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SENSORS & TRANSDUCERS

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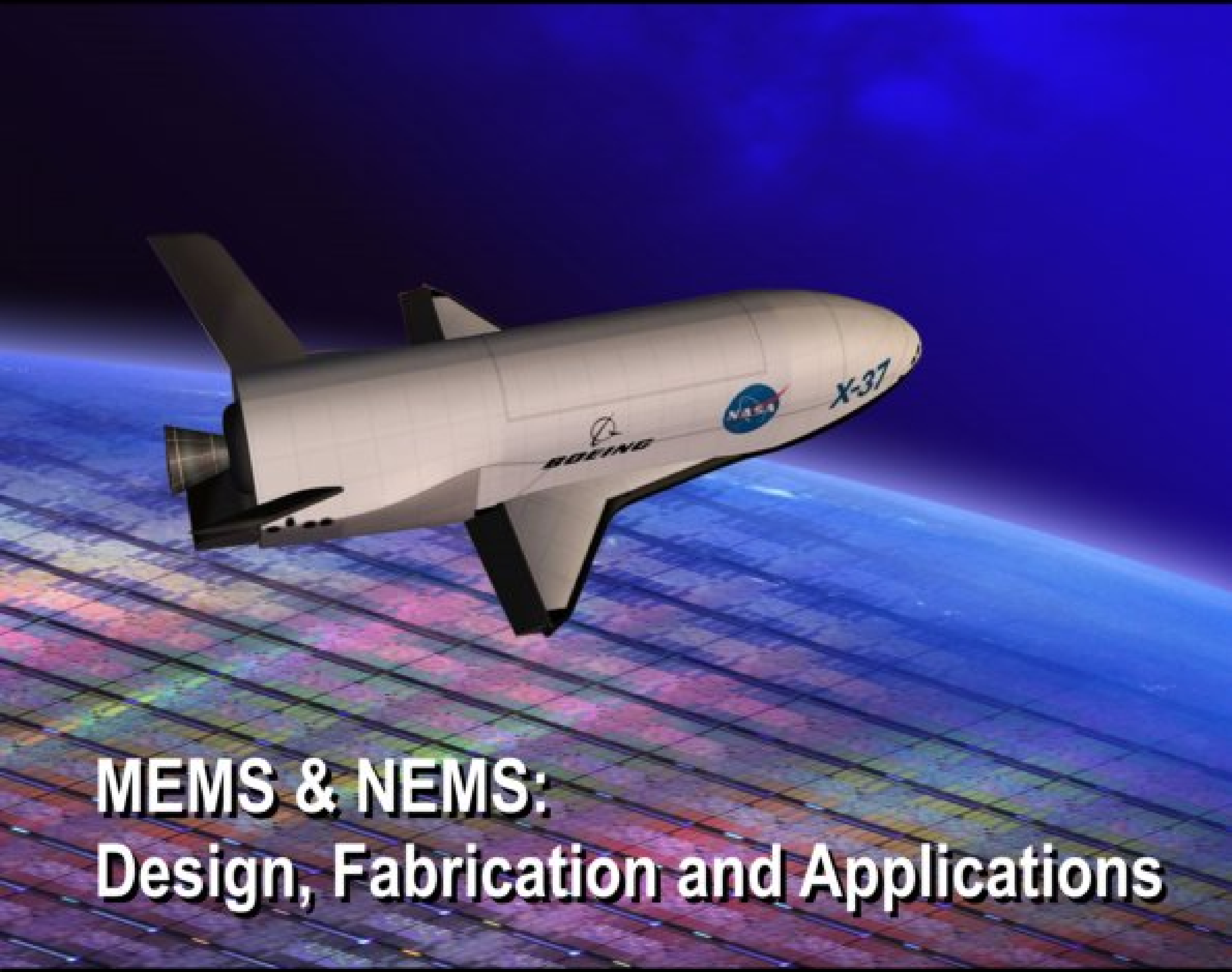
Special



MEMS & NEMS: Design, Fabrication and Applications

International Frequency Sensor Association Publishing
IFSA

Sensors & Transducers

Volume 13, Issue 12
December 2011

www.sensorsportal.com

ISSN 1726-5479

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Sensors & Transducers Journal

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Volume 13
Special Issue
December 2011

