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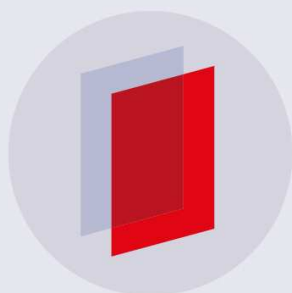
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Direct observation of spin polarization in GaAs quantum wires by transverse electron focusing

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Abstract. We present transverse electron focusing measurements in the two dimensional electrons gas formed at the interface of a GaAs/AlGaAs heterostructure. The experimental arrangement consists of two orthogonal quantum point contacts (QPCs), one acting as injector and the other as detector of the collimated 1D electrons as a function of transverse magnetic field. The focusing spectrum shows anomalous behaviour, the first and third focusing peaks split into two sub-peaks while second peak remains as a single peak. The observed splitting, a signature of spin states, arises from the spin-orbit interaction when the 1D electrons are injected into the 2D regime, thus allowing us to manipulate the spin states within the 1D channel.

There is considerable interest in the spin properties of clean one-dimensional (1D) quantum wires, the science of which has potential for spintronics and spin-based logic devices. Generally electrons in a quantum wire are spin degenerate, but spin polarisation becomes observable on the application of a large in-plane magnetic field[1]. Although spontaneous spin polarisation is forbidden in a strictly 1D system of infinite length, according to the Lieb-Mattis theorem[2], phenomena attributed to spin polarisation[3, 4] such as the 0.7 anomaly[1, 5, 6] and source-drain bias induced 0.25 structure[7] have been observed in quasi-1D systems. A direct measurement of the degree of spin freedom is thus necessary to lead to a comprehensive understanding of these features to complement conductance measurements[8].

A typical transverse electron focusing setup consists of an injector and a detector, generally along a plane such that on application of a small perpendicular magnetic field (B_{\perp}) the electrons will exhibit cyclotron motion[9, 10]. Once the cyclotron radius (r_c) matches the condition $N \times 2r_c = L$ (N is an integer and L is the separation between the injector and detector), the injected electrons are guided into the detector and result in a voltage drop across the detector (referred as V_{cc} hereafter). The cyclotron radius is directly proportional to B_{\perp} , thus giving rise to focusing peaks periodic in B_{\perp} .

It has been predicted theoretically[8] that an imbalance of the spin-split branches, due to the spin-orbit interaction, can be detected using transverse electron focusing by means of observation



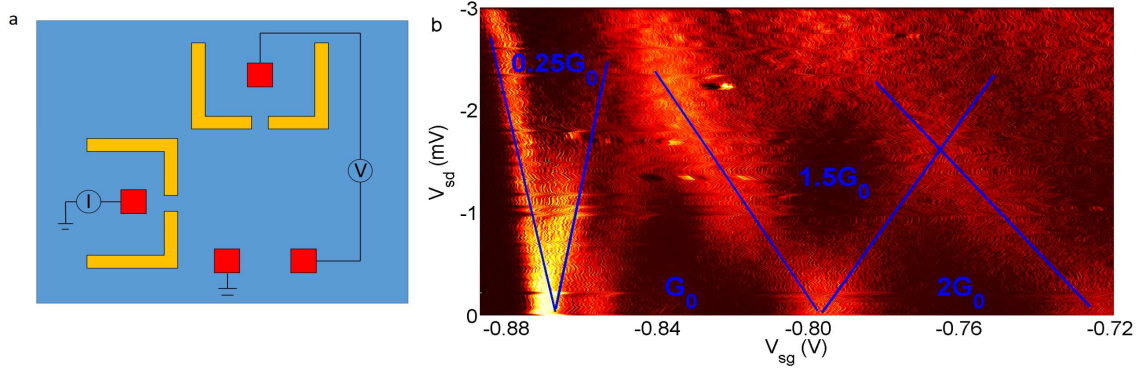


Figure 1. Experiment setup and characteristic of the QPC. **a**, schematic of the focusing device; the yellow bars are metallic gates and the red blocks are Ohmic contacts. **b**, colour plot of the transconductance $\frac{dG}{dV_{sg}}$ as a function of dc source-drain bias, where V_{sg} is the voltage on the split gates to define the QPC. The bright (dark) regime is for high (low) transconductance. Conductance plateaus quantized in the units of G_0 occur with zero bias voltage while additional structures appear with subsequent increment of the source-drain bias voltage.

