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Possible zero-magnetic field fractional quantization in $In_{0.75}Ga_{0.25}As$ heterostructures

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ABSTRACT

In this Letter, we report a systematic study of a structure found in zero magnetic field at or near $0.2\times(e^2/h)$ in $In_{0.75}Ga_{0.25}As$ heterostructures, where e is the fundamental unit of charge and h is Planck's constant. This structure has been observed in many samples and stays at near constant conductance despite a large range of external potential changes, the stability indicating a quantum state. We have also studied the structure in the presence of high in-plane magnetic fields and find an anisotropy which can be related to the Rashba spin–orbit interaction and agrees with a recent theory based on the formation of coherent back-scattering. A possible state with conductance at $0.25\times(e^2/h)$ has also been found. The quantum states described here will help with the fundamental understanding of low-dimensional electronic systems with strong spin–orbit coupling and may offer new perspectives for future applications in quantum information schemes.

Recently, non-magnetic fractional quantization at a series of conductance values was discovered for hole conduction in one-dimensional transport in Ge[1] and electrons in GaAs[2] systems using patterned gate devices with an additional top-gate. This was the first time that non-magnetic fractional quantization was identified in a conductivity experiment, though several theoretical models have already been proposed.[3–7] It was found in a quasi-1D system which was weakly confined, suggesting a completely different origin from that underlying the fractional quantum Hall effect and indicating new physical processes. A theoretical explanation was proposed by Shavit and Oreg[8] to explain such 1D fractions, which is based on a strong electron–electron interaction and coherent scattering between backscattered left-moving and right-moving electrons, particularly in the presence of an asymmetric 1D confinement potential. This may also be regarded as an entanglement between the two channel directions when momentum conserving backscattering occurs. A significant difference with earlier results on GaAs is that it was not necessary to apply an asymmetric bias, which would produce different carrier concentrations in the spin–split bands.

The Rashba spin–orbit interaction (RSOI) in heterostructures[9] is particularly appropriate for nanostructures and is based on a lack of inversion symmetry due to the imposition of an electric field. This couples to the electron motion and can be regarded as resulting in a "synthetic magnetic field."[10,11] As the RSOI strength can be tuned, in principle, by changing the shape of the confining potential via external gate bias voltages,[12] it can be considered as a basis for possible spintronic devices.[13–15] In this work, we have used $In_{0.75}Ga_{0.25}As$ heterostructures to study spin-effects as it provides a large Zeeman energy spin-splitting in a moderate magnetic field as well as a band bending displaying RSOI.[16] Consequently, any states appearing due to coherent backscattering may be modified by a coupling between the interaction and the RSOI. Here, the Landé g-factor, $|g^*| = 9$ in $In_{0.75}Ga_{0.25}As$[17] compared to 0.44 in GaAs,[18,19] with a consequently larger spin-splitting in applied magnetic field for the case of $In_{0.75}Ga_{0.25}As$.

The devices are fabricated from $In_{0.75}Ga_{0.25}As/Al_{0.75}In_{0.25}As$ heterostructures grown using molecular beam epitaxy[20–22] with the 2D electron gas forming ~120 nm beneath the surface. The low temperature mobility of the measured devices is 2.5×10^5 cm^2/V s (3.4×10^5 cm^2/V s), and the electron density is 2.2×10^{11} cm^{-2} (4.9×10^{11} cm^{-2}) in the dark (light) conditions. The devices have a strong Rashba coefficient[16,21] $\alpha\sim10^{11}$ eV m. The electron beam lithography defined gates

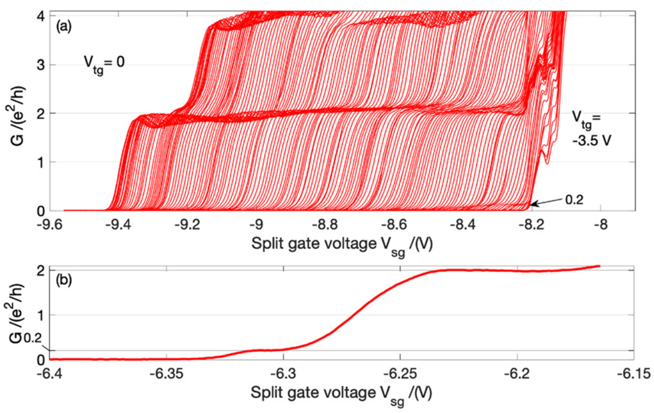

FIG. 1. (a) The conductance in units of e^2/h as a function of patterned gate voltage against top-gate voltage (V_{tg}) from 0 V (left) to -3.5 V (right) in intervals of -0.02 V, the lowest carrier concentration is on the right and highest on the left. A plateau at $0.2 \times (e^2/h)$ is observed when the top-gate voltage reached -3 V. (b) A single trace that shows the detailed $0.2 \times (e^2/h)$ structure.

