
ELECTRON TRANSPORT THROUGH SINGLE-BISMUTH TRANSISTORS

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ABSTRACT

THE NEED FOR QUANTUM COMPUTATION IS BECOMING MORE RELEVANT EACH DAY. ELECTRON SPINS BOUND TO A DOPANT IN SINGLE-ATOM TRANSISTORS ARE ONE WAY TO REALIZE THE FUNDAMENTAL COMPONENT FOR QUANTUM COMPUTATION: THE QUANTUM BIT. NOW AN IMPORTANT STEP TO TAKE IS FINDING THE IDEAL DOPANT FOR THESE TRANSISTORS. HERE, WE STUDY ELECTRON TRANSPORT THROUGH ELECTRON STATES OF INDIVIDUAL BISMUTH ATOMS IMPLANTED IN SILICON. THE DEVICES MAKE USE OF MULTIPLE DIFFERENT GATES THAT PROVIDE A HIGH-LEVEL OF CONTROL OVER THE MEASURED REGION IN THE DEVICE. WE SUCCESSFULLY IDENTIFY TRANSITIONS CORRESPONDING TO CHARGE STATES OF SINGLE-ATOMS. A DEVICE IS FOUND OF WHICH THE CHARGING ENERGIES OBSERVED FALL WITHIN THE EXPECTED BOUNDARIES FOR SINGLE BISMUTH DONORS IN SILICON-BASED GATED NANOSTRUCTURES.

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Chapter 1

Introduction

1.1 Background

In 1965 Gordon Moore first predicted that the amount of components on an integrated circuit would double every year for at least a decade. 10 years later he revised his statement to a doubling every 2 years for the foreseeable future and it came to be called Moore's law [1]. This law has been used by the semiconductor industry as a guideline for long-term planning of research and development. However, we are coming closer and closer to the point where transistors, which are the main components on an integrated circuit, can not be made any smaller. So instead of decreasing the size researchers are trying to realize a quantum computer.

The first quantum computer was proposed by Kane in 1998 [2]. This was a silicon-based nuclear-spin quantum computer which would use both the nuclear spin of ^{31}P and the electron spin to make single quantum bit (qubit) operations. Based on this a lot of research has been done towards realizing qubits that can ultimately be used to perform quantum computations.

Devices using single atoms are strong candidates for solid-state quantum computer architectures. A single-atom transistor gives control over the electron transport and can thus be used to isolate a single electron. Such devices have shown long spin coherence times, which is essential for efficient quantum computations [3]. Single atom devices are also compatible with existing complementary metal oxide semiconductor (CMOS) technology. These devices can then be implemented in pure ^{28}Si , which has zero nuclear spin and provides coherence times that are without peer in the solid state [4].

1.2 State of the art

Different aspects of single-atom transistors in silicon have already been researched. Phosphorous and arsenic are the most widely used donors in these devices.

Tan et al. have resolved transitions corresponding to two charge states successively occupied by spin down and -up electrons. They have found charging energies close to half of those expected of phosphorous in bulk, which is consistent with the expectations for donors in gated nanostructures [5]. Fuechsle et al. use the tip of a scanning tunneling microscope to selectively desorb hydrogen atoms that are located on their substrate. After this they dose the surface with phosphine gas

which adsorbs onto the exposed substrate. This way they are able to create a single-atom transistor where the phosphorous dopant was deterministically placed in the device with a spatial accuracy of one lattice site. For this device they found charging energies very close to those expected of phosphorous in bulk, which is attributed to the fact that their atom is less influenced by external effects because it is encapsulated in an epitaxial silicon environment [6]. The single-shot, time-resolved readout of an electron spin in silicon for a phosphorous dopant has also been shown, with a spin lifetime of ~ 6 seconds in a magnetic field of 1.5T. A readout fidelity has been found for ^{31}P better than 90 per cent [7, 8].

Arsenic has also been tested to see if it could be used as dopant for a single-atom transistor. The effect of a single arsenic dopant atom on the room-temperature of a device has been tested by Pierre et al. [9]. They found that the ionization energy of the dopant had increased compared to the value in bulk, which they attributed to its proximity to the buried oxide, and this explains the large variability seen in nanoscale transistors. Voisin et al. have shown that they could control the ionization state of three arsenic donors [10]. They have done simulations and experiments that allowed them to resolve the electronic transport signatures of three doubly occupied states As^- at strong electric fields. A lot of transport measurements have been done by Lansbergen et al. who have shown that the gate potential of a standard one-gate structure can be used to control the degree of hybridization of a single electron donor state between the nuclear potential of its donor atom and a nearby quantum well. They were also able to correctly determine the species of donor using their tight-binding model implemented in NEMO 3D [11].

For bismuth doped silicon the research has been more focused on the decoherence time. Morley et al. have found that the electron spin coherence time is at least as long as for phosphorous doped silicon with non-isotopically purified silicon [12]. They also demonstrated quantum control over states in 32 ns. They noted that the coherence times are limited only by superhyperfine couplings to naturally occurring non-zero nuclear spin isotopes [13]. A special regime of ‘cancellation resonances’, where a component of the hyperfine coupling is in resonance with the external field, was found by Mohammady et al. This regime was shown to have beneficial consequences for quantum information applications, such as the reduction of decoherence, fast manipulation of the coupled electron-nuclear qubits, and spectral line narrowing [14]. Wolfowicz et al. have shown particular spin transitions, inherently robust to external perturbations, that can be observed for electron spins in the solid state using bismuth donors in silicon. These spin transitions can lead to dramatic enhancements in the electron spin coherence time. They have found that electron spin qubits based on these transitions are less sensitive to the local magnetic environment. These transitions can be of significance for donor spins in nanodevices, removing the effects of magnetic field noise that comes from nearby interfaces and gates [15].

1.3 Aim of this research

In this research we aim at measuring electron transport through transistors comprising a single Bi atom. We want to find an approximation of the amount of times single atom signatures can be found in a field effect transistor with a dose of $1 \cdot 10^{11}$ bismuth atoms. cm^{-2} . This study might give an indication of the viability of this dose, i.e. if this is the optimal dose or if it would be better to take a lower or higher dose. We expect to find a much larger charging energy for bismuth than for phosphorous or arsenic, which would make it easier to distinguish in measurements.

Chapter 2

Theory and Device

Introduction

This section will explain most of the necessary theory to understand the workings of the single-atom transistors studied in this project.

2.1 Classic Transistor Operation

When looking for single-atom characteristics in single-atom transistors it is important to understand the fundamental physics that are at work. Figure 2.1 shows a cross sectional cut of a basic metal-oxide-semiconductor field-effect transistor (MOSFET). A basic transistor consists of three terminals (source, drain and gate) and a substrate. The substrate is located between the source and the drain and the density of free electrons in this substrate can be varied using the gate. The gate is disconnected from the substrate, by a thin insulating layer. When the gate voltage (V_G) is zero the substrate will be insulating and no electrons should be able to move through, but as the potential on the gate electrode is increased the positive potential on the gate will force electrons to the gate-insulator interface, which leaves a carrier-free region of positively charged acceptor ions. This way the gate can induce a channel in the substrate. Electrons will be able to move through this channel between the source and the drain when V_G is higher than the turn-on voltage of the transistor, thus creating a current [16].

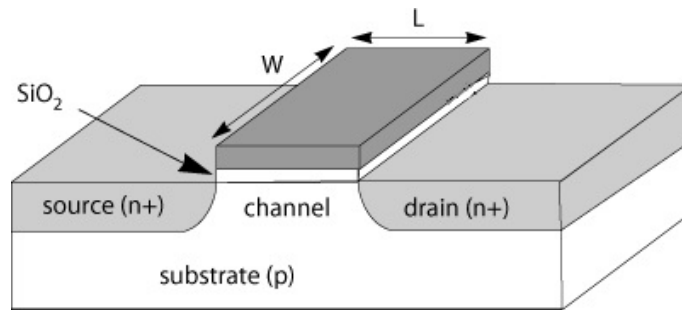


Figure 2.1: Cross section of a basic transistor. From [17]

2.2 Quantum Transistor Operation

Classical physics are no longer sufficient when devices reach the size of several tens of nanometers. For this size range an understanding of quantum mechanics is necessary. Quantum mechanics adds several concepts which are important to understand how a single-atom transistor functions.

2.2.1 Quantum dots

Potential barriers can be used in a nanotransistor to create an ‘island’ where electrons can be confined. Such an island is called a quantum dot. The amount of electrons in a quantum dot can range from a single electron to a couple of thousand. These electrons are only able to interact with the other electrons confined in the dot. The confinement of a small number of electrons in all spatial directions results in a quantized energy spectrum [18]. Unintentional quantum dots can occur naturally during the fabrication of a device. These unintentional quantum dots can display similar electrical signatures compared to single atoms, thus making the interpretation of the results a lot harder.

2.2.2 Discrete energy levels

When reaching extremely low temperatures it becomes possible to see discrete energy levels. Discrete energy levels are always present, but they are unobservable if the system is not abiding to certain conditions. The first condition is that the thermal energy of the electron $K_B T$, with K_B being the Boltzmann constant and T is the temperature, should be smaller than the Coulomb energy $\frac{e^2}{2C}$, with ‘e’ being the charge of the electron and C the sum of all the relevant capacitances. The Coulomb energy is the energy that is needed by an electron to move to a quantum dot. The second condition is that the tunnel effect should be too low to cause the charge of the tunneling electrons to become delocalized over the electrodes. For an electron to be able to hop onto an island, its energy needs to equal the Coulomb energy. So if the source-drain potential is zero, electrons are unable to enter the island, as there is not enough energy available. If the bias voltage is increased the energy in the system will at some point equal the Coulomb energy and then an electron can pass through the island. The critical voltage needed to transfer an electron onto the island, $\frac{e}{C}$, is called the Coulomb gap voltage. Figures 2.4.I-V show different potential landscapes for a donor. Here the discrete energy levels are indicated by μ_D [16].

2.2.3 Tunneling

In a quantum system an electron is able to ‘tunnel’ through a potential barrier. This tunneling means that even though the electron does not have enough energy to pass the barrier it is able to ‘borrow’ energy from the environment and still pass through the barrier. Tunneling can partly be interpreted using Heisenberg’s uncertainty principle $\sigma_x \sigma_p \geq \frac{\hbar}{2}$, which dictates that there is always a non-zero chance that something happens. So, there is always a non-zero probability that an electron will appear on the other side of a potential barrier, which means that electrons will appear on the other side of the potential barrier with a relative frequency proportional to this probability. Tunneling can happen with both the potential barriers of quantum dots or atoms. Tunneling can also occur when the system is between two discrete energy levels. There should not be enough energy for electron transport, but this can arise from higher-order tunneling processes. This can occur if two or more electrons participate in the process. This is called co-tunneling and

it occurs via intermediate virtual states on the dot, which can only be occupied for a time $t_H \simeq \frac{\hbar}{E_c}$ which is also limited by Heisenberg's uncertainty principle [19].

