Real-space mapping of a disordered two-dimensional electron system in the quantum Hall regime

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Abstract. By using scanning tunnelling spectroscopy, we study the influence of potential disorder on an adsorbate-induced two-dimensional electron system in the integer quantum Hall regime. The real-space imaged local density of states exhibits transition from localized drift states encircling the potential minima to another type of localized drift states encircling the potential maxima. While the former states show regular round shapes, the latter have irregular-shaped patterns. This difference is induced by different sources for the potential minima and maxima, i.e., substrate donors and an inhomogeneous distribution of the adsorbates, respectively.

1. Introduction

The interplay between a high magnetic field \( B \) and electrostatic disorder is a fundamental physical aspect of the integer quantum Hall effect [1]. At a high magnetic field, an electron of a two-dimensional electron system (2DES) performs cyclotron motion leading to discrete Landau levels (LLs). An additional electric field caused by potential disorder leads to drift of the guiding center of the cyclotron motion. The resulting quantum mechanical states, so-called drift states, meander along equipotential lines with a width of about the cyclotron radius \( r_c = \sqrt{(2n+1)\cdot \frac{\hbar}{|e|B}} \) (\( n \), LL index; \( \hbar \), Dirac’s constant; \( e \), electron charge) [2]. When the drift states are trapped around a potential minimum, such localized states split off from the degenerate LL in energy, composing the low-energy tail of the LL. In contrast, the drift states localized around a potential maximum form the high-energy tail. The transition between these two types of localized states through the critical state, i.e. the extended state, is the so-called quantum Hall transition, which we had previously probed [3] and which was recently observed also within a graphene 2DES [4] and a quasi-2DES on the graphite surface [5].
This paper presents a scanning tunnel spectroscopy (STS) study of a disordered 2DES, focusing on the influences of the disorder potential. The 2DES is induced on the $n$-InSb(110) surface. At $B = 0$ T, the local density of states (LDOS) shows wave patterns scattered by the weak potential disorder with a wave length according to a non-parabolic dispersion relation which is in agreement with a self-consistent calculation. At $B = 12$ T, we observe the evolution from localized drift states encircling the potential minima to localized states encircling the potential maxima by mapping the energy dependent LDOS of the lowest Landau level (LL0). While the former localized states show round-shaped LDOS patterns, the latter localized states exhibit irregular-shaped patterns. To clarify the cause of the difference, we map the potential landscape by measuring the spatial peak-energy fluctuations of LL0. Comparison between the potential landscape and the topographic scanning tunneling microscopy (STM) image of the same area reveals that the difference is induced by different sources of the potential minima and maxima, i.e., substrate donors and an inhomogeneous distribution of Cs atoms, respectively.

2. Methods

2-1. Experiments

The 2DES was prepared by depositing 0.01 - 0.02 monolayer Cs on an atomically smooth, clean $n$-InSb(110) surface prepared in ultrahigh vacuum ($\sim 1 \times 10^{-10}$ mbar) by cleavage. The donor (acceptor) density, $n_d$ ($n_a$), of the $n$-InSb is determined to be $9 \times 10^{21}$ m$^{-3}$ ($5 \times 10^{21}$ m$^{-3}$) from compensation electron density ($n_d - n_a$) and compensation ratio ($n_a/n_d$) measured by transport and STM images [6]. Cs was deposited from a well out-gassed Cs dispenser [7] at a pressure of about $10^{-10}$ mbar. The Cs induces downward band bending at the InSb surface and, thereby, creates the 2DES [8]. To minimize an inhomogeneous distribution of Cs atoms due to the formation of chain structures [9], the deposition was carried out onto the cold surface at $T \sim 30$ K and, subsequently, the Cs atoms were stabilized by annealing the sample at a temperature of $T = 100 - 300$ K for about 5 - 30 min. We obtained a homogeneous distribution of Cs with less than 4 % in chain structures.

We performed STS at $T = 0.3$ K by using an ultra-high vacuum scanning tunnelling microscope [10] homebuilt at Hamburg University. The distance between tip and sample was stabilized at a current $I_{stab}$ and a voltage $V_{stab}$ prior to opening the feedback. Then, the $\text{d}I/\text{d}V(V_s)$ curves were recorded at a sample voltage $V_s$ using lock-in technique with an ac modulation of amplitude $V_{mod}$ (modulation frequency ~ 1.5 kHz). We used an ex-situ etched W-tip which is subsequently prepared in-situ by flash annealing and voltage pulses on W(110) [10].

2-2 Calculations

The self-consistent calculation used to determine the adsorbate induced band bending is described elsewhere in detail [11]. As input parameters, the experimentally determined compensation electron density $n_c = n_d - n_a = 4 \times 10^{21}$ m$^{-3}$, the standard values for InSb of static dielectric constant $\varepsilon = 17.9$, band gap $E_{\text{Gap}} = 235$ meV, and spin-orbit splitting $E_{SO} = 850$ meV as well as a surface band-shift of $\Delta E = 278$ meV as estimated at band-bending saturation by photoemission spectroscopy [8] are used. The calculation does not use further fitting parameters and considers the non-parabolicity of the conduction band.

