International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 10 Issue 1 ǁ 2022 ǁ PP. 29-33

New Way to Control Electron-Phonon Interaction in Quantum Wells

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Abstract
This paper suggests a new method for controlling the intensity of the electron-phonon interaction in quantum wells.This method is based on the use of compounds differing in their dielectric properties as materials for the left and right barrier fabrication. It is shown that by choosing the dielectric parameters of the barriers, it is possible to change the effective constant of the electron-phonon interaction by several times. This provides an opportunity to study the change in such interaction from weak to strong. It is found that for the formation of large-radius polarons, quantum wells with asymmetric barriers can be a more advantageous object than standard quantum wells with symmetric barriers. The results obtained open up possibilities for the fabrication of quantum nanostructures with new properties.

Keywords: *Phonon engineering, Quantum wells, Dielectric properties, Optical phonons.*

Date of Submission: 03-01-2022 Date of acceptance: 15-01-2022

I. INTRODUCTION

The parameters of the electron-phonon interaction change significantly in quantum nanostructures in comparison with bulk materials.The engineering of phonon states is very important for the thermal properties of nanostructures and it plays an important role in modifying electrical and optical properties.The main interest is the interaction of charged particles with polar optical phonons in nanostructures.The modern technology of fabrication of semiconductor nanostructures makes it possible to change effectively the phonon properties of such objects.It turns out that for symmetric quantum wells under conditions of strong electron-phonon interaction, the formation of large-radius polarons is possible [1]. To provide such conditions, it is necessary to use quantum wells with barriers made of materials with a high degree of ionicity. In this case, the ionicityof the quantum well material itself does not really matter. The most significant change in the parameters of the electron-phonon interaction should be expected in quantum wells with the barriers which are asymmetric in their dielectric properties. Such structures have been actively studied experimentally in recent years [2-4]. One of the actual applications is their use as constituent elements in multilayer structures in the creation of solar cells [5,6]. The change in the nature of the electron-phonon interaction is due to the fact that a comparable contribution to the this interaction in asymmetric structures should be made by several branches of the phonon spectrum. In the case of symmetric structures, as a rule, only one phonon mode makes the main contribution.

In this article, we theoretically investigate the features of the interaction of charged particles with optical phonons for quantum wells with barriers that are asymmetric in their dielectric properties. The dielectric continuum model is used to determine the phonon spectrum and features of the electron-phonon interaction. This approach makes it possible to adequately describe the phonon properties of heterostructures in cases where all the characteristic parameters which have the dimension of length, exceed the lattice constant of the materials used. Within the framework of our approach, it is shown that by changing the properties of the barriers, it is possible to change the magnitude of the electron-phonon interaction by several times. The conditions are found under which the interaction can be enhanced in asymmetric quantum wells in comparison with symmetric ones using the same barrier materials.

II. RESULTS AND DISCUSSIONS

A three-layered planar structure is investigated. This structure consists of a quantum well region with dielectric function $\varepsilon_{(w)}(\omega)$ and two barriers with dielectric functions $\varepsilon_{(l)}(\omega)$ and $\varepsilon_{(r)}(\omega)$ which are different in their dielectric properties.The indices (*l*)and (*r*) indicate the dielectric functions of the left and right barriers, respectively.For all layers of the structure under consideration, the standard relationship for the frequencies of longitudinal ω_{LO} and transverse ω_{TO} optical vibrations is satisfied and it has the form:

$$\varepsilon_{0,m} = \varepsilon_{\infty,m} \frac{\omega_{LO,m}^2}{\omega_{TO,m}^2}. \quad (1)$$

