Journal of
Nanoscience and Nanotechnology
Vol. 5, 1015–1022, 2005

Nanophononics: Phonon Engineering in Nanostructures and Nanodevices

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Phonons, i.e., quanta of lattice vibrations, manifest themselves practically in all electrical, thermal and optical phenomena in semiconductors and other material systems. Reduction of the size of electronic devices below the acoustic phonon mean free path creates a new situation for phonon propagation and interaction. From one side, it complicates heat removal from the downscaled devices. From the other side, it opens up an exciting opportunity for engineering phonon spectrum in nanostructured materials and achieving enhanced operation of nanodevices. This paper reviews the development of the phonon engineering concept and discusses its device applications. The review focuses on methods of tuning the phonon spectrum in acoustically mismatched nano- and heterostructures in order to change the phonon thermal conductivity and electron mobility. New approaches for the electron–phonon scattering rates suppression, formation of the phonon stop-bands and phonon focusing are also discussed. The last section addresses the phonon engineering issues in biological and hybrid bio-inorganic nanostructures.

Keywords: Phonon Engineering, Nanophononics, Phonon Depletion, Thermal Conduction, Acoustically Mismatched Nanostructures, Hybrid Nanostructures.

CONTENTS

1. PHONONS IN BULK SEMICONDUCTORS AND NANOSTRUCTURES

Phonons are quantized modes of vibration occurring in a rigid crystal lattice, such as the atomic lattice of a solid. One can speak of a gas of phonons, which are quasi-particles of the energy $\hbar\omega$ and quasi-momentum $p = \hbar q$ obeying Bose-Einstein statistics.[1] Phonons manifest themselves practically in all properties of materials. For example, acoustic and optical phonons limit electrical conductivity. Optical phonons strongly influence optical properties of semiconductors while acoustic phonons are dominant heat carriers in insulators and technologically important semiconductors. The long-wavelength phonons gives rise to sound waves in solids, which explains the name *phonon*.

Similar to electrons, one can characterize the properties of phonons by their dispersion $\omega(q)$, i.e., dependence of the phonon frequency ω on its wave vector q. In bulk semiconductors with g atoms per unit cell, there are $3g$ phonon dispersion modes for every value of q. In the limit of long waves, three modes describe the motion of the unit cell, and form the three acoustic phonon branches. The other $3(g-1)$ modes describe the relative motion of atoms in a unit cell, and form the optical phonon branches. Acoustic phonons have nearly linear dispersion, which can be written as $\omega = V_S q$ (where V_S is the sound velocity). Optical phonons, in general, are nearly dispersion-less for small q values (long-wavelength approximation) and have a small group velocity $V_G = d\omega/dq$.

Spatial confinement of phonons in nanostructures and thin films can strongly affect the phonon dispersion and modify phonon properties such as phonon group velocity, polarization, density of states, and affect phonon interaction with electrons, point defects, other phonons, etc. Figure 1 shows the phonon energy dispersion in a thin film and a three-layered heterostructure for of the symmetric (SA) and antisymmetric (AS) modes. The results are

1533-4880/2005/5/1015/008/$17.00+.25

doi:10.1166/jnn.2005.175

shown for the 6 nm-wide AlN slab and the three-layer heterostructure with the core layer thickness $d_2 = 4$ nm. One can see that the phonon dispersion in these structures is very different from the bulk phonon modes. Modification of the acoustic phonon dispersion is particularly strong in freestanding thin films or in nanostructures embedded into elastically dissimilar materials. Such modification may turn out to be desirable for some applications while detrimental for others. Thus, nanostructures offer a new way of controlling phonon transport via tuning its dispersion relation, i.e., *phonon engineering*.[2] The concept of engineering (or rather re-engineering) the phonon dispersion in nanostructures has the potential to be as powerful as the concept of the band-gap engineering for electrons, which revolutionized the electronic industry.

In this paper I focus on acoustic phonons in hetero-nanostructures. The optical phonon confinement in quantum dots, Raman scattering from localized optical phonons in nanostructures, phonon bottleneck and related issues deserve a special analysis, which goes beyond the scope of the present review. In the remainder of the paper, I provide a brief description of the phonon engineering concept (Section 2), discuss the thermal conductivity in nanostructures (Section 3), describe a possibility of phonon depletion in acoustically mismatched heterostructures (Section 4), and present results related to phonons in biological systems and hybrid bio-inorganic nanostructures (Section 5).

