# Toggle Switch - Investigations of an RF MEMS Switch for Power Applications

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**Abstract - RF MEMS switches have improved electromagnetic properties compared to solid state switches. Therefore these devices are a promising alternative. Various designs have been studied which show lower insertion loss in closed state (0.25 dB @ 35 GHz), high isolation in open state (>14 dB @ 30 GHz) and allow high power handling (>2.5 W @ 5 GHz). Reliability and life time are critical parameters of these new structures and only little data is available today. This paper reports on reliability and power handling investigations of the recently published Toggle Switch, an ohmic contact switch. More than 2.4 x $10^5$ switch cycles were successfully performed, the measured switch time was 12 µs and the release time was 25 µs. Contact resistances in the range of 5 – 16 Ohm were measured and a temperature dependency of the pull-in voltage of – 0.3 V/degree was observed.**

## I. INTRODUCTION

Starting in 1995 fundamental investigations on RF MEMS devices have been undertaken [1-3]. Since then, different types of switches for various applications were realized. They can be splitted into two groups, which base on capacitive coupling [4] and metal contacting [5-7].

The Toggle Switch, developed by DaimlerChrysler and IMST [8-13], consists of a movable metallic cantilever in the signal line of a coplanar waveguide (CPW) environment (Fig. 1). When activated by a DC voltage, which can be supplied by separate leads to the push and pull electrodes, the cantilever opens or closes an ohmic contact. The distance between the cantilever and the contact paddle can be increased by an additional DC voltage at the push electrode.

## II. FABRICATION PROCESS

The Toggle Switches are fabricated on oxidized high-resistivity silicon wafers (ρ > 4000 Ωcm) with a wafer thickness of 525 µm. The lower electrode (underpass metallisation) is defined by a lift-off process with 50 nm Ti and 250 nm Au and is isolated by a 100 nm thick PECVD (plasma enhanced chemical vapour deposition) silicon nitride layer. The transmission lines are defined by a lift-off process with 50 nm Ti and 2500 nm Au. An air-bridge resist with a height of 2.8 µm is patterned as first sacrificial layer. To create a hard contact-paddle surface a 85 nm thick WTi layer is used. A second 570 nm thick isolation-layer is deposited to form the torsion spring for the

Toggle Switch. Afterwards the cantilever metallisation is sputtered. The cantilever material consists of 0.4 µm Au / 0.2 µm Ni / 0.4 µm Au. The Ni layer is used for the adjustment of stress in the cantilever. The stress in the layer can be adjusted by thickness modification and by variation of the sputtering process parameter. Finally, the cantilever resist is defined and the cantilever is etched. A flexible metal band and standard airbridges are applied on top. Therefore a second air-bridge resist of 3 µm is patterned as second sacrificial layer before the metallisation is evaporated. The metallisation consists of 1.2 µm Au and is defined by a lift-off process. In the last step the two air-bridge resists (sacrificial layers) are removed with a critical point drying (CPD) process.

## III. Basic DC and RF Performance

The toggle switch has been designed to achieve an excellent RF performance from DC up to 40 GHz. This has been obtained by the usage of small inductive lines for the compensation of the capacity from the cantilever [13].

S-parameter measurements (50 Ohm system) were performed over a frequency range from 0.5 GHz up to 40 GHz using a HP network analyser 8510C. A Line-Reflect-Match (LRM) calibration was used. The DC switching voltage has been applied by a Keithley Voltage/Current source. A voltage of 8 V is necessary to close the switch. Due to the high residual stress in the cantilever material, the contact opens and returns to the original position by reducing the DC voltages to 0 V. In closed position the attenuation of the toggle switch is from DC up to 35 GHz less than 0.25 dB (without the metal loss of the feeding CPW line). The measured return loss of the closed switch is below 25 dB up to 30 GHz (Fig. 2).

The Toggle switch in open position acts as an ideal open at DC and shows up to 30 GHz an isolation above 14 dB. With such a single Toggle Switch a large bandwidth of operation can be achieved. The isolation at high frequencies can be increased easily by the usage of a simple shunt airbridge switch in serial to the Toggle switch.

