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Radio-frequency characterization of varactors based on carbon nanotube arrays**

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Keywords:
Carbon nanotube, varactor, RF measurements

Abstract

Arrays of carbon nanotubes were reversibly actuated by applying a bias voltage. The actuation results in a variable capacitance between the arrays, which can be used to build a varactor. The capacitances were evaluated by simulating the scattering parameters in an equivalent electrical circuit while using the capacitance between the arrays as a fitting parameter. These simulations were compared with RF measurements on devices. A very good agreement between measurement and model was obtained. The capacitance could be varied by more than 20 % before the arrays were pulled into contact, partially destroying the device.

1. Introduction

Carbon nanotubes have been proposed for many applications during the last years, for example as interconnects [1], sensors and composites [2] and in many more electrical and mechanical devices [3]. Here we study the use of arrays of carbon nanotubes as varactors. A varactor is a device where the capacitance can be varied by applying a bias voltage across it. These devices can be found in for example tuneable filters, tuneable antennas, phase shifters or voltage controlled oscillators [4].

The actuation of single nanotubes has been studied theoretically [5]. The capacitance between two single nanotubes is however very small, making it necessary to use many in parallel. Dragoman et al.[5] suggested a network with 1000 x 1000 single nanotubes. Here however, we focus on actuating relatively large arrays of carbon nanotubes. We show that we can accurately model this system with an equivalent electrical circuit. By comparing simulated and measured scattering parameters we obtain the capacitance between the arrays of nanotubes at selected actuation voltages. We show an increase in capacitance of more than 20 % when the arrays are fully actuated compared to the absence of any bias voltage.

More information about the actuation of the arrays and the modelling of the actuation behaviour can be found in [6]. Here we focus on the details of the RF capacitance characterisation.

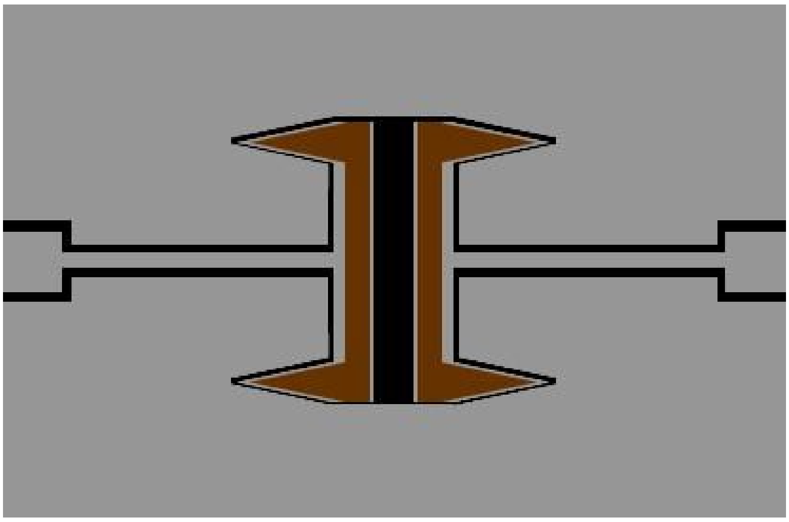
2. Experimental Method

Wafers of p-type high resistive Si (resistivity > 9000 Ω·cm) coated with a 600 nm polysilicon layer and topped with a 400 nm SiO_2 layer were used as substrate. The polysilicon layer is used to trap electrons that would otherwise build-up between the highly resistive Si and the oxide layer leading to transmission line losses [7].

