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CURRENT RESPONSE OF A SUPERLATTICE IRRADIATED BY NONEQUILIBRIUM PHONONS

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We studied a biased superlattice and found a considerable current response to irradiation by nonequilibrium acoustic phonons with effective temperature of the order of few Kelvins. We discussed two phonon source-superlattice configurations for which the current response is due to the interwell and intrawell electron transitions, respectively. We showed that the response is sensitive to both, direction and spectral distribution of the phonons. The results explain recent experiments on phonon-induced current responce and prove the possibility to use superlattices for characterization of high-frequency phonon flux.

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Semiconductor superlattices (SLs) demonstrate a number of interesting electron transport phenomena, including Bloch oscillations [1], electron hopping conduction [2, 3], charge domain formation [4] etc. It is well established also that the electric current in a SL can be changed substantially under irradiation by electromagnetic waves. In particular, the powerful THz irradiation of a biased SL gives rise to such an extreme effect as the change of the sign of the electric current (absolute negative conductance) [5]. The interest in effects resulting from irradiation of SLs is stimulated both by the fundamental character of the phenomena and a possibility of applications. Among these applications there are photodetection [6] and active control of the electric currents in devices.

During last decades significant progress in the development of techniques of detection, generation and control of phonons is achieved [7]. This makes possible to irradiate different quantum heterostructures by phonon fluxes and to study effects resulting from such irradiation [8]. Very recently the first experimental observation of the current response (CR) of the SL irradiated by phonons was reported [9]. In this letter we analyze the main mechanisms of the CR to the acoustic phonon flux. Our results explain the main features observed in [9] and demonstrate that the CR provides valuable information on the phonons, i.e., it can be used for phonon flux characterization. The results also show the way to control of the electric current by phonons.

In a SL under the hopping transport regime [2, 3], basically, there are two mechanisms through which acoustic phonons affect the SL current. First, the phonons provide the direct contribution to the current causing ***interwell electron transitions.*** Second, nonequilibrium phonons induce ***intrawell electron transitions***, giving rise to the electron heating, and thus change electric current indirectly. It is important, that both mechanisms result in qualitatively different types of the CR and can be easy discriminated in an experiment.

The scheme of the system under consideration is depicted in Fig.1. The presented semiconductor structure is similar to that used in [9]. The SL is situated on the top of the substrate of thickness L_s. On the opposite side of the substrate there are sources of

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nonequilibrium phonons. Typically phonon sources are thin metallic films. Being heated up to a temperature T_f by a short laser pulse or an electric current pulse, such a metallic film emits acoustic phonons to the substrate. The emitted phonons can be characterized by the Plank distribution with the temperature T_f, which exceeds the substrate temperature T. At low temperatures T_f and T almost all emitted phonons have the mean free path greater than typical substrate thickness $L_s \sim 300 - 500\ \mu$m. Since that, the phonons propagate from the source through both, the substrate and the SL, almost ballistically. In the SL the phonons induce the electron transitions and cause changes of the current.

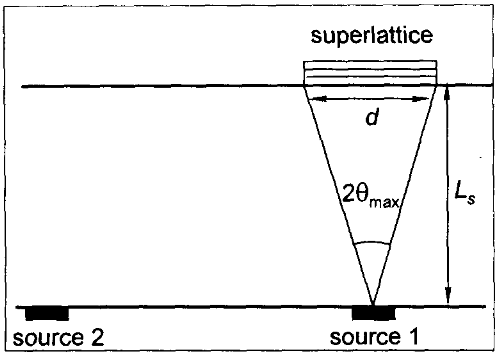

Fig.1. The scheme of the system under consideration. The biased SL is irradiated by nonequilibrium phonons produced by the phonon sources. The two shown sources produce qualitatively different electron transitions and the CR

In III-V-SLs the acoustic mismatch is relatively small and gives rise to the modifications of the phonon spectra (phonon folding). These modifications are significant only close to the boundary and the center of the superlattice Brillouin zone, while the nonequilibrium phonons generated by a heat pulse have a relatively broad distribution over q. Thus, for our purposes we can treat the nonequilibrium phonons in the bulk model and characterize them by the wavevector $\mathbf{q}$. Let θ be the angle between $\mathbf{q}$ and the SL axis. Since usually the SL width, L_w, and thickness, D, as well as the source dimensions, are substantially less than the substrate thickness, the ballistic phonons coming to the SL have very narrow distribution in θ. The characteristic value of θ is determined by the position of the phonon source with respect to the SL. In Fig.1 we show schematically two different source-superlattice configurations. Source *1* is placed exactly under the SL. In this case phonons reaching the SL have small values of θ, $\theta < \theta_{max} \approx L_w/(2L_s)$. In contrast, source *2* is situated aside from the SL, and phonons of interest have rather $\theta \approx \pi/2$. As we show below, these two sorts of phonons with $\theta \ll \pi/2$ and $\theta \sim \pi/2$ cause qualitatively different effects on the electron transitions and give rise to the different CR. The experimental set-up in [9] was rather similar to source-superlattice configuration I.

