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Using Landau quantization to probe disorder in semiconductor heterostructures

Asser Elsayed ; Davide Costa ; Lucas E. A. Stehouwer ; Alberto Tosato; Mario Lodari; Brian Paquelet Wuetz; Davide Degli Esposti ; Giordano Scappucci

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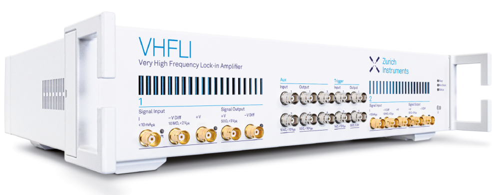

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ABSTRACT

Understanding scattering mechanisms in semiconductor heterostructures is crucial to reducing sources of disorder and ensuring high yield and uniformity in large spin qubit arrays. Disorder of the parent two-dimensional electron or hole gas is commonly estimated by the critical, percolation-driven density associated with the metal–insulator transition. However, a reliable estimation of the critical density within percolation theory is hindered by the need to measure conductivity with high precision at low carrier densities, where experiments are most difficult. Here, we connect experimentally percolation density and quantum Hall plateau width, in line with an earlier heuristic intuition, and offer an alternative method for characterizing semiconductor heterostructure disorder.

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The ability to probe disorder from random potentials is crucial to accelerate the development cycle of semiconductor heterostructures for spin qubits in gate-defined quantum dots.[1,2] When the conductive channel in the heterostructure is separated from the semiconductor-dielectric interface by an epitaxial barrier, the typical sources of disorder affecting the electrical quality of the two-dimensional (2D) charge-carrier gas include uniform background charged impurities within or near the channel and remote charged impurities at the semiconductor–dielectric interface.[3] As a consequence of the disordered potential landscape, a metal-insulator transition occurs in the 2D charge-carrier gas.[4–6] This transition is characterized by a critical density n_c that separates an effective metallic phase from an effective insulating phase, and its origin has been established as a density-inhomogeneity-driven percolation transition.[7–9] As such, it has become common practice in the electrical characterization of heterostructures to evaluate at zero magnetic field B the percolation behavior of the density-dependent conductivity $\sigma_{xx}(n) \propto (n - n_c)^{\alpha}$,[10–12] where n_c and α are the percolation transition density and exponent, respectively. The obtained n_c is considered a key indicator of disorder in the low-density regime, which is relevant for single charge occupation in quantum dots. Importantly, quantum dots with a diameter of approximately $1/\sqrt{n_c}$,[13] which indicates the average distance between impurities, could be essentially disorder-free. However, a reliable evaluation of n_c is challenged theoretically by the choice of the percolation exponent and the density range used for fitting as well as experimentally by the difficulty of measuring the charge density n using the Hall effect,[14,15] due to the increasing channel and contact resistance as n_c is approached from the high-density side of the transition.

In this Letter, we evaluate disorder in semiconductor heterostructures by demonstrating the connection between the percolation transition density and the width of the plateau of the integer quantum Hall effect (QHE), in line with earlier heuristic intuitions.[16] Unlike the common percolation fits, we approach the critical density from the low-density side of the metal–insulator transition. Conceptually, we rely on Landau quantization to precisely tune the charge density eB/h within a Landau level via magnetic fields, filling the localized states inside the disorder-induced mobility gap.