www.sensorsportal.com

ISSN 1726-5479

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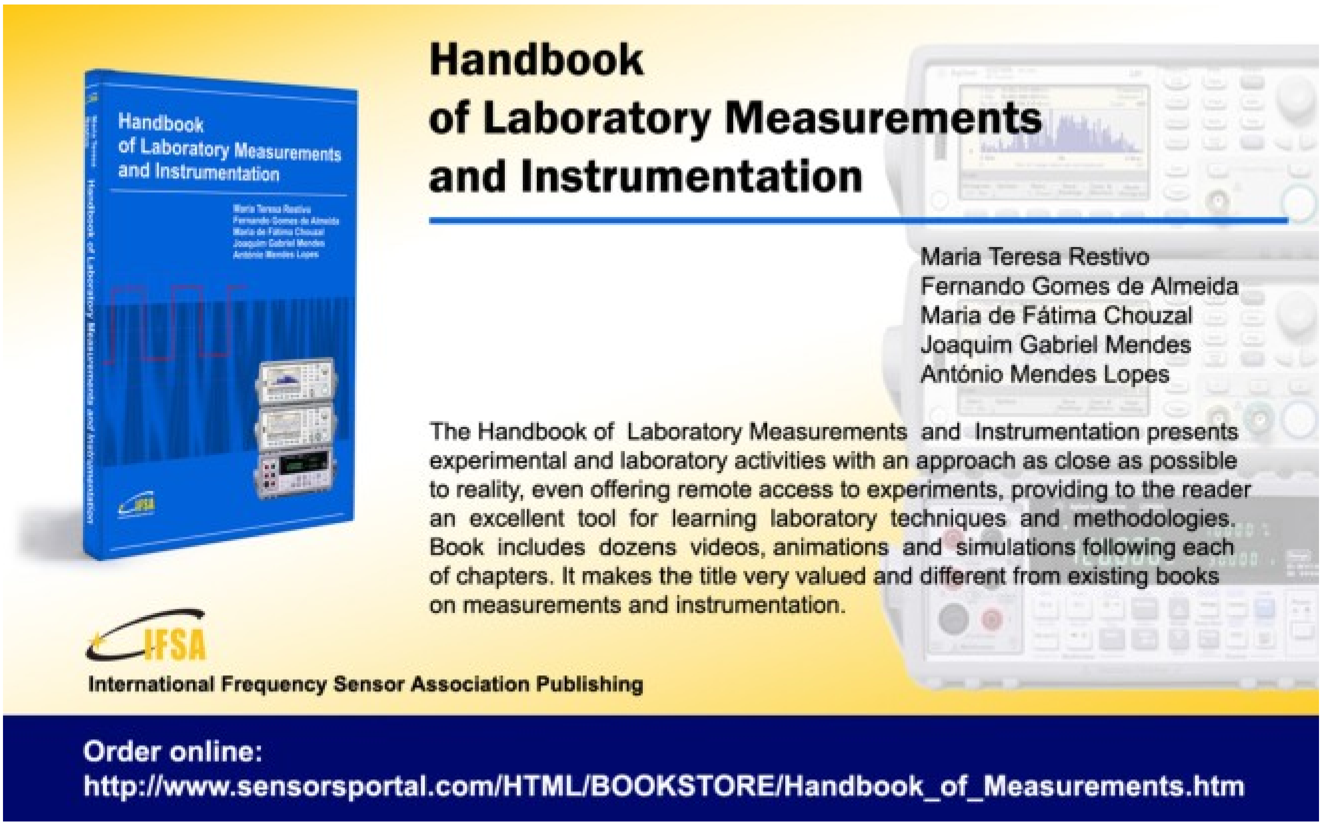

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Sensors & Transducers
ISSN 1726-5479
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A Novel Silicon-based Wideband RF Nano Switch Matrix Cell and the Fabrication of RF Nano Switch Structures

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Received: 29 June 2011 /Accepted: 16 November 2011 /Published: 28 December 2011

Abstract: This paper presents the concept of RF nano switch matrix cell and the fabrication of RF nano switch. The nano switch matrix cell can be implemented into complex switch matrix for signal routing. RF nano switch is the decision unit for the matrix cell; in this research, it is fabricated on a tri-layer high-resistivity-silicon substrate using surface micromachining approach. Electron beam lithography is introduced to define the pattern and IC compatible deposition process is used to construct the metal layers. Silicon-based nano switch fabricated by IC compatible process can lead to a high potential of system integration to perform a cost effective system-on-a-chip solution. In this paper, simulation results of the designed matrix cell are presented; followed by the details of the nano structure fabrication and fabrication challenges optimizations; finally, measurements of the fabricated nano structure along with analytical discussions are also discussed. *Copyright © 2011 IFSA.*

Keywords: RF MEMS, Nano switch matrix, Silicon-based, Electron beam lithography, Terahertz technology

1. Introduction

Terahertz (THz) frequencies technology has large potentials in wide variety of applications including wideband communications, imaging and sensing. With the THz spectrum covers most unallocated frequency bands from 300 GHz to 10 THz, this technology opens up the prospect of large bandwidths which can facilitate the ultra-high-data-rate communications; additionally, electromagnetic waves at high frequencies give sub-millimeter resolution of objects that can be essentially applied in imaging for medical, non-destructive testing and security applications. To realize this future technology, it is required that communication systems satisfy the low insertion loss and high isolation performance at high frequency domain; furthermore, there are still requirements of miniaturization and ideally low power consumption to compromise the overall system performance improvement.

The RF Micro-Electro-Mechanical-Systems (MEMS) technology has recently been considered as one of the promising candidate technologies to produce RF components for future applications. This technology can be applied to mobile telephone, automotive, aeronautics and aerospace [1]. RF MEMS devices have demonstrated advanced performances in terms of isolation, insertion loss, power consumption, and size [2-3]. Some of the RF MEMS devices are proposed to replace the semiconductor counterparts in the advance wireless communication system [4-6]. However, significant improvements are still desired in wideband applications and the actuation voltage reduction.

The emerging Nano-Electro-Mechanical-System (NEMS) technology is expected to inherit the advantages of RF MEMS, it can potentially enable revolutionary advances in future wireless communication. NEMS devices are defined to have a characteristic length scale below 1μm (most strictly, 1-100nm) [7]. Two major perspectives motivate the research of RF NEMS devices: firstly, from an electromagnetic aspect, RF NEMS devices with reduced dimensions can propagate a smaller wave length corresponds to the switch size, hence it can accommodate a higher frequency and wider bandwidth. The parasitic of the devices can theoretically be reduced by shrinking in structure size, therefore nano device is possible to exhibit high RF performance. Secondly, from a mechanical aspect, reducing physical dimensions can theoretically lead to the reduction of switch actuation voltage, while increasing response time [2].