in these devices are separated by 400 and 200 nm in length. A global top-gate was patterned on the 1D channel and was insulated by a 200 nm thick layer of cross-linked poly-methyl-methacrylate.

In all the experiments, the two-terminal conductance (G) is measured in the absence of a DC source–drain voltage, by sweeping the split-gate voltage (V_{sg}) at constant top-gate voltage (V_{tg}), in the presence of a 10 μV ac voltage source at 77 Hz applied between the source and drain contacts. The devices were measured in a cryogen-free dilution refrigerator with a base temperature of 25 mK. Structure was found near $0.2 \times (e^2/h)$ and was observed in five devices from three different wafers of similar design. This systematic study with different conditions was repeated in two different devices during three different cooldowns.

Figure 1(a) shows the conductance at 25 mK vs a symmetric split-gate voltage, producing a parabolic confinement potential over a range of stepped top-gate voltages from 0 to -3.5 V in steps of -0.02 V, corresponding to decreasing the electron density in the channel. At $V_{tg} = 0$, the 1D channel is well-defined with conductance plateaus quantized at $G = n \times G_0$ with $G_0 = 2 \times (e^2/h)$ and n is an integer.[23] In Figs. 1(a) and 1(b), the structure forms a conductance plateau at value $0.2 \times (e^2/h)$ in addition to integer quantized plateaus when V_{tg} is changed from -3 to -3.4 V. As seen in Fig. 1(b), the $0.2 \times (e^2/h)$ structure stays constant to form a plateau despite an external V_{sg} changing by 20 mV. More detailed consideration shows that the conductance deviation of the $0.2 \times (e^2/h)$ structure is between 0.7% and 1.0%, which demonstrates that it is reasonably flat. Here, our results are consistent with previous reports[1,2] where zero-field fractions are observed at low carrier densities. As with the latter cases, fractional plateaus are found when the lateral confinement is weakened so allowing the electron–electron interactions to dominate and the electrons relax in the second dimension. We note that the existence of a conductance plateau indicates that the state is independent of the change in external potential so fitting the definition of a quantum state, i.e., is locked and independent of small changes in the potential environment.

Figure 2 shows the temperature dependence of the $0.2 \times (e^2/h)$ conductance structure measured at a fixed $V_{tg} = -3.4$ V with the temperature stabilized between 30 mK and $\sim$1.6 K in steps of 50 mK. Figure 2(b) is an expanded part of Fig. 2(a). Plateaus at integer multiples of G_0 show up as expected and the $0.2 \times (e^2/h)$ appears at 30 mK. With increasing T, however, the $0.2 \times (e^2/h)$ structure is observed to form a resonant shape at $\sim 0.2 \times (e^2/h)$ before rising at the highest temperatures eventually disappearing at 1.6 K. The transition between a plateau and resonant shape is predicted in Shavit and Oreg[8] and reproduced experimentally here. We point out that each trace has been repeated ten times at fixed temperature to check the reproducibility. We note an absence of any other structure below e^2/h indicating the absence of impurity scattering of disorder. The structure reported here is the only type which is observed.