of a split in the odd-numbered focusing peaks, where the height of each sub-peak is proportional to the population of detected spin states. It has been confirmed experimentally in a GaAs hole gas[11, 12] and an InSb electron gas[13], the materials with large spin-orbit interaction, that the first focusing peak splits into two sub-peaks where each sub-peak was associated with a spin state.

Here we present results of transverse electron focusing experiments in GaAs based electron gas where a pronounced splitting of the first focusing peak was observed.

The devices were fabricated from a high mobility two dimensional electron gas formed at the interface of GaAs/ $Al_{0.33}Ga_{0.67}As$ heterostructure. At 1.5 K, the measured electron density was $1.80 \times 10^{11} \text{cm}^{-2}$ and the mobility was $2.17 \times 10^6 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$, therefore the mean free path is over $10 \mu\text{m}$ which is much larger than electron propagation length which is around $2 \mu\text{m}$. The experiments were performed in a cryofree dilution refrigerator with an electron temperature of 70 mK, using the standard lockin technique. For the two-terminal conductance (G) measurement, an excitation voltage of $10 \mu\text{V}$ at 77 Hz was applied whereas for the four-terminal focusing measurement a current excitation of 10nA at 77 Hz was used[14, 15].

In contrast to the conventional linear focusing device geometry[9, 10] where the central gate is shared between the injector and detector, we used an orthogonal focusing device geometry to allow independent control of the injector and detector as shown in Fig. 1(a). The orthogonal configuration avoids the possible cross-talking between the injector and detector[14]. Both the injector and detector exhibited well defined 1D characteristics as shown in Fig. 1(b). The conductance plateaus were quantized at integer multiple of G_0 ($2e^2/h$) for zero dc source-drain bias, and at half integer plateaus, i.e., $1.5 G_0$, $2.5 G_0 \dots$ etc. at $V_{sd} \approx -1.5 \text{mV}$. A structure at $0.25 G_0$ appears at large source-drain bias voltage ($< -2 \text{mV}$) which is similar to the previous report[7].

The focusing result is shown in Fig. 2 with the injector and detector fixed at G_0 , respectively. With negative transverse magnetic field the focusing signal is almost zero (result is not shown) while with positive magnetic field the periodic focusing peaks are well defined and the peaks position is in good agreement with calculation according to

