

Magnetocapacitance signatures of electrons and holes in InAs/GaSb quantum wells separated by an AlSb barrier

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We observed magnetocapacitance oscillations in InAs/GaSb quantum wells separated by a 20 nm AlSb middle barrier. By realizing independent ohmic contacts for electrons in InAs and holes in the GaSb layer, we found an out-of-plane oscillatory response in capacitance representing the density of states of this system. We were able to tune the charge carrier densities by applying a DC bias voltage, identifying the formation of beating signatures for forward bias. The coexistence of two distinguishable two-dimensional (2D) charge carrier systems of unequal densities was verified. By developing a theory to describe the magnetocapacitance response of the system, we were able to validate that we have an electron-hole bilayer system. The Landau phase diagram presents distinct features originating from the bilayer channel with the additional presence of a 2D electron system at the surface of the InAs layer.

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I. INTRODUCTION

The inverted band alignment present in InAs/GaSb quantum wells (QWs) provide a rich platform to investigate bulk and edge state properties [1–9]. Tunable via electric field, the properties of confined electrons and holes in the InAs/GaSb QWs have been studied in the past years [1,10–14]. Arising from the band inversion for corresponding QW layer thicknesses, the predicted quantum spin Hall effect insulators (QSHIs) [15–20], known as two dimensional topological insulators (2DTI), have been demonstrated [16,17]. The interlayer tunability is achieved by means of gate control, which offers the possibility of transitioning from a non trivial TI semimetal towards a conventional semiconductor [21–23].

Given the inverted band alignment, the lowest conduction band (CB) energy level for electrons in InAs is spatially separated from and lies below the highest valence band (VB) hole states in GaSb. Adding an AlSb barrier in between InAs and GaSb layers, this unique arrangement offers the chance to investigate the tunability and coupling of 2D electron-hole correlated systems, depending on the thickness of the AlSb layer separating them [24–26]. This scenario opens the opportunity to create a bound excitonic state with overlapping wave functions along the interface of InAs and GaSb with the AlSb barrier, enabling the potential Bose-Einstein condensation [4,27–29]. Due to the insulating barrier, this device geometry with broken band gap can be associated with a plate

capacitor, where each plate is charged with electrons and holes separately. In addition, the inserted middle AlSb barrier offers the possibility of tuning the coupling of both charge carrier types and, as a consequence tailoring the hybridization gap.

In this work, we realize magnetocapacitance investigations in such a InAs/GaSb system separated by a 20 nm AlSb insulating barrier. In contrast to previous in-plane Shubnikov-deHaas (SdH) transport, we introduce an out-of-plane measurement technique. By employing independent ohmic contacts to each channel, we obtain a capacitive response, revealing an unconventional Landau phase diagram with tunable densities modulated by a DC bias voltage. The existence of two distinct charge carrier systems was experimentally confirmed in addition to the presence of a surface 2D electron system in the InAs layer. Our measured capacitance is in good agreement with the values theoretically expected for an electron-hole bilayer system.

II. EXPERIMENTAL APPROACH

We consider a symmetric heterostructure constituted of 50 nm of InAs and GaSb quantum wells, separated by a 20 nm AlSb barrier, grown by molecular beam epitaxy in the (001) crystal orientation, using an undoped GaSb substrate, as displayed on the left panel of Fig. 1. For further growth details, please refer to the Supplemental Material [30].

A lamella film was prepared via the focused ion beam (FIB) method. Scanning transmission electron microscopy (STEM) images taken at different magnifications are displayed in the middle and right panel of Fig. 1. In the center, we see an overview image covering the whole layer stack corresponding to the left most panel enclosing the InAs surface toward the beginning of the buffer layer. In the right most panel, we display a zoomed in image denoted by the black rectangle area in the middle panel of Fig. 1. We clearly see

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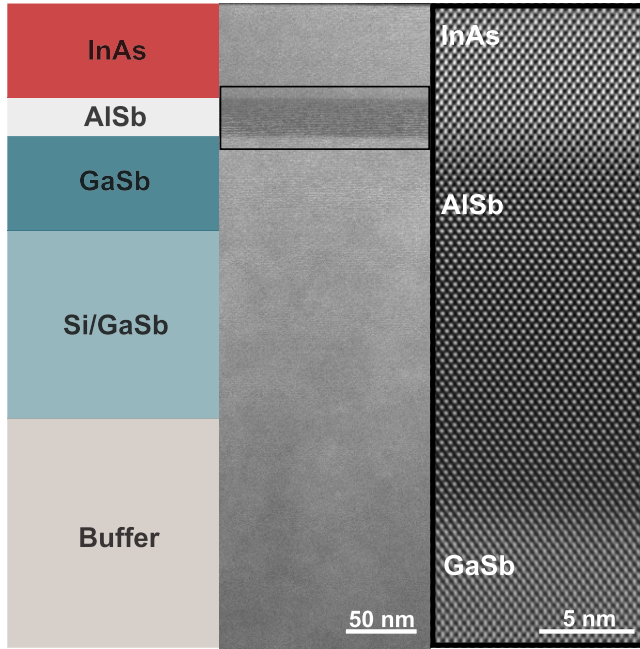


