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REVIEW

Steps toward an all-electric spin valve using side-gated quantum point contacts with lateral spin–orbit coupling

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Abstract
Spin-based electronics or ‘spintronics’ has been a topic of interest for over two decades. Electronic devices based on the manipulation of the electron spin are believed to offer the possibility of very small, non-volatile and ultrafast devices with very low power consumption. Since the proposal of a spin-field-effect transistor (SpinFET) by Datta and Das in 1990, many attempts have been made to achieve spin injection, detection and manipulation in semiconductor materials either by incorporating ferromagnetic materials into device architectures or by using external magnetic fields. This approach has significant design complexities, partly due to the influence of stray magnetic fields on device operation. In addition, magnetic electrodes can have magneto-resistance and spurious Hall voltages that can complicate device performance. To date, there has been no successful report of a working Datta–Das SpinFET. Over the last few years we have investigated an all-electric means of manipulating spins, one that only relies on electric fields and voltages and not on ferromagnetic materials or external magnetic fields. We believe we have found a pathway toward this goal, using in-plane side-gated quantum point contacts (QPCs) that rely on lateral spin–orbit coupling to create spin polarization. In this paper we discuss several aspects of our work, beginning with our finding what we believe is nearly complete spin-polarization in InAs QPCs by purely electrical means, our theoretical work to understand the basic mechanisms leading to that situation (asymmetric lateral confinement, lateral spin–orbit coupling and a strong e–e interaction), and our recent work extending the effort to GaAs and to dual QPC systems where one QPC acts as a polarizer and the other as an analyzer.

Keywords: SpinFET, spintronics, quantum point contact, lateral spin–orbit coupling, conductance anomaly

Classification numbers: 5.01, 5.02

1. Introduction
Spintronics refers to electronics using the spin of the electrons—working with and manipulating both the spin and charge of electrical currents. The ultimate goal of spintronics is to create devices (‘spin valves’) that control the direction of the spin of the electrical currents passing through them. Spintronics research was first stimulated by the discovery of giant magneto-resistance materials in the 1980s. This is a quantum magneto-transport phenomenon seen in layered thin-film structures made from alternating ferromagnetic and
This is exemplified by a suggestion by Datta and Das [11] more than two decades ago and shown schematically in figure 1.

Here we report on devices made from single and dual quantum point contacts (QPCs) that allow us to achieve almost completely spin-polarized electric currents. We have examined the single QPC devices experimentally and theoretically and determined three important factors necessary to achieve this level of polarization: (a) lateral spin–orbit coupling; (b) a strong asymmetry in that coupling; and (c) strong electron–electron interactions. We also discuss our initial results for dual QPC devices where the QPCs act as a polarizer–analyzer pair and can be used to create a spin valve or SpinFET.

2. Historical overview

To realize spin-based electronics we need to be able to inject, manipulate and detect the spin of an electrical current. Since a magnetic moment is associated with the electron spin, early attempts to do this incorporated ferromagnetic materials embedded in the device architecture to first polarize, and then detect, the spins of the electrons in the current, and used external magnetic fields to rotate the plane of polarization. But the magnetic fields (internal and external) have many undesirable side effects and a goal of spintronics for the past 10 years has been to find ways of creating, manipulating and detecting spin-polarized electric currents by purely electrical means—without ferromagnetic materials or external magnetic fields [1–4].

The Datta–Das conceptualization has become the prototype for a SpinFET. The source (S) and drain (D) contacts are ferromagnetic and magnetized along the direction of the current flow in the (one-dimensional (1D)) channel. The spin injection and extraction efficiency of the source and drain contacts are assumed to be 100%. It assumes that ballistic motion of the electrons prevails in the channel and that the electron’s spin coherence length is much longer than the channel. Under those assumptions, when there is no potential applied to the gate, electrons in the channel, spin-polarized by the source, will travel to the drain (red arrows, figure 1) without changing their spin orientation, and will be able to enter the drain. This is the SpinFET ‘ON’ state.

When a potential is applied to the gate, creating an electric field \( E \), a moving electron ‘sees’ that field as a magnetic field. The direction of that effective magnetic field is perpendicular to both the electron’s momentum, \( k \), and \( E \). This effective magnetic field, known as the Rashba field \( B_R \), will interact with the electron’s spin, yielding a spin–orbit coupling (SOC) known as the ‘Rashba interaction’. The spins of the electrons precess around \( B_R \) as they travel along the channel. \( B_R = \alpha k / \mu_B \), where \( \alpha \) is the Rashba SOC parameter. The precession angle is given by, \( \theta = 2m^* \alpha L / \hbar^2 \) where \( L \) is the length of the channel and \( \alpha = \alpha^* |e| E / \hbar^2 \); a material specific intrinsic SOC parameter. Since the transport in the channel is assumed to be purely 1D and is along \( x \), and the applied electric field points along \( y \), the precession axis is very well-defined and along \( z \). The precession angle \( \theta \) is controlled by the gate potential and can be adjusted so that the spin precesses \( 180^\circ \) by the time it arrives at the drain. The spin orientation will be anti-parallel to that of the drain, and the electron cannot enter the drain. This is the SpinFET ‘OFF’ state. The Datta–Das SpinFET is therefore the spin analogue of a conventional MOSFET.

