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FIGURES

1 INTRODUCTION

The objective of this report is to present the characterization of RF NEMS devices fabricated in the WP3.

The results on the DC switch fabricated on Nano-RF are presented in this report. These switches with a simplest structure have facilitated the development of an experimental assembly to measure RF switches devices by improving the understanding of the critical parameters of the measure.

These measures have helped to define a new design.

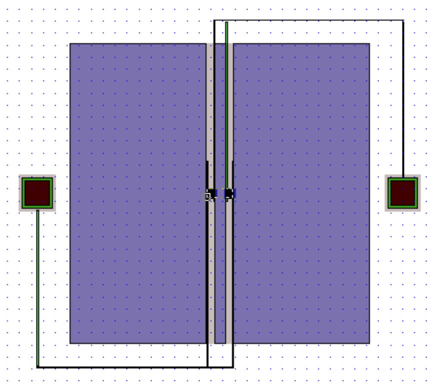
2 CHARACTERISATION OF THE RF NEMS SWITCH

The technological fabrication of the RF NEMS devices has been carried out to validate the process flow. Preliminary device testing has been performed on frozen NEMS devices for comparison with simulated results.

The frozen NEMS devices are fabricated using a similar process flow except for the CNT growth. Actually in the fabricated frozen NEMS devices, the connection between the signal and earthed electrodes is done using a thin layer of metallization, Mo, in this case instead of using CNTs.

The characterization results presented in this section relates to the measurement carried out on test samples at different steps of the process flow using an AIXAXCT 2000 setup.

The switches are CNT RF-NEMS shunt switches as were designed early in WP2 and fabricated in WP3. As was identified then, two CNT cannot be actuated by applying a direct voltage to create the needed electrostatic force because the moment they touch they would be destroyed by the current density going through them. In order to compensate, side electrodes have been implemented to generate an Electric field in which the two movable CNT will be bathed. We then only slightly polarize the two movable CNTs with a really low voltage so that they are interacting with the E field surrounding them without the risk of being destroyed due to current density when they contact.



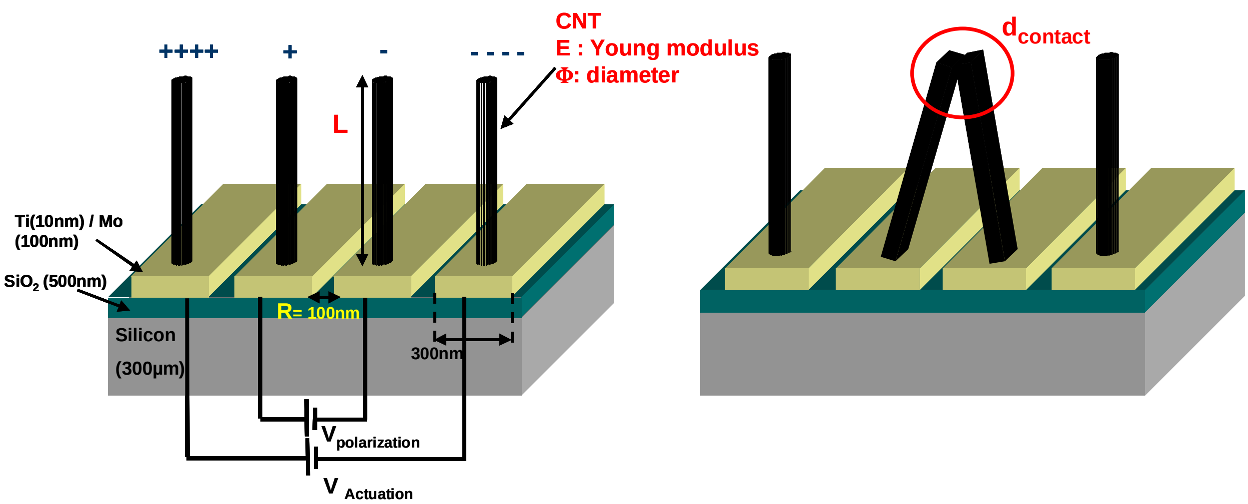


Figure 1: CNT RF-NEMS actuation system

As is shown on Figure 1, the high voltage for the basking E field generation is applied on the outside CNTs and the very low voltage polarized CNTs are on the inside.

1.1. CNT RF-NEMS SHUNT SWITCHES AND TEST STRUCTURES

The Figure 2 below shows the mask of a single chip on which CNT growth is made. It contains multiple structure types such as RF lines, alone then with added steps toward the RF-NEMS structure to check on the impact of each architecture step, Frozen RF-NEMS and normal RF-NEMS to be measured in both actuated and unactuated states.

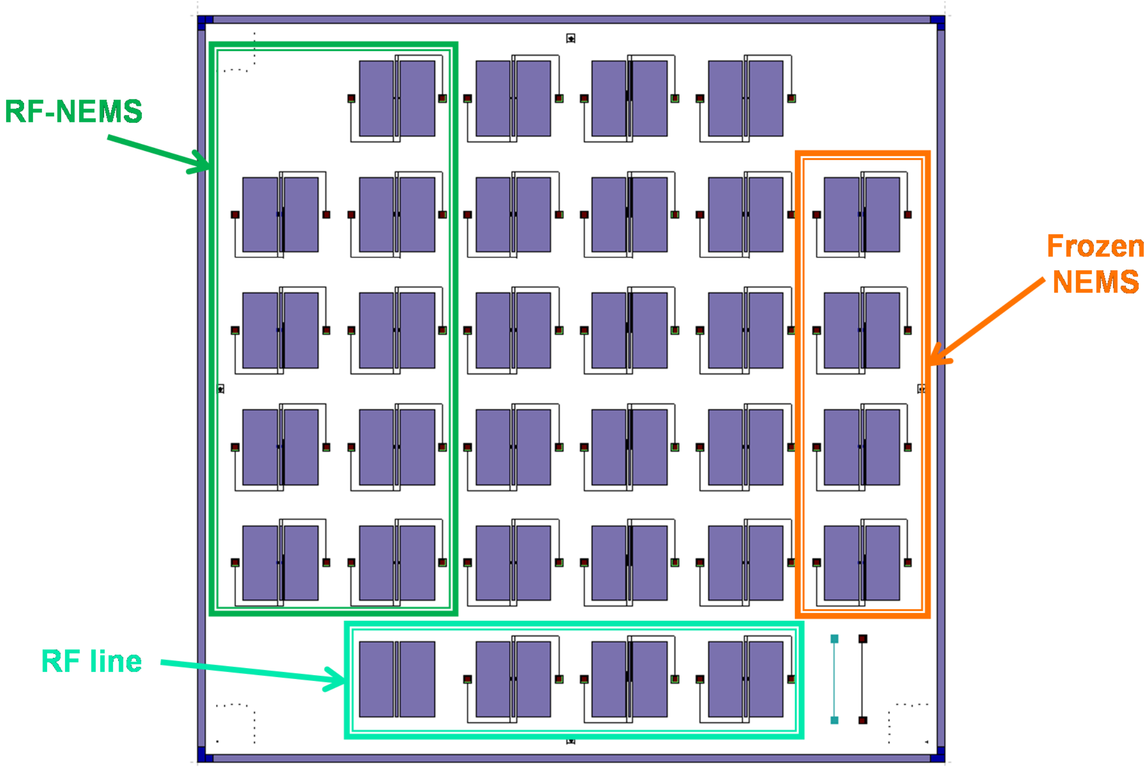


Figure 2 : Mask of the wafer showing the RF-NEMS and test structures used for DC characterizations.

