Coulomb blockade in 2DEG potential fluctuations revealed by Scanning Gate Microscopy

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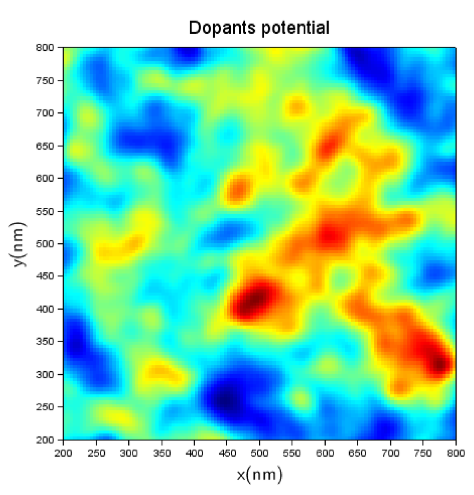
Disorder in mesoscopic devices

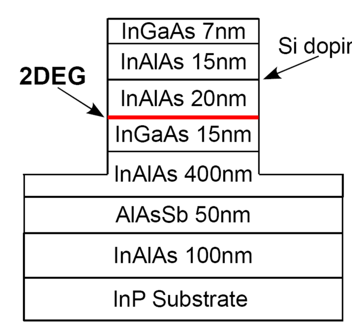
Origin of disorder :

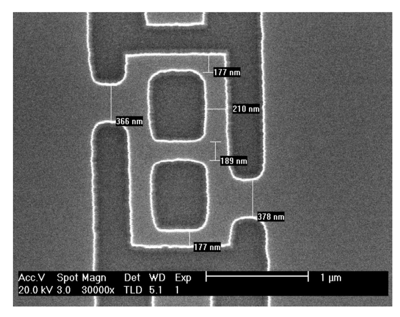
High mobility two-dimensional electron gases (2DEG) use remote doping with dopants at a finite distance.
The random distribution of the ionized dopants induces potential fluctuations in the 2DEG plane.
The length scale of the fluctuations is set by the distance between the 2DEG and the dopants.
The amplitude of the fluctuations increases with decreasing doping density due to lower statistical averaging.
This disorder is responsible for mesoscopic fluctuations in the properties of nanoscale devices.
We present an investigation of this disorder in a mesoscopic device by means of scanning gate microscopy.



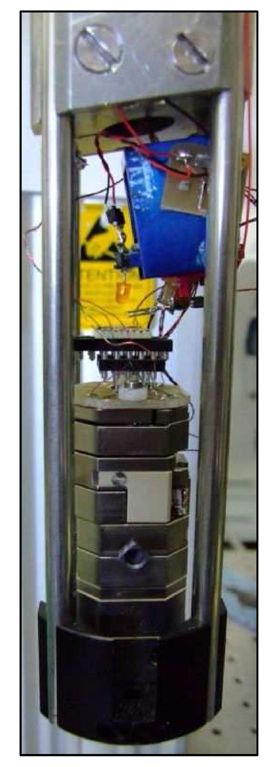
Description of the device :

- InGaAs / InAlAs heterostructure grown by molecular epitaxy
- 2DEG density = 3.5 × 10^{11} cm^{-2} and mobility = 100 000 $cm^2/V/s$
- e-beam lithography and wet etching of a network nanostructure



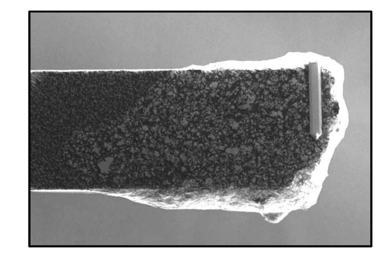


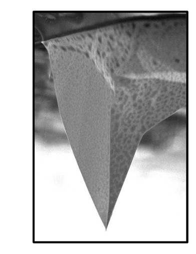
Scanning Gate Microscopy



AFM microscope :

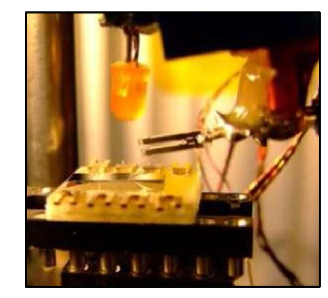
- cryogenic inertial motors and piezoelectric scanner.
- piezoelectric quartz tuning fork used as force sensor.
- Pt-Ir coated tip and cantilever glued on tuning fork arm.