For a number of technological reasons (lower power dissipation, possibilities for quantum computing, etc), considerable effort [6, 7] was made to create a Datta–Das SpinFET, using Rashba SOC. The energy required to ‘flip’ an electron’s spin is much less than that needed to drive or change an electric current since the energy difference between spin-up and spin-down states, the Zeeman energy \( g \mu_B B \), is very small. Furthermore, it can be adjusted by changing the Rashba field strength (by varying the gate potential). Therefore a SpinFET is a candidate for overcoming some of the limitations faced by standard CMOS technology. Unfortunately, to date no one has been able to create a workable SpinFET. The problem lies in the ferromagnetic materials used in the source and drain electrodes. These electrodes invariably induce magnetic fields in the channel which seriously impact spin transport [8, 9]; furthermore, the ferromagnetic-semiconductor interface makes spin injection (and extraction) very inefficient. This is the so called conductivity mismatch problem [10].

Our goal was to create an all-electric SpinFET—using no magnetic materials—following a new avenue: ‘spintronics without magnetism’ [1–4]. This alternative track still relies on spin–orbit coupling to manipulate the spins, but does not use the Rashba effect—instead relying on lateral spin–orbit coupling (LSOC), as first proposed in 2006 [11–13]. ‘Lateral’ in this sense refers to SOC originating from an electric field across the channel, an electric field resulting from a lateral confining potential defining the channel. This early work predicted that opposite spins would accumulate along the edges of a 1D channel. However, none of that work predicted a net spin polarization.

Over the last 6 years, our group demonstrated experimentally [14–17] that it is possible to have nearly complete spin polarization in a QPC—a short quantum wire between two large electron reservoirs—if there is LSOC and if the lateral confining potential is highly asymmetric. It was the first experimental demonstration that a spin-polarized current can be achieved through purely electrical means in a QPC in the presence of LSOC. LSOC is different from Rashba...
Figure 2. (a) A QPC created by two surface gates, UG and LG, deposited on a semiconductor heterostructure; (b) an AlGaAs/GaAs heterostructure with a 2DEG at the interface, depleted by a potential on surface Schottky gates to create a 1D channel or constriction.

Figure 3. An atomic force microscope image of a QPC with two in-plane side gates (G1 and G2) (reprinted with permission from [15]).

Figure 4. Energy subbands in a quasi-1D channel.

SOC: for LSOC the electric field is in the plane of the two-dimensional electron gas (2DEG) from which the channel is formed, whereas the electric field which causes Rashba SOC is perpendicular to the 2DEG.

In the next three sections we describe briefly several concepts necessary to understand how we generate spin-polarized electrical currents: QPCs, types of spin–orbit coupling, and 1D versus two-dimensional (2D) devices.

3. Quantum point contacts

A QPC is a very short quantum wire or constriction. It is usually made by depositing a pair of surface gates (Schottky or metal) over a 2DEG (e.g. the one that exists at the interface of a semiconductor heterostructure such as an AlGaAs/GaAs). Figures 2(a) and (b) are schematic illustrations of a QPC with top gates [18, 19].

A negative bias applied to the gates UG and LG depletes the 2DEG directly under and adjacent to the gates, creating a narrow constriction or 1D channel between the gates. The width of this channel can be controlled by appropriately biasing the gates. Because of the small aspect ratio $w/L$ (channel width/channel length) a QPC is inherently a 1D system. QPCs can be made using side gates instead of surface gates and this is how we obtain a lateral confining potential [14–17].

Our QPCs are fabricated from both AlGaAs/GaAs and InAs/InAlAs heterostructures [20]. Figure 3 is an atomic force microscope (AFM) image of a side-gated quantum well used in this work. The side gates G1 and G2 are formed lithographically; the etched trenches shown separate the gates from the constriction. Figure 4 is a schematic illustration of the band structure of a typical quasi-1D system. It consists of a number of subbands, the bottoms of which are at $E_1$, $E_2$, $E_3$, ..., $E_n$. $E_F$ is the Fermi level and $k$ the wave vector. The conductance $G$ of the QPC is given by

$$ G = \frac{2e^2}{h} \sum_{n,m=1}^{N} |t_{mn}|^2, \tag{1} $$

where $N$ is the total number of electron subbands below the Fermi energy and $w$ the width of the wire. The wire dimensions are smaller than both the elastic and inelastic scattering lengths (i.e. conduction is ballistic) and the transmission coefficient $|t_{mn}|^2 = 1$ and 0 for $m \neq n$. The sum in the conductivity shown in equation (1) is needed to take into account that the Fermi level moves through the various subbands as the width of the channel is varied by changing the gate voltage. In the assumption of ballistic transport, the conductance is seen to be quantized in units of $2e^2/h = G_0$ [18, 19]. Equation (1) assumes that the spins are degenerate—hence the factor of two. If the spins are not degenerate, e.g. the degeneracy is removed by a magnetic field, the conductance will then be quantized in integral values of $(1/2)G_0$. This implies that an experimental signature of a completely spin-polarized electric current is the occurrence of
shows the energy dispersion curve (2) appearing around $G_0/2$ indicates that the spin degeneracy is lifted (reprinted with permission from [14]).

An example of this can be seen in figure 5, where we have plotted the conductance of a QPC with and without a strong magnetic field applied in the direction perpendicular to the plane of the 2DEG. Without the magnetic field, the conductance is quantized at integral values of $G_0$ ($\approx 2e^2/h$). With the field present and Zeeman splitting lifting the spin-degeneracy, the conductance is quantized at integral values of $(1/2)G_0$.

QPCs are very versatile devices. The channel width is ‘easily’ controlled by the gate voltage. This allows control of both the electron density and the position of the Fermi level among the subbands. In a 1D wire the available k-space is severely limited compared to 2D or 3D wires. When the Fermi level is in the lowest subband, transport is strictly 1D and the Fermi surface consists of two points in k-space: $\pm k_F$.

When a large number of the subbands are occupied, the transport becomes quasi-1D. It is important to note that when the Fermi level is close to the bottom of the lowest subband, the electron density is very low and strong electron–electron interactions will exist.