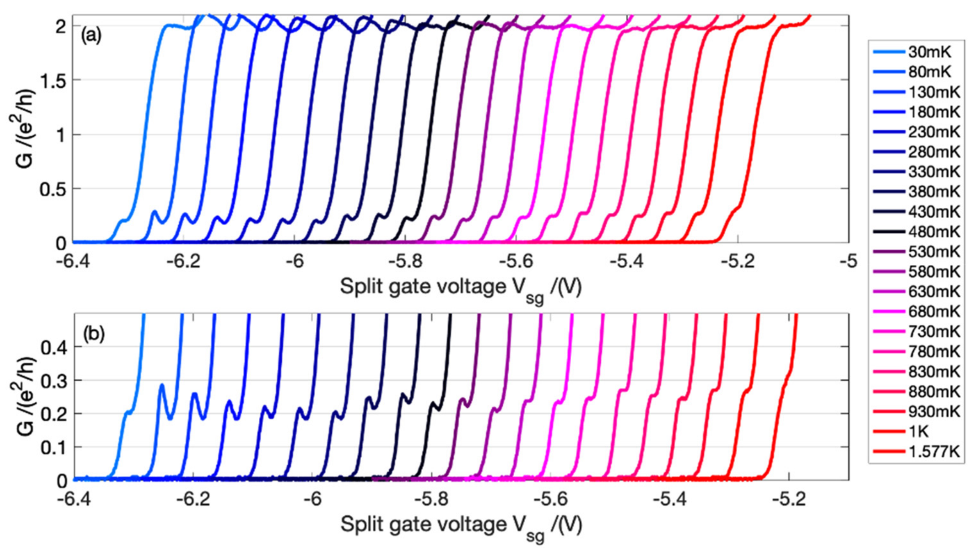

FIG. 2. (a) The conductance in units of e^2/h as a function of V_{sg} at fixed $V_{tg} = -3.4$ V against temperature (T) from 30 mK to $\sim$1.6 K. (b) Expanded figure of (a). The conductance traces have been shifted horizontally for clarity.

The role of disorder has also been investigated and is shown in Fig. 3(b). In this sample, there is clearly some disorder induced scattering as what should be a spin–split plateau at e^2/h has a distinct resonance line shape. In this plot, the carrier concentration, confinement, and asymmetry of confinement are reduced from right to left. It is seen that the $0.2 \times (e^2/h)$ structure is present initially with a resonant shape but as the asymmetry evolves to the right it increases in magnitude and changes shape to merge with the spontaneously spin–split state (e^2/h). However, as shown in Fig. 3(b), as the asymmetry increases at a low carrier concentration, the $0.2 \times (e^2/h)$ structure reappears and forms a plateau before climbing toward a higher conductance with no structure indicating the transition to 2D. The appearance of the 0.2 with a symmetric confinement potential and its disappearance and re-emergence with increasing asymmetry is a different form of behavior to that found in GaAs.[2] It is noteworthy that the fractional plateau is pulled out of the disorder at the weakest confinement and lowest carrier concentration.

To explore whether the spin–orbit interaction affects the formation of fractional states, an in-plane magnetic field was applied transverse to the current (i) direction [$B_\perp$, shown in Fig. 4(a)] and also parallel to i [$B_{//}$, shown in Fig. 4(b)]. In both measurements, G is measured as a function of V_{sg} at a fixed V_{tg} against stepped B in intervals of 0.1 T. The pinch-off voltage is different in Figs. 4(a) and 4(b) as the sample is measured during different cooldowns.

As shown in both Figs. 4(a) and 4(b), a conductance structure at $0.2 \times (e^2/h)$ appears at zero-magnetic field. Furthermore, as a result of the Zeeman effect, a spin-polarized state is shown in both figures as the conductance forms a plateau at e^2/h in high fields.[24] There is some disorder scattering present as seen by the shape of what should be quantized plateaus. The structure above e^2/h behaves in a similar way for both figures, though fractional structures below it are sensitive to the magnetic field direction and behave completely differently. As shown in Fig. 4(a) when $B_\perp$ is applied, the $0.2 \times (e^2/h)$ structure gradually vanishes when the magnetic field approaches 1T. However, the behavior is different when the field is parallel to the current direction. In Fig. 4(b), the $0.2 \times (e^2/h)$ structure is present at zero-magnetic field

