Quantum transport in high-quality shallow InSb quantum wells

Zijin Lei, Christian A. Lehner, Erik Cheah, Matija Karalic, Christopher Mittag, Luca Alt, Jan Scharnetzky, Werner Wegscheider, Thomas Ihn, and Klaus Ensslin

ARTICLES YOU MAY BE INTERESTED IN

Electric-field-induced two-dimensional hole gas in undoped GaSb quantum wells
Applied Physics Letters 114, 232102 (2019); https://doi.org/10.1063/1.5093133

Thermoelectrically cooled THz quantum cascade laser operating up to 210 K
Applied Physics Letters 115, 010601 (2019); https://doi.org/10.1063/1.5110305

Bright electroluminescence in ambient conditions from WSe2 p-n diodes using pulsed injection
Applied Physics Letters 115, 011103 (2019); https://doi.org/10.1063/1.5100306
Quantum transport in high-quality shallow InSb quantum wells

Cite as: Appl. Phys. Lett. 115, 012101 (2019); doi: 10.1063/1.5098294
Submitted: 1 April 2019 · Accepted: 17 June 2019 · Published Online: 1 July 2019

Zijin Lei, a),b) Christian A. Lehner, a) Erik Cheah, Matija Karalic, Christopher Mittag, Luca Alt, Jan Scharnetzky, Werner Wegscheider, Thomas Ihn, and Klaus Ensslin

AFFILIATIONS
Solid State Physics Laboratory, Department of Physics, ETH Zurich, 8093 Zurich, Switzerland

a) Contributions: Z. Lei and C. A. Lehner contributed equally to this work.
b) Electronic mail: zilei@phys.ethz.ch

ABSTRACT

InSb is one of the promising candidates to realize a topological state through proximity induced superconductivity in a material with strong spin–orbit interactions. In two-dimensional systems, thin barriers are needed to allow strong coupling between superconductors and semiconductors. However, it is still challenging to obtain a high-quality InSb two-dimensional electron gas in quantum wells close to the surface. Here, we report on a molecular beam epitaxy grown heterostructure of InSb quantum wells with substrate-side Si-doping and ultrathin InAlSb (5 nm, 25 nm, and 50 nm) barriers to the surface. We demonstrate that the carrier densities in these quantum wells are gate-tunable and electron mobilities up to 350,000 cm²(V s)⁻¹ are obtained from magnetotransport measurements. Furthermore, from temperature-dependent magnetoresistance measurements, we obtain an effective mass of 0.02 m₀ and find Zeeman splitting compatible with the expected band edge g-factor.

InSb elicits special interest in electronic, 1,2 electro-optical, 3 and spintronic 4 applications due to its unique and extreme properties compared to other binary III-V compound semiconductors. Apart from the small bandgap and electron effective mass, InSb is considered a candidate for the fabrication of topological quantum devices owing to its strong Rashba spin–orbit interaction (SOI) 5–7 and its intrinsic giant band edge g-factor (|g| ≈ 51). 8 As proposed by Oreg et al., 10 a topological superconducting phase can be induced in a one-dimensional semiconductor with strong Rashba SOI in a Zeeman field by the coupling to an s-wave superconductor. Reports in this regard have been published for InAs 1 and InSb 11 nanowire-based Majorana devices. In contrast to nanowires, two-dimensional electron gas (2DEG) systems are far more versatile for topological applications. Various types of scalable superconductor-semiconductor hybrid devices have been proposed, 13–15 and experimental research in Al-InAs heterostructures 16–18 has hence followed. However, despite the superior intrinsic material properties, the progress of InSb 2DEGs is still hampered. Recently, there has been development in free-standing InSb nanostructures and their transport measurements, such as nanosails 19 and nanosheets. 20–22 These layered InSb structures have advantages to achieve direct metal/superconductor contacts on them. Nevertheless, the research on InSb quantum wells (QWs) is still lacking due to the difficulties with heterostructure growth although QWs have significant potential leading to high-quality devices. 23,24 In QW systems, a thin barrier is required to induce superconductivity in the 2DEG through the proximity effect. However, the closeness of the 2DEG to the surface can limit the mobility of the carriers as a consequence. In this work, we present a quantum transport experiment, where the InSb 2DEG is close to the sample surface. Our magnetotransport measurements show that the 2DEGs still preserve a high mobility, even for the case of a QW with a barrier to the surface of only 5 nm. We also investigate other unique characteristics of InSb, such as the light electron effective mass ² and the large band edge g-factor.

