RSD 8961-PH-01

AD

PHONON TECHNOLOGIES FOR HIGH-SPEED MICROELECTRONICS AND OPTOELECTRONICS.

Final Technical Report
by
Prof. V. A. Kochelap
(January 2002)

United States Army

EUROPEAN RESEARCH OFFICE OF THE U.S. ARMY

London, England

CONTRACT N68171-01-M-5166

Institute of Fundamental Problems
for High Technology
Kiev, Ukraine

Approved for Public Release; distribution unlimited

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	January 2002	Final Report, January 2002

4. TITLE AND SUBTITLE
PHONON TECHNOLOGIES FOR HIGH-SPEED MICROELECTRONICS AND OPTOELECTRONICS.

5. FUNDING NUMBERS
c- N68171-01-M-5166

6. AUTHOR(S)

Prof. V. A. Kochelap

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Institute of Fundamental
Problems for High Technology
Kiev, PO Box 58, 03028
UKRAINE

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EUROPEAN RESEARCH OFFICE
OF THE U.S. ARMY,
Edison House, 223 old Marylebone Road
London, England

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 Words)*

In this report we present the results on innovative phonon technologies for high-speed microelectronics an optoelectronics. The electrical methods of generation of high-frequency coherent phonons in quantu heterostructures are studied. Efficient electric generators of sub-terahertz and terahertz acoustic and optica phonons are suggested on the base of practically important materials and heterostructures including Si/SiGe AlGaAs/GaAs, GaSb/InAs, etc.

The presented results create solid fundamentals for practical developing electric generators of high-frequency coherent phonons and implementation of the phonon technologies, which will gain strategic advantages for numerous applications in high-speed microelectronics and optoelectronics

14. SUBJECT TERMS Phonon technology, terahertz frequency range, quantum heterostructures, coherent phonons, phonon generators, electric methods of phonon generation.

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	UL	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

FINAL REPORT

PHONON TECHNOLOGIES FOR HIGH-SPEED MICROELECTRONICS AND OPTOELECTRONICS.

Contract N68171-01-M-5166

Abstract:

In this report we present the results on innovative phonon technologies for high-speed microelectronics and optoelectronics. The electrical methods of generation of high-frequency coherent phonons in quantum heterostructures are studied. Efficient electric generators of sub-terahertz and terahertz acoustic and optical phonons are suggested on the base of practically important materials and heterostructures including Si/SiGe, AlGaAs/GaAs, GaSb/InAs, etc.

The presented results create solid fundamentals for practical developing electric generators of high-frequency coherent phonons and implementation of the phonon technologies, which will gain strategic advantages for numerous applications in high-speed microelectronics and optoelectronics.

Keywords:

Phonon technology, terahertz frequency range, quantum heterostructures, coherent phonons, phonon generators, electric methods of phonon generation.

Participants of the project:

Prof. V. A. Kochelap (PI), Dr. B. A. Glavin, Dr. A. A. Demidenko, Dr. V. N. Sokolov, Dr. V. V. Naumov, T. L. Lynnik and I. A. Fedorov (PhD-students).

Table of Contents:

Background:

It is well known that in solids the electron-phonon coupling is always much stronger than the coupling between microwave emission and electrons. If there existed reliable high-frequency phonon sources, it could trigger a number of phonon applications to control both, high-speed electric and optical signals. Indeed, phonon frequencies cover a very wide frequency range including sub-THz and THz frequencies. Being excited high-frequency *coherent phonons* can control the electric current due to electron-phonon coupling. Particularly, a flux of coherent phonons or a coherent phonon standing wave can modulate the electric current, i.e., it provides new methods of generation of ultra-high frequency electric oscillations. Similarly, interaction of coherent phonons with a light beam leads to modulation of light at phonon frequency (stimulated Brillouin and Raman scattering by intense coherent acoustic or optical phonons) and can provide an efficiently controlled beam deflection. Besides, engineered and controlled phonons (lattice vibrations) can significantly enhance the performance of a wide range of devices.

In addition, intense fluxes of short-wave phonons could have other technological applications, for example, nondestructive testing and treatment microstructures and materials.

Thus a wide range of novel phonon-based devices and applications are possible. These phonon technologies demand the elaboration of special technique to generate, detect and control the lattice vibrations.

The elaboration of *electrical methods* of generation of coherent phonons in solids is the problem of primary importance. Generators of high-frequency coherent phonons would open wide possibilities for development of innovative concepts and methods, and novel devices for ultra-high-speed microelectronics and optoelectronics. Among these generators those are the most interesting, which can be directly integrated with semiconductor devices.

The advantages of using phonon-technologies include:
- Ultra-high frequencies; ultra-short-wavelengths; highly collimated beams; electric methods; efficient electric control; high efficiency of transformation of electric energy.
- Possibilities to be integrated with other microelectronic circuits and optoelectronic systems.
- The use of different materials: III-V compounds, including wide-gap nitrides, GaN/AlGaN, which possess strong electron-phonon coupling, Si/Ge heterostructures.

Some applications of high-frequency coherent phonons to solve actual problems are:
- THz-modulation of optical signals. THz-electric oscillations.
- Phonon enhancement of electronic and optical devices through phonon active control of electron transport, phonon induced photo-transitions in indirect-gap semiconductors and heat removal through stimulated phonon decay, etc
- Miniature deflectors for light-beam control integrated with semiconductor lasers. Nondestructive testing of nanostructures by short-wave coherent phonon beams (phonon wavelengths can be scaled down to 10 nm).
- Processing (treatment) of surfaces and interfaces, fabrication of nano-relief with 10 nm scale (phonon-lithography).
- X-ray deflectors.

Development of efficient electric generators of coherent high-frequency phonons is a long-standing problem. This study proposes and justifies innovative approach to practical realization of phonon technologies.