2.2.4 Electron Transport

Most often some conductance peaks can be observed before V_G reaches the turn-on voltage of the transistor. Rather than being caused by electrical noise these conductance peaks can be attributed to the presence of e.g. dopants or defect states in the channel. For larger transistors these fluctuations are always averaged out, but in nanoscale transistors these conductance peaks become more apparent, because there are only several defects or atoms causing the peaks.

Figure 2.2 shows the three types of transport that can contribute to conductance in nanotransistors. The first type of transport, Mott hopping, occurs when an electron hops via several localized states between source and drain. This type of transport decreases exponentially with temperature. When electron transport occurs via direct tunneling it tunnels directly from the source to the drain, without occupying or being scattered by localized states between source and drain. This type of transport decreases if the barrier height or the length of the channel is increased. The last, and for this research most important type of transport, is transport through a single defect. The conductance peaks caused by resonant tunneling through a single defect can give hint as to whether the transport is through a single atom or a different kind of defect [20].

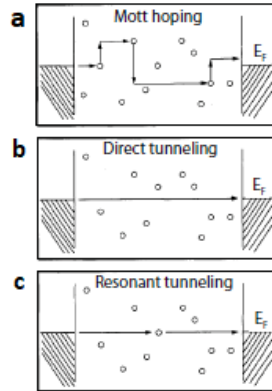


Figure 2.2: Three major methods of electron transport. **a.** Mott hopping via several localized states, **b.** Direct tunneling from source to drain. **c.** Resonant tunneling through a single defect state. From [21]

2.2.5 Coulomb Interactions

The figure 2.3 is a schematic depiction of the source-drain current (I_{SD}) as a function of V_G and the source-drain bias voltage (V_{SD}), this kind of figure is called a charge bias spectroscopy. The red and blue lines indicate lines of conductance. Charge bias spectroscopies provide information about the amount of states in the system, the respective charging energies (E_c) and relative capacitances. This information in turn is very useful when trying to find out what is being measured, e.g. a quantum dot or a single-atom. The height a diamond in a charge bias spectroscopy is equal to the charging energy of that diamond. For quantum dots the charging energy of the first diamond is

generally around 10meV [22].

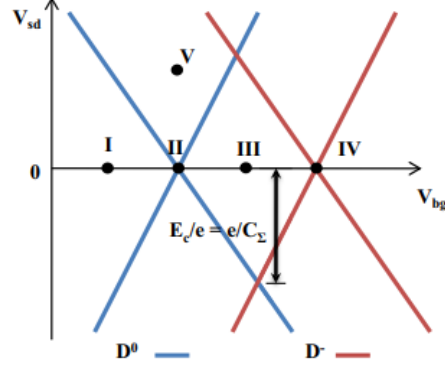


Figure 2.3: Schematic of a charge bias spectroscopy of a one donor system. The height of the diamond, $\frac{e}{C_\Sigma}$, is also known as the charging energy. From [23]

Figures 2.4.I-V show different potential landscapes of a donor atom. Here μ_s and μ_d are the chemical potentials of the source and drain respectively and μ_D shows the energy levels of the donor. The level of μ_D can be tuned up or down by changing V_G . In this system current is only able to flow if at least one single quantized charge state (μ_D) is available within the energy window defined by μ_s and μ_d . If there is no quantized charge state available no current can flow between the source and drain and the system is in so-called Coulomb blockade.

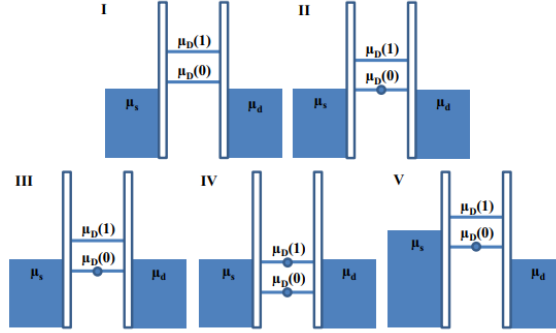


Figure 2.4: The electrochemical potentials of the one donor system seen in figure 2.3. From [23]

Inside the charge bias spectroscopy of figure 2.4 are roman numerals (I-V) that correspond to potentials of the potential landscapes. Points I, II, III and IV all are at $V_{SD} = 0$ and at these points $\mu_s = \mu_d$. At points I and III the system is in Coulomb blockade. For I $\mu_D > \mu_s \geq \mu_d$, there has not yet been an energy level within the boundaries set by μ_s and μ_d . At III there has been an energy level within those boundaries, namely at II, and thus $\mu_s \geq \mu_d > \mu_D(0)$. Points II

and IV are the transition points, where there is an energy level between μ_s and μ_d . Point II is the $N = 0 \rightarrow N = 1$ transition and here $\mu_D(0)$ is between μ_s and μ_d , while point IV indicates the $N = 1 \rightarrow N = 2$ transition so the relevant energy level is $\mu_D(1)$. V is located at a positive V_{SD} , where the chemical potential of the source is raised and at this point $\mu_D(0)$ is between μ_s and μ_d , and there is a finite current [24].

2.3 Single-Atom Transistor

An important theoretic difference between single-atom transistors and quantum dot is in the amount of electrons they both can take on. A single-atom can only take on a few electrons, while the amount of electrons in a quantum dot can go up to thousands. Most single-atom transistors are made using phosphorous, arsenic or bismuth. This is because the addition of these donors to the silicon crystal results in electron states that are close in energy to the conduction band but weakly bound to the donor site at low temperatures. These dopant atoms have three charge states in silicon: an ionized D^+ state, a neutral D^0 state and a negatively charged D^- state. In a charge stability diagram like Figure ?? these charge states would show as three diamonds, the $N=0$ being the D^+ state (which is a non closing diamond), $N=1$ is the D^0 state and $N=2$ the D^- state.

The devices measured for this research are single-atom transistors using bismuth as the donor. The atom should be recognizable in the measurements due to it having a high binding energy of 70meV, compared to phosphorous (~ 45.6 meV) [25]. The binding energy is different from the charging energy. The binding energy is the minimum energy required to disassemble a system of particles into separate parts. The charging energy is equal to the binding energy of the first transition of a device minus the binding energy of the second transition [24], with an environmental factor. The environmental factor is mostly the proximity of the dopant to the Si-SiO₂ interface, and for devices like ours that have the dopant close to the interface we expect this factor to approximately half the charging energy [26].

2.4 Device

For this study, we measured devices comprising a field effect transistor (FET), with 11 tunable gates. Figure 2.5 shows a cross sectional view of a similar device, only showing three of the gates (Lead, B1 and B2). In this figure the n++ regions are the source and drain, which are doped with a high concentration of phosphorous to make them conductive. The lead gate is metallic, has a height of 30 nm and spans the entire device, it is disconnected from the channel by 7.5 nm of insulating SiO₂ (shown as ‘Oxide’). Additionally the FET also has two barrier gates (B1 and B2). These barriers are 30 nm wide and 15 nm high, the insulating layer between the barriers and the lead gate is 5 nm Al₂O₃. The lead gate is able to induce a two-dimensional electron gas (2DEG) at the Si-SiO₂ interface, thus being able to connect the source and drain regions [27]. B1 and B2 can be used to deplete the 2DEG underneath them and in this way control the electrical potential in these regions. The 2DEG underneath the barrier gates should be depleted if the gates are kept at 0V, because this part of the channel is almost only influenced by the barriers and the lead is further away. The lead can eventually open the channel and allow current to flow from source to drain, but for this the voltage applied on the lead needs to be very high.

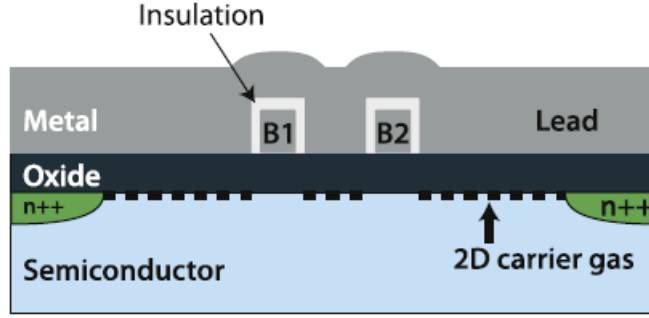


Figure 2.5: Cross sectional schematic of the implanted region of the device. From [28]

Figure 2.6 shows a top down view of the FET. This figure shows the three gates discussed before and also eight ‘lateral’ gates (E1/E2, D1/D2, A1/A2 and C1/C2). The lateral gates can be used to fine tune the potential applied in one of the regions (the implanted region or the reference region). The lateral gates surrounding the reference region (E2, D2, A2 and C2) are not used, because there should be no interesting signatures in this region. The implanted region is the region where atoms have been implanted in a dose of $1 \cdot 10^{11} \text{ cm}^{-2}$. Nothing has been implanted in the reference region. When trying to interpret measurements it is not clear whether the signatures measured originate from atoms or defects located under the barrier gates or the lead gate. If a signature that looks like a single atom is measured, while doing measurements with B1, a measurement can be performed with B2 to verify that this object is located under B1. The measurement using B2 should show signatures measured under B2 and under L, so if the single atom signature is not measured here it confirms that the object is located under B1.

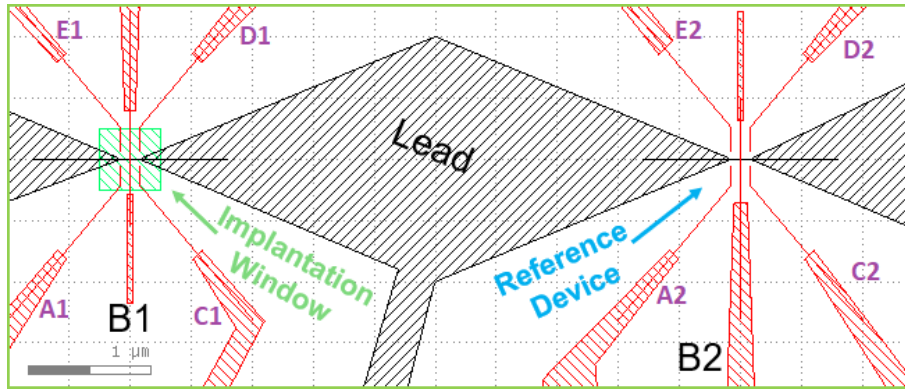


Figure 2.6: A schematic of the top down view of the device, highlighting the implantation and reference region. From [27]

Chapter 3

Measurements

3.1 Introduction

In this chapter the measurements done will be explained and shown. It will give an summary of the steps taken to start the measurement, what results are expected and it will give an overview of the measured results. The main goal of the measurements is to find signatures associated to single bismuth atoms and to find electron transport through these atoms.

