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EFFECTS OF VIBRONIC COUPLING IN LOW-DIMENSIONAL SYSTEMS

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Abstract. The influence of vibronic coupling on the properties of donor impurities in semiconducting systems is discussed. The effects are seen in infrared photoconductivity and Fourier transform spectroscopy experiments. This is particularly the case for 'the resonant polaron effect' when the electronic transition energy matches the longitudinal-optical phonon energy. The spectra analysed here involve transitions to metastable states in the presence of high magnetic fields (~14 T). A new variational-type approach for the calculation of the energies of analytical expressions for the wave functions of the metastable states has been developed, so that the effects of polaron interactions on the transition energies can be calculated. Experimental and theoretical transition energies are compared. The polaron effect at resonance causes a repulsion in the transition energies of ~15 cm^{-1} in bulk GaAs. Nonresonant polaron effects are found to be much smaller in bulk but ~5 cm^{-1} in multiquantum well (MQW) systems.

Key words: low-dimensional systems, resonant polaron effect, nonresonant polaron effect.

1. INTRODUCTION

For over 50 years, the coupling between electrons and the vibrations of any surrounding lattice (often called 'vibronic coupling') has played a highly significant role in many areas of condensed matter physics. However, this coupling takes many forms and its magnitude varies widely in various situations. In 1937, Jahn and Teller [1] considered in detail the case of a substitutional magnetic impurity ion (such as a transition metal ion) in a dielectric or a semiconducting host. In such cases, the vibronic coupling, which describes the interactions between the electrons and the vibrations of the surroundings, is then usually written in terms of an interaction Hamiltonian of the form ([e.g. [2, 3]):

$$\mathcal{H}_{int} = \mathcal{H}_{JT} = V_E (E_\theta Q_\theta + E_\varepsilon Q_\varepsilon) + V_T (T_{yz} Q_4 + T_{zx} Q_5 + T_{xy} Q_6) \,. \quad (1.1)$$

The Qs are the (acoustic) phonon displacements, the Ts and Es are orbital operators and the Vs are the coupling constants of E and T_2 symmetry.

Thus the vibronic coupling enters by modulating the crystal field at the ion in question. This coupling results in the very well known Jahn–Teller (JT) effect which manifests itself through the appearance of JT reduction factors in effective Hamiltonians used to describe the spectroscopic properties of such ions.

A totally different set of circumstances arises for the case of a donor impurity in a semiconducting host. Firstly, the donor electron is only weakly coupled to its nucleus and thus it has a very large hydrogen-like orbit with a radius much larger (of order 10 nm) than the atomic spacing of the host and a small effective mass (of order 0.067 m_e where m_e is the free electron mass). The influence of other ions is thus very small so that crystal field effects are minimal. This means, secondly, that the electron–phonon interaction or vibronic coupling is of a long-range Coulomb-type interaction and thus it involves the longitudinal-optical (LO) phonons. This is often referred to as the 'polaron effect', as the electron then becomes surrounded by phonons, due to the distortion of the lattice induced by the electric field of the electron, and a 'polaron' is formed. The interaction can be written down by using the Fröhlich Hamiltonian [4]:

$$\mathcal{H}_{int} = \mathcal{H}_F = \sum_q (V_q a_q e^{iq.r} + V_q^* a_q^\dagger e^{-iq.r}) \qquad (1.2)$$

for an electron at r and a phonon of momentum q where V_q is the coupling constant and a_q, $a_q^\dagger$ are phonon annihilation and creation operators. One effect of $\mathcal{H}_F$ is to introduce anisotropy in the effective mass of the electron which in turn affects its magnetic properties [5]. This effect is much more pronounced in quasi-two-dimensional systems such as in a multiquantum well (MQW) as generated by MBE-grown semiconductor layers. This has been highlighted in two very recent papers [6, 7] as the polaron effect influences strongly the optical and transport properties of such materials.