2. THE PHONON ENGINEERING CONCEPT

The idea of looking at the changes that acoustic phonon spectrum experiences in heterostructures has a rather long history. In 1950s, Rytov published a series of theoretical papers[3] where he analyzed acoustic vibrations in "artificial thinly-laminated media," a structure, which now would be referred to as a superlattice, and described folded acoustic phonons in such media. The folded phonons were later observed in quantum well superlattices made of GaAs/AlGaAs and other semiconductors.[4] In 1980s and early 1990s there have been large amount of theoretical work done aimed at calculating the confined acoustic phonon–electron scattering rates in free-standing thin films and nanowires. Some notable examples of this work include papers from the research groups of Stroscio,[5] Mitin,[6] Nishiguchi[7] and Bandyopadhyay.[8] Most papers on the subject used the elastic continuum approach for calculating phonon dispersion and adopted solution techniques developed in acoustics and mechanics. The prime motivation was to see if the spatial confinement and quantization of the acoustic phonon modes in freestanding thin films or nanowires produces noticeable effect on the deformation potential scattering of electrons. The opinions were split about how important the acoustic phonon confinement in the description of electron transport in low-dimensional structures. Some theorists argued that the phonon-confinement induced changes for macroscopic characteristics, such as carrier mobility, are not pronounced.[7,9] Others have found that the deformation potential scattering can be substantially suppressed for certain electron energies.[6,8] This earlier work focused on the effects of the acoustic phonon confinement on electron transport in free-standing quantum wells and quantum wires did not lead to experimental claims of significantly

Professor Alexander A. Balandin received his M.S. degree in Applied Physics and Mathematics from the Moscow Institute of Physics and Technology (MIPT), Russia in 1991. He received his second M.S. and Ph.D. degrees in Electrical Engineering from the University of Notre Dame, USA in 1995 and 1996, respectively. He worked at the Electrical Engineering Department, UCLA from 1997 to 1999. In 1999, he joined the Department of Electrical Engineering of the University of California–Riverside (UCR) as an Assistant Professor. Currently, he is a Professor of Electrical Engineering and Director of the Nano-Device Laboratory (NDL), which he organized in 2001. Professor Balandin's research interests are in the area of electronic materials, nanostructures and nanodevices. Current research topics in his group include phonon engineering at nanoscale, electron–phonon transport in nanostructures and nanodevices, hybrid bio-inorganic nanostructures, wide band-gap semiconductor materials and nanostructures, electronic noise phenomena, thermal management and reliability of nanoscale devices. He carries both theoretical and experimental research. Professor Balandin is an author or coauthor of more than 80 journal publications, ten invited book chapters, and a book *Nanophononics*. He edited books *Noise and Fluctuations Control in Electronic Devices, Handbook of Semiconductor Nanostructures and Nanodevices*, and others. He chaired many international conference sessions and served as a SPIE conference chairman. Professor Balandin is an Editor-in-Chief of the *Journal of Nanoelectronics and Optoelectronics* (*JNO*). He also serves on the editorial board of the *Journal of Nanoscience and Nanotechnology* (*JNN*). His research work was recognized by the ONR Young Investigator Award (2002), National Science Foundation CAREER Award (2001), University of California Regents Award (2000), and the Merrill Lynch Innovation Award for "commercially valuable engineering research" (1998). He is an Associate Scholar of the Pembroke College, University of Cambridge, UK and a member of Eta Kappa Nu. He is a senior member of IEEE, and a member of APS, AAAS, SPIE and the Electrochemical Society, Inc. More information on his research can be found at http://ndl.ee.ucr.edu.