Even on more complex switch structures such as single pole double throw (SPDT) [9] or double pole double throw (DPDT) [10] architectures it is possible to route signals to different ports with low loss and high isolation. An appropriate arrangement of SPDT or DPDT switches in a matrix allows the routing of n-input to m-output ports.

## IV. Power Measurements Results

Power measurements of the single pole single throw (SPST) Toggle switch have been done at the IMST GmbH Kamp-Lintfort, Germany. A Wiltron 360B network analyser was used to control the Wiltron 68069B source. The power amplifier was an HP 83020A working from 2 GHz up to 26 GHz and the Alessi probe station was equipped with Picoprobe probes. The RF power was measured with an Anritsu ML2438A power meter.

In the first calibration set-up (Fig. 3) the RF signal from the source was amplified by a power amplifier (PA) and routed to the power meter (PM) through a bias-T and a 30 dB attenuator. In the second calibration the probes were contacted to a CPW through line which is inserted between the bias-T and the 30 dB attenuator. These two calibrations were necessary to calculate the losses of the RF probes and the CPW line up to the Toggle switch. The results were considered for the calculation of the power that is transmitted to port 1 of the Toggle Switch in the measurement set-up.

In the measurement set-up an additional bias-T is placed at the output port of the Toggle Switch behind the probes. This second bias-T is necessary to apply the same DC voltage to both ports of the Toggle Switch. A too large potential difference between the two ports would weld the cantilever to the metal contact during the actuation. DC ground is applied to the DC switch pad which is used to pull the cantilever down. It is not necessary to apply a DC signal to the push up electrode to open the switch.

The following procedure was carried out for the power measurements:

step 1: DC voltage applied to close the switch

step 2: DC voltage reduced to the holding voltage

step 3: RF power is applied

step 4: DC voltage turned off

step 5: RF power turned off

The switch should open after the DC voltage is turned off (step 4). If the switch did not open after step 4 the membrane adhered due to the DC part in the RF power to the metal contact pad (see column RF adhesion in Tab. 1). As soon as the RF power is turned off, these switches opened until the RF power was large enough to weld the metal membrane to the contact pad (see column 'reopen after 10 sec' in Tab. 1).

In the measurement procedure the toggle switch was closed by a DC voltage of 39 V. Fig. 4a shows the investigated Toggle Switch in open and Fig. 4b in closed position.

In the next step the RF power is applied and afterwards the DC actuation voltage is turned off. In the last step the RF power is turned off. The RF power at the switch increases due to the non-linearity of the power amplifier from 0.36 W at 25 GHz to 1.99 W at 5 GHz. After being closed for 10 s the switch could be reopened up to an RF power of 1.58 W. The switch could not be reopened after an RF power of 1.6 W was applied at 7 GHz. The switch has hits the DC pad due to the high actuation voltage of 39 V in conjunction with the high RF power of 1.6 W. The thin nitride isolation stroke through and the cantilever welded to the electrode. This can be prevented by reducing the high switching voltage of 39 V to lower holding voltage before applying the RF power.

An RF power of 1.6 W at 50 Ω causes an equivalent DC voltage of 8.9 V according to $U = \sqrt{P \cdot 50\Omega}$. The RF power of 0.36 W at 25 GHz, which is equal to a DC holding voltage of 4.25 V, was already enough to cause an RF-adhesion of the switch. The switch only reopened after the RF power and the DC voltage was turned off.

Another set of measurements has been done at 25 GHz to determine the RF power that is necessary to keep the switch in closed position without applied DC voltage. The layout of the switch used for this measurement is equal to the one shown in Fig. 4 but the switch was from a different die on a different wafer. A DC voltage of 42 V was necessary for actuation while 25 V was enough for holding. Tab. 2 shows that an RF power above 200 mW - equal to a holding voltage of 3.2 V - keeps the switch in closed position without applying a DC voltage. At an RF power of 158 mW the switch opens when the DC voltage is turned off. A hot switching with a DC voltage of 42 V is only possible up to this RF power.