2. BACKGROUND

In the last decade, many studies of donor impurities in the presence of high magnetic fields have been undertaken. Experiments are generally carried out by using far-infrared techniques incorporating either photoconductivity or Fourier transform spectroscopic measurements. Originally, the simple donor D^0 was studied in bulk materials such as GaAs but recently there has been much interest in donors in quantum well and superlattice systems. Most of the many publications on this subject concentrate on hydrogen-like transitions such as $1s_0$ to $2p_\pm$. However, the spectrum usually contains many additional sharp lines at higher energies. It was recognized some time ago (e.g. [8–11]) that much of the observed fine structure in both bulk and MQW systems, particularly at the higher energies, arises from transitions to the so-called 'metastable' states. This is the name given to those states which are bound in high magnetic fields but which become unbound as the field is reduced to zero [11]. To understand

these states we note that, in a strong field and with no impurity, these eigenstates are Landau states. For an impurity in zero field, the eigenstates are hydrogen-like. For an impurity in a large field, we have a mixed system and thus the metastable states are defined to be those eigenstates which are not present in zero field.

In giving a detailed description of such shallow donor spectra, with the emphasis on the transitions to the metastable states, it is clear that the electron–phonon interaction is important. In particular, a much larger effect is found when the LO phonon energy exactly matches a transition energy and the so-called resonant polaron effect arises. Its study gives valuable information on the metastable state wave functions. In particular, previous experiments on a high-purity n-GaAs sample using a far-infrared laser [11] were extended [12] up to the energies of 330 cm^{-1} and with fields up to 14 T. This energy is above the LO phonon energy of 296 cm^{-1} so that the resonant electron–phonon interaction of some of the metastable states could be studied. The other most recent work which is closest to this [13] considers transitions to hydrogen-like 2p states only.

A new approach to the problem of calculating expressions for those metastable states which are needed to estimate the strength of resonant polaron interactions was given very recently [12]. The method involved a simple variational procedure and it gave simple analytical expressions for those metastable states involved in the most prominent transitions in the spectrum. It is this method that is used here.

Our discussion here on the effects of vibronic coupling in donor impurities is divided into three parts. The first two parts give an account of the polaron effect in bulk GaAs involving metastable states, firstly, away from the resonance position and, secondly, in the resonance region where the coupling is the strongest. The third part gives new results for the polaron effect in low-dimensional systems but in the nonresonant regime only.

3. THE POLARON EFFECT IN BULK GaAs

For the reasons stated above, we concentrate on those infrared transitions to the metastable states. However, it is useful to have a convenient notation to describe all states of the donor impurity. Thus we refer to both the hydrogenic and metastable states, using the high-field notation (N, m, ν), where N is the principal Landau quantum number, m is the usual magnetic quantum number and ν is the number of nodes of the wave function in the z direction [11]. Equivalences between the high-field and hydrogenic notations are well known. Thus the ground 1s-like state is written as (0, 0, 0), $2p_+$ as (1, 1, 0) and $2p_-$ as (0, −1, 0), for example. In most experiments, the Faraday configuration ($\boldsymbol{E} \perp \boldsymbol{B}$) is used, so that, according to the electric dipole selection rules, transitions from the ground state to the states $(N, \pm 1, \nu)$ for ν even dominate the spectrum. The strongest transitions observed are expected to be to states with $\nu = 0$.

3.1. Experimental data

The experimental results [12] with which we compare our calculations, were obtained from MBE-grown samples consisting of epitaxial layers of n-GaAs on a semi-insulating substrate, intentionally doped with Si ($N_d = 5 \times 10^{14}$ cm^{-3} and $N_a = 1 \times 10^{14}$ cm^{-3}). Previous magneto-optical experiments on this system had been carried out using a conventional optically-pumped FIR laser for laser energies up to 264 cm^{-1} and a 6 T superconducting magnet [11]. These experiments were subsequently extended by FIR laser spectroscopy with fields up to 14 T. For the energies below that of the transverse-optical (TO) phonon at 270 cm^{-1}, where the polaron interaction is small, a nearly linear field-energy relation for the transitions was observed. In that energy region, therefore, the experiments using a relatively small number of different laser wavelengths were found to be sufficient to determine accurately the field-dependent transition energies. For the energies near that of the LO phonon energy, however, this relation becomes very nonlinear due to resonant polaron interaction. As the limited number of available FIR laser lines in that energy region (≥ 295 cm^{-1}) could not give the information necessary for the detailed observation of the resonant polaron effect, further FIRPC experiments were performed [12] by using a Fourier transform spectrometer. Because of the Reststrahlen reflection band of GaAs, no spectra were observed between 270 and 296 cm^{-1}. Also, no signals were seen above 330 cm^{-1} probably due to system limitations. The experimental results for transitions to the (3, 1, 0) and (4, 1, 0) metastable states are shown in Fig. 1. A clear resonant behaviour can be observed in the 296 cm^{-1} to 330 cm^{-1} region resulting from the interaction with the nearby $1s_0$ state with one LO phonon excitation and the $2p_-$ state with one LO phonon excitation.