Extensive studies indicated that NEMS devices, particularly nano switches, are mostly reported for memory applications. These devices are fabricated using bulk micromachining, shallow trench isolation techniques and suspended carbon nanotubes [8-11]. The developments of RF NEMS had not been made significantly.

This research focuses on the development of silicon-based RF NEMS switch matrix. Switch matrixes are mainly used for signal routing. Complex switching networks allow flexible interconnections between various ports and channels [12-15]. RF nano switch is the fundamental component for the nano switch matrix network. The target frequency range 550-650GHz is a free band that can facilitate submilimeter-wave and terahertz applications. The RF NEMS components in this research are proposed to be fabricated by surface micromachining approach. In order to achieve good RF performance, the NEMS devices are designed on a tri-layer silicon wafer constructed with high resistivity <100> orientation silicon, thermal growth oxide and PECVD nitride. The <100> single crystal silicon is an industrial preferred base-material for integrated circuits (IC) and MEMS. RF NEMS devices implemented according to industry standard have high potential of IC integration to perform a system-on-a-chip, therefore size-reduced and cost effective devices can possibly be produced. In the development of nano fabrication process, electron beam lithography (EBL) is introduced for defining pattern; evaporation deposition method with standard lift-off process has been used to construct the switch metal layers.

In the following sections, the operation principle, design and simulation of the RF nano switch matrix cell are presented. Followed by the fabrications of RF nano structures and optimizations of fabrication challenges. Finally, the measurement and analysis of the fabricated nano devices are discussed.

2. RF Nano Switch Matrix Cell

2.1 Operation Principles

The switch matrix enables multiple signals routing, it provides flexible interconnects between different ports from input to output. The RF nano switch matrix, as illustrated in Fig. 1, expand the matrix concept into the nano scale. The nano switch matrix are implemented by single cell unit, the size to the matrix can be enlarged by adding columns and rows to facilitate the additional signal paths.

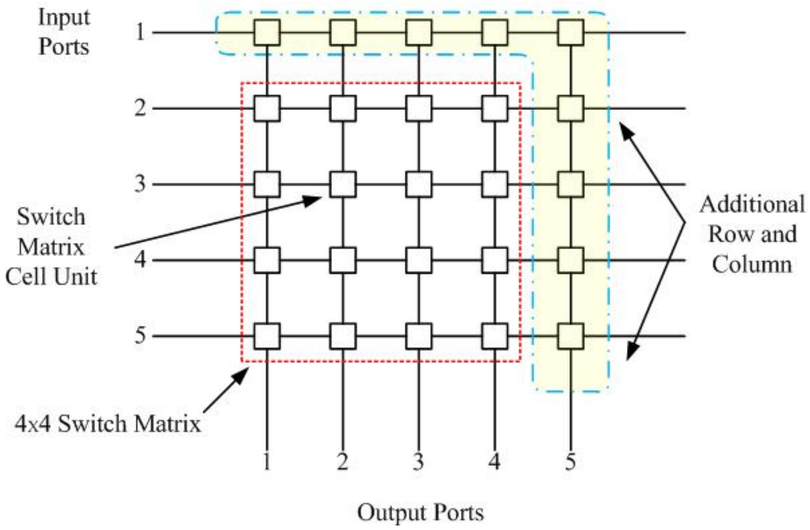


Fig. 1. Scalable RF nano switch matrix architecture.

In order to realize the flexible signal routing function, each cell unit is capable to operation in two states. Fig. 2. illustrates the model of switch matrix single cell unit, each cell unit has four ports to interconnect between its neighbour cell; it can operate in 1) Turn and 2) Thru states. In the "Turn" operation, it routes the input signal to the 90-degree rotation output, therefore Port 1 and Port 4 are connected whereas Port 2 and Port3 are at their open states. In the "Thru" operation, connections are switched into connections between two opposite ports, such that Port 1 connects to Port 4 and Port 2 connects to Port 3.

2.2. RF Nano Switch Matrix Cell Design and Simulation

Fig. 3 illustrates a complete geometry design of the RF nano switch matrix cell. This single cell unit occupies area of 9×9 μm^2. In the design of the nano switch matrix cell, RF nano switch and transmission line are the two critical structures; the switch decide the open and close states of the signal paths, whereas the transmission line propagates the RF signal. The coplanar waveguide (CPW) technology is introduced as basic structure in the design of both switch and transmission line, this technology provides the opportunity for scalable design and lower dispersion [16]; therefore, it can possibly accommodate wideband submilimeter-wave propagation. Physical model of the RF nano switch, as illustrated in Fig. 4, is designed using a series in-line cantilever. The cantilever beam has length of 1.4 µm, thickness of 30 nm and anchor of 600 nm. The overlap and gap between beam and signal line are 400 nm and 40 nm respectively. The CPW with gap\signal\gap (G\S\G) dimensions are 150 nm\200 nm\150 nm. Gold (Au) is selected as the structure material to fabricate cantilever beam and CPW. It has high elastic modulus (E=78 GPa) and low compressive residual stress [17]; additionally, as structure material, gold has enough stiffness to allow the return of the membrane to its original position [18-19].