Technical results:

The project aim was the analysis of new phonon technologies for microelectronic and optoelectronic applications. We have identified and developed innovative efficient and powerful electrical methods of generation coherent phonons in THz-frequency range. These include generation of short-wave sub-THz-acoustic phonons and THz-optical phonons under electron drift in quantum heterostructures (the Cerenkov generators), and generation of THz-phonons under vertical electron transport through multi-barrier structures (the 'phonon laser').

Quantum heterostructures based on different practically important materials have been analyzed including Si/Ge-based structures and III-V-compound-based structures, some estimates have been made for nitride-base heterostructures. Analysis of basic parameters of generated phonons - frequency bandwidths, intensities of phonon fluxes, efficiency of conversion of the electric energy into the energy of high-frequency phonons has been performed.

The Cerenkov electric generation of sub-THz confined acoustic phonons in quantum wells (QWs). To study the generation of high-frequency phonons in QWs we have analyzed acoustic phonon confinement in elastically anisotropic (cubic) QW-heterostructures grown in a direction of high symmetry. We have established a general criterion for phonon confinement and found the dispersion curves, the displacement fields corresponding to the confined phonons for $Si/Si_{0.5}Ge_{0.5}/Si$, Si/Ge/Si and AlAs/GaAs/AlAs QW-heterostructures. It has been shown that confinement of acoustic phonons in these QW layers is especially strong in the sub-terahertz and terahertz frequency range. Two main electron-phonon coupling mechanisms – interaction via deformation potential and piezoelectric interaction – have been considered. Using these results we have analyzed amplification of the confined modes by the drift of the two-dimensional carriers as function of phonon frequency, crystal temperature, electron drift characteristics and other parameters of the heterostructures. It has been established that the amplification coefficient of the confined phonons can exceed 10^3 cm^{-1} for the Si/Ge-based structures and 10^2 cm^{-1} for the AlAs/GaAs-based structures. In both cases, Si/Ge- and III-V-based structures, the electric current amplifies the shear-vertical confined phonons, which comprises both longitudinal

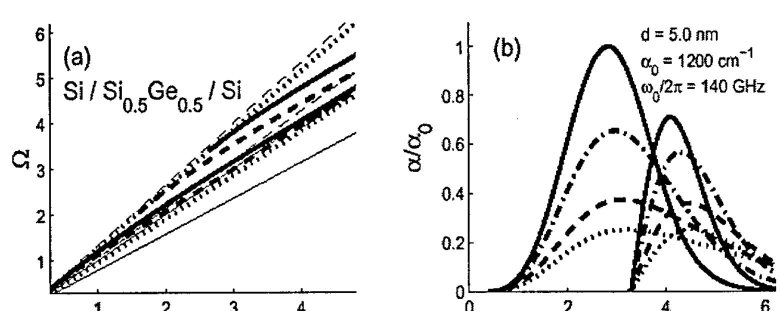

Fig. 1 The dispersion dependence (the left panel) and the amplification coefficient (the right panel) for confined modes in Si/SiGe QW.

and transverse lattice vibrations. Purely transverse vibrations can be amplified as shear-horizontal waves in III-V-compounds devices. In Fig. 1, *a* the dispersion of lowest confined shear-vertical phonon modes are presented (thick solid and dashed lines for anti-symmetric and symmetric modes, respectively). In Fig. 1, *b* spectral dependences of the amplification coefficient is shown for the 5 nm width QW for two modes at four temperatures 50, 100, 150 and 300 K, the carrier concentration is 2.10^{12} cm^{-2}. The electrons amplify the symmetric shear-vertical modes, the amplification coefficient decreases when the temperature increases.

Frequencies for generated phonons as functions of the QW width are presented in Fig. 2 (SiGe - the upper curves, AlGaAs - the lower curve). It can be seen that a wide sub-terahertz frequency range is covered by the electrical method of generation of the acoustic phonons. The appreciable frequency tuning can be made by choosing the QW width parameter.

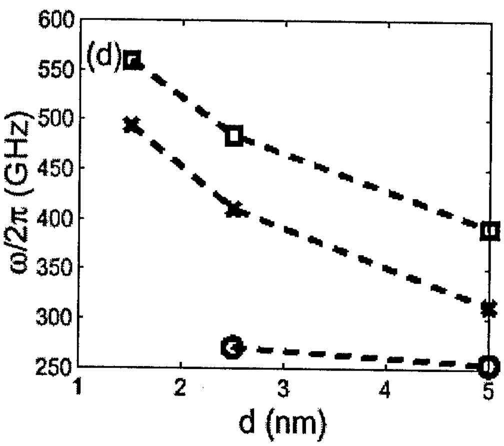

Fig. 2. The frequencies generated by the electric current in SiGe and AlGaAs QW heterostructures.

<u>*The Cerenkov electric generation of optical phonons in quantum wells.*</u> We have analyzed he drift of two-dimensional electrons in QWs under conditions of strong coupling to confined optical phonons. We have found that the electric current can excite the instability of the optical phonon subsystem: populations of the optical phonon modes confined within the QW layer can grow exponentially in time, if for the drifting electrons the Cerenkov criterion is met. A general formula for the phonon increment has been derived. The electron screening of the electron-confined optical phonon interaction is incorporated into this formula. The phonon increment has been analyzed in detail as a function of the phonon wave vector, electron-phonon coupling and