$$B_{focus} = \frac{\sqrt{2}\hbar k_F}{eL} \quad (1)$$

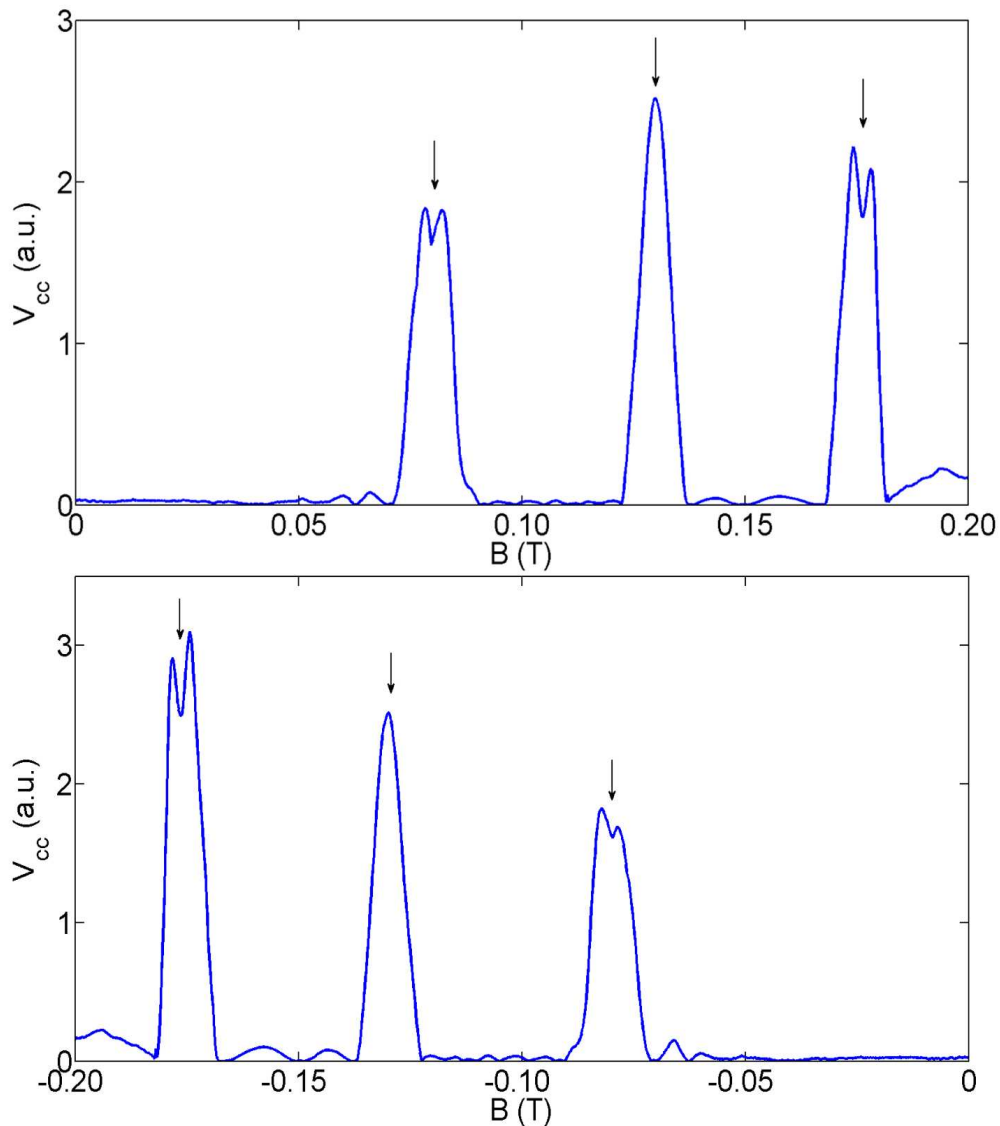


Figure 2. Representative focusing spectrum. Both injector and detector are fixed at first conductance plateau. Periodic focusing peaks are well defined and their position is in good agreement with calculation as highlighted by the arrows. The upper plot shows the result with current flowing from the injector to detector and vice-versa for the lower plot.

A comparison between negative and positive magnetic field results suggests that the Quantum Hall effect and Shubnikov-de Haas (SdH) oscillations are negligible in the regime of focusing[9, 14, 15], and all the features are due to transverse electron focusing only. The first and third focusing peaks split into two sub-peaks, on the other hand, the second focusing peak remains as a single peak. These observations are similar to that reported for p-type GaAs and n-type InSb[11, 12, 13], however, the splitting of first focusing peak (around 6 mT) is much smaller compared to p-type GaAs (around 36 mT) and n-type InSb (around 60 mT), which is consistent with the fact that the energy difference between different spin branches in n-type GaAs is much smaller compared with materials with strong spin-orbit interaction[11, 12, 13]. The focusing spectrum remains qualitatively the same after swapping the role of injector and detector as