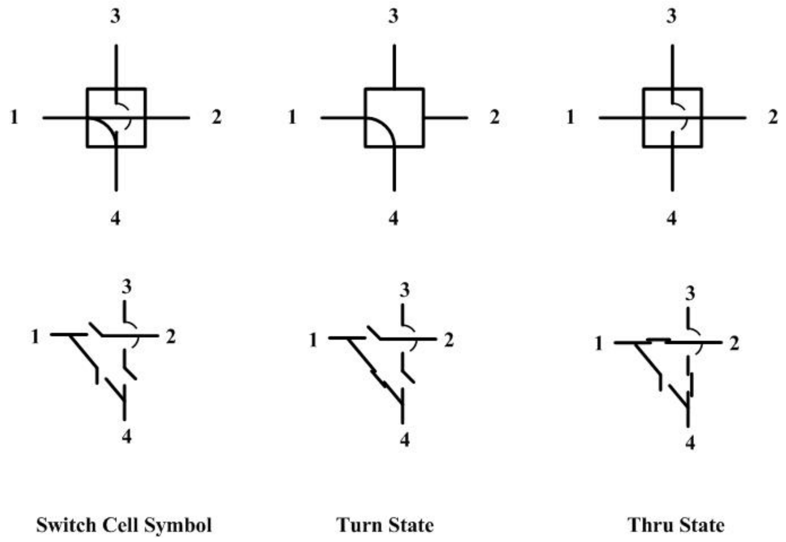


Fig. 2. Switch cell symbol and operation states.

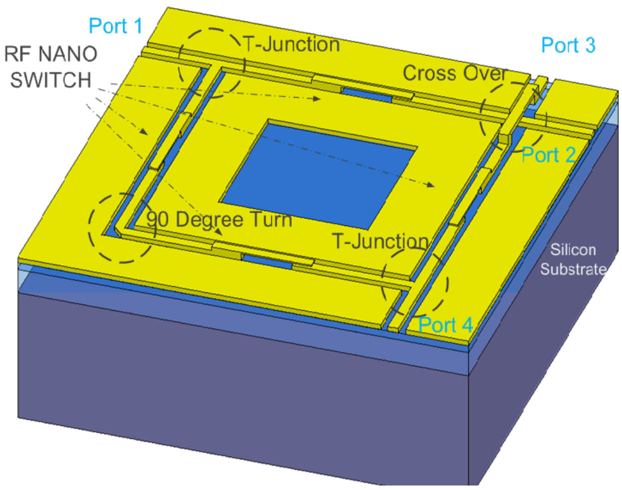


Fig. 3. 3D model of RF nano switch matrix cell.

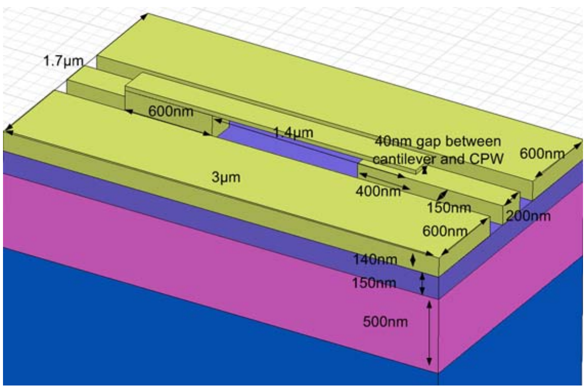


Fig. 4. 3D model of RF nano switch.

In the realization of the "Thur" state which opposite ports are connected, a crossover is used to pass the crossing signals. Physical dimensions of the crossover are correspondent with the nano switch and CPW. The two transmission lines of crossover are designed perpendicular to each other in order to reduce the coupling area and reduce signal coupling [20].

The entire switch matrix cell is placed above a tri-layer silicon wafer, which consist of high resistivity silicon, silicon dioxide and silicon nitride. The silicon substrate has resistivity of 10,000 Ohm-cm and dielectric constant (ε) of 11.9, 500 nm silicon dioxide buffer layer is placed on top of the silicon. Chromium (Cr) based lower electrode with dimensions of 700×250×40 nm for electrostatic actuation is placed on top of silicon dioxide layer. Finally, 150 nm silicon nitride is placed above the oxide as insulating layer to isolate the dc control signal and RF signal.

S-parameters of the RF nano devices are simulated by Ansys HFSS. Analysis frequency range is 550-650 GHz, two wave ports are placed at the two ends of CPW signal line. The port-to-port simulation results indicate that the proposed RF nano devices have potential to achieve high RF performance in the interconnection with nano devices that have identical CPW properties (contact resistance of the nano switch are neglected in the simulation model.) Fig. 5 depicts S-parameter simulation results of the two operation states for single cell. Simulation frequency sweep from 550 to 650 GHz. In turn state, insertion loss (S41) is less than 0.9 dB, return loss (S11) is better than 15 dB and isolation (S21) is above 35 dB. In thru state, insertion loss (S21) and (S43) are both around 0.6 dB, return loss (S11) and (S33) approach 20 dB, isolation (S41) is above 40dB.

(a)

(b)