3.2 Measurement Setup

The devices seen in figure 2.6 are located on a chip of 1x1cm. 25 of these devices fit on one chip. To measure one of these devices it needs to be bonded, using a wirebonder, to a printed circuit board (PCB). Using the wirebonder the contact pads of the device are connected, with aluminium wires, to different channels on the PCB. The PCB can then be connected to a dipstick, which is put inside of a cryotank filled with liquid helium. This ensures that the device will always stay at a temperature of 4.2K during the measurements. The dipstick in turn connects the channels of the PCB to channels on a matrix module. The channels of the matrix module can be powered or measured with an IVVI-rack. The IVVI-rack applies different voltages on digital-to-analog converter outputs. These outputs are connected with the channels of the matrix module and this way voltage can be applied on different contact pads of the device. The IVVI-rack also has a module that can be used to convert measured voltage to current, this module uses a gain that interchanges range for resolution i.e. a higher gain decreases the maximum current measurable but gives more resolution in the levels that are measured. These currents are then measured using a Keithley 2000. The IVVI-rack is controlled using a code written in python that can be found in appendix C

More information about the measuring equipment can be found in appendix A.

3.3 Performed Measurements

3.3.1 Initial Measurements

Before performing measurements using the python code it is important to check whether the device works and between what voltages. These measurements are done by using a source measure unit (SMU) to apply voltages on different gates of the device with a certain compliance, i.e. maximum current applied until a voltage is reached. This can be used to see if one of the gates has a open current path to either ground or a different gate. If this happens it is called leakage.

Two different measurements are done to check whether the device is operable: a turn-on test and a leakage test.

For the turn-on test a BEEP-R is connected to the source and drain of the device, the BEEP-R applies $\pm 10\text{mV}$ on two channels and measures the resistance between these channels. If the resistance is open, which is expected when all the gates are at 0V because silicon is insulating at 4.2K, the device is ‘off’ and when the resistance approaches a finite resistance in the range of $100\text{K}\Omega$ the device is ‘on’. Voltage is applied on L, B1 and B2 until there is a sharp decrease in resistance, indicating the turn-on of the device. If a device has no turn-on it can not function as a transistor and can not be used for further measurements. For arsenic implanted devices the turn-on was found to be around 2.3V [29].

The leakage test is done by applying a voltage on only L and checking if the gate starts to leak to B1 and B2. Leakage may be tested until a certain voltage and if the device does not leak you know that the device can safely be operated until that voltage. If the device leaks to one of the lateral gates it might still be operable if that lateral gate is disconnected, but if one of the gates leaks to ground it is most often not measurable.

3.3.2 Python Measurements

The python measurements are done by editing a standard python measurement file and start it on the computer. Using this python script it is possible to sweep voltages on gates with different step sizes. This can be used to make two- or three-dimensional plots. The standard measurement script can be found in appendix C. The first measurement that is done is almost always another turn-on measurement, but this measurement shows very clearly where the turn-on starts and also how high the current is for certain voltages. After this the pinch-offs of B1 and B2 need to be found. The pinch-off is the voltage at which one of the barriers starts to block the current through the channel. B1 and B2 should both be able to pinch the channel independently, and the pinch-offs are measured separately. No measurements can be done in the region of a barrier gate that does not pinch, because the signatures that we are interested in are only visible when only a few electrons tunnel through the channel. If B1 does not pinch it might be possible to pinch the channel using two opposite lateral gates (so E1&A1 or C1&D1). The pinch-off measurements are done by sweeping one of the barriers and keeping the other barrier and the lead gate at a constant voltage in the ‘on’ region.

Generally transport measurements are performed after these plots. In these measurements multiple gate voltages are swept. Two different kinds of transport measurements can be identified: Gate-space plots and charge bias spectroscopies. Gate-space plots show the logarithm of the absolute current as a function of two gates (B1, B2 or L). A charge bias spectroscopy shows the logarithm of the absolute differential conductance as a function of the source-drain voltage and one of the gates.

3.4 Results

Seven devices have been measured. All of these devices were nanoFET structures with a $1 \cdot 10^{11}$ bismuth atoms per cm^{-2} . The different devices are identified using a two letter code, the codes for the measured devices are: AW, BW, CV, CW, DX, DY and EY.

Two of these devices (BW & AW) were broken before any measurements using the python script could be done. However, for these devices we were able to find a turn-on before they died.

The turn-ons were: BW - 3.8V and AW - 2.8V. These values are still helpfull since they give an indication of the expected turn-on of the devices.

3.4.1 Device DX

Turn-on

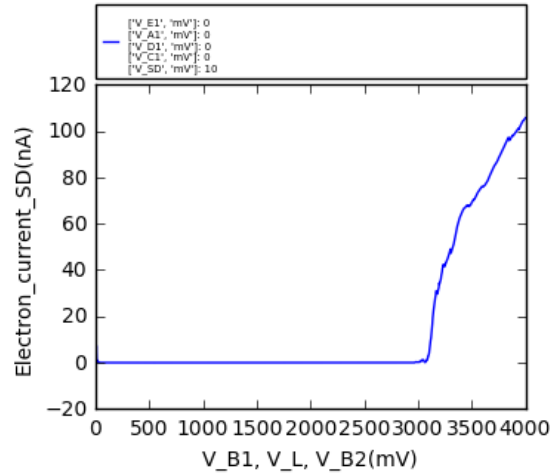


Figure 3.1: The turn-on of device DX, $V_{SD}=10\text{mV}$

Figure 3.1 shows the turn-on measurement performed for device DX. This figure shows the current between the source and drain as a function of the voltage applied on L, B1 & B2. This device turns on just after 3V, reaches a current of $\sim 110\text{nA}$ at $V_{B1}=V_{B2}=V_L=4.0\text{V}$. No spikes in conductance are visible during turn-on.

Pinch-off

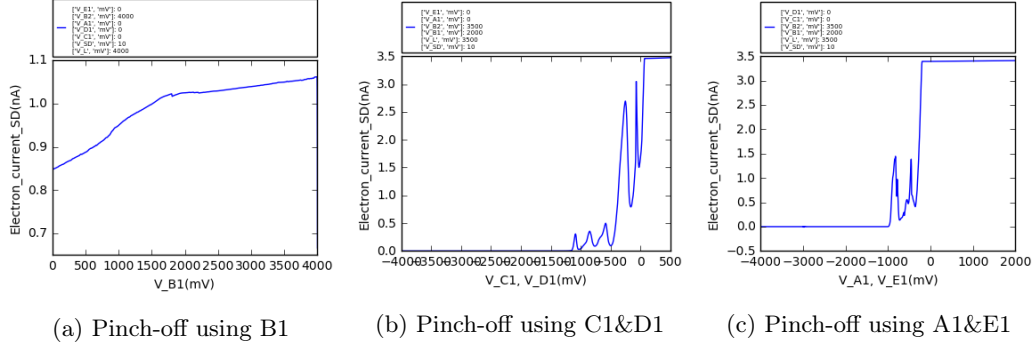


Figure 3.2: Pinch-offs of device DX using different gates, $V_{SD}=10\text{mV}$

Figure 3.2a shows the pinch-off of this device using B1. However, for this device B1 does not work as expected and B1 is not able to deplete the channel and current keeps flowing. Because of this we tried to pinch the channel using the lateral gates, the plots for this can be seen in figures 3.2b and 3.2c for C1&D1, and A1&E1 respectively. Fortunately both of the pairs of opposite lateral gates are able to pinch the channel, albeit with a lot of current spikes. Appendices B.1 and B.2 show two additional pinch-off plots for this device using B1 and B2. These plots were made with a lower voltage applied to L.

Transport Measurements

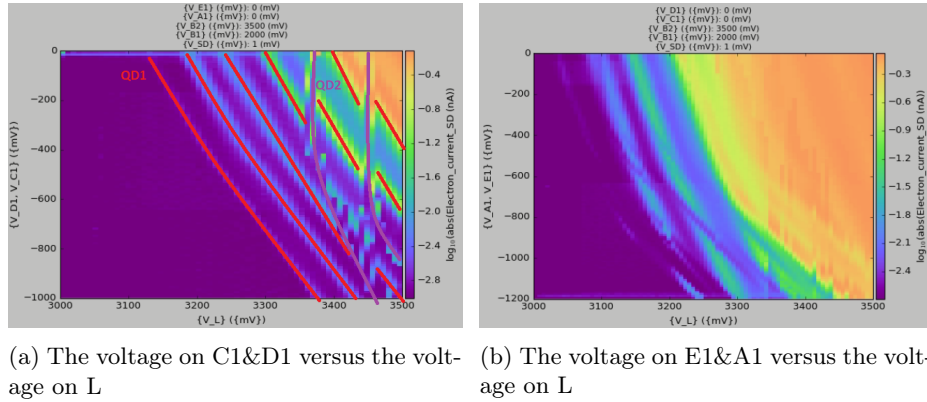


Figure 3.3: Gate-space plots of the lateral gate voltages versus the lead voltage for device DX, $V_{SD}=1\text{mV}$

Figures 3.3a and 3.3b show the gate-space plots of device DX. In these gate-space plots L is plotted versus a combination of lateral gates. These lateral gates are swept together and work as a single gate.

The parallel lines show different transitions for objects. For single atoms you should see only two lines, indicating the $D^+ \rightarrow D^0$ transition and the $D^0 \rightarrow D^-$ transition. More than two parallel lines means that the object is most likely a quantum dot. In figure 3.3a two quantum dots are more clearly indicated by the red and purple lines. The red lines show a quantum dot mostly coupled to L, with five transitions visible in this figure. The purple object only shows two transitions, which could mean that it is a single-atom, but because the atoms should be coupled to B1, or in this case the lateral gates, there is a high chance that this object is a quantum dot as well. Figure 3.3b also shows two objects. Both of these objects are mostly coupled to L which leads us to believe that these are most likely the same objects also seen in figure 3.3a.