FIG. 1. *Layer structure and STEM images.* Displayed from left to right: the layer structure of the grown InAs/AlSb/GaSb heterostructure, next to scanning transmission electron microscopy (STEM) images in different magnification scales (middle and right panel). The middle panel shows an overview image of the layer structure from the semiconductor surface down to the beginning of the buffer layer, according to the left most panel. The AlSb barrier surrounded by the InAs/GaSb quantum well interfaces, denoted with a black rectangle, is depicted with atomic resolution in the right most panel.

that the InAs/AlSb/GaSb interfaces are free of defects and that intermixing is negligible. This is important for the reliability of our heterostructure with respect to the insulation of the AlSb barrier.

Conventional optical lithography fabrication was performed to define the mesa pattern in a pillar geometry, facilitating the capacitance measurement, as illustrated in Fig. 2. Individual contacts to InAs and GaSb quantum wells were realized using wet chemical etching with a $\text{H}_2\text{O}:\text{C}_6\text{H}_8\text{O}_7:\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2$ solution, with an etching rate of 0.4 nm/s for the present 20 nm wide AlSb barrier. To provide an ohmic contact, we metalized Ti/Au: 50/150 nm on the GaSb—*p*-type—layer. For the InAs—*n*-type—surface, a thin layer of Ti/Pt: 15/5 nm was evaporated. A silver epoxy paste was used to connect Au wires to the *n*-type region, while In soldering was used for the *p*-type region. The I-V traces from the *p* to the *n* layer demonstrate a diodelike behavior ranging from $-0.1 < V_{\text{DC}} < +0.1$ V (see Supplemental Material [30]), exhibiting a central insulating low conductive region, of maximal resistance ≈ 100 k Ω .

Using standard lock-in techniques coupled with an AC/DC voltage adder and an I-V converter connected directly to the lock-in input signal, as depicted in Fig. 2, we performed magnetocapacitance measurements with DC bias applied from the *p* (GaSb) to the *n* (InAs) layer as a function of perpendicular magnetic field, using a frequency of 1.43 kHz. This frequency provided the best signal to noise ratio quality of the

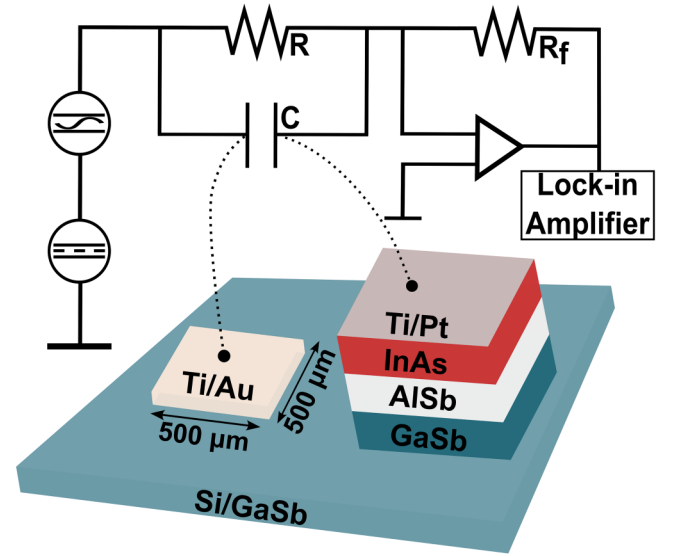


FIG. 2. *Capacitance measurement setup with sample geometry.* The upper schematic displays the setup used for the magnetocapacitance experiment. The pillar geometry on the bottom represents the out-of-plane measurement technique, which allows to contact holes in the GaSb layer and electrons in the InAs layer.

out-of-phase signal output required for the magnetocapacitance measurements.

III. RESULTS

We simulate the band structure alignment around the 20 nm AlSb barrier in between InAs and GaSb layers, by solving the 1D Schrödinger and Poisson equations in the Nextnano platform [31,32]. Results for different applied bias voltage are depicted in Fig. 3. Due to the expected inverted band alignment, we see the confinement of electrons in the InAs and holes in the GaSb layers. The probability densities of electron (1e) and heavy holes (1HH) in the ground state predict the formation of a two-dimensional electron gas (2DEG) and a two-dimensional hole gas (2DHG), respectively, within the corresponding quantum wells.