The test structures are the RF lines and the frozen RF-NEMS. They each are representative of a static state and gives us information on the near perfect behavior we are to expect from the CNT RF-NEMS switches.

1.1.1. RF-lines

First the CPW lines (Co-Planar Waveguide) were measured. They represent the base structure in which the RF-NEMS switches are built. The quality of that transmission line, its losses in particular, will give us the minimum losses we are to expect for the RF-NEMS device. The difference in insertion loss measurement between the line and the RF-NEMS will be the added losses/impedance missmatch introduced by the RF-NEMS architecture. The dimensions of this CPW line are a central line 36 µm wide spaced from the ground plan by a distance of 26 µm. the whole structure is built on a SiO_2/Si with Si being High resistivity Silicon.

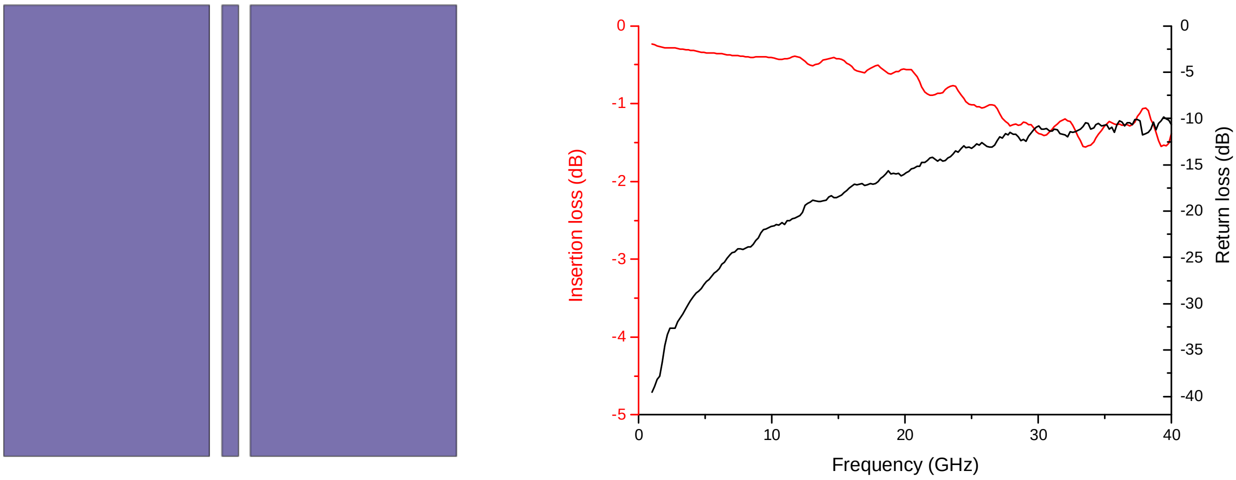


Figure 3: CPW design (left) and its [S] parameter measured (right)

The insertion loss is 0.4 dB with a return loss of 22 dB at 10GHz. The losses increase to 1.5 dB at 40 GHz with a decreasing return loss of 10 dB. This is due to the increasing mismatching of the line at higher frequency.

1.1.2. Frozen RF-NEMS shunt switch

As was stated previously, the frozen RF-NEMS switch is a test structure representative of the actuated CNT RF-NEMS switch. In this case, the RF-NEMS switch is a shunt type switch whose role is to short-circuit the signal line with the ground planes when actuated.

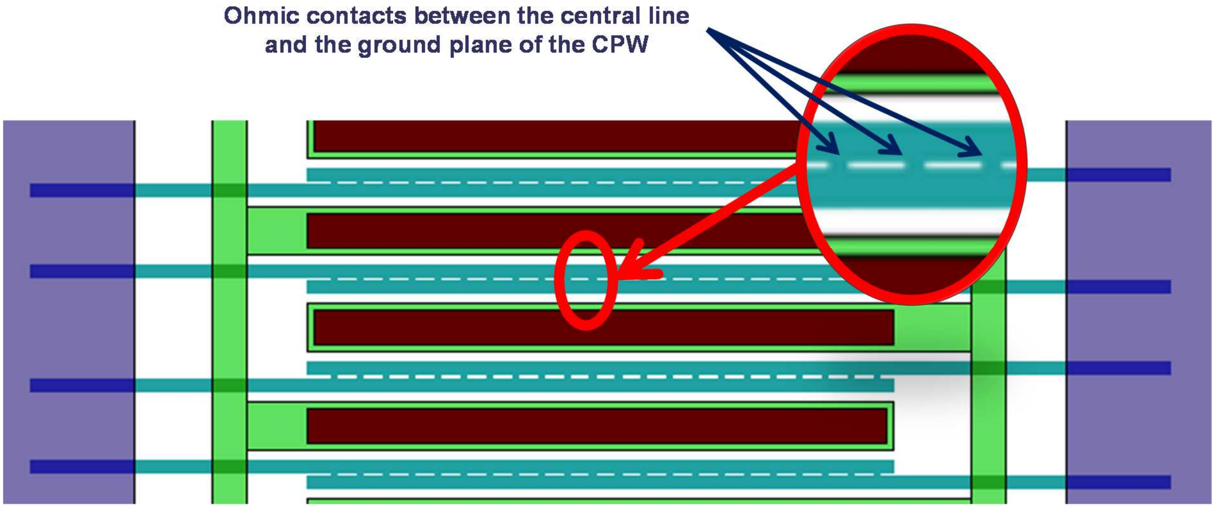


Figure 4 : Detail of the contact area between signal and ground lines in a frozen RF-NEMS.

Figure 4 shows that the small lines coming from the central conductor and the one coming from the ground plane are in ohmic contact. The contacts are not continuous and made from a very thin metal layer in order to represent at best the actuated CNT-CNT contact of the CNT RF-NEMS switch.
The measurement of this test structure gives us the near perfect behaviour of the RF-NEMS switch in the OFF state with very good CNT-CNT transmission (i.e. low CNT-CNT contact resistance).

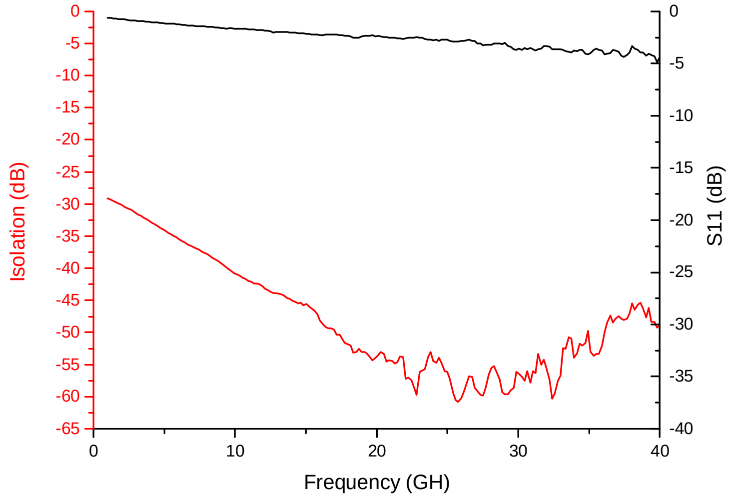


Figure 5 : Isolation and return loss of a Frozen RF-NEMS switch.