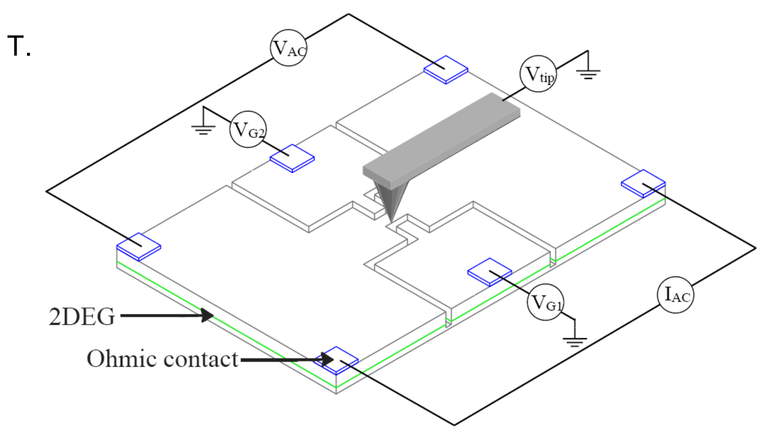




Environnement :

- 4He cryostat on two vibration damping stages.
- central tube at 4.2 K in exchange gas.
- superconducting magnet with field up to 9 T.





Scanning Gate Microscopy (SGM) :

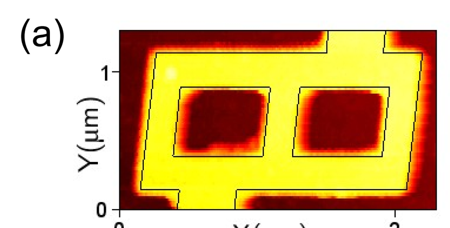
- the AFM tip is used as a local gate flying above the sample surface with a tunable voltage.
- the device conductance or resistance is measured as a function of tip position and tip voltage.

SGM on the network

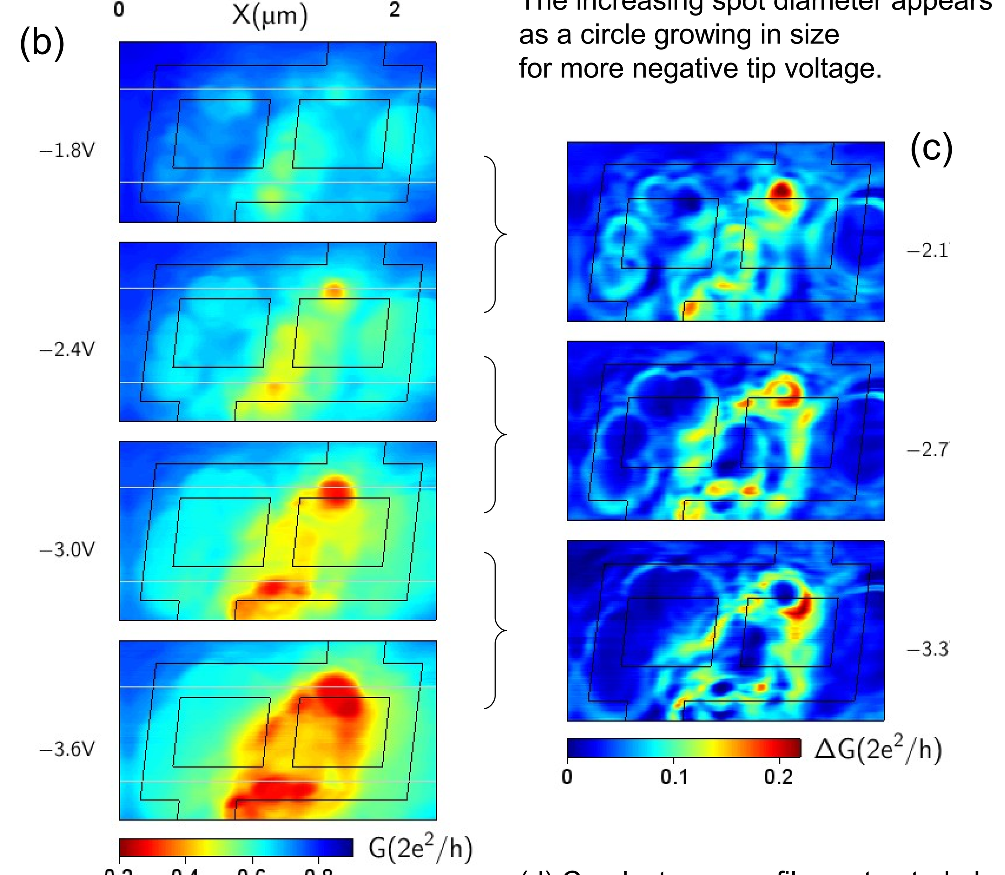
SGM images of the conductance :

