Localizing and detecting single spins in semiconductor nanostructures

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We review recent experiments in which we have used wavefunction coupling between quantum point contacts as an approach to electrically isolate and detect single spins. The physical basis for our experiments is the idea that a well-defined bound state develops in these nanostructures near pinch-off, where the electron density becomes vanishingly low and many-body interactions are consequently enhanced. By coupling the bound state in one point contact to another that serves as a detector, with the nature of this coupling being provided by the mutual wavefunction overlap between the two nanostructures, a Fano resonance is observed in the detector conductance. In this perspective we discuss how this resonance provides an experimental means to characterize the microscopic properties of the bound state that localizes the single spin.

1. Introduction

There has long been great interest in the modifications to bulk properties that arise when charge carriers are strongly confined in nanostructures, such as nanotubes, nanowires, and quantum dots. By enhancing the influence of many-body interactions, this confinement can give rise to novel spin-dependent phenomena in transport, even in nanostructures realized from nonmagnetic semiconductors. A prominent illustration of these concepts, which provides the focus for this review, is given by recent work suggesting that electrons in nonmagnetic quantum wires can spontaneously spin polarize at zero magnetic field, forming a local magnetic moment, when their density is reduced such that conduction through the wire is close to its threshold [1]. This remarkably rich behaviour is predicted for the simplest of nanostructures, namely the quantum point contact that can be defined in the high-mobility two-dimensional electron gas (2DEG) of a suitable heterostructure. A quantum point contact (QPC) is essentially a nanoscale electrical structure, consisting of a short and narrow constriction through which electrons move ballistically between two macroscopic reservoirs. The current flow associated with this motion is carried by a small number of one-dimensional (1D) subbands, each of which is associated with a specific quantized mode for motion in the two dimensions orthogonal to the direction of current flow.
A well known experimental signature of quasi-1D current flow in QPCs is the observation of a sequence of quantized steps in their low-temperature conductance, in integer units of $2e^2/h (≡ G_0)$ [2, 3]. It has long been understood that this remarkable phenomenon can be well explained by a model of noninteracting transport, in which transmission of the 1D subbands is regulated by the self-consistent potential of the QPC [4]. In spite of this, however, there has been much interest in recent years in the idea that many-body phenomena can lead to novel spin-dependent transport in these structures. The driving force for this work has been provided by experimental studies that have shown the presence of a noninteger conductance plateau at a value close to 0.7$G_0$ [1, 5]. The spin-related origin of this “0.7-feature” was first proposed in Ref. [5] and subsequent experiments have provided support for this idea, suggesting the feature is associated with a spontaneous lifting of spin degeneracy that occurs as the electron density in the 1D channel vanishes in the region close to pinch-off. The notion of a spin phenomenon is also central to many of the theoretical models that attempt to account for this feature. In one scenario, for example, ferromagnetic ordering of electron spins has been argued to occur near pinch-off, as the electron density in the QPC is lowered so that the exchange energy of the carriers eventually exceeds their kinetic energy [6–8]. According to this model, the many-body interactions therefore result in the formation of a local magnetic moment in the QPC, whose magnetization may be viewed as static. Another (Kondo) approach, on the other hand, is based upon the presence of a dynamic local magnetic moment, which originates from the correlated many-body state that is formed between a localized electron in the QPC and its reservoirs [9–12]. Although electrons constantly tunnel back and forth between the QPC and the reservoirs, the equivalence of the number of spin-up and spin-down electrons visiting the contact is broken, resulting in a net spin polarization. This scenario is thus roughly equivalent to the conventional Kondo effect for a spin localized on an impurity, or in a quantum dot. A critical concept here is that the self-consistent forces that develop as the electron density in the QPC is lowered result in the formation of a bound state (BS) for one of the spin projections [12], which serves to trap a single electron in the QPC.

While there is ongoing debate regarding the microscopic nature (static vs dynamic) of the spin polarization in QPCs, recent work in our group has provided independent support for BS formation, using coupled QPCs to achieve electrical readout of this state [13–18]. Although the results of our experiments are presented in detail below, they basically involve using a measurement of the conductance of one QPC (the detector QPC) to detect BS formation in another (the swept QPC). In such experiments, a resonant peak is observed in the conductance of the detector QPC when the swept QPC is driven into the region where BS formation is expected. Theoretical work developed in support of this experiment has provided strong evidence that the observed conductance anomaly corresponds to electrical detection of the BS, which arises from the binding of a single spin to the BS of the QPC [14, 16]. In this perspective article, we present a detailed review of our recent work, discussing evidence in support of the idea that we do indeed achieve single-spin confinement and detection in our system. The ability of QPCs that we demonstrate to function as an all-electrically controlled single-spin system, could ultimately have important applications in areas like spintronics and quantum computing.
2. Spin detection using the resonant interaction of coupled QPCs