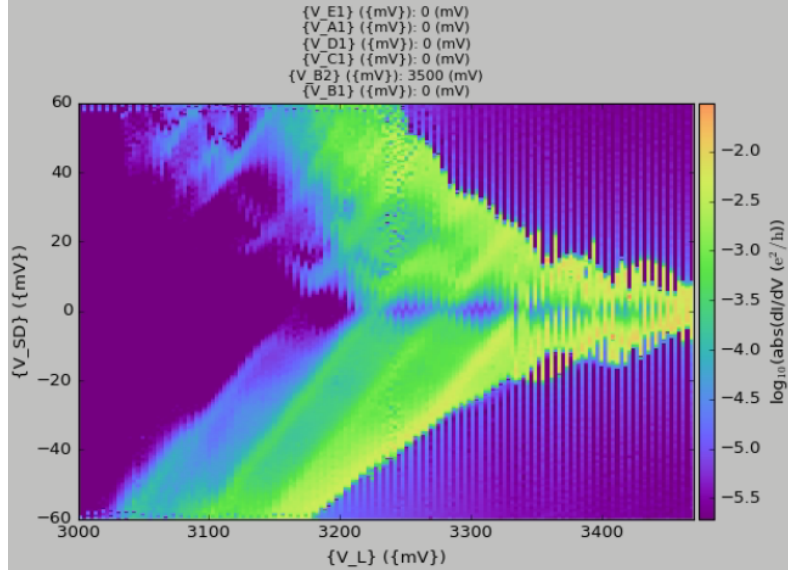


Figure 3.4: Charge bias spectroscopy of V_L , with all lateral gates and B1 at 0V

The charge bias spectroscopy seen in figure 3.4 is taken with all the lateral gates at zero volts. The charge bias spectroscopy can also be seen as a linecut through both figures 3.3a and 3.3b at the top of the vertical axis. The gap between the red lines in figure 3.3a is an approximation of the broadness of the diamonds seen in this figure. The diamonds starting at $V_L=3.15V$ correspond to the first quantum dot in figure 3.3a. The second object, the purple lines, should start at $L=3.4V$, however, the charge bias spectroscopy becomes very unclear after $L=3.4V$, which may be an indication that there are multiple objects interacting.

3.4.2 Device CV

Turn-on

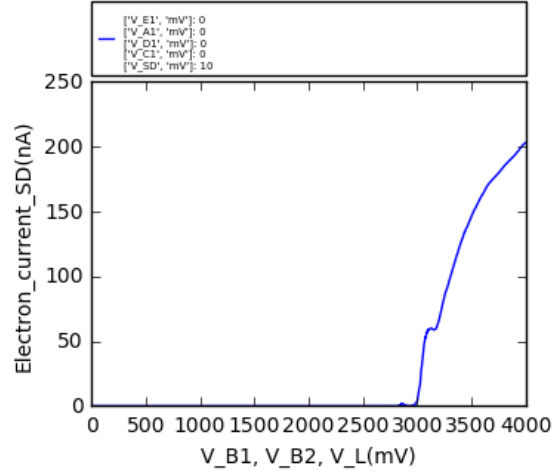


Figure 3.5: The Turn-on of device CV, $V_{SD}=10\text{mV}$

Figure 3.5 shows the turn-on of device CV. The turn-on starts just after 3V. A very small peak is visible just before turn-on (close to 2.9V), which might indicate some kind of object, and a second peak when turn-on has started (close to 3.2V).

Pinch-off

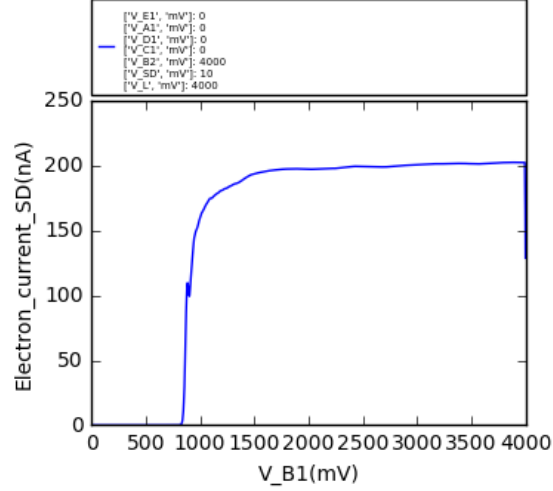
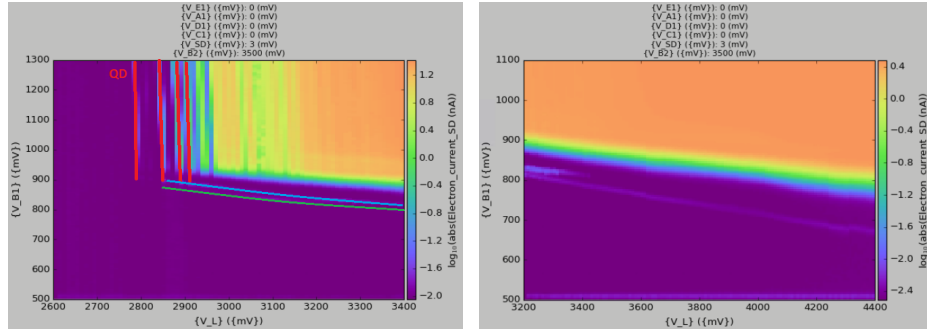


Figure 3.6: Pinch-off of device CV using B1, $V_{SD}=10\text{mV}$

For device CV both of the barrier gates are able to pinch the channel. Figure 3.6 shows the pinch-off for B1, which happens at about 0.9V and only shows one small peak. The pinch-off for B2 of this device is available in appendix B.3.

Transport Measurements



(a) plot of V_{B1} versus V_L , with $2.6V \leq V_L \leq 3.4V$ (b) plot of V_{B1} versus V_L , with $3.2V \leq V_L \leq 4.4V$

Figure 3.7: Gate-space plots of B1 versus L for device CV, $V_{SD}=3\text{mV}$

Figures 3.7a and 3.7b show the gate-space plots of B1 versus L. In figure 3.7a you can see a quantum dot very coupled to L (the red lines) that disappears as L increases in voltage. Also there are

two horizontal lines (the green and cyan lines), coupled to B1, that are very close together that are also visible in figure 3.7b. However, one of the lines disappears when the voltage on L goes above 3.4V. The second line continues and the distance between this line and the on-region also increases, this indicates an increase in capacitance for this object.

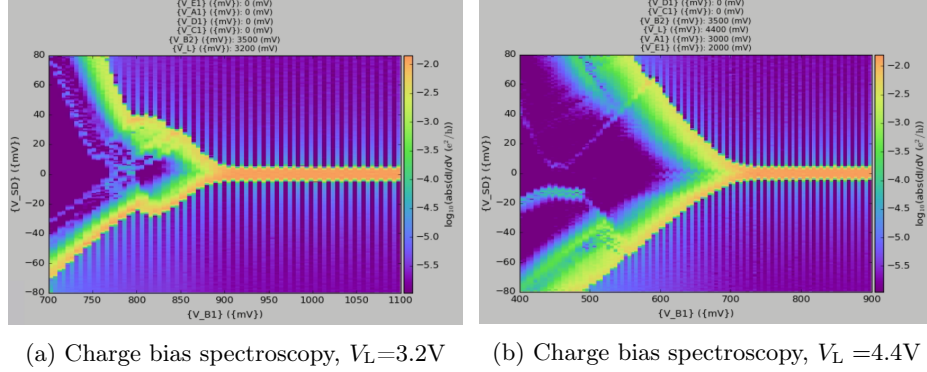


Figure 3.8: Charge bias spectroscopy for device CV, measured **a** with the lateral gates at 0V and measured **b** with tuned lateral gates

Two charge bias spectroscopies are visible in figures 3.8a and 3.8b taken at different voltages on L and different voltages on the lateral gates. Figure 3.8a is taken at $L=3.2V$, which is before one of the two horizontal lines disappears. In this figure there appear to be two different diamonds overlapping each other, corresponding to the two different lines. Of one diamond only the peak is really distinguishable, which is located at $V_B = \sim 0.8V$. The other diamond is more clear and shows a Coulomb blockade.

Figure 3.8b is taken at $L=4.4V$, so after one of the lines disappears. This figure is also taken after having tuned the lateral gates, gate-space plots of A1 versus B1 and of E1 versus B1 can be found in appendices B.5 and B.4. In figure 3.8b there is clearly only one non-closing diamond with a charging energy of $\sim 47 \pm 10\text{meV}$. This indicates that both objects are interacting with each other in some way causing them to merge in the bias spectroscopies and giving rise to a very large charging energy. Most likely both of these objects are atoms, because they do not seem to have the amount of charge states that is normally associated with a quantum dot and at least one of the objects in figure 3.8a, the left one, seems to have a higher charging energy than normally expected of a quantum dot. However, this could also be because of the interaction between the two objects. A charge bias spectroscopy which shows the maximum obtained charging energy for this device can be found in appendix B.6, for this plot all the lateral gates are at 4.0V and $V_L=4.4V$.

3.4.3 Device CW

Turn-on

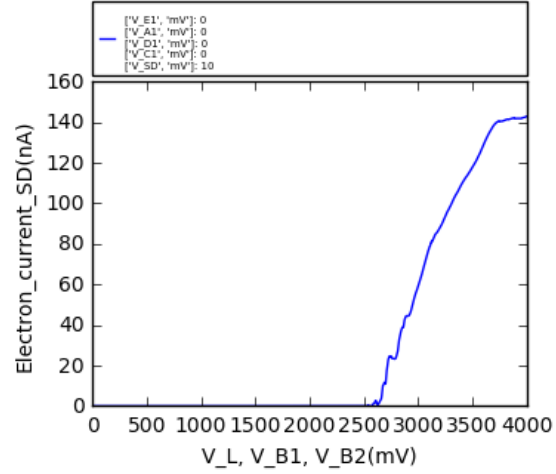


Figure 3.9: The turn-on of device CW, $V_{SD}=10\text{mV}$

Device CW has a normal turn-on, starting at 2.5V, visible in figure 3.9. The current seems to saturate at 3.6V and here the device has a maximum current of $\sim 140\text{nA}$.