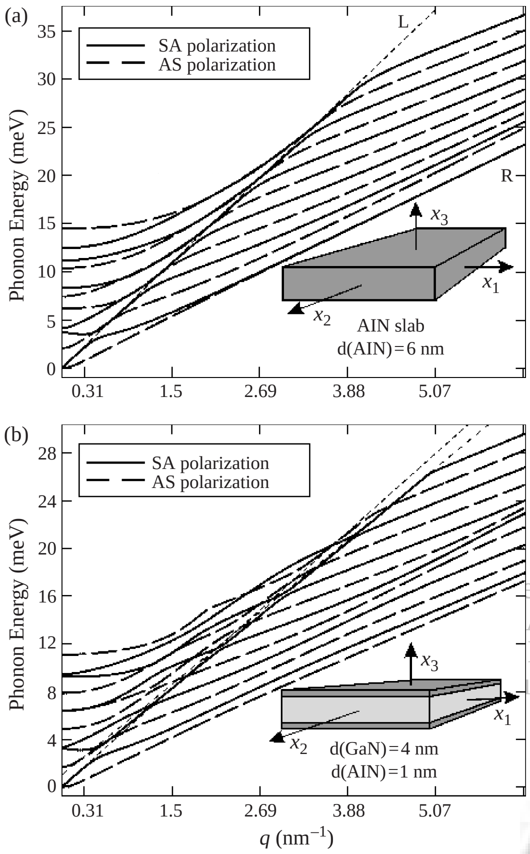

Fig. 1. Phonon energy dispersion in the thin film (slab) and three-layered heterostructure of the symmetric (SA) and antisymmetric (AS) modes. The results are shown for (a) the 6 nm width AlN slab and (b) the heterostructure with the cladding (barrier) layer thickness $d_1 = d_3 = 1.0$ nm and the core layer thickness $d_2 = 4.0$ nm. Inset shows the geometry of the slab and three-layered structure. The results are after Ref [14].

improved or deteriorated career mobility due to the modification of acoustic phonon dispersion.

The interest to the subject has been renewed after Balandin and Wang[10] have pointed out that the confinement-induced changes in the acoustic phonon dispersion can lead to a much stronger effect on thermal conductivity. Specifically, it was shown that cross-plane confinement of acoustic phonon modes leads to in-plane decrease of the average phonon group velocity with corresponding increase of the phonon scattering and reduction in the in-plane thermal conductivity. Before that, the acoustic phonon confinement was only considered in the context of its effect on the charge carrier mobility and electrical conductivity. Decreased averaged phonon group velocity in freestanding thin films or nanowires leads to the increased acoustic phonon relaxation on point defects (vacancies, impurities, isotopes, etc.), dislocations, as well as changes in three-phonon Umklapp processes.[11] Thermal conductivity reduction, being a bad news for thermal management of downscaled electronic devices, is good news for the thermoelectric devices, which require materials with high electrical conductivity and low thermal conductivity.[12]

It was later shown theoretically[13–14] that in the thin films (quantum wells) or nanowires (quantum wires) embedded in the "acoustically fast" or "acoustically hard" materials, the phonon group velocity and thermal conductivity can be enhanced along certain directions (see Fig. 2). Here, an "acoustically fast" material is the one with a higher sound velocity V_S, while an "acoustically hard" material is the one with higher acoustic impedance $Z = \rho V_S$ (ρ is the mass density of the material). The phonon group velocities in Figure 2 are shown as the functions of the phonon wave vector for the shear polarization in AlN/GaN/AlN heterostructure with dimensions 2.5 nm/1 nm/2.5 nm. Notice that the presence of the barrier layers with higher sound velocity increases the phonon group velocity for the whole heterostructure. A possibility of forming the *phonon stop-bands* in quantum dot superlattices made of materials with periodic modulation of Z, and inhibition of the thermal conductivity, beneficial for thermoelectric applications has also been predicted.[15] As a result, the concept of phonon engineering has been extended to include tuning of the acoustic phonon transport to achieve the desired thermal conductivity of the material. Due to the continuing reduction in the electronic device feature size and increased integration densities, the thermal management at nanoscale gains a particular importance.

More recently, the idea of engineering the phonon–electron scattering rates received a new impetus. It was suggested, based on theoretical calculations,[13, 16–18] that the strong phonon confinement could be achieved if one considers a hetero- or nanostructure coated with elastically dissimilar material. Nanostructures embedded into acoustically mismatched matrix are more practical than free-standing ones. In the case of embedded nanostructures, the phonon depletion with corresponding scattering rate suppression can be achieved in acoustically harder materials, while the phonon accumulation occurs in the

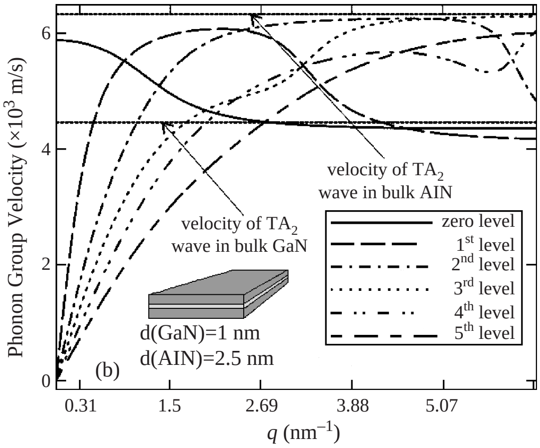

Fig. 2. Phonon group velocities as the functions of the phonon wave vector for the shear polarization. Results are shown for the AlN/GaN/AlN three-layered heterostructure with dimensions 2.5 nm/1 nm/2.5 nm. Notice that the presence of the barrier layers with higher sound velocity increases the phonon group velocity for the whole heterostructure.