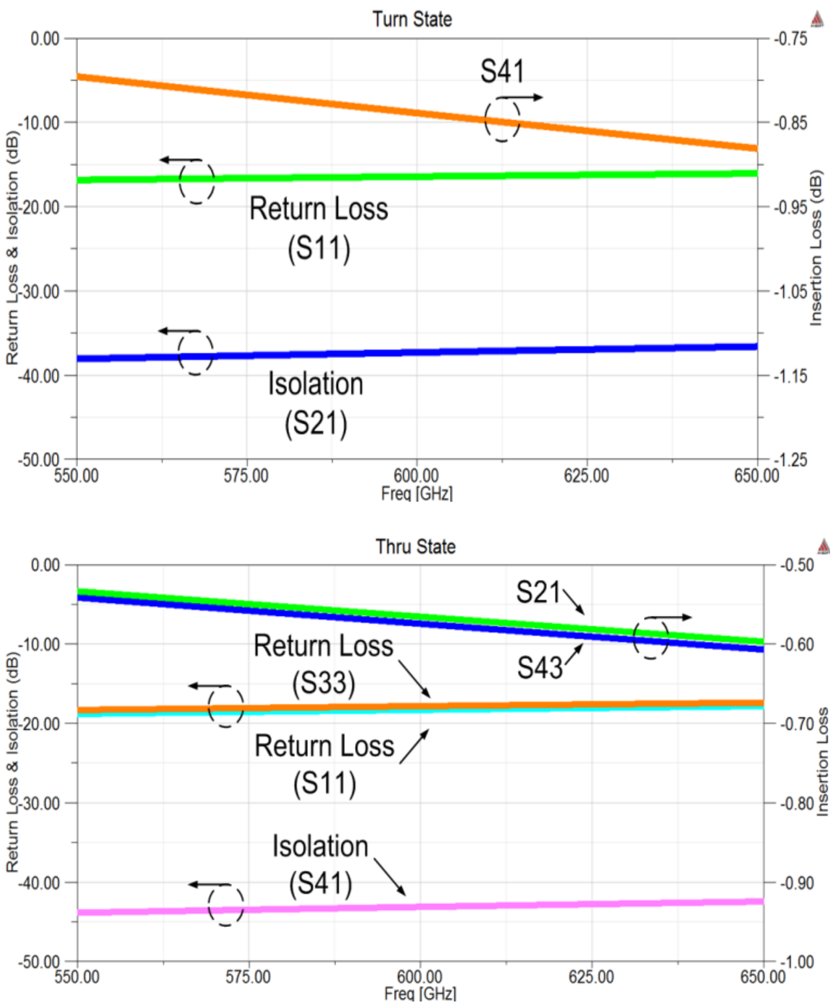


Fig. 5. S-parameters simulation of (a) "Turn" and (b) "Thru" states.

3. Nano Structure Fabrication and Challenges Optimizations

3.1. Fabrication of RF Nano Structure

In the fabrication experiments, the RF nano switch and CPW structure are firstly fabricated for testing. Fabrication process, as illustrated in Fig. 6, is developed using surface micromachining approach. It consists of four metal layers and two dielectric layers on top of silicon substrate. The metal layers are achieved by standard lift-off process. Electron beam lithography (EBL) direct writing is introduced as mask-less pattern generator with polymethyl methacrylate (PMMA) coated as e-beam sensitive resist for EBL dose exposure.

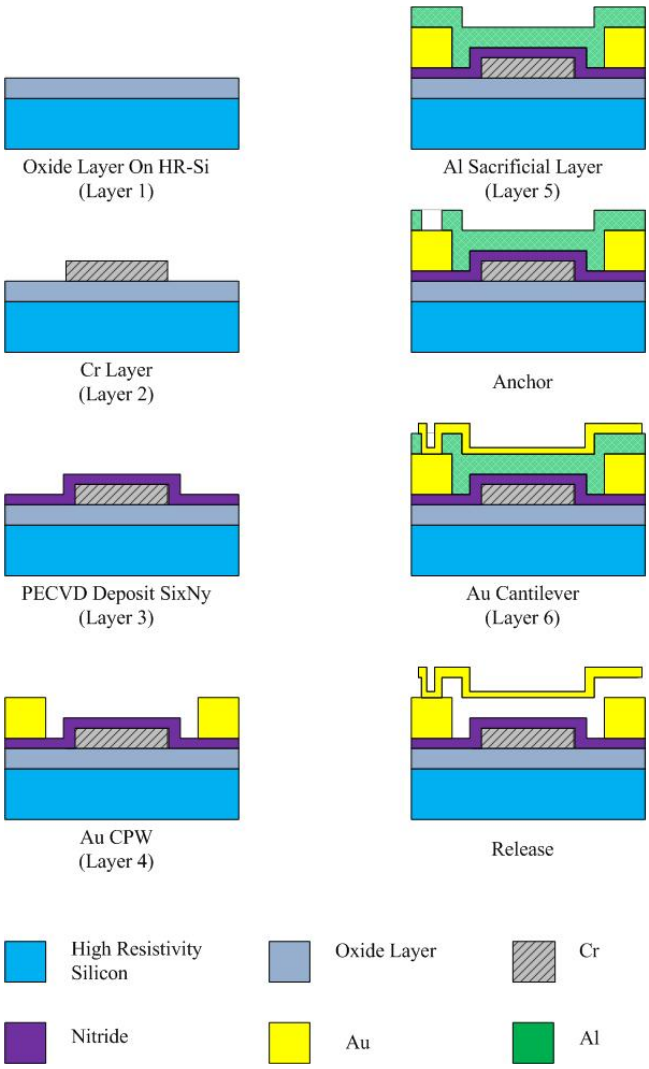


Fig. 6. Fabrication Process.

Firstly, a 500 nm SiO_2 is formed by thermal oxidation on top of the silicon substrate (Layer-1). Followed by evaporated 40 nm chromium (Cr) based lower electrode and DC bias line (Layer-2). EBL pattern defined for this layer are 30 KeV, 450 µC/cm2 dose with spot 1 and spot 4. Secondly, 150 nm silicon nitride is plasma-enhanced chemical vapour deposition (PECVD) deposited as insulating layer (Layer-3). Above the nitride, a 100/40 nm Au/Cr metal layer (Layer-4) of CPW, this layer was patterned by EBL writing at 30 KeV, 550 µC/cm2 dose with spot 1 and 450 $\mu C/cm^2$ dose with spot 4. A SEM picture of the fabricated CPW structure with bias line is illustrated in Fig. 7.