Pinch-off

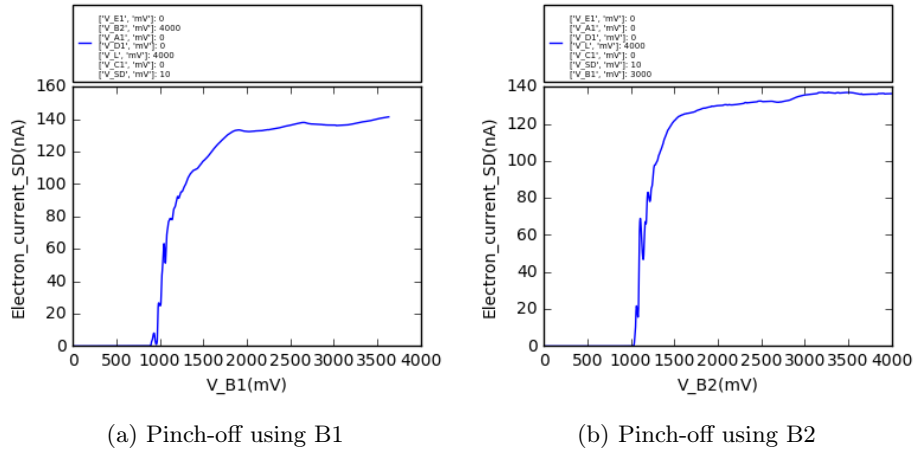


Figure 3.10: Pinch-offs of device CW using both barrier gates, $V_{SD}=10\text{mV}$

Figures 3.10a and 3.10b show the pinch-offs for B1 and B2 respectively. B1 pinches the channel when the voltage is at or below 0.9V and B2 does the same at 1.0V. Both of the pinch-offs show multiple peaks during the pinching.

Transport Measurements

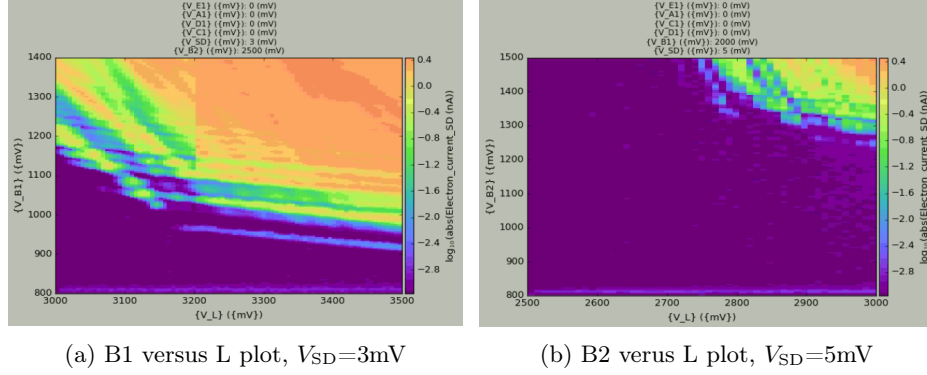


Figure 3.11: Gate-space plots of the barriers versus L for device CW

Figures 3.11a and 3.11b show the gate-space plots for this device. The diagonal lines seen in figure 3.11a seem to be a quantum dot mostly coupled to L, because there are multiple states visible of the same object. This quantum dot again disappears for higher values of L. There is also a quantum dot visible that is coupled to B1, because the lines are almost solely influenced by the voltage on B1. This quantum dot seems to disappear for high values of B1. A continuation of this gate-space plot can be seen in appendix B.7.

Figure 3.11b shows a small part of the B2 versus L plot. In this figure a quantum dot mostly coupled to L is visible, this lead us to believe that it is most probably the same quantum dot observed in figure 3.11a. There might also be a quantum dot coupled to B2, however, only a small part of the conducting region is visible in figure 3.11b and the resolution is not very high so this is not certain.

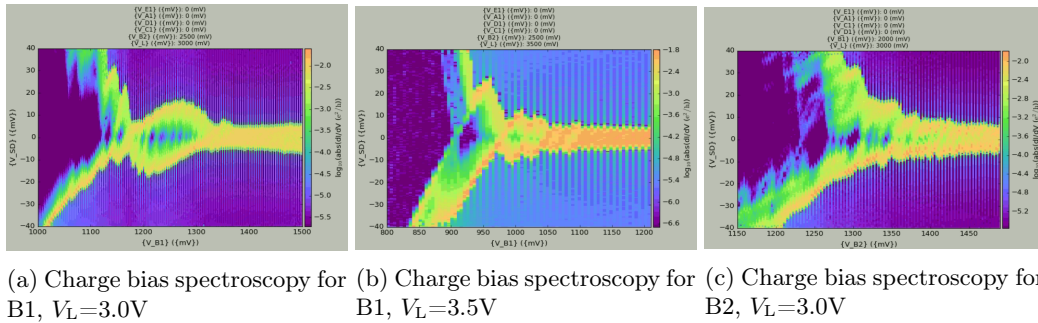


Figure 3.12: Charge bias spectroscopies for device CW

Figures 3.12a and 3.12b show two charge bias spectroscopies made for B1 with different voltages on L. The first charge bias spectroscopy is taken at $L=3V$, in figure 3.11a you can see that at this point the quantum dot coupled to L is still very prevalent, this is also clearly visible in the first stability diagram (figure 3.12a). Between $\sim 1.2V$ and $1.3V$ there is a larger object visible that is filled with diamonds of a quantum dot. The larger object here is the gap between the first two transitions visible of the quantum dot coupled to L, while the smaller quantum dot signatures are the quantum dot coupled to B1. When L reaches a higher voltage the quantum dot coupled to L disappears. This can be seen in figure 3.12a that is taken for B1 with L at $3.5V$. In this figure only one clear object can be identified: the quantum dot coupled to B1. This dot starts with a larger diamond of $\sim 20meV$ and as B1 increases in voltage, and more electrons hop onto the island, the charging energy decreases.

Figure 3.12c shows a charge bias spectroscopy made for B2. This charge bias spectroscopy is taken at $L=3V$ and shows a lot of disorder. Disorder under the reference region is not ideal, normally this region should be very clean because no atoms have been implanted here. Disorder measured using B2 could mean that this same disorder is also measured when using B1.

3.4.4 Device DY

Turn-on

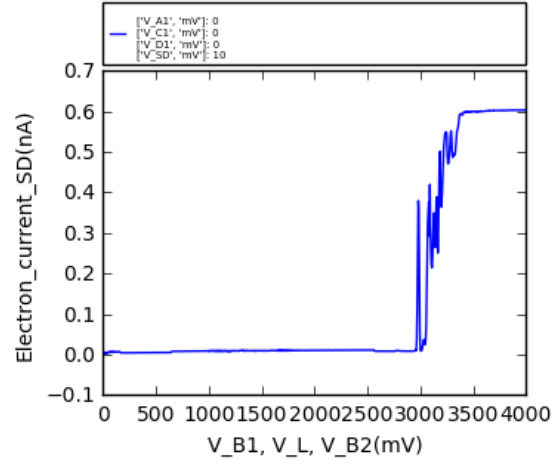


Figure 3.13: Turn-on of device DY, $V_{SD}=10mV$

The turn-on of device DY starts at $\sim 2.9V$ and reaches a maximum current of $0.6nA$ at $L=\sim 3.4V$. There are a lot of peaks in the turn-on, but this is due to scale. These kinds of peaks also exist in other turn-ons, but because this turn-on has a much smaller scale (maximum current of $0.6nA$ instead of $\sim 150nA$) they are more distinguishable.

Pinch-off

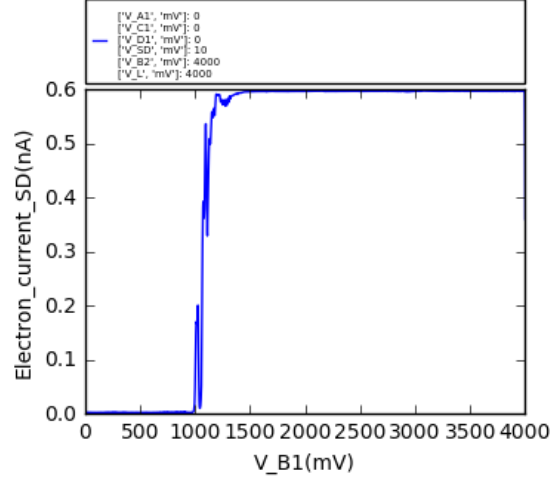
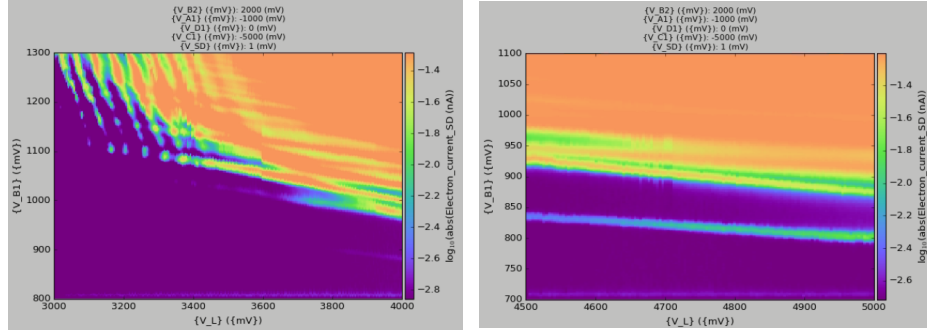


Figure 3.14: Pinch-off of device DY using B1, $V_{SD}=10\text{mV}$

Figure 3.14 shows the pinch-off for B1 for this device. The complete channel is pinched when B1 has 1V applied to it. Peaks are again visible during the pinching, but again for this device these peaks might not have been visible if the current could reach higher amounts. The pinch-off of B2 can be found in appendix B.8.

Transport Measurements



(a) B1 versus L plot, $3.0\text{V} \leq V_L \leq 4.0\text{V}$

(b) B1 versus L plot, $4.5\text{V} \leq V_L \leq 5.0\text{V}$

Figure 3.15: Gate-space plots of B1 versus L for device DY, $V_{SD}=1\text{mV}$

Figures 3.15a and 3.15b show two gate-space plots for device DY. In figure 3.15a there is a quantum dot visible similar to ones seen in other devices that is mostly coupled to L and disappears after L reaches 3.6V. There is also a faint line that starts after L reaches 3.8V at $B1 \sim 0.9\text{V}$. Between

this line and the next line is a significant gap, $\sim 0.1\text{V}$. This gap is an indication for how broad the Coulomb diamond is in the charge bias spectroscopy, where a broader gap most often relate to a higher charging energy. There are, however, multiple lines visible in the on-region of the device, so there might just be one quantum dot, of which the line mentioned before is the first transition, or there might also be a quantum dot and a single atom signature. Figure 3.15b sheds more light on this case. The line that was very faint before now is very visible and it can also be seen that some of the lines in the on-region of the device have a different angle than the bright line at the bottom. The fact that lines from the same object have the same angle, lead us to believe that this is possibly a single atom and a quantum dot.