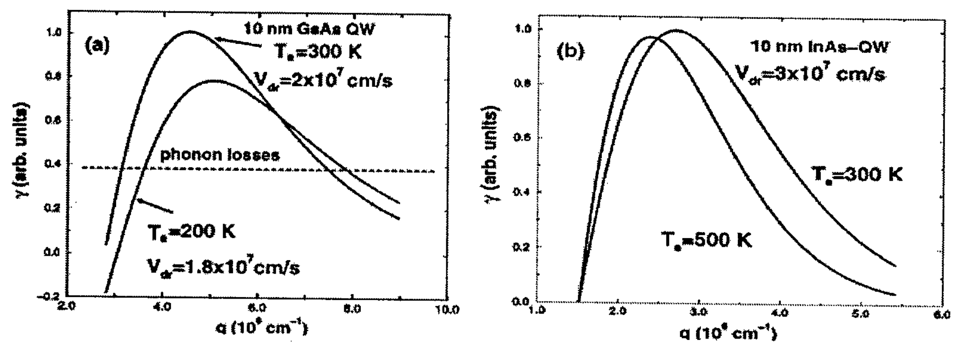

Fig. 3. The phonon increment as a function of the optical phonon wave vector for two particular heterostructures: AlAs/GaAs/AlAs - the left panel and AlGaSb/InAs/AlGaAs - the right panel.

electron kinetic parameters – the electron temperature and the drift velocity. The optical phonon losses (the phonon lifetimes) have been estimated. Next, we have performed numerical estimates of the phonon increment for several particular heterostructures. It was established that in selectively doped AlAs/GaAs/AlAs and AlGaSb/InAs/AlGaAs quantum wells – which exibit high drift velocities – electric current can generate coherent confined optical modes. In Fig. 3 the optical phonon increment is shown for these heterostructures, the WQ width is supposed to be 10 nm. The electron parameters – the drift velocity and temperature are indicated in the figure. The frequencies of generated optical phonons are 8.8 THz and 7 THz for AlAs/GaAs/AlAs and AlGaSb/InAs/AlGaAs, respectively.

We have shown that the phonon increment depends critically on the electron drift velocity. One of the important results is that if the criterion for the Cerenkov emission is met, the phonon increment has a maximum as a function of the phonon wave vector. The latter leads to discrimination among the different optical phonon modes and to the generation of a very narrow phonon distribution, i.e., to generation of highly-coherent optical phonons.

We have analyzed regimes of generation of confined optical phonons in QWs under the electric pumping. To treat the phonon and drifting-electron subsystems self-consistently we have calculated the phonon increment as a function of the electron temperature and drift velocity, while in the balance equations of the electron energy and momentum we have incorporated the terms describing the energy and momentum losses due to coherent phonon emission. As a result of the analysis of the coupled nonlinear equations, we have found steady-state generation regimes with macroscopic populations of the optical phonon modes and electron transport appreciably controlled by the generated phonons. The generation regimes have a pronounced threshold character under variation of the applied electric field, as shown in Fig. 4 (the left panel). Above the threshold, a fast narrowing of the range of wave vectors of generated phonons results practically in a single mode generation. The generated mode is highly populated, which leads to coherent macroscopic optical displacements of the lattice and large amplitudes of oscillations of the electrostatic fields conveying the optical vibrations. We have established that the electron parameters, such as the temperature and drift velocity, are affected by the generated phonons: at a given electric field their magnitudes are considerably suppressed and negative differential conductivity can occur. We have estimated the efficiency of transformation of the electric power to coherent optical vibrations, the efficiency can reach values of the order of 50%, as presented in Fig. 4 (the right panel).

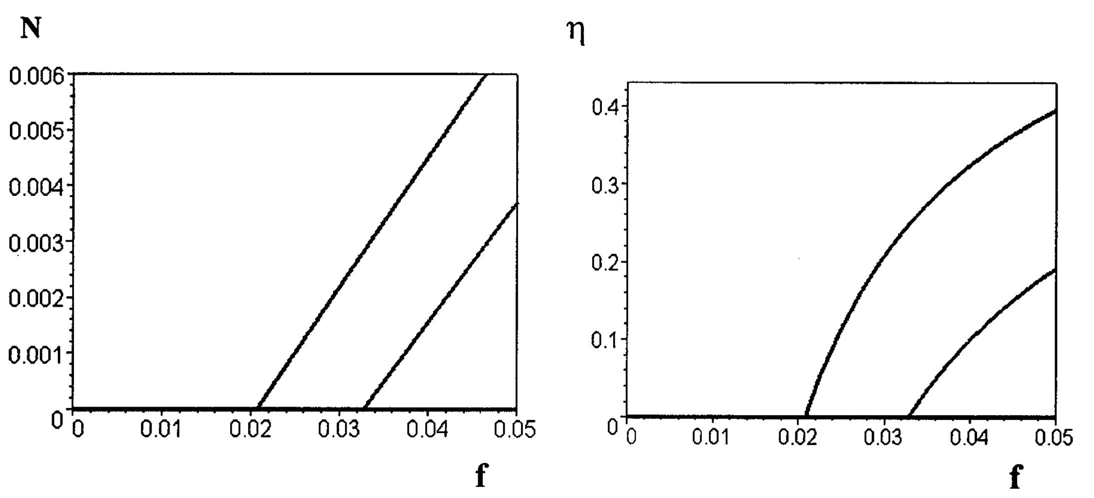

Fig. 4. Demensionless population of generated optical phonons **N** (the left panel) and the efficiency of optical phonon generation η (the right panel) as functions of the electric field **f** for AlGaAs-QW at two values of phonon losses (the phonon lifetime is 10^{-11} s for upper curves and 5 10^{-12} s for lower curves). The frequency of generated phonons is 8.8 THz. **N =1** corresponds to 1.6 10^{16} phonon/cm^2.

Electron transport under strong electron-optical phonon interaction. Besides the results on generation of the coherent phonons, analyzing drift of carriers in high-electric fields we have found that strong electron-optical phonon coupling leads to extremely non-equilibrium distribution function of the electrons. Particularly it has been established that in nanoscale samples emission of optical phonons gives rise to population inversion of the carriers. This provides for a high-frequency electron instability and microwave generation in sub-terahertz range (0.2..0.5 THz). The results have been applied to nitride-based semiconductor nanoscale heterostructures such as AlGaN/GaN and GaN/InGaN.