However, the RF power can be extended by combining the single Toggle Switch with a shunt airbridge switch [11]. In this application the shunt airbridge switch can be closed in the first step. This reduces the RF power at the Toggle Switch which then can be opened in the next step. Furthermore, the behaviour of the Toggle Switch under RF power for the duration of 60 s was investigated (see Tab. 2). The Toggle Switch reopened directly up to a power of 129 mW. When a power of 158 mW is applied to the closed switch for 60 s, instead of 10 s as used for the RF adhesion tests, the metal cantilever welds to the metal contact pad. This seems to be caused by a temperature rise in the contact area.

Power measurements of several different types of Toggle Switches were carried out (Tab. 3). Comparing the different Toggle Switches it can be seen that the switches which needed a higher actuation voltage allow a higher RF power before adhering to the contact pad. The RF power causing the Toggle Switches to adhere to the contact pad lies between 28 and 447 mW. The maximum power handling capability is achieved from the Toggle Switch with the highest actuation voltage (50 V).

A power of 2.51 W at 5 GHz could be switched several times (10…20 times, no more investigations were done) with an on state signal time of 10 seconds. Four of the six investigated switches could handle powers between 1 W and 2.5 W at a frequency range between 5 GHz and 15 GHz.

Power measurements of the open Toggle Switch in the frequency range from 5 GHz to 18 GHz have shown that there is no power induced self actuation up to 2 W input power.

## V. SWITCH TIME MEASUREMENT RESULTS

Switch time measurements of the SPST Toggle Switch were done at the IMST with the set-up shown in Fig. 5.

A Wiltron 360B network analyser was used to control the Wiltron 68069B source and the Alessi probe station was equipped with Picoprobe probes. The 1 GHz RF power was measured with an Anritsu 8991a peak power meter. A transistor circuit was used together with a Keithley voltage source to create a rectangular DC voltage signal with a signal rise time of 5 µs. The capacitance in the bias-T increases the signal rise time to about 65 µs until the needed switching voltage of 20 V is reached. The DC signal fall time is about 5 µs.

The switch time measurement results of the single Toggle Switch for the closing and releasing event are shown in Fig. 6 and 7.

The distance between the cantilever tip and the contact pad was about 3 µm in the open state. In the static case a voltage of 20 V was needed to close the switch. For the switch cycle measurement a slightly higher maximum voltage of 25 V was applied. The time needed to get a first contact of the membrane after reaching 20 V actuation voltage was 12 µs and a stable state is achieved directly without any bouncing. If the switch is opened a stable state is achieved for all three switch cycles after 25 µs (see Fig. 7).

## VI. SWITCH CYCLE MEASUREMENT RESULTS

Switch cycle measurements on a fabricated single Toggle Switch were performed to investigate degradation of the membrane, the contact paddle, and the mounting suspensions. The DC measurement set-up depicted in Fig. 8 was used.

It is important to prevent a large potential difference between the cantilever and the contact paddle during the closure of the Toggle Switch. A too large potential difference will weld the cantilever to the paddle due to a high current running over the contact. To prevent this, the set-up realized in Fig. 8 applies the switching voltage $U_1$ to the contact paddle (left side) and a slightly higher voltage $U_2 = U_1 + \Delta U$ (usually 100 mV) to the cantilever (right side). At the time the pull electrode is switched to ground (0 V) the contact will close causing a current flow $I_{mess}$ that can be measured. The contact resistance including all serial resistances and the contact resistance of the needles is given by $\Delta U / I_{mess}$. To open the contact $U_1$ and $U_2$ have to be released simultaneously. The voltage source $U_2$ is additionally limited to a current of 100 µA to prevent the welding.

The measurement is automated using HP-VEE. Two Keithley current/voltage sources are connected and automatically set to the appropriate voltages. Fig. 9 shows typical times, voltages, and failure criteria for the switch cycle measurement. Using this set-up more than $2.4 \times 10^5$ switch cycles were successfully performed. The Toggle Switch did not show any visual degradation during the switching process. The measurement was carried out for a couple of days before the stopping criteria $I_{mes} < I_{\_low}$ was reached. After 2.4 x $10^5$ cycles the flexible metal band which connects the cantilever to the signal line at the end was lifted. Therefore the contact resistance could not be measured. This problem was an adhesion problem between the flexible metal band material (in this case Au) and the signal line metallisation (also Au). It could be solved by inserting a thicker adhesion layer (we used 20nm Ti) and by extending the size of the flexible metal band in the area which connects it to the signal line.