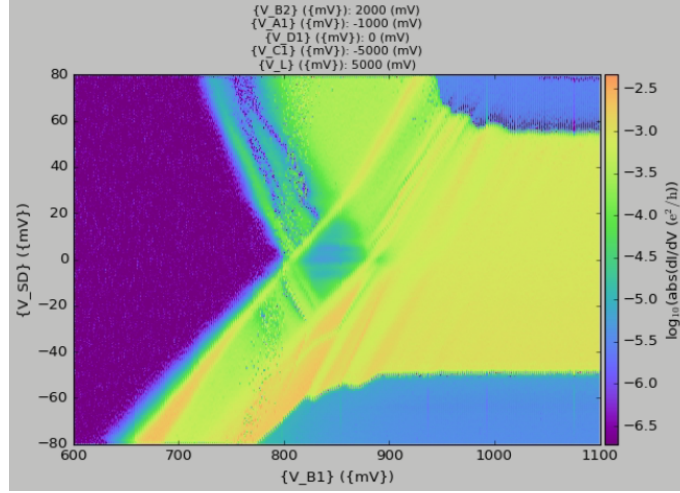


Figure 3.16: Charge bias spectroscopy of device DY, $V_L=5.0\text{V}$

A charge bias spectroscopy at $L=5\text{V}$ can be seen in figure 3.16. In this figure there is a diamond that starts at $\sim 0.8\text{V}$ and ends at $\sim 0.88\text{V}$ with a charging energy of $\sim 21\text{meV}$. There are also conduction lines visible inside of the diamond, these lines could be attributed to co-tunneling, because they are symmetrical over the x-axis, but this could also be because of the low maximum current. There is a small shape after the diamond that might be the second diamond, but this is not clear. The charging energy does not rule out the possibility of this signature being a quantum dot. A charge bias spectroscopy with $V_L=3.4\text{V}$ can be seen in appendix B.9, in this plot the influence of the quantum dot at lower values of L is much more prevalent.

3.4.5 Device EY

Turn-on

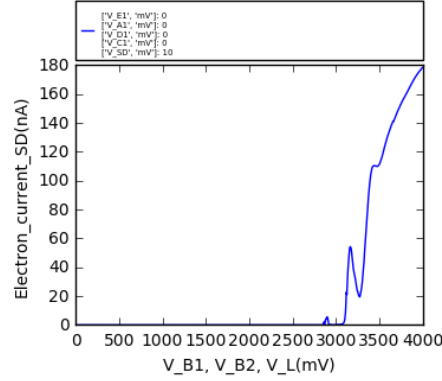


Figure 3.17: Turn-on of device EY, $V_{SD}=10\text{mV}$

Figure 3.17 shows the turn-on of device EY. There is a small peak just before 3V, but the turn-on starts at about 3.1V. Three peaks are visible: the small one just before 3V, one at $\sim 3.2\text{V}$ and one at $\sim 3.4\text{V}$. The maximum current reached in this figure is 180nA, but it seems as if the current could go higher if the voltages are increased more.

Pinch-off

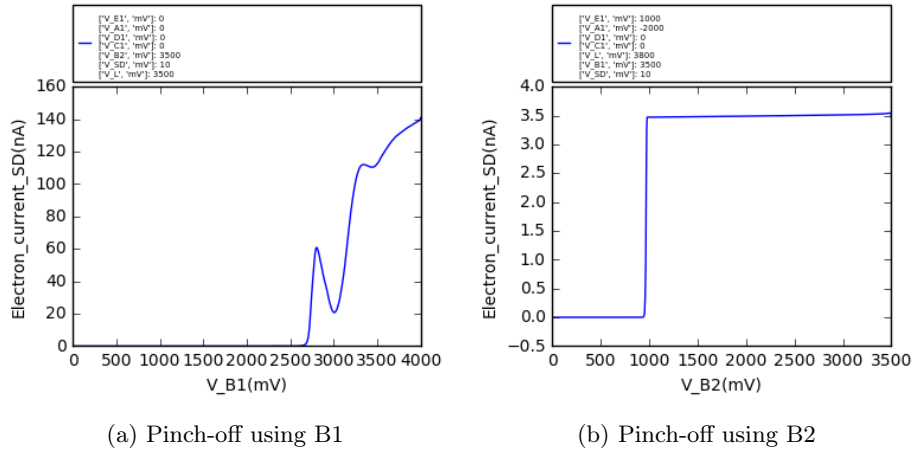


Figure 3.18: Pinch-offs of device EY using both barriers, $V_{SD}=10\text{mV}$

Figures 3.18a and 3.18b show the pinch-offs for B1 and B2. B1 pinches the channel at 2.6V and shows a couple of peaks. One large peak at 2.8V and one at 3.3V. Peaks like these can indicate

that there is some kind of object in the channel which allows electrons to flow. The pinch-off for B2 seems very straight, just below 1V the current suddenly drops from 3.4nA to 0nA. This straight drop is because the current is clipping to 3.4nA at 1V, the gain of the IVVI-rack is set to the highest level which gives more resolution at low currents but decreases the measurable range to ± 3.4 nA.

Transport Measurements

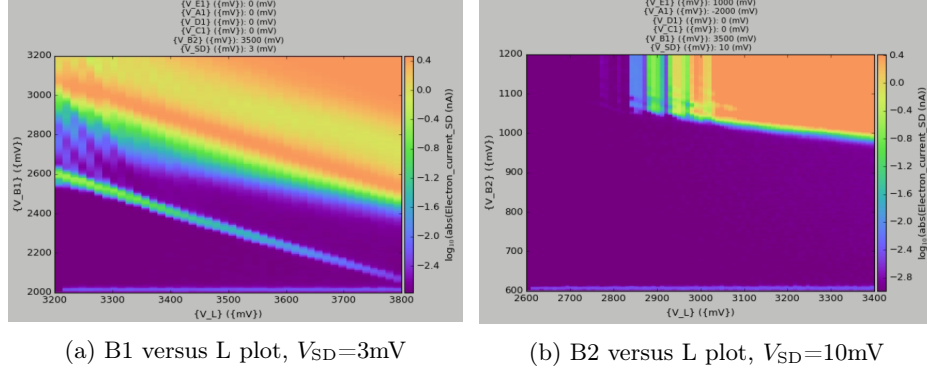


Figure 3.19: Gate-space plots of the barriers versus L for device EY

In figure 3.19a we see quantum dot coupled to L that disappears after 3.3V, just like observed in the other devices. There is also a very clear line, mostly coupled to B1, with a large gap to the next line. In the on-region there is a lighter part that could be the second diamond of an object. No value for L and the lateral gates could be found where this region was depleted of current. Appenices B.10 and B.11 show the gate-spaces to the left and right of figure 3.19a. Figure 3.19b shows a quantum dot coupled to L and seems to be empty otherwise.

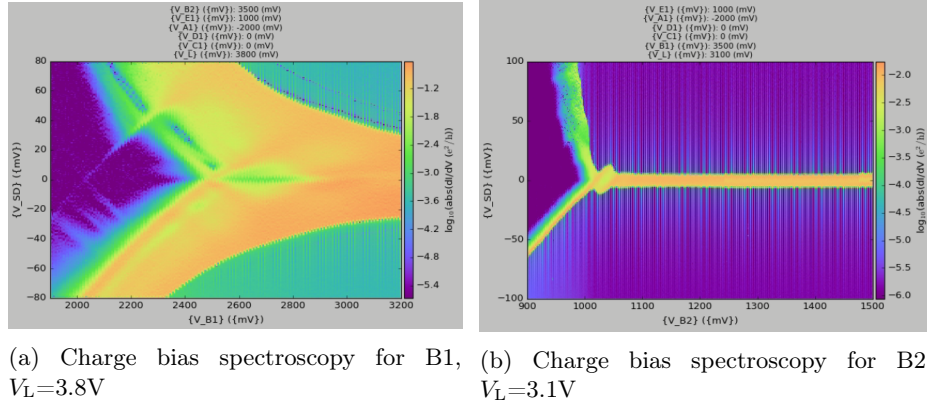


Figure 3.20: Charge bias spectroscopies of device EY

A diamond is visible in figure 3.20a with a charging energy of $\sim 37\text{meV}$. There is also a very small second diamond between 2.4V and 2.8V. This small diamond is filled with current and has a charging energy smaller than 20meV. This current is because at those voltages B1 is unable to pinch the channel enough to only allow current to flow through the atom. This can be confirmed by checking figure 3.18a, the second diamond corresponds to the dip in current around B1=1V but even then the minimum current is larger than 20nA. Current can also be seen at the rightmost edges of the large diamond, which can be explained by the same thing. The object seen in this region has all the features expected of a single-atom and does not seem to be a quantum dot. The charge bias spectroscopy of B2 is very clean. Figure 3.20b shows no clear objects before 1.0V (where the device turns on) and only one very small object just after the turn-on. This object has a very small charging energy and does not appear in figure 3.20a. Thus it does not invalidate the findings in the implanted region. Appendices B.12, B.13 and B.14 show extra charge bias spectroscopies. These charge bias spectroscopies show the same signatures, with a quantum dot visible at low values of V_L .

3.4.6 Summary

We have measured a total of seven FETs with a dose of $1 \cdot 10^{11}$ Bi atoms.cm $^{-2}$. Of these seven devices two have died before any python measurements could be performed, BW and AW. Devices DX and CW show no clear single-atom signatures and exhibit only quantum dot signatures. Device CV shows signs of two atoms interacting with each other, giving rise to a large increase in charging energy. Both devices DY and EY show signatures that correspond to single-atoms. Device DY has a maximum current of 0.6nA and the charging energy of the visible diamond is only $\sim 21\text{meV}$. This devices also shows co-tunneling signs. Device EY shows a very clear first diamond with a charging energy of $\sim 37\text{meV}$ and also has a small second diamond of which the charging energy is harder to conclude. All of the measured devices show a quantum dot heavily coupled to the lead gate that disappears as the voltage on the lead gate increases.

Table 3.1 gives an overview of the turn-ons and B1 pinch-offs for all the measured devices. In this figure you can see that most of the devices have had a turn-on at around 2.9V, also most of the B1 pinch-offs were around 1.0V except for device EY which has a pinch-off that is a lot higher.