We restrict ourselves by the consideration of the SL in the hopping conduction regime due to the electron transitions between the neighboring QWs [2, 3]. This occurs when the Stark splitting, Δ, is larger than the SL miniband width. The electron states forms the Stark ladder spectrum,

$$E_{n,k} = \hbar^2 k^2/2m - n\Delta + E_0, \tag{1}$$

where k is the in-plane wavevector, n is the number of a quantum well and E_0 is the energy reference. For the electron wavefunctions we will use the so-called two-well model, described, for example, in [2, 10]:

$$\Psi_{n,\mathbf{k}} = \frac{1}{\sqrt{S}} \exp(i\mathbf{k}\rho)\, \psi_n(z), \tag{2}$$

$$\psi_n = \chi(z-nd) - \frac{t}{\Delta}\left(\chi(z-(n+1)d) - \chi(z-(n-1)d)\right).$$

Here $\rho = (x,y)$ is the in-plane coordinate of electrons, z direction is parallel to the SL axis, S is the normalizing area of the QW layer, χ is the normalized wavefunction in an individual QW, t is the overlap integral $t = V_0 \int \chi(z-nd)\chi(z-(n+1)d)dz$. The wavefunctions of Eqs. (2) describe the Stark ladder states under the condition $t \ll \Delta \ll V_0$ with V_0 being the height of the barriers. Then, we assume electron-phonon interaction via deformation potential and use the standard Hamiltonian for this interaction [11, 12].

The introduced above intrawell transitions occur between the electron states within the same QW: $\{n,\mathrm{k}\} \leftrightarrow \{n,\mathrm{k'}\}$, while the interwell transitions occur between the electron states belonging to the neighboring QWs: $\{n,\mathrm{k}\} \leftrightarrow \{n \pm 1,\mathrm{k'}\}$. It is easy to see, that due to the energy and momentum conservation laws the intrawell phonon-assisted transitions occur mainly for the phonons with $\theta > s/v_F$, where s is the sound velocity and v_F is Fermi velocity of electrons. Therefore, if the geometry of the system meets the condition $(L_w/2L_s) \le (s/v_F)$ for source-superlattice configuration-I, phonons result mainly in the interwell transitions. In such a case the CR can be written as the sum of contributions of different interwell processes:

$$\Delta J^I = \frac{e}{S}\sum_q \left(P_{em}^{(down)} + P_{ab}^{(down)} - P_{em}^{(up)} - P_{ab}^{(up)}\right) N_q \equiv \tag{3}$$

$$\equiv \Delta J_{em}^{(down)} + \Delta J_{ab}^{(down)} - \Delta J_{em}^{(up)} - \Delta j_{ab}^{(up)},$$

where $P(q)$ are the probabilities of phonon emission and absorption with the electron transfer "up" and "down" the Stark ladder, and N_q are the population numbers of the nonequilibrium phonons. Equations for P reads:

$$\begin{aligned} P_{(em,ab)}^{(down,up)}(q) = {} & \frac{2\pi}{\hbar}\left|M(n,n'|q_z)\right|^2 \sum_{k,k'} \delta_{\mathbf{k}\mp\mathbf{q}_{||},k'}\,\delta\left[E_{n,\mathbf{k}} - E_{n',\mathbf{k}'} \mp \hbar\omega\right] \times \\ & \times \mathcal{F}_{n,\mathbf{k}}\left[1 - \mathcal{F}_{n',\mathbf{k}'}\right]. \end{aligned} \tag{4}$$

Here $M(n,n'|q_z)$ is the matrix element calculated on the wavefunctions $\psi_n, \psi_{n'}$; $q_{||}$ is the in-plane projection of $\mathbf{q}$, $\mathcal{F}_{n,\mathbf{k}}$ is the Fermi distribution function for the electrons in $n^{th} - QW$, the upper signs stand for emission, the lower ones stand for absorption processes. The "down" and "up" transitions correspond to $n' = n \pm 1$. Similarly the intrawell transitions can be evaluated.