The THz acoustic phonon generator using voltage biased multi-barrier structures. We have considered high-frequency phonon generation in a weakly coupled, n-doped semiconductor superlattice. Electric bias, applied to such a superlattice, destroys the electron minibands, creates electron states localized in the individual quantum wells (the Stark-splitting effect) and forms population inversion between these states. An electric current occurs due to the phonon-induced interwell hops. We have shown that under such conditions the electric current produces a phonon instability: populations of phonon modes propagating almost collinearly with the superlattice axis increase exponentially in time. It has been demonstrated that the population growth increment can be as high as several times 10^8 s^{-1} and exceeds considerably the internal phonon scattering rates. The frequency (energy) dependence of the increment is shown in Fig. 5 (the right panel) for a given electric field (Stark-splitting). Effects influencing the increment, such as screening of the electron-phonon interaction and modification of phonon spectrum in superlattices, have been discussed. For electrically biased superlattices demonstrating the effect of phonon instability we have analyzed nonlinear problem of high-frequency acoustic phonon generation. We developed the theory treating self-consistently the phonon generation and electron transport through the superlattice. We found that the main mechanism providing the steady-state generation regime is the electron heating caused by the nonequilibrium phonons. It is shown that under the generation regime the spectral distribution of phonons is extremely narrow (a single mode generation – the 'phonon laser'). The generated power density can be as high as 10^5 W/m^2 for terahertz phonons (see Fig. 5, the left panel). The electric current is controlled by the nonequilibrium phonons and is higher by an order of magnitude than that under the subthreshold conditions.

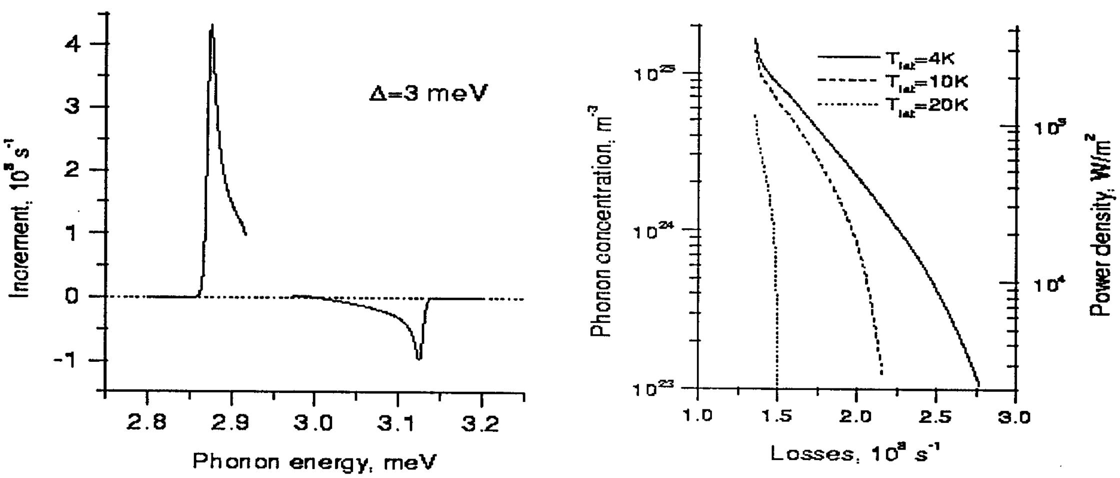

Fig. 5. Left panel: the phonon increment as a function of the phonon energy. Right panel: the phonon occupation density (left axis) and generated power density (right axis) as functions of phonon losses under generation regimes at different lattice temperatures. For both panels Stark-splitting is 3 meV.

Brief summary. The study of amplification and generation of acoustic and optical phonons under the electron current has been carried out. Three different generators of high-frequency phonons have been suggested: (i) the sub-terahertz Cerenkov phonon generator of acoustical phonons in multilayered heterostructures; (ii) the the Cerenkov phonon generator of confined optical phonons; (iii) the THz-acoustic phonon generator using voltage biased superlattices. All suggested generators are based on practically important materials and heterostructures. A high efficiency of transformation of the electric energy into the energy of coherent phonons is proved. The obtained results create solid fundamentals for practical development electric generators of high-frequency coherent phonons and implementation of the phonon technologies, which will gain strategic advantages for numerous applications in microelectronics and optoelectronics.

Implementation of the results:

During the course of this project the working relations with US Army Research Office (Research Triangle Park, NC, USA) have been established. Particularly, all the results of the project were discussed with Dr. M. A. Stroscio from the Electronic division of ARO. The PI of this project, Prof. V. A. Kochelap, and researcher Dr. B. A. Glavin visited North Carolina in February - 2001 and April - 2001 for discussion of the results and their implementation for the Army. Application of the results to wide gap materials was also discussed with Dr. J. Zavada.

Besides a close collaboration and exchange of technical information have been set up with the group of Prof. K. W. Kim, which works on the problems of phonon enhancement of electronic device performance. These studies are supported by the US Army Research Office, as well as by the Air Force Office of Scientific Research in the frame of MURI-project "A COMPREHENSIVE APPROACH TO PHONON CONTROL FOR ENHANCED DEVICE PERFORMANCE" monitored by Maj. D. Johnstone.

