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Scanning gate microscopy on a graphene nanoribbon

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The metallic tip of a scanning probe microscope operated at a temperature of 1.7 K is used to locally induce a potential in a graphene nanoribbon. Images of the conductance through the device as a function of tip-position show that two centers of enhanced conductance are formed inside the structure. By applying a linescan-technique, it can be demonstrated that these two features correspond to two charge localizations, exhibiting the characteristics of quantum dots. Scanning gate microscopy allows us to characterize them with high resolution both in real space and as a function of energy. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4742862]

Graphene is a material which was recently isolated and deposited as a monolayer. It has various special properties including considerable charge carrier mobilities at room temperature,[1,2] making it a valid candidate for possible applications in electronics.[3] The material consists of a single layer of carbon atoms forming a two-dimensional crystal. Due to expected long spin lifetimes, graphene is also a candidate for various applications in nano- and quantum electronics.[4] The basic building block for any electronic device are wires and constrictions that connect the different parts of the device.[5] These small stripes of graphene are usually called "nanoribbons." It has been shown that graphene nanoribbons can exhibit an effective transport gap which is attributed to the formation of charge localization within the ribbon.[6–8]

In graphene, a two-dimensional electron gas (2DEG) is formed, which lies directly at the surface. This makes it especially accessible for scanning probe techniques.[9,10] While conventional transport experiments just integrate over the entire structure obtaining little or no spatial information, scanning gate microscopy (SGM) allows to probe the 2DEG with high resolution and accuracy both in real space and energy. This measurement technique uses the conducting tip of an atomic force microscope (AFM) to locally gate the nanostructure, while its conductance is measured as a function of the tip position. The method is perfectly suited to probe graphene nanostructures, as some very fundamental mechanisms, like the formation of charge localization inside the narrow constriction, are still subject of intense theoretical debate. Various microscopic mechanisms for the formation of charge localization have been postulated.[8,11–13] Many of these theories make assumptions about the position of the localized charges in real space. Thus, it is promising to combine transport measurements with methods offering spatial resolution.

It has been observed in transport experiments that a so called "transport gap" can be opened if the width of a graphene flake is made small enough.[7,14–16] This transport gap depends strongly on the geometry of the ribbon.[6,7,16] The results of the transport experiments described here are depicted in Fig. 1. The graphene flake was processed by mechanical exfoliation on a Si-SiO_2 substrate.[17] The nanostructure is then defined by electron beam lithography and afterwards etched with reactive ion etching as reported previously.[18] The inset of Fig. 1(a) shows a scanning force micrograph of the nanostructure recorded at ambient conditions. The ribbon has a length of 750 nm and a width of 110 nm. It is contacted via two gold contacts. A source-drain voltage is applied symmetrically and the current through the device is measured. The electric structure can be tuned globally via the backgate and locally via the tip as a movable topgate. If the conductance of the structure is recorded as a function of the backgate-voltage, a linear increase of the conductance on both sides of the transport gap is observed (Fig. 1(a)). The gap-size seen in Fig. 1(a) is compatible to the systematics found by Han *et al.*[7] given the ribbon width. The electrostatic structure turned out to be relatively stable, yet a steady shift of the transport gap towards larger backgate-voltage values could be observed with time. This leads to difficulties in comparing absolute values in backgate-voltage for measurements which were recorded a few days apart. For the data presented in the following the relevant time-scales for the experiment are short enough so that this effect is not relevant.

In the transport gap Coulomb blockade can be observed.[11,13,19] In addition, "Coulomb blockade diamonds" as shown in Fig. 1(b) can be observed. Their shape suggests the presence of several localized charge puddles which act like several quantum dots (QDs). Again the size of the Coulomb diamonds in the source-drain bias direction is compatible with the results of previous experiments on ribbons of similar width.

SGM uses the conducting tip of an AFM to locally induce a potential perturbation into a 2DEG. The structure's conductance is then measured as a function of tip-position. This allows to extract detailed information about the local properties of a nanostructure.

The effect of the voltage-biased tip on transport through a quantum dot has been studied extensively in various material systems, e.g., GaAs, graphene and many other material systems.[9,20–23] Localized charges have been imaged with this technique in InAs nanowires[24–27] and carbon nanotubes.[28,29] Previous experiments show concentric rings, which originate where quantum dots form either due to fabrication or localization in a disorder potential.

