All-electrical injection and detection of a spin polarized current using a 1D conductor

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There is considerable interest in being able to control the spin dynamics, particularly in mesoscopic and nanoscale semiconductor devices, as this could lead to the development of a range of electronic functions not presently available. In order to develop successfully such concepts it is necessary to controllably generate, manipulate, and detect spin currents by electrical means and so minimize, or eliminate, the use of ferromagnetic contacts or external magnetic fields. Here we demonstrate on-chip spin polarizing/filtering actions by driving the gate-defined one dimensional (1D) conductor, one of the simplest geometries for integrated quantum devices, away from the conventional Ohmic regime. Direct measurement of the spin polarization of emitted current was performed when the momentum degeneracy was lifted, wherein both the 1D polarizer for spin injection and the analyser for spin detection were demonstrated. The results showed that a configuration of gates and applied voltages can give rise to a tunable spin pumping efficiency, which has implications for the development of spintronic devices and future quantum information processing.

All-electrical control of spin transport in nanostructures has been one of the biggest challenges to the development of spintronics. Most research towards implementation of this electrical approach has focussed on using the spin-orbit interaction to induce spin polarized transport, as reported in various nanostructures, including one-dimensional (1D) conductors. However, it is essential to develop a more general approach in which materials with a strong intrinsic spin-orbit coupling are no longer necessary, and consequently a longer spin dephasing (relaxation) time will be obtained of crucial importance for quantum information processing.

In theory, it is possible to produce transition from antiferromagnetic to ferromagnetic behaviour by controlling the exchange interaction, although this can be difficult to achieve in practice. The use of electrostatic-confinement gates using electron-beam lithography in recent years has allowed lower-dimensional quantum devices to be developed within various electronic systems. If such a system could be successfully utilized for on-chip spin injection, the problems associated with conventional methods of spin injection — such as the impedance mismatch, which drastically limits the spin polarization (spin pumping efficiency) of the injected current — can be avoided. Furthermore, the fast-gating technique, which has been well developed in conventional microelectronics, allows it to be used for rapid control of the spin content. In this work, we utilize the exchange interaction in gate-defined 1D conductors to develop an electrically tunable spin injector/filter.

Studies of quasi one-dimensional conduction have been of interest for a considerable time due to its strong electron-electron interaction, much of this work has been with reference to the spin properties. The variation of the current with the dc source-drain voltage has been shown to be particularly useful in providing quantitative measurements on the energies of the 1D subbands in the channel. For ballistic transport this voltage is dropped at the two ends of the channel and lifts the momentum degeneracy, and has been used, for example, to derive the value of the Lande g factor by measuring the spin splitting in a magnetic field. It has also been used to show that there is a spontaneous lifting of the spin degeneracy in the absence of a magnetic field, which is related to the 0.7 structure.

Furthermore, there is a feature which appears as a plateau, or structure, with increasing dc source-drain voltage at, or near, the value of 0.25(2e²/h) in the differential conductance. Although this feature was apparent in early work on one-dimensionality, it was in general regarded as a spin degenerate state with a decreased differential conductance. However, it was recently proposed that the 0.25(2e²/h) feature could be a consequence of a lifting of both momentum and spin degeneracy. The loss of the momentum degeneracy on its own producing a value of e²/h and an absence of spin degeneracy accounting for the remaining factor of 1/2. This is a very surprising result of increasing the source-drain voltage, and in order to substantiate this conclusion it is crucial to provide direct evidence of spin polarization which does not rely on an inference from conductance plateaux, particularly because it has been suggested that it is possible for the differential conductance value to be reduced in the non-Ohmic regime.

In this work, we have utilized a technique called electron focusing to directly measure the degree of...
spin polarization of the current. The focusing device geometry is shown in Figure 11, wherein a small perpendicular magnetic field $B_z$ is applied to bend and inject ballistic electrons from an emitter, a short one dimensional region formed by split gates (quantum point contact), which acts as a spin analyzer in this work. The electrons pass through the two-dimensional base region, which is grounded, into the collector which is an identical device to the emitter; in the context of this experiment the collector acts as a spin analyzer. With current flowing into the device from the emitter, and with the base connected to ground, the collector-base voltage shows periodic peaks as a function of $B_z$ which is due to the focusing of electrons into the collector. These focusing peaks occur whenever an integer multiple of the cyclotron diameter, $2m^*v_F/eB_{1z}$, where $m^*$ is the electron effective mass and $v_F$ is the Fermi velocity, equals the distance, $L$, between emitter and collector.