3.2. A summary of the theory for metastable states

In order to undertake the necessary calculations, explicit expressions for metastable states are required. Neglecting spin, the nonrelativistic Hamiltonian for the electron associated with the donor impurity atom placed at the origin may be written in the form [14]

$$\mathcal{H} = \frac{\pi^2}{2m_0} + V(r) , \tag{3.1}$$

where $\pi = p + eA$ is the momentum operator, A is the vector potential of the uniform magnetic field B, $V(r)$ is the Coulomb potential, and m_0 is the effective mass of the electron. The z-axis is chosen to be along the direction of B. In the absence of the Coulomb term, the eigenstates of (3.1) are the well-known Landau functions $\Phi_{Nm}(\rho, \phi)$ which, in cylindrical coordinates, have the form

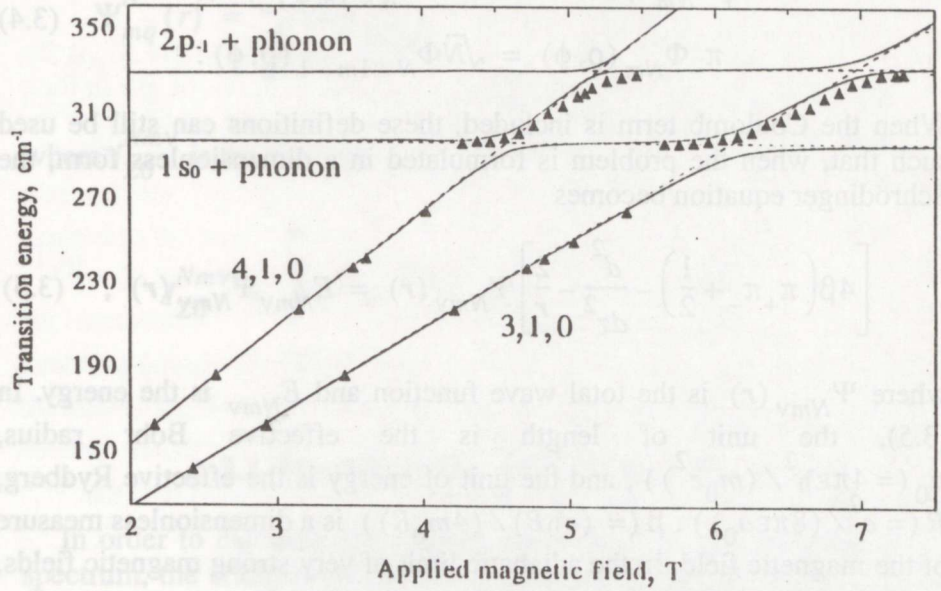

Fig. 1. Calculated transition energies (shown by continuous curves) of the $1s_0$ [(0, 0, 0)] to the (3, 1, 0) and (4, 1, 0) metastable states including the full effects of polaron interaction and band nonparabolicity for the complete field range are shown. The resonant polaron effect is clearly seen to lead to avoided crossings of the (3, 1, 0) and (4, 1, 0) metastable states with the states $|\Psi_{1s}, q\rangle$, and $|\Psi_{2p_-}, q\rangle$. The experimental points are shown by ▲. The calculated transition energies excluding the polaron effect are also shown (by dashed curves).

$$\Phi_{Nm}(\rho, \phi) = \frac{1}{\sqrt{2\pi\lambda^2}} e^{im\phi} e^{-\frac{1}{2}\zeta} \zeta^{\frac{1}{2}|m|} P_{Nm}(\zeta) , \qquad (3.2)$$

where N and m are the Landau and the magnetic quantum number, respectively, $\zeta (= \rho^2/(2\lambda^2))$ is a dimensionless variable and $\lambda (= \sqrt{(\hbar/eB)})$ is the magnetic length. The polynomials P_{Nm} are closely related to the associated Laguerre polynomials. It is useful to introduce the operators

$$\pi_{\pm} = \frac{\lambda}{\hbar} \frac{(\pi_x \pm i\pi_y)}{\sqrt{2}} , \qquad (3.3)$$

which act as raising and lowering operators on N and m such that

$$\pi_+ \Phi_{Nm}(\rho,\phi) = \sqrt{N+1}\,\Phi_{N+1\,m+1}(\rho,\phi),$$
$$\pi_- \Phi_{Nm}(\rho,\phi) = \sqrt{N}\,\Phi_{N-1\,m-1}(\rho,\phi). \tag{3.4}$$