Early investigations of the relationship between quantum Hall plateau width and the transport properties of two-dimensional charge-carrier gases were constrained by the use of modulation-doped structure with fixed carrier density.[17] However, recent developments in spin qubits using gate-defined semiconductor quantum dots have led to numerous reports of percolation fits of the density-dependent conductivity in gated Hall bars,[18–25] with QHE measurements provided as additional side information. In Fig. 1, we consider measurements from high-mobility two-dimensional hole gases (2DHGs) in Ge/SiGe heterostructures[26] to make a first qualitative connection between percolation density and quantum Hall plateaus. In Fig. 1(a), devices from 3

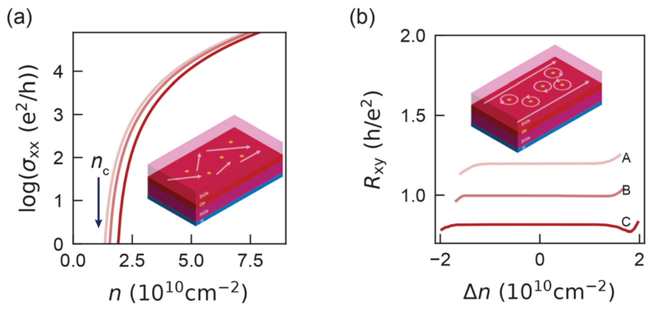

FIG. 1. (a) Fit to the longitudinal conductivity (σ_{xx}) as a function of density (n) for three different strained Ge quantum well heterostructures (A, B, and C) with increasing percolation density n_c. Light red curve (heterostructure A) is obtained using data from Ref. 18, $n_c = 1.2 \times 10^{10}$ cm^{-2}; red curve (heterostructure B) is obtained using data from Ref. 19, $n_c = 1.4 \times 10^{10}$ cm^{-2}; dark red curve (heterostructure C) is obtained using data from Ref. 20, $n_c = 1.8 \times 10^{10}$ cm^{-2}. Inset: a schematic representation of the classically measured percolation density. (b) For the same heterostructures, measurements of the transverse resistance (R_{xy}) as a function of the carrier density deviation $\Delta n = (eB/h - n)$ from the integer filling factor condition $\nu = 1$. Heterostructure A is measured at $n = 6 \times 10^{10}$ cm^{-2} with $\mu = 2 \times 10^6$ cm^2/Vs, heterostructure B is measured at $n = 4.55 \times 10^{10}$ cm^{-2} with mobility $\mu = 1 \times 10^5$ cm^2/Vs, and heterostructure C is measured at $n = 6.9 \times 10^{10}$ cm^{-2} with $\mu = 6 \times 10^5$ cm^2/Vs. Samples with lower percolation densities show narrower quantum Hall plateau. Measurements for heterostructures A and C are offset for clarity. Inset: a schematic representing how the cyclotron orbits are pinned around the same defects represented in the schematic in panel (a).

different heterostructures A,[18] B,[19] and C[20] of decreasing electrical quality show percolation fits of the density-dependent longitudinal conductivity $\sigma_{xx}(n)$ that shift to increasingly higher density, yielding larger n_c. Figure 1(b) shows, for the same devices, the quantum Hall plateaus at filling factor $\nu = 1$ in the transverse resistance R_{xy}, measured at varying magnetic field B and a density n that is fixed but different across devices. To facilitate a comparison, we plot R_{xy} as a function of $\Delta n = (eB/h - n)$, which represents the carrier density deviation from an integer-filled Landau level. Here, $\Delta n = 0$ corresponds to the integer filling factor condition $\nu = 1$, $\Delta n > 0$ measures the density of empty states within the partially filled first energy level ($\nu < 1$), and $\Delta n < 0$ indicates the filled states of the partially filled second energy level ($\nu > 1$). A direct comparison between Figs. 1(a) and 1(b) establishes a clear trend: samples with lower percolation densities, and hence less disorder, show narrower plateaus. As illustrated in the insets of Fig. 1, this observation underscores the role of defects in stabilizing QHE plateaus.[27]

