Monochromatic terahertz acoustic phonon emission from piezoelectric superlattices

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Abstract. We demonstrate that mismatch of the piezoelectric coefficients of the layers of a superlattice structure gives rise to the drastic enhancement of electron-phonon interaction for resonant acoustic phonons, propagating at small angle to the superlattice axis and having frequency close to $2\pi ns/d$, where $s$ is sound velocity, $d$ is superlattice period, and $n$ is integer. As a result, strong collimated quasi-monochromaticic beams of resonant phonons can be emitted under the relaxation of hot electrons in superlattices. This prediction is confirmed experimentally for a GaAs/AlAs superlattice photoexcited by intense femtosecond laser pulses. The spectrum of the emitted phonons is analyzed with the use of an additional filter superlattices, whose phonon stop-bands are designed to be matched or unmatched to the frequency of resonant transverse phonons of the photoexcited superlattice (in our case the latter is about 450 GHz). According to these results, a considerable portion of the phonon flux is formed by quasi-monochromatic resonant phonons. In addition, we show that the matched-filter design provides phonon-laser (saser) action under the less intense, nanosecond-pulse excitation. We attribute this to the origination of the electron inversion in the system and phonon Fabri-Perot cavity formation due to the resonant phonon reflection by the filter superlattice and the top surface of the sample.

1. Introduction

The electron-acoustic phonon interaction in bulk semiconductors is usually treated within deformation potential and piezoelectric models. In nanostructures, their inherently nonuniform character gives rise to essential modification of both of the mentioned mechanisms (see for example, [1, 2]). Here we show that superlattices (SLs) composed of piezoelectric semiconductors materials provide strong enhancement of piezoelectric electron-phonon coupling for resonant acoustic phonons, propagating at small angle to the superlattice axis and having frequency close to $2\pi ns/d$, where $s$ is sound velocity, $d = d_{QW} + d_B$ is superlattice period, and $n$ is integer. The reason of such enhancement is mismatch of piezo-parameters of the quantum well and barrier layers. Our experiments suggest that such enhancement does occur in photoexcited GaAs/AlAs SLs. In particular, spontaneous or stimulated emission of quasi-monochromatic beams of resonant phonons can be achieved for femtosecond and nanosecond excitation regimes.
2. Piezoelectric electron-phonon interaction in superlattices

Piezoelectric electron-phonon interaction is due to macroscopic electrostatic potential energy $\phi$ caused by the phonon induced strain. Such energy is determined by the Poisson equation

$$\nabla^2 \phi = \frac{e}{\varepsilon_\infty} \nabla \cdot P,$$

where $P_i = e_{ijk}(z)u_{jk}$ is polarization caused by strain, $u_{jk}$. Here the SL axis is assumed to be parallel to the $z$-axis, and $z$-dependence of the piezoelectric constants $e_{ijk}$ take into account their mismatch in the quantum well and the barrier layers. For plane-wave strain of a phonon, characterized by the wavevector $\{q_x, q_y, q_z\}$, solution of Eq. (1) can be expressed as a series expansion

$$\phi = -\exp(iq_x x + iq_y y) \sum_{n=-\infty}^{\infty} \frac{R_n \exp(i(q_z + q_0 n)z)}{(q_0 n + q_z)^2 + q_0^2},$$

where $q_\parallel = \sqrt{q_x^2 + q_y^2}$, $q_0 = 2\pi/d$, and particular expression for coefficients $R_n$ depend on the symmetry of the SL materials and growth direction. Expressions for (001) GaAs/AlAs SL can be found in [3]. For example, as we see, if $q_z + q_0 n \approx 0$ for some $n$, $\phi$ is a smooth function of $z$. In addition, if $q_\parallel$ is small, the amplitude of this smooth component is great (in the following, we will call such phonons resonant). Such behavior is qualitatively different from the case of bulk semiconductor, where a plane-wave phonon produces plane-wave piezo-potential of the same wavevector. This affects strongly coupling of such phonons with 2D electrons. Its strength is proportional to the so-called form-factor, $J = |\int dz \chi^2(z)\phi|^2$, where $\chi$ is the envelope function of the 2D electrons. As a result, for solitary quantum wells coupling to high-frequency short-wavelength phonons with $q_\parallel d_{QW} \gg 1$ is suppressed [4]. As we see from Eq. (1), this is not the case for resonant phonons in SL, where coupling to high-frequency resonant phonons is enhanced. This is illustrated in Fig. 1, where the dependence of $J$ on $q_z$ is shown for TA phonons in GaAs/AlAs SL with $d_{QW} = 6.2 nm$, $d_B = 1.2 nm$ and two values of $q_\parallel$. The absolute value of $J$ is normalized to the value corresponding to the bulk-like phonon at $q_z = 0$, which is also shown as a reference. For LA phonons in (001) GaAs/AlAs SL there is no such strong enhancement of coupling of resonant phonons.