4. Spin–orbit coupling

As mentioned earlier, spin–orbit coupling is a possible mechanism for creating, manipulating and detecting spin-polarized currents. SOC once referred to the coupling of an electron’s spin to its orbital motion but it has come to mean any coupling of an electron’s spin with the magnetic field an electron ‘sees’ when it is moving in an electric field perpendicular to its direction of motion. In semiconducting materials there are several different types of SOC possible, with different physical origins—we either have to use them to create spin-polarized currents or we have to eliminate or minimize them to extend the spin relaxation time of the channel.

The Hamiltonian for spin–orbit coupling is [21]

$$H_{SOC} = \lambda \sigma \cdot (\mathbf{k} \times \nabla U),$$

(2)

where $\lambda$ is the SOC parameter, $\sigma = (\sigma_x, \sigma_y, \sigma_z)$ are Pauli spin matrices and $U$ is the electrostatic potential. In the original formalism (for an electron in an atom) the energy gap (the Dirac gap) between an electron’s positive and negative energy plays a role in determining the magnitude of the SOC; it has to be relatively small for SOC to be large. This carries over into semiconductor physics where it is replaced by the energy gap between the conduction and valence bands. This is on the order of 1 eV or less in III–V semiconductors.

In InAs-based materials, where both the band gap and the electron effective mass are small ($\sim 0.36$ eV and 0.023$m_0$, respectively) there can be very large spin–orbit coupling. This is why the InAs-based quantum wells are thought to have interesting spin-dependent properties and why we selected them for our work.

There are three types of SOC that concern us here: Rashba, Dresselhaus and lateral SOC.

4.1. Rashba SOC

As seen in equation (2) above, the SOC Hamiltonian depends on the electrostatic potential $U$. An SOC-causing potential (or electric field) can have many different physical origins, e.g., an internal potential gradient or an externally applied electric field [22]. This was first studied by Rashba [23] in quantum structures with asymmetric wells. It has been observed in triangular wells formed at the interface between narrow and wide bandgap semiconductors or in quantum wells with different barrier heights on the two sides. This creates a gradient in the potential energy profile and an internal electric field. The latter can be further controlled with a gate voltage. An electron moving in the well sees this electric field as an effective magnetic field lying in the plane of the 2DEG and perpendicular to the electric field. This effective magnetic field creates SOC, lifts the degeneracy, and is responsible for spin splitting. This is known as the ‘Rashba interaction’ or ‘Rashba spin–orbit coupling’ (RSOC).

The Rashba Hamiltonian and the corresponding spin-splitting energy dispersion relations are given by

$$H_{Rashba} = \alpha (\mathbf{p} \times \mathbf{z}) \sigma,$$

$$E_k = \frac{\hbar^2 k^2}{2m^*_e} \pm \alpha k. \quad (3)$$

The Rashba electric field points along the direction of growth of the asymmetric heterostructure. $\alpha = \alpha^*|E|\alpha$ is the RSOC parameter) can be tailored externally by applying a gate voltage. Figure 6 shows the energy dispersion curve for spin-up and spin-down electrons in the 1D case. We note that electrons with opposite spins travel with different Fermi velocities. Thus, they have two different wave vectors which correspond to two electron gases with slightly different carrier concentrations (this can be seen in the beating pattern of the Shubnikov–de Haas oscillations [24, 25]).

RSOC can be intrinsic or extrinsic depending on its source. It arises from a structural inversion asymmetry which can be tailored by introducing either internal (through...
Dresselhaus SOC is caused by bulk inversion asymmetry \[4.2.\) Dresselhaus SOC success. A successful experimental demonstration would pave the way for realization of the mechanism for spin excesses as 'Dresselhaus spin–orbit coupling'. While it has not been considered as a possible mechanism to generate spin excesses in semiconductors, it must be considered as a spin relaxation mechanism.

Opposite spins travel with different velocities.

Figure 6. Energy dispersion curves for RSOC in the 1D case. Opposite spins travel with different velocities.

Asymmetric confinement of the 2DEG or QW) or external (applying voltages through top gates) electric fields. Note that unlike Zeeman splitting, Rashba spin splitting does not result in a net magnetization of the system, as its Hamiltonian (equation (3)) is invariant under time reversal and no common spin quantization axis is available for its spin eigenstates. As seen from the parabolic dispersion curves shown in figure 6, opposite spins are shifted along \(k\), rather than along the energy axis as in the case of Zeeman splitting.

There have been intense efforts to manipulate the electron spin in 2D systems by controlling the electric field which produces RSOC \[22, 23\]. A successful experimental demonstration would pave the way for realization of the Datta–Das SpinFET. To date there have been no reports of success.

4.2. Dresselhaus SOC

Dresselhaus SOC is caused by bulk inversion asymmetry \[26\]. Unlike structural inversion asymmetry—which can be engineered into a QW—bulk inversion asymmetry arises from the lack of an inversion center in the zinc-blend structure of some semiconductors (e.g. InAs, GaAs, etc). In solids, time inversion symmetry means \(E ↑(k) = E ↓(−k)\) and space inversion symmetry means \(E ↑(k) = E ↑(−k)\). The symmetry operator (space and time) changes \(k\) to \(−k\). Combining time and space inversion yields \(E ↑(k) = E ↓(k)\), a relation valid in semiconductors such as Si and Ge. But, in the semiconductor systems used to make quantum wells (the III–V semiconductors such as InAs, GaAs, etc) there is no inversion center and therefore, \(E ↑(k) \neq E ↓(k)\). The result is a lifting of the spin degeneracy for a non-zero \(k\). This was first noted by Dresselhaus and is referred to as ‘Dresselhaus spin–orbit coupling’. While it has not been considered as a possible mechanism to generate spin excesses in semiconductors, it must be considered as a spin relaxation mechanism.