In equilibrium regime, where no bias voltage is applied, the simulation certifies the existence of a built-in electric field. We note that for the nonequilibrium regime, the confinement of carriers remains and the band alignment is modified as the Fermi energy level (ϵ_F) is modulated for forward and reverse bias. It enables the tuning of charge carrier densities in both channels simultaneously. This shifts the position of the electrochemical potential of the conduction and valence bands, respectively, described by the quasi-Fermi energy for electrons and holes—here assigned exclusively to distinguish the Fermi levels for each carrier type. This variation causes a split in both quasi-Fermi levels, as seen in the simulation (Fig. 3), under both forward and reverse DC bias polarity. The density probability of holes in the GaSb quantum well becomes nonlocalized for a reverse bias larger than -0.04 V, not shown in Fig. 3 for clarity.

In Fig. 4, we present magnetocapacitance oscillations performed in a dilution refrigerator at a base temperature of 25 mK. We clearly identify the similarity to an in-plane

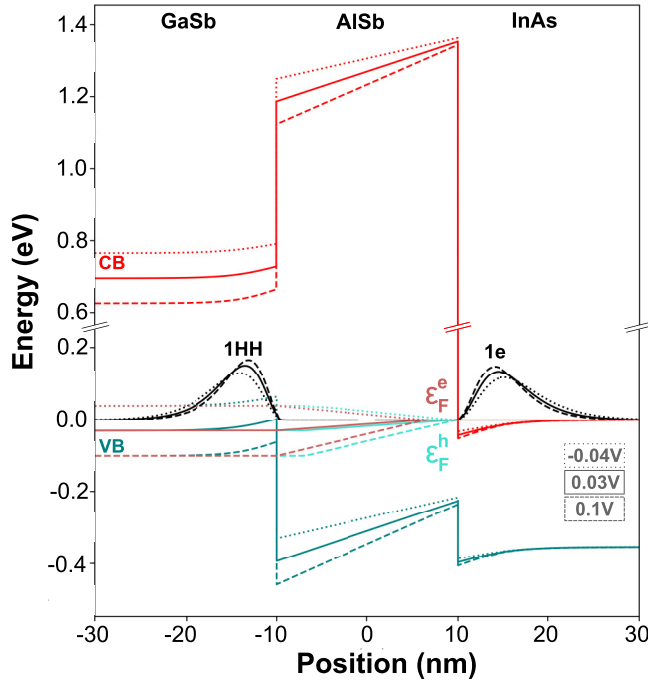


FIG. 3. *Band structure simulation.* The band alignment for the grown InAs/AISb/GaSb heterostructure for -0.04 V (dotted lines), 0.03 V (solid lines), and 0.1 V (dashed lines) bias voltage applied from the p (GaSb) to the n (InAs) region are shown. The conduction band (CB) in red and the valence band (VB) in teal color for heavy holes are depicted, in addition to the quasi-Fermi energy levels ϵ_F for electrons (light brown) and holes (turquoise) for both bias polarities. The ground state probability density distribution of electrons in InAs (1e) and heavy holes in GaSb (1HH) are illustrated by black curves.

longitudinal resistivity behavior, i.e., SdH oscillations, with the presence of Zeeman spin splitting (roughly at 1.1 T) already for low magnetic field values. This measurement result is in good agreement with the presence of a 2D carrier system as predicted by the simulation shown in Fig. 3. We also note that the oscillations appear for an out-of-plane scheme, due to the measurement design itself. A beating pattern for forward bias voltages larger than 0.025 V emerges, pointed out with a dashed black line, for clarity. Apart from the usual periodicity in $1/B$, this is a typical signature of two different carrier densities present in the system leading to oscillations with different frequencies. As described later, this is associated with an electron-hole bilayer system.

Magnetocapacitance oscillations are a direct measurement of the quantum capacitance. The latter originates from the modified density of states of a 2D layer (DOS^{2D}), resulting from the quantization of Landau levels (LLs) for a perpendicular magnetic field. According to the equation for the effective Capacitance C_{eff} ,

$$\frac{1}{C_{\text{eff}}} = \frac{1}{C_g} + \frac{1}{C_q} + \frac{1}{C_\psi}, \quad (1)$$

the contribution of the geometrical C_g , quantum capacitance C_q , and the stand-off distance in between the wave function center of mass and the center of the AISb barrier C_ψ , has to be considered. In the absence of a magnetic field B , the

