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THE ROLE OF INTERFACES IN PLASMON-PHONON COUPLING IN SEMICONDUCTOR QUANTUM WELLS AND SUPERLATTICES

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Modulation doped microstructures such as heterostructures, quantum wells, wires, dots and superlattices attract much interest because of their novel fundamental physical properties and the resulting potential device applications. Within these layered structures it is possible to produce a low-dimensional electron gas with an electron number density varying in a large range. The confinement of the electron motion perpendicular to the heterointerfaces leads to size quantization in one, two or three directions.

Electrons in the conduction band of a polar semiconductor strongly interact with longitudinal (LO) phonons. It is well known that the electron gas of a heavily doped semiconductor can support charge-density oscillations organized by long-range Coulomb fields. The polar of Fröhlich-type of electron-phonon interaction leads to a strong coupling between these charge-density oscillations, the plasmons, and the LO phonons if their frequencies are comparable, forming a polaron gas. In modulation-doped semiconductor microstructures this coupling also occurs. But there are two basic differences between a microstructure, which is a layered system, and an ordinary 3D bulk crystal, that one must consider:
(i) Confinement of the electron motion and, hence, the electrons form a low-dimensional electron gas.
(ii) The spectrum of the optical phonons interacting with the electrons of the low-dimensional electron gas is altered by the interfaces of the system. The ordinary dispersion-free LO phonons are changed to be modes confined in each individual layer. And further new states, interface phonons, occur in the spectrum of the optical phonons with electric fields mainly localized at the interfaces of the system and decaying exponentially from them.

For the investigation of the plasmon-phonon coupling in the presence of interfaces we use as an example the simple geometry of a double heterostructure (DHS, interfaces are assumed to be perpendicular to the z-axis). This structure consists of a smaller-gap-semiconductor in $a>z>0$, which is symmetrically embedded by a wider-gap-semiconductor.

According to the symmetry of the DHS the electron motion is quasi-free in the x-y plane with the wave vector component $\vec{k}_{\parallel}$. Using the simple infinite barrier model potential for the DHS and neglecting band-bending, the energy eigenvalues are

$$\mathscr{E}_k(\vec{k}_{\parallel})=\frac{\hbar^2 k_{\parallel}^2}{2m}+\frac{\hbar^2\pi^2}{2ma^2}(K+1)^2\,; \quad K=0,1,2,\ldots \tag{1}$$

The long-wave length optical phonons in the absence of quasi-free electrons in a DHS are given by Maxwell's equations and matching boundary conditions across the two interfaces. We describe both semiconductors by lattice dielectric functions of the form

$$\varepsilon_\nu(\omega)=\varepsilon_{\infty\nu}\,\frac{\omega_{\mathrm{L}\nu}^2-\omega^2}{\omega_{\mathrm{T}\nu}^2-\omega^2} \tag{2}$$

where $\nu=1$ denotes the small-gap-semiconductor and $\nu=2$ the wider-gap one. In a DHS with the dielectric functions according to Eq. (2) LO phonons with $\omega_{\mathrm{L}\nu}$ and interface phonons exist. For the single layer geometry there are two types of interface phonon modes [1]: antisymmetric $\omega_{\mathrm{A}\pm}$ and symmetric $\omega_{\mathrm{S}\pm}$.

To calculate the properties of the Q2D polaron gas of a DHS we have derived the longitudinal dynamically screened interaction potential [2–4]. It reads within the electric quantum limit

$$W_{KK'}(\vec{q}_{\parallel},\omega)=\sum_L(\delta_{LK}-W_{KL}(\vec{q}_{\parallel},\omega)\,\chi_L^{(1)}(\vec{q}_{\parallel},\omega)\times W_{LK'}^{\mathrm{sc}}(\vec{q}_{\parallel},\omega)\,. \tag{3}$$

Herein $W_{LK'}^{\mathrm{sc}}(\vec{q}_{\parallel},\omega)$ is the screened and $W_{KK'}(\vec{q}_{\parallel},\omega)$ is the bare interaction potential given by

$$W_{KK'}(\vec{q}_{\parallel},\omega)=V_{KK'}^{\infty}(\vec{q}_{\parallel})+V_{KK'}^{\mathrm{ph}}(\vec{q}_{\parallel},\omega)\,. \tag{4}$$

