High Power RF MEMS Switch Technology

Invited Talk at 2005 SBMO/IEEE MTT-S **International Conference** on **Microwave and Optoelectronics Conference**

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Acknowledgements

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The project partners include

1. Heriot-Watt University, U.K.
2. Rutherford Appleton Laboratory, U.K.
3. BAE Systems, U.K.

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Outline

- Introduction - Motivation
- Concept for the development
- Design and Modelling
- Fabrication Processes
- Experiments
- Summary

Why an interest in RF MEMS switches?

- Many applications for RF MEMS switches
  - Radar systems for defence applications (5-94 GHz)
  - Automotive radars (24, 60 & 77 GHz)
  - Satellite communication systems (12-35 GHz)
  - Wireless communication Systems (0.8-6 GHz)
  - Instrument systems (0.01-50 GHz)

Advantages of RF MEMS switches

- Near-zero power consumption
- High isolation
- Low insertion loss
- Low intermodulation products
- Low cost manufacture

Disadvantages

- Relatively low stitching speed
- Low power handling
- High activation voltage
- Lack of suitable packaging and low reliability

Types of RF MEMS switch

- Cantilever beam
- Membrane (Bridge)
- Others (such as thermal)

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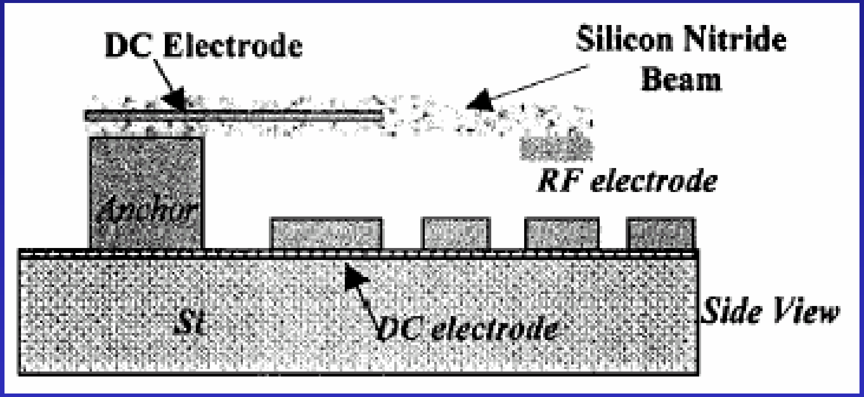
Cantilever beam

- Silicon nitride beam
- Separate DC and RF electrodes
- RF electrode completes signal line



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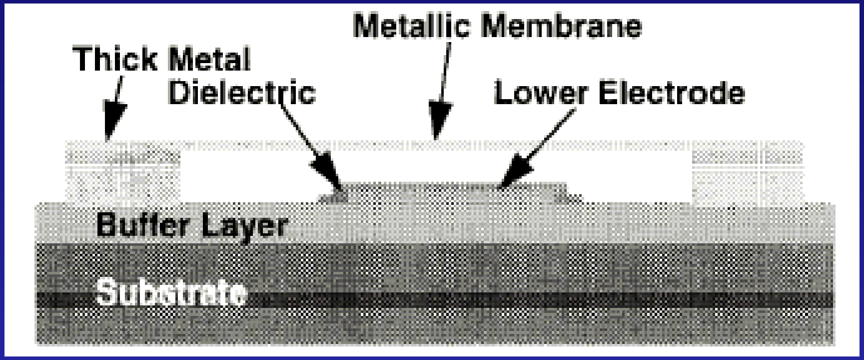
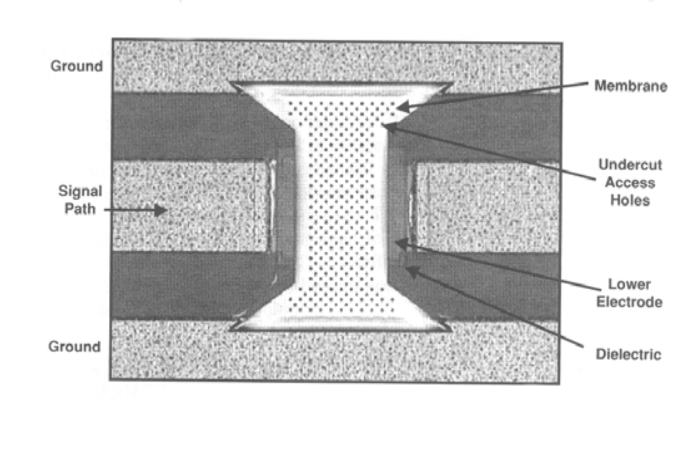
Membrane Switch

- DC electrode in signal line
- Metallic membrane
- Appling DC voltage RF line shorted to ground i.e. high isolation





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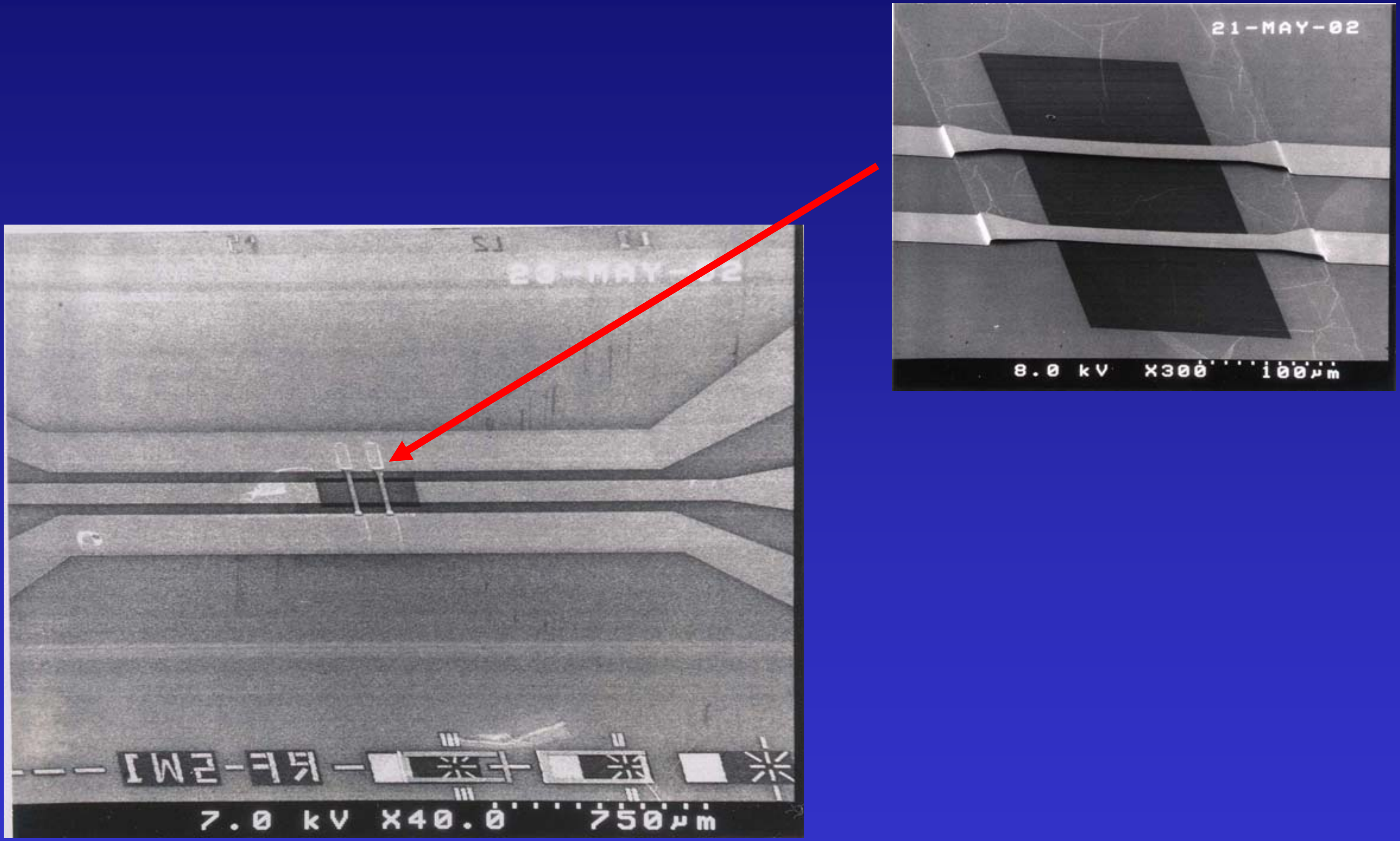
MEMS Switch, Bridge Structure on CPW Fabricated at RAL



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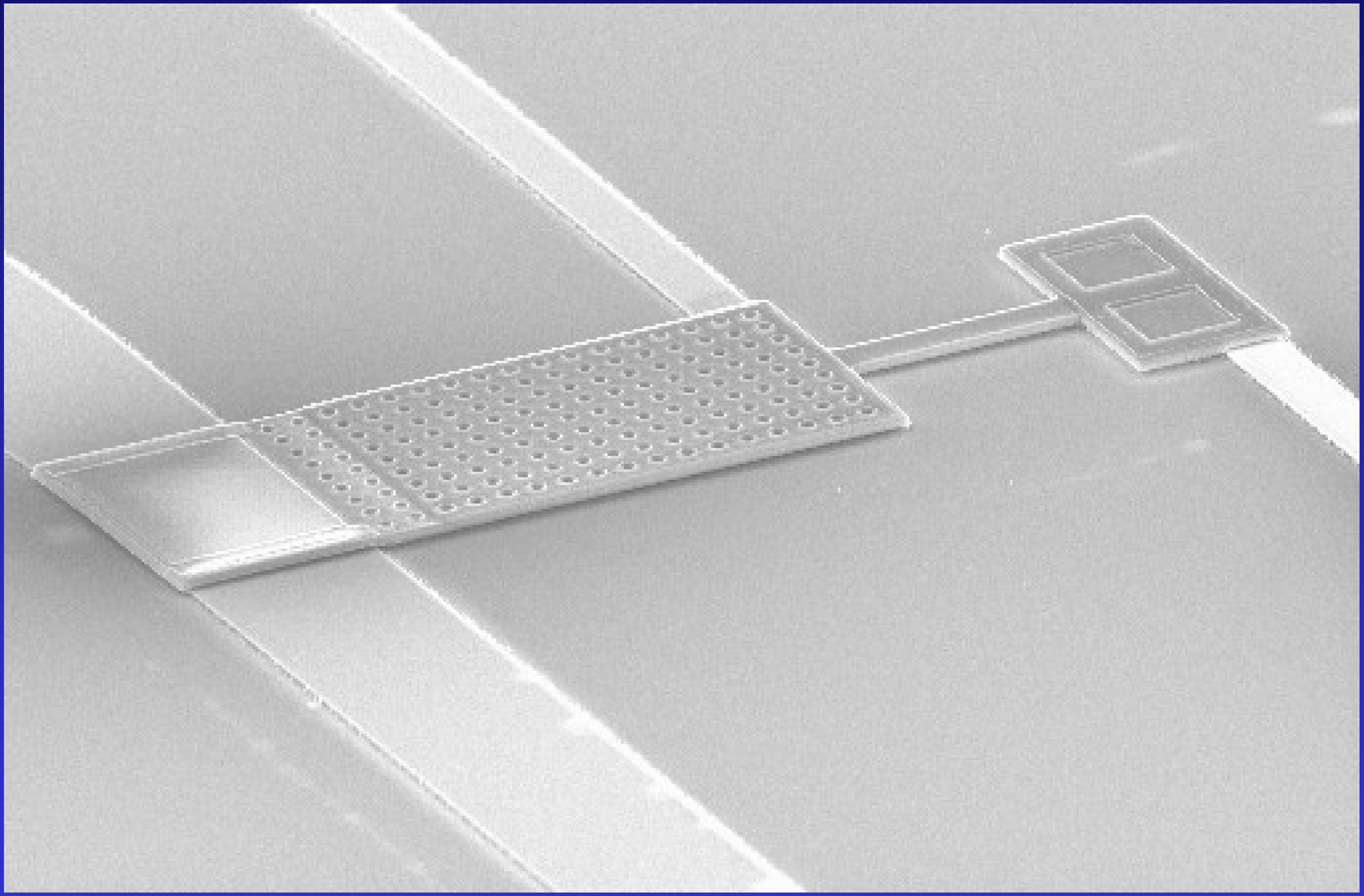
MEMS Switch, Cantilever Structure on microstrip from BAE SYSTEMS



