Resonances in Conductance Through Tunable Attractors

YONG S. JOE* and RONALD M. COSBY

Department of Physics and Astronomy, Ball State University, Muncie, IN 47306, USA

We present the effects of resonant tunneling through doubly-coupled attractors in series in a quantum nanosystem. It is found that multiple split-tunneling peaks arise from resonant tunneling through multiple nondegenerate quasi-bound-states of the coupled attractors. We show that the tunability of coupling is achieved by modulating the strength of the attractor for a *fixed* separation length between the attractors, and by adjusting the geometrical separation length for a *fixed* intervening barrier strength.

Keywords: Nanostructures, Semiconductors, Tunneling

1. INTRODUCTION

Current state-of-the-art techniques result in surface-independent probes or contacts that may be biased to introduce tunable scattering potentials ("impurities") in quantum nanosystems [1]. Many theoretical and experimental works then have studied the elastic scattering by impurities in these systems. In particular, for a quantum structure containing a *finite-size* attractive impurity, called an 'attractor', it is shown that an attractor introduces multiple quasi-bound-states (QBSs) in the channel for a sufficiently strong attractor, and these states give rise to multiple resonant peaks *before* the first plateau in the conductance [2]. These conductance peaks appear due to resonant tunneling through the QBSs.

In this paper, we study the splitting of multiple resonant peaks before the first plateau in the conductance for a quantum nanosystem with two identical attractors in series. The separation of the split-conductance peaks through both the first and the second QBSs depends strongly on the coupling between the two attractors, which can be tuned by modulating the intervening barrier strength [3] and/or changing the geometrical separation length.

2. MODEL AND METHOD

A sketch of the model two-dimensional nanosystem with two identical attractors in series is illustrated in Figure 1(a), where relevant para-

*Corresponding author. Tel.: (765) 285-8879, Fax: (765) 265-5674, e-mail: ysjoe@bsu-cs.bsu.edu.
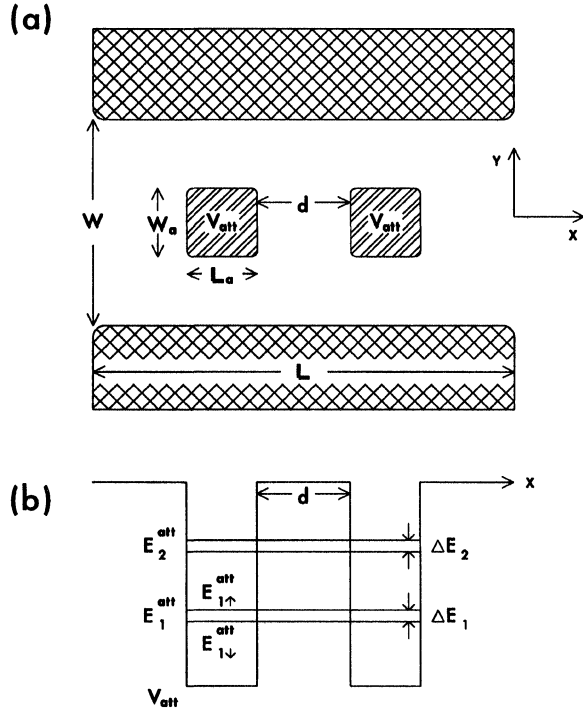
(a)

(b)

FIGURE 1 (a) Quantum structure studied: Two identical finite-size attractors are coupled with the coupling length d along the transport direction. (b) A schematic potential profile of double attractors along the channel, where two-nondegenerate sets of QBSs are shown in a potential well.

meters are defined. We present results for the case where $W/W_a = 2$, $W_a/L_a = 1$, and the attractors are centered in the channel. We note that similar types of the structure modeled here, using several different techniques, have been realized experimentally [4]. For instance, Geim et al. [5] studied resonant tunneling through "donor pair-molecules" with random separation in quantum devices. Figure 1(b) illustrates a schematic potential profile of double attractors along the channel, where two-nondegenerate sets of QBSs are shown in a potential well.

Our calculations of the conductance are based on a nearest-neighbor tight-binding (TB) Hamiltonian and a recursive Green's function technique. Electrons in this system are free to move in the x-direction but are confined in the y-direction, as described by the Schrödinger equation $\{-\hbar^2/2m$

$\nabla_y^2 + V_c(y) - E_n\} \psi_n(y) = 0$, where $V_c(y) = \infty$ for the regions defined by hard walls [shown as cross-shaded regions in Figure 1(a)], and $V_c(y) = -V_{att}$ in the region with the attractors for $|2y| \leq W_a$ [shown as shaded regions], and otherwise $V_c(y) = 0$.