As is common in most experiments, the QPCs we study are implemented in a GaAs/AlGaAs heterostructure, by making use of the split-gate technique. In this approach, application of a negative bias ($V_g$) to surface gates (Fig. 1) is used to confine the high-mobility 2DEG of the heterostructure, thereby forming a quasi-1D channel in the narrow gap between the gates. While most experiments that have explored the potential signatures of spin polarization in QPCs have done so by focusing on the characteristics of the 0.7 feature, observed under conditions where the QPC is partially transmitting, theory has suggested that an interesting precursor to this regime should involve the selective binding of a single spin to the QPC when it is strongly pinched off [12]. While conventional experiments on single QPCs are poorly suited to explore the behaviour under such conditions, we have been able to use coupled QPCs to shed new light on the behaviour in this regime. Our approach involves using a measurement of the conductance of a detector QPC to monitor the state of another QPC to which it is closely coupled. As the voltage applied to the gates of this swept QPC is varied, the detector is found to exhibit a resonance in its conductance that occurs as the swept QPC is pinching off. Motivated by suggestions that the QPC potential may develop a quantum dot-like form near pinch-off, we have developed a theoretical model [14, 16] that relates this resonance to the formation of a BS in the swept QPC. As the voltage applied to the gates of this QPC is made more negative, the BS is driven upwards in energy until, when it aligns with the Fermi level, the detector-BS interaction produces a Fano-type resonance that is seen in the detector conductance ($G_d$). An important feature of the experiment is that only a single, isolated, resonance is ever observed in $G_d$. This is explained within our model by the fact that the resonance arises from the population of the BS by a single electron, and that a large on-site energy prevents the addition of further electrons.

An example of one of the devices that we have used to study BS formation in QPCs is shown in Fig. 1. The device has eight independent gates that may be used to realize pairs of coupled QPCs with different special configurations. In Fig. 2, we show results obtained by using two different gate configurations to realize the swept QPC. Each panel in this figure shows the results of two measurements. The black curve was first obtained by using appropriate ohmic contacts to apply a fixed voltage across the swept QPC, after which its conductance was determined by measuring the current flowing through it as its gate voltage ($V_g$) was varied. In

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the second measurement (red curve), the conductance of the detector QPC was measured for a fixed voltage applied to its two gates, while once again sweeping the swept-QPC gate voltage over the same range used in the first measurement. The same phenomenon is observed in both panels, namely a peak in $G_d$ that systematically occurs just after the swept QPC pinches off. We emphasize again that just a single peak, with approximately the same amplitude, is observed in each measurement, consistent with our notion that this feature is associated with the population of the BS by just a single electron. If the resonance was somehow associated with the formation of a charge puddle containing an arbitrary number of electrons, one would presumably expect instead a greater variation in the characteristics of the detector response. Since our measurements are performed at 4.2 K, where only the 0.7 feature survives, this also confirms the detector resonance is unrelated to populating the normal 1D subbands of the swept QPC. The striking consistency between the two measurements of Fig. 3 moreover rules out a random-impurity effect. Indeed, the characteristics that we report here were found in measurements performed over a fifteen-month period, on six different thermal cycles.

![Graph](image)

**Figure 2.** Resonant interaction of coupled QPCs at 4.2 K. The detector (red) and swept (black) QPCs are indicated by the insets to each panel. Dotted lines indicate grounded gates [17].

To investigate the characteristic energy scale associated with the BS, we have studied the temperature dependence of the resonant interaction between the QPCs. Fig. 3 shows that the detector peak quenches remarkably slowly with increase of temperature (persisting weakly at 35 K), behaviour which is reproduced quantitatively in other QPC combinations. The peak clearly shifts to more negative $V_s$ with increasing temperature, suggesting that stronger gate confinement is needed to confine the self-consistently formed BS at higher temperatures. The quenching of the peak in this figure suggests the effective confinement of the BS is of the order of a few meV, although this should be considered a lower bound since several mechanisms could possibly cause the quenching. One is thermal excitation out of the BS by overcoming its potential barriers. Since the peak corresponds to a Fano resonance, and so requires coherent electron-wave transmission, another possibility is loss of coherence between the QPCs. Coherence lengths for high mobility 2DEGs at ~35 K should be ~100 nm, comparable to the QPC spacing in our device. The quenching of the peak may thus indeed be due to decoherence, although more work is required to confirm this.