## VII. CONTACT RESISTANCE MEASUREMENTS

The contact resistance of the flat contact between the golden tip of the Toggle cantilever and the golden paddle was measured at a single Toggle Switch. Three different test series were performed at room temperature (RT), each including 20 current-voltage measurements. The gradient was extracted from a linear fit to determine the appropriate resistance (Fig. 10).

The resistance of the measurement lines and probes is given by $R_3$. The resistance of the Toggle cantilever is given by $R_2 - R_3 = 1.3\ \Omega$. The extracted pure contact resistance is given by $R_1 - R_2 = 8.8\ \Omega$.

Small voltages are required to pull the cantilever down to the contact paddle. Any further increase in the applied voltage would lead to an instability called pull-in. Pull-in occurs if the electrostatic forces grow faster than the spring forces with respect to the displacements. As a consequence, the structure snaps down to the counter electrode. Usually pull-in happens if the structure is displaced to about 33-43% of the initial gap [12]. Higher pull-in voltages increase the contact force and decrease the contact resistance. The RF measurements (Fig. 2) were done with a higher Pull-in voltage reducing the insertion loss to less than 0.25 dB up to 35 GHz (contact resistance < 1.5 Ohm).

## VIII. TEMPERATURE DEPENDENCY OF THE ACTUATION VOLTAGE

Temperature measurements of fabricated single Toggle Switches were performed to investigate temperature dependence on the actuation voltage. Fig. 11. shows the measurement set-up for all temperature measurements.

Open Toggle Switches were identified by contacting both sides of the signal line and observing the current flow $I_{meas}$ due to a voltage $U_{meas}$ of 0.5 mV. Open switches do not show a relevant current at this state. An actuation voltage $U_{act}$ was applied to close the open switch and the corresponding current $I_{meas}$ was recorded. This allows to calculate the contact resistance $R_{contact} = 0.5\ mV / I_{meas}$. Contact resistances were observed in the range from 5 Ω up to 16.5 Ω. This agrees the results from section VII.

This contact resistance is not de-embedded and the sum of all resistances (the probes, the measurement lines, and the signal line). Higher temperatures increase the resistance in the metal of the signal line.

The wafer is placed on a thermo-chuck for the on-wafer measurements. Due to condensation below RT (20 °C) only higher temperatures up to 100 °C could be applied. The actuation voltage of the Toggle Switch was adjusted to lead to a constant contact resistance of approximately 16 Ω over the entire temperature range from 20 °C to 70 °C. The actuation voltage decreased from 39 V at 20 °C to 26 V at 70°C. This is equal to gradient of -0.3 V/ °C on a linear fit (Fig. 12).

The decreased actuation voltages are caused by a smaller stress gradient in the gold-nickel-gold cantilever compound. Each gradient leads to a warping of the cantilever. Higher the stress gradients lead to increased distances from the cantilever to the electrode and higher actuation voltages are needed.

This stress gradient influences the temperature dependence on the actuation voltages because the warping of the cantilever changes due to temperature. The stress gradient depends on the sputtering process parameters (gas pressure, the sputter time and sputter power). A reduction of the temperature dependence can be achieved by compensation structures as well as other materials.

A Toggle Switch with an actuation voltage of 10 V at RT is expected to show a temperature dependent drop of 4 V from 20 °C to 80 °C if a linear decrease is assumed. This corresponds to a gradient of -0.07 V/ °C.

## IX. Summary

The new measurement results give a deeper insight into performance, reliability, and life-time of ohmic contact switches. Single switches show excellent RF performance, low switching times and high power capability up to 2.5 W without any self actuation. The statistical data shows differences in the measurement results which attribute to variations during the fabrication processes. Therefore, additional investigation of critical steps during fabrication process are necessary to improve yield and uniformity. This Toggle Switch concept with its excellent performance from DC up to 30 GHz would be well suited for the creation of large switch matrices which cover several frequency bands within one matrix.