By discretizing the system spatially with lattice constant a, the resulting TB Hamiltonian is exactly solved by using the recursive Green's function method [6]. The Green's function G of a system in the presence of a perturbation $\hat{V}$ is related to the Green's function G° in the absence of $\hat{V}$. The necessary recursion relations are obtained by taking the appropriate matrix elements of Dyson's equation, $G = G^\circ + G^\circ \hat{V} G$. The conductance is then obtained using the Landauer equation [7], $G = (2e^2/h) \sum_{\mu\nu} |t_{\mu\nu}|^2 = (2e^2/h) \text{Tr} (tt^\dagger)$, where t is the transmission matrix.

3. RESULTS AND DISCUSSIONS

We investigate conductance peak splitting due to resonant tunneling through multiple QBSs in a quantum system with two attractors in series. Figure 2 shows the conductance G of the structure as a function of the Fermi energy for different attractor strengths. (Here, the Fermi energy is
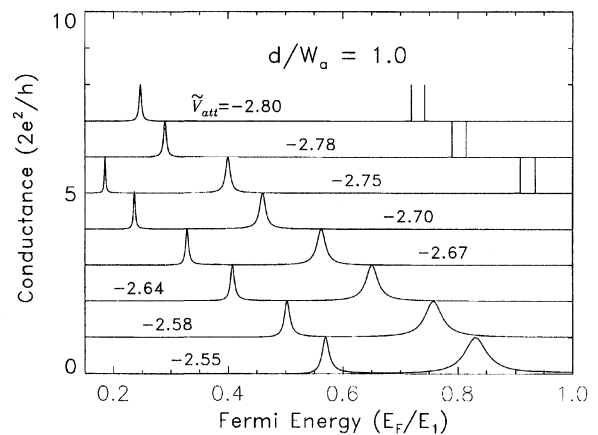

FIGURE 2 Splitting of conductance peaks before the first plateau as a function of the Fermi energy for different attractor strengths V_{att} and a constant coupling length.

normalized with respect to the first subband in the channel W, $E_1 = \hbar^2 \pi^2 / 2mW^2$). These curves are vertically offset one with respect to the other by one conductance unit for clarity. It is clearly seen that resonant tunneling peaks [two for $\tilde{V}_{att}$ $(= \sqrt{V_{att}/E_1})$ in the range from -2.55 to -2.70 and four for $\tilde{V}_{att}$ from -2.75 to -2.80] appear before the first plateau $(E_F/E_1 = 1)$ in the conductance. The appearance of these peaks is a consequence of both the formation of multiple QBSs in the attractor [2] [when an incident energy of the electron becomes the resonant energy E_F^{res}, the longitudinal momenta $p_{n,x}$ are enhanced because the QBSs E_n^{att} have negative values $(p_{n,x} = \sqrt{2m(E_F^{res} - E_n^{att})})$], and the overlap of these QBSs due to the coupling between the two attractors [3].

First, we note that the resonance widths of each peak through E_1^{att} and E_2^{att} are very different; a qualitative explanation follows. While E_F varies from 0 to E_1, all subbands E_m in the narrow channel without an impurity are evanescent modes. The mode coupling between E_m and E_n^{att} plays an important role in determining the interaction matrix element, which is a vital factor in the calculation of the transmission coefficient and the conductance. Intermode couplings between E_m and E_n^{att} for (m, n) combinations with even and odd modes yield negligible contributions because the modes have opposite parities. The resonant tunneling through E_1^{att} is mainly due to the coupling between E_1 and E_1^{att}. Similarly, the resonant peak through E_2^{att} is due to the coupling between E_2 and E_2^{att}. However, since the evanescent mode E_2 is always energetically further away from the Fermi energy than E_1, the coupling between E_2 and E_2^{att} is weaker than that between E_1 and E_1^{att}. Therefore, when an electron moves from E_2 to the E_2^{att} state, it stays a longer time in E_2^{att} and barely tunnels through it because of weak coupling. This indicates that the mean lifetime is larger and the width of the tunneling peak is narrower.