We report the fabrication and characterization of three InSb QW samples doped on the substrate side, which are grown on (100) GaAs substrates by molecular beam epitaxy (MBE). Two schematic layer sequences are shown in Figs. 1(a) and 1(b). The growth details introduced in Ref. 25 are only briefly outlined here. To overcome the lattice mismatch between GaAs and InSb, an interfacial misfit GaSb buffer and an interlayer InAlSb buffer are employed. The total thickness of this buffer system amounts to roughly 3 µm. The 21 nm-thin InSb QWs are then surrounded by In₀.₉Al₀.₁Sb confinement barriers, while n-type carriers are introduced to the active region by a Si δ-doping layer incorporated 30 nm below the QW in the barrier on the substrate...
Using wet chemical etching, standard Hall bar structures are defined with etch depth higher than 120 nm, which is thus deeper than the Si-doping layer. Hall bar samples 1 and 2 have lateral dimensions of $50 \times 25 \, \mu m^2$ (contact separation$\times$width), while sample 3 is $10 \times 4 \, \mu m^2$ in size. Layers of GeNi/Au evaporated on the contact areas of the samples after an Ar sputtering process provide Ohmic contacts to the 2DEG without the necessity of annealing.26 The samples are coated with a 40 nm-thick aluminum oxide (ALO) dielectric layer using atomic layer deposition at a temperature of 150°C. Finally, Ti/Au top gates covering the Hall bars are evaporated using electron beam evaporation. As a comparison, van der Pauw geometry samples without chemical etching and ALO are fabricated from the same wafers of the Hall bar samples. Their magnetotransport measurement is introduced in the supplementary material.

Magnetotransport characterization is performed using standard low frequency (12 Hz) lock-in techniques at a temperature of 1.3 K. Figures 1(c) and 1(d) show the dependence of the longitudinal and transverse resistivities $\rho_{xx}$ and $\rho_{xy}$ of samples 1 and 2 in a magnetic field $B$ applied normal to the QW plane, where the top gate voltages $V_{TG}$ are 0.8 V and 0.4 V, respectively. Shubnikov-de Haas oscillations in $\rho_{xx}$ and plateaus in $\rho_{xy}$ can be seen. In addition, the positive magnetoresistance and the nonlinear Hall resistance found in both samples at fields below about 4 T imply the existence of parallel conducting channels with distinct mobilities. Thus, the plateaus in $\rho_{xy}$ are not quantized at the expected values of the single-subband quantum Hall effect. The origin of the parallel channels is discussed below.

In the following, we describe the properties of sample 2 in detail, as it comprises the thinnest barrier. It is, therefore, most interesting with regard to a superconducting proximity effect induced by a superconducting contact. The details of samples 1 and 3 are given in the supplementary material. Figures 2(a) and 2(b) show $\rho_{xx}$ and $\rho_{xy}$ for sample 2 as a function of the top gate voltage $V_{TG}$ and the magnetic field $B$, respectively. Figure 2(a) shows two Landau fan diagrams, the first of which appears at low $V_{TG}$ and is marked with blue dashed lines, while the second Landau fan diagram at high $V_{TG}$ is marked with white dashed lines. The double-fan structure confirms the presence of two parallel conducting channels in the heterostructure. We extract their carrier densities $n_1$ and $n_2$ from the $1/B$ periodicity of the SDH oscillations. As shown in Fig. 3(a), at lower $V_{TG}$, only the first channel is populated and the density $n_1$ increases linearly with increasing $V_{TG}$. When $V_{TG} > -0.1$ V, the increase in $n_1$ saturates, while the second channel gets populated and $n_2$ increases linearly instead. The gate capacitances of the first and second channels are estimated to be $C_1 = 0.7$ mF/m$^2$ and $C_2 = 1.02$ mF/m$^2$, respectively. We attribute $n_1$ to carriers in the Si-doping layer and $n_2$ to carriers in the QW. The calculated capacitances are within a factor of two of what is expected by considering the layer thicknesses and dielectric constants. The saturation of $n_1$ is due to screening of the gate electric field by the electrons populating the QW.