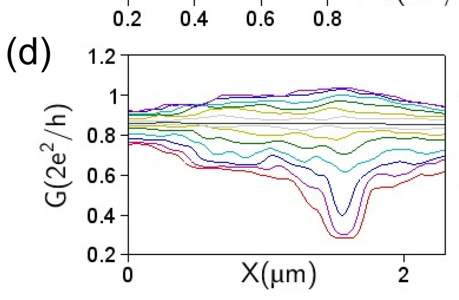
(a) After cooling down to T = 4.2 K, an AFM topography image is recorded. Then, the tip is lifted by 100 nm from the surface and scanned at fixed height.

(b) SGM images are plots of the device conductance versus tip position. The tip is polarized with a finite negative voltage (indicated near each image). The conductance decrease is not uniform along the structure. Several sensitive spots can be recognized with strong local gate effect.

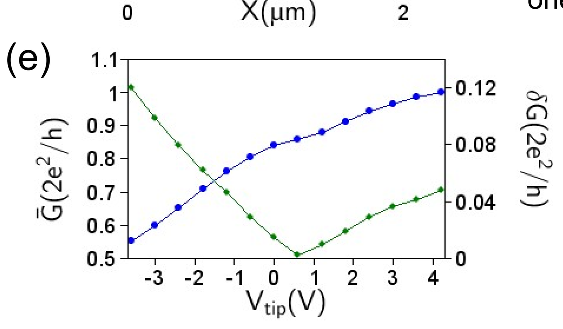


(c) Each sensitive spot is enhanced by plotting the difference between two consecutive conductance images recorded at nearby tip voltages. The increasing spot diameter appears as a circle growing in size for more negative tip voltage.





(d) Conductance profiles extracted along the top gray line for different tip voltages. Negative voltages decrease conductance below the black line. Positive voltages increase conductance above the black line. The unperturbed conductance is around one conductance quantum 2e²/h.

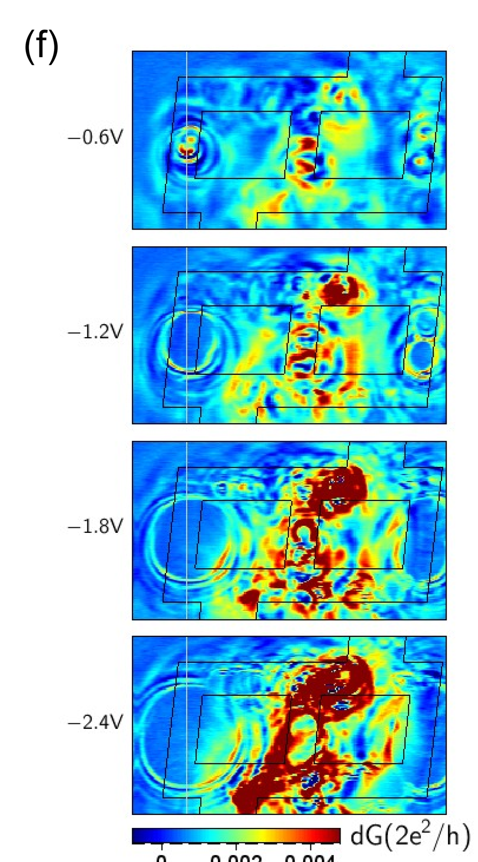


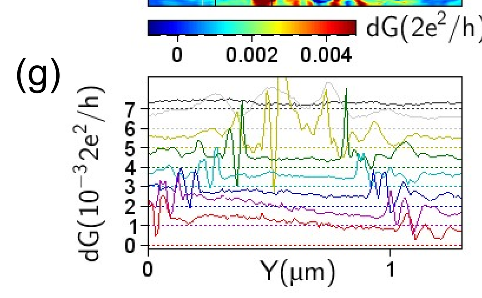
(e) The device conductance averaged over all tip positions decreases almost linearly with negative tip voltages. The conductance variations induced by the tip are minimized at 0.6V due to the work function difference between the tip and the surface.

