

Imaging Electron Transport By Scanning Gate Microscopy

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Introduction

By scanning a metal coated silicon cantilever acting as a local gate, it is possible to modulate the potential of a two-dimensional electron gas (2DEG) as well as the electron states beneath the sample surface. In this presentation, we report our observation of electron scattering at liquid helium temperature in an ellipse-shaped mesoscopic device.

Atomic Force Microscopy

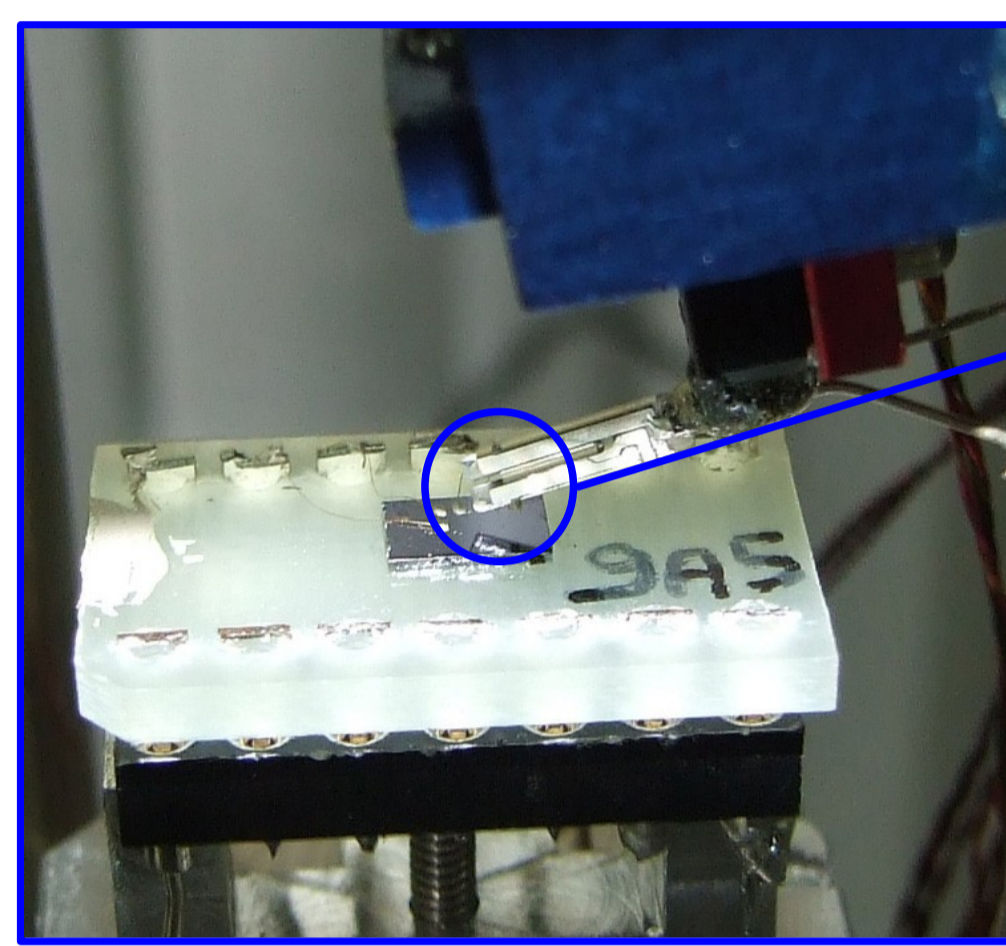


Figure 1: Tuning fork based AFM, piezo driven motor and scanner are placed below sample holder (not shown).