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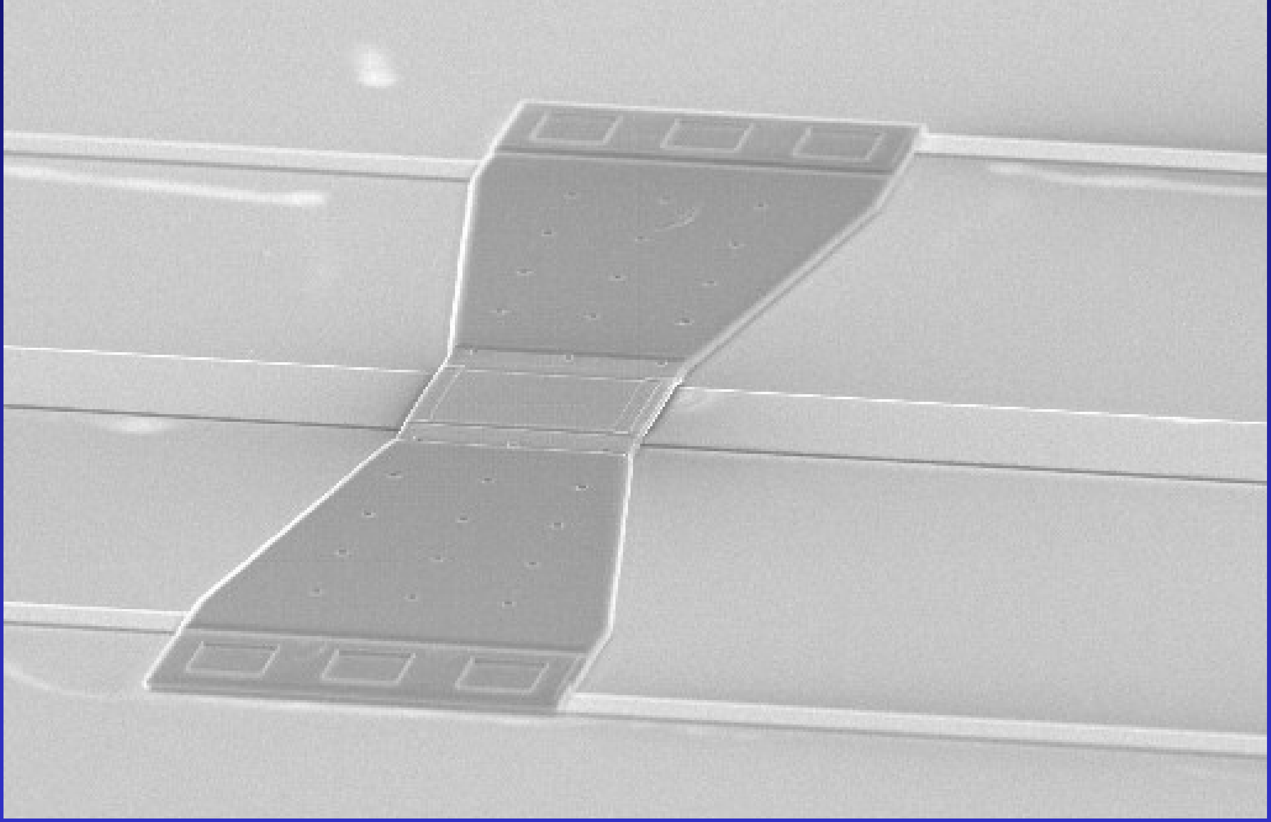
MEMS switch, Bridge Structure on microstrip from BAE SYSTEMS



Why this Project ?

- The above shown RF MEMS switches can only handle a low RF power, say up to a few hundreds milliwatts.

- High power RF MEMS switches,however, are of interest for many applications.

- It is the purpose of this collaborated project to design and demonstrate RF MEMS switches capable of handling 10 Watts RF power

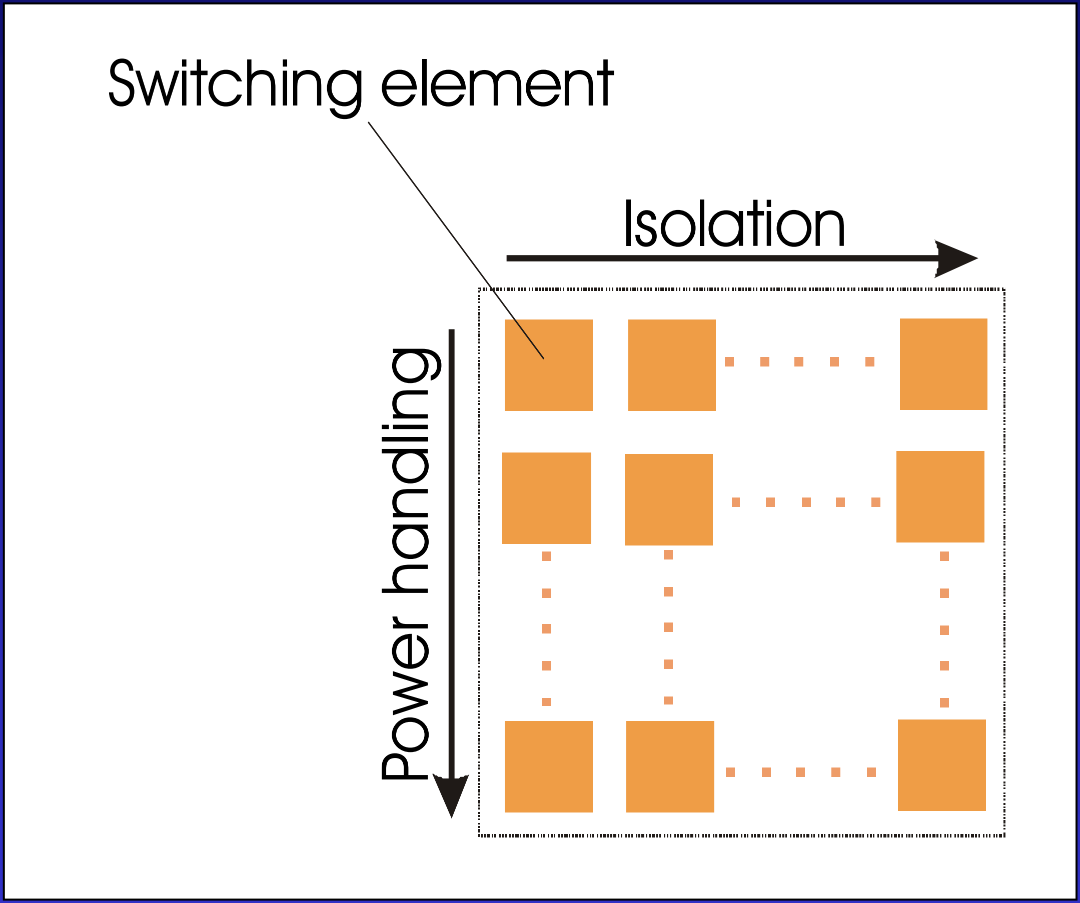
Switch Specification

Characteristic	Capability
Operating Frequency	Centred at 10 GHz with 10% bandwidth
Power Handling	10 W
Insertion Loss (on)	<0.2 dB
Return Loss (on)	>20 dB
Isolation (off)	>20 dB
Power Consumption	<100 μW
Threshold Voltage	<50 V
Switching Speed	10 μs
Characteristic Impedance	50 Ω

It is anticipated that there are great challenges in developing such high power RF MEMS switches.

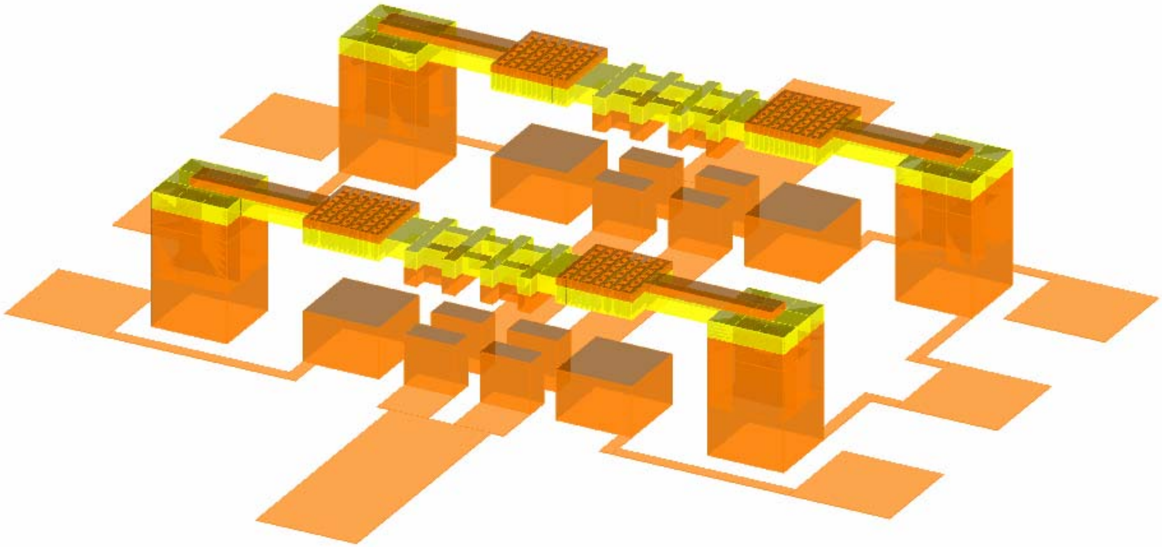
How can we do it?

Switch Matrix Concept for the Development



- This approach allows configuring the switch matrix to be tailored for different power and isolation requirements while maintaining a low RF power level and low actuation voltage at each individual switching element.