The connection between the width of integer quantum Hall plateaus and the critical density of the metal–insulator transition, in the framework of percolation theory, has been approached heuristically by Efros.[16] At zero magnetic field, the metal–insulator transition occurs at a critical density n_c, which reflects the percolation threshold of the disorder potential. Efros' model proposes that at finite fields, the width of a quantum Hall plateau n_{LL}, expressed as a density with respect to the integer filling condition (i.e., $\Delta n = 0$), scales with n_c, linking transport in the quantum Hall regime to the $B = 0$ percolation transition.[16] At low fields, multiple Landau levels contribute to screening, and a proportionality relationship $n_{LL} \propto n_c \Delta \kappa / e^2 \sqrt{C}$ is expected, characterized by an unknown proportionality factor. Here, κ is the dielectric constant of the 2D channel, $\Delta = \hbar eB/m^*$ is the cyclotron energy related to the effective mass m^* within the channel, and C is the randomly distributed remote impurity density, typically located at the semiconductor-dielectric interface in contemporary spin qubit heterostructures.[3] In Efros' model at high magnetic fields, n_{LL} approaches an asymptotic limit n_{LL_0}, becomes insensitive to B, and saturates at approximately $2n_c$. Experimentally, we expect n_{LL} evaluated at $\nu = 1$ (n_{LL_1}) to approximate closely to this limit.

We investigate this correlation systematically by using magnetotransport data from a 2DHG in Ge/SiGe,[20] measured at a temperature below 100 mK. We extract n_{LL} values at increasing filling factors at an average hole density of 5.75×10^{10}cm^{-2} and plot them in Fig. 2(a) against the magnetic field value B corresponding to integer filling factor. Here, n_{LL} refers specifically to the region where the longitudinal resistivity (ρ_{xx}) is zero. At low fields, n_{LL} increases approximately linearly, while at high fields, it approaches a constant. To capture both regimes described by Efros, we fit the data by introducing the fitting function:

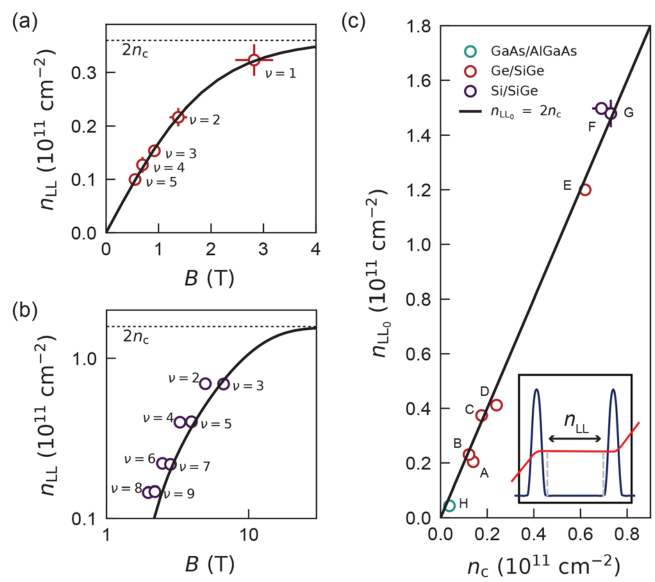

FIG. 2. (a) Width of the quantum Hall plateaus (n_{LL}, red circles) at different filling factors (ν) as a function of magnetic field (B) for holes in Ge/SiGe (heterostructure C), analyzing data from Ref. 20. n_{LL} is obtained by averaging, for each ν, over 35 measurements at different hole densities in the range $(4.5, 7) \times 10^{10}$ cm^{-2}. The uncertainty is 1 s.d. from the average. The black line is a fit to Eq. (1). The dashed lines is placed at twice the percolation density n_c. (b) n_{LL} (purple circles) at different ν as a function of B for electrons in Si/SiGe heterostructures for heterostructure G, obtained by analyzing data from Ref. 24. n_{LL} is evaluated at an electron density of 1×10^{11} cm^{-2}. The fit to Eq. (1) (black lines) considers only the odd filling factors, which correspond to valley split levels. The dashed lines is placed at twice the percolation density n_c. (c) Fitted asymptotic width of the QHE plateau n_{LL_0} as a function of percolation density n_c for Ge/SiGe heterostructures (red), GaAs/AlGaAs heterostructures (green), and Si/SiGe heterostructures (purple). The uncertainties over the fitted n_{LL_0} values from Eq. (1) are less than 10% across all systems. The data point for Heterostructure A is obtained by analyzing data from Ref. 18; for heterostructure B from Ref. 19; for heterostructure C from Ref. 20; for heterostructure D from Ref. 21; for heterostructure E from Ref. 22; for heterostructure F from Ref. 23; for heterostructure G from Ref. 24; and for heterostructure H from Ref. 25. The black solid line corresponds to $n_{LL_0} = 2n_c$ as suggested by Efros.[16]