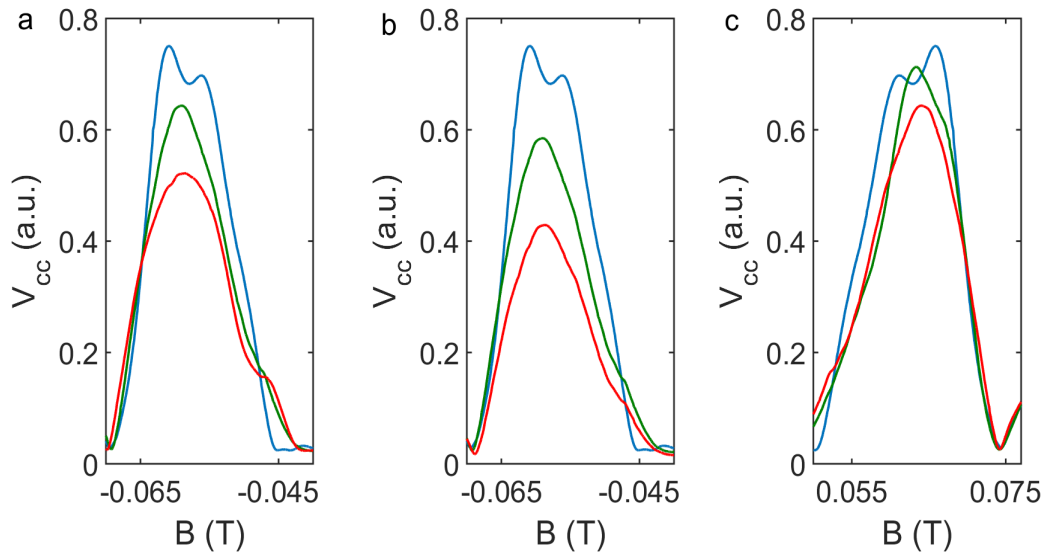


Figure 3. First peak at higher conductance. **a**, injector conductance was set to G_0 (blue), $3G_0$ (green) and $4G_0$ (red), respectively. Detector was fixed at G_0 . **b**, detector conductance was set to G_0 (blue), $3G_0$ (green) and $4G_0$ (red), respectively while the injector was fixed at G_0 . **c**, result after swapping the polarity of the magnetic field. Injector conductance was fixed at G_0 (blue), $3G_0$ (green) and $4G_0$ (red). Detector was fixed at G_0 .

shown in lower panel of Fig. 2. The result shows that the effect is reproducible and free from impurity after the swap of injector and detector. We also illuminated the device with a red LED and the effect was reproducible with a noticeable change in focusing peaks position due to an increase in carrier concentration. We realise that the odd-even peak splitting arises from the spin-orbit interaction[8, 14, 15, 16]. In addition, the observation was further confirmed to be spin related via in-plane magnetic field dependence study where the splitting of first focusing peak was enhanced with increasing in-plane field[15].

We noticed that the first focusing peak showed a pronounced splitting when the injector conductance was smaller than $2G_0$ ($G_0 = \frac{2e^2}{h}$), however, such splitting was absent at large injector conductance value (e.g. $3G_0$ and $4G_0$) and only a single peak was observed as shown in Fig. 3(a). Similar result was obtained by fixing the injector conductance at G_0 and tuning the detector conductance (Fig. 3(b)) and swapping the polarity of the magnetic field (and the role of injector and detector, Fig. 3(c)). It is also important to emphasize that a single peak at large injector conductance value aligns with the dip between the two sub-peaks rather than one of the sub-peaks. This observation suggests the result is disorder free and does not arise from the shape of wavefunction within the injector. Assuming the peak splitting is due to disorder, then with an even larger angular spreading at larger injector conductance the splitting should persist[17].

In conclusion, we have observed a split in the odd-numbered focusing peaks in GaAs electron gas using transverse electron focusing measurement. The result provides a direct method of probing the spin polarisation in 1D electrons thus opens new opportunities for spintronics and other quantum schemes.

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