Electron-beam lithography of a bi-layer resist system was used to pattern the electrodes. 200 nm Mo with an adhesion layer of 10 nm Ti was deposited by sputtering and formed by lift-off. The layout is shown in figure

1. Mo was chosen since it can withstand high temperatures, has a low electrical resistivity and is compatible with nanotube growth. It was found that sputtered Mo yields a resistivity one order of magnitude lower than electron-beam evaporated Mo thin films, which is beneficial for electrical measurements. The electrodes were patterned as two opposing T-shapes and connected to pads for electrical contacting. The electrode area was minimized and surrounded by shield electrodes in order to reduce the parasitic capacitance and optimize the capacitance measurements [8]. The catalyst layer of 5 nm Al_2O_3 and 1 nm Fe was deposited by electron-beam evaporation on top of the Mo in a subsequent step. In order to improve the mechanical stability and thereby also the alignment of the nanotube arrays the catalyst layer was deposited in a U-shape with a length of 200 µm, width of 4µm and a separation of 10 µm. Carbon nanotubes were grown by thermal chemical vapour deposition at 700°C for 150 s using a gas mixture of 5 sccm acetylene, 500 sccm hydrogen and 500 sccm argon. This resulted in MWCNTs with a length of 135 ± 5 µm.

(a)



(b)

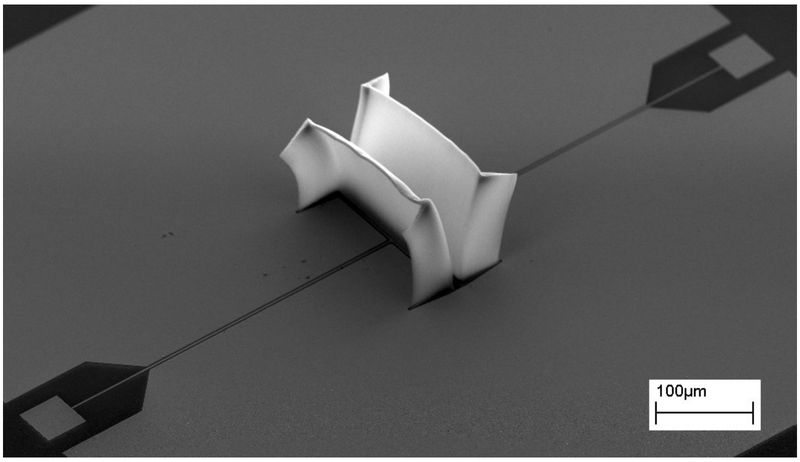


Figure 1. a, Sketch of the pattern used for electrode deposition, grey, and catalyst deposition, brown. b, SEM picture of a varactor device.

The arrays of carbon nanotubes were actuated by applying an increasing DC voltage to one of the arrays while the other was grounded. The actuation was studied under an optical microscope focused on the top of the arrays and in SEM enabling studies in more detail and with a larger depth of focus.

The S-parameters were measured at selected actuation voltages in the range from 200 MHz to 1.5 GHz using a probe station connected to an Agilent 5071B network analyzer. A GSG-probe (ground-signal-ground) was used to contact the CPW-shaped (coplanar waveguide) electrodes and thereby grounding the shield electrodes. The setup was calibrated by a SOLT (short-open-load-thru) calibration. The devices were modelled by the equivalent electrical circuit shown in figure 2. The S-parameters of the model were simulated and compared to the measurements using the capacitance between the nanotube arrays, C_{CNT}, as a fitting parameter. The shunt capacitances to the ground electrodes are modelled by $C_{ground1}$ and $C_{ground2}$ whereas the capacitance between the electrodes themselves is modelled by $C_{parasitic}$. These capacitances, which are inherent to the geometry of the devices, were found by fitting the capacitances in the model with measurements on samples without nanotubes (OPEN). Depending on the type of substrate these capacitances might change for an increased bias voltage. No such dependence was found here, however, just as reported by Gamble et al. for the same substrate material [7].