When the Coulomb term is included, these definitions can still be used such that, when the problem is formulated in a dimensionless form, the Schrödinger equation becomes

$$\left[4\beta\left(\pi_+\pi_- + \frac{1}{2}\right) - \frac{d^2}{dz^2} - \frac{2}{r}\right]\Psi_{Nm\nu}(\boldsymbol{r}) = E_{Nm\nu}\Psi_{Nm\nu}(\boldsymbol{r}), \tag{3.5}$$

where $\Psi_{Nm\nu}(\boldsymbol{r})$ is the total wave function and $E_{Nm\nu}$ is the energy. In (3.5), the unit of length is the effective Bohr radius, $a_0 (= 4\pi\varepsilon\hbar^2/(m_0 e^2))$, and the unit of energy is the effective Rydberg, $R (= e^2/(8\pi\varepsilon a_0))$. $\beta (= (e\hbar B)/(4m_0 R))$ is a dimensionless measure of the magnetic field. In the adiabatic limit of very strong magnetic fields, when the cylindrically-symmetric magnetic field dominates, the wave function $\Psi(\boldsymbol{r})$ can, to a good approximation, be written in the separated form:

$$\Psi_{Nm\nu}(\boldsymbol{r}) = \Phi_{Nm}(\rho,\phi) f^N_{m\nu}(z), \tag{3.6}$$

where $f^N_{m\nu}(z)$ is a function of z only. The method which we adopted [12] to obtain values for $E_{Nm\nu}$ and $f^N_{m\nu}(z)$ used simple variational methods. Thus $f^N_{m\nu}(z)$ was treated as a trial function of the form

$$f^N_{m\nu}(z) = z^\nu e^{-b_{Nm}z^2} \tag{3.7}$$

for the two cases where $\nu = 0$ and 1 and where b_{Nm} is the variational parameter. For these particular cases, ν gives the parity of the wave function in the z direction. The energy of the metastable state and its associated wave function are then found by minimizing the energy expression

$$E_{Nm\nu} = 2\beta(2N+1) + 3^\nu b_{Nm} - (4b_{Nm})^\nu \sqrt{\frac{8b_{Nm}}{\pi}} \int_0^\infty I_r^{NN} z^{2\nu} e^{-2b_{Nm}z^2}\, dz \tag{3.8}$$

with respect to the parameter b_{Nm}. The resultant normalized wave function is given by

$$\Psi^{N}_{mq}(r) = \frac{a_0}{\sqrt{2\pi\lambda^2 I^{Nm\nu}_{Z0}}} e^{im\phi} e^{-\frac{1}{2}\zeta} \zeta^{\frac{1}{2}|m|} P_{Nm}(\zeta) z^{\nu} e^{-b_{Nm}z^2}, \quad (3.9)$$

where $I^{Nm\nu}_{Z0}$ is the integral

$$I^{Nm\nu}_{Z0} = \int_{-\infty}^{\infty} z^{2\nu} e^{-2b_{Nm}z^2} dz = \frac{1}{(4b_{Nm})^{\nu}} \sqrt{\frac{\pi}{2b_{Nm}}}. \quad (3.10)$$

3.3. The calculation of transition energies

In order to calculate the transition energies corresponding to the FIR spectrum, the energies of both the ground and relevant excited states are required. However, as the electron is most tightly bound to the nucleus when it is in its two lowest energy states, $1s_0$ and $2p_-$, the above method of calculation is not sufficiently accurate. Therefore, the method of Dunn and Pearl [15] was used for these states in which the hydrogenic wave functions are written in the form

$$\Psi_H = \sum_i c_i \rho^{|m|} e^{im\phi} e^{-(\beta_i + \delta)\rho^2} z^q e^{-\alpha_i z^2}. \quad (3.11)$$

Here c_i are wave function coefficients, α_i and β_i are the numbers chosen from the Gaussian expansion of the Slater-like function of the hydrogenic wave function and $\delta = 0.2\beta$ (to allow for the constriction of the wave function in the ρ direction with the increased magnetic field).