acoustically softer material. Figure 3 presents a phonon depletion coefficient for a three-layered acoustically mismatched heterostructure with the barrier layers made of the acoustically soft material. The phonon depletion coefficient ζ_s is defined as a ratio of the elastic energy inside the core layer to the elastic energy in the whole heterostructure.[17] Note that the positive values of depletion coefficient for symmetric phonon modes $\zeta_s^{(SA)}$ indicate the ranges of the phonon wave vector q, for which the lattice vibrations in the core layer of the heterostructure are suppressed. For example, the value $\zeta_s^{(SA)} = 2$ corresponds to the two orders of magnitude suppression. The phonon depletion effect can be used in the design of the nanoscale transistors, vertical metal-oxide-semiconductor field-effect transistor (MOSFET), alternative-gate dielectric transistors, etc. As the transistor feature size W reduces well below the acoustic phonon mean free path (MFP), the possibilities for engineering phonon dispersion to improve the carrier and heat transport increase tremendously.

3. ENGINEERING THE PHONON THERMAL CONDUCTION IN NANOSTRUCTURES

The change in the thermal conductivity of semiconductors due to the phonon confinement bares important consequences for electronic industry in a view of continuous miniaturization. Heat in technologically important semiconductors is mostly carried by acoustic phonons. The feature size of the state-of-art transistor is already well below the room-temperature phonon MFP in Si, which is about 50 nm–200 nm according to different estimates and measurements. In hetero- and nanostructures with feature size W smaller than the phonon MFP, the acoustic phonon spectrum undergoes strong modification and appears quantized provided the structures are free standing or embedded within material of different elastic properties.[14, 17] This modification is particularly strong when the structure feature size becomes much smaller than the phonon meat free path, $W \ll$ MFP, and approaches the scale of the dominant phonon wavelength $\lambda_0 \cong 1.48\ V_S\hbar/k_BT$. Here k_B is the Boltzmann constant, T is the absolute temperature, $\hbar$ is the Plank's constant, and V_S is the sound velocity. For many crystalline materials λ_0 is on the order of 1.5 nm–2 nm at room temperature, which is about the size of the transistor gate dielectric thickness.

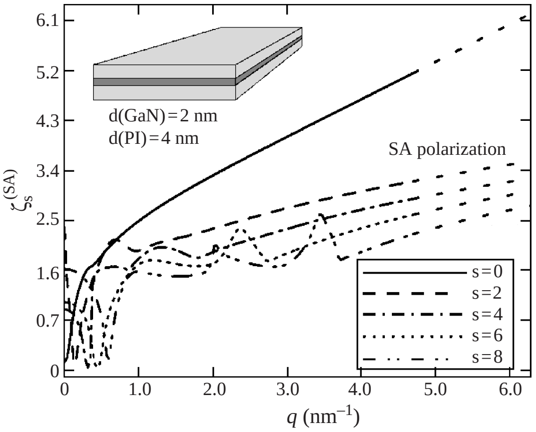

Fig. 3. Phonon depletion coefficient for even symmetric (SA) phonon modes in the core layer of the acoustically mismatched heterostructure. Positive values of depletion coefficient $\zeta_s^{(SA)}$ indicate ranges of the phonon wave vector q, for which the lattice vibrations in the core layer of the heterostructure are suppressed.

Thermal conductivity in plane of thin films or along the length of nanowires can decrease for two basic reasons. The first is the co-called classical size effect on thermal conductivity related to the increased phonon-rough boundary scattering.[19] This effect is pronounced when W is on the order of phonon MFP.[1] It can be observed even in bulk samples at sufficiently low temperature when the phonon MFP is long. The phonon-rough boundary scattering is also referred to as diffuse phonon scattering as opposed to the specular phonon scattering from smooth interfaces. The diffuse phonon boundary scattering contributes to the structure thermal resistance, and thus is always detrimental to excess heat removal and thermal management of ICs. As a result, the "classical size effect" can hardly be viewed as phonon engineering since it does offer tuning capability for phonon properties other than the interface quality. The situation is analogous to the electron band-structure engineering, which essentially constitutes a tuning of the electron wave function through the width and height of the confining potential (not through the electron-boundary scattering). In case of the phonon engineering, acoustic impedance mismatch (or elastic constants discontinuity) plays the role of the band-gap offset.[2]