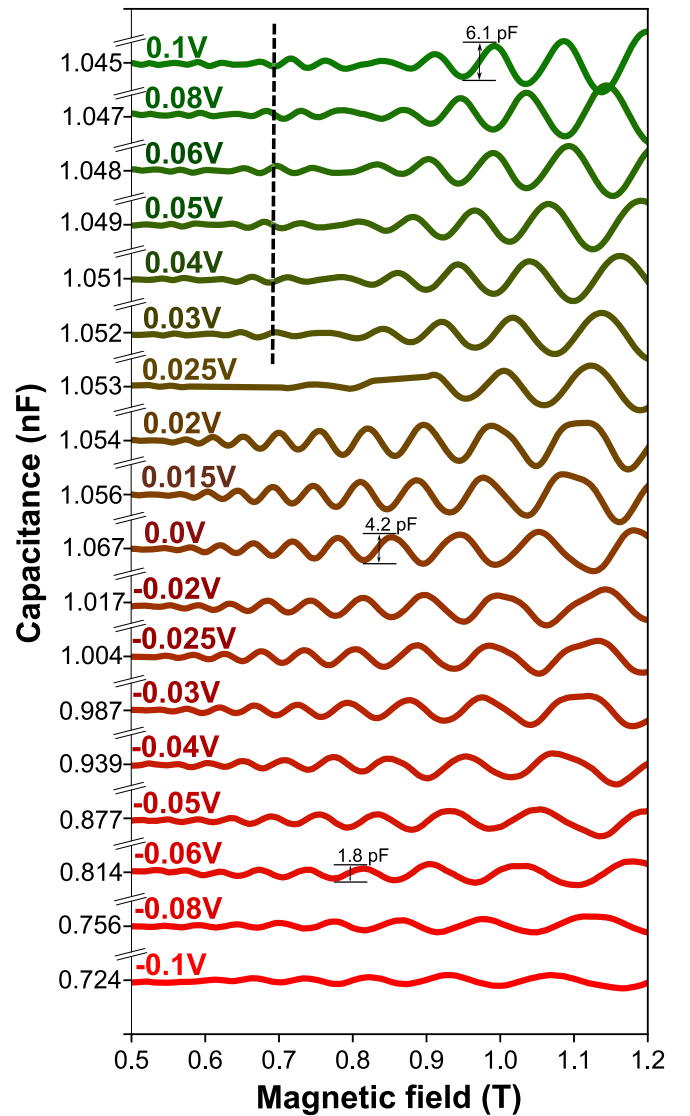


FIG. 4. *Carrier density tunability.* Magnetocapacitance signatures for forward and reversed DC bias modulation measured in the low magnetic field range. The black dashed line indicates the occurrence of beating signatures for forward bias. The amplitudes in capacitance values for a few curves are depicted for comparison.

first term dominates as there is no quantization of LLs. In principle we have two quantum capacitances, one for the InAs and another for the GaSb layer, which are connected in series to the geometric capacitance C_g . In the presence of a magnetic field, the second term C_q , leads to oscillatory behavior. The finite DOS in each 2D gas corresponds to the length scale given by the effective Bohr radius [33] $a_B^{*GaSb}/4 = 0.5$ nm and $a_B^{*InAs}/4 = 7.2$ nm, taking into account the electrical permittivity and the m^* of the respective charge carriers in the GaSb and the InAs layer, which increases the effective separation of the capacitor plates.

In order to extract charge carrier densities for each DC bias in the magnetocapacitance traces shown in Fig. 4, a fast Fourier transform (FFT) analysis was performed. We analyze the power spectra considering two cases according to different magnetic field (B) ranges. We refer to case (I), the analysis

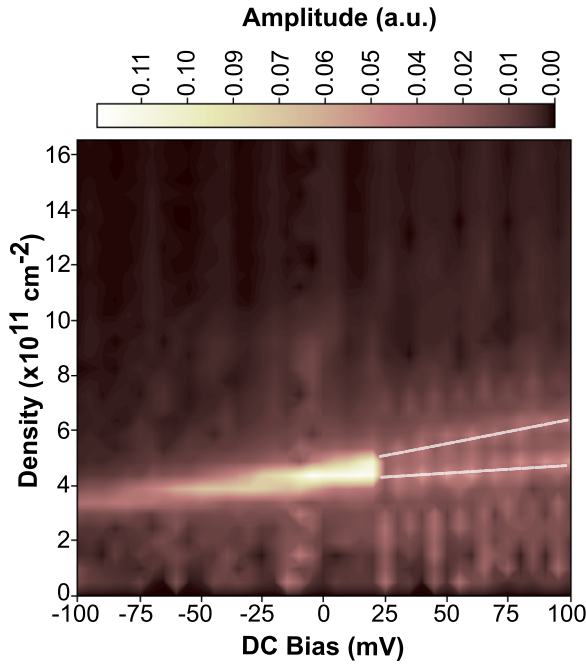


FIG. 5. *Density evolution for the low magnetic field range.* Power spectra calculated by the FFT of the magnetocapacitance curves at various DC bias voltage applied (as in Fig. 4), determined for magnetic field up to one Tesla, addressed as case (I). The abrupt transition around 0.02 V is correlated to the imminence of beating signatures for forward bias, presented previously. The white dashed lines serve as an eye guide.

related to magnetocapacitance oscillations considering magnetic fields up to 1 T. As case (II), the whole magnetic field range up to 7 T was analyzed instead. The respective power spectra for case (I) seen in Fig. 5 demonstrate the existence of a carrier density channel for reversed and forward bias voltages up to 0.025 V, identified as the average electron-hole bilayer density. For higher forward bias, the hole channel gets resolved along with the electron one (marked with dashed lines for clarity). This refers to the two distinct densities already depicted in Fig. 4 in the form of beating signatures.