Publications of the results:

The basic obtained results were discussed on several international conferences and described in series of the papers. The support by the European Research Office is acknowledged. The list of published or submitted to research journals papers is:

1. S. M. Komirenko , K. W. Kim, V. A. Kochelap, I. Fedorov, M. A. Stroscio. Coherent optical phonon generation by the electric current in quantum wells Appl. Phys. Lett., **77**, (25): 4178-4180 (2000).
2. M. A. Stroscio, S. M. Komirenko, K. W. Kim, A. A. Demidenko, V. A. Kochelap, Amplification and generation of high-frequency coherent acoustic phonons under the drift of 2D-electrons. The "Proceedings of the 25th International Conference on the Physics of Semiconductors" ed. by N. Miura and T. Ando. Springer Verlag (2001).
3. S. M. Komirenko, K. W. Kim, V. A. Kochelap, I. Fedorov, M. A. Stroscio, Generation of coherent optical phonon under the drift of two-dimensional electrons. Phys. Rev. **B 63**, 165308 (2001).
4. 62. B. A. Glavin, V. A. Kochela, T. L. Linnik, K. W. Kim, M. A. Stroscio. Generation of High-Frequency Coherent Acoustic Phonons in Biased Superlattices. Proceedings of 14-th International Conference on the Electronic Properties of Two-Dimensional Systems, p. 357-360, Prague (2001).
5. S. M. Komirenko, K. W. Kim, V. A. Kochelap and M. A. Stroscio. Amplification of transverse acoustic phonons in quantum well heterostructures with piezoelectric interaction. J. Appl. Phys., **90**, n. 8, 3934-3941 (2001).
6. S. M. Komirenko, K. W. Kim, V. A. Kochelap, M. A. Stroscio, Runaway effects in nanoscale group-III-nitride devices. Phys. Rev. **B 64**, 113207 (2001).
7. E. A. Barry , K. W. Kim and V. A. Kochelap. Group-III Nitrides Hot Electron Effects in Moderate Electric Fields Phys. Stat. Sol.**(b) 228** ,No.2, 571 –574 (2001).
8. B. A. Glavin, V. A. Kochelap, T. L. Linnik, K. W. Kim, M. A. Stroscio. Generation of high-frequency coherent acoustic phonons in superlattices under hopping transport. II.~Steady-state phonon population and electric current in generation regime. Phys. Rev. **B 65**, February, 15 (2002).
9. B. A. Glavin, V. A. Kochelap, T. L. Linnik, K. W. Kim, M. A. Stroscio. Generation of high-frequency coherent acoustic phonons in superlattices under hopping transport. I.~Linear theory of phonon instability. Phys. Rev. **B 65**, February, 15 (2002).
10. S. M. Komirenko, K. W. Kim, V. A. Kochelap and M. A. Stroscio. Theory of electrical generation of confined THz acoustical phonons in quantum wells. To be published in Physica B (2002).
11. S. M. Komirenko, K. W. Kim, V. A. Kochelap and M. A. Stroscio. Confinement and amplification of acoustic waves in cubic heterostructures. Submitted to Phys. Rev. B.

Appendixes:

APPLIED PHYSICS LETTERS VOLUME 77, NUMBER 25 18 DECEMBER 2000

Coherent optical phonon generation by the electric current in quantum wells

S. M. Komirenko and K. W. Kim[a)]
Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina 27695-7911

V. A. Kochelap and I. Fedorov
Department of Theoretical Physics, Institute of Semiconductor Physics, National Academy of Sciences of Ukraine, Kiev, 252650, Ukraine

M. A. Stroscio
U.S. Army Research Office, Research Triangle Park, North Carolina 27709-2211

(Received 14 July 2000; accepted for publication 25 October 2000)

This letter addresses the effect of generation of confined LO phonons by drifting electrons in quantum wells. We have derived a general formula for the phonon increment as a function of phonon wave vector, electron drift velocity, and structure parameters. Numerical estimates of the phonon increment and the phonon lifetimes have shown that AlAs/GaAs/AlAs and GaSb/InSb/GaSb quantum well structures can demonstrate the effect of coherent LO phonon generation by the electric current. © *2000 American Institute of Physics.* [S0003-6951(00)03152-1]

High-frequency coherent acoustic and optical phonons have been observed for a number of semiconductor materials and heterostructures.[1,2] These studies provide information on the excitation mechanisms of the coherent phonons, their dynamics, electron-phonon interactions, and other important phenomena. Intense coherent phonon waves can be exploited for various applications, particularly for terahertz (THz) modulation of light and generation of high-frequency electric oscillations. Usually, high-frequency coherent phonons are excited optically by ultrafast laser pulses.[1,2] The development of electrical methods of coherent phonon generation is a long-standing and important problem.

An electric current flowing though a semiconductor can produce coherent acoustic and optical phonons via the Cerenkov effect when the electron drift velocity exceeds the phonon phase velocity. Following three requirements are necessary for practical use of the Cerenkov effect: high electron mobilities, large electron densities, and strong coupling between electrons and amplifying phonons. For *acoustic phonons* this effect has been studied intensively for bulk samples.[3] Generation of phonons of frequency below 10 GHz has been achieved. Very recently, it was found that in heterostructures the drifting two-dimensional (2D) electrons can provide amplification of confined acoustic phonons in the sub-THz frequency range.[4] Analysis of the Cerenkov effect for *optical phonons*[5] has shown that their amplification (generation) by drifting electrons in bulk materials is practically impossible: the rate of the phonon generation cannot compete with the large rate of phonon losses.

Advanced technology of semiconductor heterostructures allows one to manipulate electron and phonon properties and opens new possibilities to employ the Cerenkov effect for optical phonon generation. Indeed, for confined electrons in modulation doped heterostructures, two conditions—high electron drift velocities (much greater than that in necessarily-heavy doped bulk samples) and large electron densities—are already realized. Then, *simultaneous confinement* of electrons and optical phonons within the same quantum well (QW) provides the necessary strong coupling. These can result in a large Cerenkov effect, which now may compete with phonon losses. This letter addresses generation of *confined optical phonons* by the electric current in a QW layer.