As shown on Figure 5, the frozen RF-NEMS shunt switch displays an isolation of about 40 dB at 10 GHz which then slightly increase to reach 45 to 50 dB around 40 GHz. These are very good results but were obtain using Ohmic contact to short circuit the central line. It nevertheless gives a fork of value in which to expect the CNT RF-NEMS shunt switch behaviour.

1.1.3. CNT RF-NEMS shunt switch

The characterized CNT RF-NEMS shunt switch is shown on Figure 6 below.

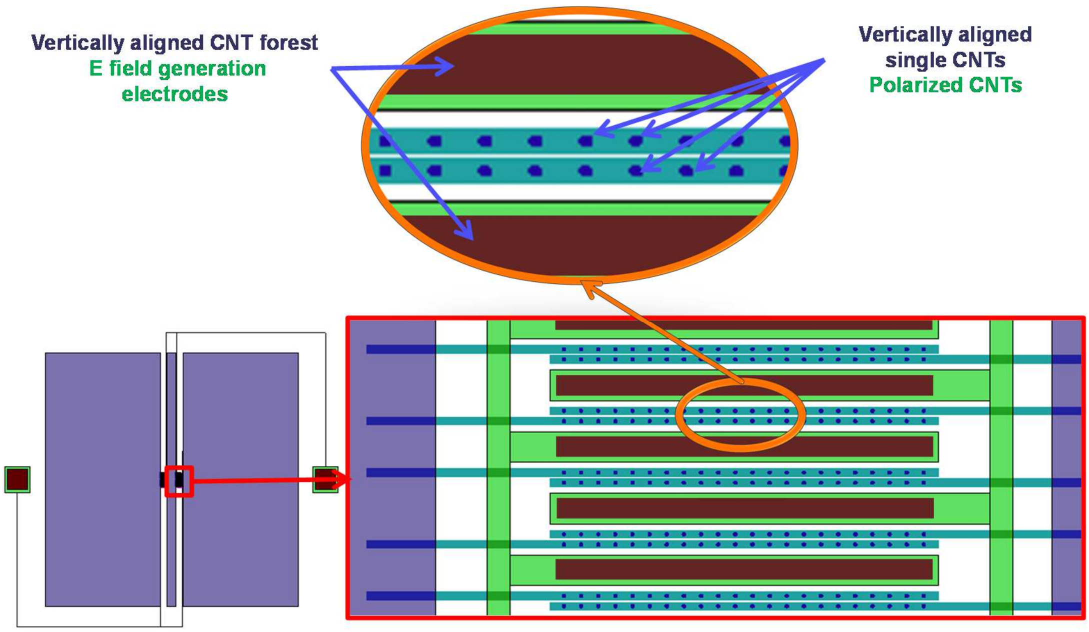


Figure 6 : Design of the CNT RF-NEMS shunt switch with details on the CNT architecture.

By applying the high voltage on the two external pads the strong E field will be generated between the CNT forests then while keeping the E field up we apply a very small voltage to polarize the vertically aligned array of single CNTs as described above on Figure 1.

During the process of actuating the CNT RF-NEMS structures, not everything worked as expected and we decided to push the polarization voltage from a few mV up to a dozen V in order to see some behaviour change. The behavior change happened around 12 V which was much higher than anticipated.

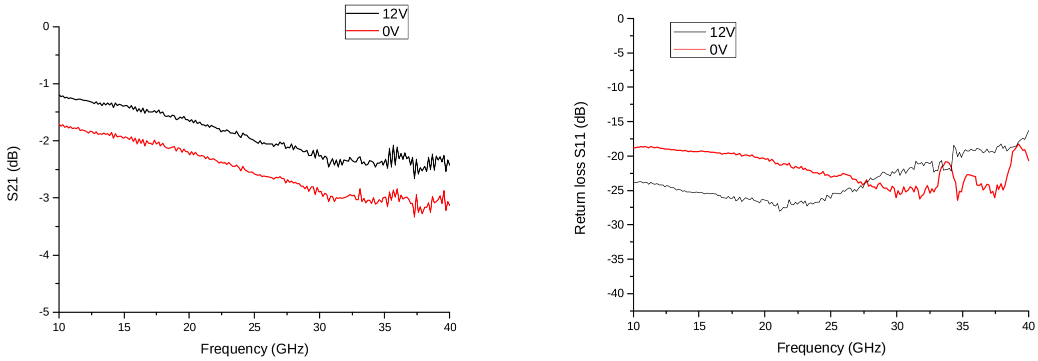


Figure 7 : Insertion loss (left) and return loss (right) with and without actuation bias.

Figure 7 shows non actuated insertion losses of the CNT RF-NEMS shunt switch to go from 1.2 dB at 1 GHz to 2.2 dB around 40 GHz with a good impedance matching of about 20 dB on the whole frequency range. This shows that the structure is well matched and that the losses we see are from withing the architecture and the material losses.

For the actuated state, as a result of such voltage on the polarized CNTs, as shown on Figure 7, we obtained a general improvement of the insertion losses from 1 to 40 GHz and at first an improvement on the return losses up to 25 GHZ followed by a degradation up to 40 GHz. This result, which goes in the opposite direction of what should have been the actuated state is irreversible. Once the bias voltage applied on the polarized CNTs is removed, the RF measurements are unchanged.

The reason why this happened is that we altered the CNT RF-NEMS structure when we applied up to 12 V on the polarized CNTs. Destruction of CNTs, alteration of the molybdenum lines that supported the vertically aligned arrays of single CNTs as 12 V is about a thousand time more than the recommended polarized voltage.

We are currently investigating why CNTs were not being actuated, leads are on the length average of the CNTs and their diameters as it determine the mechanical behavior, their exact positioning, the distance between each paire… As was reported in earlier deliverables from WP2 and the CNT RF-NEMS design, there is a very small margin in which the CNT RF-NEMS can work and small variations may alter the structure more than expected.

1.1.4. DC characterisation of the RF NEMS switches and test structures

In order to understand and explain the RF results we obtained, DC characterizations have been performed on NEMS switches and test structures.
To do so, current-bias measurements have been performed on different structures:

- RF-Lines
- Frozen RF-NEMS
- RF NEMS

1.1.4.1. RF-Lines

RF-lines have been polarized between signal and ground lines. The gap between these two gold lines is 26 µm.

When a bias is applied, a current appears between the lines through the Si_3N_4 passivation layer. This current has been measured and is below 1nA at 1V. This high resistor is in good agreement with the low insertion losses measured in RF.

1.1.4.1. Frozen NEMS

When the same set up is applied on the frozen RF-NEMS switch, it shows an ohmic behavior (Figure 8). This is also in good agreement with the high isolation measured during RF characterization.

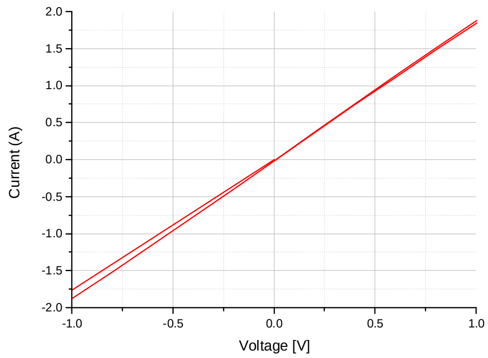


Figure 8 : I(V) performed on a frozen MEMS.

1.1.4.2. RF-NEMS

Concerning RF-NEMS, the current-bias characteristic has also been measured. The bias has been applied between the signal line and one of the ground lines.