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The resonant mechanism that we have described is essentially nothing more than a Fano resonance, which arises quite generally in systems that exhibit coherent interference of resonant and nonresonant channels for some process [19, 20]. In the system that we study, the resonant channel corresponds to the BS on the swept QPC, while the nonresonant channel is formed by the 1D modes of the detector. These two channels are coupled indirectly to each other, via the intervening region of 2DEG, leading to an interference geometry that is quite different to that in the usual experiments. The role of the 2DEG in mediating the interaction between the QPCs can be demonstrated directly in an experiment, by using an appropriate gate to regulate the coupling. This characteristic was demonstrated in Ref. [18], in which we showed, for example, how the resonance exhibited when using gates $G_1$ & $G_2$ as the detector and $G_7$ & $G_8$ as the swept QPC can be suppressed completely by biasing gate $G_5$ so that the coupling of the QPCs through their common 2DEG is completely cut off.

In typical discussions of the Fano resonance it is common to observe a resonance with a highly asymmetric lineshape, with a local minimum present in close proximity to its maximum. While this characteristic lineshape is not apparent in the data of Fig. 2, in Ref. [18] we demonstrated that it develops systematically as the detector and swept QPCs are brought in closer proximity to each other. This property is illustrated in Fig. 4: Fig. 4(a) corresponds to a configuration equivalent to that used in Fig. 2, while Fig. 4(c) corresponds to the smallest (~300 nm) inter-QPC separation that we can realize with our device. Fig. 4(b) is for a configuration intermediate between these limits, and it is clear that these three configurations show a systematic trend for increasing the asymmetry of their resonance as the QPC separation is reduced. In the case of Fig. 4(c), this asymmetry has developed to such an extent that we can clearly see the classic Fano form, with closely separated local maximum and minimum. Quite generally, the symmetry of Fano resonances is related to the strength of the coupling between their resonant and nonresonant channels, becoming more asymmetric for increased coupling. For further insight into our system, we have performed fits of the detector resonance to the Fano

Figure 3. Temperature dependence of the detector peak. Detector QPC: $G_7$ & $G_8$. Swept QPC: $G_1$ & $G_2$ [17].
form [19, 20], $G_d(\varepsilon) \propto (\varepsilon + q)^2/(\varepsilon^2 + 1)$, where $\varepsilon \equiv 2(V_g - V_o)\Gamma$, and $V_o$ and $\Gamma$ are, respectively, the resonance position and width. $q$ is a parameter related to the strength of the coupling between the different channels and determines the symmetry of the resonance. With increasing coupling, the magnitude of $q$ decreases (from $q = \infty$ for no coupling) and the asymmetry of the resonance becomes more pronounced. The results of our fits are shown as the solid lines in Fig. 4 and reproduce the experimental behaviour. We emphasize here the systematic decrease of the $q$ parameter (from $|q| = 20$ in Fig. 4(a) to $|q| = 1.1$ in Fig. 4(c)) with decreasing separation between the QPCs, a result that is consistent with increased coupling of the resonant and nonresonant channels. In Ref. [18], we demonstrated that this behaviour is reproduced systematically for equivalent coupled-QPC configurations, quite consistent with the Fano mechanism that we have proposed.

Figure 4. Resonance in $G_d$ (open symbols, solid line through symbols denotes fit to Fano form) and variation of $G_s$ for various coupled-QPC configurations at 4.2 K. The corresponding Fano factor ($q$) is shown. The circle in the schematics indicates where the BS is formed. The device is that of Fig. 1, and the insets to each panel indicate the gates used to form swept (blue) and detector (red) QPCs [18].

