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PHONON-INDUCED 2e⁻-TUNNELING IN GaAS QUANTUM DOTS

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Abstract

In this paper, we give a brief account of pair-tunneling in GaAs quantum dots. We show that while GaAs is a weakly-polar semiconductor, coupling to optical phonons is sufficiently strong to mediate a negative-U pairing state. As a result, two electrons can tunnel coherently from the source lead to the quantum dot as a Cooper pair would across a Josephson junction.
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One of the key experimental results that has come out of single-electron capacitance[1] spectroscopy (SECS) on GaAs quantum dots is the observation of pair electron tunneling. As GaAs is not a superconductor, it is even more surprising that pair-tunneling events are at all stable. In this brief report, we will sketch our solution to the pair-tunneling problem in semiconductor dots[2]. This paper is intentionally brief as a more complete paper on the same subject is already in press[2]. It is first instructive to focus on the experimental facts. Ashoori and co-workers[1] reported a series of measurements on a GaAs tunnel capacitor in the sub-Coulomb blockade regime. A tunnel capacitor is a layered structure consisting of a source lead, a tunnel junction, a laterally-confined GaAs quantum well, a δ-doped backing layer of AlGaAs and a gate electrode[1]. Direct confirmation of pair (or two electron)-tunneling is obtained from the evolution of the tunneling peaks in the presence of a magnetic field. The pair peaks, labeled X, Y, and Z in Fig. 6b of Ref. [1b], were shifted to higher gate voltages (V_G) and were observed to split into two distinct tunneling peaks at critical values of the field, $B_c \approx 2T$. Above B_c, the spectroscopic signal now corresponds to two energetically-resolved tunneling events. The amplitude for each peak is consistent with that for single-electron tunneling. Hence, above B_c, each state carries a single electron, whereas the charge in the states X, Y, and Z at zero-field must be 2e⁻. At a field of $10T$, the splitting between the two states for all three pair states is roughly 3 meV. The Zeeman energy at this field strength is 0.25 meV. Hence, breakup of the

pair cannot be attributed to a simple Zeeman effect. Another curious feature is that the pair states were not observed[3] in defect-free quantum dots with a physical diameter of 3000Å or equivalently a lateral confining length of 400Å.

Consequently, a theory of the pair states must explain the following facts: 1) the stability of a $2e^-$ tunneling state at zero magnetic field, 2) a pair instability at a critical field $B = B_c$, 3) the emergence of two distinct tunneling peaks for $B > B_c$, and 4) the absence of pair-tunneling states in defect-free quantum dots with a confining diameter approximately ≤400Å. We propose here a model which is capable of explaining each of these observations.

To develop some physical understanding of the nature of the confining potential for the pair states, it is expedient to examine more closely the experimental data. Consider the pair states labeled *X*, *Y*, and *Z* in ref[1b]. A consistent trend in these pair states is that above B_c, the two electronic states evolve with fundamentally different slopes, indicating two distinct confining potentials. The upper state consistently has a slope close to $\hbar\omega_c/2$ whereas the slope of the lower state is almost constant as a function of magnetic field. States which exhibit an asymptotic slope of $\hbar\omega_c/2$ as a function of magnetic field originate from parabolic confinement. In a tunnel capacitor, the δ-dopants cluster to form a 2D harmonically-confined potential. On the other hand, states whose energy increases slowly as a function of magnetic field originate from singular types of potentials, for example a $1/r$ potential. In fact, Ashoori and co-workers have attributed the states whose energy is relatively insensitive to a magnetic field as arising from Si impurities that diffuse into the quantum well from the source lead[1]. In such hydrogenic impurities, the $1/r$ potential competes with the parabolic potential generated by the magnetic field to suppress the asymptotic $\hbar\omega_c/2$ slope. The effective Bohr radius of a Si impurity in GaAs is $a_0^* \approx 100$Å. Consequently, the pair states appear to be hybrid states composed of a Si-impurity and a parabolic well formed from the δ-dopants in the backing layer. A hybrid potential of this sort will give rise to two different length scales once the electron pair breaks up. Hence, such a potential will be the starting point for our analysis of the pair states.