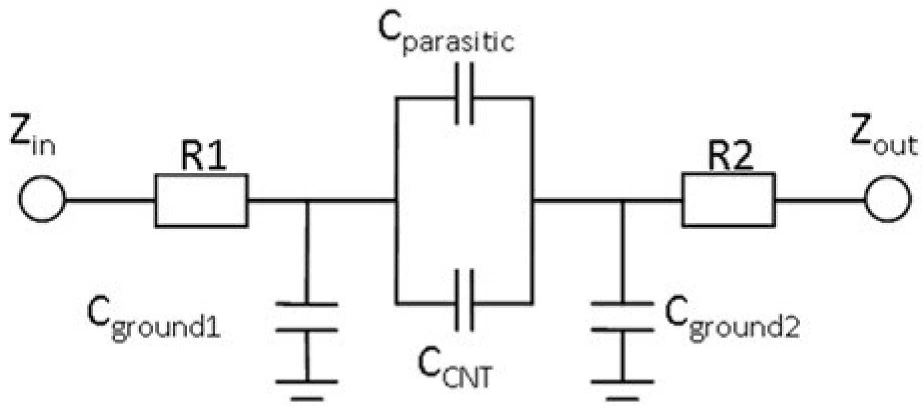


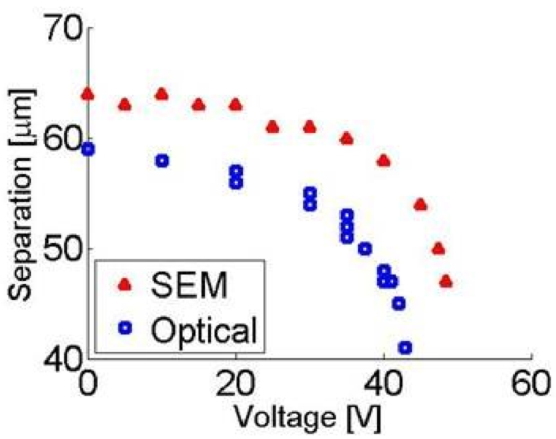
Figure 2. Equivalent circuit used to model the varactor devices.

The resistive losses through the transmission lines are modelled by the resistances R1 and R2. These were found by fitting the resistances to reference measurements on samples with a short between the electrodes (THRU). These measurements were performed on samples without nanotubes, however, the samples had been exposed to the high temperature used for nanotube growth, although without exposure to acetylene.

3. Results and discussion

The grown arrays of nanotubes are not perfectly vertical, but lean away from each other such that the tops of the arrays were separated significantly more than the 10 μm at the bottom. This is predominantly a consequence of slight inhomogeneity during the growth process related to precursor depletion [9]. The separation between the walls decreases as the applied voltage is increased, as shown in figure 3a. The change in separation per change in voltage increases as the applied voltage is raised. The actuation response was thus the highest just below the pull-in voltage. When the voltage is increased above the pull-in voltage the arrays are pulled together and a high current density flow through the electrodes. This permanently damages the arrays of nanotubes, as can be seen in figure 3b. The actuation under the optical microscope and in the SEM appears to be different, see figure 3a. However, this is due to different initial separations at the top of the nanotube walls and not a consequence of the different techniques. A more thorough discussion of the actuation can be found in [6].

(a)



(b)

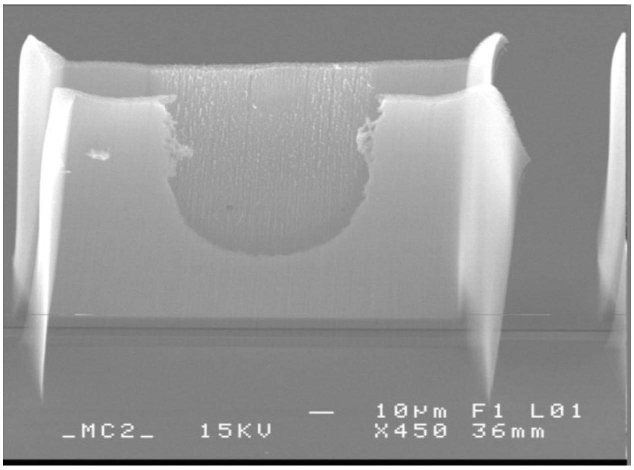


Figure 3. a, Separation of the top of the nanotube arrays plotted versus the applied voltage, studied under an optical microscope (blue) and in SEM (red). b, SEM image of the nanotube arrays after the pull-in voltage has been reached.