## X. Acknowledgement

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## XI. REFERENCE


[1] **C. Goldsmith, T-H. Lin, B. Powers, W-R. Wu and B. Norvell:** "Micromechanical membrane switches for microwave applications", Tech. Digest, IEEE Microwave Theory and Techniques Symp., pp. 91-94, 1995

[2] **V. K. Varadan, K.J. Vinoy, K.A. Jose:** "RF MEMS and their applications", ISBN: 0-470-84308-X, 2003

[3] **G. M. Rebeiz:** "RF MEMS – Theory, Design, and Technology", ISBN: 0-471-20169-3, 2003

[4] **C. Goldsmith, J. Randall, S. Eshelman , T-H. Lin, D. Denniston, S. Chen and B. Norvell:** "Characteristics of micromachined switches at microwave frequencies", Tech. Digest, IEEE Microwave Theory and Techniques Symp., pp. 1141, 1996

[5] **D. Hah, E. Yoon, and S. Hong:** "A Low Voltage Actuated Micromachined Microwave Switch using Torsion Springs and Leverage", 2000 IEEE MTT-S Digest, pp. 157-160

[6] **R. E. Mihailovich,M.Kim, J. B. Hacker, E.A. Sovero, J. Studer,J. A. Higgins, J. F. DeNatale:** "MEM Relay for Reconfigurable RF Circuits", IEEE Microwave and Wireless Components Letters,vol. 11, no. 2, February 2001, pp. 53-55.

[7] **P. M. Zavracky, N. E. McGruer, R. H. Morrison, D. Potter:** "Microswitches and Microrelays with a View Toward Microwave Applications", International Journal of RF and Microwave Computer Aided Engineering, vol. 9, no. 4, July 1999, pp.338-47

[8] **B. Schauwecker, K. M. Strohm, W. Simon, J. Mehner, J.F. Luy: „**A new type of high bandwidth RF MEMS switch – Toggle Switch", Journal of Semiconductor Technology and Science, Special Issue on MEMS, Vol. 2, No. 4, pp. 237 – 245; December 2002

[9] **B. Schauwecker, K. M. Strohm, T. Mack, W. Simon, J.-F. Luy:** „A Single-Pole-Double-Throw Switch based on the Toggle Switch", Electronic Letters, Vol. 39, No. 8, pp. 668 – 670; March 2003

[10] **B. Schauwecker, T.Mack, K. M. Strohm, W. Simon, J.F. Luy:** „RF MEMS for Advanced Automotive Applications", MSTNEWS, Vol. 04, pp. 36-38, September 2003

[11] **B. Schauwecker, K. M. Strohm, T. Mack, W. Simon, J.-F. Luy:** „Serial Combination of Ohmic and Capacitive RF MEMS Switches for Large Broadband Applications", Electronic Letters, Vol. 40, No. 1, pp. 44 – 46, January 2004

[12] **B. Schauwecker, J. Mehner, J.-F. Luy:** "Modeling and Simulation Considerations for a new Micro-Electro-Mechanical Switch – Toggle Switch -"; IV. Topical Meeting on Silicon Monolithic Integrated Circuits in RF systems, pp. 192 – 195, near Garmisch, Germany, April 2003

[13] **W.Simon, B.Schauwecker, A.Lauer, A.Wien:** "Designing a novel RF MEMS switch for broadband power applications", European Microwave Conference, pp.519-522, Mailand, September 2002