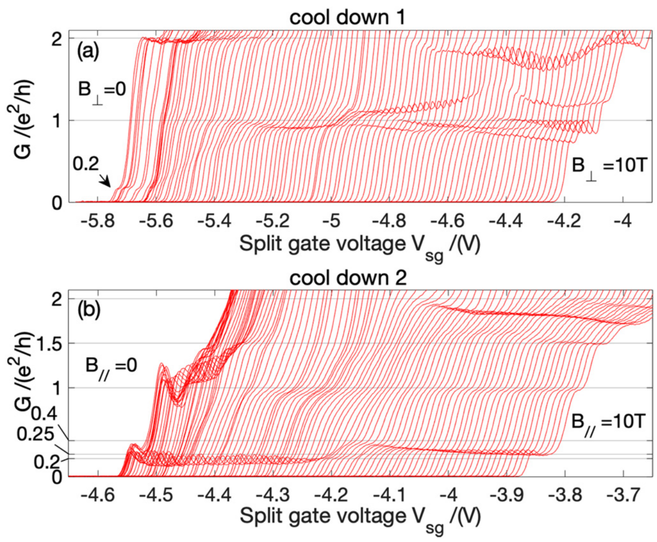

FIG. 4. (a) Conductance in units of e^2/h vs V_{sg} at fixed V_{tg}, the in-plane magnetic field (B), which is normal to the current direction ($B_\perp$) is stepped in intervals of 0.1 T (cooldown 1). (b) Similar to (a) but with the direction of magnetic field in-plane-parallel to the current. Here, $B_{//}$ is varied from 0 T (left) to 10 T (right) in steps of 0.1 T. For clarity, all traces in both figures have been shifted horizontally by 0.01 V.

although it forms a resonant peak rather than a plateau (deviation of the mean value is about 5%). When $B_{//}$ is increased from 0 to 6 T, the mean value of the peaks stays near $0.2 \times (e^2/h)$ with decreasing oscillatory amplitude. Increasing the field to 6.3 T, the conductance suddenly jumps to $0.4 \times (e^2/h)$, followed by a gradual decrease with increasing field until it eventually settles at $0.25 \times (e^2/h)$ at $B_{//} = 10$ T.

The differences between the two orientations of magnetic field point to the role of the Rashba spin–orbit interaction. As pointed out in Ref. 25, the electric field can come either from the confining 2D electric field, producing the heterostructure, or the 1D field arising from the split-gate voltage. However, in this instance, it is not essential to know the relative strengths to understand the phenomenon. The anisotropy of magnetic effects in 1D transport when the RSOI is operative has been explored in Refs. 25–27, where there is a lifting of the spin-degeneracy for perpendicular orientation and formation of a gap when parallel (schematic figure is given in Fig. 5). Hence, the backscattering process considered by Shavit and Oreg cannot operate for B perpendicular when only one spin level is occupied but is operative for B parallel. The field orientation dependence of the 0.2 feature agrees with this expectation of the theory.

The transition from a fraction of 0.2–0.4 fits the Shavit and Oreg formula $\frac{(n_1-n_2)^2}{n_1^2+n_2^2} \times (e^2/h)$ with a value of $0.2 \times (e^2/h)$ when the numbers of forward and backscattered electrons are $n_1 = 1$ and $n_2 = 2$. If this changes to $n_1 = 1$ and $n_2 = 3$, then the increase to $0.4 \times (e^2/h)$ follows. The subsequent decrease to 0.25 cannot be explained by this model and possibly points to a pairing which has been suggested can be a consequence of the RSOI[28] or found due to a repulsive potential.[29]

A similar phenomenon has been reported in Ge,[1] where a $0.25 \times (e^2/h)$ plateau is also observed when $B_{//} = 8$ T. However, the $0.25 \times (e^2/h)$ originated from a $0.5 \times (e^2/h)$ plateau at zero-field and was halved as a result of spin-polarization at a high field. Here, the electron spin starts to polarize at 4 T indicated by a clear quantized plateau at

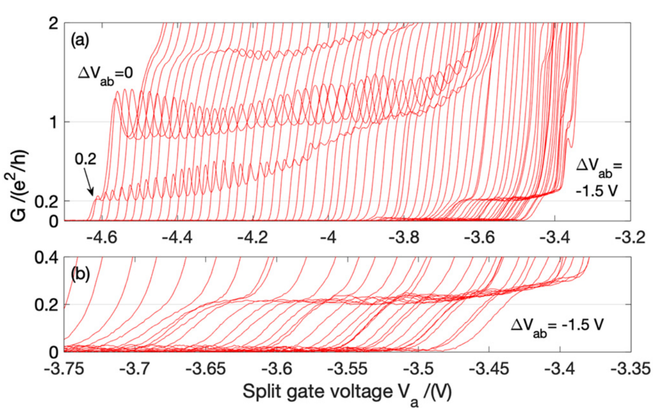

FIG. 3. (a) The conductance in units of e^2/h as a function of asymmetric split-gate voltage at fixed V_{tg}. The voltage difference between the split-gates (ΔV_{ab}) was incremented from 0 V (left) to -1.5 V (right) in steps of -0.02 V. (b) Expanded figure of (a) to give details on the $0.2 \times (e^2/h)$ plateau emerging at the lowest carrier concentrations. All traces have been shifted laterally by 0.01 V for clarity.