2 X 2 High Power Switch Matrix for a SPST Switch----Bridge Structure



Two pairs of bridge beams for a good stress balance

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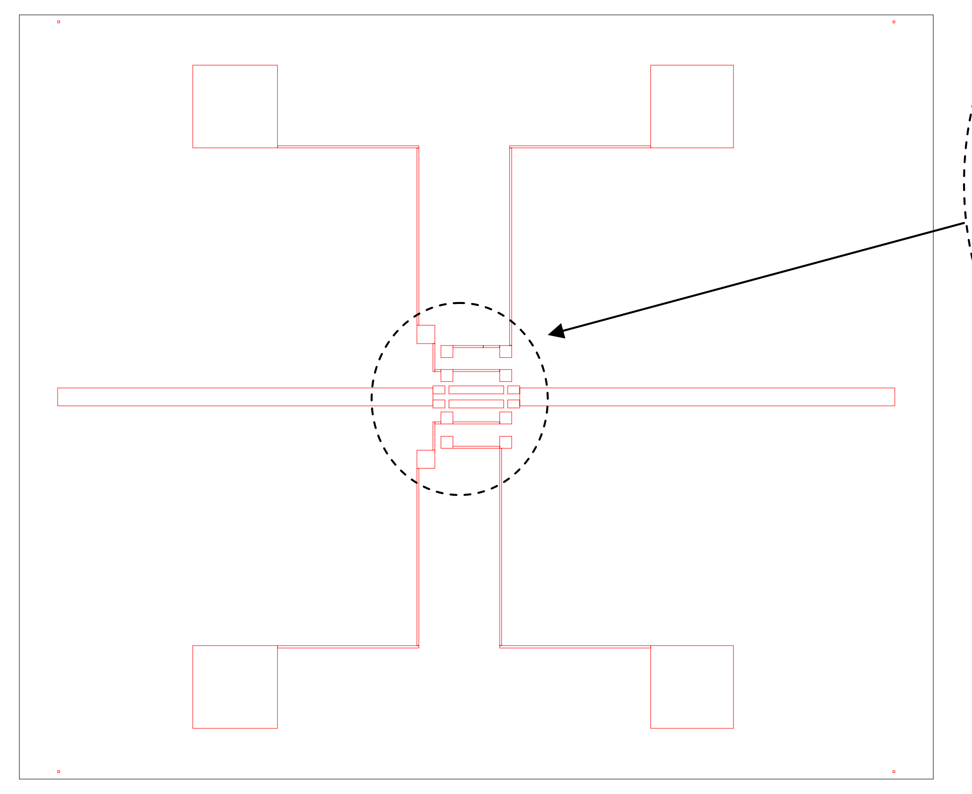
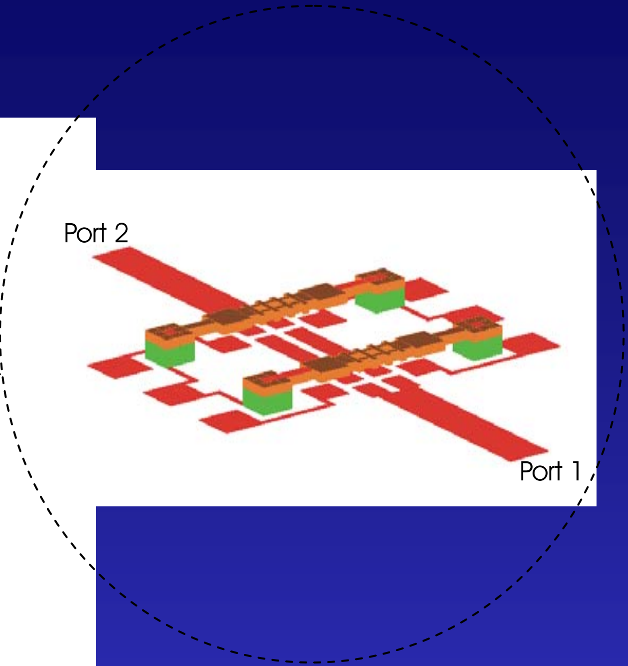
Design Layout





Each of the cantilever switching elements is 600 μm by 150 μm, and the whole high power switch chip, including a built in DC bias circuit, is 1.05 mm by 1.75 mm on a 250μm thick high resistivity (10K Ω-cm), silicon wafer.

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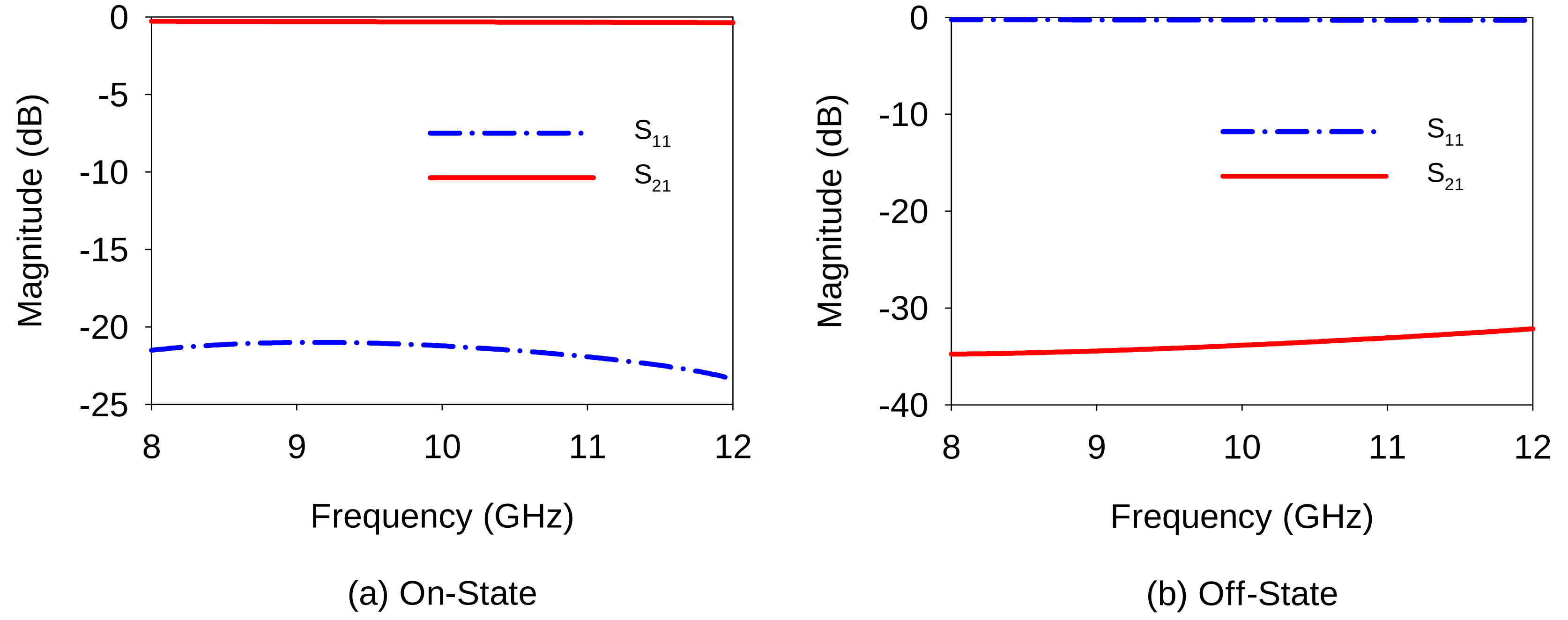
Electromagnetic (EM) Modelling

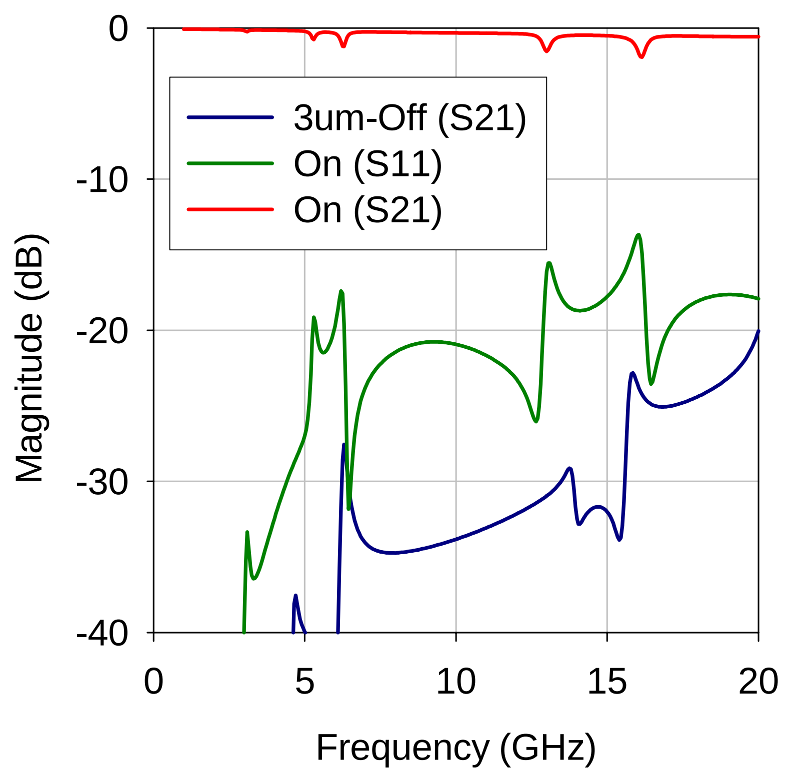


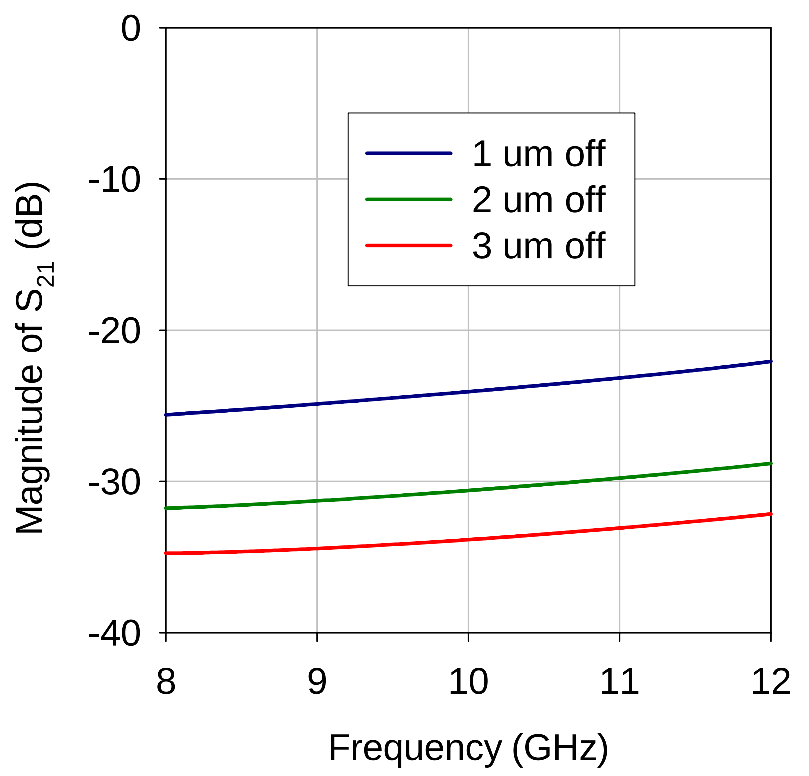
(a) On-State

(b) Off-State

The switch is designed for operation at X-band. When all the switching elements are pulled down, the switch is in the RF “On” state. When all the beams are in the unactuated position, which is 3 μm away from the RF transmission line on the wafer, the switch is in the RF “Off” state.

Electromagnetic (EM) Modelling





Wideband responses

Isolation against the beam position (height) at Off-state

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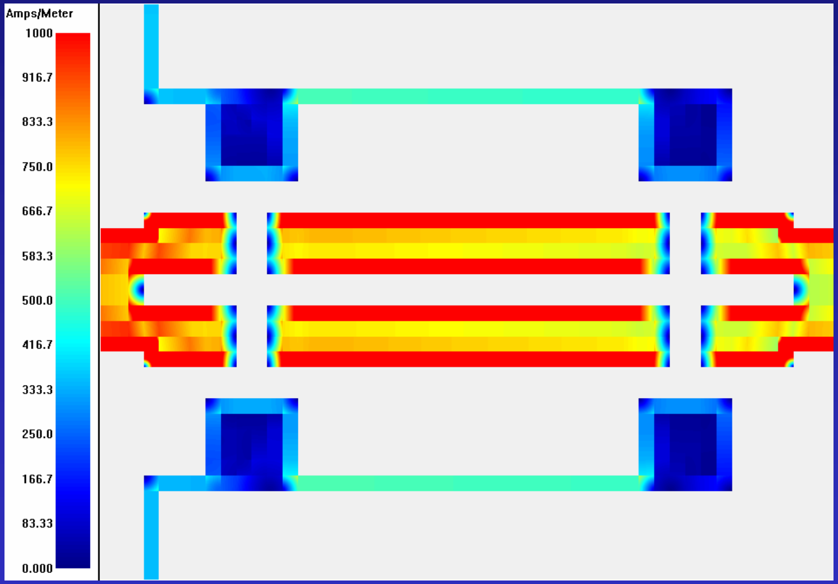
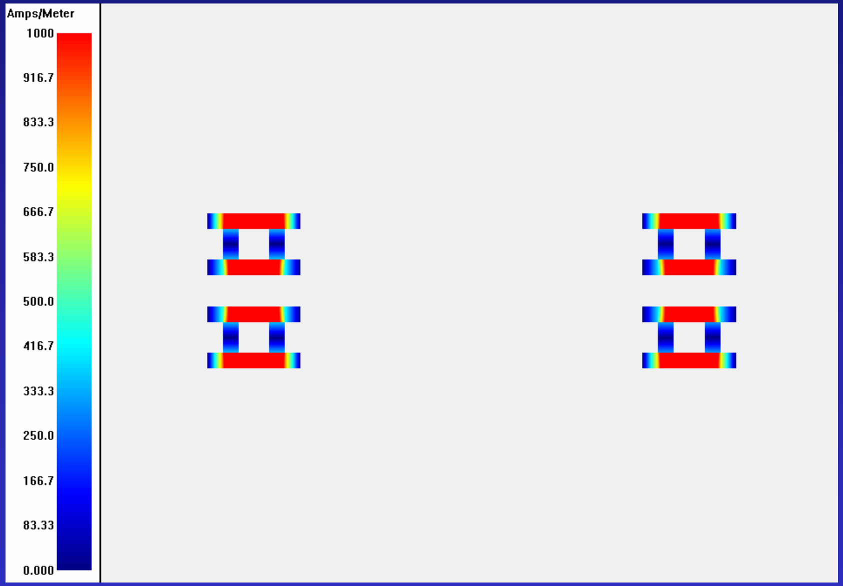
Electromagnetic (EM) Modelling