SGM images of the trans-conductance :

(f) AC-response of the conductance to a tip voltage modulation of 40 mV at 930 Hz. Images show that each spot can be surrounded by several circles with a uniform value inside. This measure of the trans-conductance gives a better resolution of the circular features.

All points at the center of the circles are located above the device arms hosting the 2DEG and never in the etched regions. This fact indicates that the origin of the features are in the 2DEG itself or in the barrier above (not below because of 2DEG screening).

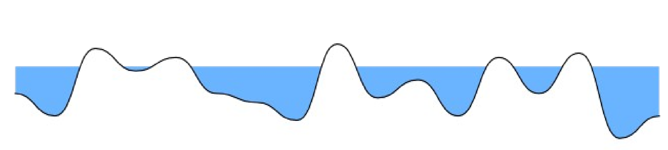




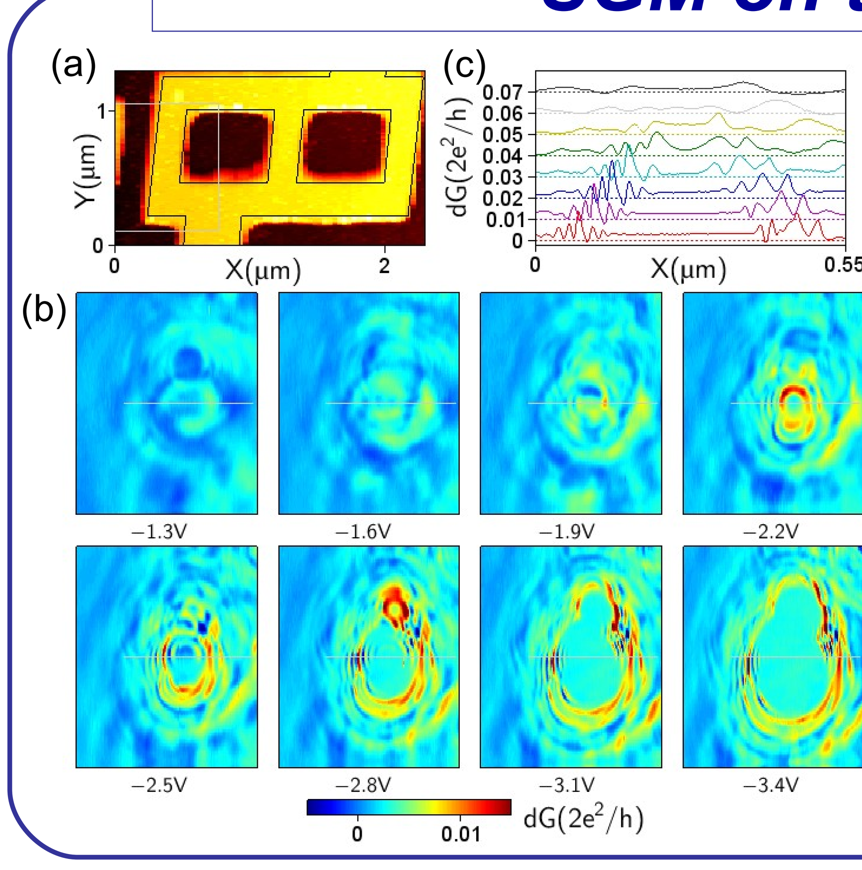
(g) Profiles of trans-conductance extracted along the vertical gray line on the left arm. The signal is dominated by a single spot. The trans-conductance oscillates around a mean value corresponding to periodic increase and decrease of the conductance.