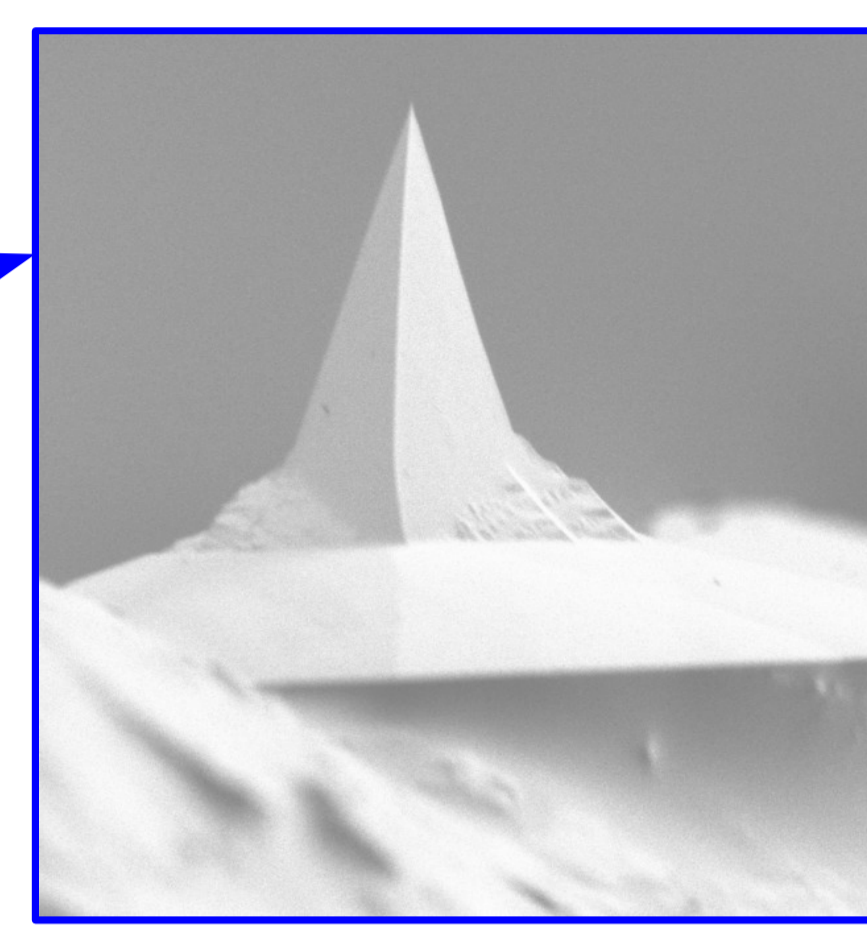


Figure 2: SEM image of silicon cantilever glued on prong of tuning fork.