Below we discuss the CR of Eq. (3) for the SL with the following parameters. The thicknesses of the quantum well and barrier layers are taken to be 4.5 nm and 6 nm respectively, $L_w = 100\,\mu$m and $L_s = 500\,\mu$m. The electron effective mass is $m = 0.067\,m_0$ and the barrier height $V_0 = 1$ eV, which provides the SL miniband width equal to 0.1 meV. Then, the electron density is $n_e = 2 \cdot 10^{14}$ m^{-2}. To describe the phonons interacting with the electrons we set the longitudinal sound velocity $s_l = 4800$ m/s and material density $\rho = 5300$ kg/m^3. The deformation potential constant is taken to be $E_1 = 7$ eV. We performed calculations also for GaAs/AlGaAs superlattice with different parameters under the hopping transport and found the results similar to the discussed below.

In Fig.2 we present the partial contributions to the current CR as functions of the Stark splitting Δ for source-SL configuration-I. The source temperature is set 5 K. The results are given in the limit of zero temperature of the SL.

The obtained dependences can be explained qualitatively as follows. The interwell matrix element $|M(n, n \pm 1|q)|$ decreases when Δ increases, as seen from Eq. (2) (see also [2, 10].) Then, the energy and momentum conservation laws impose limitation on possible electron states involved in the transitions. Combining these limitations with the Fermi distribution at $T \to 0$, we obtain that the "up"-transitions are entirely prohibited for phonon emission ($\Delta J_{em}^{(up)} = 0$), while the up-transitions with phonon absorption are allowed for the phonon energy $\hbar\omega > \Delta$. The "down"-processes with phonon absorption are possible for any phonons. These explain monotonously decreasing functions $\Delta J_{ab}^{(up)}$ and $\Delta J_{ab}^{(down)}$. The down-transitions with phonon emission are allowed at $\hbar\omega < \Delta$. This cut-off in the number of phonons participating in these down-transitions results in a decreasing $\Delta J_{em}^{(down)}$ at small Δ: the function $\Delta J_{em}^{(down)}(\Delta)$ becomes nonmonotoneous.

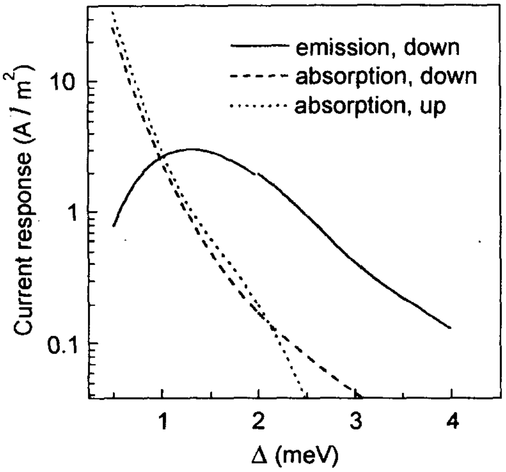

Fig.2. The dependence of the partial contributions to the CR on the Stark splitting Δ for the phonon source temperature $T_f = 5$ K

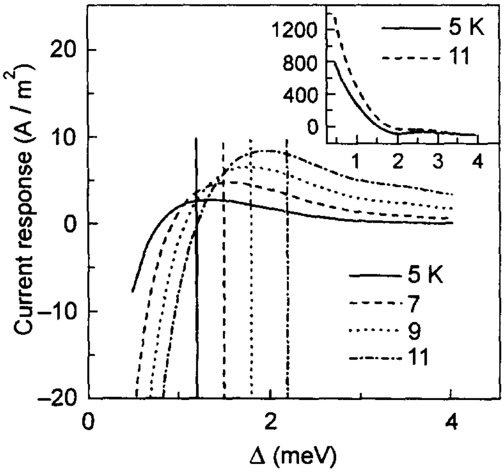

Fig.3. The CR due to interwell electron transitions as a function of the Stark splitting for several temperatures of the phonon source. The vertical lines correspond to critical Stark splittings Δ_c. In the Insert: the change in the current, ΔJ^{II}, due to electron heating for different electron temperature T_e

The net CR as a function of the Stark splitting is shown in Fig.3. Two remarkable peculiarities of the CR are seen from this figure. First, the CR can be of both, negative and positive, signs. At low values of Δ the CR is negative, since the up-absorption processes dominate and the phonons drive the electrons up the Stark stairs. A negative CR means that the phonons partially suppress the SL current. With decreasing Δ the suppression effect increases. It is quite similar to the effect observed at THz-electromagnetic irradiation [5]. At higher Δ the down-emission processes prevail, the CR becomes positive.