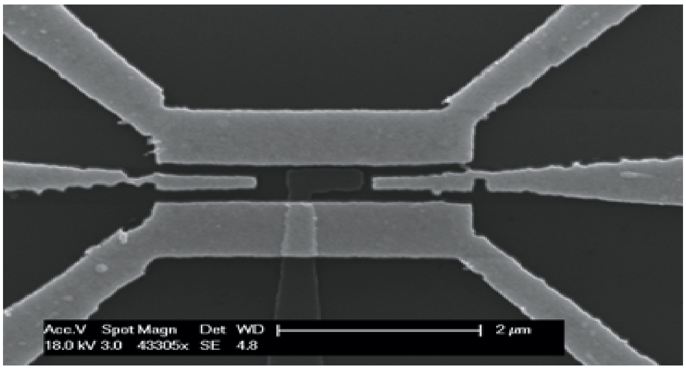


Fig. 7. The fabricated CPW structure with bias line.

A 40 nm aluminum (Al) is deposited as sacrificial layer (Layer-5). The anchor window is created by Al etching. Followed by a 30 nm Au cantilever beam deposition (Layer-6) with EBL patterned at 30 KeV, 450 $\mu C/cm^2$ dose with spot 1. A SEM picture of the fabricated cantilever beam before release process is illustrated in Fig. 8.

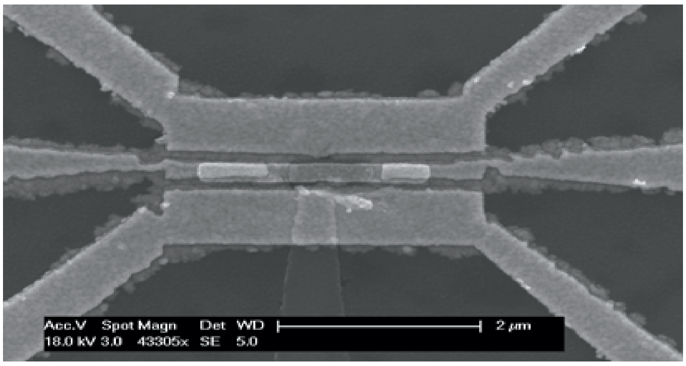


Fig. 8. SEM of the deposited cantilever beam.

Finally, the cantilever structure is proposed to be released by a combination process of wet etch and dry etch using reactive ion etching (RIE). The etching process begins with wet etch to remove over-left PMMA; followed by anisotropic etch and isotropic etch to release the structure. A SEM picture of complete view of the RF NEMS switch including bias pads is illustrated in Fig. 9.

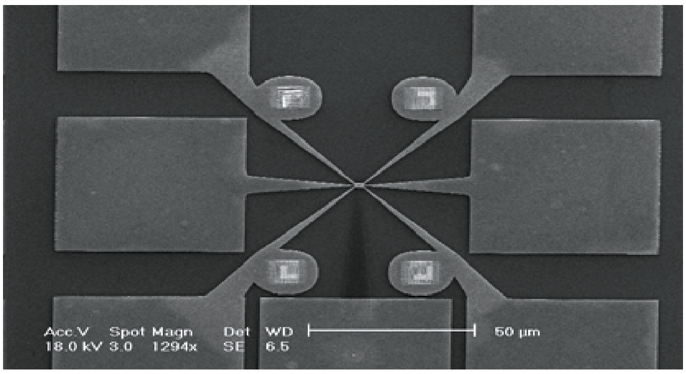
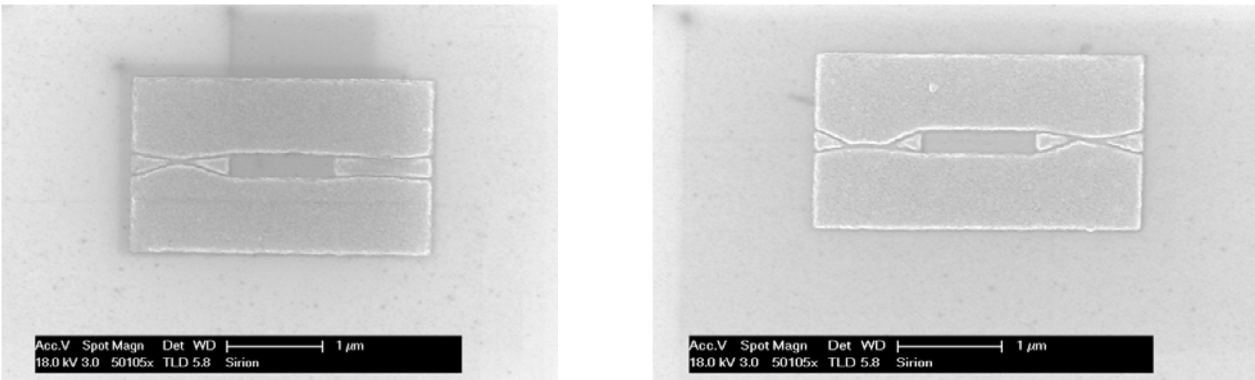


Fig. 9. The fabricated CPW structure with bias pads.

3.2. Optimizations of Fabrication Challenges

In the developed fabrication process, electron beam lithography is introduced as pattern generator for direct writing. This technology provides feasibility in modifying the dimensions of patterns and accuracy of defining nano scale features. However, it also brings up the fabrication challenges by using this equipment.