Consider a heterostructure where electrons are confined in the QW layer A embedded in a semiconductor material B (the barrier layers). The thickness of layer A is L. Let the z coordinate be perpendicular to the layers and x and y be the in-plane coordinates. The electron drift is along the x direction. Both materials, A and B, are supposed to be polar cubic crystals. Let the relative displacement of ions in the primitive cell be $\mathbf{u}^{(0)}(\boldsymbol{\rho},z,t)$, where $\boldsymbol{\rho}=\{x,y\}$. The macroscopic polarization vector $\mathbf{P}(\boldsymbol{\rho},z,t)$ is proportional to $\mathbf{u}^{(0)}(\boldsymbol{\rho},z,t)$. Periodic changes of $\mathbf{u}^{(0)}$ (and $\mathbf{P}$) in space and time correspond to the *optical vibrations* of the lattice. If the frequencies of the optical vibrations in materials A and B are different, different types of optical modes exist in such a double heterostructure: the interface modes; the confined LO and TO modes; and half-space LO and TO modes in the barrier layers. For QWs wider than about 60 Å, the electrons are coupled mainly to the confined LO modes. For the rest of this letter we concentrate on the latter phonons.

The confined LO phonons can be characterized by 2D phonon wave vectors $\mathbf{q}$ and discrete (transverse) numbers m. Because the dispersion of the optical phonons is small in the long-wavelength limit, we can attribute the same frequency ω to all confined LO modes. Let $\mathbf{w}_{q,m}(\boldsymbol{\rho},z,t)$ be the complete set of orthogonal and normalized solutions describing the confined LO vibrations. In the dielectric continuum model of the confined LO phonons,[6] the explicit form for these solutions is

[a)] Electronic mail: [illegible]

Generation of coherent confined LO phonons under the drift of two-dimensional electrons

S. M. Komirenko and K. W. Kim
Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina 27695-7911

V. A. Kochelap and I. Fedorov
Department of Theoretical Physics, Institute of Semiconductor Physics, National Academy of Sciences of Ukraine, Kiev, 252650, Ukraine

M. A. Stroscio
U.S. Army Research Office, Research Triangle Park, North Carolina 27709-2211
(Received 9 November 2000; published 3 April 2001)

This paper addresses the effect of generation of confined LO phonons by drifting electrons in quantum wells. We have obtained a general formula for the phonon increment as a function of the phonon wave vector, the electron drift velocity, and parameters of the structure. The kinetic parameters of the drifting electrons are estimated by using momentum and energy balance equations for electron scattering by the confined optical phonons. We have performed numerical estimates of the phonon increment, as well as the phonon lifetimes, and found that AlAs/GaAs/AlAs and GaSb/InSb/GaSb quantum well structures with high drift velocities can demonstrate the effect of generation of the coherent confined optical modes. Essentially, the phonon increment has a maximum as a function of the wave vector. This implies a strong selection of the generated phonon modes. We briefly discuss the nonlinear electron mechanism which stabilizes the increase of the phonon populations and provides for the steady-state phonon generation.

DOI: 10.1103/PhysRevB.63.165308 PACS number(s): 73.50.Bk, 63.22.+m, 63.20.Kr, 63.20.Pw

I. INTRODUCTION

High-frequency coherent acoustic and optical phonons have been observed for a number of semiconductor materials and heterostructures (see Refs. 1 and 2 for a recent review). These studies provide information on the excitation mechanisms of the coherent phonons, their dynamics, electron-phonon interactions, and other important phenomena, including effects of interference of coherent lattice vibrations and phonon control of ionic motion.[3] Intense coherent phonon waves can be exploited for various applications, particularly for terahertz modulation of light[4] and generation of high-frequency electric oscillations. Usually, high-frequency coherent phonons are excited optically by ultrafast laser pulses.[1,2] The development of electrical methods of coherent phonon generation is a long-standing and important problem.

It is expected that an electric current flowing though a semiconductor can produce coherent acoustic and optical phonons.

Transitions of carriers between bound electron states (hopping transport) can lead to a population inversion between these states and, eventually, to generation of coherent phonons. Examples of heterostructures with this type of population inversion include three-barrier heterostructures similar to those used in the cascade lasers,[5,6] as well as superlattices with vertical hopping transport.[7]

If the current is due to free electron motion in an electric field, amplification (generation) of a phonon mode can be achieved via the Cherenkov effect when the electron drift velocity exceeds the phonon phase velocity. It has been well established that the following three requirements are necessary for practical use of the Cherenkov effect: high electron mobilities, large electron densities, and strong coupling between electrons and amplifying phonons. For *acoustic phonons* this effect has been studied intensively in bulk samples.[8,9] Generation of coherent acoustic phonons of frequency below 10 GHz has been achieved. Very recently[10] it was found that in heterostructures drifting two-dimensional electrons can provide amplification of confined acoustic phonons in sub-THz frequency range. Analysis of the Cherenkov effect for *optical phonons*[11–13] has shown that their amplification (generation) by drifting electrons in bulk materials is practically impossible: the rate of the phonon generation cannot compete with the large rate of phonon losses.

Advanced technology of semiconductor heterostructures allows one to manipulate to electron and phonon properties and opens new possibilities to employ the Cherenkov effect for optical phonon generation. Indeed, for confined electrons in modulation-doped heterostructures, two conditions—high electron drift velocities (much greater than that in necessarily heavily doped bulk samples) and large electron densities—are already realized. Then, *simultaneous confinement* of electrons and optical phonons within the same quantum well (QW) provides a necessary strong coupling. These can result in a large Cherenkov effect, which now may compete with phonon losses. This paper addresses the analysis of generation of *confined optical phonons* by drifting electrons in a QW layer. The general results are applied to AlAs/GaAs and GaSb/InSb heterostructures.