4.3. Lateral spin–orbit coupling

Lateral spin–orbit coupling, a more recent concept than Rashba or Dresselhaus SOC, was first proposed in 2006 by three theory groups \[11–13\]. We consider a 1D quantum wire (figure 7(a)) where the current flows in the \(x\)-direction and the motion of the electrons is restricted along the (lateral) \(y\)-direction.

The electric potential \(U(y)\) is constant along \(y\) in the central part of the wire (around \(L/2\)), but rises steeply toward the edges (figure 7(b)). This implies a lateral electric field \(E = \nabla U\) that points toward the edges of the channel as shown. A moving electron will see the electric field as an effective magnetic field \((B_{SO}\) along \(z\), as shown in the figure) which will couple to the electron spin. Since the origin of this SOC is a lateral electric field it is called ‘lateral spin–orbit coupling’ or LSOC. The LSOC Hamiltonian caused by the lateral in-plane electric field is given by \[14\]

\[
H = H_0 + H_{SO}.
\]

\[
H_0 = \frac{1}{2m^*}(p^2 + p_y^2) + U(y).
\]

\[
H_{SO} = \beta H_{SO}(k \times \nabla U(y)) = \sigma B_{SO}.
\]

From this we see that for electrons with \(+k\) in the 1D channel, on the \(y = 0\) side of the wire the effective potential is lower for the spin-down electrons \((\sigma_z = -1)\) than for the spin-up electrons \((\sigma_z = +1)\). On the opposite side of the wire \((y = \pm L)\) the effective potential for the spin-up electrons is lower than for spin-down electrons. The result is a spin imbalance and an accumulation of opposite spins along the edges of the wire \[7\]. For electrons with \(−k\), the sign of spin accumulation is reversed. Thus, a lateral confining potential can cause opposite spin accumulation along the two sides of the 1D quantum wire but no net spin polarization or spin-polarized current is predicted for a 1D system—the spin polarizations on the opposite edges of the sample effectively cancel one another \[11–13\].

We have shown \[14\] that if the confining potential is made highly asymmetric, a net spin polarization can result. This is easily seen when we tune the side gate voltages so the confinement is asymmetric. In that case \(+\sigma_z\) on one edge of the channel will dominate \(−\sigma_z\) on the other edge, yielding a spin imbalance and net spin polarization of the channel. Reversing the asymmetry reverses the direction of the spin polarization. The net polarization is small but, as we will see, it is enhanced considerably when strong electron–electron interactions are present.

5. One-dimensional versus two-dimensional devices

In deciding how to construct a device dependent on the properties of the spins of electrons, a crucial requirement is that the important conducting lengths—the length and width of the ‘channel’—of the device be much smaller than the spin coherence length \(L_\text{S}\). We need to choose a material and a device design that ensures the largest possible value of \(L_\text{S}\). In III–V semiconductors there are two important spin relaxation mechanisms: the Elliot–Yafet (EY) \[27, 28\] and the D’yakonov–Perel (DP) \[29\]. The mechanism for spin relaxation in the EY process arises from phonon and...
impurity scattering, with a subsequent change in the electron’s momentum. Since SOC produces electron eigenstates that mix spin-up and spin-down states, for each scattering event there will be a non-zero probability of a spin flip, making $L_S$ proportional to the electron mean-free-path $L_e$. In the DP process, spin relaxation is related to the precession of the spins around the effective magnetic field producing the SOC. At each scattering event the electron’s $k$-vector changes direction and it sees a ‘different’ SOC-induced magnetic field. The precession axis and the precession frequency change in a random manner, producing dephasing of the spins. This latter mechanism is found to be more prominent in semiconductors without a center of symmetry—e.g. GaAs. In both cases we need as little scattering as possible, therefore we want essentially ballistic motion of electrons in the conducting channel.

A 1D system—made from a laterally confined 2D electron gas—offers several advantages over 2D or three-dimensional (3D) systems. Firstly, the severe restrictions on the available $k$-space significantly reduces scattering. This strongly suppresses the EY mechanism. Secondly, the 1D channel has an essentially unidirectional propagation vector $k$, making the spin quantization axis, defined by the SOC magnetic field, well-defined. This suppresses spin relaxation due to the DP mechanism and the drastic reduction in available $k$-space volume reduces it still more. Therefore, one expects enhanced spin-relation coherence lengths in a 1D channel. This is supported by experiment [25] and theory [29, 30]. These calculations show that when $w$, the 1D channel width, is smaller than the bulk $L_S$, spin-coherence increases sharply as $w$ is reduced. This increase of $L_S$ with decreasing $w$ has been experimentally observed [31]. Based on the above, we concluded that we needed to explore a 1D system. When we connect this to the discussion of the QPCs earlier, we see that a QPC device will give us all the benefits of a 1D system and will also allow for electrically controlling the spin relaxation by controlling the channel width via the gate voltages. An additional advantage of using a 1D system is that the electron–electron scattering is significantly increased (because the electron density is low), yielding a much larger effective $g$-factor in 1D than in 2D and a much enhanced Zeeman splitting. As we will see this is a very important factor in obtaining spin-polarized currents.