A two-band Drude model allows us to estimate the mobilities $\mu_1$ and $\mu_2$ of Si and the QW layer electrons. Using $n_1$ and $n_2$ obtained from the SDH oscillations, only the two mobilities remain as fitting parameters. As shown in Fig. 3(b), the mobility $\mu_2$ increases with the increase in $V_{TG}$. The inset of Fig. 3(b) shows data (circles) and fitted curves (lines) of the low field $\rho_{xx}$ and $\rho_{xy}$ of sample 2 at a gate voltage of $V_{TG} = 0.4$ V in a small magnetic field range. With $n_1 = 3 \times 10^{15}$ m$^{-2}$ and $n_2 = 3 \times 10^{15}$ m$^{-2}$, we find that mobilities are $\mu_1 = 7500$ cm$^2$ (V s)$^{-1}$.
and $\mu_2 = 67,000 \text{ cm}^2/(\text{V s})^{-1}$, respectively. Phenomenologically, samples 1 and 3 behave similarly, and their densities and mobilities are listed in Table I. Specifically, compared to previous related publications, $^5,9,23,24,27–30$ sample 1 still holds similar or higher mobility of the 2DEG with a comparable or thinner barrier thickness.

From temperature-dependent SdH oscillations, it is found that the effective mass of the electrons in the InSb QWs can be determined. Figure 4(a) shows the corresponding measurements for sample 2 with $n_2 = 3.8 \times 10^{15} \text{ m}^{-2}$ determined from the $1/B$-periodicity. The oscillations of the resistivity $\Delta \rho_{\text{xx}}$ are obtained by subtracting the smooth background of the magnetoresistance $\rho_{\text{xx}}$. $^31$ Figure 4(b) shows fits of the Dingle factor $^{25}$ to $\ln (\rho_{\text{xx}} / \rho_{\text{xx}}(T))$. The obtained effective mass is $m^* \approx 0.019 \, m_e$, where $m_e$ is the electron mass in vacuum. Using the same method, we find that the effective mass is density-independent within the range between $1.8 \times 10^{15} \text{ m}^{-2}$ and $3.8 \times 10^{15} \text{ m}^{-2}$. This result is consistent with the recent work of Ke et al. $^{24}$

The spin-splitting of Landau levels is observed at a magnetic field of 2 T, as shown in the inset of Fig. 4(a). With increasing $B$, the integer filling factor sequence changes from even to even and odd numbers. The magnetic field value beyond which the spin-splitting is resolved in the experiment is consistent with the band edge g-factor values determined in similar InSb QWs $^{25}$ and the works in InSb nanoconstrictions. $^8,24,33,34$ A very rough estimate of the band edge g-factor for our device is found in the supplementary material.

In summary, we have presented an InSb QW heterostructure with inverted doping and ultrathin InAlSb barriers to the sample surface. Using a standard Hall bar geometry, we performed magneto-transport measurements and found that the InSb QWs still show tunable densities and high mobilities, despite the small barrier thickness. The parallel conducting channel induced by the Si doping found in FIG. 2. The detailed transport characterization of sample 2 at 1.3 K with $\rho_{\text{xx}}$ (a) and $\rho_{\text{xy}}$ (b) as functions of $V_{\text{TG}}$ and $B$. The Landau fan diagrams and filling factors of the electrons in the doping layer and QW layer are labeled with blue and white dashed lines, respectively.

FIG. 3. Analysis of the data shown in Fig. 2. (a) Carrier densities of the two conductive channels vs $V_{\text{TG}}$. (b) The mobility $\mu_2$ extracted from the two-band model vs $V_{\text{TG}}$. Inset: the data (circles) and fitting (lines) of $\rho_{\text{xx}}$ (red) and $\rho_{\text{xy}}$ (blue) vs $B$ when $V_{\text{TG}} = 0.4 \text{ V}$.