The paper is organized as follows. In Sec. II we formulate the model for confined electrons and phonons and their interaction. In Sec. III we calculate the rate of spontaneous and stimulated emission of confined optical phonons by the drifting electrons. An analysis of the phonon increment is given in Sec. IV. Section V is devoted to numerical estimates of both the phonon increment and the phonon lifetime in different heterostructures. The discussion of the results is presented in Sec. VI. The calculation of the electron permittivity

0163-1829/2001/63(16)/165308(10)/$20.00

JOURNAL OF APPLIED PHYSICS VOLUME 90, NUMBER 8 15 OCTOBER 2001

Amplification of transverse acoustic phonons in quantum well heterostructures with piezoelectric interaction

S. M. Komirenko and K. W. Kim[a)]
Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina 27695-7911

A. A. Demidenko and V. A. Kochelap
Department of Theoretical Physics, Institute of Semiconductor Physics, National Academy of Sciences of Ukraine, Kiev 252650, Ukraine

M. A. Stroscio
U.S. Army Research Office, Research Triangle Park, North Carolina 27709-2211

(Received 4 April 2001; accepted for publication 12 July 2001)

We have analyzed amplification of transverse phonons confined in quantum well (QW) heterostructures through piezoelectric electron–phonon interaction with drifting electrons. It was found that this mechanism of interaction couples the low-dimensional electrons and the shear-horizontal (SH) confined phonons. We have studied the electrostatic potential accompanying the SH waves and found that efficient interaction can be achieved for the lowest antisymmetric SH phonon branch in a narrow band of phonon frequencies. For AlGaAs QWs the amplification coefficient was calculated to be on the order of 100 cm^{-1} in the sub-THz phonon frequency range. These results suggest an electrical method for coherent phonon generation in the technologically well-developed AlGaAs QW heterostructures. © *2001 American Institute of Physics.*
[DOI: 10.1063/1.1402145]

I. INTRODUCTION

Recently the problem of high-frequency coherent phonons has attracted considerable attention. Coherent phonons have been observed for a number of semiconductor materials and heterostructures (see Refs. [1–3] for a recent review). New effects have been discovered in coherent phonon dynamics, electron–coherent phonon interactions, optical control of coherent phonons, etc. Coherent phonon waves can be exploited for various applications. These include terahertz modulation of light and generation of terahertz-frequency electromagnetic oscillations.[4] Typically, high-frequency coherent phonons are excited optically by ultrafast laser pulses.[1,2] The development of electrical methods of coherent phonon generation is an important problem that has presented many technical challenges.

Very recently it was found that electric current flowing though semiconductor heterostructures can produce high-frequency coherent acoustic phonons. These heterostructures include superlattices with vertical hopping electron transport[5] and quantum well (QW) heterostructures with parallel transport.[6] In the former case, the current results from transitions of carriers between bound electron states in the weakly coupled QWs composing the superlattice. In such a case the generation of coherent phonons may be achieved because of a population inversion between these states.

In QW heterostructures, when the current is due to semiclassical electron motion in an electric field, phonon amplification (generation) may be achieved via the Cerenkov effect when the electron drift velocity exceeds the velocity of sound. For practical use of the Cerenkov effect, the following three requirements have to be met:[7] high electron mobilities, large electron densities, and strong coupling between electrons and amplifying phonons. The first two conditions—high electron mobility and large electron densities—are already realized for confined electrons in modulation doped heterostructures. Then, if there are phonons confined near the location of the electrons, it is obvious that the electrons will be coupled more strongly just with these phonons. QW structures may provide confinement of both electrons and acoustic phonons near the QW layer.[8–10] General analysis of amplification of the confined acoustic phonons[9] has shown that the amplification can be efficient for well confined phonons.

In general, both mechanisms of electron–acoustic phonon interaction, i.e., the deformation potential and piezoelectric mechanisms, can lead to the phonon amplification effects.[7] In cubic crystals with the electrons (holes) from the central valley, the deformation potential gives rise to the coupling with those confined phonons, which comprise both longitudinal and transverse vibrations, while the piezoelectric interaction couples the electrons with transverse vibrations. To review the basic properties of the confined phonons, let us consider the heterostructure shown in Fig. 1, where electrons are confined in a QW layer A embedded in a semiconductor material B. The thickness of the layer A is $2d$. It is supposed that the localized waves propagate along the layer and decay outside it. To be specific, we assume that both materials A and B are cubic crystals, the growth direction is [001], and the direction of wave propagation is [100], i.e., x. Under the latter assumptions, the classification of the confined phonons

[a)]Author to whom correspondence should be addressed; electronic mail: kwk@ncsu.edu

PHYSICAL REVIEW B, VOLUME 64, 113207

Runaway effects in nanoscale group-III nitride semiconductor structures

S. M. Komirenko and K. W. Kim
Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina 27695-7911

V. A. Kochelap
Institute of Semiconductor Physics, National Academy of Sciences of Ukraine, Kiev-28, 252650, Ukraine

M. A. Stroscio
U.S. Army Research Office, Research Triangle Park, Raleigh, North Carolina 27709-2211
(Received 8 May 2001; published 31 August 2001)

We have revisited the problem of electron runaway in strong electric fields in polar semiconductors focusing on nanoscale group-III nitride structures. By developing a transport model that accounts for the main features of electrons injected in short devices under high electric fields, we have investigated the electron distribution as a function of electron momenta and coordinates. Runaway transport is analyzed in detail. The critical field of this regime is determined for InN, GaN, and AlN. We found that the transport in the nitrides is always dissipative (i.e., no ballistic transport). For the runaway regime, however, the electrons increase their velocities with distance, which results in average velocities higher than the peak velocity in bulklike samples. We have demonstrated that the runaway electrons are characterized by a distribution function exhibiting a population inversion.

DOI: 10.1103/PhysRevB.64.113207 PACS number(s): 72.20.Ht, 72.20.Dp, 73.23.−b, 85.35.−p

Group-III nitride semiconductors have unique fundamental material properties.[1] These materials are characterized by energy-band gaps ranging from 1.9 eV (InN) to 6.2 eV (AlN); relatively small electron effective masses $m = 0.11m_0$, $m = 0.2m_0$, and $m = 0.48m_0$ for InN, GaN, and AlN, respectively, where m_0 is the free-electron mass; high breakdown fields in the MV/cm range; large optical-phonon energies (about 90–100 meV); and strong electron–polar-optical-phonon coupling. The Fröhlich phonon-coupling constants are estimated to be $\alpha = 0.22$, 0.41, and 0.74 for InN, GaN, and AlN, respectively. In comparison, $\alpha = 0.075$ in GaAs. The values of the peak velocities in the nitrides in the steady-state regime are large:[1,2] 4.3×10^7 cm/s (InN), 3.1×10^7 cm/s (GaN), and 1.7×10^7 cm/s (AlN).