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$$n_{\mathrm{LL}} = n_{\mathrm{LL}_0} \tanh\left(\frac{\Delta\kappa}{2e^2\sqrt{K}}\right), \tag{1}$$

which interpolates smoothly between the low- and high-field limits. Here, we use as free fitting parameters n_{LL_0} and K, which is related to C by an unknown proportionality factor to reconcile with the model in Ref. 16. The parameters κ and m^*, instead, are fixed to values of 16 and 0.07, respectively, from Ref. 20. From this fit, we extract a characteristic value n_{LL_0} of 3.6×10^{10} cm^{-2} and parameter K of 5.0×10^{12} cm^{-2}. In line with the suggestion of Efros,[16] the obtained n_{LL_0} is approximately twice the critical density $n_c = 1.76 \times 10^{10}$ cm^{-2} (black dotted line) obtained independently from percolation fits in Ref. 20.

We perform the same analysis on data from a 2D electron gas in Si/SiGe ($\kappa = 12$, $m^* = 0.19$) from Ref. 24, measured at a temperature below 100 mK and at a single density of 1×10^{11} cm^{-2} and show the results in Fig. 2(b). We observe comparable plateau widths for even and odd filling factors, suggesting additional effects beyond the simple model of Efros.[16] These effects are possibly related to the additional valley degree of freedom, which enriches the Landau level energy ladder in silicon.[28,29] For this reason, we restrict the fit to Eq. (1) to the valley-resolved odd filling factors 3, 5, 7, and 9. As for holes in germanium also for electrons in silicon, the data align with the model, and we find that the fitted n_{LL_0} of 1.56×10^{11} cm^{-2} is approximately twice the n_c value of 0.78×10^{11} cm^{-2} (black dotted line) reported in Ref. 24.

In Fig. 2(c), we extend the same analysis to a range of heterostructures, including a 2DHG in GaAs/AlGaAs[25] ($\kappa = 13$, $m^* = 0.35$), 2DEGs in Si/SiGe[23,24] as well as 2DHGs in Ge/SiGe,[18–22] for which percolation densities and QHE measurements have been previously reported at milliKelvin temperatures. We observe that the extracted n_{LL_0} is consistently about twice the reported n_c, overlapping with the theoretical prediction $n_{\mathrm{LL}_0} = 2n_c$ (black line) over about an order of magnitude in percolation density. Quantitatively, a linear fit of n_{LL_0} against n_c yields a slope of 2.12(7) and an intercept of -0.04(4). This result confirms the correlation between percolation density measured at low charge density and zero magnetic field, and the width of quantum Hall plateau at high charge density n and strong magnetic fields.

Having established the correlation between the classical and quantum transport regimes in quantum wells, we give further insights into the temperature dependence of this relationship. As the temperature increases, the dielectric function changes, and the screening length decreases, effectively activating additional defects.[30] These defects influence both the scattering properties of the two-dimensional system and the percolation density.[7,31] In Fig. 3(a), we present n_c as a function of temperature. The data, from 2DHG in Ge/SiGe in Ref. 18, show a decrease in percolation density with decreasing temperature, eventually reaching saturation at low temperatures. The results are fitted to an activation energy model in the form of

$$n_c = n_0 + A\exp\left(-\frac{b}{T}\right), \tag{2}$$

where b is an effective energy gap related to the impurity distribution of the system and n_0 is the critical density for the metal-insulator transistion in the limit of $T = 0$.[7] From the fit, we find $b = 500$ mK and $n_0 = 1.45 \times 10^{10}$ cm^{-2}. Given this value of b, the thermally activated contribution at our lowest measurement temperature is strongly suppressed, such that the measured $n_c = 1.52 \times 10^{10}$ cm^{-2} is close to the $T = 0$ limit set by n_0.