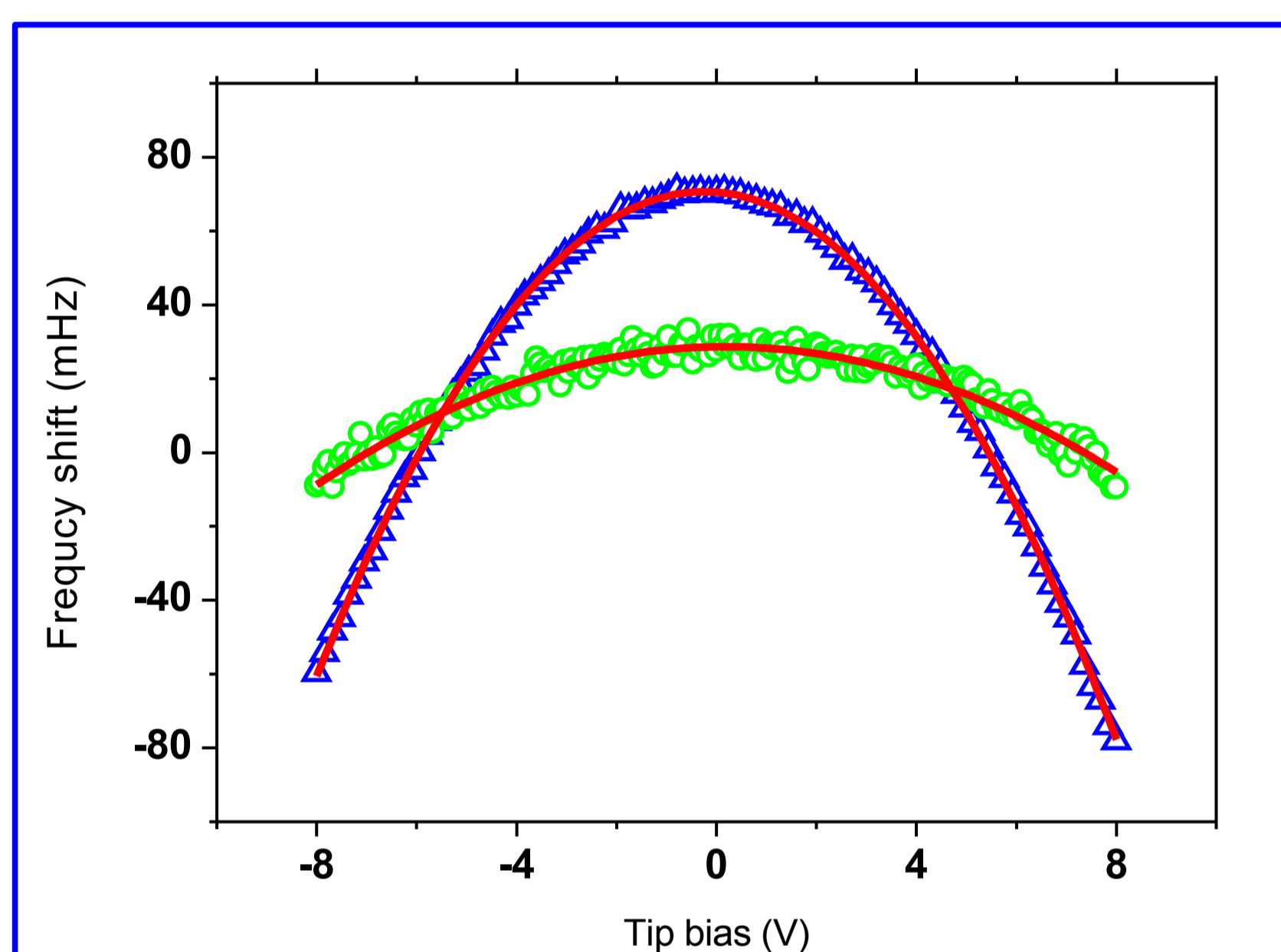


Figure 3: Frequency shift versus bias applied on silicon cantilever, which is placed at a fixed distance (d) above the grounded sample surface.

- Green circle: $d = 30 \text{ nm}$
InAlAs surface
 $T = 4.2 \text{ K}$
- Blue triangle: $d = 50 \text{ nm}$
aluminum surface
 $T = 300 \text{ K}$

Considering capacitive force model:
$$\Delta f = \frac{f_0}{2k} \frac{\partial F}{\partial d} = \frac{f_0}{2k} \frac{\pi \epsilon_0 (V - V_c)^2 R}{d^2}$$

where f_0 and k are the resonant frequency and spring constant of tuning fork ($f_0 \sim 32 \text{ kHz}$), R is the effective curvature radius of the apex part, d is the tip-surface distance, ϵ_0 is the vacuum dielectric constant, V is voltage applied on the tip, and V_c is the contact potential difference between tip and sample.

The fitted formula are:

$$\Delta f = -0.558(V - 0.19)^2 + C_1 \quad \text{InAlAs surface} \quad \Delta f = -2.183(V + 0.245)^2 + C_2 \quad \text{Aluminum surface}$$

These results are consistent with $R \sim 10 \text{ nm}$ and $k \sim 10,000$.

Sample

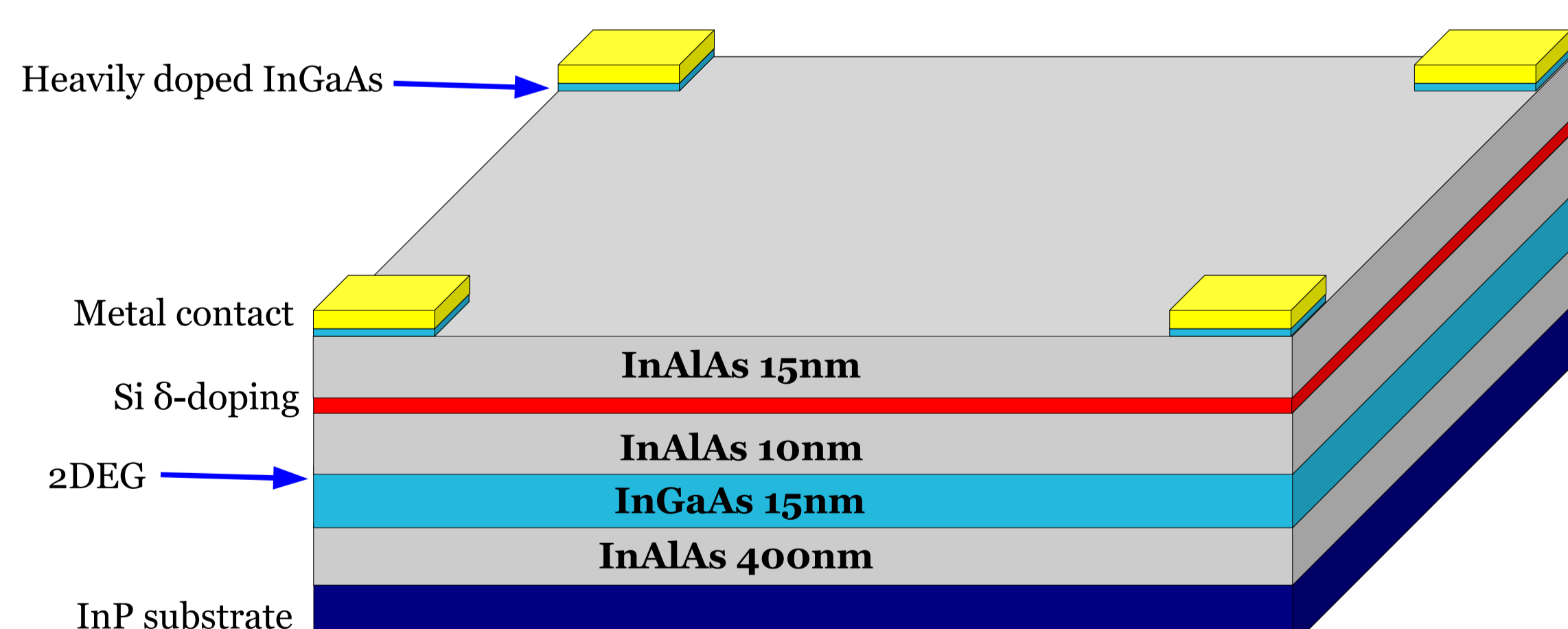


Figure 4: heterostructural devices used in SGM experiments.