3. Spontaneous emission of resonant phonons excited by femtosecond light pulse

The described above enhancement of coupling of resonant phonons to electrons was confirmed by the experimental analysis of the spectrum of phonons emitted from SL excited by femtosecond laser pulse. Such analysis was accomplished with use of two kinds of structures. Sample A is 40-period GaAs/AlAs SL (active SL) with $d_{QW} = 6.2 nm$ and $d_B = 1.2 nm$. In sample B, the same SL structure was preceded by an additional (filter) SL from the bottom side of substrate, with parameters $d_{QW} = 1.7 nm$, $d_B = 2.2 nm$. The active and filter SLs are separated by 0.5 $\mu$m GaAs spacer. Active SL is excited by femtosecond laser pulse, and the emitted phonons are detected by superconducting Al bolometer deposited at the bottom side of the substrate. Further details of the structure, experimental setup, and bolometric measurements of the phonon signals can be found in [3]. The parameters of the of the active and mirror SL are selected such that frequency of resonant phonons matches the stop-bands of the mirror SL. Since such stopbands relatively narrow due to small elastic mismatch of GaAs and AlAs (in our case their with is about 50 GHz), mirror SL is expected to have very little effect on the phonon flux except most of phonons are resonant ones. In fact, we have found qualitatively different behavior of the TA phonon signal as a function of the photon energy. This is shown in Fig. 2. In sample A we see apparent enhancement of the TA phonon signal as the photon energy cross the absorption edge of the SL, $E_0$. Naturally, this is attributed to the set up of photoexcitation of carriers in SL, which is followed by the phonon emission under their relaxation. No such behavior was observed.
for filtered sample B, which suggests that considerable portion of the emitted TA phonons is due to resonant phonons. Previously, similar behavior was observed for LA phonons, which was attributed to the stimulated Raman phonon emission [5]. For TA phonons, however, such process is forbidden by symmetry restrictions.

4. Stimulated emission of resonant phonons

It is easy to see that, in principle, sample B can work as a phonon laser (saser). Indeed, filter SL and the top surface of the sample form Fabry-Perot cavity for resonant phonons. If, in addition, electron distribution in the SL is characterized by inversion, strong electron coupling with resonant phonons facilitates saser action. We claim, that such situation is realized under the long laser pulse excitation (pulse duration about 30 ns, diameter of the laser spot about 50 μm). Experimentally, this is supported by the threshold-like dependence of the phonon signal on the laser power, observed for the photon energy above the absorption edge of active SL, Fig. 3. No threshold was observed in sample A. In addition, phonon imaging measurements suggest that above threshold phonon emission is more directional. This is illustrated in Fig. 4, where linescans of the phonon images are shown for above-threshold and below-threshold laser power. We suggest that the reason for electron inversion is formation of relatively wide electron miniband in active SL (miniband width about 10 meV). As a result, the photogenerated electrons

Figure 1. Form-factor of piezoelectric electron-phonon interaction in SL for two values of in-plane wavevector. Bulk-like form-factor is also shown for comparison. The numbers near the peaks indicate the amplitudes of the peaks for $q_{\parallel} = 10^7$ m$^{-1}$.

Figure 2. Phonon signal as a function of the photon energy of femtosecond laser pulse for filtered and unfiltered samples.
are removed from the active SL ballistically. Apparently, the corresponding electron distribution is characterized by inversion. We performed calculations of the phonon increment, determined as a difference of phonon emission and absorption probabilities. It was found that increment of resonant phonons can be as high as $10^9$ s$^{-1}$ for $q_{||} \approx 10^7$ m$^{-1}$. This value is high enough to exceed the rate of phonon losses due to leakage out of the Fabry-Perot cavity, provided that the phonon reflection coefficient at the surface is above 0.8. Details of the increment calculations will be given elsewhere. Note, that under the femtosecond excitation electron relaxation in SL is too fast to allow development of the phonon lasing.

5. Conclusions
In conclusion, we demonstrated that mismatch of the piezo-parameters of the quantum well and the barrier layers of SL gives rise to strong enhancement of electron-phonon interaction of resonant phonons. Based on this effect, we demonstrate emission of quasi-monochromatic beams of resonant phonons from photoexcited GaAs/AlAs SLs. In particular, under the 30-ns pulse photoexcitation phonon lasing was observed in samples with the phonon Fabry-Perot cavities.

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