If the structure dimensions $W \ll$ MFP, a more interesting effect takes place.[10] Due to flattening of the dispersion branches, the population average phonon group velocity decreases leading to the increased phonon scattering on defects and in Umklapp processes.[10–11] As a result, the in-plane thermal conductivity in freestanding thin films or nanowires can be significantly reduced. As one can see in Figure 4, acoustic phonon confinement leads to the reduction of the thermal conductivity even in a nanowire with ideally smooth surface. The effect is analogous to the group velocity change of the electromagnetic wave when it propagates in a waveguide instead of an unbounded free medium. Thus, a semiconductor nanowire can be viewed as a phonon waveguide with loss due to phonon scattering on point defects, dislocations, etc. This mechanism constitutes the *phonon confinement effect* on thermal conductivity along the axis of a nanowire or in-plane of the thin film. It is independent from the "classical" phonon-rough boundary scattering mechanism of thermal conductivity reduction (see Table I). Since the features of phonon spectra determine the phonon confinement effect, the latter can be re-engineered in nanoscale structures through the choice of their materials, sizes and shape.

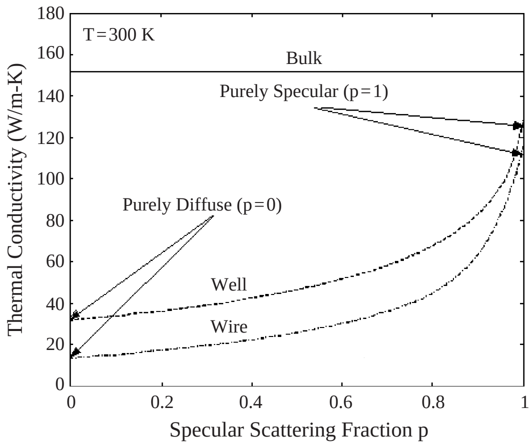

Fig. 4. Thermal conductivity in Si nanowire of diameter 20 nm and Si thin film of 20 nm as a function of the interface roughness parameter (specular scattering fraction p). The results are shown at room temperature. For comparison the bulk thermal conductivity value in Si is shown by the straight line.

Thermal conductivity reduction is bad news for heat removal from downscaled electronic ICs or integrated optoelectronic devices. For some period of time, it has been assumed that the phonon spectrum modification, much like the phonon–rough boundary scattering, can only lead to the reduction of thermal conductivity. Very recently, Balandin et al.[13–14] suggested that embedding nanostructures into "acoustically faster" or "acoustically harder" barrier (cladding) layers could cure the situation or even reverse it (see Figure 2). In the described phenomena, the lateral (cross-plane) confinement of acoustic phonon modes in structures with $W \ll \text{MFP}$ affects the in-plane (along the length) phonon and heat transport. This example shows how the phonon engineering (controlled modification of the phonon spectrum) can mitigate the problem of heat removal.

Our discussion so far was limited to the thermal conduction along the length of a nanowire or in plane of a thin film. The role of the boundaries was to change the phonon dispersion relation (spectrum) and, unavoidably, introduce an extra thermal resistance owing to the phonon-rough boundary scattering. Thermal transport through the interface between two materials (cross-plane) is strongly affected by the Kapitza resistance, which is also referred to as the thermal boundary resistance (TBR). The significance of Kapitza resistance in thermal management of electronic circuits increases due to the increasing number of layers and interfaces in ICs, the use of dissimilar materials, like those in silicon-on-insulator (SOI) structures, and the fact that a large thermal gradient in ICs is across the layers. In the case of nanostructured materials such as quantum dot superlattices (QDS), the Kapitza resistance can be strongly entangled with the phonon spectrum modification and phonon scattering.[20]

Table I. Phonon transport regimes.

Scale	Phonon dispersion	Dominant scattering processes
$L \gg \text{MFP}$	bulk dispersion	• three-phonon Umklapp • point defects
$\lambda_0 \ll L \leq \text{MFP}$	bulk dispersion	• three-phonon Umklapp • point defects • boundary scattering
$\lambda_0 \leq L \ll \text{MFP}$	modified dispersion with many phonon branches populated	• three-phonon Umklapp • point defects • boundary scattering
$L < \lambda_0$	modified dispersion; only lowest phonon branches populated	• ballistic transport