The second peculiarity is that the CR is a nonmonotoneous function of Δ. With an increase in the temperature of the phonon sources, T_f, the maximal value of ΔJ^I increases and occurs at larger Δ. Nonmonotoneous behavior of the CR at a fixed T_f, an increase of the maximal response, as well as its shift for larger T_f have been observed in experiments [9].

The above results were obtained for phonon source-superlattice configuration-I, when the intrawell phonon processes are excluded and no electron heating occurs. The insert to Fig.3 shows the change in the SL current $\Delta J^{\mathrm{II}} \equiv J(T_e) - J(0)$ caused by electron heating. The shape of function $\Delta J^{\mathrm{II}}(\Delta)$, its sign and values completely different from that of ΔJ^{I}. Thus for source-superlattice configuration-II, when mostly the intrawell transitions occur, one should expect different character of the CR. On the other hand, comparison of ΔJ^{I} and ΔJ^{II} proves that in the experiments [9] the interwell phonon induced transitions were observed. Note, that we used the isotropic elastic model for the crystal, which provides electron-phonon coupling with LA-phonon only. However, crystal anisotropy as well as LA-TA-phonon mixing in SLs can lead to a CR for TA-phonons as well, which was detected in [9].

One more interesting conclusion can be drawn from calculations of the partial contributions to the CR presented in Fig.2. Let Δ_c solves the equation $\Delta J_{em}^{(down)}(\Delta) = \Delta J_{ab}^{(up)}(\Delta) + \Delta J_{ab}^{(down)}(\Delta)$. Then for $\Delta > \Delta_c$ the rate of stimulated emission exceeds the total rate of all absorption processes. This, in fact, corresponds to *amplification* of the phonon flux in the SL. It is in agreement with the results of paper [13], where we have shown that under hopping transport in a biased SL the phonons of energies below Δ are amplified. Indeed, the values of $\Delta_c(T_f)$ are indicated in Fig.3. We see that $\Delta_c(T_f) > k_B T_f$, i.e., almost all propagating phonons should be amplified by the SL current.

In conclusion, we have studied irradiation of SL by nonequilibrium phonons and calculated the CR. We have analyzed different mechanisms of phonon-induced electron transfer, which contribute to the CR. We have shown that the character of the CR is highly sensitive to the phonon source-superlattice configuration, as well as to the phonon temperature. This sensitivity allows one to use the CR for detecting and characterizing phonon fluxes. For the average phonon energy below the Stark splitting we found that the stimulated emission processes dominate over those with absorption, i.e., corresponding phonon flux can be amplified propagating through the SL.

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1. F.Agullo-Rueda and J.Feldmann, in *Semiconductor Superlattices*, World Scientific, 1995.
2. R.Tsu and G.Döhler, Phys. Rev. **B12**, 680 (1975).
3. A.Wacker and A.-P.Jauho, Phys. Rev. Lett. **80**, 369 (1998).
4. H.Grahn, in *Semiconductor Superlattices*, World Scientific, 1995.
5. B.J.Keay, S.Zeuner, S.J.Allen, et al., Phys. Rev. Lett. **75**, 4102 (1995).
6. A.A.Ignatov and A.-P.Jauho, J. Appl. Phys. **85**, 3643 (1999) and references therein.
7. Proceedings of the Intern. Conf. Phonons-98, Physica **B263-264** (1999).
8. D.N.Hill, S.A.Cavill, A.V.Akimov, et al., Phys. Stat. Sol. (b) **204**, 431 (1997).
9. S.A.Cavill, A.V.Akimov, F.F.Ouali, et al., Physics **B263-264**, 537 (1999).
10. F.T.Vasko, Fiz. Tech. Polupr. **26**, 825 (1992) (Sov. Phys. Semicond. **26**, 464 (1992)).
11. V.E.Gantmakher and Y.B.Levinson, *Carrier scattering in metals and semiconductors*, Nort-Holland, Amsterdam, 1987.
12. V.V.Mitin, V.A.Kochelap, and M.A.Stroscio, *Quantum Heterostructures*, Cambridge University Press, 1999.
13. B.A.Glavin, V.A.Kochelap, and T.L.Linnik, Appl. Phys. Lett. **74**, 3525 (1999).