Interpretation :

Localization of electrons in traps of the disordered potential landscape.
Disorder come from random distribution of dopants and surface charges.
The SGM tip brings the potential hills up to the Fermi level and above.
The trap charge is decreased one by one when the tip approaches.
The conductance oscillates probably due to Coulomb blockade.



SGM on the left arm



Evolution of the circles up to full depletion :

(a) Zoom on the left arm as indicated by the gray rectangle. Experiment after an electrostatic discharge that changed the pattern.

(b) SGM trans-conductance images for several negative voltages. Several spots are visible, very close to each others. Each spot presents a series of concentric circles. Below -2.8 V on the tip, the signal disappears inside the circles because the 2DEG is fully depleted in this arm of the network (other arms still contribute).

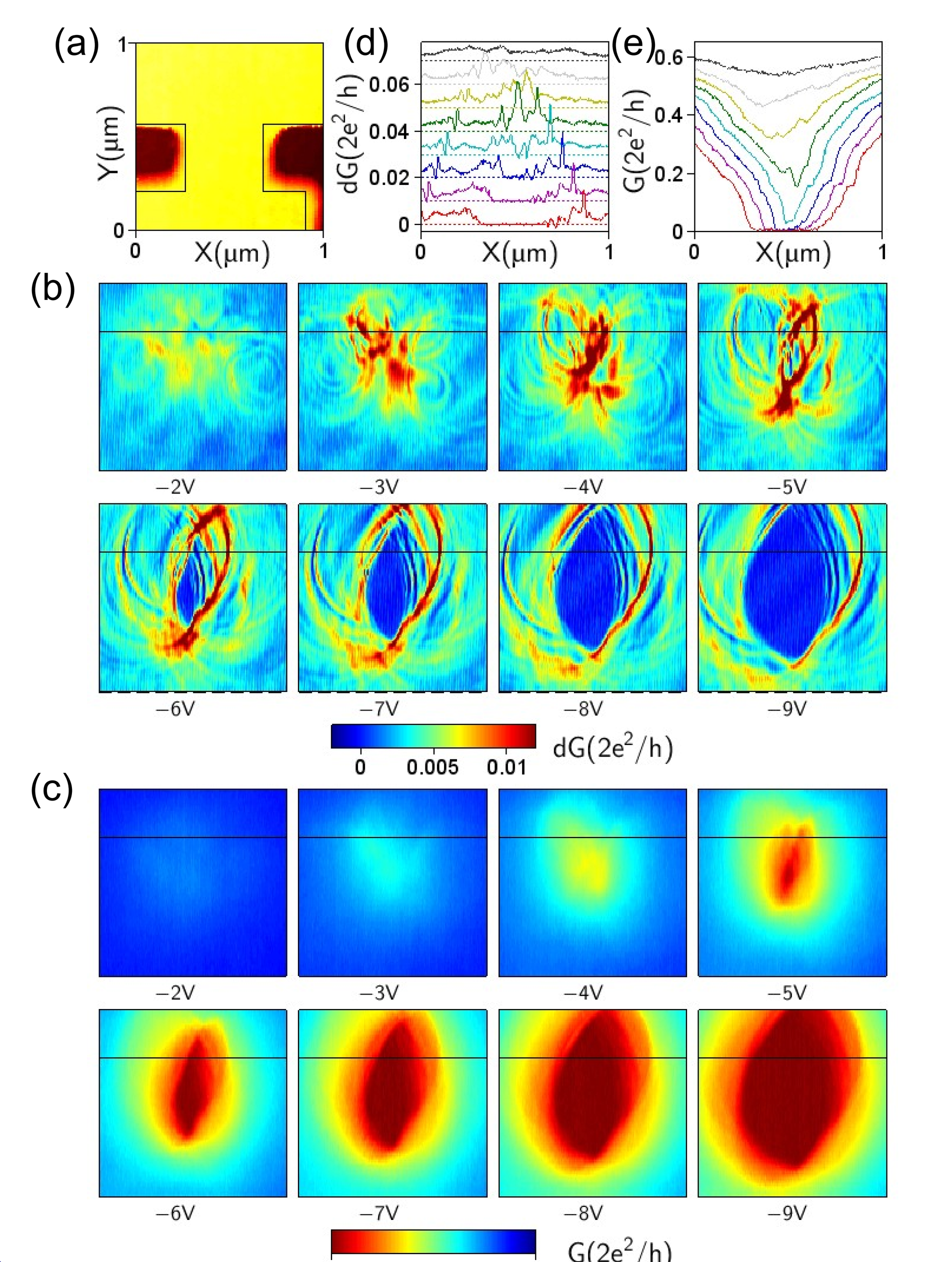
(c) Profiles extracted along the horizontal gray line in the central spot. The oscillating behavior of the trans-conductance appears clearly. The flat region in the middle corresponds to the full depletion of the network arm around the location of the spot. The size of the flat region increases like the innermost circle.