When a III–V semiconductor heterostructure with an interface between a narrow and a wide band-gap material is used, a 2DEG will form at the interface. Here, electrons are trapped and their motion constrained along the growth direction, yielding the 2DEG. In our work, we use such heterostructures, grown by molecular beam epitaxy, followed by e-beam, optical lithography and wet etching processes, to form appropriate QPCs. We use high-mobility InAs/InGaAs-based symmetric heterostructures. InAs is a low band-gap ($\sim 0.36\text{ eV}$) material with high spin–orbit coupling and, when the channel is properly oriented, Dresselhaus SOC can be minimized. Our sample fabrication and characterization processes have been thoroughly explained elsewhere [14–17].

6. Experimental observation of spin-polarized currents

The properties of our devices are studied by measuring their linear conductance, $G (= I/V)$ using standard four-probe ac lock-in techniques. The data are taken at liquid helium temperature (4.2 K). The physical channel widths of our specimens ranged from 250 to 400 nm, and channel lengths were on the order of 500 nm. The effective width of the channel and the carrier density are controlled by the bias voltages on the two side-gates, which are supplied by a battery-powered voltage source. Since we are interested in the fundamental transport mode, we want the 1D subband separation to be large. This is achieved in QPCs by making the channel width small.

In a QPC with top or split gates, where the 1D channel is created by depleting the 2DEG underneath by application

Figure 7. (a) Schematic of a 1D quantum wire with current along $+x$ (black arrow). (b) The potential profile $U(y)$ which confines the motion of the electrons along $y$. The electrons flow perpendicularly to the page, leading to spin accumulations of opposite polarity (green and blue arrows) along the edges of the wire.
of negative bias potential to its gates, an asymmetric bias cannot be applied effectively because it will simply shift the channel spatially. But, it can be easily done in a side-gated QPC, because the side gates, which create the 1D channel, are well-defined by cutting trenches. This is the main reason why we chose to work with side-gated QPCs. Since there is very little surface depletion at the InAs 2DEG/vacuum interface, the channel will conduct at 4.2 K in a QPC with a very narrow channel width. This is an added advantage for InAs side-gated QPCs. (We note that we have observed this is not true for GaAs 2DEGs, because the latter have a large surface depletion. It is extremely difficult to get a side-gated GaAs QPC device with a conducting channel at 4.2 K.)

The conductance in the QPC channel ($G = I/V$) was measured as a function of the applied gate voltage. To avoid hot electrons (heating of the electron gas) in the channel we kept $eV_{DS} \ll kT$. The channel current and voltage were measured at 17 Hz. The lithographic width of the channel was changed by applying bias voltages to the metallic in-plane side gates, depleting the channel near the side walls of the QPC. Battery operated dc voltage sources were used to apply constant voltages, $V_{G1}$ and $V_{G2}$, (figure 8) to the two gates. An asymmetric potential $\Delta V_G = V_{G1} - V_{G2}$ was applied between the two side-gates to create spin polarization in the channel. The QPC conductance was then recorded as a function of a common sweep voltage, $V_G$, applied to the two gates (in addition to the potentials $V_{G1}$ and $V_{G2}$ which create the asymmetry). The linear conductance $G$ of the channel was measured for different $\Delta V_G$ as a function of $V_G$, with a drain–source drive voltage of 100 $\mu$V.

Figure 9(a) shows the measured conductance (in units of $G_0$) at 4.2 K of a QPC device as a function of a sweep voltage $V_G$ applied to both side gates for symmetric ($V_{G1} - V_{G2} = 0$) and asymmetric ($V_{G1} - V_{G2} \neq 0$) lateral confining potentials. This figure is typical behavior for a number of nominally identical QPCs. Figure 9(b) illustrates the case when the confining potential of the QPC is highly asymmetric. Measurements made on several QPC devices gave fairly similar and reproducible results, differing only in the pinch-off voltages due to differences in the lithographic channel widths. In addition to a short plateau at conductance $G \approx G_0$, a short plateau at conductance $G \approx (1/2)G_0$ was observed in the absence of any applied magnetic field when the lateral confining potential of the QPC was made significantly asymmetric by appropriate voltage biasing of the side gates. The 1/2 plateau was also observed when
Figure 9. (a) Conductance of a QPC measured in zero magnetic field for symmetric (S, \(V_{G1} - V_{G2} = 0\)) and asymmetric (AS, \(V_{G1} - V_{G2} \neq 0\)) transverse confining potentials. The 1/2 plateau appears only when the confinement is asymmetric. (b) Conductance of a different QPC measured at \(V_{G1} - V_{G2} = 7.5\ V\), showing the 1/2 plateau in the absence of applied magnetic field. (Reprinted with permission from [14].)

the asymmetry of the confining potential was reversed by reversing the constant bias voltages on the gates.

As mentioned, although it is not direct evidence, the occurrence of a 1/2 plateau is considered to be a clear signature of complete spin polarization [14]. The 1/2 plateau observed in figures 9(a) and (b) results from spin splitting of the first quantized conductance plateau. Effects such as fluctuations and resonance due to quantum interference caused by impurities, channel wall irregularities and reflections at QPC ends do not result in a plateau in the conductance: they give rise to oscillations or other structures superimposed on the plateaus. Moreover, such structures are suppressed in a relatively small perpendicular magnetic field [32]. The 1/2 plateau we observe survives a fairly strong magnetic field in the plane of the 2DEG and in the direction of current flow. We see that strong spin-polarization is taking place for side-gated QPCs with asymmetrical LSOC—even though it is not obvious why the spin polarization is so strong.