The capacitance between two parallel plates can be calculated by $C = \varepsilon_0 A/d$, where ε_0 is the electrical permittivity in vacuum, A is the area of the plates and d is their separation. This yields a capacitance of 24 fF and 4 fF by assuming that the plates are separated by 10 μm, as at the bottom, and 60 μm, as at the top, respectively. Consequently a capacitance around 14 fF can be expected as a first approximation for our devices. A more accurate way to find the capacitance is to measure the S-parameters of the device, compare these measurements with the modelled equivalent electrical circuit, shown in figure 2, and extract the capacitance from the model.

The resistive losses along the wires connecting the nanotube arrays were found by measuring samples with a short between the electrodes (THRU), yielding losses of around 14 dB. By simulating a device with a short-circuit it was found that these losses can be modelled by the resistances R1 = R2 = 160 Ω. This could however be reduced by increasing the size of the wires. An increase in the width would on the other hand result in an increase of the parasitic capacitance, consequently cancelling the gain arising from a lower resistance. It was not possible to deposit thicker electrodes since the thickness is limited by the lower resist layer in order to enable lift-off.

The capacitances inherent to the geometry of the devices were found by measurements on an OPEN sample without nanotubes. The capacitances, $C_{ground1}$ and $C_{ground2}$, are found by plotting the S_{11} and S_{22} parameters in a Smith chart, see figure 4, where the impedance, Z, can be extracted for every frequency, f. The S_{11} response is found to the far right of the chart, showing a purely capacitive behaviour. The S_{21} response is also plotted, located in the centre, showing a good matching to the 50 Ω system. The impedance of a purely capacitive circuit can be found by $Z_C=1/j\omega C=1/j2\pi fC$, where ω is the angular frequency. This can be rearranged to give the capacitance as $C=1/(2\pi*f*IM(Z))$, resulting in 100 fF. The parasitic capacitance between the electrodes is found from the S_{21} response by fitting $C_{parasitic}$ in the model to the OPEN measurements without any nanotubes, yielding 5.5 fF. The capacitance between the nanotube arrays at selected actuation voltages is similarly found by fitting the modelled to the measured S_{21}-parameters, see figure 5.

The S_{21} response of the device with nanotubes is 14 dB higher than the response of the electrodes on the OPEN structure without nanotubes, see figure 5. The model fits the experimental values very well for all actuation voltages indicating that the model describes the device accurately. By fitting the model to the measurements the initial capacitance between the nanotube arrays was found to be 13 fF. This was gradually increased to 16 fF as the bias voltage was raised to just below the pull-in voltage. This corresponds to an increase of more than 20 %, see figure 6. Note that the results reported here are for a different device to the one discussed in [6].

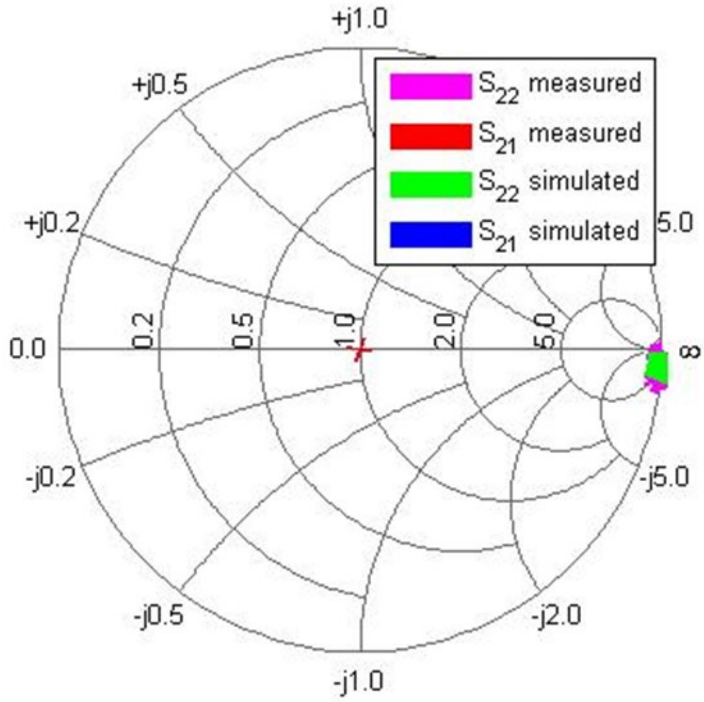


Figure 4. Smith chart of the measured and simulated S_{21} and S_{22} parameters for the structure device without nanotubes (OPEN), used to determine the capacitances inherent to the geometry.