Barring something truly exotic, the only tool available to mediate pair tunneling is coupling to optical phonons. GaAs is a weakly-polar semiconductor with an optical phonon energy of $\hbar\omega_{LO} = 36.6$ meV and coupling constant of $\alpha = 0.08$. The question that must be answered is, can the phonons offer sufficient screening of the bare Coulomb potential

to allow two electrons to occupy the same state. This question can be re-stated mathematically as a pair-binding problem, namely is $\tilde{E}(2) - 2\tilde{E}(1) < 0$, where $\tilde{E}(2)$ and $\tilde{E}(1)$ are the exact two and one-particle energies of the full Hamiltonian for the quantum dot. Of course, this pair constraint necessitates solving the coupled electron-phonon problem exactly. The relevant quantity that must be calculated is the bi-polaron attractive interaction, E_B. However, as GaAs is in the weak electron-phonon coupling regime, $\alpha = 0.08 << 1$, it can be shown[4] that the result based on perturbation theory[5], $E_B = 2E_p$, is an excellent approximation, where E_p is the polaron binding energy. Our approach will be to solve the electron problem separately using Quantum Monte Carlo (QMC) techniques. The pair-binding condition can now be recast as $E(2) + 2E_p - 2E(1) < 0$ where $E(2)$ and $E(1)$ are the exact two and one-particle energies of the exact quantum dot Hamiltonian in the absence of phonons.

For a free electron, the polaron binding energy is simply $E_p = -\alpha\hbar\omega_{LO}$[6]. The magnitude of this energy is determined by the coupling of the electron charge to the electrostatic field created by the lattice distortion. In addition to having its energy lowered, an electron forming a polaron now has a localized wavefunction. The spatial extent of the wavefunction is r_p, the polaron radius. To form a stable state, the polaron energy must compensate for the increase in the kinetic energy when an electron becomes localized by the lattice distortion. The stability of a polaron is determined by the delicate balance between the increased kinetic energy and the lowering of the potential energy through the coupling to the electrostatic field of the lattice. Polarons are only stable if the electrostatic contribution to the potential energy outweighs the subsequent increase in the kinetic energy. In the problem at hand, however, the electrons in the pair state are not free. The potential in which they occur is a bound potential consisting of a hybrid hydrogenic/parabolic well. We must then solve the bound polaron problem. For an electron in a bound potential, the distortion of the wavefunction to form a bound polaron is not as severe as in the free electron case. As a result, the increase in the kinetic energy upon polaron formation is less in the bound case than in the free problem. Hence, more of the coupling of the electron charge to the electrostatic field of the ions goes directly into lowering the energy of the electron. As a result, the bound polaron binding energy should always be lower than that for the free electron. We have re-formulated Feynman's variational polaron calculation[7,8] for the hybrid pair potential in an external magnetic field. We found that[2] E_p is relatively insensitive to a magnetic field[2]. (The correction at 10T is 0.05meV which is five times smaller than the corresponding Zeeman energy). At $B = 0$, the confining potential has enhanced the polaron binding energy from $E_p = -\alpha\omega_{LO}$ to

$E_p = -1.1\alpha\omega_{LO}$. For GaAs, this corresponds to an enhancement of 0.3 meV or equivalently an enhancement of 0.6 meV for the bi-polaron binding energy.

We now combine our variational estimates for the polaron energy with our exact QMC calculations for $E(2)$ and $E(1)$ to solve the pair-binding condition, $\Delta_p = E(2) + 2E_p - 2E(1) < 0$. When pair-binding occurs, $\Delta_p < 0$ and both electrons reside in the same electronic state with energy $\varepsilon = (E(2) + 4E_p)/2$ as measured in SECS. If $\Delta_p > 0$, two distinct states are occupied: a lower one with energy $\varepsilon_1 = E(1) + E_p$ and a higher one with energy $\varepsilon_2 = E(2) + 3E_p - E(1)$. Using the method outlined above, we have calculated Δ_p at three separations between the hydrogenic and parabolic wells: $x_0 = 5a_0^*$, $x_0 = 8a_0^*$, and $x_0 = 10a_0^*$. We have plotted in Fig. 1 the energy of two electrons on the quantum dot as a function of the magnetic field. The salient features of these graphs are as follows: 1) at $B = 0$, pair states form only when x_0 exceeds a critical value $\approx 8a_0^*$, 2) a magnetic field inhibits pair-binding at critical fields of $0.2T$ ($x_0 = 8a_0^*$) and $1.5T$ ($x_0 = 10a_0^*$) and 3) as in the experiments[1], two new states emerge above B_c; ε_1 has a weak field dependence and ε_2 scales asymptotically as $\hbar\omega_c/2$. The absence of pair-binding for $x_0 \leq 8a_0^*$ is a signature that the electronic wavefunctions are too localized for the electron-phonon attraction to outweigh the Coulomb repulsion. Similarly, increasing the magnetic field further confines the wavefunction of the electrons in the pair state. As a result, the Coulomb repulsions increase and at a critical value of the field, the polaron effect can no longer hold the pair together, resulting in pair-breaking.