In Fig. 6 we consider the power spectra for the complete magnetic field range regarding case (II). We observed the presence of two distinct 2D carrier systems where the lower density curve is equivalent to the curve shown in Fig. 5.

We concentrate initially in the lower density trace from Fig. 6. By using the slope of the linear fit, we calculated the distance d between the capacitor plates, providing a value of 55 ± 3 nm (see the Supplemental Material [30]). Taking into account the geometrical capacitance formula— $\epsilon\epsilon_0/d$, where ϵ and ϵ_0 denote the electrical permittivity of AlSb and vacuum, respectively,—the estimated Bohr radius for each QW (a_B^{*GaSb} and a_B^{*InAs}), and the distance in between the center of the AlSb barrier and the wave function center of mass, we were able to determine the expected distance d between the hole and the electron layer in our structure to be ≈ 50 nm. This is in very good agreement with the experimental results.

Having a look into the upper curve in Fig. 6, the hypothesis that it belongs to two subbands either from InAs or GaSb QW being occupied is addressed. By considering the

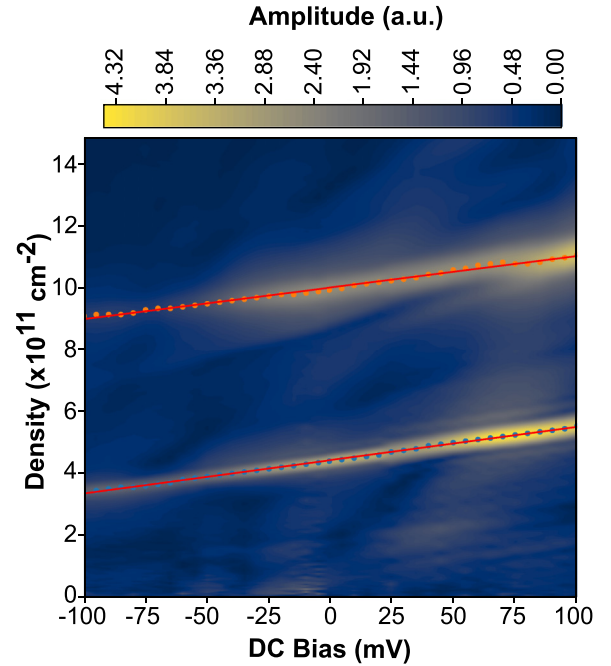


FIG. 6. *Density evolution for the complete magnetic field range.* Fast Fourier transform of the complete magnetocapacitance range as a function of DC bias [case (II)]. The clear definition of both curves reveals the coexistence of two 2D gases in the system. From the FFT analysis for all DC bias voltage applied, the respective densities were determined and plotted as a function of DC bias. Red lines indicate the linear fit of both curves.

subband energy difference between the ground and first excited state, the calculations for both QWs separately yields a value of $\Delta n = 2.575 \times 10^{11} \text{ cm}^{-2}$ for the InAs layer and $\Delta n = 1.288 \times 10^{11} \text{ cm}^{-2}$ for the GaSb layer. These values are much smaller than the experimental result of $5.547 \times 10^{11} \text{ cm}^{-2}$ that we present in Fig. 6 at equilibrium, demonstrating that the higher density trace can not originate from a second occupied subband. Hence, we attribute the higher density trace to an additional 2D carrier system forming at the surface of the InAs layer. Due to an expected lower mobility of this extra 2DEG, the magnetocapacitance oscillations only emerge for higher magnetic field range and are therefore missing in Fig. 5 [34,35].

In Fig. 7 we show the complete magnetocapacitance measurements for various applied DC bias voltages displaying an unconventional Landau phase diagram. In addition to that, we plot a few values of expected filling factors (ν), determined according to nh/eB , where n is the carrier density extracted from the power spectra analysis for case (II) shown in Fig. 6. We note that ν lines for the lower density in Fig. 6, named here as n_1 , are displayed in red lines. The dashed or solid lines distinguish the parity of the filling factors (either even or odd). Analogously, the ν values associated with the higher carrier density, called n_2 , are illustrated in green lines with the respective parity distinction likewise. We observed two different Landau fans over the whole DC bias range clearly demonstrating the presence of two 2D charge carrier systems. We therefore attribute the red lines in Fig. 7 to the bilayer system and the green lines the surface 2DEG.