Previous study of the transient, time- or space-dependent transport in nitrides[3] revealed that the velocity-overshoot effect takes place in the subpicosecond time scale and 10 nm spatial-scale ranges with maximum velocities of about $(6-8)\times10^7$ cm/s for InN and GaN. This result, obtained by Monte Carlo calculations, suggests great perspectives of group-III nitrides for high-power and high-frequency electronics. However, some interesting and important high-field effects have not been investigated in detail. The purpose of this paper is to address one such problem, namely, the electron runaway effect in short group-III nitride structures.

The runaway effect is a well-known hot-electron phenomenon[4,5] that arises in *polar crystals* with predominant scattering by polar optical phonons.[5] Because of the Coulomb nature, the rate of such a scattering process decreases for the electrons with large moments and energies. As a result, the momentum and energy gained by the electrons from the field cannot be relaxed to the lattice above a certain critical field. The carriers then run away to higher energies. In a *bulklike* sample, the electron runaway is stabilized by one of the following effects: a breakdown due to impact ionization of impurities or across the gap, a nonparabolicity or transfer to upper valleys, an additional scattering at high energies, etc. In a *short* sample, the limiting mechanisms mentioned above are not important and the electron transport can occur in the runaway regime. Since the runaway effect is more pronounced for crystals with stronger electron–optical-phonon coupling, the group-III nitrides are considered prime candidates for this phenomenon.

For a detailed analysis, we solve the Boltzmann equation for the distribution function $f(\vec{P},z)$, where $\vec{P}$ and z are the electron momentum and coordinate. The energy associated with electron motion along the z coordinate is defined as $W = P_z^2/2m - eEz$, where $-e$ is the electron charge and E is the electric field. The characteristic energy is the phonon energy $\hbar\omega$ and the characteristic momentum is $P_0 = \sqrt{2m\hbar\omega}$. The dimensionless momentum, energy, coordinate, and field are $\vec{p} = \vec{P}/P_0$, $w = W/\hbar\omega$, $\zeta = z/l_\alpha$, and $\varepsilon = eEl_\alpha/\hbar\omega$, respectively. Here we define the characteristic length $l_\alpha = \hbar^2\kappa_0\kappa_\infty/e^2m(\kappa_0-\kappa_\infty)$, where κ_0 and κ_∞ are the low- and high-frequency permittivities. Assuming only optical-phonon emission at low temperatures, the Boltzmann equation can be expressed in the dimensionless form as

$$\frac{\partial f}{\partial p_z} + 2\frac{\partial f}{\partial \zeta}p_z = -\frac{f(\vec{p})}{\pi\varepsilon}\int\frac{d^3p'\,\delta(p^2-p'^2-1)}{(\vec{p}-\vec{p}\,')^2} + \frac{1}{\pi\varepsilon}\int\frac{d^3p'\,f(\vec{p}\,')\,\delta(p^2-p'^2+1)}{(\vec{p}-\vec{p}\,')^2}$$

$$\equiv -\frac{1}{\varepsilon}[f(\vec{p})\nu(p) - r(\vec{p})]. \quad (1)$$

It is remarkable that this equation contains a single "controlling" parameter—the dimensionless field ε. We will analyze

phys.stat.sol.(b) 228, No.2, 571–574 (2001)

Group-III Nitrides Hot Electron Effects in Moderate Electric Fields

E. A. Barry[1] (a), K. W. Kim (a), and V. A. Kochelap (b)

(a) Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina 27695-8617, USA

(b) Institute of Semiconductor Physics, National Academy of Sciences of Ukraine, Kiev-28, 252650, Ukraine

(Received June 25, 2001; accepted July 9, 2001)

Subject classification: 72.10.Di; 72.20.Ht; S7.14

We studied the distribution function and basic characteristics of hot electrons in InN, GaN and AlN under moderate electric fields, and found that in relatively low fields (of the order of kV/cm) the optical phonon emission dominates the electron kinetics.This strongly inelastic process gives rise to a spindle-shaped distribution function and an extended portion of quasi-saturation of the current–voltage characteristics (the streaming-like regime).We prove that this hot electron regime holds for all three nitrides. We suggest that the effects can be detected by the measurement of the I –V characteristics, or the thermopower of hot electrons in the transverse direction.

Introduction. Recent intensive studies of the electron kinetics in group-III nitride materials are mostly focused on two subjects: the problem of the low-field mobility and the problem of the peak (saturation) velocity in extremely high electric fields (hundreds of V/cm, see Refs.[1–5]).Meanwhile, such basic properties of the nitrides such as relatively low effective masses, high optical phonon energies, strong electron–optical pho-non interaction and large energy separations of the upper valleys bring about a number of new hot electron effects in moderate electric fields.These effects can be of interest for both the understanding of fundamentals of the electron kinetics in the nitrides and their applications.This paper addresses the hot electron kinetics in group-III nitrides at moderate electric fields.

Model and Results. We analyzed the electron kinetics in the nitrides by the Monte-Carlo method.The electron bands for InN, GaN and AlN were considered in the isotropic and parabolic approximation.Scattering by ionized impurities, acoustic phonons, and polar optical phonons were taken into consideration with all material parameters given by Ref.[6].Corresponding scattering rates as functions of the electron energy are presented in Fig.1.

1)Corresponding author; Phone:919 515-5402; Fax:919 515-3027;e-mail: eabarry@eos.ncsu.edu