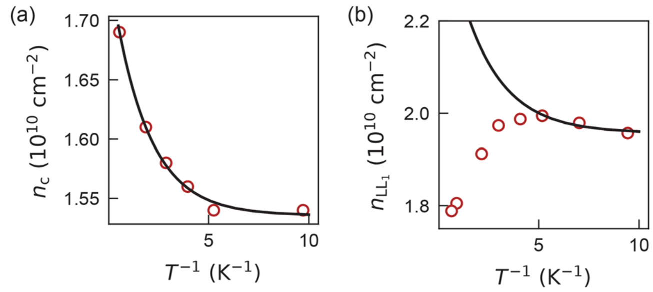

FIG. 3. (a) Percolation density n_c as a function of inverse temperature $1/T$. The data points are obtained from percolation fits, with conductivity measurements performed on a device from heterostructure A studied in Ref. 18. The solid line is a fit to Eq. (2). (b) Width of the quantum Hall plateau for the first filling factor n_{LL_1} as a function of inverse temperature [same sample as in panel (a)]. The solid line is an activation energy fit considering the three coldest temperatures. At higher temperature, Landau level broadening smears out the quantum Hall plateaus.

The Landau levels in the QHE are broadened by both collisional and thermal effects.[32–34] As the temperature increases, the thermal energy k_BT becomes comparable to the energy gap between Landau levels, leading to thermal broadening. In this regime, electrons and holes can occupy higher energy states, diminishing the discrete nature of the Landau levels. This increases the likelihood of carriers scattering between levels, which disrupts the quantized Hall conductance. In Fig. 3(b), we observe the behavior of the $\nu = 1$ plateau width (n_{LL_1}) as a function of temperature. Initially, the plateau width increases with temperature due to enhanced collisional broadening. However, as thermal broadening becomes dominant, the plateau width begins to decrease once k_BT approaches the Landau level energy gap. This restricts the determination of percolation density to low temperatures, where collisional broadening outweighs thermal broadening.

In summary, we consider a variety of two-dimensional electron and hole gases and demonstrate the connection between percolation density extracted from the density-dependent conductivity at zero magnetic field and the Landau level plateau widths at high magnetic fields, in line with earlier heuristic intuitions. This method offers an alternative approach to characterizing disorder in semiconductor heterostructures, critical for spin qubit development. However, this method requires magnetic fields high enough to resolve the first filling factor and low temperatures, where Landau levels are collisional- rather than thermal-broadened.

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AUTHOR DECLARATIONS

Conflict of Interest

Yes, G.S. is a founding advisor of Groove Quantum BV and declares equity interest.

Author Contributions

Asser Elsayed: Data curation (lead); Investigation (lead); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Davide Costa:** Formal analysis (supporting); Writing – review & editing (supporting). **Lucas E.A. Stehouwer:** Formal analysis (supporting); Writing – review & editing (supporting). **Alberto Tosato:** Formal analysis (supporting); Writing – review & editing (supporting). **Mario Lodari:** Data curation (supporting); Writing – review & editing (supporting). **Brian Paquelet Wuetz:** Formal analysis (supporting); Writing – review & editing (supporting). **Davide Degli Esposti:** Data curation (supporting); Formal analysis (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **Giordano Scappucci:** Funding acquisition (lead); Supervision (lead); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are openly available in Zenodo, https://doi.org/10.5281/zenodo.17909536, Ref. 35.

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