The device pattern was defined by electron beam lithography (EBL), followed by wet etching. After deposition of metal contact, the capping layer (doped InGaAs) was removed by solvent.

In dark condition, electron mobility of 2DEG at 4.2K is about $10^5 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$

Scanning Gate Microscopy

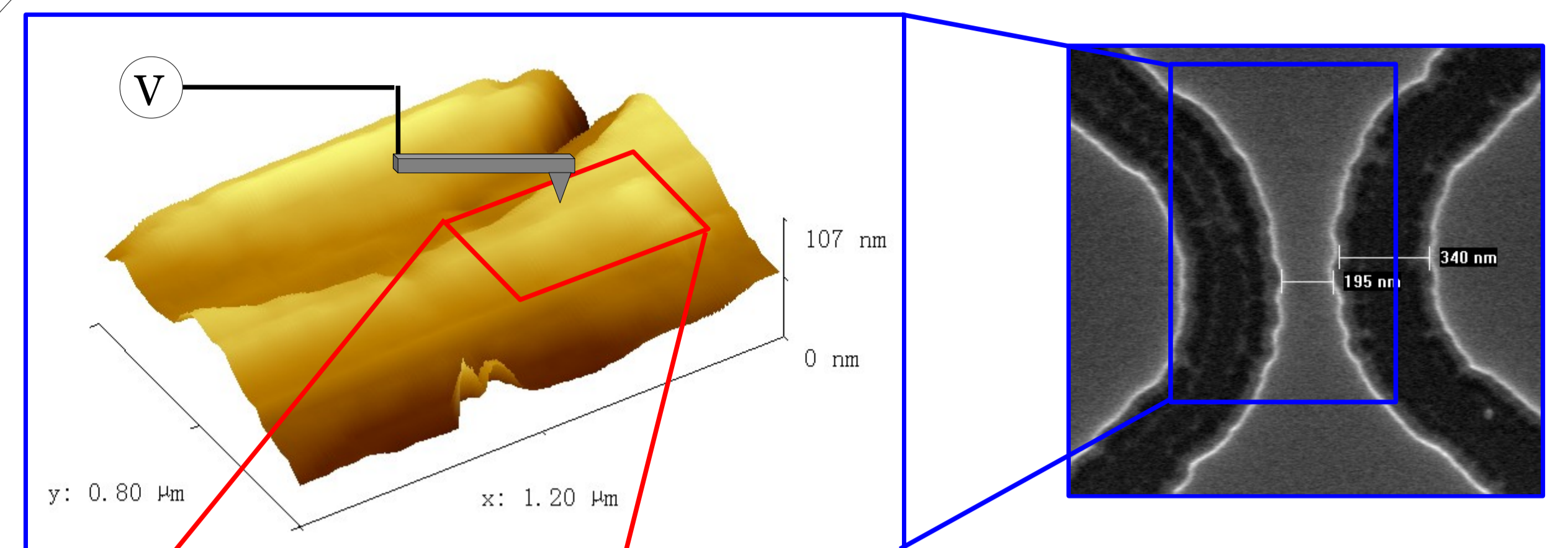


Figure 5: schematic of SGM working principle

Figure 6: SEM image of constriction device.