The spin-splitting of Landau levels is observed at a magnetic field of 2 T, as shown in the inset of Fig. 4(a). With increasing $B$, the integer filling factor sequence changes from even to even and odd numbers. The magnetic field value beyond which the spin-splitting is resolved in the experiment is consistent with the band edge g-factor values determined in similar InSb QWs $^{25}$ and the works in InSb nanoconstrictions. $^8,24,33,34$ A very rough estimate of the band edge g-factor for our device is found in the supplementary material.

In summary, we have presented an InSb QW heterostructure with inverted doping and ultrathin InAlSb barriers to the sample surface. Using a standard Hall bar geometry, we performed magneto-transport measurements and found that the InSb QWs still show tunable densities and high mobilities, despite the small barrier thickness. The parallel conducting channel induced by the Si doping found in the supplementary material.

### Table I

| Properties       | Sample 1 | Sample 2 | Sample 3 |
|------------------|----------|----------|----------|
| Upper barrier thickness | 50 nm    | 5 nm     | 25 nm    |
| $\mu_2(\text{max})$ [cm$^2/(\text{V s})^{-1}$] | 350,000  | 67,000  | 160,000  |
| $n_2$ [x $10^{15}$ m$^{-2}$] | 0–3.5    | 0–3     | 0–3     |
| $m^*$ | 0.020 $m_0$ | 0.019 ± 0.02 $m_0$ | ... |

The spin-splitting of Landau levels is observed at a magnetic field of 2 T, as shown in the inset of Fig. 4(a). With increasing $B$, the integer filling factor sequence changes from even to even and odd numbers. The magnetic field value beyond which the spin-splitting is resolved in the experiment is consistent with the band edge g-factor values determined in similar InSb QWs $^{25}$ and the works in InSb nanoconstrictions. $^8,24,33,34$ A very rough estimate of the band edge g-factor for our device is found in the supplementary material.

In summary, we have presented an InSb QW heterostructure with inverted doping and ultrathin InAlSb barriers to the sample surface. Using a standard Hall bar geometry, we performed magneto-transport measurements and found that the InSb QWs still show tunable densities and high mobilities, despite the small barrier thickness. The parallel conducting channel induced by the Si doping found in the supplementary material.
the investigated samples can be eliminated by reducing the doping concentration in future devices. We determined the effective in-plane mass of electrons in the InSb QWs to be $0.019 m_0$, with a carrier concentration in future devices. We determined the effective in-plane mass of electrons in the InSb QWs to be $0.019 m_0$, with a carrier concentration in future devices.

See the supplementary material for the band edge g-factor estimation, the self-consistent band structure simulation, and the magnetotransport measurements of sample 1, sample 3, and the van der Pauw geometry samples.

This work was supported by the Swiss National Science Foundation through the National Center of Competence in Research (NCCR) Quantum Science and Technology.

REFERENCES

1. T. Ashley, A. Dean, C. Elliott, G. Pryce, A. Johnson, and H. Willis, "Uncooled high-speed InSb field-effect transistors," Appl. Phys. Lett. 66, 481–483 (1995).

2. J. Ott, P. Buckle, M. Fearn, C. Storey, L. Buckle, and T. Ashley, "A surface-gated InSb quantum well single electron transistor," New J. Phys. 9, 261 (2007).

3. H. Chen, J. Heremans, J. Peters, A. Govorov, N. Goel, S. Chung, and M. Santos, "Spin-polarized reflection in a two-dimensional electron system," Appl. Phys. Lett. 86, 032113 (2005).

4. Ł. Zuziś, J. Fabian, and S. D. Sarma, "Spintronics: Fundamentals and applications," Rev. Mod. Phys. 76, 323 (2004).

5. M. Leontiadou, K. Litvinenko, A. Gilbertson, C. Pidgeon, W. Branford, L. Cohen, M. Fearn, T. Ashley, M. Emeny, B. Muldin et al., "Experimental determination of the Rashba coefficient in InSb/InAlSb quantum wells at zero magnetic field and elevated temperatures," J. Phys.: Condens. Matter 23, 035801 (2011).