Current distribution at On-state for a 10 W input at 10 GHz



RF signal line layer



Top RF electrode layer

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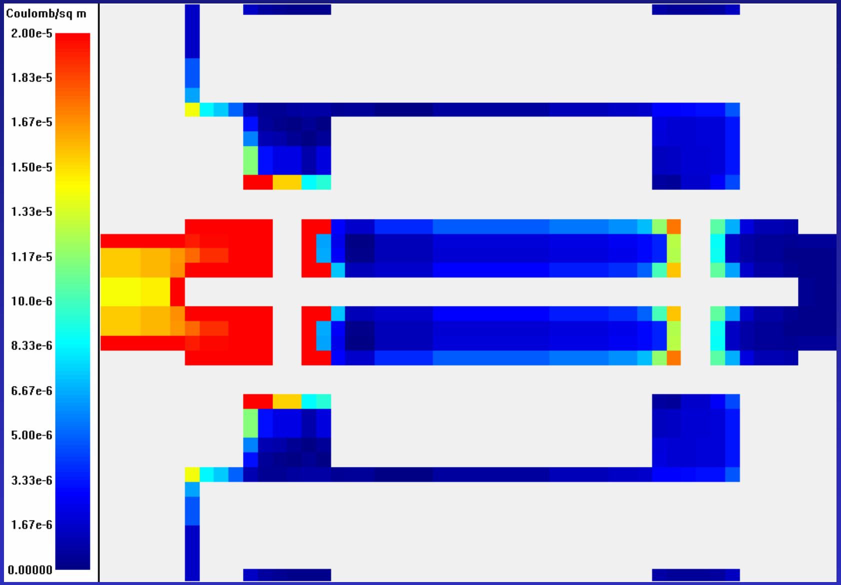
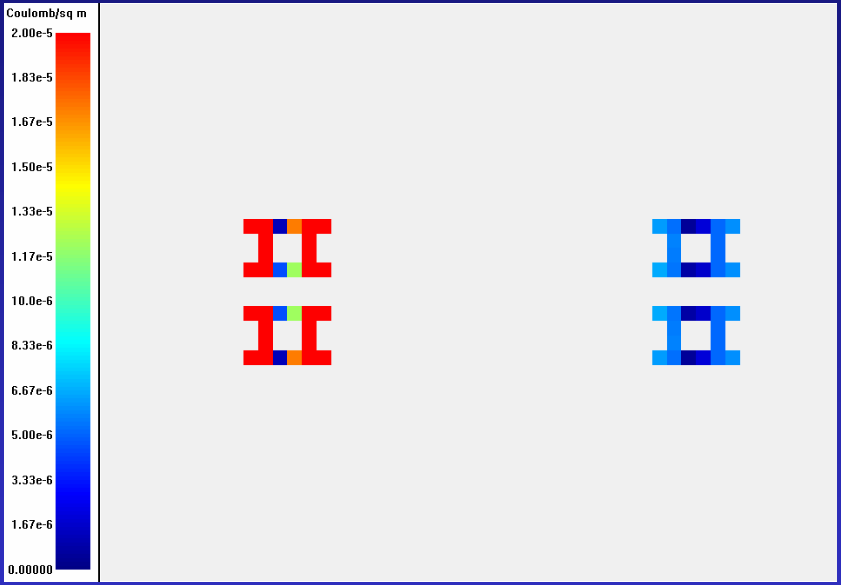
Electromagnetic (EM) Modelling

Charge distribution at Off-state for a 10 W input at 10 GHz



RF signal line layer



Top RF electrode layer

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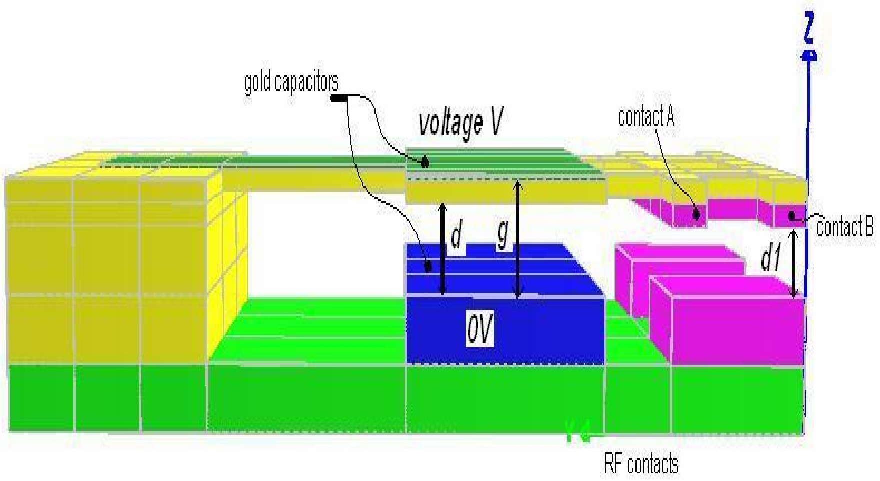
Electromechanical Modelling

- Electromechanical modelling is important for the development of high power, RF MEMS switches.
- For our designs, it is important to characterise the single switching element, especially the RF contact.
- To this end, a simple mode is used first.



Points A and B are the two particular RF contact points on the beam, and d1 denotes the ‘Off state’ separation between the beam and the RF transmission line on the wafer.

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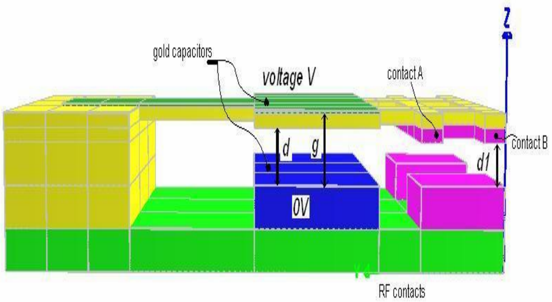
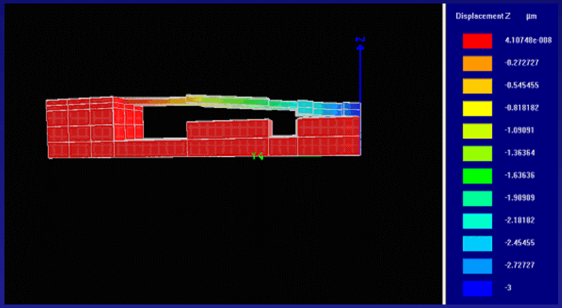
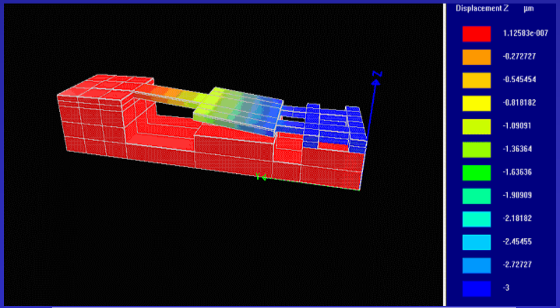
Electromechanical Modelling (simple model @ d1=3um)



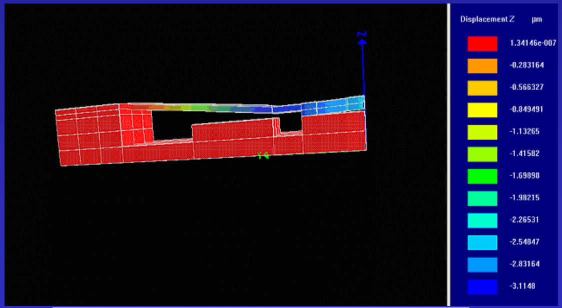
(a) 0 V



(b) 7.7 V



(c) 22 V (full contact)

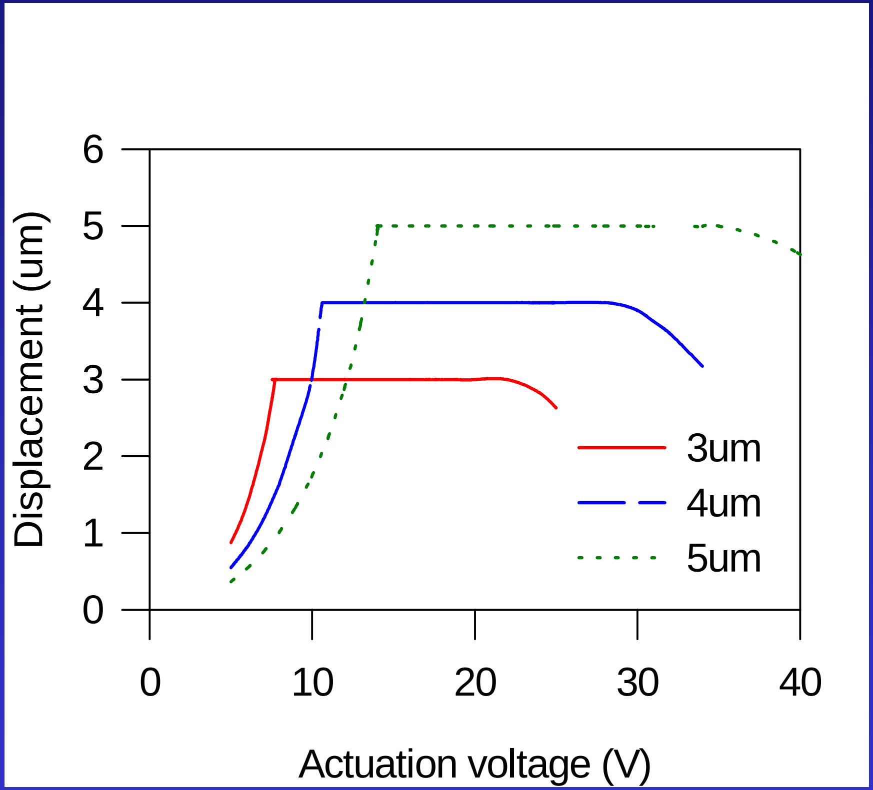


(d) 25 V (buckling)

- When V = 7.7 V, the beam or the contact B makes the first RF contact.
- The contact A only makes a contact until the actuation voltage is increased to 22 V, and this corresponds to the case in which the largest RF contact area is obtained.
- Further increasing the actuation voltage can results in an undesired deformation that causes the tip of the beam deformed upwards as shown for V = 25 V, and thus reduce the RF contact area.

Electromechanical Modelling (simple model)

Displacement of the beam tip against the actuation voltage for d1 = 3, 4 and 5 um respectively



- ➢Each of the curves shows three distinct regions.
- ➢The first region shows that displacement increases against the actuation voltage before the beam makes the first RF contact.
- ➢The second region is a straight line indicating that the beam tip is in contact with the RF transmission line so that there is no change in the displacement.
- ➢The third region shows a decrease of the displacement, implying the beam tip has lost the contact with the RF line.
- ➢The actuation voltage at the transition point between the first and second regions is the minimum voltage required for making an RF contact, which increases against the initial height of the beam.