3. Results and discussion

First we sketch the influence of a potential disorder on the Cs-induced 2DES at $B = 0$ T. The solid curve in Fig. 1(a) is the spatially averaged $\text{d}I/\text{d}V$ curve which represents the energy dependence of the macroscopically averaged LDOS, i.e. the DOS [12]. The three steplike features marked by arrows represent the first ($E_1$), second ($E_2$), and third ($E_3$) subband edges [13]. They are in good agreement with the subband energies $E_1 = -116$ meV, $E_2 = -51$ meV, and $E_3 = -22$ meV (measured from the Fermi energy $E_F$) resulting from the self-consistent calculation [Fig. 1(b)]. The band edge, however, locally fluctuates in energy owing to the potential disorder [12]. Indeed, local $\text{d}I/\text{d}V$ curves A and B obtained by locally averaging $\text{d}I/\text{d}V$ curves (diameter of about 20 nm) show lower and higher band edge energies, respectively, than the one in the DOS, indicating that they are influenced by a lower and
higher electrostatic disorder potential. The measured areas A and B are marked in the STM image (inset of Fig. 1(a)). In the area A, the Cs atoms are homogeneously distributed as in the surrounding area. However, in the area B, the Cs atoms form chain structures, suggesting that the inhomogeneous distribution of Cs due to the chain formation induces a higher potential. Notice that the band edge of the $dI/dV$ curve A shows an additional peak structure which can be understood as a shallow bound state due to an attractive potential [14, 15].

Fig. 1 (colour on line) Zero-field property of the Cs-induced disordered 2DES. (a) Dotted (A) and dashed (B) $dI/dV$ curves are locally averaged in area A and B (diameter of about 20 nm) marked in the STM image (inset). Solid $dI/dV$ curve is averaged in a large area (48 x 48 points, 350 x 350 nm$^2$). Arrows mark subband energies $E_i$ ($i=1, 2, 3$). (b) Self-consistently calculated band bending at the InSb surface (solid curve) and electron density distribution of $i$th subband indicated by $E_i$. (c)-(f) $dI/dV$($x,y$) images recorded in the same surface area at $V_s = -66$ mV (c), -46 mV (d), -26 mV (e), and -6 mV (f); $V_{stab} = 100$ mV, $I_{stab} = 0.2$ nA, $V_{mod} = 1.5$ mV, insets show Fourier transforms of the real-space images. (g) Dispersion of electron energy $E$ plotted as a function of wave number $k$. The dots represent the dominant $k$ values extracted from (c)-(f). The solid curve represents a dispersion curve of the lowest subband ($E_1 = -116$ meV) self-consistently calculated taking full account of the non-parabolic conduction-band dispersion of InSb, in comparison with the parabolic dispersion using the band-edge effective mass (dashed curve).
Figures 1(c)-(f) show $\frac{dI}{dV}$ images of the 2DES at different $V_s$ values. The wave length of the visible standing wave patterns apparently decreases with increasing energy. The corresponding Fourier transforms of the real-space images are shown in the insets. In each Fourier transform, the dominating feature is a ring which is increasing in diameter for increasing energy. This feature reflecting the 2DES dispersion cannot be resolved within a strongly disordered system [15]. The dots in Fig. 1(g) show the extracted wave numbers $k$ of the rings as a function of the energy. We perform a self-consistent calculation which takes full account of the non-parabolic conduction-band dispersion of InSb [11]. The resulting dispersion curve of the lowest subband ($E_1 = -116$ meV) is plotted as a solid line. For the sake of comparison, the dispersion curve assuming a parabolic conduction band with the band-edge effective mass is also plotted as a dashed line. The experimentally obtained results are in agreement with the calculated non-parabolic dispersion, evidencing that the underlying potential disorder acts as a weak disorder which does not disrupt general properties of the 2DES on InSb. Similar results are also obtained in a 2DES induced by Cs on $p$-InSb(110) [16] and by Fe on $n$-InAs(110) [12].