As the collector is not connected to ground, a voltage $V_c = I_c/G_c$ develops between the collector and base, where $I_c$ is the current flowing through the collector which has conductance $G_c$. Both the conductance and current can be further written as $G_c = e^2/h(T_↓ + T_↑)$ and $I_c = \alpha L_c(T_↓ + T_↑)$ where the arrows represent the electron spins, $I_c = I_↓ + I_↑$ is the current injected from the emitter, $T_↓ (T_↑)$ is down-spin (up-spin) transmission of the collector and $\alpha$ is a parameter, accounting for spin-independent imperfections during the focusing process [22].

This situation has been considered by Potok et al. [22], who have shown that a simple derivation gives the magnitude of the height of the peaks in collector-base voltage. This can be written in terms of the degree of spin polarization induced by the emitter $P_e = (I_↓ - I_↑)/(I_↓ + I_↑)$ and the spin selectivity of the collector $P_c = (T_↓ - T_↑)/(T_↓ + T_↑)$. They found the following relation

$$V_c = \frac{\hbar}{2e^2}I_c(1 + P_eP_c),$$

which was confirmed by inducing a Zeeman spin splitting with a strong in-plane magnetic field [22, 23]. Consequently, if both emitter and collector are spin polarized the collector voltage is doubled compared to when either emitter or collector allows spin degeneracy.

Here we investigated the spin balance in the focusing stream as the conductances of both emitter and collector were varied in the absence of a magnetic field (except for the small focusing field $B_{1z}$). The particular objective was to clarify the spin content of the current when the differential conductance was in the region of the 0.25 plateau. This work used samples comprising a high-mobility two-dimensional electron gas formed at the interface of GaAs/Al$_{0.33}$Ga$_{0.67}$As heterostructures. The low temperature mobility was $2.3 \times 10^6$ cm$^2$/Vs at a carrier density $1.17 \times 10^{11}$ cm$^2$ giving a mean free path for momentum relaxation $\sim 13$ µm. This is much longer than the focusing path, although we note that the small angle scattering length is much less and may contribute to a broadening of the focusing peak.

Measurements were performed in a dilution refrigerator at a temperature of 80 mK, the electrical connections are shown in Figure 11. Two devices were measured and gave similar and reproducible results. Simultaneous lock-in measurements of the emitter and collector conductances and the focusing signal were performed by applying two independent excitation sources of (i) a 77 Hz ac voltage $20 \mu$V with a dc bias $V_{sd}$ applied to the emitter and (ii) 31 Hz ac current 1 nA with a dc bias $I_{sd}$ applied to the collector. It was verified that the focusing signal $V_c$ was linear with current $I_e$; for clarity, all the data presented here was rescaled for $I_e = 1$ nA. The current-bias excitation, i.e., source (ii), is required to prevent the collector from sinking injected current, as well as increasing the bias across the collector pushing it into the 0.25 regime.

Both the emitter and collector show one-dimensional conductance quantisation and a source-drain voltage induced plateau at $0.25(2e^2/h)$ at $B = 0$ [21], as shown in Figure 11. The measured focusing peaks are shown in Figure 11 when the emitter and collector are set at the described values of conductance for $V_{sd} = I_{sd} = 0$. Focusing peaks appear periodically, at intervals of $B_z = 0.05$ T, which is consistent with the cyclotron motion $B_z = 2m^*v_F/eL$ calculated from the two-dimensional electron concentration. The height of the focusing peaks, as anticipated, barely changes with decreasing conductance of both emitter and collector from $2e^2/h$ to $0.25(2e^2/h)$, indicating that there is no change in their spin polarization, i.e., $P_e$ and/or $P_c = 0$. As expected the peak height is independent of $G_c$ and $G_c$ for constant current $I_e$ injected from the emitter point contact.

When a dc bias is applied across the emitter and collector the focusing peak exhibits very different behaviour to that previously observed at zero bias. In Figure 11, the focusing peaks are shown for various $G_c$ when $G_e$ is fixed at $0.25(2e^2/h)$, and when the dc biases across the emitter and collector were set at $V_{sd} = 1.5$ mV and $I_{sd} = 30$ nA, respectively. It was observed that the peak height stays constant with decreasing $G_e$ from $1.5(2e^2/h)$ to $0.5(2e^2/h)$, but rises considerably when this approaches $0.25(2e^2/h)$, i.e., where the anomalous plateau is found as shown in Figure 11. This substantial rise is predicted by Equation (1), if there is an increasing degree of spin polarization in both the emitter and collector.