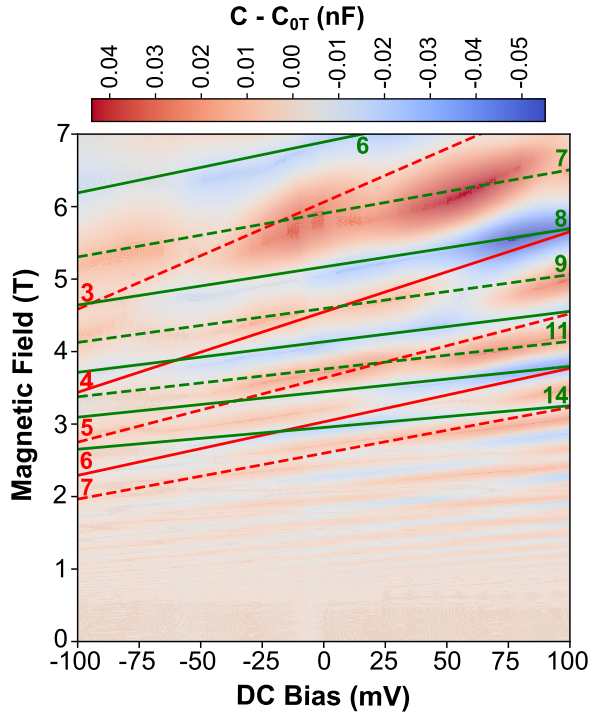


FIG. 7. Landau phase diagram with expected filling factors. The magnetocapacitance oscillations as a function of the applied DC bias for the complete magnetic field range are shown. The colorbar indicates the difference between the measured capacitance values and the offset value at zero magnetic field for the respective DC bias curve. We also display the calculated filling factor positions from a partial range of the Landau phase diagram for clarity. The lines represent the predicted occupation of the first (red) and second (green) channel, where full (dashed) lines correspond to even (odd) filling factors.

IV. CONCLUSION AND OUTLOOK

We have investigated magnetocapacitance signatures modulated by DC bias applied in InAs/GaSb quantum wells, separated by a 20 nm AlSb barrier, realized by independent ohmic contacts with respect to InAs and GaSb channels. We probed an oscillatory behavior of capacitance as a function of magnetic field, representing the density of states of the confined two dimensional electron and hole charge carrier systems formed in the InAs and GaSb QW, respectively, in good agreement with our simulation. This oscillatory behavior shifts with DC bias applied, marking the adjustable charge carrier density via bias voltage. In particular for forward bias

greater than 0.025 V, we observed the formation of beating signatures, defining two different densities coexisting in the system. The unique Landau phase diagram exhibits exceptional agreement with filling factor expectation curves, indicating the electron-hole bilayer in addition to the InAs surface 2D system. We have also developed a theory to describe the capacity of the bilayer system (Supplemental Material [30]) and we found good agreement with our experiments. The two distinct densities observed for the lower magnetic field range are associated with electrons in the InAs layer and holes in the GaSb QW, as known for the InAs/GaSb system and now confirmed with the presence of the AlSb barrier in between the two QWs.

The spin orbit interactions also carry attractive features creating a promising and relevant platform to explore spin orbit properties in the InAs/AlSb/GaSb systems [36], enabling the investigation of further physical aspects toward spin-based devices as spin field effect transistors. The potential impact of out-of-plane magnetocapacitance measurements is expandable [2,37–39]. It can lead to the capability to access physical parameters and contribute to our comprehension of excitons. Understanding how the electric field influences the charge carriers in each channel is a significant aspect towards the accessibility of a stable excitonic condensate [24,25]. The magnetocapacitance experiment presented in this paper represents a powerful technique to approach this research environment, which is also applicable toward infrared laser and detector research [40].

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DATA AVAILABILITY

The data that support the findings of this article shown in Figs. 4–7 are openly available under the [41]. The code for the simulation displayed in Fig. 3 can be found in [42] PhD thesis. The data for Fig. 1 are available upon reasonable request from the authors.

- [1] F. Qu, A. J. A. Beukman, S. Nadj-Perge, M. Wimmer, B. M. Nguyen, W. Yi, J. Thorp, M. Sokolich, A. A. Kiselev, M. J. Manfra, C. M. Marcus, and L. P. Kouwenhoven, Electric and magnetic tuning between the trivial and topological phases in InAs/GaSb double quantum wells, *Phys. Rev. Lett.* **115**, 036803 (2015).
- [2] M. J. Yang, C. H. Yang, B. R. Bennett, and B. V. Shanabrook, Evidence of a hybridization gap in “semimetallic” InAs/GaSb systems, *Phys. Rev. Lett.* **78**, 4613 (1997).