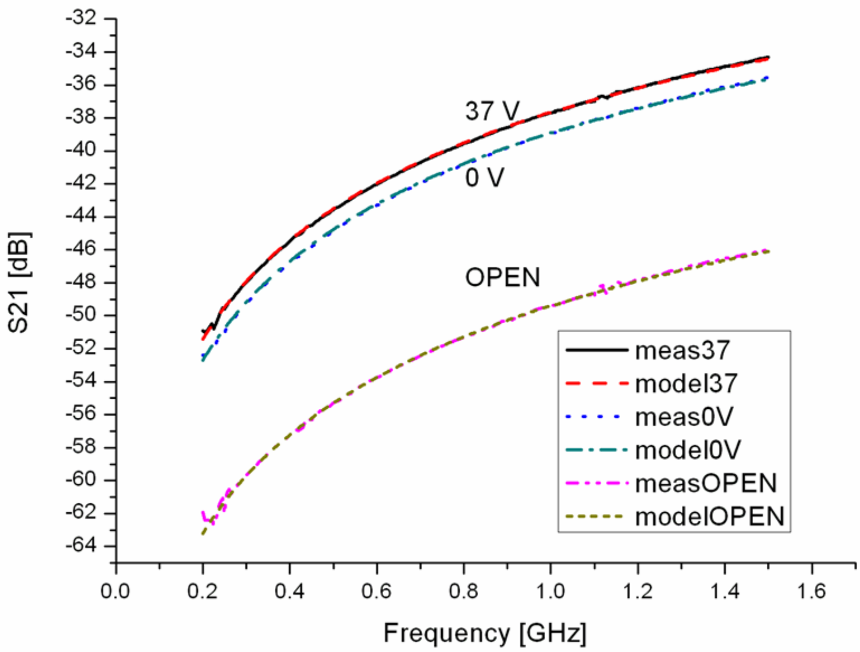


Figure 5. Measured and simulated S_{21} responses of the device at 0 V and 37 V, which is just below the pull-in voltage, together with the S_{21} response of the OPEN structure.

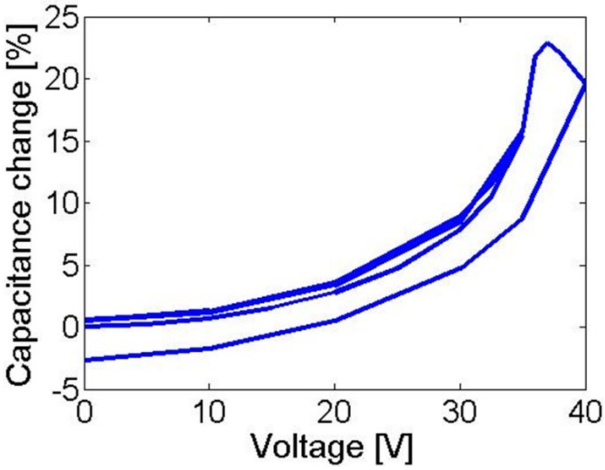


Figure 6. Change in capacitance plotted against the actuation voltage.

The capacitance could reproducibly be varied below the pull-in voltage, however when the voltage was increased above the pull-in voltage the nanotube arrays were permanently damaged, as depicted figure 3b. Consequently the capacitance was irreversibly decreased.

4. Conclusions

We have successfully actuated arrays of carbon nanotubes by applying a bias voltage between them. The capacitances were found by simulating the S-parameter response of the devices and comparing them with measurements, keeping the capacitance between the arrays as a fitting parameter. The details of this procedure are presented here. The response of the equivalent circuit used for modelling resulted in very good agreement with measurements. A change in capacitance of more than 20 % was observed before the voltage was increased above the pull in voltage, at which the nanotube arrays come into contact. The separation between the arrays, and thereby also the capacitance, could reversibly be varied below this voltage.

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