Figure 10 shows more recent work [16]. Here we see that distinct steps in the conductance are observed but they are not always at \(G_0\) or \((1/2)G_0\). For more than a decade, such ‘anomalies’ have been seen in experimental reports of quantized conductance of QPCs. These anomalies appear at non-integer multiples of \(G_0\), and include the observation of conductance plateaus around \(0.5G_0\) and \(0.7G_0\) [16, 33–40]. There is a growing consensus that these conductance anomalies are indirect evidence for the onset of spin polarization in the narrow portion of the QPC [14, 41–45]. There is also mounting evidence that the number and location of the conductance anomalies can be further tuned by deliberately introducing a broken symmetry in the electrostatic confinement in the narrow portion of the QPC [46, 47]. More recently, the change in the impurity potential in a GaAs QPC with an asymmetric lateral confinement due to an offset bias between two split-gates has been shown to strongly affect the location of the conductance anomalies [48].

Figure 10. The conductance of the QPC (in units of \(2e^2/h\)) measured as a function of the common sweep voltage \(V_G\) applied to the in-plane gates, at \(T = 4.2\ K\). The sweep voltage is superimposed on initial potentials \(V_{G1}\) and \(V_{G2}\) applied to the gates to create an asymmetry. The left-most curve shows the conductance for the symmetric case, i.e. with only the common sweep voltage \(V_G\) applied to the gates. For the other curves, from left to right, the initial potential \(V_{G2}\) applied to gate G2 is fixed at 2.0 V and the initial potential \(V_{G1}\) on gate G1 is equal to 0.0, −0.1, −0.3, −0.6, −0.9, −1.2, −1.5, −1.8, −2.0, −2.3, −2.6, −2.9, −3.1, −3.4, −3.7, −4.0, −4.5, −5.0, −5.5 and −6.5 V, respectively.

7. The origin of the 1/2 \(G_0\) plateau

To understand theoretically the origin of the 1/2 plateau and the ‘anomalous’ plateaus, we consider the free electron Hamiltonian of the QPC as given in equation (4). We use a symmetric InAs QW to make our QPCs, so RSOC is minimal and we do not include the Rashba term in the spin–orbit Hamiltonian. We do not consider Dresselhaus SOC because the current in our InAs QPCs flows along the [100] direction, for which Dresselhaus SOC is found to be minimal [49]. Therefore, LSOC is the only SOC term retained in the Hamiltonian. Since the 1/2 plateau appears below the first conductance quantization at \(1G_0\), that is, close
to pinch-off of the channel, we are only interested in transport in the fundamental mode, or in the lowest 1D subband. It is noteworthy that the Fermi energy of the 1D electron gas is often considerably smaller than the Fermi energy of the 2DEG. This happens when the conductance channel is narrowed by negative gate bias voltages which can raise the bottom of the 1D potential well relative to the 2D subband bottom [50, 51]. As a result, even though the 1D subband separation may be much smaller than the 2DEG Fermi energy, it is possible to have transport in the fundamental mode. We solved the Schrödinger equation with the Hamiltonian in equation (4) using a non-equilibrium Green function (NEGF) formalism [52]. Our solution took electron–electron interactions into account. We found that three ingredients are of paramount importance to produce spin polarization in a side-gated InAs QPC:

- LSOC induced by the lateral confining potential of the QPC;
- an asymmetric lateral confinement potential; and
- a strong electron–electron interaction.

LSOC inevitably exists in our QPC channels because etching the sample to form the gates creates two hard boundaries on either side of the channel and creates an air/2DEG interface. The asymmetry in the confining potential of the QPC is needed, as mentioned earlier, to trigger an initial imbalance between the densities of spin-up and spin-down electrons in the channel. Then, once that imbalance is established a strong electron–electron interaction enhances it to nearly 98% polarization and gives rise to the 1/2 plateau [14, 53].

In our simulations, the electron–electron interaction was considered to be a simple short range repulsive potential whose strength was varied via a parameter $\gamma$. From figure 11, we see that the 1/2 plateau smoothly rises to the normal conductance plateau ($G_0$) as the electron–electron interaction strength decreases (in the case shown $\gamma$ varies from 5.4 to 3.4) demonstrating the importance of the electron–electron interactions in creating a spin-polarized current in the channel.

8. Possible explanation for other conductance anomalies

To understand our observation of other conductance anomalies in InAs based QPCs, we conducted more extensive NEGF numerical simulations of the conductance for a wider range of QPC dimensions and biasing parameters [54]. We found that the number of coexisting conductance anomalies increases when the aspect ratio of the narrowest portion of the QPC channel is increased. These anomalies can be related to a plethora of spin textures in the QPC. Near the integer conductance steps, the spin texture is reminiscent of the spin Hall effect [55]. The conductance anomalies can also be fingerprints of spin textures associated with several other things, including a leaky single qubit state, a leaky singlet state, or a leaky spin-density wave in the narrow portion of the QPC as its aspect ratio is increased.

We considered theoretically a side-gated QPC InAs quantum well structure. All our calculations were performed at 4.2 K. Figure 12 shows the value selected for $\gamma$ (following Lassl et al [56]), the strength of the electron–electron interaction, and $\beta$ the LSOC parameter Hamiltonian (equation (4)) [21]. Unless otherwise stated, the geometrical parameters $l_1, l_2, w_1$ and $w_2$ are as displayed in the caption to figure 13. These parameters are smaller than the experimental values of the QPC and were chosen to reduce computational time. The potential at the source–drain potential difference was set to 0.3 V and an asymmetry in the potential of the side gates introduced, also shown in figure 13. The conductance of the constriction was studied as a function of the common mode potential, $V_{\text{Sweep}}$. The Fermi energy was equal to 106.3 meV in the source contact and 106 meV in the drain contact, ensuring single-mode transport through the QPC.