We have also shown that the addition of anharmonic corrections to the potential created by the δ-dopants increases the tunnel barrier between the states in the hybrid potential. As a result pair-binding occurs at smaller separations and pair-unbinding occurs at larger values of the field. For $x_0 = 8a_0^*$ the critical field is $2T$. We conclude then that the experimental observations of pair-binding can be explained by a model in which optical phonons bind two electrons in a Si impurity and a roughly parabolic well (created by the δ-dopants) that are sufficiently far apart. Based on our results, we would predict then an absence of pair-binding in quantum dots that are either clean (no Si) or laterally smaller than $\approx 7a_0^*$ in confining diameter, consistent with experiments reported in Ref. [1b]. Now that the phonon-induced pairing of electrons in semiconductor quantum dots has been established, future experiments which exploit such states, for example as electron switches, should certainly be designed.

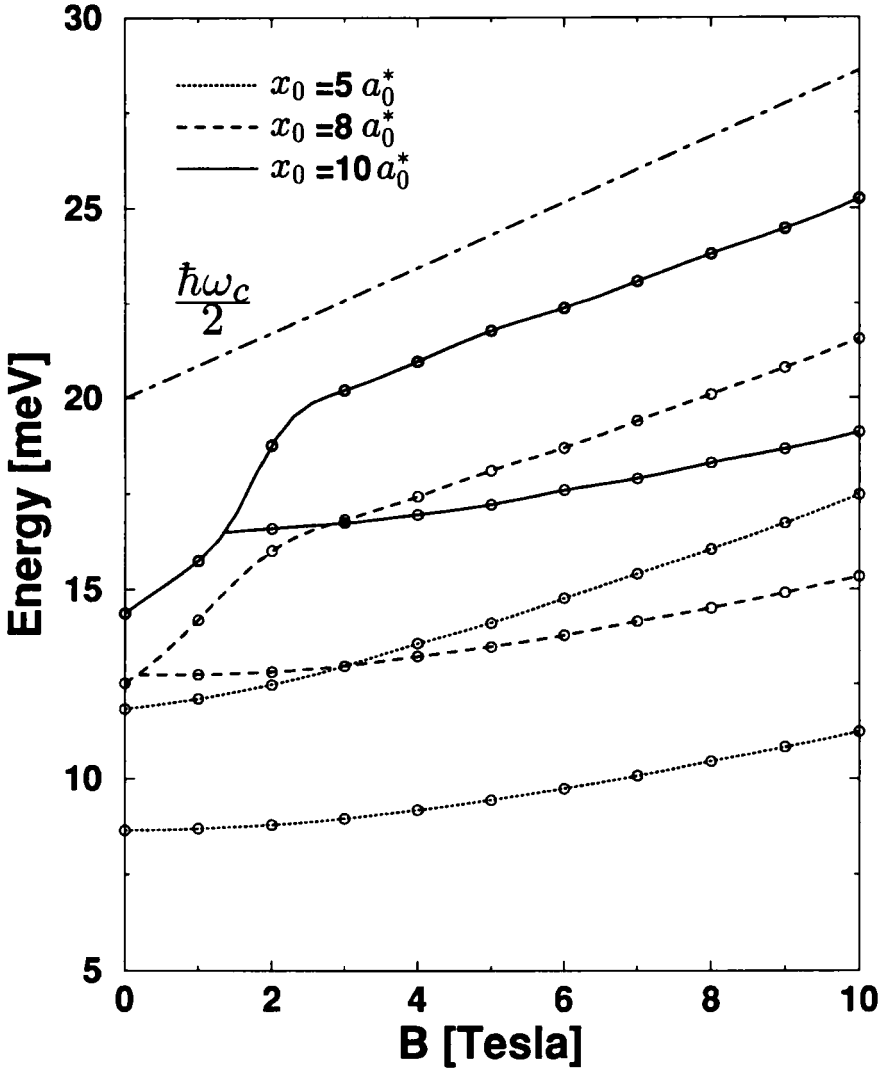

Figure 1

Electron energies as a function of magnetic field B. For each pair-potential separation x_0, the lower branch is $\varepsilon_1 - E_p$ while the upper one corresponds to $\varepsilon_2 - E_p$. The open circles represent the QMC results whose statistical error bars are 0.06 meV (smaller than the size of the circles). The curves are spline interpolations to the QMC data. The dashed-dotted line represents the field dependence of the lowest Landau level $\frac{\hbar\omega_c}{2}$.

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