Second, we discuss the splitting of tunneling peaks in the presence of coupling between attractors. For two identical series attractors, the single resonant peak through the first QBS of E_1^{att} splits into two well-separated peaks, shown in Figure 2 in the lower range of the Fermi energy for most values of $\tilde{V}_{att}$ displayed. [Here, the first half of the split peaks is not shown for $\tilde{V}_{att} = -2.78$ and -2.80]. In addition to these peaks, a conductance peak through the second QBS of E_2^{att} also splits into two sharp spikes for $\tilde{V}_{att} = -2.75, -2.78$ and -2.80. A more careful examination shows that each tunneling peak through E_2^{att} has a Lorentzian shape centered around the resonance energy [2]. We attribute this peak splitting to the elimination of the energy degeneracy due to the coupling between two attractors. In other words, if the separation between identical attractors is small enough, then the aligned, uncoupled QBSs in each attractor overlap and produce new nondegenerate states of the coupled attractor system. For a simple two-attractor model, one coupled state is slightly higher $(E_{n,\uparrow}^{att})$ and the other slightly below $(E_{n,\downarrow}^{att})$ the uncoupled energy (E_n^{att}) [see Fig. 1(b)], with a perfect tunneling rate indicated (i.e., transmittance through these states reaches one). Therefore, multiple split-conductance peaks arise from the resonant tunneling through multiple nondegenerate QBSs of the coupled attractors.

Next, we discuss the effect of the coupling between the attractors on conductance peak splitting. It is expected that the separation of the split-tunneling peaks in conductance is reduced, as the coupling between two attractors becomes weaker. This result is observed in the double and triple quantum dots, where a coupling (i.e., tunnel barrier) between the dots is controlled by separate gates [8]. Here, we show that the tunability of coupling can also be achieved by modulating (1) the strength of the attractor $\tilde{V}_{att}$ for a *fixed* separation length between the attractors, and (2) the coupling length d (i.e., geometrical separation) for a *fixed* intervening barrier strength.

As the attractor depth $|\tilde{V}_{att}|$ increases, in Figure 2, the separation of the split peaks through both the first and the second QBS becomes smaller. This is clearly seen in Figure 3, where the energy
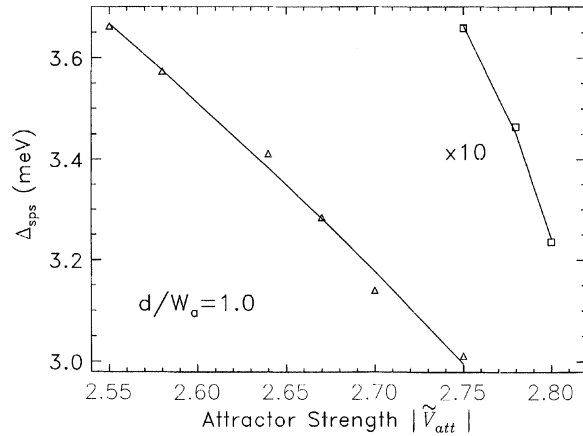
FIGURE 3 The separation of peak splitting Δ_{sps} as a function of $|\tilde{V}_{att}|$ is plotted, for a fixed coupling length $d/W_a = 1.0$, indicating that weak coupling between the attractors can be achieved by increasing $\tilde{V}_{att}$ resulting in strong localized QBSs in the attractor.
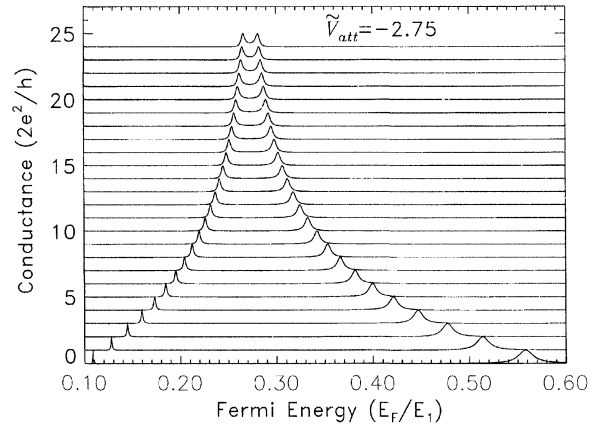

FIGURE 4 The doubly split-conductance peaks through the *first* two-nondegenerate QBSs for different coupling length. The geometrical separation length varies from $d/W_a = 0.5$ (bottom curve) to $d/W_a = 3.0$ (top curve) in steps of 0.1, and the curves are vertically shifted for clarity.

separation of peak splitting, Δ_{sps}, as a function of $|\tilde{V}_{att}|$ is plotted. Here, Δ_{sps} through both non-degenerate states E_1^{att} (triangles) and E_2^{att} (squares; multiplied by a factor of 10 for clarity) decreases, albeit with different slopes. This can be explained by the fact that for a constant geometrical coupling between the attractors, a larger $|\tilde{V}_{att}|$ makes the QBSs lower in energy and more localized in the attractor, and therefore results in less interactions or overlaps between them. As a consequence, the separation of peak splitting in conductance decreases as $|\tilde{V}_{att}|$ increases. We expect that the peak splitting will physically disappear when $|\tilde{V}_{att}|$ is large enough to produce strong localized QBSs in each attractor, i.e., for an extremely weak coupling case.