6. R. Kallaher, J. Heremans, N. Goel, S. Chung, and M. Santos, "Spin–orbit interaction determined by antilocalization in an InSb quantum well," Phys. Rev. B 81, 075303 (2010).

7. G. Khodaparast, R. Doeezema, S. Chung, K. Goldammer, and M. Santos, "Spectroscopy of Rashba spin splitting in InSb quantum wells," Phys. Rev. B 70, 155322 (2004).

8. P. Qin, J. van Veen, F. K. de Vries, A. J. Beukman, M. Wimmer, W. Yi, A. A. Kiselev, B.-M. Nguyen, M. Sokolich, M. J. Manfra et al., "Quantized conductance and large g-factor anisotropy in InSb quantum point contacts," Nano Lett. 16, 7509–7513 (2016).

9. A. Gilbertson, W. Branford, M. Fearn, L. Buckle, P. D. Buckle, T. Ashley, and L. Cohen, "Zero-field spin splitting and spin-dependent broadening in high-mobility InSb/InAlSb asymmetric quantum well heterostructures," Phys. Rev. B 79, 235333 (2009).

10. Y. Oreg, G. Refael, and F. von Oppen, "Helical liquids and Majorana bound states in quantum wires," Phys. Rev. Lett. 105, 177002 (2010).

11. M. Deng, S. Vaitiekunas, E. B. Hansen, J. Danon, M. Leijnse, K. Flensberg, J. Nygård, P. Krosgstrup, and C. M. Marcus, "Majorana bound state in a coupled quantum-dot hybrid-nanowire system," Science 354, 1557–1562 (2016).

12. H. Zhang, C.-X. Liu, S. Gazibegovic, D. Xu, J. A. Logan, G. Wang, N. Van Loo, J. D. Bommer, M. W. De Moor, D. Car et al., "Quantized Majorana conductance," Nature 556, 74 (2018).

13. B. P. Røver, M. Houzet, J. S. Meyer, and Y. V. Nazarov, "Multi-terminal Josephson junctions as topological matter," Nat. Commun. 7, 11167 (2016).

14. A. Stern and E. Berg, "Fractional Josephson vortexes and braiding of Majorana zero modes in planar superconductor-semiconductor heterostructures," Phys. Rev. Lett. 122, 107701 (2019).

15. Y. Peng, F. Pienikia, E. Berg, Y. Oreg, and F. von Oppen, "Signatures of topological Josephson junctions," Phys. Rev. B 94, 085404 (2016).

16. H. J. Suominen, M. Kjaergaard, A. R. Hamilton, J. Shabani, C. J. Palmstroem, C. M. Marcus, and F. Nichele, "Zero-energy modes from coalescing Andreev states in quantum wires," Phys. Rev. Lett. 119, 176805 (2017).

17. A. Fornieri, A. M. Whiticar, F. Setiawan, E. B. Hansen, J. Danon, M. Leijnse, K. Flensberg, J. Nygård, P. Krosgstrup, and C. M. Marcus, "Majorana bound state in a coupled quantum-dot hybrid-nanowire system," Science 354, 1557–1562 (2016).

18. A. Whiticar, A. Fornieri, E. O’Farrell, A. Drachmann, W. Thomas, S. Gronin, R. Kallaher et al., "Evidence of topological superconductivity in planar Josephson junctions," Nature 569, 1 (2019).

19. A. Whiticar, A. Fornieri, E. O’Farrell, A. Drachmann, W. Thomas, S. Gronin, R. Kallaher, G. Gardner, M. Manfra et al., "Interferometry and coherent single-electron transport through hybrid superconductor-superconductor Coulomb islands," preprint arXiv:1902.07085 (2019).

20. R. de la Mata, R. Leturcq, S. R. Plissard, C. Rolland, C. Magen, J. Arbiol, and P. Caroff, "Twin-induced InSb nanosails: A convenient high mobility quantum dot single-electron transport through hybrid superconductor-semiconductor platforms," Nano Lett. 18, 43 (2018).