Here *m* refers to the material of corresponding barrier (left or right) or to the quantum well one.The presence of barriers in all cases should lead to the localization of carriers in the region of the quantum well. This is the circumstance that is essential for our consideration. It is really important to study the spectrum of interface optical phonons. It can be determined using the boundary conditions on both boundaries of the quantum well [7]. In our case, it is necessary to find a solution to the following equation:

$$e^{-|\mathbf{q}|L} \frac{\varepsilon_{(w)}(\omega) - \varepsilon_{(l)}(\omega)}{\varepsilon_{(w)}(\omega) + \varepsilon_{(l)}(\omega)} - e^{|\mathbf{q}|L} \frac{\varepsilon_{(w)}(\omega) + \varepsilon_{(r)}(\omega)}{\varepsilon_{(w)}(\omega) - \varepsilon_{(r)}(\omega)} = 0, \quad (2)$$

where*L* is the quantum well width, $\mathbf{q}$ is two-dimensional phonon vector in the well plane. The solutions of Eq. (2) contains two branches each for both optical phonons localized near the left and right boundaries of the quantum well. The interaction of these branches of the spectrum with each other leads to significant difficulties in describing the electron-phonon interaction. If the quantum well is narrow enough, that is,

$$qL \ll 1 \quad (3)$$

spectrum of optical phonons and the electron-phonon interaction are greatly simplified for such structures. Usually, the greatest interest is represented by the interaction in a region with a length of the order of the radius of the polaron state ρ_{pol} [8], which corresponds to the values $q \approx \rho_{pol}^{-1}$ of the wave vector $\mathbf{q}$ .The condition from Eq. (3) is realizedusuallyin semiconductor wells with a width of $L \ll 50$ ÅIn this case, Eq. (2) is greatly simplified. In the highest order in parameter from Eq. (3), it turns out to be independent of the dielectric properties of the quantum well region.In the presence of asymmetric barriers, it has only two solutions for interface phonons.Moreover, for our three-layered structure, the first solution has a maximum intensity on the left boundary and the second solution on the right one of the well.The regions of existence of solutions depend on the phonon spectra of the barrier materials.If the phonon frequency regions of the materials of the left and right barriers overlap, then the order of arrangement of these frequencies turns out to be important. When the regions of the phonon frequencies of the barriers do not coincide, the frequencies of the interface phonons lie in the intervals:

$$\begin{aligned} \omega_{TO,(l)} < \omega_1 < \omega_{LO,(l)} \\ \omega_{TO,(r)} < \omega_2 < \omega_{LO,(r)} \end{aligned} \quad (4)$$

The expression for the Hamiltonan describing the electron-phonon interaction can be written similarly to it for a quantum well with symmetric barriers [9] and has the form:

$$H_{e-ph,k} = \sum_{\mathbf{q}} \left(\frac{2\pi\omega_k e^2}{L^2} \right)^{1/2} \frac{\exp(i\mathbf{q}\mathbf{r})}{\sqrt{2q}} f_k(\mathbf{q},z) F_m(q,\omega_k) \left(a_k(\mathbf{q}) + a_k^+(\mathbf{q}) \right). \quad (5)$$

Here *k* isthe optical phonon branch number, $a_k(\mathbf{q})$ and $a_k^+(\mathbf{q})$ are the operators of annihilation and creation of phonons, respectively. The function $f_k(\mathbf{q},z)$ describes the distribution of the intensity of excitations in the direction *z*perpendicular to the quantum well plane. Inside the quantum well, it can be written as:

$$\begin{aligned} f_k(\mathbf{q},z) &= e^{-qL} \frac{\varepsilon_{(w)}(\omega_k) - \varepsilon_{(l)}(\omega_k)}{\varepsilon_{(w)}(\omega_k) + \varepsilon_{(l)}(\omega_k)} e^{qz} + e^{qL} \frac{\varepsilon_{(w)}(\omega_k) + \varepsilon_{(l)}(\omega_k)}{\varepsilon_{(w)}(\omega_k) - \varepsilon_{(l)}(\omega_k)} e^{-qz} = \\ &= e^{qL} \frac{\varepsilon_{(w)}(\omega_k) + \varepsilon_{(r)}(\omega_k)}{\varepsilon_{(w)}(\omega_k) - \varepsilon_{(r)}(\omega_k)} e^{qz} + e^{-qL} \frac{\varepsilon_{(w)}(\omega_k) - \varepsilon_{(r)}(\omega_k)}{\varepsilon_{(w)}(\omega_k) + \varepsilon_{(r)}(\omega_k)} e^{-qz} \end{aligned}. \quad (6)$$