The I(V) curve is plotted Figure 9. This kind of behavior is characteristic of the current crossing a dielectric. However it is as high as 30mA at 3V.

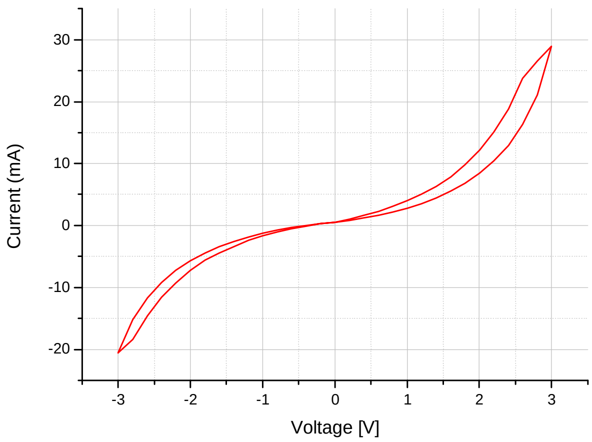


Figure 9 : Current vs bias in an RF-NEMS.

3 CHARACTERISATION OF THE DC NEMS SWITCH

In order to understand the reason why CNTs were not actuated, we decided to fabricate simplest devices with only 4 CNTs and measure in DC. Indeed, as was reported in earlier deliverables from WP2 and the CNT RF-NEMS design, there is a very small margin in which the CNT RF-NEMS can work and small variations may alter the structure more than expected.

3.1 DC STRUCTURES

Figure 6 below shows a brief description of the designs to be used for the feasibility process with metal electrodes of 220µm and a spacing of 3µm as well as an alignment of the catalyst dots of 200nm diameter within a spacing of 300nm. Figure 10 represents different masking level.

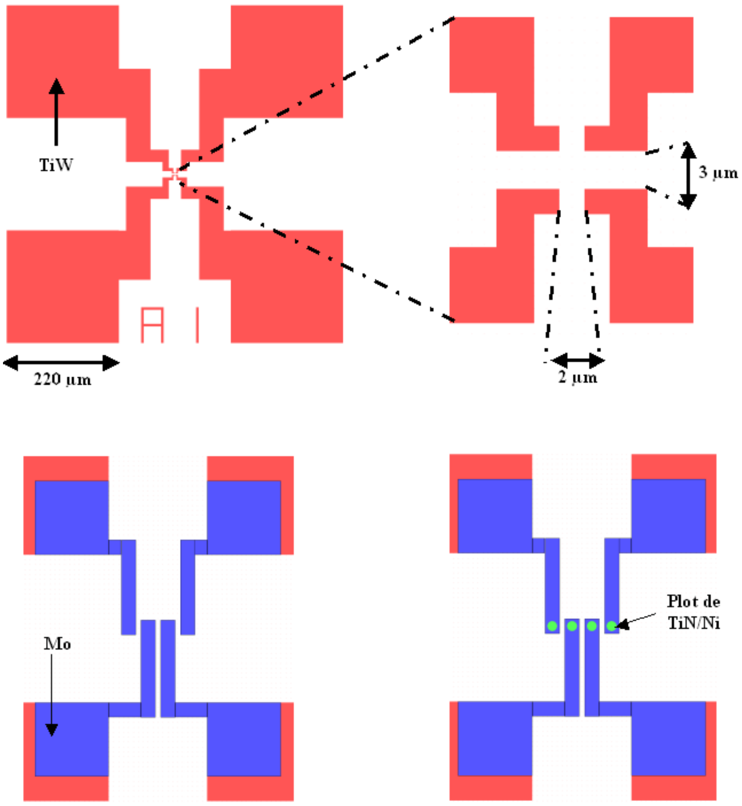


Figure 10 : Mask design for the CNT-based mechanical NEMS switch

The process flow is summarized below:

- ***Step 1*** : Electrode contact in TiW metal using optical photolithography. This is carried out by a full wafer deposition of TiW followed by optical photolithography and ion-beam etching.
- ***Step 2*** :This step consists in precisely defining the Mo electrodes (300-350nm wide) at the end of the contact deposited in step 1. This has been carried out by electron beam lithography followed by a lift-off process. Figure 7 below shows an example of this processing step.
- ***Step 3*** : This is the most critical step because it is important to align by electron-beam lithography a 250nm diameter dot in between the 300-350nm electrode. This process of defining the catalyst dots is carried out by a combination of sputtering and lift-off process for TiN (15nm) and Ni (7nm) deposition to be positioned at the extremity of the Mo electrodes.

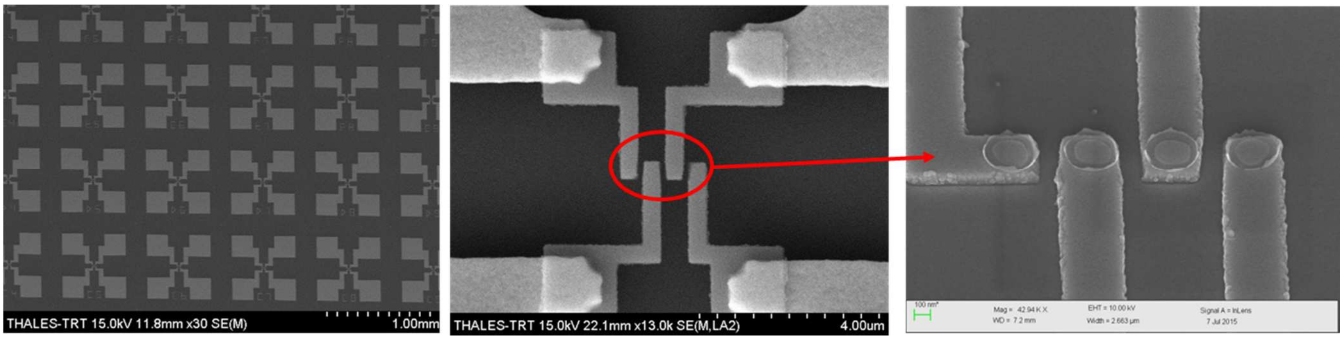


Figure 11 : SEM images of the Mo electrodes

Based on the process trial runs and on the choice of the suitable metal, a preliminary fabrication process has been carried out to validate the feasibility of the fabrication process of a mechanical NEMS switch using CNTs. The process has been based on the typical 3-step process defined in the previous section and the choice of the electrodes has been TiW and Mo. Figure 12 below illustrates a close-up SEM image of the grown CNTs at the extremity of the contact electrodes, hence validating the process flow.

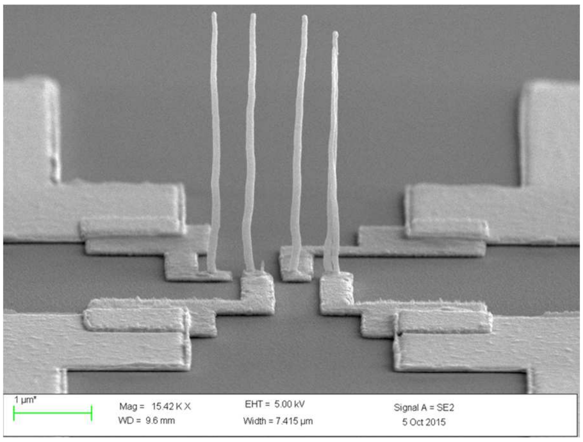


Figure 12 : CNT DC switch

3.2 DC MESUREMENTS

3.2.1 Preliminary DC measurement

Figure 13 below illustrates the result obtained from a typical switch as shown above. At an actuation voltage of 40V, a typical current step of 4nA has been observed (Figure 13). This proves that the 2 CNTs are actually connected – switching has occurred.