The transition energies from the $1s_0$ ground state to various excited metastable states have been calculated. However, to compare these calculations with the experimental data it is necessary to take into account two corrections. The first is nonparabolicity of the conduction band. To do this we use the standard Kane model [16] for the corrected energy E and write:

$$E = E^0 \left(1 - \delta' \frac{E^0}{E_g} \right), \quad (3.12)$$

where E^0 is the energy calculated for a parabolic conduction band, E_g is the GaAs band gap (= 1520 meV). The parameter δ' is taken to be 0.73 [17]. The second correction, which follows, is due to the polaron effect which is the main subject of this paper.

4. THE POLARON EFFECT

Consider an unperturbed state $|\Psi_g, 0\rangle$ of the energy E_g where Ψ_g is the electronic wave function and '0' indicates that all LO phonons are in their ground state. The correction ΔE_g to the energy of this state from the polaron effect is given in the second-order perturbation theory by [18]

$$\Delta E_g = -\sum_h \sum_q \frac{\left|\langle \Psi_h, q|\mathcal{H}_F|\Psi_g, 0\rangle\right|^2}{E_h + \hbar\omega_{LO} - E_g - \Delta E_g}, \tag{4.1}$$

where Ψ_h is another electronic wave function with the energy E_h and q denotes that there is a single excitation of a LO phonon of the wave vector q with the energy $\hbar\omega_q \simeq \hbar\omega_{LO} = 296$ cm^{-1}. $\mathcal{H}_F$ is the Fröhlich polaron Hamiltonian given in (1.2). V_q and V_q^* are constants for a given q such that

$$|V_q|^2 = \frac{4\pi\alpha}{V}\sqrt{\frac{\hbar}{2m\omega_{LO}}}\left(\frac{\hbar\omega_{LO}}{q}\right)^2. \tag{4.2}$$

We concentrate here on the $|\Psi_{310}, 0\rangle$, $|\Psi_{410}, 0\rangle$ metastable states and in particular on the region where they have energies very close to those of the $|\Psi_{1s_0}, q\rangle$ and $|\Psi_{2p_-}, q\rangle$ hydrogen-like states. The polaron interaction between these states is calculated by using the form of wave function (3.6) and (3.7) obtained from the variational procedure for the metastable states described above and the hydrogenic form (3.11) from [15] for hydrogen-like states. Thus we have, for example,

$$\sum_q \left|\langle \Psi_{1s_0}, q|\mathcal{H}_F|\Psi_{310}, 0\rangle\right|^2 =$$

$$= \frac{3\pi^3\alpha}{4} R^{\frac{1}{2}} (\hbar\omega_{LO})^{\frac{3}{2}} \frac{\beta^2}{\pi I_{Z0}^{310}} \sum_j \sum_i \frac{c_i^{1s_0} c_j^{1s_0}}{\sqrt{(\alpha_i + b_{Nm})(\alpha_j + b_{Nm})}\, D_i^2 D_j^2} \times \tag{4.3}$$

$$\times \int_0^\infty q_\rho^2 F_i^{1s_0, 310}(q_\rho) F_j^{1s_0, 310}(q_\rho)\, e^{-\frac{(B-A)}{4} q_\rho^2} \left[1 - \Phi\left(\frac{q_\rho}{2}\sqrt{A}\right)\right] dq_\rho,$$

where

$$F_i^{1s_0, 310}(q_\rho) = \frac{\beta^2}{96 D_i^2}\left(\frac{q_\rho^4}{D_i^2} - 24\frac{q_\rho^2}{D_i} + 96\right) + \frac{\beta}{4D_i}\left(\frac{q_\rho^2}{D_i} - 8\right) + 1 \tag{4.4}$$

and for other states it is similar. In the above, we have used the notation $D_i = \beta_i + 0.7\beta, A = 1/(\alpha_i + b_{Nm}) + 1/(\alpha_j + b_{Nm})$ and $B = 1/D_i + 1/D_j$. q_ρ is the ρ component of the LO-phonon wave vector and the function $\Phi(x)$ is the probability integral. $c_i^{1s_0}$, etc. and I_{Z0}^{310}, etc. are the constants associated with Ψ_{1s_0}, etc. and Ψ_{310}, etc. wave functions, respectively. For simplicity, the summation over the states Ψ_h has been limited to the nearest states.