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Electromechanical Modelling (simple model)

- ❑For a given cantilever switch design and from the point of view of the RF contact, the desired actuation voltage would be that resulting in a largest contact area as well as a largest contact force.

- ❑The contact force for the proposed model can be estimated from the reaction force of the beam, which is shown in the next slide.

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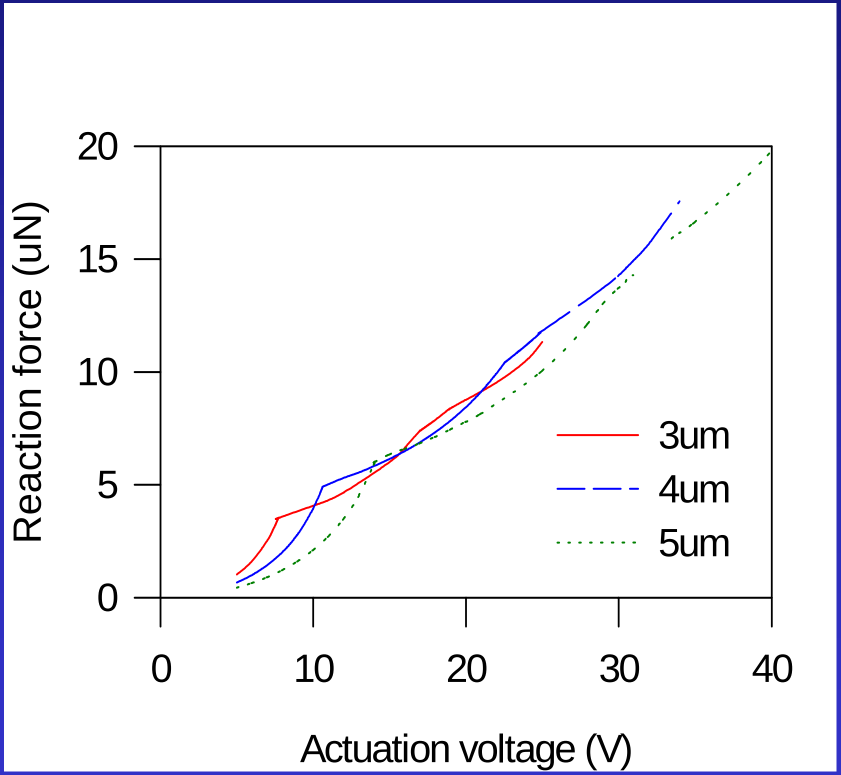
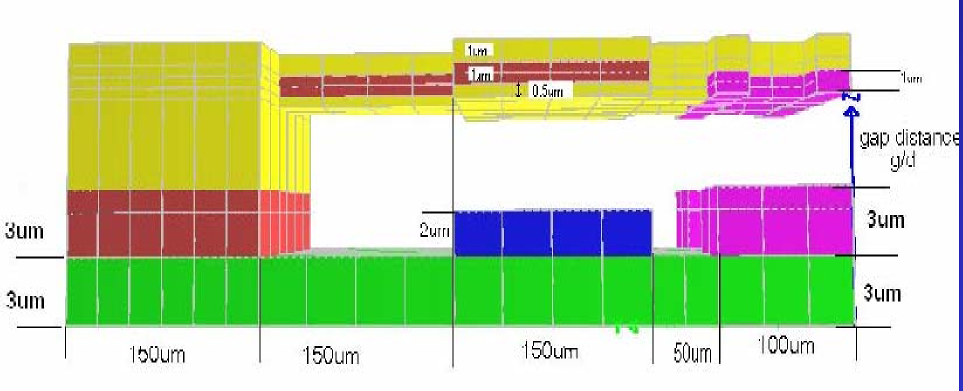
Electromechanical Modelling (simple model)

Reaction force of the beam against the actuation voltage for the beam height = 3, 4 and 5 um respectively



- In general, the reaction forces increase against the actuation voltage/beam displacement.
- There is a clear transition point for each of the three curves shown, which correspond to the point at which the beam tip makes the first contact with the RF line.
- Up to the transition point the reaction force is only the spring or mechanical restoring force of the beam.
- On making first contact, a contact force is generated and increased as the actuation voltage increases.
- In practise the contact force is expected to be smaller than the reaction force since the later includes the restoring force of the beam. In this case, the contact force is in a range of a few to several-tens of micro-Newtons.

Electromechanical Modelling (Bridge model)



Join two cantilevers head-to-head to from a bridge model

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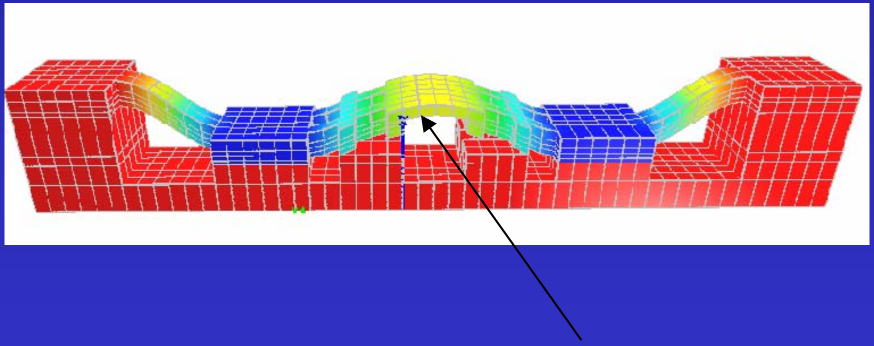
Electromechanical Modelling (Bridge model @ d1=4um)

Actuation Voltage = 0 V

Actuation Voltage = 36 V



Actuation Voltage = 63 V

buckling

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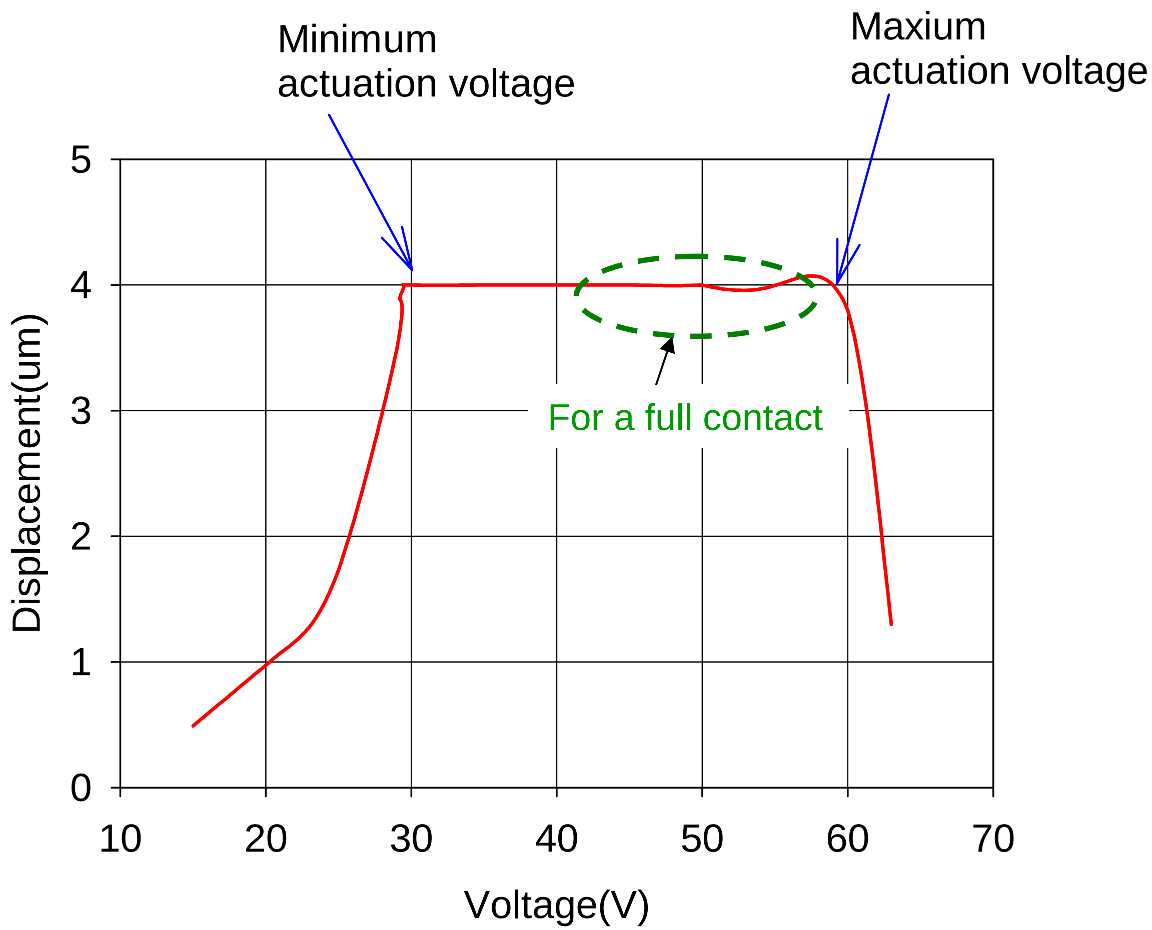
Electromechanical Modelling (Bridge model @ d1=4um)



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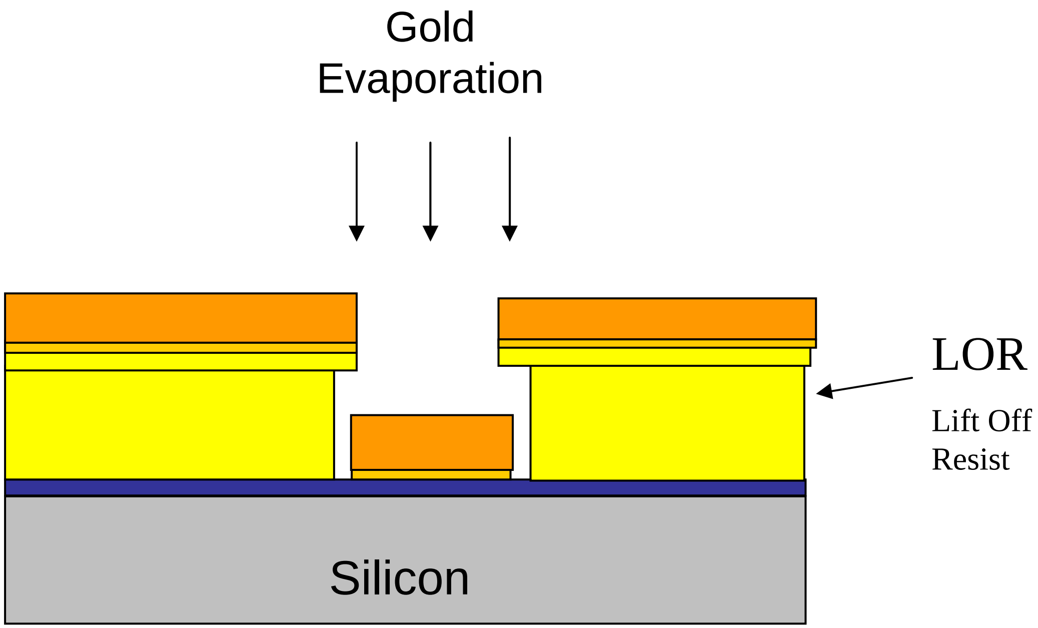
Fabrication Process Steps

Fabrication Flow Chart: Step 1-3

1.A thin layer of SiO2 deposition.

2. Resist patterning, **Mask 1**. (layer 1)

3. 5nm Cr (Chromium) then 2μm Au deposition.