Expression (6) for $f_k(\mathbf{q},z)$ differs from similar expressions for structures with symmetric barriers because in this case it is impossible to distinguish symmetric and antisymmetric modes. However, the most significant difference from symmetric quantum wells is contained in the factors $F_m(q,\omega_k)$ from Eq. (5). These functions $F_m(q,\omega_k)$ contain frequency dependences that can be written in terms of the coefficients $A_m(\omega)$ which are equal to

$$A_m(\omega) = \frac{1}{\varepsilon_{m,opt}} \left(\frac{\omega_{LO,m}}{\omega} \frac{\omega^2 - \omega_{TO,m}^2}{\omega_{LO,m}^2 - \omega_{TO,m}^2} \right)^2 . \quad (7)$$

Here $\varepsilon_{m,opt}$ is the optical dielectric function and $\frac{1}{\varepsilon_{m,opt}} = \frac{1}{\varepsilon_{m,\infty}} - \frac{1}{\varepsilon_{m,0}}$ .The main contribution is made by the interaction containing the parameters $A_{(l)}(\omega)$ and $A_{(r)}(\omega)$ for the left and right barrier, respectively. It is determined by the dielectric properties of the barrier materials.Contributions due to the dielectric properties of the quantum well material contain the function $A_{(w)}(\omega)$ and appear only in higher orders in parameter (3).For sufficiently narrow quantum wells, when condition (3) is satisfied, the problem is less cumbersome to solve. An analogue of the Frohlich constant for bulk materials can be represented for the quantum well with asymmetric barriers in the following form:

$$\alpha_k = e^2 \sqrt{\frac{m}{2\omega_k}} R_{as}(\omega_k), \quad (8)$$

Where *k* is the interface optical phonon branch number and *k* = 1,2; *m* is the mass of carriers in the quantum well, and the last factor $R_{as}(\omega_k)$ can be written as:

$$R_{as}(\omega_k) = \left| F_m(q,\omega_k) f_k(\mathbf{q},z) \right|^2 \cong \frac{2A_{(r)}(\omega_k)A_{(l)}(\omega_k)}{A_{(r)}(\omega_k) + A_{(l)}(\omega_k)}. \quad (9)$$

It can be seen from Eq. (9) that in sufficiently narrow quantum wells the energy of the electron-phonon interaction can be represented as a constant value independent of the well width *L*. This value corresponds to the polarization created by the barriers. This polarization changes little over the width of the well *L* in rather narrow quantum wells. In this case, the difference in the spatial position of the interaction maxima of the frequencies ω_1 and ω_2 turns out to be insignificant. The dielectric properties of the quantum well material in this approximation also turn out to be insignificant. The expression for the parameter $R_{as}(\omega_k)$ should be compared with a similar expression $R_{sym}(\omega_k)$ that arises when finding the electron-phonon interaction constant in symmetric quantum wells. Earlier it was shown in [1] that in symmetric structures under condition (3), this value turns out to be equal to $R_{sym}(\omega_k) = R_{sym} = 1/\varepsilon_{opt}$ .The value of ε_{opt} here is determined by the barrier material properties. In this case, the frequency of the interface mode is close to the frequency of longitudinal optical phonons of the barrier materialexclusively.

When studying an asymmetric structure with different barriers, the phonon frequency slightly differ from both $\omega_{LO,(l)}$ and $\omega_{LO,(r)}$. Although this distinction is rather small, it is important to take it into account for the correct determination of the electron-phonon interaction parameters.In Figure1,our model calculations for the function $R_{as}(\omega_k)$ are shown for theratios of the phonon barrier material frequencies defined by the parameter*x*. The dependencies are calculated for three different values of the dielectric constant ε_0 . Such linear phonon frequency dependencieson some external parameter *x* can be realized, for example, when solid solutions of various compositions are used as the barriers.

For comparison, the dependences were calculated for the quantum well with symmetric by its dielectric properties barriers.The material for both barriers is taken as for the right barrier in an asymmetric structure.These dependencies are shown in Figure 2.