In Fig. 2(a), the scanning gate image taken with a tip-sample distance of 20 nm at a temperature of 1.7 K, a

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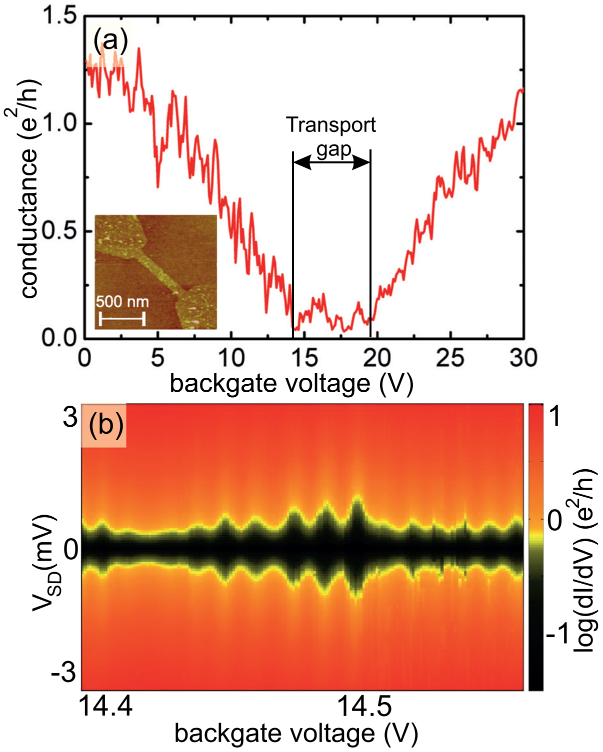

FIG. 1. (a) Conductance as a function of backgate voltage. The transport gap can be seen between 14 V and 19 V. The measurement was taken at 1.7 K with a source-drain bias of 100 μV. Inset: scanning force micrograph at ambient conditions of the nanoribbon under investigation. (L = 750 nm, W = 110 nm). (b) Finite bias measurement in a small range inside the transport gap.

source-drain bias of 100 μV and a backgate voltage of 18 V is related to the lithographic outline (white dashed lines) of the nanoribbon. The tip-voltage of 2 V was determined to be a parameter, where the tip is little invasive.[22] A rich pattern is visible, with a correlation with the ribbon geometry. There are two centers of enhanced conductance in the middle of the structure. If the average conductance over all lines scanned vertically is taken, an increased conductance can be seen at the position of the ribbon (see Fig. 2(b)).

This image also shows very pronounced features which are far away from the nanoribbon. For the tip-induced potential, a Lorentzian shape can be assumed.[20,30] This potential might have tails, which extend for many microns,[31] yet it is surprising that these tails seem to significantly influence the transport through the nanoribbon, leading to features in Fig. 2(a) which have a contrast similar to when when the tip is placed directly on top of the structure. Intuitively, one would expect the tip to have a much more limited influence on the transport through the graphene, when it is placed far from the ribbon on top of the substrate.[32] The complicated patterns can be interpreted by taking into account that the Si-SiO_2-substrate is not expected to be perfect and contains trapped charges. As the field lines emanating from the tip always end on a charge, this might lead to a position-dependent tip-induced potential, which is significantly different from the peaked lineshape that is usually expected for a conical tip. Theoretical estimates have shown that single elementary charges already have a huge influence on the details of the scanning gate image.[20,33] For the tip induced potential, a full width at half maximum between 500 nm and several μm can be estimated.[20] That means that for the experiments presented here, the flank of the peak-potential is still expected to have a considerable effect on transport through the nanoribbon, even if it is placed in a corner of the scan-frame. This was confirmed by scanning the tip at greater distances from the structure, where no influence could be seen any more.

Compared with previous experiments on quantum dots, the pattern is surprisingly complicated, which gives rise to the assumption, that also the mechanism of charge localization is more complicated than anticipated in the first place. The electrostatic potential of the quantum dots might not be totally fixed in their position, they might shift laterally due to the influence of electrostatics,[34] thus, giving rise to smearing of the features. Also the influence of several localized charges on each other is not clear.

To further energetically characterize the quantum dots, which are formed inside the narrow channel, the following technique is used: the same line parallel to the ribbon (blue line in Figure 2) is scanned many times. After each linescan is finished, the backgate voltage V_{BG} is changed by a few mV. The resulting measurement is shown in Fig. 3.

Figure 3(a) shows the raw data, in Fig. 3(b) the results of an analysis are shown, where the blue pixels mark local minima, as found by a numerical routine which determines local minima in y-direction. Figure 3 exhibits a complicated pattern, however, one observes at least two series of curves. (Solid blue Lorentzian lineshapes as guide for the eye manually overlaid using the local minima. Dots mark their centers.) Within each series, the curves are offset in backgate voltage. These series of curves have their maxima at the positions of the regions of enhanced conductance in the area scans. The picture shows that the centers of the curves move in real space as a function of backgate voltage, indicating that they are sensitive to electrostatic influences.[34] The curvature indicates that the tip-induced potential is repulsive for electrons. These findings lead us to propose the intuitive energy scheme shown in the inset of Fig. 3(a) to characterize the transport inside this nanostructure. Transport is dominated by two quantum dots, which are formed at the positions of the maxima of the two families of curves. This