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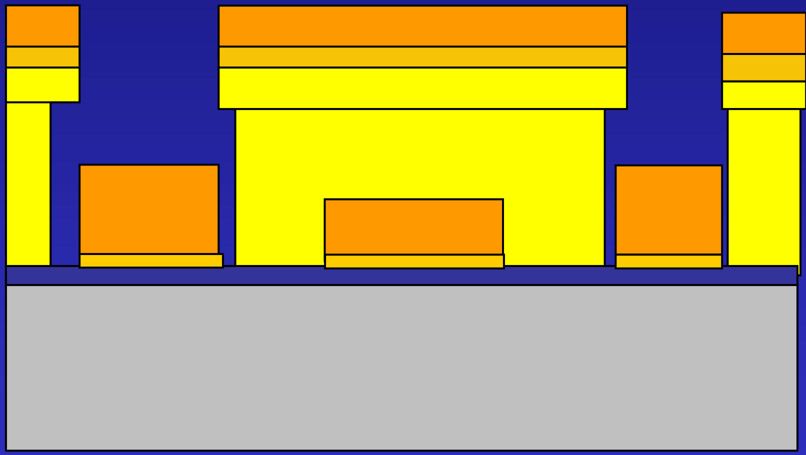
Fabrication Process Steps

Fabrication Flow Chart: Step 4-5

4. 1st layer lift off

5. The second layer of Au deposition**.** **Mask 2**



Fabrication Process Steps

Fabrication Flow Chart: Step 6-10

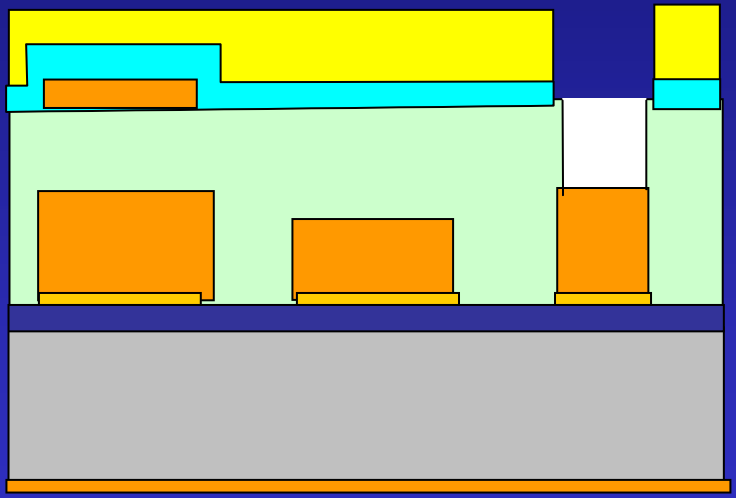
6. The 2nd lift-off

7. Sacrificial layer deposition, followed by contact metal Au define. (**Mask 3)**

8. Thin Al (Alumnium) layer deposition.

9. gold layer deposited on the backside of wafer.

10.Post hole definition and sacrificial layer etched to open the post hole. **(Mask 4)**



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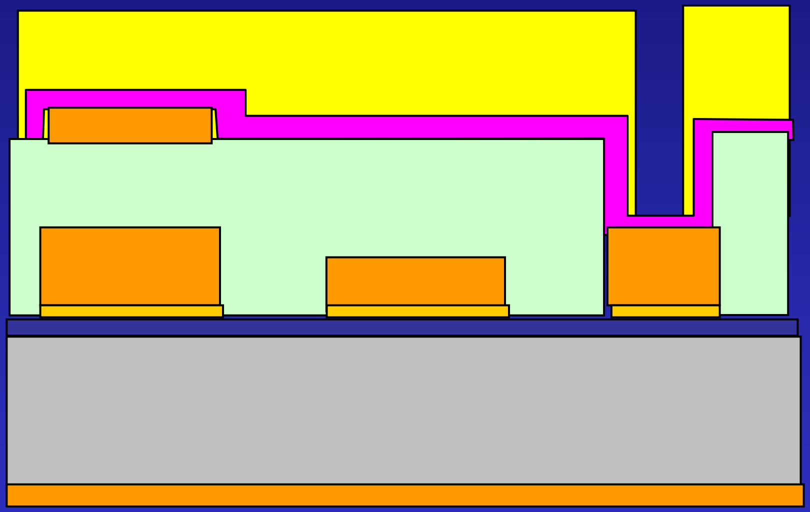
Fabrication Process Steps

Fabrication Flow Chart: Step 11-12

11. Photoresist and Al layer removed, followed by a 0.5um SiN deposition.

12. Photoresist patterning, **Mask 5**.



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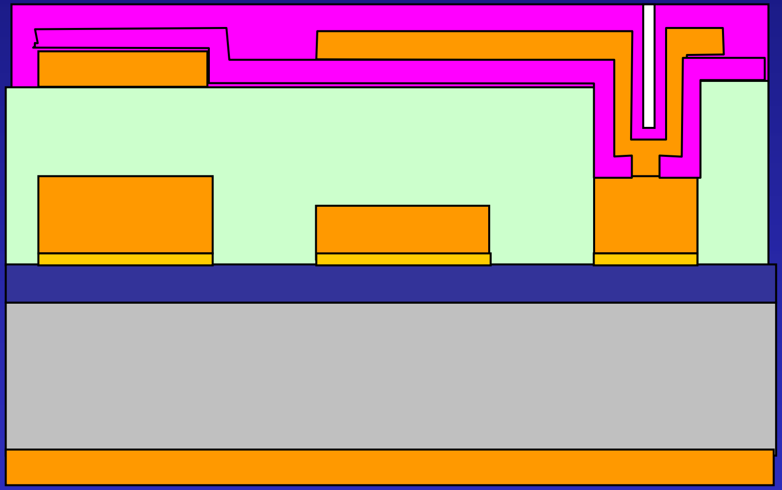
Fabrication Process Steps

Fabrication Flow Chart: Step 13-15

13. SiN layer dry etch by RIE.

14. Resist removing, then Au deposition. (~1um). (**Mask 6**)

15. Another layer of SiN (~0.5um) deposition and define.**Mask 7** (layer 5)



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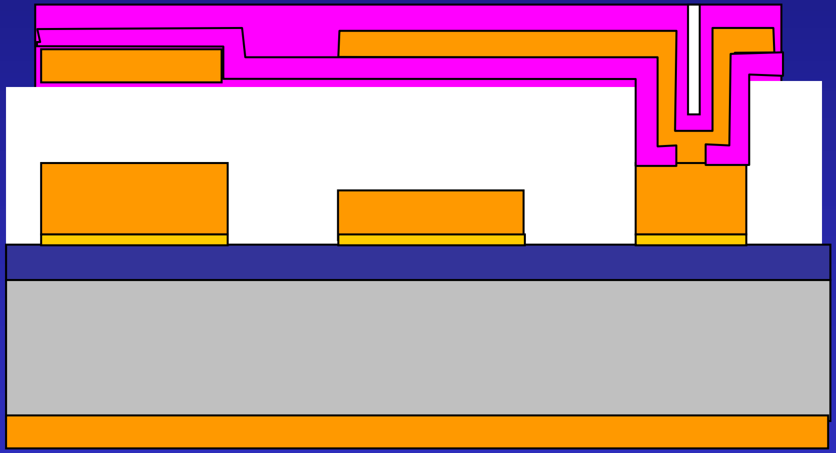
Fabrication Process Steps

Fabrication Flow Chart: Step 16

16. Sacrificial layer removing for released the cantilever.



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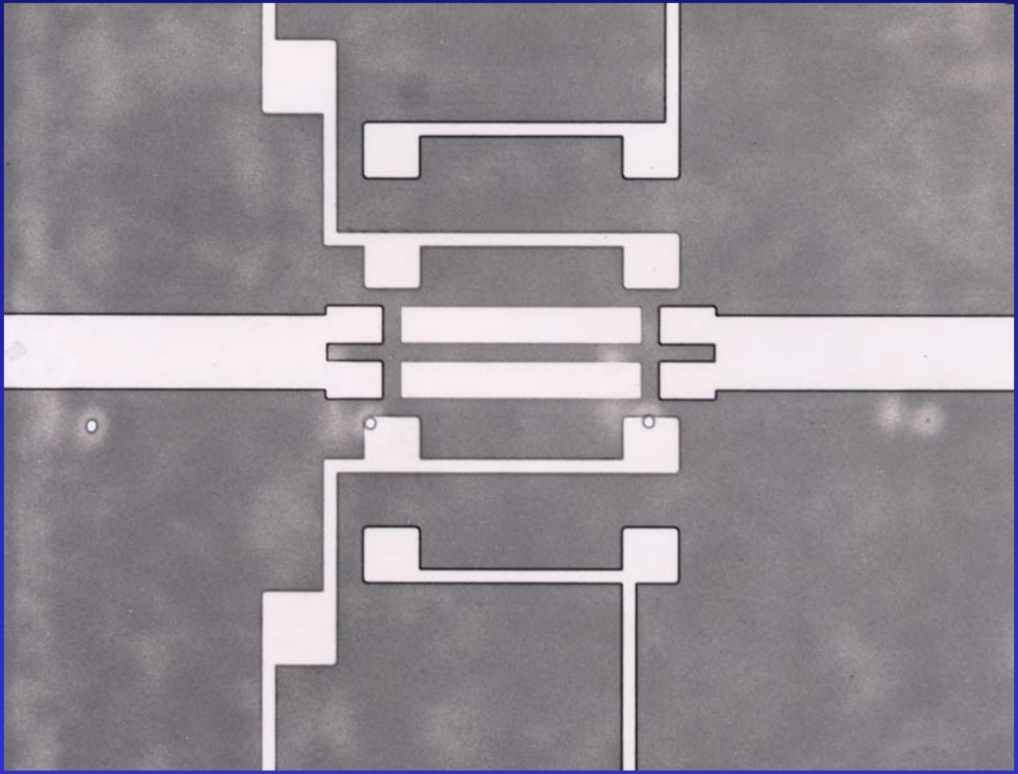
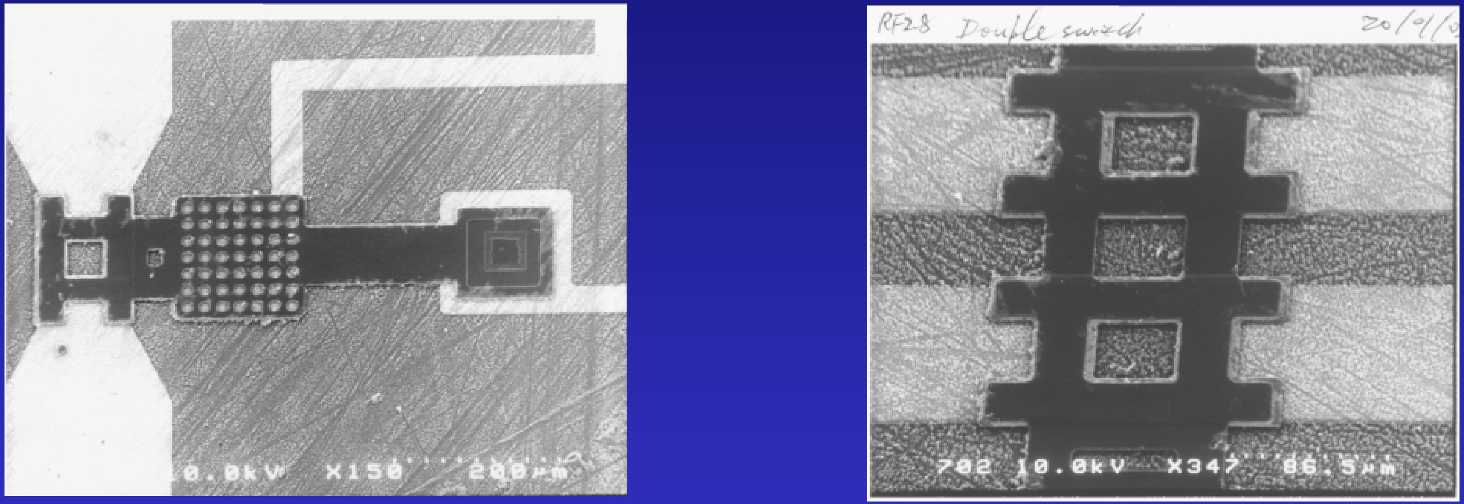
Fabrication and Results

Optical images of layer 1 and 2 on wafer



Fabrication and Results

Optical images -- Before removing the sacrificial layer.