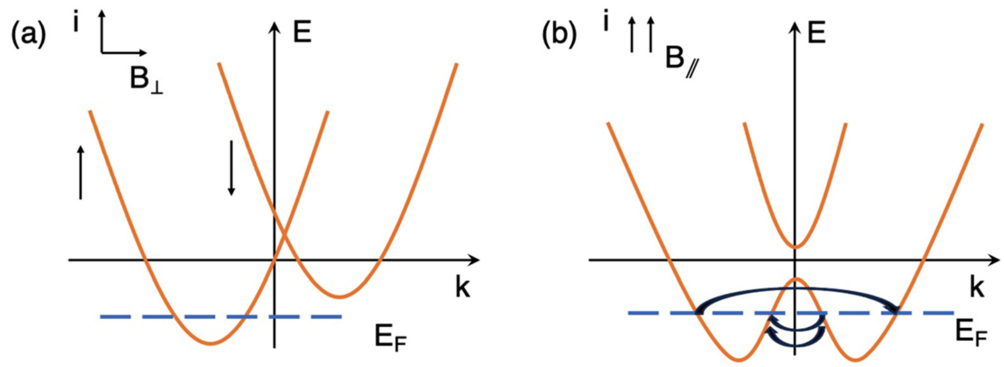

FIG. 5. A schematic figure of energy dispersion showing the effect of an in-plane (a) transverse ($B_\perp$) and (b) parallel ($B_{//}$) applied magnetic field on the spin-gap structure observed with weak RSOI coupling. The field direction is expressed compared to the direction of current (i). We also show the directions of scattering for parallel configuration. E_F indicates the Fermi energy.

e^2/h, and as shown in Fig. 4(b), the 0.2 $\times$ (e^2/h) structure is not affected by the lifting of spin-degeneracy and stays constant until 6 T. Therefore, it suggests that the fractional conductance quantized at 0.25 $\times$ (e^2/h) is already a spin-polarized state. Another possible explanation for the 0.25 $\times$ (e^2/h) state is fractional charge,[30] where such conductance value can be easily understood by substituting (1/2) $\times$ e for e.

A similar 0.2 $\times$ (e^2/h) structure has been observed in $LaAlO_3$/$SrTiO_3$-based 1D electron waveguides at zero magnetic field.[31,32] Both $LaAlO_3$/$SrTiO_3$ and InGaAs systems possess strong spin–orbit coupling, although the electron–electron interaction can be attractive in $LaAlO_3$/$SrTiO_3$ heterostructures, in the InGaAs systems, it is repulsive.

As a final comment, we point out that the 0.7 structure,[33] which was initially found some time ago and has been explored in depth is not related to the present findings. The 0.7 corresponds to 1.4 $\times$ (e^2/h) and its characteristic is that it declines to e^2/h in the presence of a magnetic field indicating the dependence on spin-polarization. Here, the structure is below e^2/h and does not show a decline with increasing magnetic field. The theory of Shavit and Oreg[8] has been quoted as this gives a good agreement with the discovered odd denominator fractions and alternatives are not available.

In summary, we have presented evidence for the existence of non-magnetic fractional quantization of conductance combined with the RSOI, which produces differences from the results found in materials with weak RSOI. The spin-dependent lateral displacement of the E–k relations produces the requisite band structure for coherent back scattering which is created by asymmetric confinement when the RSOI is absent. In addition, the orientation of a magnetic field produces markedly different effects on fractionalization. Increasing the strength of the 1D confinement will produce a range of different aspects of fractionalization, and this work illustrates the role of manipulation of the wavefunction, which can lead to a number of new physical phenomena.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Lei Liu: Data curation (equal); Formal analysis (equal); Investigation (equal); Writing – original draft (equal); Writing – review & editing (equal). **Yilmaz Gul:** Data curation (equal); Formal analysis (equal); Investigation (equal); Supervision (equal); Writing – review & editing (equal). **Stuart N. Holmes:** Investigation (equal); Writing – review & editing (equal). **Chong Chen:** Resources (equal). **Ian Farrer:** Resources (equal). **David A. Ritchie:** Resources (equal). **Michael Pepper:** Conceptualization (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Supervision (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.1063/5.0170273, Ref. 34.