Proximity effect is one of the major challenges encountered using EBL. It is either caused by non-uniform distribution of the dose that are received in the exposed area when using uniform exposure, or caused by scattering electrons from the incident beam. This effect results in the dose delivered by e-beam not confining with the original shape, thus causes a pattern variation. Fig. 10 illustrates proximity effect causes the pattern variation of CPW on left side (a) and both sides (b). The variation of the exposure dose can be more significant when the defined area becomes smaller.

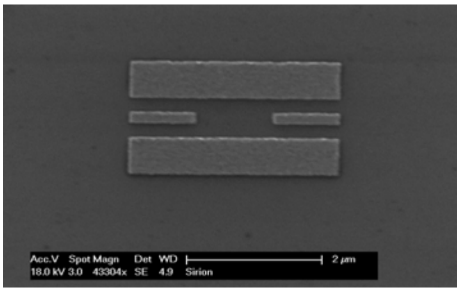


(a) (b)

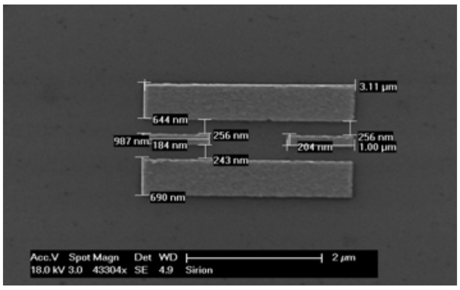
Fig. 10. Pattern variation of CPW structure due to proximity effect on a) left side and b) both sides.

A dose-shape correction method [21] is adopted to compensate the proximity effect. The principle of this method is that EBL system writes at a constant dose and exposes from high resolution features down to the resolution limit to find the most suitable resolution feature for each dose profile. In order to achieve the desired dose profile for each pattern, varied dose profiles are performed to decide a certain dose for a desired structure with precise dimensions. Finally, different features with different dose profiles are obtained by experimentally repetition. Fig. 11 illustrates dose-share correction for the CPW structure.

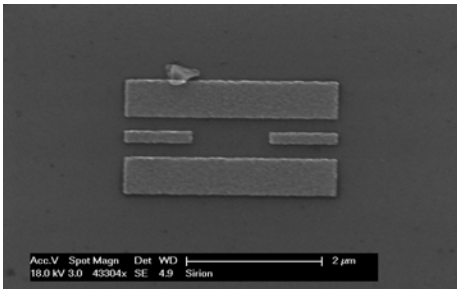
Field stitching is the alignment ability of an EBL tool to line up features in field A with features in field B. Feature shifting or notches can occur when lines are written across the boundary of two field gaps. Large area can be exposed by excessive dose in several fields during EBL writing. When stitching is transferring from one field to the other, the sample holder also moves along with the field, this can also introduce errors. The errors can be optimized by e-beam deflection calibration. Optical exposures are performed when the borders of the alignment markers of one field exactly matches the borders of the alignment markers of the adjacent field. A field stitching error of less than 5nm was recorded during the writing when e-beam moved on the horizontal axis.



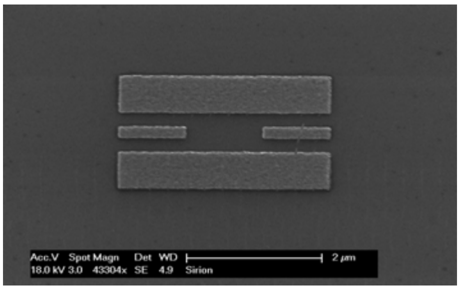
(a) 400 ($\mu C/cm^2$)



(b) 450 ($\mu C/cm^2$)



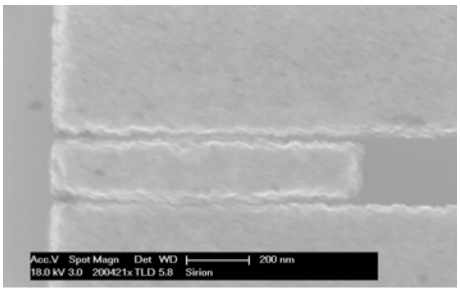
(c) 500 ($\mu C/cm^2$)



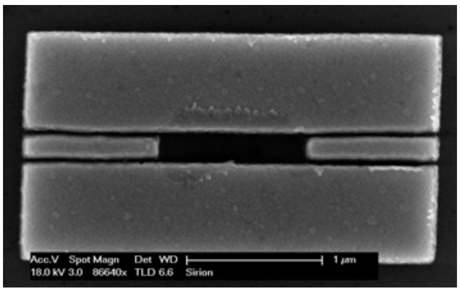
(d) 550 ($\mu C/cm^2$)

Fig. 11. 3D CPW structure under dose-shape correction.

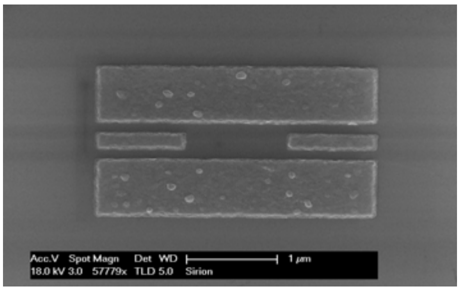
The minimum possible space to define between two lines is termed as resolution. The contrast between printed and non-printed area is very low when features are small. Fig. 12 illustrates an example of optimizing the resolution limits for the CPW gap between the center signal transmission line and ground. A minimum gap of 20 nm is achieved after feature adjustment; it is possible to form a 20 nm anchor hole for the smaller cantilever beams in the developed fabrication process.