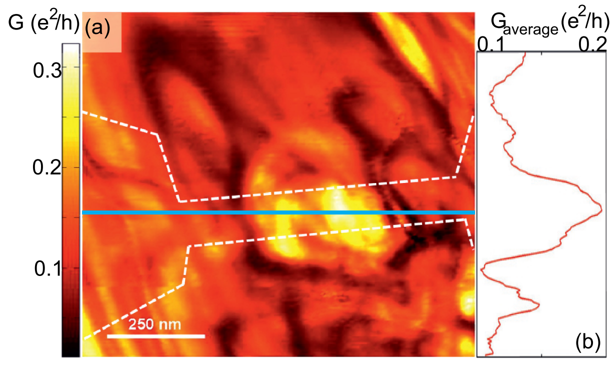

FIG. 2. (a) SGM image of the nanoribbon. The lithographic outline is shown via the white dashed lines. Two centers of enhanced conductance can be seen as bright spots. The rich pattern far away from the graphene structure is attributed to the effect of trapped charges inside the substrate. (b) Averaged conductance over the vertical lines in (a). An increased intensity along the nanoribbon is clearly visible.

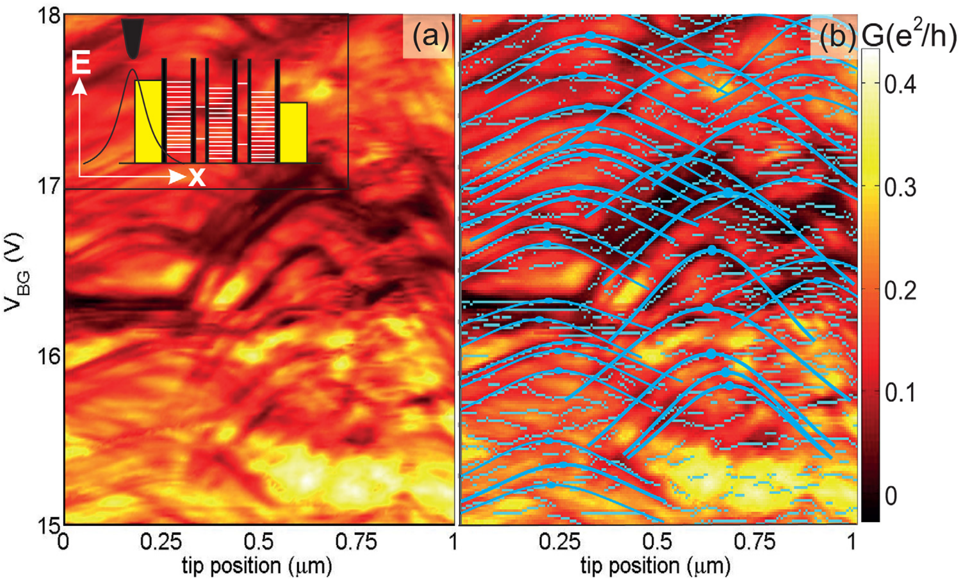

FIG. 3. Linescan parallel to the nanoribbon. After each line is finished, the voltage applied to the backgate is changed. (a) Raw data. Inset: proposed model for interpretation. Transport is dominated by two small quantum dots with large spacing of quantized energy levels. (b) Light blue pixels describe positions of local minima in y-direction as evaluated numerically. The series of Lorentzian curves (solid blue lines as guide for the eye manually overlaid using the local minima. Dots mark their centers.) represent at least two QDs forming inside the structure. The shifting of the centers of the curves indicates that the QDs shift in real space as a function of backgate voltage.

assumption is in good agreement with the transport-data shown in Fig. 2. There might be a few other charge puddles present, which have a rather limited influence on the characteristics. They might be larger, so their level spacing is small. For electron tunneling through this structure, only the most localized puddles with a large level spacing are relevant.

When the tip-induced potential is scanned along a line across a quantum dot, alternately the conditions of electron tunneling will be fulfilled and not fulfilled, thus, a Coulomb-peak like pattern is expected to occur for every line. If the backgate voltage is changed, this leads to a rising or lowering of the ladder of energy states inside the dot. Thus, to fulfill the condition for electron tunneling, a different part of the peaked lineshape of the tip-induced potential will be probed and this change of the energy relations of the quantum dot and the tip will lead to a shifted peak-pattern as a function of tip position. For each quantum dot which is located inside the channel we expect peak shaped curves reflecting the tip induced potential. Thus, this pattern is expected to allow us to characterize the existing QDs with spatial resolution.

The presence of the families of peaked curves, which occur because the tip-induced potential helps to overcome Coulomb-blockade, allows to identify the two sites as QDs. If there were just two local tunnel-barriers present in the structure, such behavior could not be observed.

Scanning gate microscopy proves to be a powerful tool to characterize transport properties of graphene quantum structures. Particularly important is the possibility to find and locate localized sites, which unintentionally form inside a narrow constriction. In the nanoribbon which is examined here, we find that transport must be dominated by two rather small quantum dots, which is consistent with previous transport experiments. Future experiments will have to focus on how to minimize the contrast arising from charges in the substrate.

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