Figure 13 shows plots of the conductance of the QPC as a function of $V_{\text{Sweep}}$ for an asymmetric value of $\Delta V_{\text{SG}} = V_{\text{sg1}} - V_{\text{sg2}} = 0.4$ V and for different values of $l_2$. A wide variety of conductance anomalies can be seen which depend strongly on the QPC dimensions. In figure 13(a), the first hint of a developing conductance anomaly appears as a shoulder for $l_2 = 26$ nm, equivalent to a QPC aspect ratio of $l_2/w_2 = 1.625$. For $l_2 = 28$ nm, the small shoulder has grown into a fairly broad anomalous plateau slightly below 0.7$G_0$. The latter is accompanied by the onset of a negative differential region (NDR). The latter becomes more pronounced as the length or aspect ratio $l_2/w_2$ of the QC increases. As $l_2$ keeps increasing, there is a saturation in the conductance curve around $0.5G_0$ prior to the onset of the NDR. For $l_2 = 42$ nm, the conductance curve actually shows two simultaneous anomalous plateaus, one around $0.5G_0$ and the other around $0.75G_0$. In figure 13(b), for $l_2 = 50$ nm (aspect ratio of 3.125), the small NDR which originally appeared for $l_2 = 42$ nm has grown into a second NDR with nearly the same peak and valley location on the conductance axis as the first NDR but located past the $0.5G_0$ plateau.

The conductance anomalies illustrated in figure 13 are all linked to non-zero values of the conductance spin polarization $\alpha = (G_{\uparrow} - G_{\downarrow})/(G_{\uparrow} + G_{\downarrow})$, where $G_{\uparrow}$ and $G_{\downarrow}$ are, respectively, the conductance associated with the spin-up and spin-down electrons. Values of $\alpha$ as high as 0.98 were calculated in [57]. We further illustrated the relation between...
Figure 12. Schematic of the QPC configuration used in the numerical simulations [21, 54].

Figure 13. Conductance $G$ of asymmetrically biased QPC as a function of $V_{\text{sweep}}$. The potential on the two SGs are $V_{\text{sg1}} = 0.2 V + V_{\text{sweep}}$ and $V_{\text{sg2}} = -0.2 V - V_{\text{sweep}}$. The temperature is 4.2 K. The geometrical dimensions of the QPC are: $l_1 = l_2 + 32$ nm, $w_2 = 16$ nm, and $w_1 = 48$ nm. In the left figure, the curves labeled 1 through 11 correspond to $l_2 = 22, 24, 26, 28, 30, 32, 34, 36, 38, 40$ and 42 nm, respectively. In the right figure, the curves labeled $l_1$ through $l_5$ correspond to $l_2 = 42, 44, 46, 48, 50$ nm, respectively. For both plots, $V_{\text{ds}} = 0.3$ mV, $\gamma = 3.7$ in units of $\hbar^2/2m^*$, and $\beta = 200$ Å$^2$ ($\beta$ is the strength of the LSOC) (reprinted with permission from [54]).

The conductance anomalies and the onset of spin polarization by studying two-dimensional contours of the spin density profiles $n_\uparrow(x, y) - n_\downarrow(x, y)$ as a function of $V_{\text{sweep}}$ for QPCs of different dimension. Figure 14 is a plot of the density profile at different $V_{\text{sweep}}$ values representing different spin textures in the structure for the case corresponding to the $l_2 = 28$ nm in Figure 13.

As shown in figure 14(a), for $V_{\text{sweep}}$ below $-90$ mV, a spin Hall texture exists in and around the central part of the QPC. For $V_{\text{sweep}}$ between $-90$ and 210 mV, the spin texture is characterized by a sharply defined hump located at the center of the QPC (the spin texture for $V_{\text{sweep}} = 0$ and 210 mV is shown in figures 14(b) and (c), respectively). This regime corresponds to onset of the anomalous conductance plateau slightly below $0.7G_0$ until the first integer step is reached (see figure 13). Beyond that step ($V_{\text{sweep}} = 240$ mV), the spin texture switches back to the spin Hall regime (see figure 14(d)).

In [54], we describe more NEGF numerical examples showing that the conductance anomalies are related to a wide variety of spin textures in the narrowest portion of the QPC, associated with either a spin Hall regime of operation, or the presence of a leaky single qubit state which develops first into a leaky singlet state and then into a leaky spin-density wave in the channel as its aspect ratio increases. Our analysis is quite important since it suggests that the conductance anomalies reported by many experimental groups [35–37, 48, 58–60] using different QPC designs and biasing conditions other than the ones considered here are most likely fingerprints of complex spin textures resulting from a strong spin imbalance triggered by a small spatial asymmetry in the potential energy profile of the QPC.
Figure 14. 2D contour plots as a function of $V_{\text{sweep}}$ associated to the conductance plot shown in figure 13 for $l_2 = 28$ nm. (a) $V_{\text{sweep}} = -150$ mV, (b) $V_{\text{sweep}} = 0$ mV, (c) $V_{\text{sweep}} = 210$ mV and (d) $V_{\text{sweep}} = 300$ mV (reprinted with permission from [54]).

Figure 15. (a) Dual QPC configuration. In the simulations, the potential on the two side gates close to the source is set equal to $V_{\text{sg1}} = -0.2 \, V + V_{\text{sweep}}$, $V_{\text{sg2}} = +0.2 + V_{\text{sweep}}$; we use $V_s = 0.0$, and $V_d = 0.3 \, mV$. The potential on the two side gates next to the drain is kept the same at a fixed value. The current flows in the $x$-direction. (b) An AFM image of a dual QPC structure with two sets of in-plane side gates (G1 and G2).