SGM on the top opening

Simultaneous SGM images of conductance and trans-conductance :

(a) Topography of the top constriction, now with strong SGM response, after an electrostatic discharge that changed the pattern.

(b) Trans-conductance images show about five spots arranged in parallel. Several circles appear around each spot due to several trapping of electrons. A region with zero trans-conductance appears below -6 V. This region is delimited by circles belonging to different spots. It corresponds to the overlap of the depleted regions of individual spots.



(c) Conductance images reveal that the current is fully blocked in the region of zero trans-conductance. Each spot corresponding to a conducting path, when all conducting paths are blocked, the current is zero. These spots therefore control completely the transport through the constriction.

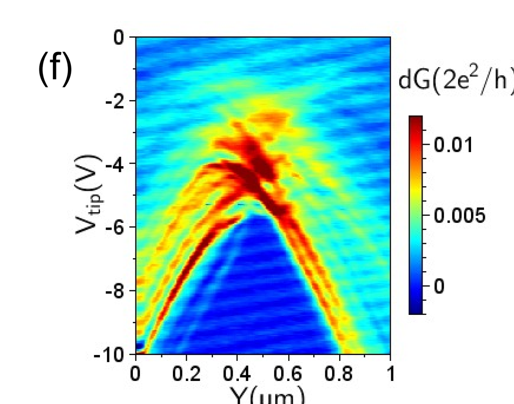
(d-e) Profiles extracted along the horizontal line crossing several spots and the region with full depletion.

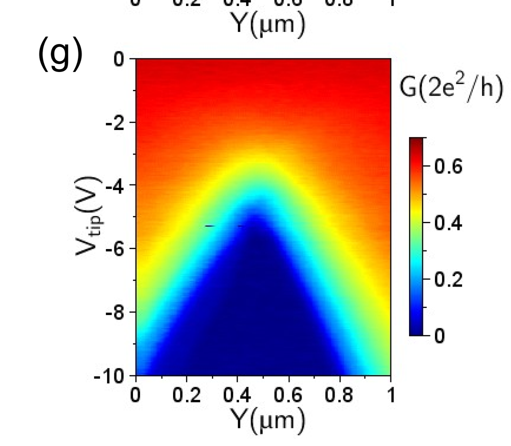
Spectroscopy in tip voltage :

(f-g) Scan of a single line vs. tip voltage (another place). Each trace of constant conductance corresponds to a charge state of the trap. These traces are isopotential lines for the electron trap whose energy writes :

$$E_{trap} = E^0_{trap} - \alpha \frac{eV_{tip}}{\sqrt{R^2 + H^2}}$$

where H is the tip height above the 2DEG and R the horizontal distance to the trap for a simple model of electrostatic interaction.