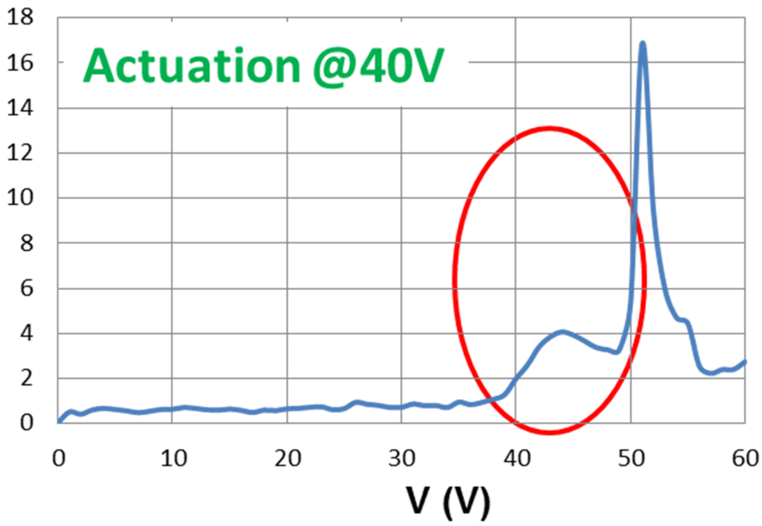


Figure 13 : Variation of the current between CNTs under actuation at 40V

Also, during commutation, SEM observation shows that the height of one the CNT reduced after actuation (Figure 14b). The actuation of the DC switch has been demonstrated.

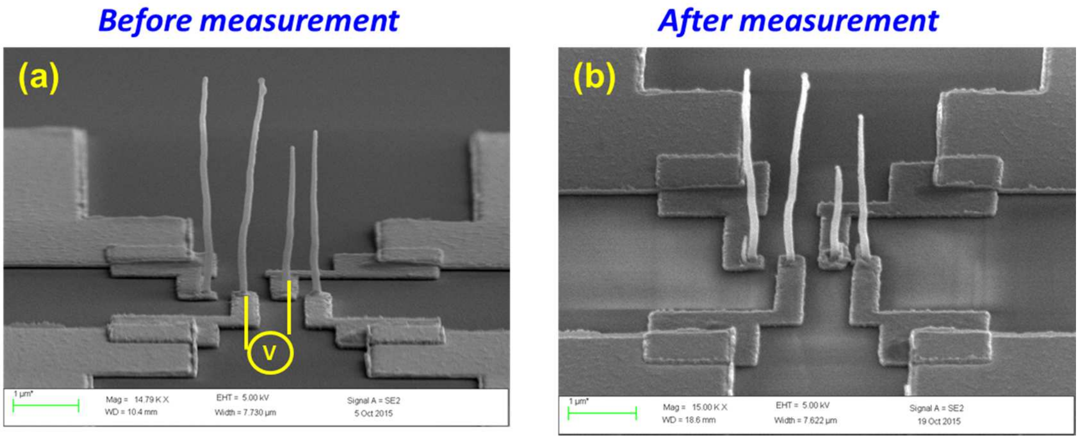


Figure 14 : CNTs switch before (a) and after measurement (b)

3.2.2 In-Situ DC Measurement

For a better understanding of the actuation mechanisms, in-situ measurements using 4 probes station coupled with SEM have used used and try to observe the actuation. These measurements were carried out in collaboration with ALTIS.

Figure 15 shows the experimental set-up used for the measurement

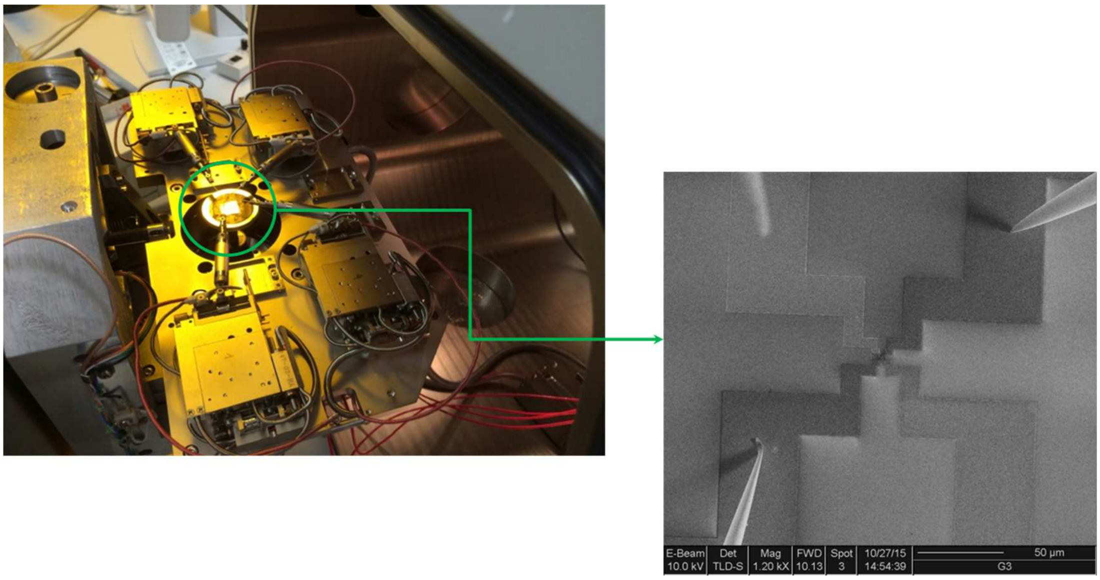


Figure 15 : 4 probes station coupled with SEM

Several measures have been carried out and the results have shown:

- Actuation can be visualized
- Switching time is too fast to be able to be detected by the scan time of the SEM
- In-situ SEM technique is limited and not adapted for this device

3.2.3 DC Measurement

A test set was built to measure the switching behavior of the Carbon-Nano-Tube (CNT).
The CNT do not stands large currents; a large resistor is needed to limit the DC current. We made the test with a 50MegOhm. Figure 16 present a schematic of the experimental set-up

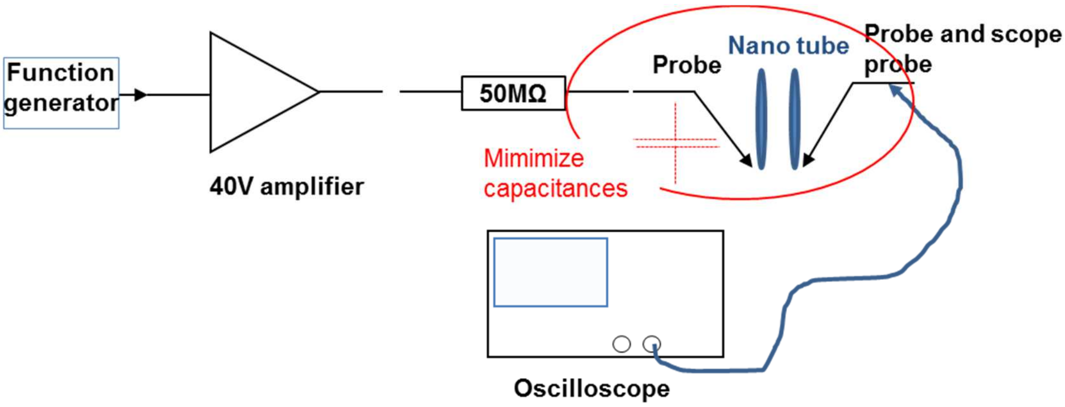


Figure 16 : test set description

A function generator provides the chosen wave shape and it is amplified up to tens of volts.
An oscilloscope is used to measure the waveforms. The scope has a very large memory, so we can store the whole waveforms and analyzed them later. The waveforms can also be read by the spice simulator, so we can fit the circuits values and behavior.