As can be seen from above, one advantage of using a simple expression for metastable wave functions is that the calculation of the polaron correction is straightforward. Also, the numerators in the polaron correction terms reduce to a one-dimensional integral which can be solved readily by numerical methods. The transition energies incorporating corrections due to the band nonparabolicity described above and the polaron interaction for the metastable states $|\Psi_{310}, 0\rangle$, $|\Psi_{410}, 0\rangle$ and for the hydrogenic states $|\Psi_{1s_0}, q\rangle$ and $|\Psi_{2p-}, q\rangle$ for all ranges of magnetic fields, including that when resonance occurs, have been obtained. The results obtained are shown in Fig. 1 for GaAs, for which $a_0 = 100.06$ Å, $R = 46.11\ \text{cm}^{-1}$ and $\beta = 0.076\,B$ (for B in Tesla), together with experimental data [12]. Also shown in the figure are transition energies without the polaron correction.

It is clearly seen from Fig. 1 that the polaron correction to the transition energies in the nonresonant regions is very small. This correction can be incorporated into the theory by simply introducing a factor $(1 + \alpha/6)$ implicitly in the value taken for the effective mass of the electron with $\alpha = 0.068$. In the resonant region, the polaron correction causes a repulsion between the relevant excited states and thus in the transition energies of 10–15 cm^{-1}. Overall, the calculated transition energies corrected by the polaron effect are in very good agreement with the corresponding experimental data when the polaron effect is included in both the resonant and the nonresonant regions.

5. THE NONRESONANT POLARON EFFECT IN MQW SYSTEMS

The same second-order perturbation theory has also been used to calculate the shift in the energy arising from the polaron effect of the low-lying hydrogen-like states of the donor impurity in a GaAs/GaAlAs MQW system as a function of the applied magnetic field in the nonresonant regions. In principle, the calculations are straightforward on using (4.1) for the polaron correction for the states given by either (3.7) or (3.11). However, the problem now contains a large number of definite integrals related to the z direction, which need to be calculated by computer. Again, to contain the calculations within manageable proportions, only one phonon excitation is included. The shifts in the energy for the low-lying

1s, $2p_+$, and $2p_-$ states have been obtained for a MQW system in which the well width (= 150 cm^{-1}) is equal to the barrier width. The results obtained so far both without and with the polaron corrections are shown in Fig. 2. At 2 T, the polaron correction decreases the energy of the $2p_+$ and $2p_-$ states by ~5 cm^{-1} and the 1s ground state by ~10 cm^{-1}. Thus the transition energies change ~5 cm^{-1}. These calculations are in very close agreement with those undertaken independently by others using variational methods (e.g. [18]).

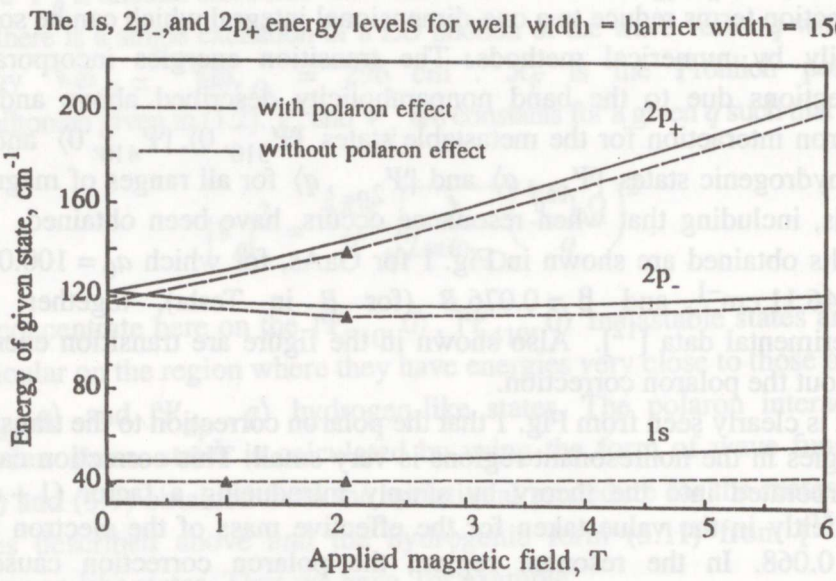

Fig. 2. The calculated polaron correction for the 1s, $2p_+$, and $2p_-$ energy levels at selected values of the magnetic field for a GaAs/GaAlAs MQW in the nonresonant region in which both the wells and barriers have a width of 150 Å.