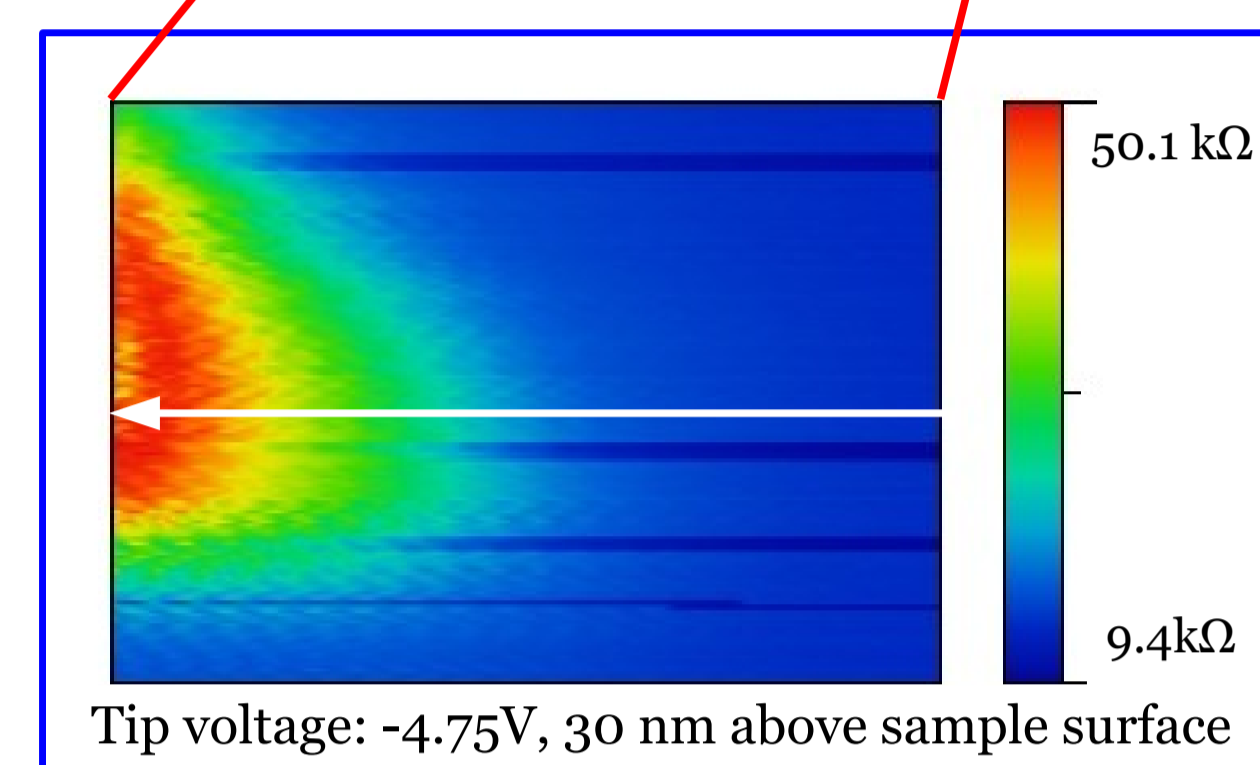


Figure 7: obtained conductance map. Scanning area: $350 \times 500 \text{ nm}$

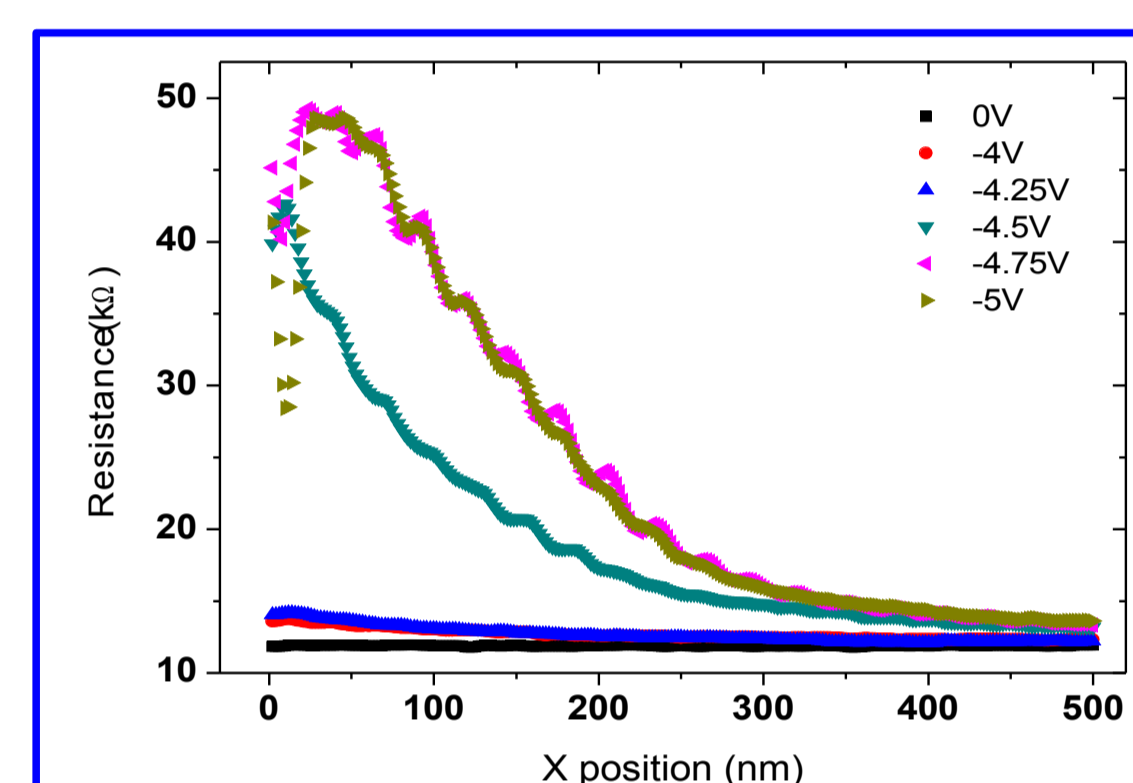


Figure 8: profile along arrow in Fig. 7, for different tip gate voltages.