(a) Single switch.

(b) Double switch.

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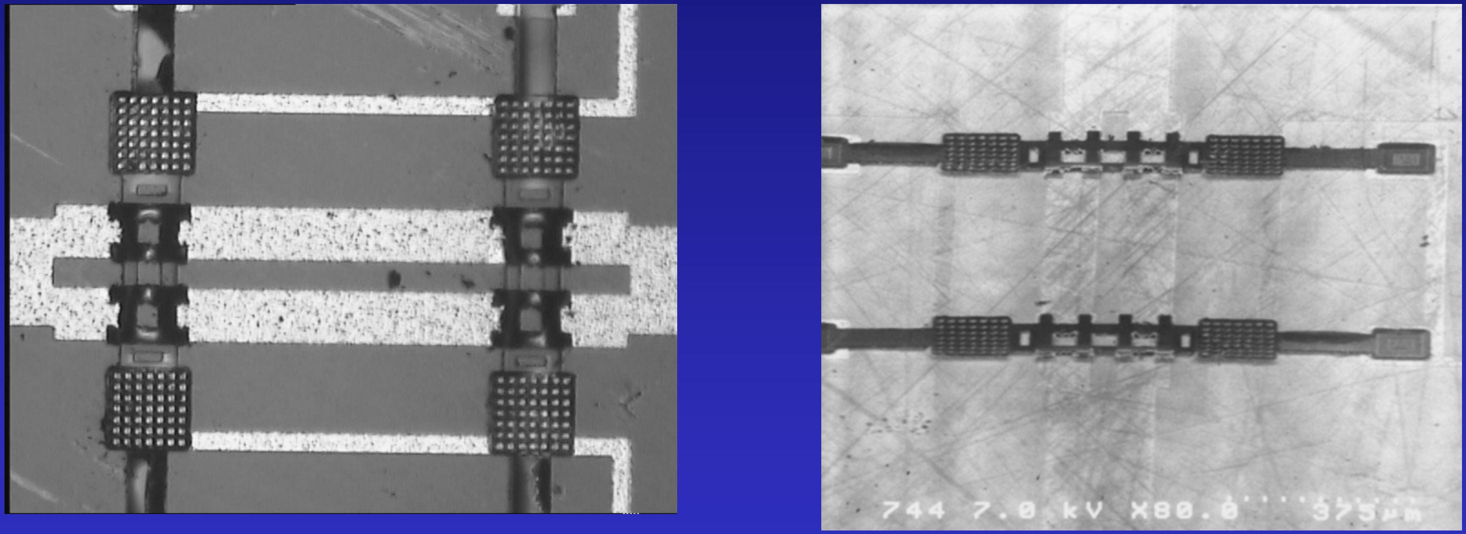
Fabrication and Results

Optical images


(a) During plasma ashing

(b) After plasma ashing

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Fabrication and Results

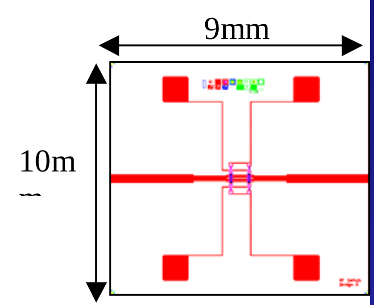
The primary fabrication results reveal some problems, including high residual stress in switch beam and large variation of the beam height. The causes may lie in

(a) Material: SiN and Au do not match to each other

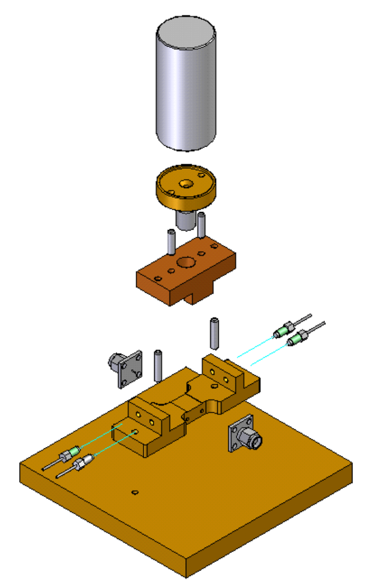
(b) Process: SiN deposition condition and the ashing process control (time, temperature etc.)

To overcome the problems, further investigation has been carried out into surface planarization on the sacrificial layer and low stress deposition with better-controlled gas flow, pressure and temperature.

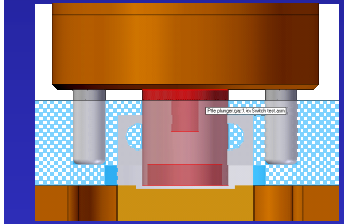
Experiments

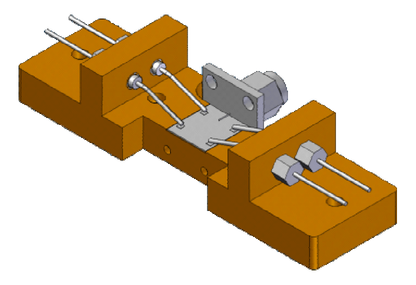


Experimental die



Showing die mount assembly and DC and RF connections





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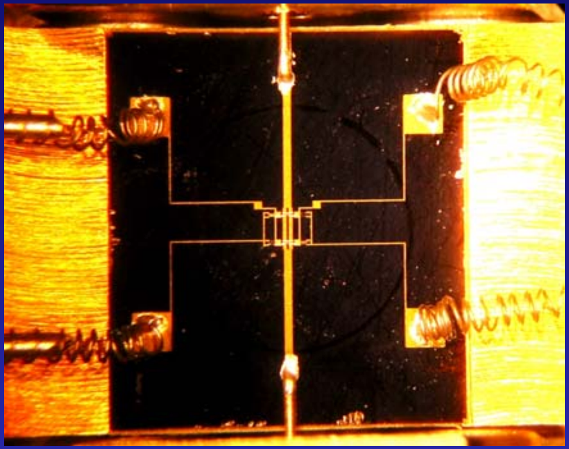
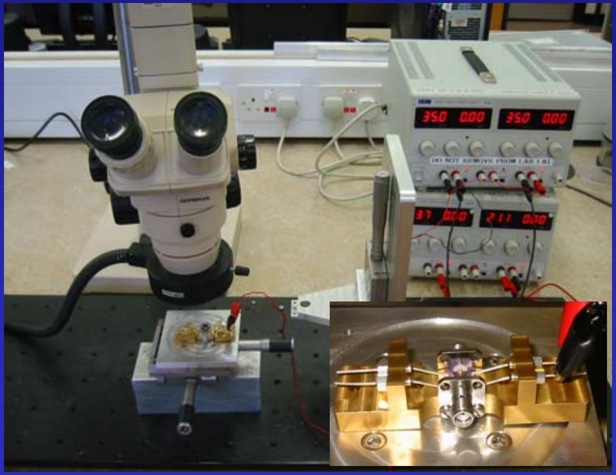
Experiments



Switch Die mounted on holder with DC and RF connections



DC test setup

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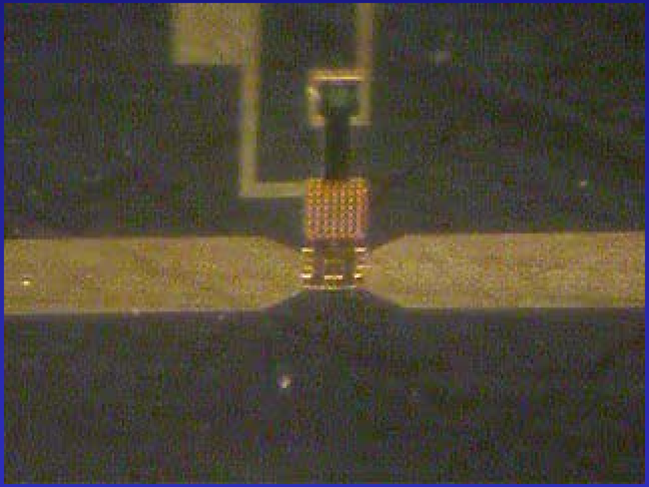
Experiments

DC actuating a test switch (video)



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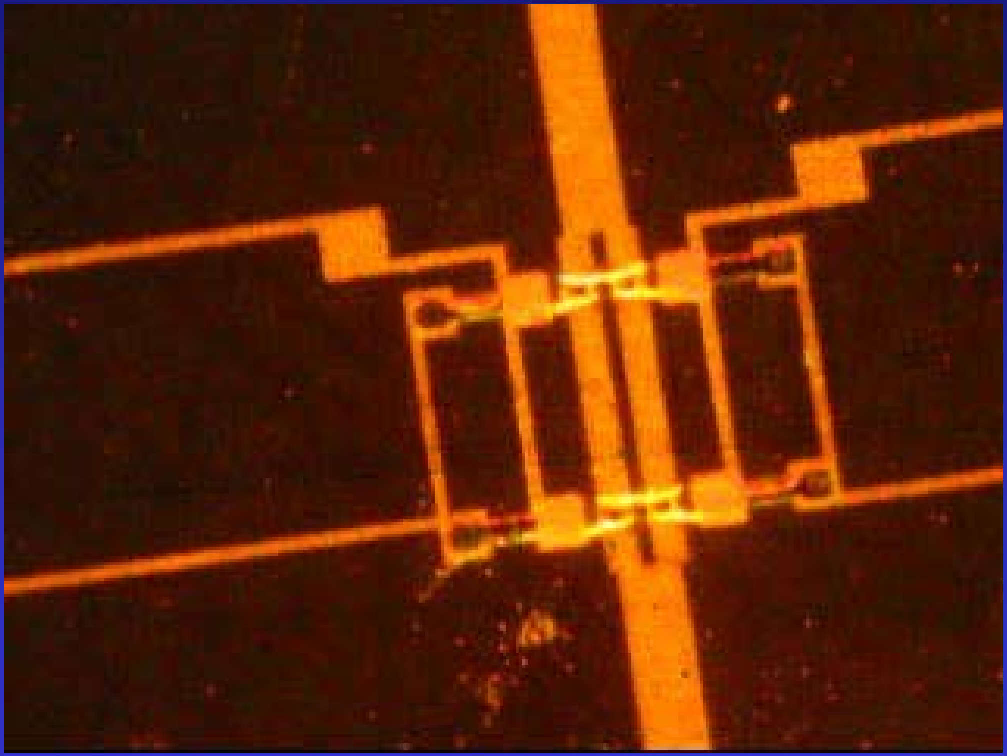
Experiments

DC actuating a test switch array (video)



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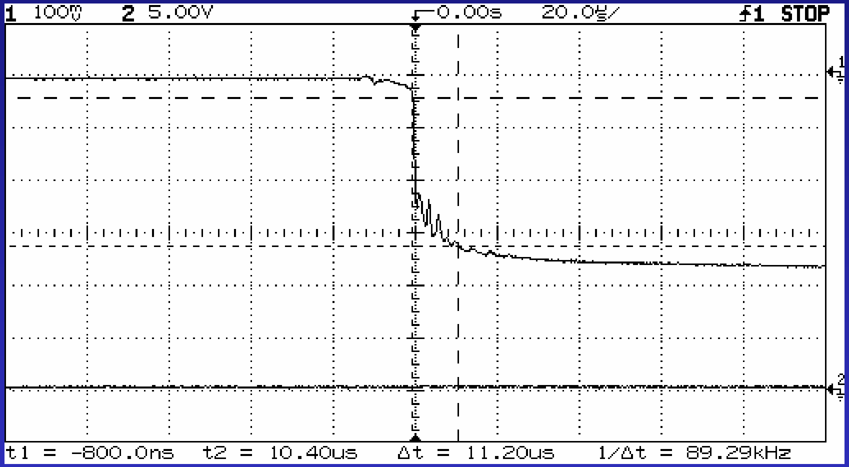
Experiments