6. DISCUSSION AND CONCLUSIONS

The effect of vibronic coupling on the properties of various types of donor impurities is currently receiving much attention and some of the very recent work is cited above. Other work includes the consideration of separate contributions from the surface and bulk phonons, the influence on the coupling of an electric field and the effects in quantum wires and quantum dots.

The calculations reported here are different from those of other investigators in that we consider metastable states for the bulk case. In general, we have found that, by modelling the excited metastable states with a very simple variational wave function, remarkably close agreement is obtained with the experimental data. In fact, a comparison between

theory and experiment on an enlarged scale of Fig. 1 clearly shows that the two agree normally to within 1% and that the maximum difference is always within 2%. To our knowledge, this is the first time that such a good quantitative agreement has been obtained between experiment and theory for the transitions involving the metastable states.

We have concentrated here on resonant effects in bulk GaAs. We find that the polaron effect is considerably enhanced when the electronic transition energies correspond to the LO phonon energy, in agreement with experiment. However, the effects of confinement have been supposed to enhance the strength of the electron–LO phonon interaction [13] due to the curtailment of the extent of the wave function. Indeed, we have found a very much larger shift in the transition energies with nonresonant polarons in MQW systems compared to the bulk GaAs; this emphasizes the point made by others [6, 7] that confinement effects enhance the polaron effect. We emphasize that our calculations are basic and that there is no input from the experimental data into the analysis. The next stage is to extend our current calculations on resonant polaron effects involving the excited metastable states to MQW systems.

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VIBROONSEOSE EFEKTID MADALADIMENSIOONILISTES SÜSTEEMIDES

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On käsitletud vibroonseose mõju doonorlisandite omadustele pooljuhtsüsteemides. Efekte on vaadeldud infrapunases fotojuhtivuses ja Fourier' spektroskoopia eksperimentides. Siia kuulub resonantne polaronefekt, kui elektronsiirde energia vastab longitudinaalse optilise foononi energiale. Analüüsitud spektrid on seotud siiretega metastabiilsetesse seisunditesse tugevas magnetväljas (~14 T). On arendatud uus variatsiooni tüüpi lähend metastabiilsete seisundite analüütiliste lainefunktsioonide energiate arvutamiseks. Sellega võib leida polaroninteraktsiooni mõju siirdeenergiatele. On võrreldud eksperimentaalseid ja teoreetilisi siirdeenergiaid. Polaronefekt põhjustab resonantsi korral siirdeenergiate tõukumise ~15 cm^{-1} GaAs sisemuses. Mitteresonantne polaronefekt on sisemuses palju väiksem, kuid kvantauksüsteemides on see ~5 cm^{-1}.

ЭФФЕКТЫ ВИБРОННОЙ СВЯЗИ В СИСТЕМАХ НИЗКОЙ РАЗМЕРНОСТИ

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Обсуждено влияние вибронной связи на свойства донорных примесей в полупроводниковых системах. Эффекты наблюдены в инфракрасной фотопроводимости и в экспериментах спектроскопии Фурье. Сюда относится резонансный поляронный эффект, имеющий место в случае, если энергия электронного перехода соответствует энергии продольного оптического фонона. Рассмотренные спектры связаны с переходами в метастабильные состояния в сильных магнитных полях (~14 Т). Развит новый подход вариационного типа для вычисления энергий аналитических волновых функций метастабильных состояний. Также можно вычислить влияние поляронного взаимодействия на энергии перехода. Сравниваются экспериментальные и теоретические энергии перехода. Резонансный поляронный эффект приводит к отталкиванию энергий перехода на 15 $см^{-1}$ в объемном GaAs. Нерезонансный поляронный эффект намного меньше в объеме, но равен ~5 $см^{-1}$ в системах квантовых ям.