REFERENCES

1. Y. Gul, S. N. Holmes, M. Myronov, S. Kumar, and M. Pepper, "Self-organised fractional quantisation in a hole quantum wire," J. Phys. **30**, 09LT01 (2018).
2. S. Kumar, M. Pepper, S. N. Holmes, H. Montagu, Y. Gul, D. A. Ritchie, and I. Farrer, "Zero-magnetic field fractional quantum states," Phys. Rev. Lett. **122**, 086803 (2019).
3. F. D. M. Haldane, "Model for a quantum Hall effect without Landau levels: Condensed-matter realization of the 'parity anomaly,'" Phys. Rev. Lett. **61**, 2015 (1988).
4. K. Sun, Z. Gu, H. Katsura, and S. D. Sarma, "Nearly flatbands with nontrivial topology," Phys. Rev. Lett. **106**, 236803 (2011).
5. E. Tang, J.-W. Mei, and X.-G. Wen, "High-temperature fractional quantum Hall states," Phys. Rev. Lett. **106**, 236802 (2011).
6. D. N. Sheng, Z.-C. Gu, K. Sun, and L. Sheng, "Fractional quantum Hall effect in the absence of Landau levels," Nat. Commun. **2**, 389 (2011).
7. T. Neupert, L. Santos, C. Chamon, and C. Mudry, "Fractional quantum Hall states at zero magnetic field," Phys. Rev. Lett. **106**, 236804 (2011).
8. G. Shavit and Y. Oreg, "Fractional conductance in strongly interacting 1D systems," Phys. Rev. Lett. **123**, 036803 (2019).
9. Y. A. Bychkov and É. I. Rashba, "Properties of a 2D electron gas with lifted spectral degeneracy," JETP Lett. **39**(2), 78 (1984).
10. E. A. de Andrada e Silva, G. C. La Rocca, and F. Bassani, "Spin-split subbands and magneto-oscillations in III-V asymmetric heterostructures," Phys. Rev. B **50**, 8523 (1994).