It is required to limit the parasitic capacitance in the test implementation and especially the capacitances after the 50MegΩ and on the measurement side.

The DC current will be limited by the 50MegΩ and the scope10MegΩ. When switching, the current is not limited except by the CNT resistance.

The available energy is set by the parasitic capacitance between the 50MΩ and the probe to ground (i.e the baseplate on which the sample is placed).
On switching, this energy will flow very quickly to the measurement probe and scope probe capacitances.

Figure 17 shows a picture of the set up used for the DC measurement with probes, 50Mohm resistance and the scope probe

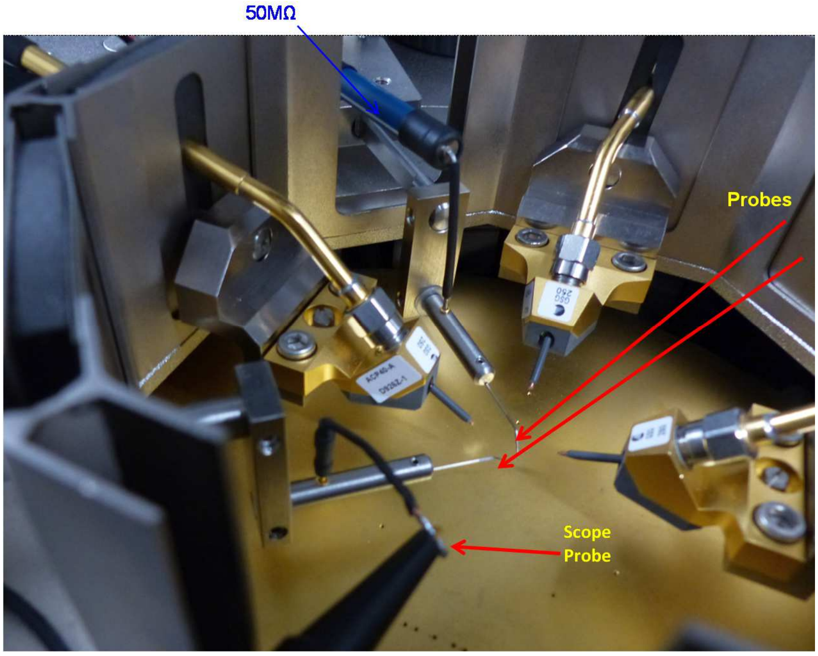


Figure 17 : picture of the probes and resistor Nota the RF probes are not used

The critical point for the measurement on the CNT DC switch is the parasitic capacitance which can cause the destruction of CNTs. The parasitic capacitance before the CNT switch is identified with preliminary measurements. The scope probe is typically 10pf and 10MegΩ. Rough order of magnitude of the current may be:
if we have 25V and a CNT resistance of 25kΩ, this is 1mA peak and it decreases to 0.5mA in ~0.12µs. (this may lead to the CNT destruction). Figure 18 show a schematic of the different capacitance

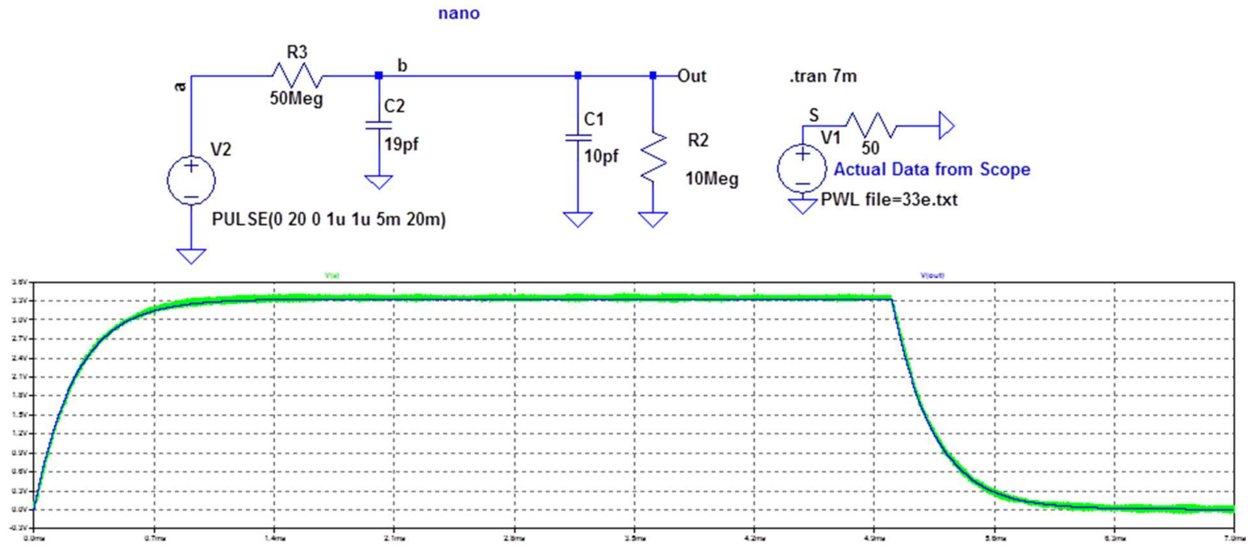


Figure 18 : Identification of the capacitance

Several measurements have been done using this experimental set-up and two successive actuations have been observed. The results are summarized on Figure 19