Experimental developments in the field have been somewhat slower than the theory. The latter is mostly explained by difficulties in measuring thermal conductivity of single nanostructures. Recently, Li et al.[21] reported results of the measurement of the thermal conductivity in a single crystalline free-surface Si nano-wires with diameters as small as 22 nm. The authors experimentally observed a more than an order of magnitude decrease of the thermal conductivity in such nanowires, from $K = 145$ W/cmK in bulk Si to $K \sim 9$ W/cmK in Si nanowire at $T = 300$ K. The measured value was in excellent agreement with the earlier theoretical prediction of thermal conductivity value of 13 W/cmK for 20 nm Si nanowire at $T = 300$ K.[11] The prediction of Zou and Balandin[11] was based on the calculation, which took into account both the acoustic phonon-boundary scattering and the phonon dispersion modification. Y. Bao et al.[22] investigated the thermal and electrical conductivity in Ge/Si quantum dot superlattices (QDS) with different quantum dot size (deposited Ge layer thickness is 12A, 15A and 18A, respectively). Thermal conductivity has been measured as a function of temperature T from 4 K to 400 K using the 3ω method. An order of magnitude decrease in the thermal conductivity and shift of its peak position to higher temperatures has been consistently observed for all samples. The thermal conductivity varied as $T^{0.7}$–$T^{0.9}$ for temperature T below 200 K (see Figure 5).

4. PHONON DEPLETION IN ACOUSTICALLY MISMATCHED NANOSTRUCTURES

Spatial confinement of acoustic phonons in nanoscale structures with the large mismatch of the acoustic impedances $Z = \rho V_S$, at the interfaces (boundaries) can strongly affect the phonon spectrum and substantially modify the electron–phonon interaction in comparison with bulk. In such structures, both confinement of electron states and acoustic phonons should be taken into account while calculating the scattering rates. Pokatilov et al.[17] have recently shown theoretically that the phonon population in thin films or nanowires embedded into acoustically softer materials can be depleted, and the carrier-phonon scattering rate is suppressed. The latter is

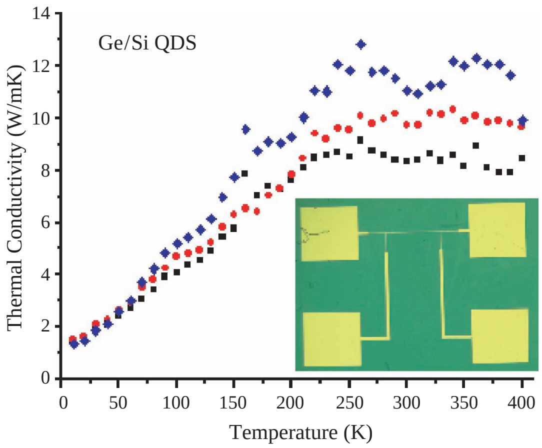

Fig. 5. Measured temperature dependence of the thermal conductivity for three Ge/Si quantum dot superlattices. Three samples are characterized by different thickness of the deposited Ge layer. Inset shows the heater-thermometer fabricated on top of the sample for the thermal conductivity measurements by the 3ω technique.

achieved if the nanostructure parameters (diameter, interface, mass density) are properly tuned and $Z_{\text{inside}} > Z_{\text{matrix}}$. This effect can be used to suppress the inelastic scattering in nanowires and increase electron carrier mobility (see Fig. 3).

The physical origin of the described phonon depletion in the core layer of the acoustically mismatched heterostructure is redistribution of the displacement components (lattice vibrations), which leads to the situation when there are much less lattice vibrations in the core layer than in acoustically "soft" cladding layers. The latter is illustrated in Figure 6, which shows the components $w^{\text{SA}}_{1,s=1}(x_3, q)$ (upper panel) and $w^{\text{SA}}_{3,s=1}(x_3, q)$ (lower panel) of the vibration amplitude vector $\mathbf{w}^{\text{SA}}_{1,s=1}(x_3, q)$ as the functions of the phonon wave vector q and coordinate x_3 along the structure growth direction (across the planes). Details of the calculations are given in Ref. [17]. Note that the displacement component surfaces are nearly flat and close to zero inside the core layer of the heterostructure while the amplitudes of vibrations are high in the cladding layers. Similar dependence is observed for other confined phonon modes.

Another interesting effect, within the phonon-engineering approach, is the predicted formation of the phonon stop-bands (PSB) in nanostructures with periodic modulation of the elastic constant values. Drawing on the analogy with the photon band gap materials, Balandin et al.[23] have shown using the elastic continuum approximation that the acoustic phonon propagation can be inhibited along certain directions in three-dimensionally (3D) regimented QDS with the appropriately chosen parameters. It has been also demonstrated that for the realistic quantum dot parameters (dot size is few nanometers) it is possible to achieve a stop band in the phonon energy range that affects the value of the thermal conductivity tensor. The latter may lead to a novel way for thermal conductivity reduction and for increasing the thermoelectric figure of merit of nanostructured materials.