This interaction potential signifies the scattering of an electron from the subband 0 to K by another electron which becomes scattered from 0 to K'. $V_{KK'}^{\infty}(\vec{q}_{\parallel})$ represents the bare electron-electron and $V_{KK'}^{\mathrm{ph}}(\vec{q}_{\parallel},\omega)$ the bare electron-phonon interaction potential. It is shown [1] that caused by the symmetry properties of the DHS the bare interaction potential has the following properties: $W_{00}\neq 0$, $W_{11}\neq 0$, $W_{10}=W_{01}=0$, $W_{22}\neq 0$, $W_{20}=W_{02}\neq 0$ and $W_{21}=W_{12}=0$. Because of the large energetic separation between the 0-th and the 2-nd subband at the usual layer thicknesses of a DHS the contribution of W_{20} is very weak. Therefore, it is a good approximation to neglect the off-diagonal elements in (3). This means that intra- and intersubband processes are decoupled. The full RPA expression of the polarization function $\chi_K^{(1)}(\vec{q}_{\parallel},\omega)$ of the quasi-two-dimensional electron gas is calculated in [2].

The condition for the existence of collective excitations is that self-sustaining collective oscillations occur. This means that the dispersion relation represents a resonance condition which defines the eigenfrequencies $\omega=\omega_j(\vec{q}_{\|})$ of the collective excitation having an infinite life-time. In the regions of the $\omega_{-q_{\|}}$ plane with $\mathrm{Im}\,\chi_K^{(1)}(\vec{q}_{\|},\omega)=0$ the dispersion relation of the coupled excitations follows from (3) to

$$W_{KK}^{-1}(\vec{q}_{\|},\omega)-\chi_K^{(1)}(\vec{q}_{\|},\omega)=0\,. \tag{5}$$

Equation (5) describes: (i) coupled intrasubband plasmon-phonon modes if $K=0$ and (ii) coupled intersubband plasmon-phonon modes if $K>0$. In the regions where $\mathrm{Im}\,\chi_K^{(1)}(\vec{q}_{\|},\omega)\neq 0$ is valid single-particle intra- and intersubband excitations occur and hence, the collective excitations are Landau-damped [4]. Due to the symmetry properties of the DHS the intrasubband plasmons couple only to the LO phonons of the layer and to the symmetric interface phonons but not to the antisymmetric one. For the intersubband plasmons the situation is *vice versa*.

If a strong magnetic field ($\hbar\omega_c \gg k_B T$) is applied perpendicularly to the heterointerfaces, the physical situation is quite changed. The magnetic field causes a quantization of the electron motion in the *x*-*y* plane in addition to the size quantization in *z*-direction. Hence, a completely quantized situation arises. The possible collective excitations of this magnetoplasma are intra- and intersubband principal magnetoplasmons and Bernstein modes. These magnetoplasmons couple to the optical phonons of the system. We found the general result that all modes are free of Landau damping for all wave vectors and temperatures for $\hbar\omega_c \gg k_B T$ because of the loss of the continuum of extended states.

The developed theory of plasmon-phonon coupling can be applied also to other layered structures. For superlattices the electrons form mini-bands representing the dimensionality of such a system between three or two. Due to the spatial periodicity the optical phonons form Bloch waves with dispersion curves forming two double bands [5]. The resulting coupled mode spectrum has a very rich resonance structure. The new development of submicron lithography (selective etching patterns into the top layer of a heterostructure and then deposition of a metal gate in nm dimensions) allows the investigation of one- and zero-dimensional electron systems due to strong electrostatic confinement. With the additional parameter, the gate voltage, it is possible to vary the dimensionality from 2D to 1D or from 2D to 0D. One of the future directions is to apply the here developed theory of collective excitations to these new microstructures and to investigate their properties in dependence of the dimensionality. Further, it is necessary to look for the effects of a magnetic field in those cases where a hybridization of the Landau levels with the quantum confined states occurs.

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