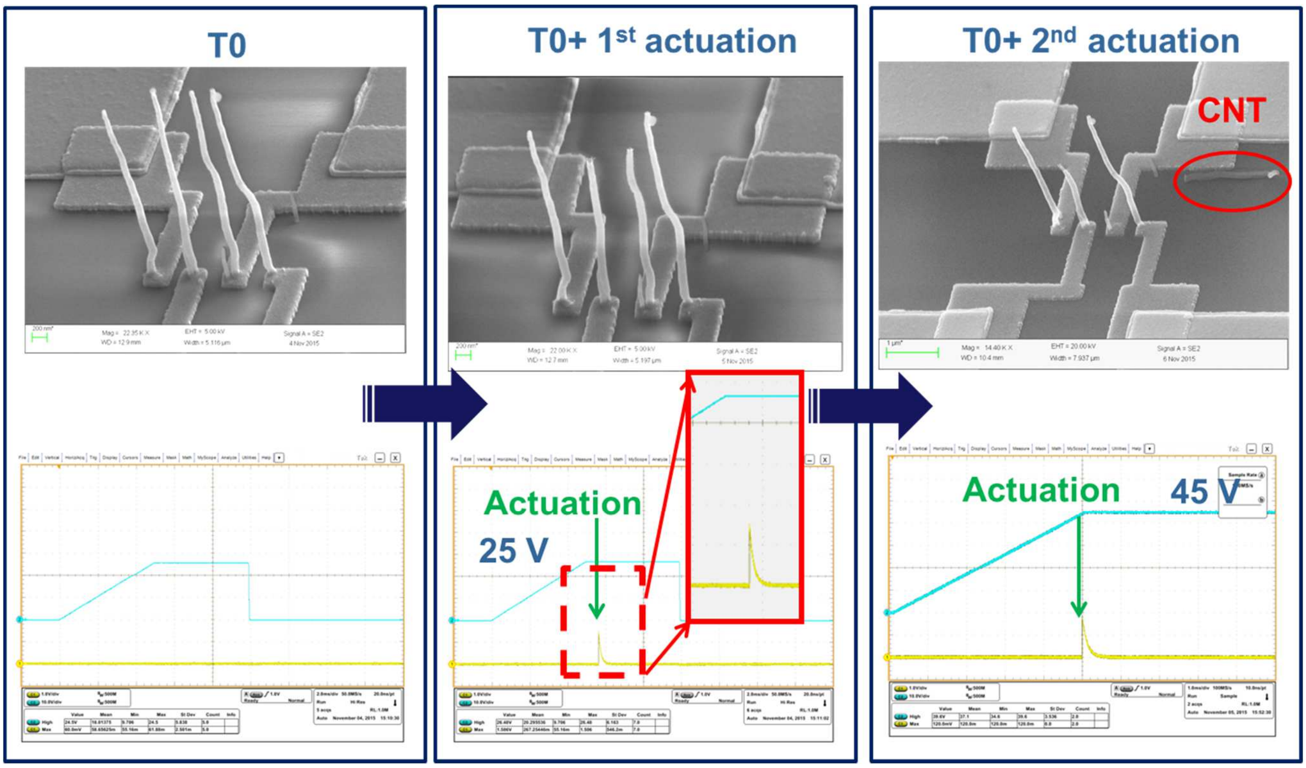


Figure 19 : Observation of two actuations on the same DC switch device

A 25 V, we observe a peak corresponding to a first actuation between 2 CNTs of middle. SEM observations show a reduction of the CNTs height and validate the actuation. Same measure on the same device is performed and a second activation is observed at 45V. The difference can be explained by the fact that CNTs are shorter and therefore requires a higher voltage for activation. As before, destruction CNT is observed (one is shorter and one moved out of the electrode)

This has been reproduced across devices and the same behavior is observed.

4 TEST SET FOR 4 CNT

The test set for 4 CNT is based on the set for 2 CNT, with a DC polarization added on the externals CNTs, with a DC power supply.

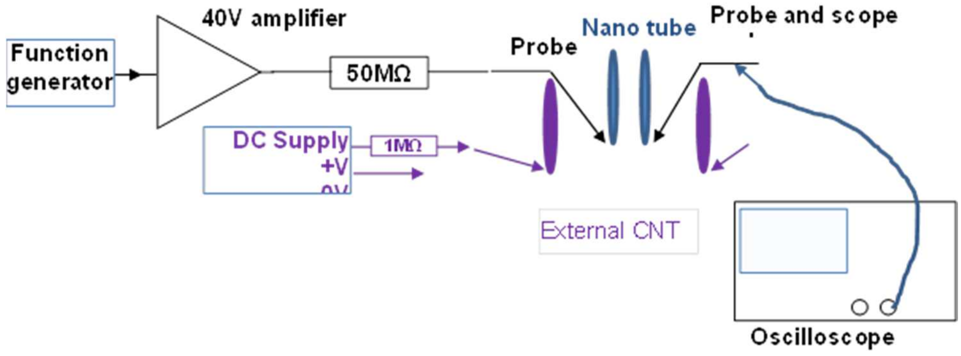


Figure 20 : test set description for 4 CNT (NOTA the DC supply may be +V/0V or symmetrical to ground: +V/2 / -V/2)

5 NEW DESIGN OF RF NEMS SWITCH

Learning from our previous experience with the shunt RF-NEMS design and the work we did around the building of a test bench, measuring NEMS has proven very difficult both in actuating and in detecting a change.

What we propose here is a new architecture for a RF-NEMS switch. It is a serial type of switch, meaning the line is discontinued and actuating the CNT will enable the signal to go through. From our RF-MEMS experience we learned that it is easier to detect the transmission of a serial switch if the contact capacitance is low or faulty than it is to detect the isolation of a shunt switch, which is why we've chosen the serial architecture for this new device.

New RF-NEMS design:

The previous work in designing CNT based components showed that it is important to be at high impedance when dealing with CNT so that transmission of the signal energy from the line to the CNT can be achieved at least partially. For that reason, the new RF-NEMS serial switch is based on a line that is 50 Ohm at the input and output and becomes a 250 Ohm when in the CNT vicinity.

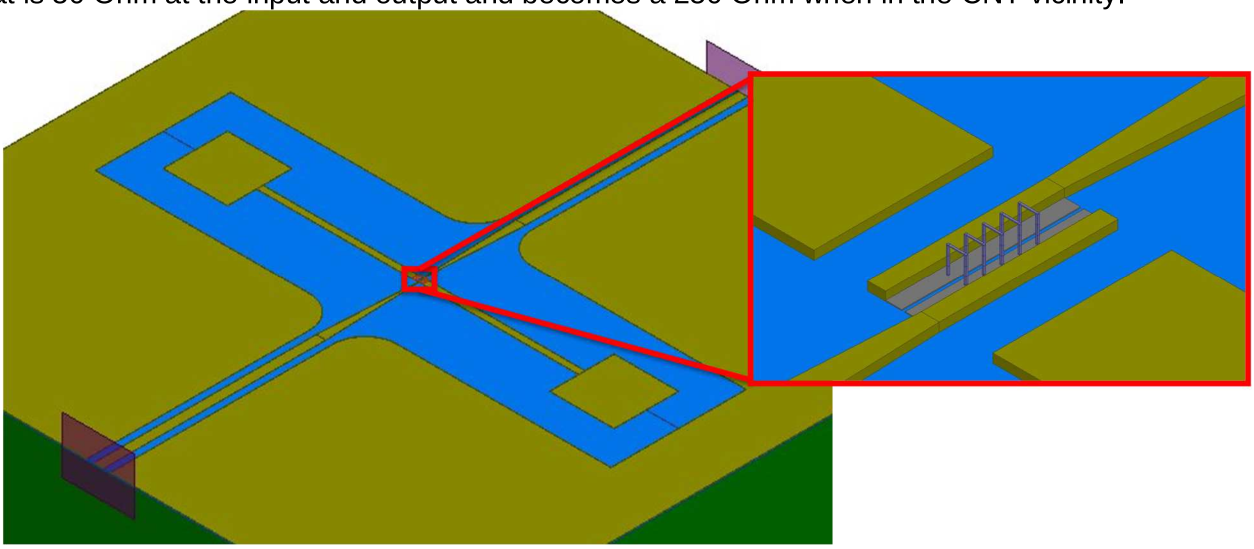


Figure 21: Global CNT based Serial NEM-RF switch design

The command is applied through gold electrodes positioned to the left and right of the signal line. CNT will be enclosed in an electric field. Once properly polarized, as in the previous design, the CNT will be moved by the field potency.

Design variations:

In order to assess the efficiency of that device, 3 different designs have been realized. They respectively feature 1, 5 and 9 CNT pairs at the connection point.

The simulation of these devices has been set up as follow:

As shown on Figure 22, a red element joins the tip of each CNT pair.

- When the switch is open (OFF), the red element is just vacuum/air. There is no contact between the CNTs.