- [3] A. Zakharova, S. T. Yen, and K. A. Chao, Hybridization of electron, light-hole, and heavy-hole states in InAs/GaSb quantum wells, *Phys. Rev. B* **64**, 235332 (2001).
- [4] L. Du, X. Li, W. Lou, G. Sullivan, K. Chang, J. Kono, and Rui-Rui Du, Evidence for a topological excitonic insulator in InAs/GaSb bilayers, *Nat. Commun.* **8**, 1971 (2017).
- [5] C.-A. Li, S.-B. Zhang, and S.-Q. Shen, Hidden edge Dirac point and robust quantum edge transport in InAs/GaSb quantum wells, *Phys. Rev. B* **97**, 045420 (2018).

- [6] L. Du, I. Knez, G. Sullivan, and R. R. Du, Robust helical edge transport in gated InAs/GaSb bilayers, *Phys. Rev. Lett.* **114**, 096802 (2015).
- [7] K. Suzuki, Y. Harada, K. Onomitsu, and K. Muraki, Edge channel transport in the InAs/GaSb topological insulating phase, *Phys. Rev. B* **87**, 235311 (2013).
- [8] F. Nichele, H. J. Suominen, M. Kjaergaard, C. M. Marcus, E. Sajadi, J. A. Folk, F. Qu, A. J. A. Beukman, F. K. De Vries, J. Van Veen, and others, Edge transport in the trivial phase of InAs/GaSb, *New J. Phys.* **18**, 083005 (2016).
- [9] S. Mueller, C. Mittag, T. Tschirky, C. Charpentier, W. Wegscheider, K. Ensslin, and T. Ihn, Edge transport in InAs and InAs/GaSb quantum wells, *Phys. Rev. B* **96**, 075406 (2017).
- [10] I. Lapushkin, A. Zakharova, S.-T. Yen, and K.-A. Chao, A self-consistent investigation of the semimetal–semiconductor transition in InAs/GaSb quantum wells under external electric fields, *J. Phys.: Condens. Matter* **16**, 4677 (2004).
- [11] L.-H. Hu, C.-X. Liu, D.-H. Xu, F.-C. Zhang, and Y. Zhou, Electric control of inverted gap and hybridization gap in type-II InAs/GaSb quantum wells, *Phys. Rev. B* **94**, 045317 (2016).
- [12] J. L. Padilla, C. Medina-Bailon, C. Alper, F. Gamiz, and A. M. Ionescu, Confinement-induced InAs/GaSb heterojunction electron–hole bilayer tunneling field-effect transistor, *Appl. Phys. Lett.* **112**, 182101 (2018).
- [13] A. Zakharova, S. T. Yen, and K. A. Chao, Landau level structures and semimetal-semiconductor transition in strained InAs/GaSb quantum wells, *Phys. Rev. B* **69**, 115319 (2004).
- [14] M. H. L. de Medeiros, R. L. R. C. Teixeira, G. M. Sipahi, and L. G. G. V. Dias da Silva, Electric field induced edge-state oscillations in InAs/GaSb quantum wells, *Phys. Rev. B* **104**, 195307 (2021).
- [15] B. A. Bernevig and S. C. Zhang, Quantum spin Hall effect, *Phys. Rev. Lett.* **96**, 106802 (2006).
- [16] T. Paul, V. F. Becerra, and T. Hyart, Interplay of quantum spin Hall effect and spontaneous time-reversal symmetry breaking in electron-hole bilayers. II. Zero-field topological superconductivity, *Phys. Rev. B* **106**, 235421 (2022).
- [17] A. Mawrie, Magnetotransport properties of the Quantum spin Hall and quantum Hall states in an inverted HgTe/CdTe and InAs/GaSb quantum wells, *J. Phys.: Condens. Matter* **34**, 245301 (2022).
- [18] C. Liu, T. L. Hughes, X. L. Qi, K. Wang, and S. C. Zhang, Quantum spin Hall effect in inverted type-II semiconductors, *Phys. Rev. Lett.* **100**, 236601 (2008).
- [19] T. Akiho, F. Couëdo, H. Irie, K. Suzuki, K. Onomitsu, and K. Muraki, Engineering quantum spin Hall insulators by strained-layer heterostructures, *Appl. Phys. Lett.* **109**, 192105 (2016).
- [20] W. Yang, K. Chang, and S.-C. Zhang, Intrinsic spin Hall effect induced by Quantum phase transition in HgCdTe quantum wells, *Phys. Rev. Lett.* **100**, 056602 (2008).
- [21] M. Drndić, M. P. Grimshaw, L. J. Cooper, D. A. Ritchie, and N. K. Patel, Tunable electron-hole gases in gated InAs/GaSb/AlSb systems, *Appl. Phys. Lett.* **70**, 481 (1997).
- [22] B.-M. Nguyen, W. Yi, R. Noah, J. Thorp, and M. Sokolich, High mobility back-gated InAs/GaSb double quantum well grown on GaSb substrate, *Appl. Phys. Lett.* **106**, 032107 (2015).