Table 3.1: Values of the turn-ons and the B1 pinch-offs of all the measured devices

Device	Turn-on (in volts)	Pinch-off B1 (in volts)
BW	3.8	-
AW	2.8	-
DX	3.0	-
CV	3.0	0.9
CW	2.5	0.9
DY	2.9	1.0
EY	3.1	2.6

Chapter 4

Conclusions and Outlook

The aim of this research was to find evidence of electron transport through single bismuth atoms implanted in nanoFETs. Comparing results should give an indication of the viability of bismuth as a dopant for single-atom transistors and, whether changes have to be made to the doping used in this research ($1 \cdot 10^{11}$ bismuth atoms.cm⁻²).

Table 4.1 gives an overview of the relevant results obtained in this study. This table shows that single-atom signatures could be found for two of the seven devices measured. These two devices both had a very clear first Coulomb diamond and an almost indistinguishable second diamond.

For the charging energies we expected about half of the charging energy of bismuth in bulk silicon, so between 30 and 40 meV. For device DY the charging energy found was ~ 21 meV, however, this device showed discrepancies from the start, namely the fact that the maximum current in this device was 0.6nA. It would not be unimaginable that there were other problems with the device that caused the charging energy to be lowered. Thus even though these signatures seem very consistent with what is expected of single-atoms it can not be concluded with certainty that this is a single atom.

Device EY showed a charging energy of around 37meV, this is within the expected range of charging energies and is probably a very good example of a single-atom transistor. For this device the reference region showed very different results when compared to the implanted region, this reinforces the idea that the signatures are located very close to B1.

The turn-on voltages measured for all the devices are significantly larger than for similar devices implanted with arsenic. This increased turn-on could be caused by a fault during the fabrication of the devices. This is only possible because all the measured devices were located on the same chip.

Table 4.1: Overview of the important obtained results

Device	Turn-on (in volts)	Signatures	Charging Energy (in milli electron volts)
BW	3.8	-	-
AW	2.8	-	-
DX	3.0	Two quantum dots	-
CV	3.0	Two atoms	separate: ~ 20 & ~ 25 ; together: $\sim 47 \pm 10$
CW	2.5	Two quantum dots	~ 17
DY	2.9	possible single-atom	~ 21
EY	3.1	Single-atom	~ 37

Nevertheless, seven devices is a very small sample size and definitely not enough to give a clear estimation of exactly how many single-atom transistors can be found in a certain amount of bismuth implanted nanoFETs. So, to get a better statistical analysis of this estimation, more devices need to be measured. This doping concentration seems to be ideal to obtain single bismuth transistors, but it will also be very interesting to compare results of this concentration with results of a device with a slightly higher dose. There is always the possibility that a slightly higher or lower dose will give a higher chance to produce a single-atom transistor. Measuring devices with different doses also means that a different chips will be measured. The turn-ons of these chips can be compared to the turn-ons shown in table 4.1 and this will show if bismuth implanted devices have generally a higher turn-on or if the higher turn-on in the devices studied in this research is caused by faulty fabrication.

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Appendices

Appendix A

Equipment

Below is a list of the equipment used during the measurements.

1. Wirebonder (<http://www.westbond.com/pdf/7400espc.pdf>)
2. Matrix Module (<http://qtwor.k.tudelft.nl/~schouten/matrix/index-matrix.htm>)
3. IVVI-rack (<http://qtwor.k.tudelft.nl/~schouten/ivvi/index-ivvi.htm>)
4. Keithley 2000 (<http://research.physics.illinois.edu/bezryadin/labprotocol/Keithley2000Manual.pdf>)
5. BEEP-R (No citation available)

Appendix B

Additional measurements

DX

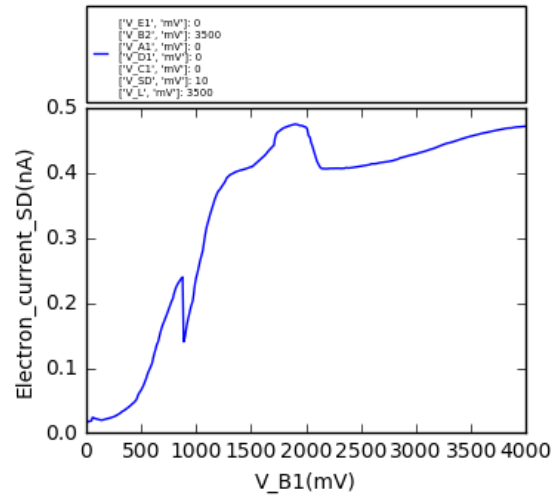


Figure B.1: Pinch-off using B1 with $V_L=3.5\text{V}$, $V_{SD}=10\text{mV}$

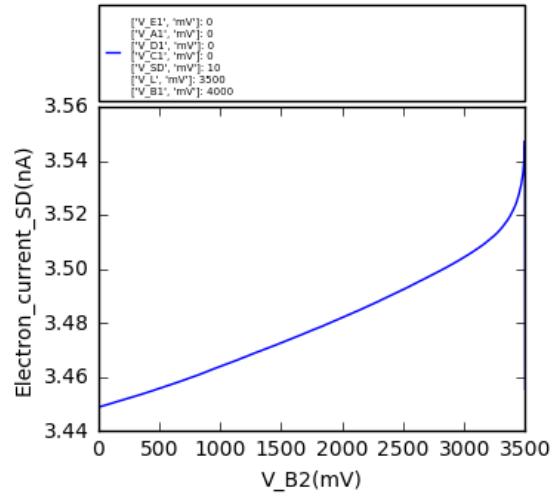


Figure B.2: Pinch-off using B2, $V_{SD}=10\text{mV}$

CV

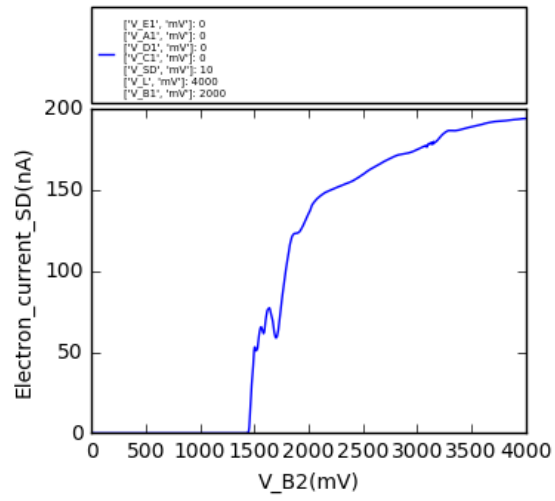


Figure B.3: Pinch-off using B2, $V_{SD}=10\text{mV}$

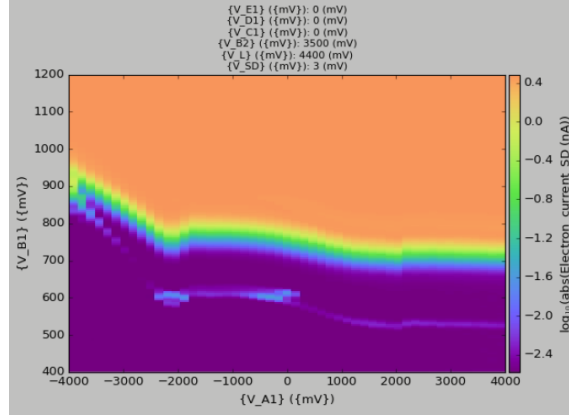


Figure B.4: Gate-space plot of A1 versus L, $V_{SD}=3\text{mV}$

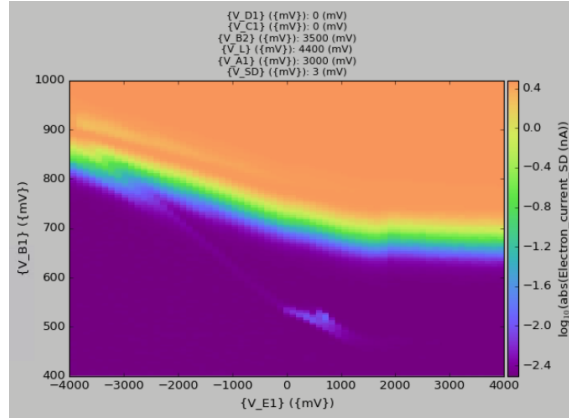


Figure B.5: Gate-space plot of E1 versus L, $V_{SD}=3\text{mV}$

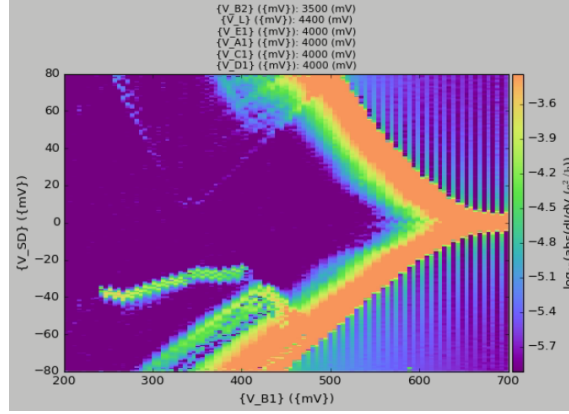


Figure B.6: Charge bias spectroscopy showing the maximum charging energy found, $V_L=4.4\text{V}$ and all the lateral gates are at 4.0V