- When the switch is closed (ON), the red element is equivalent to a 1000 Ohm resistance. This simulate the high contact resistance between 2 CNTs when they are in contact through only a small area as is the most likely outcome of a successful commutation.

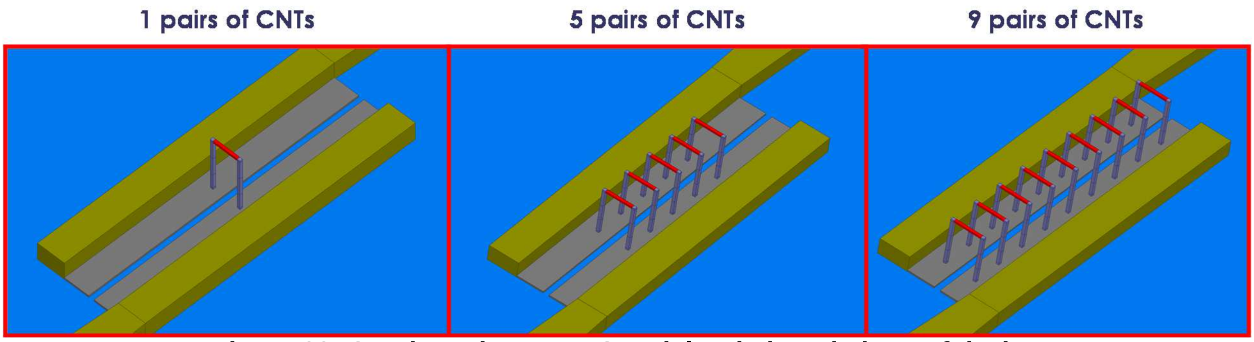


Figure 22: CNT based RF-NEMS serial switch variations of design

Simulation results:

Simulations have been made on these different structures.

As expected, as shown on Figure 23, the simulation result of the serial RF-NEMS switch with 1 pair and with 9 pairs are both very close to each other as well as being very close to the simulation of a serial RF-NEMS structure with no CNT. This, considering that the CNT model is more than likely too conductive compared to the reality of a multiwall vertical CNT, comforts us in the fact that in OFF state, the amount of CNT will have a very negligible influence on the serial RF-NEMS isolation.

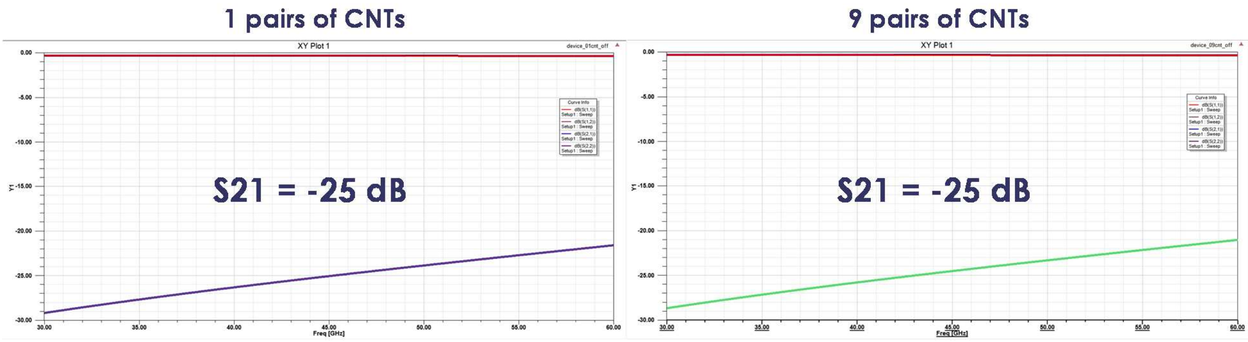


Figure 23: Simulation results of a 1 pair and 9 pairs CNT serial switch in OFF state (Open)

On the other hand, the simulation results of the serial RF-NEMS switch in the ON state shows clearly different behaviours depending on the amount of CNT pairs. Figure 24 shows that when in ON state, the insertion losses go from -25 dB to -21 dB @45 GHz for 1 pair of CNTs, to -11dB @45 GHz for 5 pairs of CNTs and to -7.7dB @45 GHz for 9 pairs of CNTs.

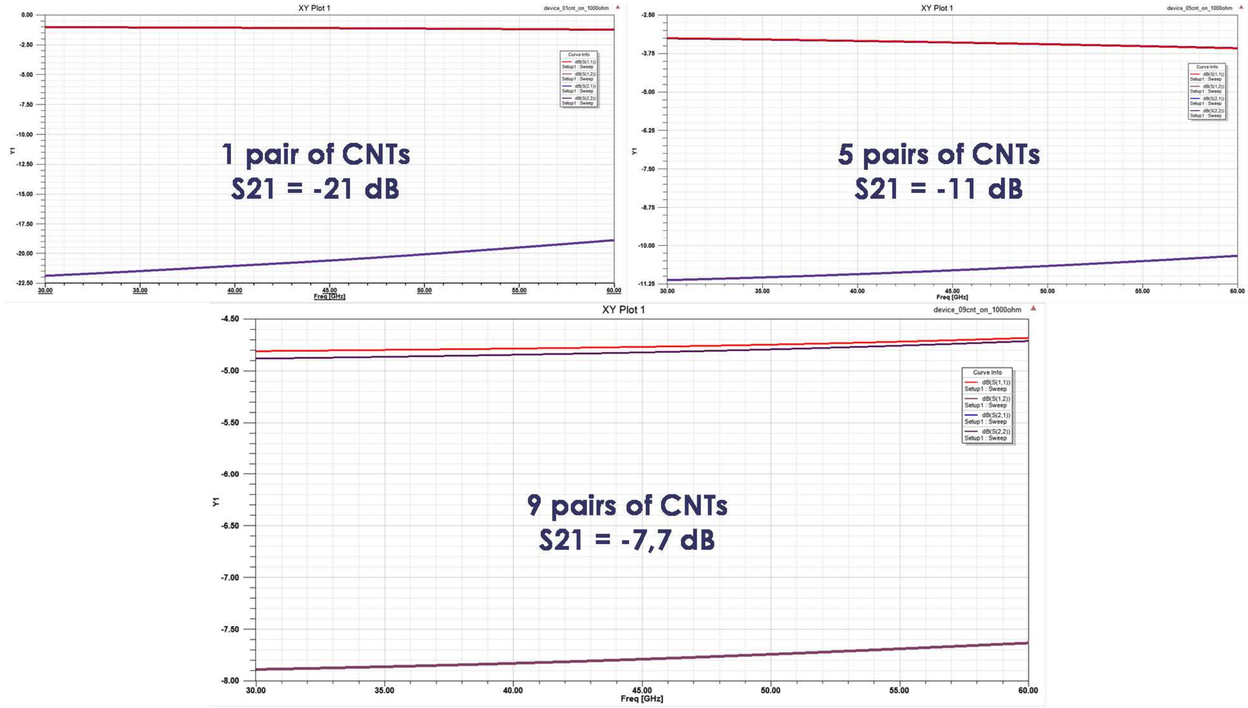


Figure 24: Simulation results of a 1 pair, 5 pairs and 9 pairs CNT serial switch in ON state (Closed)

As expected, the more CNT pairs the better for the transmission of the signal, up to an unknown maximum of efficiency at the moment, because it lowers the global contact impedance of the serial switch when in the ON state.

An optimum still has to be reached for the design of this serial switch as to how many CNT pairs and, eventually, how many rows of CNT junction will be the best, how to actuate them, the ration efficiency/complexity, etc.