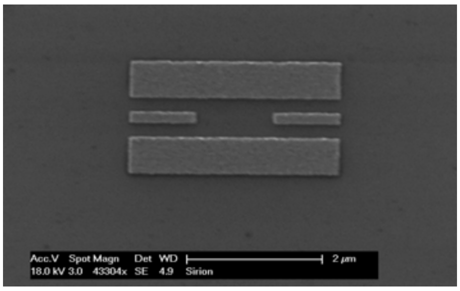
(a) 20 nm gap



(b) 50 nm gap



(c) 100 nm gap



(d) 250 nm gap

Fig. 12. CPW structure with feature adjustment.

4. Measurement and Analysis

A two port on-wafer-measurement to the fabricated RF nano switch has been performed using Agilent Technology PNA E8364C network analyzer with analysis frequency range 10 MHz-50 GHz. The measured S-parameters of the open switch is illustrated in Fig. 13. The isolation, S21 of open switch, is better than 30 dB for the frequency range of interest. The measured S11 of open switch indicates about 10 dB signal loss in the measurement result.

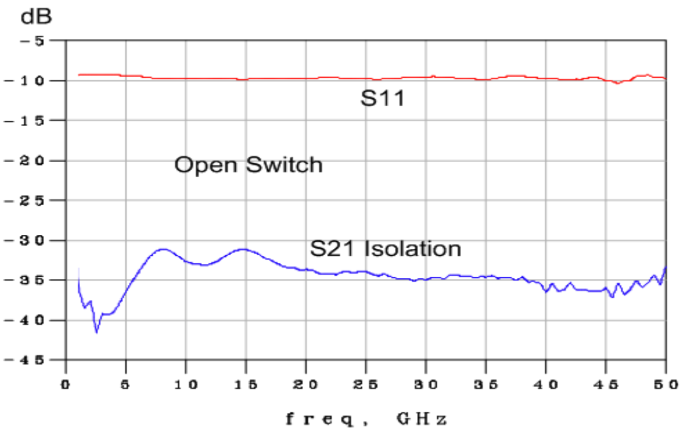


Fig. 13. S-parameters measurement for open switch.

First of all, a 200 nm width transmission line is directly coupled to the bias pad in the measurement (as illustrated in Fig. 6), the large scale difference of the two joint devices can be one of the main reasons that introduce signal loss. A more sophisticate measurement method for RF nano devices including signal path connection design is needed to be investigated. Secondly, the sacrificial layer is not completely released, this can affect the measurement results. Furthermore, CPW structure on thin dielectric layers can introduce signal leakage, the nano scale CPW characteristic also need to be inspected. Finally, the RF nano devices is fabricated on top of silicon which is semi-conductor that electromagnetic field can possibly penetrate into. In order to achieve a better RF performance, nano scale isolation structure is proposed to be developed in future work to alleviate the signal loss and improve the performance.

5. Conclusions

This paper presents the concept of RF nano switch matrix cell and the fabrication of the RF nano switch. The proposed matrix cell is targeted to be applied in high frequency domain; it can be implemented into a scalable nano switch matrix to provide flexible interconnects for signal routine. Simulation results indicate that the designed nano cell have high potential to achieve good RF performance in the frequency band of interest.

The RF nano switch is the critical component in the cell unit to control the operation states. It is fabricated by the developed surface micromachining fabrication processes which use electron beam lithography as a mask-less pattern generator. Proximity effect and field stitching errors are optimized during the fabrications.

Finally, the measurement results indicated that improvements on nano scale signal coupling techniques and improvements on fabrication process for silicon-based low loss RF nano device are needed to be investigated in future work.

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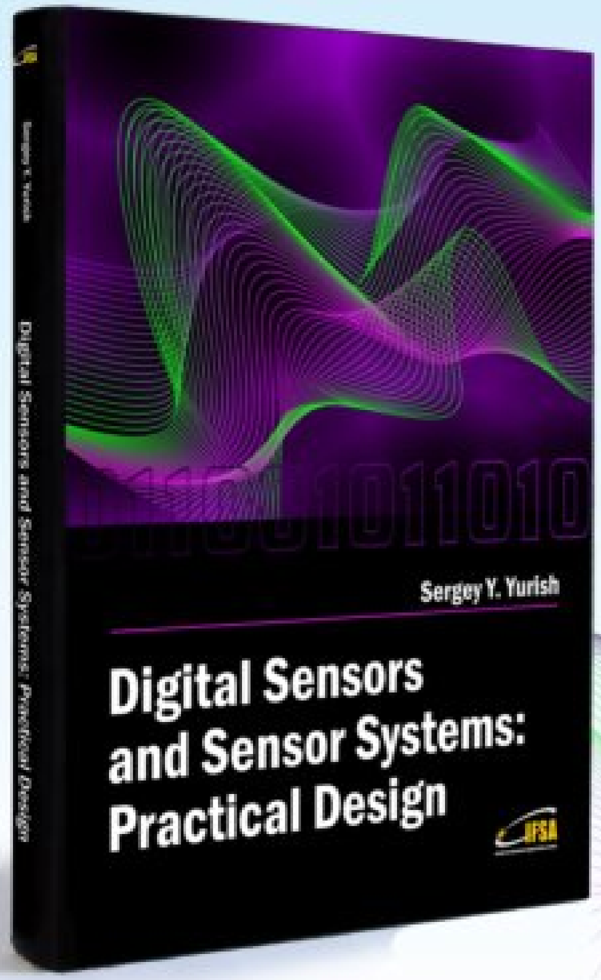

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