21. D. Pan, D. Fan, N. Kang, J. Zhi, X. Yu, H. Xu, and J. Zhao, "Free-standing two-dimensional single-crystalline InSb nanosheets," Nano Lett. 16, 834–841 (2016).

22. N. Kang, D. Fan, J. Zhi, D. Pan, S. Li, C. Wang, J. Guo, J. Zhao, and H. Xu, "Two-dimensional quantum transport in free-standing InSb nanosheets," Nano Lett. 19, 561–569 (2019).

23. J. Xue, Y. Chen, D. Pan, J.-Y. Wang, J. Zhao, S. Huang, and H. Xu, "Gate defined quantum dot realized in a single crystalline InSb nanosheet," Appl. Phys. Lett. 114, 023108 (2019).

24. W. Yi, A. A. Kiselev, J. Thorp, R. Noah, B.-M. Nguyen, S. Bui, R. D. Rajavel, T. Hussain, M. F. Gyure, P. Kratz et al., "Gate-tunable high mobility remote-
doped InSb/In$_{1-x}$Al$_x$Sb quantum well heterostructures,” Appl. Phys. Lett. 106, 142103 (2015).

24. C. T. Ke, C. M. Moehle, F. K. de Vries, C. Thomas, S. Metti, C. R. Guinn, R. Kallaher, M. Lodari, G. Scappucci, T. Wang et al., “Ballistic superconductivity and tunable $\pi$-junctions in InSb quantum wells,” preprint arXiv:1902.10742 (2019).

25. C. A. Lehner, T. Tschirky, T. Ihn, W. Dietsche, J. Keller, S. Fält, and W. Wegscheider, “Limiting scattering processes in high-mobility InSb quantum wells grown on GaSb buffer systems,” Phys. Rev. Mater. 2, 054601 (2018).

26. N. Goel, J. Graham, J. Keay, K. Suzuki, S. Miyashita, M. Santos, and Y. Hirayama, “Ballistic transport in InSb mesoscopic structures,” Physica E 26, 455–459 (2005).

27. O. Pooley, A. Gilbertson, P. Buckle, R. Hall, M. Emeny, M. Fearn, M. Halsall, L. Cohen, and T. Ashley, “Quantum well mobility and the effect of gate dielectrics in remote doped InSb/Al$_x$In$_{1-x}$Sb heterostructures,” Semicond. Sci. Technol. 25, 125005 (2010).

28. F. Gouider, Y. B. Vasilyev, M. Bugár, J. Könemann, P. Buckle, and G. Nachtwei, “Terahertz photoresponse of AlInSb/InSb/AlInSb quantum well structures,” Phys. Rev. B 81, 155304 (2010).

29. M. Uddin, H. Liu, K. Yang, K. Nagase, T. Mishima, M. Santos, and Y. Hirayama, “Characterization of InSb quantum wells with atomic layer deposited gate dielectrics,” Appl. Phys. Lett. 101, 233503 (2012).

30. J. Mlack, K. Wickramasinghe, T. Mishima, M. Santos, and C. Marcus, “In-plane magnetocconductance mapping of InSb quantum wells,” preprint arXiv:1902.07570 (2019).

31. B. Habib, M. Shayegan, and R. Winkler, “Spin-orbit interaction and transport in GaAs two-dimensional holes,” Semicond. Sci. Technol. 23, 064002 (2009).

32. T. Ihn, Semiconductor Nanostructures: Quantum States and Electronic Transport (Oxford University Press, 2010).

33. H. A. Nilsson, P. Caroff, C. Thelander, M. Larsson, J. B. Wagner, L.-E. Wernersson, L. Samuelson, and H. Xu, “Giant, level-dependent g factors in InSb nanowire quantum dots,” Nano Lett. 9, 3151–3156 (2009).

34. H. Nilsson, O. Karlström, M. Larsson, P. Caroff, J. N. Pedersen, L. Samuelson, A. Wacker, L.-E. Wernersson, and H. Xu, “Correlation-induced conductance suppression at level degeneracy in a quantum dot,” Phys. Rev. Lett. 104, 186804 (2010).