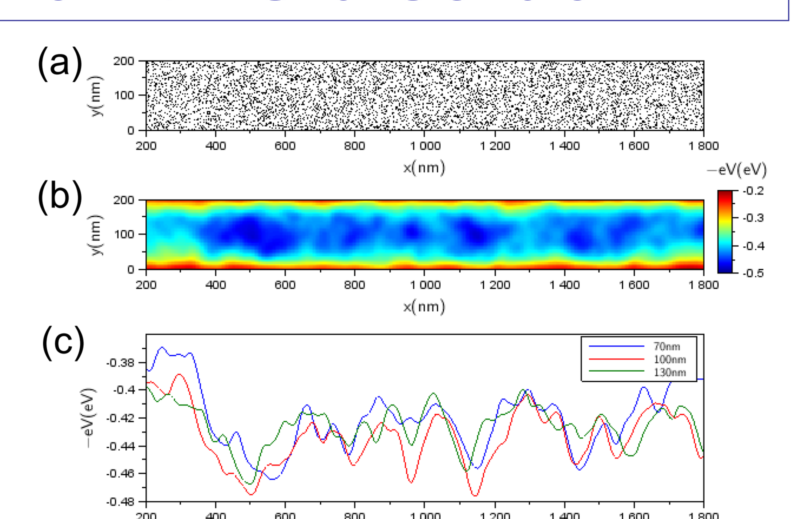
Simulation of the 2DEG disorder

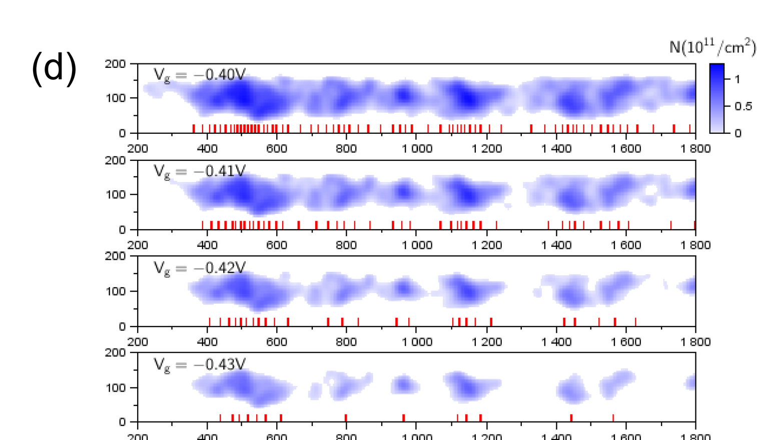
Potential fluctuations due to ionized dopants :

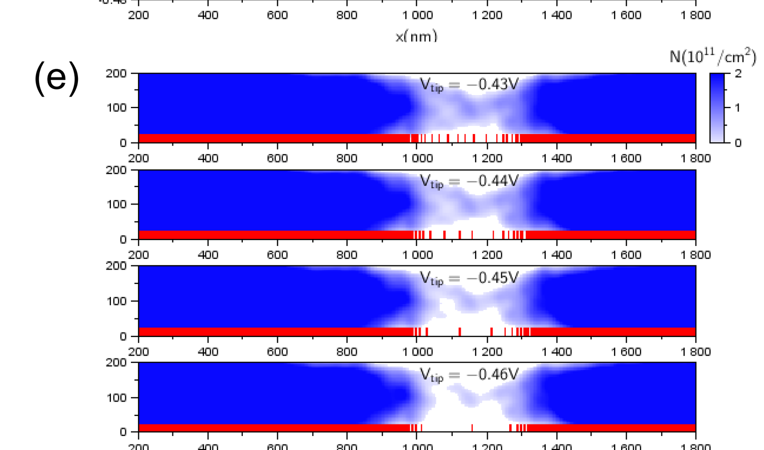
(a) Random distribution of dopants in an infinite wire. Parameters are the same as in the experiment. The doping density is 2x10¹² /cm² (1 dopant / 7 nm).

(b) Electrostatic potential induced by the ionized dopants assuming Fermi level pinning at the conduction band edge of the doped GaAs cap layer at the surface.

(c) Potential profiles along the central part of the wire. The length scale of the fluctuations is about 50 nm related to barrier thickness and not to dopant spacing.







Electron density for a uniform top gate :

(d) Local electron density close to depletion threshold. Each red bar corresponds to the position of one electron. The initial average electron density is 6x10¹¹ /cm². The 2DEG breaks progressively into electron puddles. Consecutive puddles are separated by tunnel barriers. The number of electrons per puddle decreases one by one. This gives Coulomb blockade through quantum dots in series.

Electron density for a local scanning gate :

(e) Local electron density for an SGM tip at X = 1140 nm. Approaching or decreasing the tip voltage brings a local region close to threshold while the remaining part of the wire is unperturbed with large density. An individual electron puddle can be studied and the number of electron inside can be varied one by one. This gives Coulomb blockade through a single quantum dot.

Scanning Gate Microscopy reveals electron traps with Coulomb blockade due to 2DEG potential fluctuations.

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