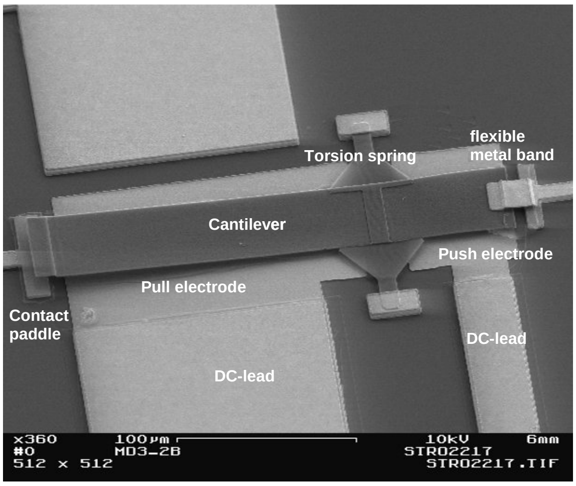


**Fig. 1:** SEM picture of the fabricated Toggle Switch

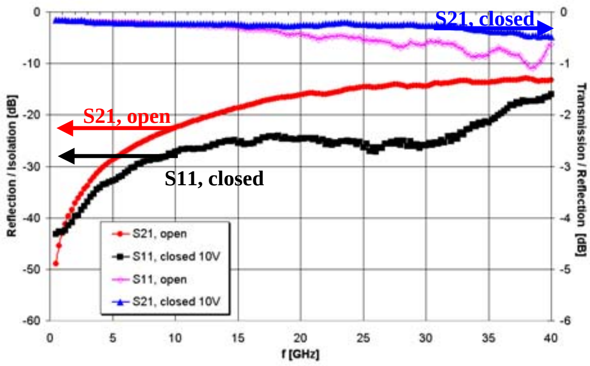


**Fig. 2:** Measurement results of the Toggle Switch in open and closed position

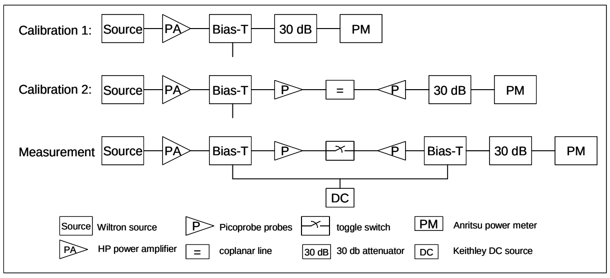


**Fig. 3:** Schematic view of the calibration and measurement set-up

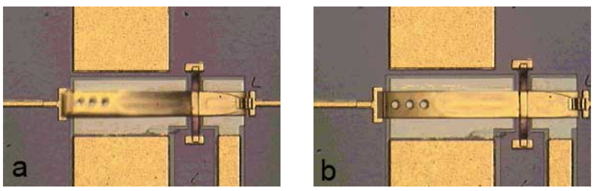


**Fig. 4:** Toggle Switch with a nitride suspension in open (a) and closed (b) state.

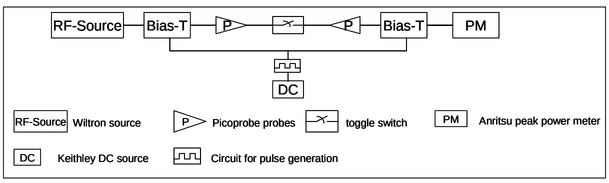


**Fig. 5:** Schematic view of the calibration and measurement set-up

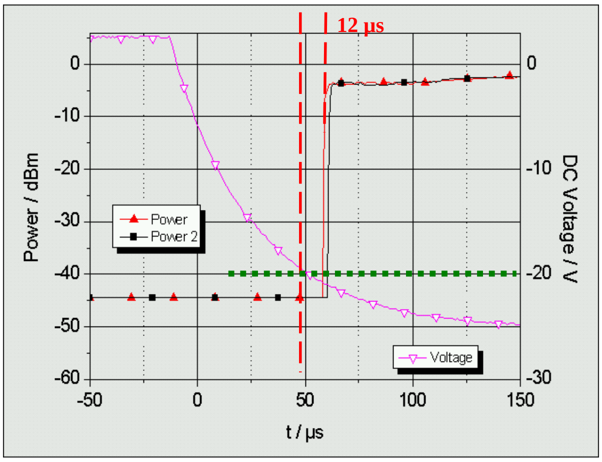