Next, we examine the disordered 2DES in the quantum Hall regime. Figures 2 (a)-(f) present the real-space $\frac{dI}{dV}$ images recorded at different $V_s$ values in the lowest spin-down LL (LL0↓) at $B = 12$ T [3]. The spatially averaged $\frac{dI}{dV}$ curve in the corresponding voltage region is shown in the right panel of Fig. 2(g). In the low-energy tail of the LL0↓ [Fig. 2(a)], we observe round disk/loop patterns as marked by arrows. With increasing $V_s$ [Fig. 2(b), (c)], they increase in size, indicating that the localized drift states probes a longer equipotential line at higher energy within the potential valley. In contrast, loop patterns marked by arrowheads in the high-energy tail [Fig. 2(e), (f)] shrink in size with increasing energy. They are, therefore, attributed to localized drift states around the potential maxima. The shapes of the localized states around the potential maxima tend to be irregular in contrast to the round-shaped localized drift states around the potential minima. At the LL center [Fig. 2(d)], the drift states delocalize in areas between the potential valleys and hills, corresponding to the extended state. The observed energy dependencies can be confirmed by the energy-position plot shown in the left panel of Fig. 2(g), which is determined by $\frac{dI}{dV}(V_s)$ curves recorded along the dashed line marked in Fig. 2 (a) or (f). The LL0↓ level fluctuates in energy with a dip (peak) structure near $x = 130$ nm (95 nm) deviating from the LL center (-101 mV) by about 19 mV (16 mV). Such LL fluctuations cause broadened LLs in the measured DOS as shown in the right panel. The accompanying low-energy LL0↑ energetically overlaps with the high-energy LL0↓ around $x = 130$ nm, causing overlapping localized LL0↑ states around the potential minima to appear at -92.4 mV as marked by arrows in Fig. 2 (f).

The LL fluctuation additionally provides information of the local 2DES potential analogous to the tip-induced quantum dot state [12, 17]. Since the drift states track the potential fluctuation down to a length scale of $r_c$, the LL0↓ fluctuation at $B = 12$ T monitors the potential landscape with a resolution of $r_c = 7.4$ nm. The corresponding fluctuation amplitude with respect to the energy of the LL center is plotted in Fig. 2(h) as a function of position within the same area shown in Figs. 2(a)-(f). One can see five potential valleys with a depth of 18±3 meV marked by arrows, and three potential hills with a height of 15±2 meV marked by arrowheads. An STM image of the same area is given in Fig. 2(i). It shows an almost homogenous distribution of the Cs atoms with only 4% chain structures. The position of the chain structures is marked by crosses on the potential map [Fig. 2(h)]. The three large potential hills as well as a number of small hills appear at the positions of the chain structures in agreement with the result at $B = 0$ T [Fig. 1(a)]. This indicates that the Cs chains dominantly induce the potential maxima in this area, although the corresponding surface-2DES region with a depth of $d \approx 15$ nm is expected to contain a finite number of substrate acceptors (~2 in a volume of $170 \times 170 \times 15$ nm$^3$) which may also contribute to the formation of the potential maxima. In Fig. 2(i), we superimpose particular equipotential line extracted from the potential hills onto the STM image. This reveals that the irregular-shaped equipotential line encircles an area where the density of the single Cs atoms is apparently lower than in the surrounding area. If we assume that the single Cs chain, analogous to a Co-island on InAs(110) [18], acts as a single donor possessing the same charge as a single Cs atom,
these areas have negative electrostatic potential due to the lower density of positively charged donors than areas without chains. We therefore conclude that the irregular-shaped localized states are induced by the inhomogeneous distribution of the Cs atoms due to the Cs chain formation. On the other hand, there is no correspondence between the position of the Cs chains and the potential valley as visible in Fig. 2(h). Additionally, there is no other specific inhomogeneity of the Cs distribution in the valley area. The most possible source for the potential minima are, thus, point charges such as single substrate donors [12, 17], which may induce the round-shaped electrostatic potential and thus round-shaped localized drift states. Indeed, the potential depth of 18±3 meV is comparable to the attractive potential of a single donor averaged over the extension of the 2DES [12]. Moreover, the number of the valleys is also nearly equal to the number of substrate donors expected in the surface-2DES region (~4).

Fig. 2 (colour on line) (a) – (f) $dI/dV(x, y)$ images; $B = 12$ T, $V_s = -116.3$ mV (a), -114.6 mV (b), -109.5 mV (c), -100.9 mV (d), -95.8 mV (e), and -92.4 mV (f); $V_{\text{stab}} = 150$ mV, $I_{\text{stab}} = 0.10$ nA, $V_{\text{mod}} = 1.0$ mV; each arrow (arrowhead) in (a) - (f) marks drift states encircling a potential minimum (maximum). (g) left: $dI/dV(V_s, x)$ measured along the dashed line marked in (a) or (f); right: spatially averaged $dI/dV$ curve with circles at the $V_s$ values used in (a) – (f). (h) Potential landscape of the same surface area as (a) – (f) determined from the energetic position of the LL0 peak. Crosses mark positions of Cs chains as determined in the corresponding STM image (i); arrows (arrowheads) mark the potential minima (maxima). Equipotential lines at an energy extracted from the three potential hills in (h) are marked by solid lines in (i).
4. Conclusions
We have shown the evolution of drift states between two different types of localized states in both the low- and high-energy tails of a LL0. While the former states have round shapes, the latter states form irregular-shaped patterns. The difference is induced by different sources of the potential disorder, i.e., substrate donors and an inhomogeneous distribution of adsorbates, which induce rather round potential valleys and irregular-shaped potential hills, respectively.

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