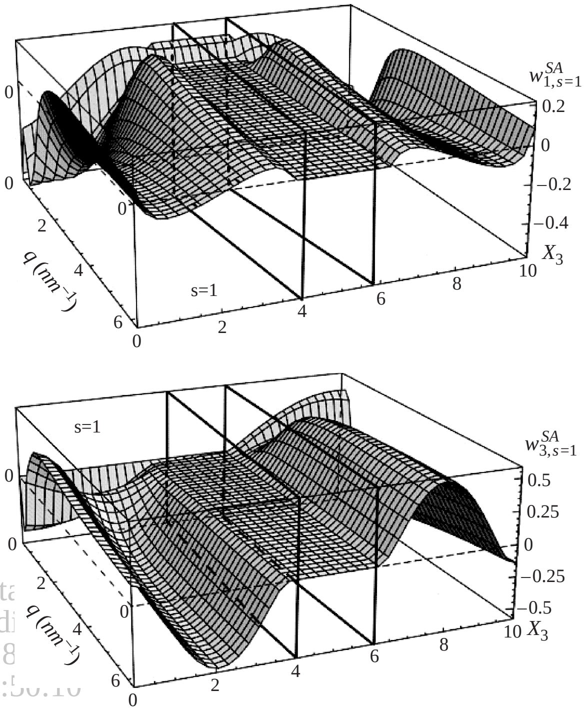

Fig. 6. Illustration of the phonon depletion in the thin core heterostructure layer embedded within acoustically soft barrier layers. Components of the vibration amplitude vector are shown as the functions of the phonon wave vector q and coordinate x_3 along the structure growth direction (across the planes). Note that the displacement component surfaces are nearly flat and close to zero inside the core layer of the heterostructure while the amplitudes of vibrations are high in the cladding layers. Results are after Ref. [17].

Imamura and Tamura[24] theoretically studied a somewhat related effect of the acoustic phonon lensing in anisotropic crystalline slabs. Lacharmoise et al.[25] have experimentally demonstrated that the low energy phonons can be strongly confined in semiconductor acoustic microcavities. The conclusion was based on Raman scattering study of acoustic phonons confined in planar GaAs/AlAs phonon cavities. The authors observed a huge increase in Raman signal in phonon cavities when the maximum of the acoustic and optical fields were tuned exactly at the same location.[25] The proposed phonon lenses and phonon reflectors together with the acoustically mismatched heterostructures[12, 17] significantly extend the phonon engineering concept and can be incorporated to the building blocks of future phonon-engineered nanodevices.

5. PHONONS IN HYBRID BIO-INORGANIC NANOSTRUCTURES

Properties of phonons in biological or hybrid bio-inorganic systems are significantly different from those in conventional semiconductor materials. Hybrid systems are particularly interesting from the phonon-engineering point

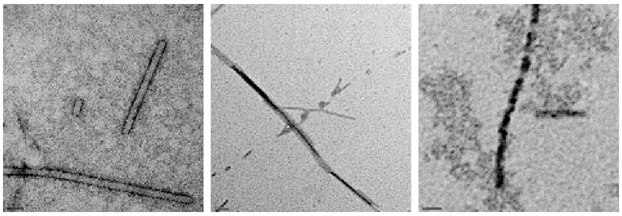

Fig. 7. TEM micrograph of a single 300 nm long TMV virus used as a rod-shaped nano-template (left panel); Pt coated TMV end-to-end assembly right after the reaction (middle panel); and Pt coated TMV end-to-end assembly 20 minutes after the reaction (right panel).

of view due to significant mismatch of the acoustic impedance at the interface between bio and inorganic materials. The specifics of phonon spectrum and phonon transport in hybrid bio-inorganic nanostructures can provide valuable information about the properties of bio-inorganic interfaces. Hybrid bio-inorganic nanostructures may also offer some properties beneficial for the carrier transport. In addition, the knowledge of phonon modes in such hybrid structures can be used to monitor the synthesis of these structures.

Interesting examples of the bio-inorganic nanostructures are functionalised plant viruses. Recently, tobacco mosaic viruses (TMV) have been utilized as biological templates in the synthesis of semiconductor and metallic nanowires.[26–27] They were also proposed as elements in the hybrid nanoelectronic circuits. TMV viruses have cylindrical shape and suitable dimensions: they are 300 nm long, 18 nm in diameter and with a 4 nm in diameter axial canal Figure 7 shows transmission electron microscopy (TEM) micrographs of a single rod-shaped 300 nm long TMV virus, Pt coated TMV end-to-end assembly right after the chemical reaction, and Pt coated TMV end-to-end assembly 20 minutes after the coating reaction. Since these viruses have the diameters of the same order of magnitude as diameters of semiconductor nanocrystals and nanowires, elastic vibrations of TMV manifest themselves in low-frequency Raman scattering spectra. The knowledge of the low-frequency vibrational modes of the viruses is important for interpretation of Raman spectra and monitoring the template-based chemical assembly processes (see Figure 8).