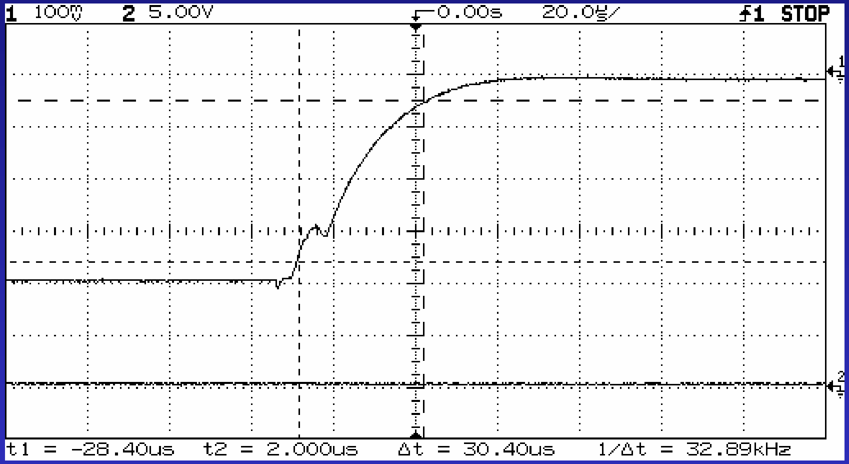
Switching time measurements

ON time measurement



~ 11 us for switching on

OFF time measurement



~ 30 us for switching off

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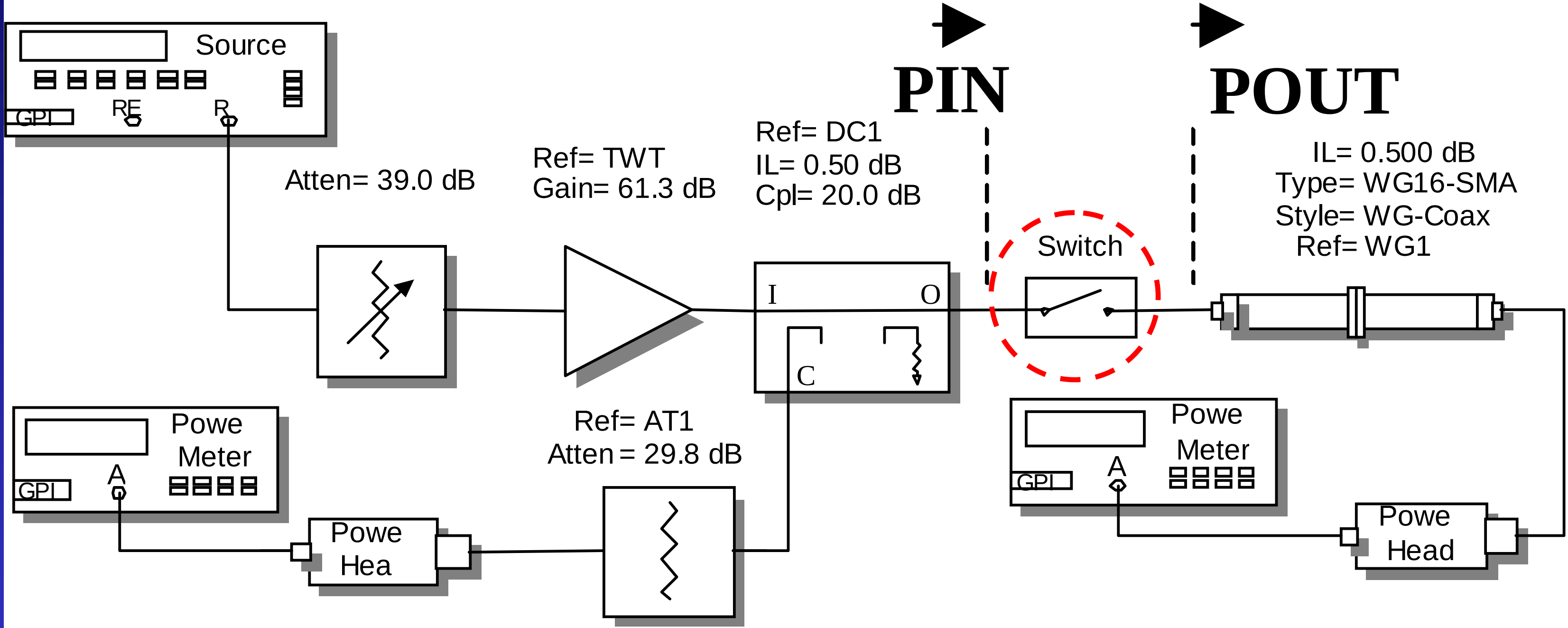
Experiments

Diagram of microwave high power measurement set-up



The microwave power was generated by a synthesised source operating at x-band. The CW signal from the source passed through a variable 0-20 dB attenuator the output signal was then amplified by a Varian travelling-wave tube (TWT) amplifier. The output signal was from the TWT was fed into a 20 dB directional coupler which drew off a signal on the attenuated port for the input power measurement. The through port was coupled to the device under test (DUT) through a coax to waveguide transition. After the DUT end-to-end coaxial to waveguide transitions were used to provide DC voltage blocking to the power sensors for the through power measurement.

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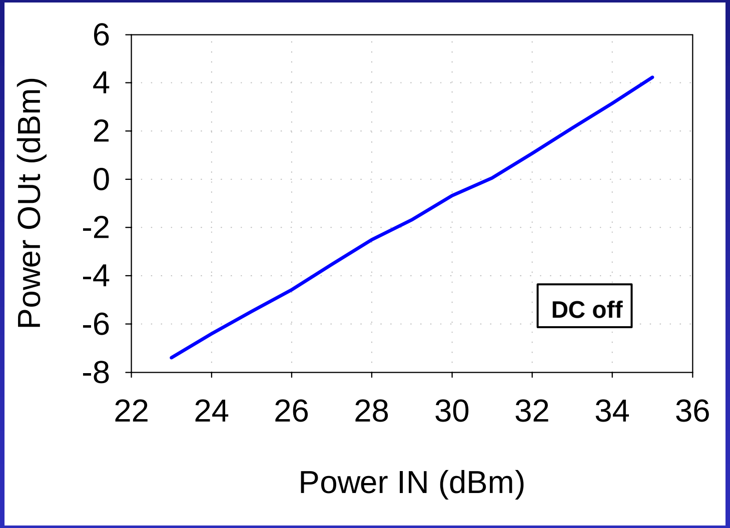
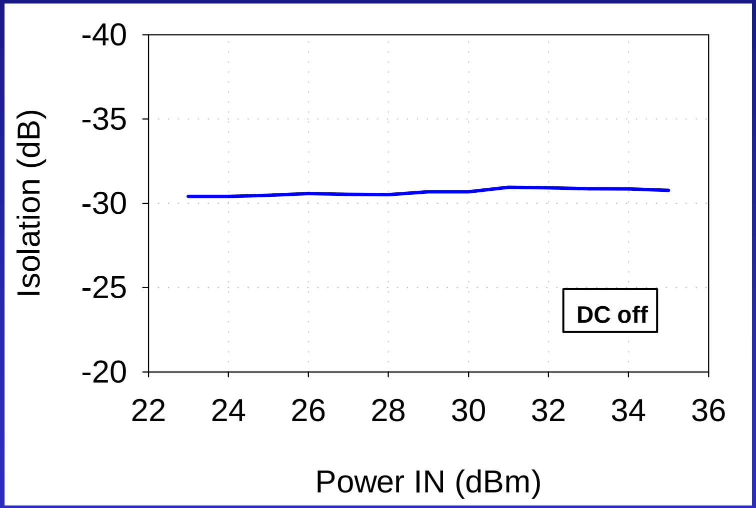
Experiments

OFF state power measurements

(a) Power-out vs. Power-in



(b) Isolation



The input power was increased until 35 dBm (about 3 W) without any noticeable change in the isolation of the switch across this range. The isolation remained at approximately -30 dB although this became lower with time due to slight drift in the gain of the TWT.

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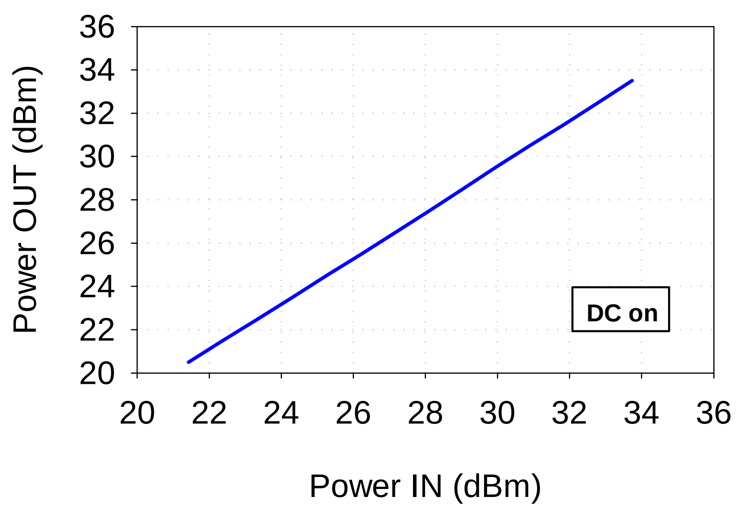
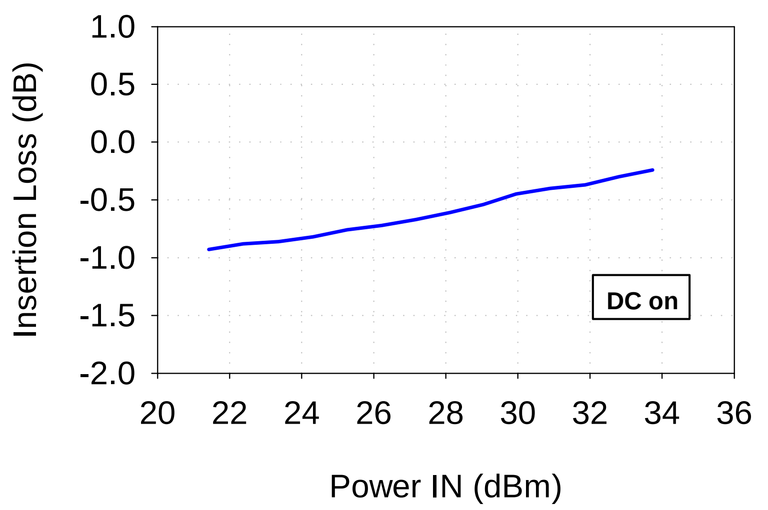
Experiments

ON state power measurements

(a) Power-out vs. Power-in



(b) Insertion Loss



After removal of the calibration measurement, the switch insertion loss was measured to be in the range -1 dB to -0.5 dB. The drift in the TWT amplifier gain resulted in the lowering loss trend recorded. The device under test cold switched a power of 2.3W without damage occurring. In this instance the switch has not been tested to its maximum limit which remains to be investigated later.

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The Si/SiO_2 combination was found to add significant loss to the S21 measurements before calibration, although both high resistive 10KΩ/cm Si and SiO_2 possess low loss.

On further investigation it was discovered that when these materials are combined the Si/SiO_2 junction can produce an attenuation mechanism at high frequencies.

In order to address this problem a suitable alternative dielectric to Si/SiO_2 will be required to provide adequate DC isolation. In recent literature the dielectric material BCB (BenzoCycloButene) has been successfully used in the fabrication for low loss high frequency applications.

Summary

- ✓ A switch matrix concept has been introduced for the development of high power RF MEMS switches.
- ✓ An implementation of a high power, high isolation SPST switch with a 2X2 matrix has been demonstrated.
- ✓ Electromagnetic, electromechanical modelling as well as fabrication processes have been described.
- ✓ A number of interesting challenges remain in particular within the manufacturing process. The reduction of material stresses and improvement of yield as well thermal issue shall be addressed before this type of high power switch can be successfully developed.