Why SGM:

- Capability of both topography imaging and investigating the transport properties of electrons underneath of insulating layers, i.e., 2DEG in semiconductors.

Working principle of SGM:

- Scanning a biased tip parallel to 2DEG, at a constant distance, and recording the conductance at the same time, to build a map of conductance as a function of tip position and bias voltage.

The effect of tip gate:

- Modify the electrostatic potential felt by the transmission electrons in nanometer scale.

Results In Ellipse Device

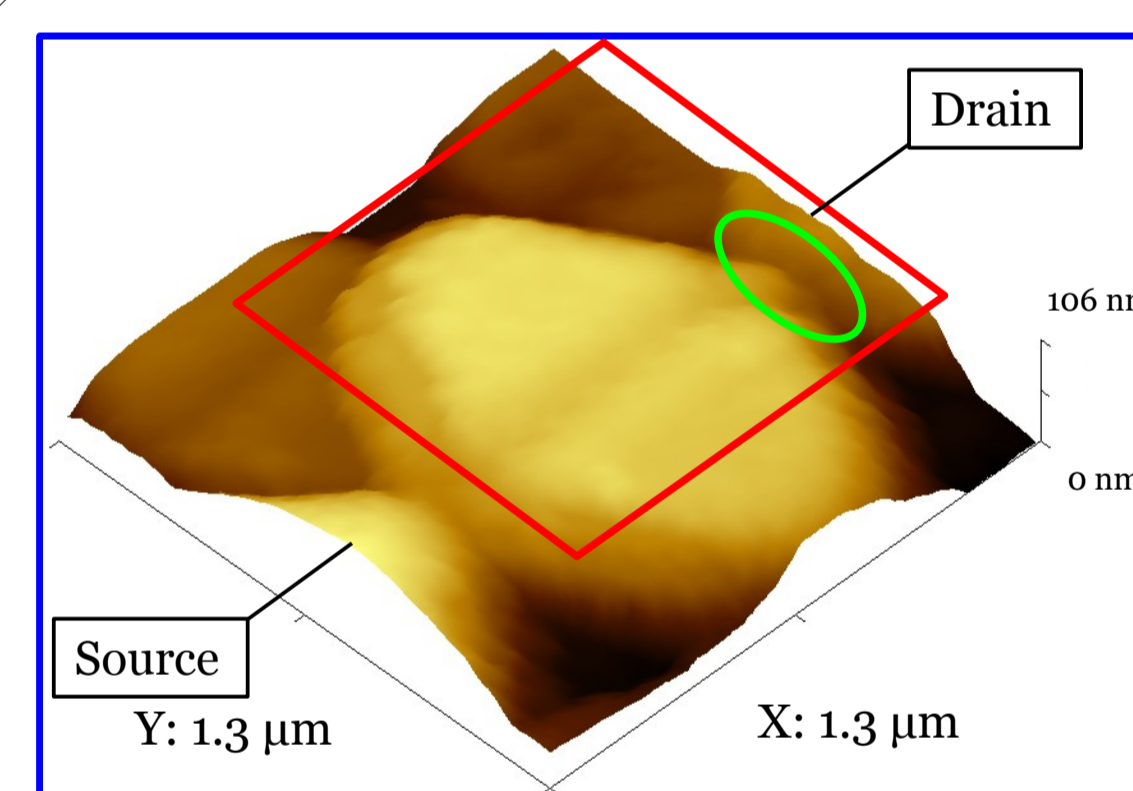


Figure 10: 3D image of ellipse device

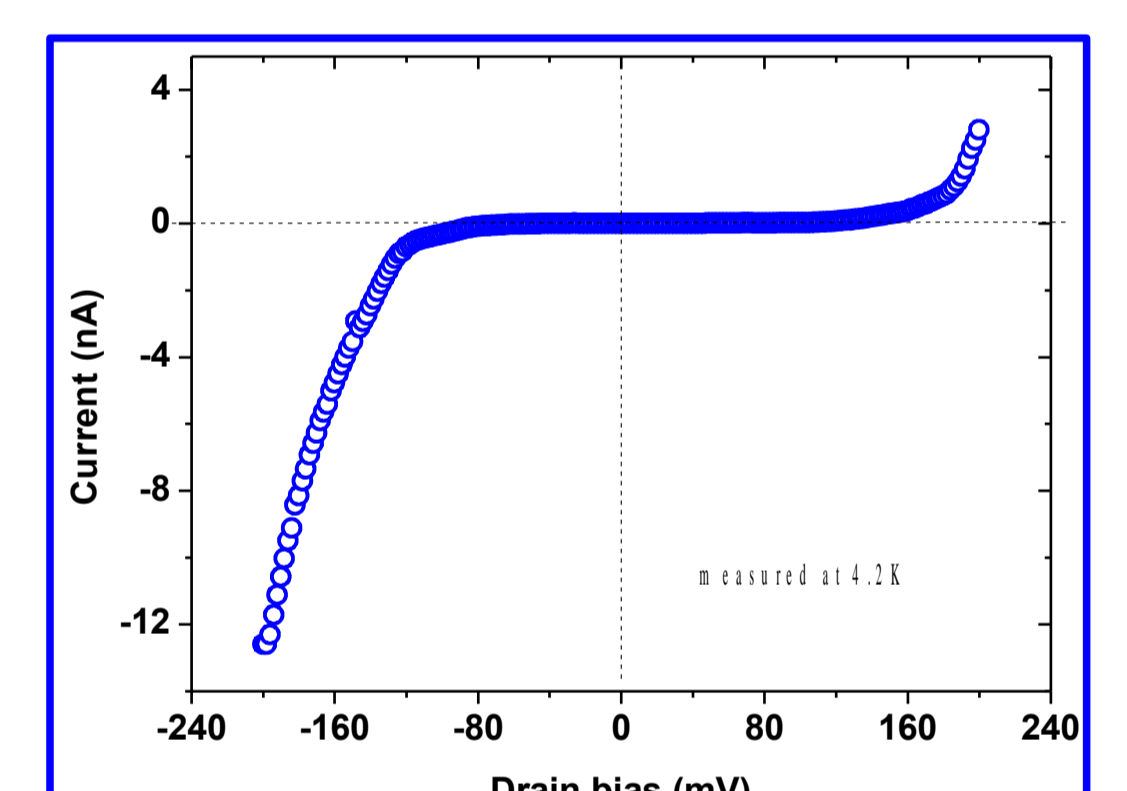


Figure 11: $I-V$ characteristics of ellipse device.