Actually, our analysis provides a potential explanation for the 0.7 conductance anomaly which has been a strongly debated issue since its discovery in 1996 [46]. We believe that the conductance anomalies reported by many other groups [35–37, 48, 58–60] in their analysis of the conductance of QPCs is most likely related to an asymmetry in the potential energy profile while fabricating or biasing the device.

Recently, we showed that the number and location of the conductance anomalies, occurring below the first quantized conductance plateau ($G_0 = 2e^2/h$), are strongly dependent on the nature (attractive or repulsive) and the location of the impurity. This is of practical importance if QPCs in series are to be used to fabricate all electrical spin valves with large ON/OFF conductance ratio [57].
9. Dual QPC structures—toward an all electrical spin valve

In view of the experimental and theoretical results described above, it seems appropriate to find a way to control and finely tune the location of a conductance anomaly to achieve the largest spin conductance polarization for a specific QPC. Recently, we investigated a dual QPC device as a tunable all-electrical spin polarizer. An AFM of a recently fabricated InAs dual QPC device is shown in figure 15. It consists of a QPC with two sets of in-plane side gates. In this structure, a bias asymmetry \( V_{sg1} - V_{sg2} \) is applied between the two leftmost gates to create a spin polarization in the channel. An additional common-mode bias \( V_{sweep} \) is applied to both gates. The second set of gates, separated by a gap ‘d’ from the first set, is biased at the same fixed potential \( V_{sg3} = V_{sg4} \). The latter is varied to control the amount of depletion between these gates.

Figure 16 shows the conductance of the dual QPC structure shown in figure 15(b). The lithographic dimensions of the device are shown in the figure caption, as are the bias conditions. \( V_{sg3} \) and \( V_{sg4} \) are set to the different values shown in the inset of figure 16. This plot shows that when a symmetric bias is applied to the two gates of the first QPC, an asymmetric bias applied on the second QPC can trigger a spin imbalance in the first portion of the QPC. The proximity of the second set of gates can therefore create a spin imbalance by altering the amount of LSOC on the two side walls in the first portion of the QPC. This allows a fine tuning of the amount of spin polarization in the dual QPC structure. Other biasing configurations of the dual QPC structure are presently being investigated.

We are currently studying the conductance of an-electric spin valve structure. Some of these structures were recently fabricated in our lab, figure 17. The latter consists of two QPCs in series separated by a channel whose length is assumed to be smaller than the spin coherence length. GaAs is a material of choice in that respect since the spin coherence length has been measured over 100 \( \mu \text{m} \) at room temperature [13].

In figure 17, the left QPC, ‘the injector’, puts polarized electron spins into the device channel. The right QPC, ‘the detector’, detects the spin state. These two QPCs replace the Datta–Das [5] ferromagnetic electrodes or contacts. The ‘ON’ condition of the device is defined when the spin orientations of the injector and detector QPCs are set parallel by fine-tuning of the confining potential of each by their respective side-gate voltages. Similarly, the ‘OFF’ condition is achieved when the spin orientations of the injector and detector QPCs are antiparallel. The middle gates in figure 17 are used to perform spin precession in the device via voltage control of the LSOC in the central portion of the structure. This would allow a gradual switching between the ‘ON’ and ‘OFF’ conditions described above. Such a voltage-controlled spin valve would be the equivalent of an all-electric Datta–Das SpinFET.

10. Summary

Over the last 6 years, we have shown LSOC, resulting from the lateral in-plane electric field of the confining potential of InAs- and GaAs-based quantum point contacts with in-plane side gates, can be used to create a strongly spin-polarized current by purely electrical means in the absence of any applied magnetic field. The QPC—a short quantum wire made from the InAs quantum wells with high intrinsic SOC—is used to generate strongly spin-polarized currents. This is accomplished by tuning the electron confinement potential of the channel using asymmetric bias voltages on the side gates. A plateau at \( G \cong 1/2(2e^2/h) \) is observed in the ballistic conductance of the QPC in the absence of a magnetic field—a signature of complete spin polarization. The spin of electrons in the QPC can be set ‘up’ or ‘down’ by tuning the voltage potential of the gates.

We used an NEGF analysis to model a small QPC and found three ingredients that are essential in generating a strong spin polarization: (a) an asymmetric lateral confinement, (b) a LSOC induced by the lateral confining potential of the QPC and (c) a strong electron–electron interaction. NEGF simulations indicate that LSOC is instrumental only in triggering the initial spin imbalance; it is the strong
electron–electron interaction that enhances it and results in the strong spin polarization. We have used an NEGF approach to study in detail the ballistic conductance of asymmetrically biased QPCs in the presence of LSOC for a wide range of QPC dimensions and gate bias voltage. Various conductance anomalies were predicted below the first quantized conductance plateau \( G_0 \); these were shown to occur due to spontaneous spin polarization in the narrowest portion of the QPC. We found that the number of conductance anomalies increases with the aspect ratio (length/width) of the QPC constriction. These anomalies are fingerprints of spin textures in the narrow portion of the QPC.

Our work opens up new possibilities for the creation of spin-polarization by purely electrical means. Recently, we have extended our investigations to the study of an electric spin valve, formed of two QPCs in series. QPC1 injects polarized spins into the device channel and is the injector. QPC2 detects the spin state and is the detector. QPC1 and QPC2 replace the magnetic electrodes or contacts of the Datta–Das SpinFET. The ‘ON’ condition of the device is defined when the spin orientations of the injector and detector QPCs are set parallel by fine-tuning the confining potential of each QPC. The ‘OFF’ condition is similarly achieved when the spin orientations of the injector and detector QPCs are set antiparallel. The addition of middle gates to perform spin precession in the channel between QPC1 and QPC2 via voltage control of the LSOC could lead to the first implementation of an all-electric Datta–Das SpinFET.

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