CW

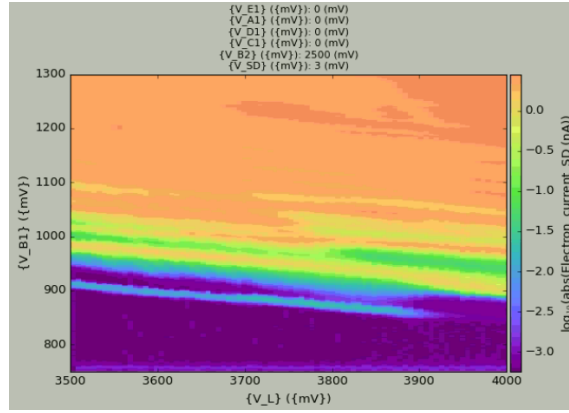


Figure B.7: Gate-space plot of B1 versus L, $V_{SD}=3\text{mV}$

Device DY

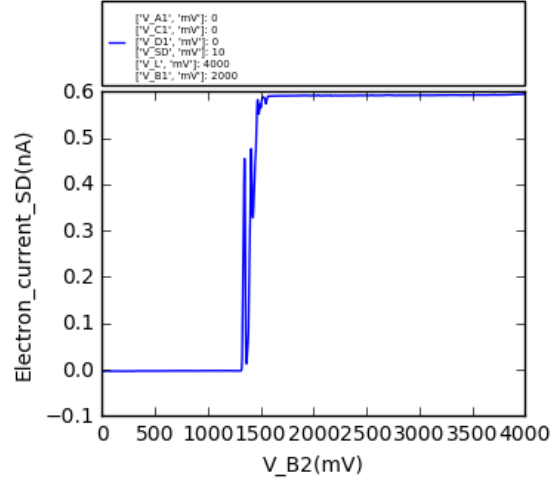


Figure B.8: Pinch-off of device DY using B2, $V_{SD}=10$ mV

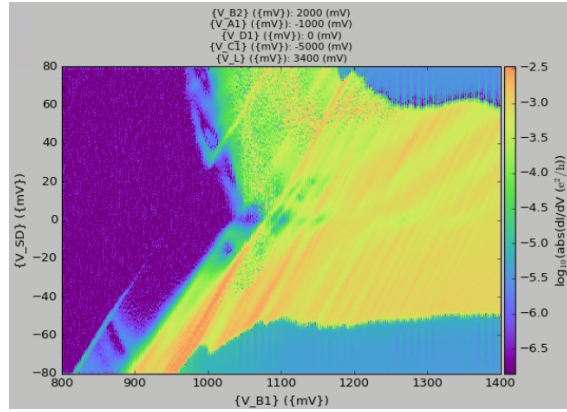


Figure B.9: Charge bias spectroscopy of device DY showing a non-closing diamond with $E_c > 20$ meV, $V_L = 3.4$ V

Device EY

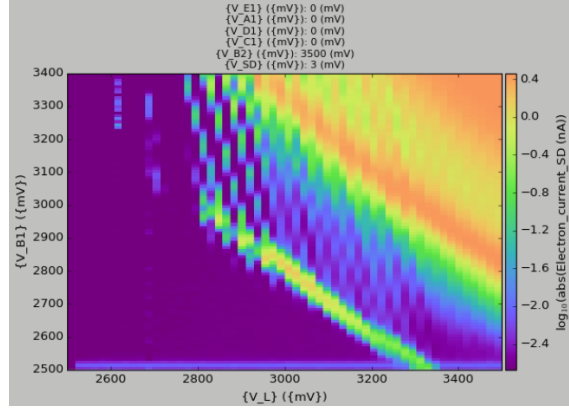


Figure B.10: Gate-space plot of B1 versus L for device EY, $V_{SD}=3\text{mV}$

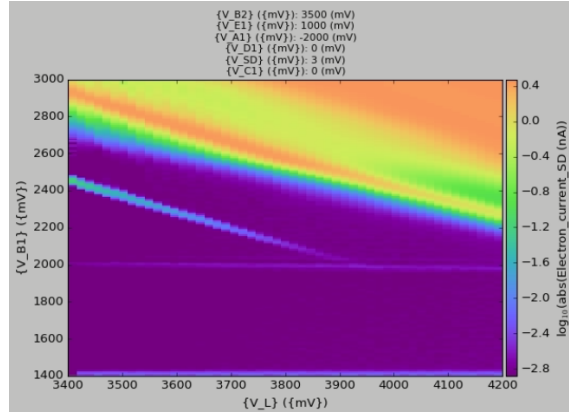


Figure B.11: Gate-space plot of B1 versus L plot for device EY, $V_{SD}=3\text{mV}$

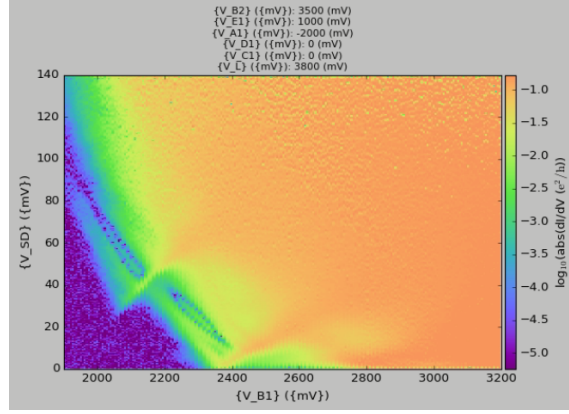


Figure B.12: Low gain charge bias spectroscopy of device EY, $0\text{mV} \leq V_{SD} \leq 140\text{mV}$ and $V_L=3.8\text{V}$

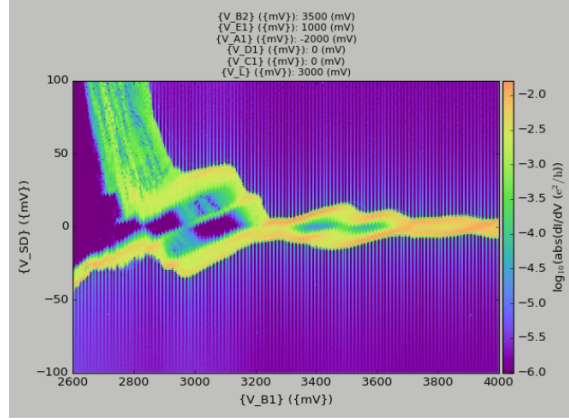


Figure B.13: Charge bias spectroscopy of device EY, $V_L=3.0\text{V}$

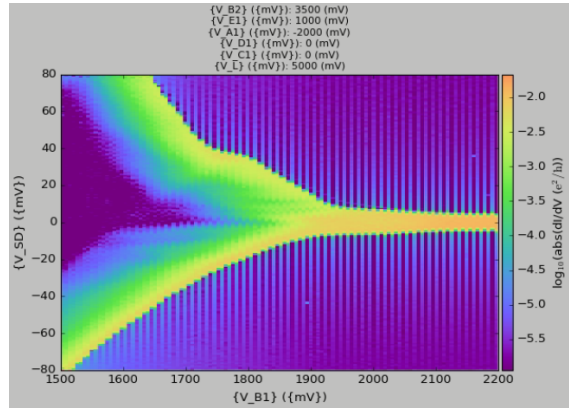


Figure B.14: Charge bias spectroscopy of device EY, $V_L=5.0V$

Appendix C

Python Code

```
#measure script for ambipolar barrier array

#summing module config
dac_sd = 'dac3' #electron side

voltage_source_gain = 100e-3 / 1 #100 mV/V
i_gain = 1e9/1e9 #volt to nA --> 10MV/A, nanoampere in a volt

#determine filename of outputfile
import inspect
import os
filename = inspect.getframeinfo(inspect.currentframe()).filename
path = os.path.dirname(os.path.abspath(filename))
base = os.path.basename(os.path.splitext(filename)[0])

devicename='.'
import lib.parspace as ps
from math import sin

# rate_delay = 50.0
# rate_stepsize = .7

rate_delay = 5.0
rate_stepsize = 1.

gates=[]
names= [ 'L', 'A1', 'B1', 'C1', 'D1', 'E1', 'B2']
gains = [5.0, 5.0, 5.0,5.0, 5.0,5.0, 5.0]
dacs = [ 10,11,12,13,14,15,16]
```

```

#dacs = [ 5, 9, 10, 11]
for j,i in enumerate(dacs):
    b = ps.param()
    b.begin = 0.0
    b.end = 0.0
    b.stepsize = 1.
    b.label = 'V_%s'%(names[j])
    b.unit = 'mV'
    b.instrument = 'Eefje'
    b.module_options = { 'rate_delay': rate_delay,
                        'rate_stepsize':rate_stepsize,
                        'var': 'dac%d'%i,
                        'gain':gains[j]}

    gates.append(b)

#unpack all gates into easily modified variables
L,A1,B1,C1,D1,E1,B2 = gates

# delay = rate_delay
# stepsize = rate_stepsize
# L.rate_stepsize = stepsize
# L.rate_delay = delay

# Le, B1e, B2e, P1e = egates
#gates = [L,B3,B5]

vsd = ps.param()
# vsd.begin = 20.
# vsd.end = -20.
# vsd.stepsize = 1.
vsd.label = 'V_SD'
vsd.unit = 'mV'
vsd.instrument = 'Eefje'
vsd.rate_stepsize = 1.
vsd.rate_delay = 25.
vsd.module_options = { 'rate_delay': vsd.rate_delay,
                        'rate_stepsize':vsd.rate_stepsize,
                        'var': dac_sd,
                        'gain':voltage_source_gain}

z = ps.param()
z.label = 'Electron_current_SD'
z.unit = 'nA'
z.module = lambda: elKeef.get_readval()/i_gain #1 GV/A #hole side
# z.module_options = {'measure_wait': 1*20*1e-3}

```

#7 moving averages further of PLC powerlinecycles

```
L.begin = 00.  
L.end = 500.  
L.stepsize = 1.  
 #(L.begin -L.end)/500.
```

```
B2.begin = 00.  
B2.end = 00.  
B2.stepsize = 3.  
 #(B2.begin -B2.end)/100.
```

```
B1.begin = 00.  
B1.end = 00.  
B1.stepsize = 4.
```

```
A1.begin = 00.  
A1.end = 00.  
A1.stepsize = 100.
```

```
C1.begin = 00.  
C1.end = 00.  
C1.stepsize =50.
```

```
D1.begin = 00.  
D1.end = 00.  
D1.stepsize = 100.
```

```
E1.begin = 00.  
E1.end = 00.  
E1.stepsize = 100.
```

```
vsd.begin= 10.  
vsd.end = 10.  
vsd.stepsize = .25
```

```
ping = ps.parspace()
```

```
# gates_comb = ps.createCombinedFromAxes([B2,L])
```

```

ping.add_param(E1)
ping.add_param(D1)
ping.add_param(C1)
ping.add_param(A1)
ping.add_param(B1)
# ping.add_param(gates_comb)
ping.add_param(B2)
ping.add_param(vsd)
ping.add_param(L)
ping.add_paramz(z)

devicename='2B4L.As.751011.SH.L.'
measname = ('%(filename)s_%(name)s_' % {"filename": base, "name": devicename})
ping.set_name(measname.replace('_', '_'))
ping.set_traversefuncbyname('sweep', n=3, sweepback=True)
ping.estimate_time(sweepback=True)
ping.traverse()

```

```

# eefje.set_dac1(0.0)
# eefje.set_dac10(0.0)
# eefje.set_dac11(0.0)
# eefje.set_dac12(0.0)
# eefje.set_dac13(0.0)
# eefje.set_dac14(0.0)
# eefje.set_dac15(0.0)
# eefje.set_dac16(0.0)

```