crystal planes and in reduction of the thermal interface conductance in comparison with the Fano-resonance concept. We study analytically phonon transmission through internal crystal plane in a model cubic lattice of Si-like atoms, partially filled with Ge-like defect atoms. Such a plane can serve as interference phonon metamirror with the transmission antiresonances in the vicinities of eigenmode frequencies of Ge-like defect atoms in the terahertz frequency range. We predict the extraordinary phonon transmission induced by the two-path constructive interference of the lattice waves in resonance with the vibrations of rare host atoms, periodically distributed in the crystal plane almost completely filled with heavy-isotope defects. We show that the phonon-interference-induced transparency can be produced by the defect nanolayer with the non-nearest-neighbor interactions, filled with two types of isotopes with relatively small difference in masses or binding force constants. In this case, relatively broad transmission antiresonance is accompanied by the narrow transmission peak close to the antiresonance frequency. We describe the softening of the flexural surface acoustic wave, localized at the embedded defect nanolayer, caused by negative surface stress in the layer. The surface wave softening results in spatially periodic static bending deformation of the embedded nanolayer with the definite wave number. The latter effect is estimated for graphene monolayer embedded in a strained matrix of polyethylene. We analyze the effect of nonlinearity in the dynamics of defect atoms on the one- and two-path phonon interference and show that the interference transmission resonances and antiresonances are shifted in frequencies but not completely suppressed by rather strong anharmonicity of interatomic bonds. The reduction of the Kapitza thermal interface conductance caused by the destructive phonon interference in a defect monolayer is described. We show that the additional relatively weak non-nearest-neighbor interactions through the defect crystal plane filled with heavy isotopes substantially reduces the interface thermal conductance, and this effect is stronger in the three-dimensional system than in the quasi-one-dimensional systems studied previously.