Figure 21 shows the height of the first peak as both the dc biases and the collector conductance were varied with the emitter conductance locked at $G_e = 0.25(2e^2/h)$; this peak was chosen for investigation because of its robust structure and is seen to stay fairly constant at $\sim 3 \mu$V, essentially independent of both $V_{sd}$ and $I_{sd}$, when $G_c \sim 2e^2/h$. However, in the low conductance region when $G_e \leq 0.25(2e^2/h)$, and $I_{sd} = 30$ nA, the focusing peaks increase as $V_{sd}$ is increased, negatively, from 0 and then saturates when $V_{sd}$ is near $-0.9$ mV. The focusing peaks at $|V_{sd}| \geq 0.9$ mV are approximately twice the value of those at $V_{sd} = 0$ for every individual value of collector
conductance below $\sim 0.25(2e^2/h)$. This, according to Eq. (1), implies that both emitter and collector are fully spin polarized, i.e., $P_e = P_c = 1$. The saturation of the peak height is also consistent with the fact that both $P_e$ and $P_c$ cannot be larger than 1.

To further verify this bias-induced spin polarization, $I_{sd}$ was decreased from 30 nA to 0 with $V_{sd}$ still at 1.5 mV. Figure 2a shows that the height of the focusing peaks drops back to almost the same value obtained when $V_{sd} = 0$ and $I_{sd} = 30$ nA as well as when both are zero. This is again expected when either polarizer or analyser are spin degenerate (i.e., either $P_e$ or $P_c$ equals 0). Finally, it is important to note that the value of source-drain bias $V_{sd} = 0.9$ mV at which the focusing peak height $V_c$ saturates is consistent with the bias at which the 0.25 anomaly appears, as shown in Figure 1a.

The evolution of the focusing peaks as a function of conductance [24] is also shown in Figure 2b, the focusing peak rises as $G_c$ is reduced below $2e^2/h$, but the manner of the increase varies for different dc source-drain biases. At $V_{sd} = 0$ and $I_{sd} = 30$ nA, the peak voltage barely increases until $G_c$ is reduced below $\sim 0.15(2e^2/h)$, in the near-pinch-off region, whereas at $V_{sd} < 0$ and $I_{sd} = 30$ nA the peak voltage starts to increase once $G_c$ is reduced below $\sim 0.6(2e^2/h)$. The near-pinch-off increase in peak voltage with the reduced value of $G_c$ could be attributed to an $\phi$-dependent enhancement; this has been suggested previously when $G_c$ is low [22] although the origin is not clear.

To remove non-spin related effects from the focusing peak, all the peak voltages are normalized by the val-
ues at \( V_{sd} = 0 \) and \( I_{sd} = 30 \) nA. Figure 2b shows the normalized peak ratio, proportional to \((1 + P_c P_e)\), and the corresponding conductance as a function of gate voltage, with \( I_{sd} \) set to 30 nA and \( V_{sd} \) swept from 0 to \(-1.5 \) mV. As seen the peak values rise with reducing conductance and then saturate when \( G_c \) reaches the region of the 0.25 plateau, suggesting that \( P_e \) has reaches its maximum value of 1. Similarly, the peak ratio in the 0.25 regime rises with increasing source-drain bias applied across the emitter and then saturates. This reaches a value of \( \sim 2 \) at \( V_{sd} = 0.9 \) mV when the 0.25 feature appears in the emitter conductance.

These results show that the emitter is functioning as a spin polarizer and the collector as a spin analyser, demonstrating that a manipulation of the degree of polarized spin current can be achieved by tuning the source-drain bias at low values of conductance. For instance, Figure 2b shows that the spin polarization of the injecting current \( P_e \) was \( \sim 30\% \) when the emitter was set to \( V_{sd} = 0.3 \) mV and \( G_c = 0.25(2e^2/h) \), whereas \( P_e \) reaches 60 \( \sim 70\% \) for \( V_{sd} = 0.6 \) mV. We note that in the region of the 0.7 anomaly which is found in the absence of bias the enhancement of the peak height will be \( \sim 10\% \) and difficult to observe unambiguously.

The effects observed here indicate that the non-equilibrium electron energy distribution and the spin coherence are maintained during the focusing transit into the collector. The transit time is sufficiently short (approximately 20 picoseconds) that phonon emission is not occurring to any significant degree, so allowing all the emitted electrons to enter the collector. The spin coherence length exceeds the path length so that the spin polarization is maintained during the focusing which augurs well for applications of this phenomenon.

Our experiments establish a link between spin and momentum which is unusual in the absence of a spin-orbit coupling. It seems most likely that the cause of the 0.25 is that a spin polarized stream of electrons is the lowest energy configuration; this configuration is retained as there is only one direction of momentum and an absence of spin scattering by electrons with the opposite momentum. A physical mechanism based on exchange interaction has recently been proposed for the 0.25 anomaly which explains the lifting of the spin degeneracy in the regime of non-equilibrium transport. How such exchange induced spin polarization is retained, or enhanced, by an absence of momentum degeneracy is puzzling. However, for practical applications, it is now possible to vary the degree of spin polarization in a way not previously possible. A complex arrangement of gates and applied voltages can be utilized for on-chip spin manipulation with applications in spintronics and quantum information processing.

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