Figure 4 shows the calculated conductance as a function of the Fermi energy for various coupling lengths. In order to see the effect of the geometrical coupling between the attractors on tunneling peak splitting, we focus on doubly split-tunneling peaks through the *first* two-nondegenerate QBSs ($E_{1,\uparrow}^{att}$ and $E_{1,\downarrow}^{att}$) for a *fixed* $\tilde{V}_{att} = -2.75$. The geometrical separation length varies from $d/W_a = 0.5$ (bottom curve) to $d/W_a = 3.0$ (top curve) in steps of 0.1, and the origin of the curve for different coupling length is shifted vertically in order to make a clear

comparison. As d/W_a increases (i.e., the attractors are weakly coupled), the level separation ΔE_1 ($= E_{1,\uparrow}^{att} - E_{1,\downarrow}^{att}$) becomes narrower and hence the separation of the split-conductance peaks through these states is reduced in Figure 4. It is expected that when the attractors are far away from each other, each one has its original QBS E_1^{att}, and these degenerate states give rise to a single resonant peak before the first plateau. Notice that as d/W_a increases, the width of the peak through $E_{1,\uparrow}^{att}$ becomes narrower because the QBS $E_{1,\uparrow}^{att}$ is more bound and localized around the attractor. As expected, this feature can be seen in the opposite way through the QBS $E_{1,\downarrow}^{att}$.

Figure 5 shows how the separation of the split peaks changes with increasing coupling length d/W_a. It appears that the energy separation of peak splitting, Δ_{sps}, decreases exponentially as coupling length d/W_a increases for $\tilde{V}_{att} = -2.75$. Therefore, for the split-conductance peaks through both E_1^{att} and E_2^{att}, the coupling length d, in general, is related to Δ_{sps} as $d \approx -W \ln (\Delta_{sps})$ for different $\tilde{V}_{att}$.

4. CONCLUSIONS

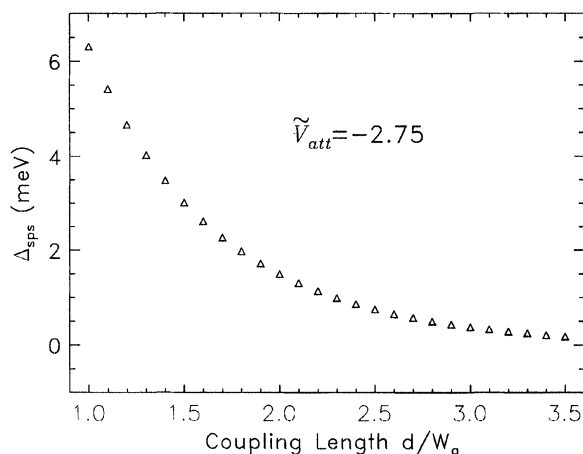In summary, we have studied the effects of resonant tunneling through doubly-coupled at-

FIGURE 5 A relationship between the separation of the split peaks Δ_{sps} and coupling length d/W_a, showing that Δ_{sps} decreases exponentially as d/W_a increases for $\tilde{V}_{att} = -2.75$.

tractors in series in a quantum nanosystem. We have found that the doubly split-conductance peaks arise from the resonant tunneling through two nondegenerate QBSs of the coupled attractors, and the separation of the split-tunneling peaks are strongly affected by the coupling length and the intervening barrier strength.

Acknowledgements

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Authors' Biographies

Young S. Joe received his Ph. D. in Condensed Matter Physics in 1992 from Ohio University, Athens, OH. Following an appointment as a Visiting Scholar at the National Research Council of Canada, he joined the faculty in the Department of Physics and Astronomy at Ball State University in 1993.

Ronald M. Cosby earned the Ph. D. in Solid State Physics at the University of Kentucky in 1971 and holds masters' degrees in physics and computer science. He is a professor of physics at Ball State University, having served on the faculty of the Department of Physics and Astronomy since 1970.