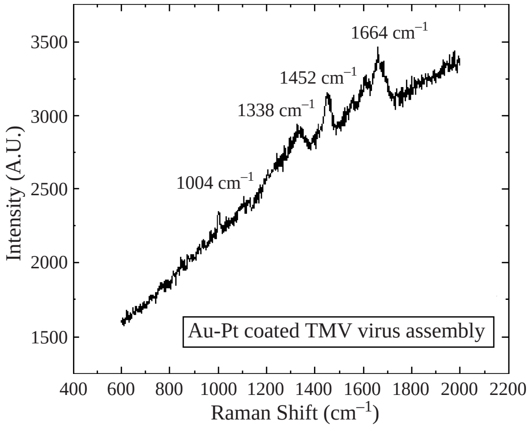

Fig. 8. Raman spectrum of Au-Pt-coated TMV viruses. Some of the characteristic optical phonon peaks are shifted from their position in pure TMV samples indicating changes in vibrational modes.

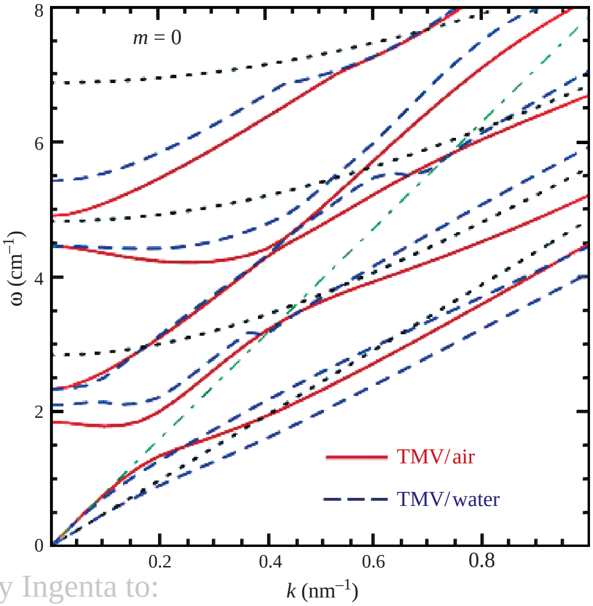

Fig. 9. Calculated dispersion of the lowest phonon modes with circumferential quantum number $m = 0$ for TMV virus used nano-template. Solid (dashed) lines correspond to the radial-axial vibrations in air (water). Dotted lines correspond to the torsional vibrations. Dash-dotted line marks the sound velocity of water. Results are after Ref. [28].

Fonoberov and Balandin[28–30] have theoretically studied the low-frequency vibrational modes of TMV and M13 viruses used for nanoelectronic self-assemblies. The radial breathing modes of TMV and M13 viruses in air are found to be 1.85 cm^{-1} and 6.42 cm^{-1}, respectively. If the viruses are in water, the above frequencies become 2.10 cm^{-1} and 6.12 cm^{-1}, respectively. Figure 9 presents the calculated dispersion of the lowest phonon modes with circumferential quantum number $m = 0$ for TMV viruses used as nano-templates. Here, solid (dashed) lines correspond to the radial-axial vibrations in air (water), while the dotted lines correspond to the torsional vibrations. The dash-dotted line marks the sound velocity of water. Details of the calculations can be found in Refs. [28–29].

6. CONCLUSIONS

The paper reviews the development of nanophononics, a new sub-field of nanoscale science, which deals with the properties of phonons in nanostructures and approaches to control phonon dispersion in nanostructures, i.e., phonon engineering. The review focuses on methods of tuning the phonon spectrum in acoustically mismatched nano- and heterostructures in order to change the thermal and electrical conductivity. Some approaches for the electron–phonon scattering rates suppression, formation of the phonon stop-bands and phonon focusing are discussed. The specifics of phonon spectrum in biological and hybrid bio-inorganic nanostructures are also addressed.

Acknowledgments: The author is indebted to the current and former members of the Nano-Device Laboratory (NDL) research group Dr. J. Zou, Dr. V. A. Fonoberov, Dr. W. L. Liu and Dr. D. Nika who contributed to the theoretical and experimental study of phonons in nanostructures. Special thanks go to Prof. E. P. Pokatilov for illuminating discussions of phonon transport during his visits to NDL. The nanophononics research in NDL (http://ndl.ee.ucr.edu/) was supported in part by NSF, SRC and ONR.

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Received: 27 January 2005. Revised/Accepted: 15 April 2005.