**Fig. 6:** Switch time measurements

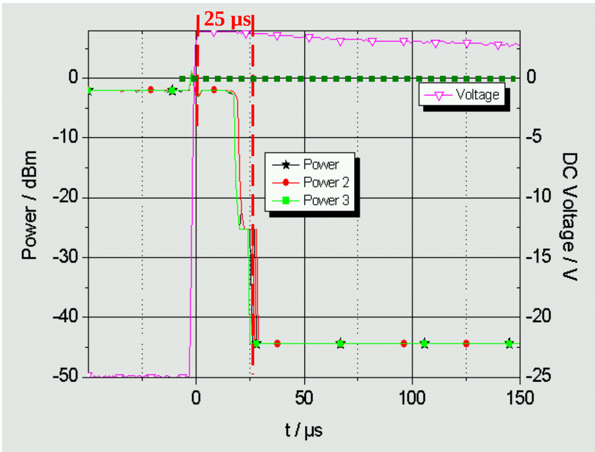


**Fig. 7:** Release time measurements

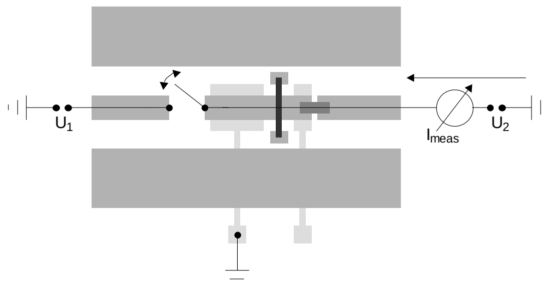


**Fig. 8:** Experimental switch cycle measurement set-up to determine degradation of contact paddle and cantilever

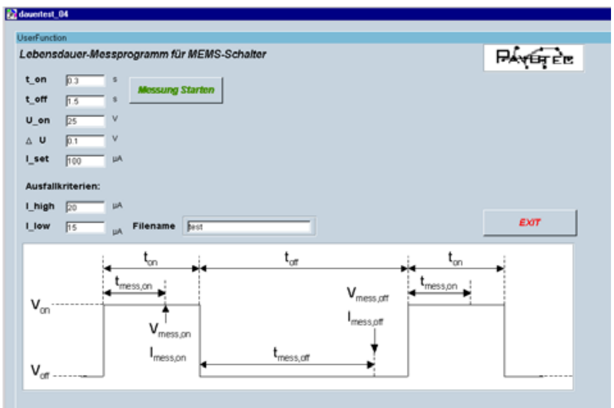


**Fig. 9:** Specification of the cycle measurement timings

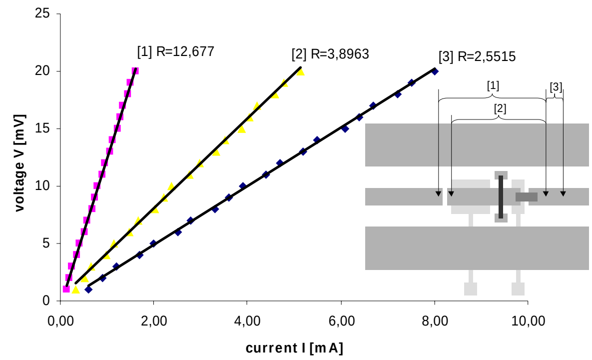


**Fig. 10:** Measurements for extracting the contact resistance: [1] measurement lines and probes + toggle cantilever + contact [2] measurement lines and probes + toggle cantilever [3] measurement lines and probes