For the situation when the regions of the phonon frequencies of the barriers overlap, a comparison of the dependences shown in the Figure 1 and Figure 2 showthat the values R_{sym} of the electron-phonon interaction parameter are larger for symmetric structures than for asymmetric ones. This parameter itself can vary in magnitude several times. It turns out that at small values of the static dielectric constant ε_0 which refers to the barrier material, the greatest changes are realized in symmetric structures. At large valuesof ε_0 , on the contrary, more significant changes are characteristic for the asymmetric quantum wells. This makes it possible to choose the optimal method for control of the electron-phonon interaction for structures with a different choice of barrier materials.

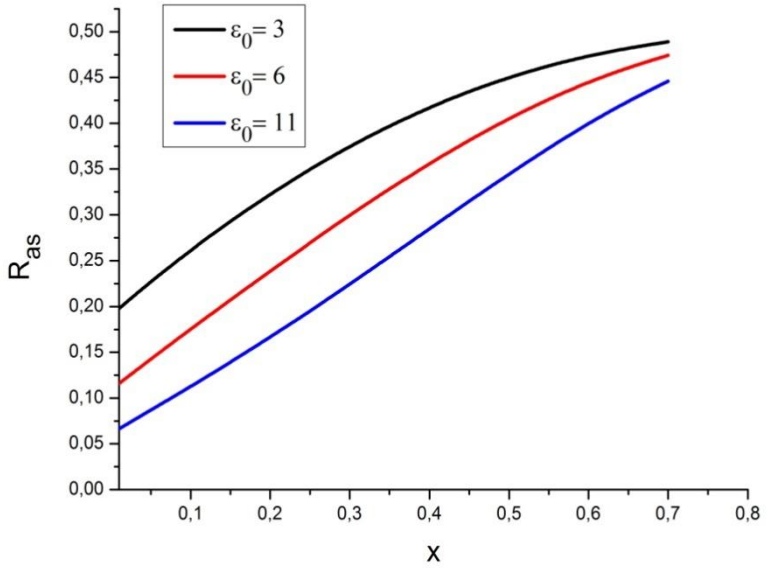

Figure 1: Parameters of Electron-Phonon Interaction $R_{as}(\omega_k)$ for Different Values of the Dielectric Constants ε_0.

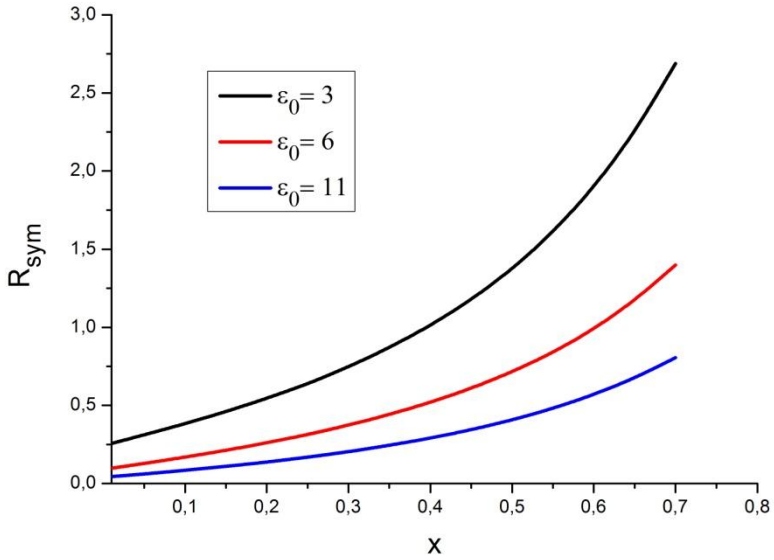

Figure 2: Parameters of Electron-Phonon Interaction R_{sym} for Different Values of the Dielectric Constants ε_0.

III. CONCLUSIONS

Thus, the use of barriers that are asymmetric in their dielectric properties leads to a significant change in the interaction of charged particles with polar optical phonons in structures with the quantum wells.The dimensionless interaction parameter in such structures can change several times.This must be taken into account when studying the relaxation processes of hot carriers, as well as the optical and transport properties of such structures. Alsothe additional opportunities open upfor creating the advanced nanostructures with new properties.It follows from our results obtained that the quantum wells with asymmetric barriers are good objects for phonon engineering.

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