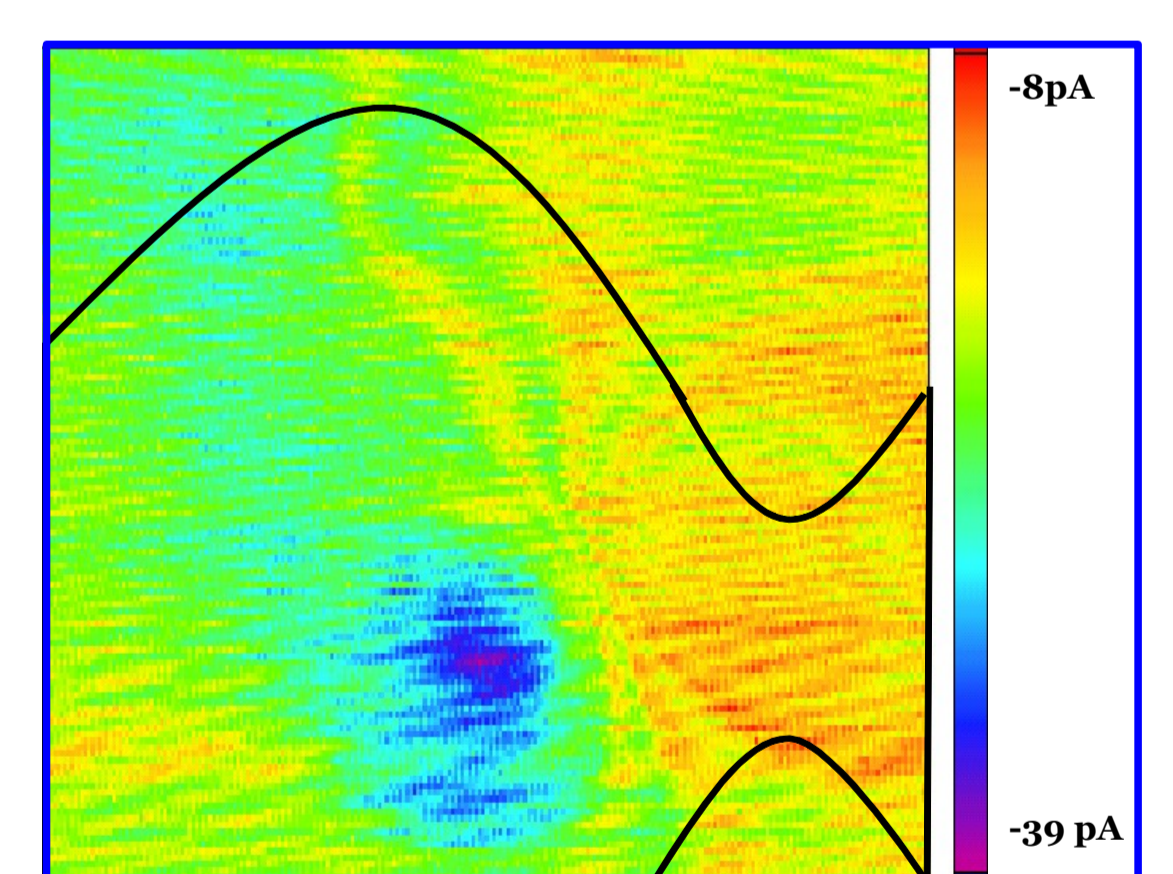
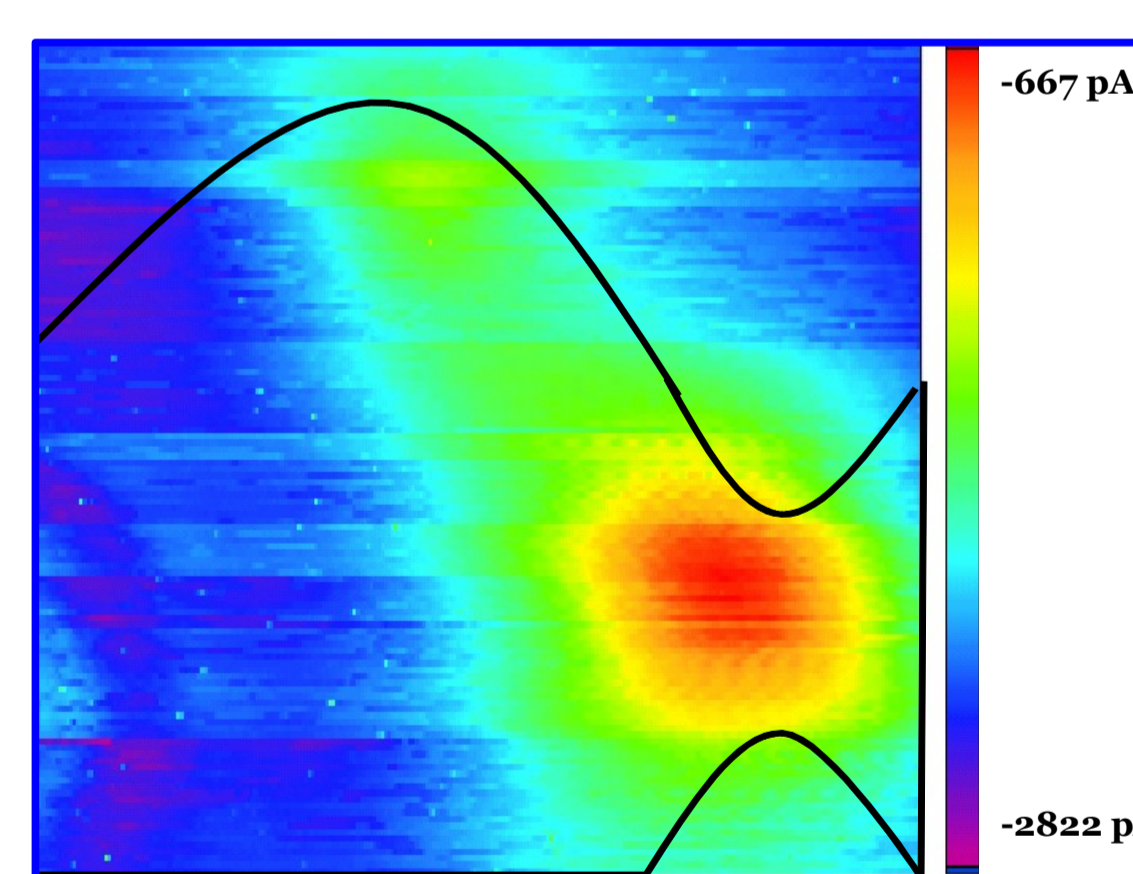


Figure 12: SGM image: $V_{\text{drain}} = -150 \text{ mV}$, $V_{\text{tip}} = -1 \text{ V}$ (left); $V_{\text{drain}} = -50 \text{ mV}$, $V_{\text{tip}} = +1 \text{ V}$ (right). Tip 30 nm above sample surface. Scanning area $1 \mu\text{m} \times 1 \mu\text{m}$, denoted by red square in Fig. 10. Black lines denoted ellipse and one constriction.

- Depletion induced by a shallow trench (denoted by green circle in Fig. 10) might be the origin of potential barrier, which can be seen in the $I-V$ curve of Fig. 11.
- Negative tip voltage induced a large current drop at the constriction due to an increase of the potential barrier (Fig. 12 left). Positive tip voltage induced a large current increase when the tip inside the ellipse (Fig. 13 right). We also observe current oscillations making a set of lines around this region. This suggests that the current is blocked by negative charges in a trap located somewhere in the heterostructure, with a number of charges changing one by one when the tip moves, due to a Coulomb blockade effect in the trap. When the tip is just above the trap, the positive voltage of the tip compensates the effect of the charges, explaining the large current increase.