- [23] H. Irie, T. Akiho, F. Couedo, K. Suzuki, K. Onomitsu, and K. Muraki, Energy gap tuning and gate-controlled topological phase transition in InAs/ $\text{In}_x\text{Ga}_{1-x}\text{Sb}$ composite quantum wells, *Phys. Rev. Mater.* **4**, 104201 (2020).
- [24] Y. Naveh and B. Laikhtman, Excitonic instability and electric-field-induced phase transition towards a two-dimensional exciton condensate, *Phys. Rev. Lett.* **77**, 900 (1996).
- [25] Y. Naveh and B. Laikhtman, Band-structure tailoring by electric field in a weakly coupled electron-hole system, *Appl. Phys. Lett.* **66**, 1980 (1995).
- [26] Z. Xiaodong, J. J. Quinn, and G. Gumbs, Excitonic insulator transition in a GaSb-AlSb-InAs quantum-well structure, *Solid State Commun.* **75**, 595 (1990).
- [27] J. P. Eisenstein and A. H. MacDonald, Bose–Einstein condensation of excitons in bilayer electron systems, *Nature (London)* **432**, 691 (2004).
- [28] S. de-Leon, L. D. Shvartsman, and B. Laikhtman, Band structure of coupled InAs/GaSb quantum wells, *Phys. Rev. B* **60**, 1861 (1999).
- [29] K. Suzuki, S. Miyashita, and Y. Hirayama, Transport properties in asymmetric InAs/AlSb/GaSb electron–hole hybridized systems, *Phys. Rev. B* **67**, 195319 (2003).
- [30] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/1fby-kgfj> for growth details, I–V response, the theory for the capacity of the bilayer system, besides of further band alignment simulations and magnetocapacitance results.
- [31] S. Birner, T. Zibold, T. Andlauer, T. Kubis, M. Sabathil, A. Trellakis, and P. Vogl, nextnano: General Purpose 3-D Simulations, *IEEE Trans. Electron Devices* **54**, 2137 (2007).
- [32] A. Trellakis, T. Zibold, T. Andlauer, S. Birner, R. Smith, R. Morschl, and P. Vogl, The 3D nanometer device project *nextnano*: Concepts, methods, results, *J. Comput. Electron.* **5**, 285 (2006).
- [33] T. Ihn, *Semiconductor Nanostructures: Quantum states and electronic transport* (OUP, Oxford, 2009).
- [34] E. Halpern, G. Elias, A. V. Kretinin, H. Shtrikman, and Y. Rosenwaks, Direct measurement of surface states density and energy distribution in individual InAs nanowires, *Appl. Phys. Lett.* **100**, 262105 (2012).
- [35] K. S. Wickramasinghe, W. Mayer, J. Yuan, T. Nguyen, L. Jiao, V. Manucharyan, J. Shabani, Transport properties of near surface InAs two-dimensional heterostructures, *Appl. Phys. Lett.* **113**, 262104 (2018).
- [36] J. Li, W. Yang, K. Chang, Spin states in InAs/AlSb/GaSb semiconductor quantum wells, *Phys. Rev. B* **80**, 035303 (2009).
- [37] H. Irie, T. Akiho, and K. Muraki, Determination of g -factor in InAs two-dimensional electron system by capacitance spectroscopy, *Appl. Phys. Express* **6**, 063004 (2019).
- [38] M. J. Yang, C. H. Yang, and B. R. Bennett, Magnetocapacitance and far-infrared photoconductivity in GaSb/InAs composite quantum wells, *Phys. Rev. B* **60**, R13958 (1999).
- [39] G. M. Minkov, O. E. Rut, A. A. Sherstobitov, S. A. Dvoretzki, N. N. Mikhailov, and A. V. Germanenko, Quantum oscillations of transport coefficients and capacitance: A manifestation of the spin Hall effect, *Phys. Rev. B* **108**, 075301 (2023).
- [40] E. Halvorsen, Y. Galperin, and K. A. Chao, Optical transitions in broken gap heterostructures, *Phys. Rev. B* **61**, 16743 (2000).
- [41] A. Solano Lopes Ribeiro, A. Solano Lopes Ribeiro, and A. Solano Lopes Ribeiro, Raw data for magnetocapacitance experiments [Data set], In Physical Review Research, Zenodo (2025), doi: <https://doi.org/10.5281/zenodo.15772312>.
- [42] A. Solano Lopes Ribeiro, *Magnetocapacitance investigations in InAs/GaSb quantum wells separated by an AlSb barrier*, Ph.D. thesis, ETH Zurich, 2024.