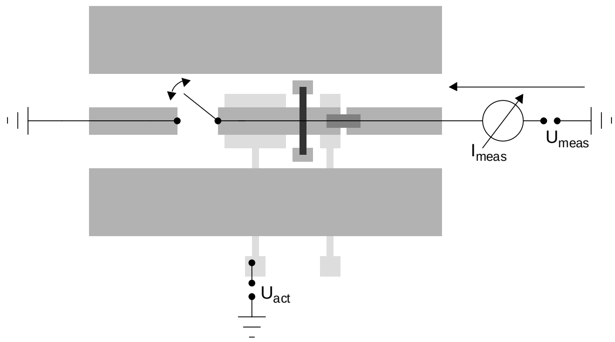


**Fig. 11:** Experimental set-up to investigate temperature dependency of actuation voltage

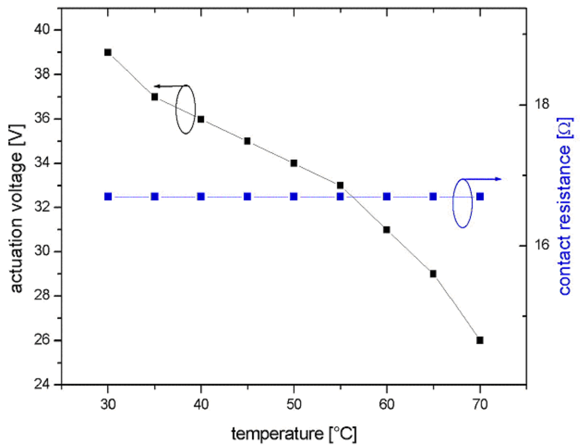


**Fig. 12:** Temperature dependency of the actuation voltage of the Toggle Switch.

| Freq. [GHz] | Power at port 1 [W] | reopen after 10 s | RF adhesion |
|---|---|---|---|
| 5 | 1,995 | | |
| 6 | 1,622 | | |
| 7 | 1,603 | no | |
| 8 | 1,585 | yes | yes |
| 9 | 1,514 | yes | yes |
| 10 | 1,334 | yes | yes |
| 11 | 1,259 | yes | yes |
| 12 | 1,175 | yes | yes |
| 13 | 1,047 | yes | yes |
| 14 | 1,047 | yes | yes |
| 15 | 0,891 | yes | yes |
| 16 | 0,794 | yes | yes |
| 17 | 0,716 | yes | yes |
| 18 | 0,646 | yes | yes |
| 19 | 0,741 | yes | yes |
| 20 | 0,724 | yes | yes |
| 25 | 0,363 | yes | yes |

**Tab. 1:** Power measurement results of the Toggle Switch

| Freq. [GHz] | Power at port 1 [mW] | reopen after 60 s | RF adhesion |
|---|---|---|---|
| 25 | 363 | | yes |
| 25 | 200 | | yes |
| 25 | 158 | no | no |
| 25 | 129 | yes | no |
| 25 | 100 | yes | no |
| 25 | 79 | yes | no |
| 25 | 68 | yes | no |

**Tab. 2:** Power measurement results of the Toggle Switch

| Freq. [GHz] | Power at port 1 [mW] | reopen after 10 sec. | | | | | | RF adhesion | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | T1 | T2 | T3 | T4 | T5 | T6 | T1 | T2 | T3 | T4 | T5 | T6 |
| 5 | 2512 | | | | | | y | | | | | | y |
| 10 | 1778 | | | | n | | y | | | | | | y |
| 10 | 1413 | | | | y | n | y | | | | y | | y |
| 10 | 1122 | | n | | y | y | y | | | | y | y | y |
| 15 | 1000 | | y | | y | y | y | | y | | y | y | y |
| 10 | 891 | | y | | y | y | y | | y | | y | y | y |
| 20 | 891 | | y | | y | y | y | | y | | y | y | y |
| 10 | 708 | | y | | y | y | y | | y | | y | y | y |
| 10 | 562 | | y | | y | y | y | | y | | y | y | y |
| 10 | 447 | | y | | y | y | y | | y | | y | y | y |
| 10 | 355 | | y | | y | y | y | | y | | y | y | n |
| 25 | 355 | | y | | y | y | y | | y | | y | y | n |
| 10 | 282 | | y | n | y | y | y | | y | | y | y | n |
| 10 | 224 | n | y | y | y | y | y | | y | y | y | y | n |
| 10 | 178 | y | y | y | y | y | y | y | y | y | y | y | n |
| 10 | 141 | y | y | y | y | y | y | y | y | y | y | y | n |
| 10 | 112 | y | y | y | y | y | y | y | y | y | y | y | n |
| 10 | 89 | y | y | y | y | y | y | y | y | y | y | n | n |
| 10 | 71 | y | y | y | y | y | y | y | y | n | y | n | n |
| 10 | 56 | y | y | y | y | y | y | y | y | n | n | n | n |
| 10 | 45 | y | y | y | y | y | y | y | y | n | n | n | n |
| 10 | 35 | y | y | y | y | y | y | y | y | n | n | n | n |
| 10 | 28 | y | y | y | y | y | y | y | y | n | n | n | n |
| 10 | 22 | y | y | y | y | y | y | n | n | n | n | n | n |
| 10 | 18 | y | y | y | y | y | y | n | n | n | n | n | n |

T1: 35 V close 25 V hold
T2: 30 V close 10 V hold
T3: 45 V close 35 V hold
T4: 50 V close 20 V hold
T5: 40 V close 30 V hold
T6: 50 V close 40 V hold

**Tab. 3:** Power measurement results of different Toggle Switches from the same wafer