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Perhaps the strongest experimental evidence that a single spin is localized on the swept QPC is provided by studies that have explored the influence of an in-plane magnetic field \( (B) \) on the detector resonance \([17]\). In the theoretical study of Ref. \([16]\) it was predicted that such a magnetic field \( (B) \) should provide a useful means to confirm that the BS is indeed occupied by only a single electron, and to probe the spin structure of the BS. Specifically, it was found that with the BS occupied by only one electron, the detector peak should shift smoothly to more negative \( V_s \) with increasing \( B \), following the associated reduction of energy of the lower Zeeman branch of the BS. At the same time, a much smaller feature was predicted to develop on the high-energy (less negative \( V_s \)) side of the detector peak, corresponding to the case where the lower Zeeman branch of the BS is now empty and the upper branch is instead occupied by a single electron. The weaker amplitude of this feature (compared to the main peak) reflects the fact that it corresponds to an excited state of the single electron that occupies the BS, the probability of whose occupation is small but nonetheless possible as a result of the nonzero temperature. In contrast to the ground state, this feature should shift to higher energy (less negative \( V_s \)) with increasing \( B \). In Fig. 5, we show behaviour \([17]\) that is fully consistent with these predictions. In Fig. 5(b), the variation of \( G_d \) and the absolute value of its derivative is plotted. At \( B = 0 \) T, the derivative shows two broad maxima that represent the left- and right-hand slopes of the peak in \( G_d \). As the magnetic field is increased, however, an additional feature develops on the right-hand side of the detector peak (indicated by the arrow), corresponding to the formation of a weak shoulder in \( G_d \). The main peak shifts to more negative \( V_s \) with increasing \( B \), while the shoulder shifts in the opposite direction. The development of this shoulder is revealed more clearly in the derivative of the conductance, as shown in the bottom part of Fig. 5(b). In Fig. 5(a), we show that the gate-voltage separation of the main peak and the weaker shoulder increases in a Zeeman-like manner with increasing \( B \). The data of Fig. 5(a) extrapolate to a nonzero splitting \( (\Delta V_g (B = 0) \sim 33 \text{ mV}) \), suggesting spin degeneracy is spontaneously broken at \( B = 0 \) and that the BS is occupied by a single electron with a specific spin. To estimate the size of this splitting, we can assume a \( g \)-factor of 0.4 to convert the slopes in Fig. 5(a) to a change of energy, and in this way we obtain an energy splitting of \( \sim 0.5 \text{ meV} \). Enhanced \( g \)-factors \( (\sim 1.5) \) have been reported \([5]\) for QPCs near pinch-off, however, so the value may actually be in the range of a few meV (consistent with the washout temperature of the detector peak). Thomas et al. inferred a spontaneous splitting of \( \sim 1 \text{ meV} \) from studies of the 0.7 feature \([5]\), so our results are consistent with this. It is clear from Fig. 5(b) that, as expected from Ref. \([16]\), the high-energy shoulder that develops on the detector peak is extremely weak. Indeed, in many cases we observe only a shift of the main peak in the magnetic field, without any clear evidence for the development of the shoulder. This points to quantitative differences in the microscopic structure of the BS formed on different QPCs and is not well understood at present.

3. Concluding remarks

The implication of our work is that, under conditions where their linear conductance is fully suppressed, QPCs may function as a natural single-spin system, confining an electron with a given spin projection on a robust BS. At this point it is worth considering the relevance of our results for the discussion of the 0.7 feature. We have seen (Fig. 2) that the detector resonance
occurs for stronger gate confinement than the 0.7 feature. We believe that this indicates that these two phenomena are separate manifestations of spin polarization in QPCs, and that a consistent discussion of these features should involve a dynamic evolution of the QPC profile as $V_g$ is varied from open conduction to pinch-off. When $G_s > G_o$, noninteracting transport should dominate and the QPC should exhibit a saddle-like profile with no BS. At the other extreme, with $G_s$ pinched off, we have found clear evidence of a robustly-confined BS that should be supported by some dramatic quantum-dot like modification of the QPC potential. The 0.7 feature occurs for intermediate confinement, however, where the gate potential is weakened away from the detector resonance and the swept QPC becomes partially transmitting. Its self-consistent potential may then correspond to some hybrid version of the quantum-dot and saddle forms, with a much more weakly confined BS that is strongly coupled to the reservoirs. In other
experiments, we have shown [21] that the 0.7 feature washes out at lower temperatures (~17 K, consistent with other reports [4–7]) than the detector peak, which could be consistent with a weakened BS in the region of the 0.7 feature. These ideas also appear to conform with discussions of a Kondo model [9–12] of QPCs, in which the 0.7 feature occurs when the reservoir Fermi energy is above the BS level, consistent with the appearance of the 0.7 feature at less negative $V_s$ than the detector peak. In this sense, our results should provide a useful alternative way to think about the formation of the many-body state responsible for the 0.7 feature, starting from the situation of a strongly-confined BS with the QPC pinched off.

More importantly, perhaps, than our confirmation of the BS model of pinched-off QPCs is our demonstration that the QPC may essentially be used as an “on-demand” single spin system. In future work it will therefore be of particular interest to investigate whether evidence of coherently coupling localized spins on separate QPCs is obtainable, a result that could open up new and scalable approaches to single-spin electronics.

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References
1. For a recent overview of the status of this field, see the collection of articles on the 0.7 feature that appeared as a special issue of the Journal of Physics: Condensed Matter, 23 April 2008.