[11]E. A. de Andrada e Silva, G. C. La Rocca, and F. Bassani, "Spin-orbit splitting of electronic states in semiconductor asymmetric quantum wells," Phys. Rev. B **55**, 16293 (1997).
[12]P. Debray, S. M. S. Rahman, J. Wan, R. S. Newrock, M. Cahay, A. T. Ngo, S. E. Ulloa, S. T. Herbert, M. Muhammad, and M. Johnson, "All-electric quantum point contact spin-polarizer," Nat. Nanotechnol. **4**, 759 (2009).
[13]D. Bercioux and P. Lucignano, "Quantum transport in Rashba spin–orbit materials: A review," Rep. Prog. Phys. **78**, 106001 (2015).
[14]A. Manchon, H. C. Koo, J. Nitta, S. M. Frolov, and R. A. Duine, "New perspectives for Rashba spin–orbit coupling," Nat. Mater. **14**, 871 (2015).
[15]K. Premasiri and X. P. A. Gao, "Tuning spin–orbit coupling in 2D materials for spintronics: A topical review," J. Phys.: Condens. Matter **31**(19), 193001 (2019).
[16]S. N. Holmes, P. J. Simmonds, H. E. Beere, F. Sfigakis, I. Farrer, D. A. Ritchie, and M. Pepper, "Bychkov–Rashba dominated band structure in an $In_{0.75}Ga_{0.25}As$–$In_{0.75}Al_{0.25}As$ device with spin-split carrier densities of $<10^{11}$ cm^{-2}," J. Phys.: Condens. Matter **20**(47), 472207 (2008).
[17]W. Desrat, F. Giazotto, V. Pellegrini, F. Beltram, F. Capotondi, G. Biasiol, L. Sorba, and D. K. Maude, "Magnetotransport in high-g-factor low-density two-dimensional electron systems confined in $In_{0.75}Ga_{0.25}As/In_{0.75}Al_{0.25}As$ quantum wells," Phys. Rev. B **69**, 245324 (2004).
[18]M. J. Snelling, G. P. Flinn, A. S. Plaut, R. T. Harley, A. C. Tropper, R. Eccleston, and C. C. Phillips, "Magnetic g factor of electrons in $GaAs/Al_xGa_{1-x}As$ quantum wells," Phys. Rev. B **44**, 11345 (1991).
[19]C. Weisbuch and C. Hermann, "Optical detection of conduction-electron spin resonance in GaAs, $Ga_{1-x}In_xAs$, and $Ga_{1-x}Al_xAs$," Phys. Rev. B **15**, 816 (1977).
[20]F. Capotondi, G. Biasiol, I. Vobornik, L. Sorba, F. Giazotto, A. Cavallini, and B. Fraboni, "Two-dimensional electron gas formation in undoped $In_{0.75}Ga_{0.25}As/In_{0.75}Al_{0.25}As$ quantum wells," J. Vac. Sci. Technol. B **22**, 702 (2004).
[21]P. J. Simmonds, S. N. Holmes, H. E. Beere, I. Farrer, F. Sfigakis, D. A. Ritchie, and M. Pepper, "Molecular beam epitaxy of high mobility $In_{0.75}Ga_{0.25}As$ for electron spin transport applications," J. Vac. Sci. Technol. B **27**, 2066 (2009).
[22]C. Chen, I. Farrer, S. N. Holmes, F. Sfigakis, M. P. Fletcher, H. E. Beere, and D. A. Ritchie, "Growth variations and scattering mechanisms in metamorphic $In_{0.75}Ga_{0.25}As/In_{0.75}Al_{0.25}As$ quantum wells grown by molecular beam epitaxy," J. Cryst. Growth **425**, 70 (2015).
[23]Y. Gul, G. L. Creeth, D. English, S. N. Holmes, K. J. Thomas, I. Farrer, D. J. Ellis, D. A. Ritchie, and M. Pepper, "Conductance quantisation in patterned gate $In_{0.75}Ga_{0.25}As$ structures up to $6\times(2e^2/h)$," J. Phys. **31**, 104002 (2019).
[24]N. K. Patel, J. T. Nicholls, L. Martin-Moreno, M. Pepper, J. E. F. Frost, D. A. Ritchie, and G. A. C. Jones, "Properties of a ballistic quasi-one dimensional constriction in a parallel high magnetic field," Phys. Rev. B **44**, 10973 (1991).
[25]A. V. Moroz and C. H. Barnes, "Effect of the spin-orbit interaction on the band structure and conductance of quasi-one-dimensional systems," Phys. Rev. B **60**, 14272 (1999).
[26]Y. V. Pershin, J. A. Nesteroff, and V. Privman, "Effect of spin-orbit interaction and in-plane magnetic field on the conductance of a quasi-one dimensional system," Phys. Rev. B **69**, 121306 (2004).
[27]C. H. L. Quay, T. L. Hughes, J. A. Sulpizio, L. N. Pfeiffer, K. W. Baldwin, K. W. West, D. Goldhaber-Gordon, and R. De Picciotto, "Observation of a one-dimensional spin–orbit gap in a quantum wire," Nat. Phys. **6**, 336 (2010).
[28]F. Damanet, E. Mansfield, M. Briggeman, P. Irvin, J. Levy, and A. J. Daley, "Spin-orbit-assisted electron pairing in one-dimensional waveguides," Phys. Rev. B **104**, 125103 (2021).
[29]G. Shavit and Y. Oreg, "Electron pairing induced by repulsive interactions in tunable one-dimensional platforms," Phys. Rev. Res. **2**, 043283 (2020).
[30]R. B. Laughlin, "Anomalous quantum Hall effect: An incompressible quantum fluid with fractionally charged excitations," Phys. Rev. Lett. **50**, 1395 (1983).
[31]M. Briggeman, J. Li, M. Huang, H. Lee, J.-W. Lee, K. Eom, C.-B. Eom, P. Irvin, and J. Levy, "Engineered spin-orbit interactions in $LaAlO_3/SrTiO_3$-based 1D serpentine electron waveguides," Sci. Adv. **6**, eaba6337 (2020).
[32]G. Shavit and Y. Oreg, "Modulation induced transport signatures in correlated electron waveguides," SciPost Phys. **9**, 051 (2020).
[33]K. J. Thomas, J. T. Nicholls, M. Y. Simmons, M. Pepper, D. R. Mace, and D. A. Ritchie, "Possible spin polarization in a one-dimensional electron gas," Phys. Rev. Lett. **77**, 135 (1996).
[34]L. Liu (2023). "Possible zero-magnetic field fractional quantization in $In_{0.75}Ga_{0.25}As$ heterostructures," Zenodo. https://zenodo.org/10.1063/5.0170273