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On Designing of MEM Switch

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Abstract

A methodology for designing MEM Switch made up of a cantilever for a given set of specifications (performance parameters) is proposed in this paper. This is based on preparing a software database with a range of performance parameters (Threshold Voltage, Switching On-Time and Switching Off-Time) and associated MEM Switch structural parameters (length, width, thickness of the cantilever beam, cross sectional area and initial gap between the electrodes). The performance parameters required for the creation of the relational data base are obtained based on intensive calculations of Threshold Voltage, Switching On-Time and Off-Time using MATLAB for different structural parameters of the MEM Switch/Switches. A search process has been designed in “JAVA” language to search for the switches that satisfy the given specifications. This search process enables the retrieval of the MEM switches which satisfy given specifications i.e. performance parameters. This paper is an attempt to focus on a novel data base and search process. This approach reduces the design cycle time of the MEM Switches.

Keywords: MEM Switch, Performance parameters, Structural parameters, DC Voltage, Threshold Voltage, On-Time, Off-Time, Search Process, Database.

Introduction

MEM switches are essentially miniature devices which use a mechanical movement for making contact. There are two distinct sections in MEM switch: one is actuation (mechanical) section and another is electrical section.Generally electrostatic, magnetostatic forces or forces due to piezoelectric effect etc. are used for producing mechanical movement. Switch can move vertically or horizontally. This paper deals with the electrostatic forces used for the mechanical movement vertically downwards [1] [14][17]. There are several MEMS design tools like INTELLISUITE, COVENTOR, COMSOL Multiphysics etc. which mostly calculate the performance of the MEM Switch for a given set of structural parameters[12] [13]. These tools calculate the performance of the MEM Switch based on trial and error approach. The real design in these cases takes several iterations before arriving at a single MEM switch which meets the specifications like Threshold Voltage, Switching On-Time and Off-Time [5]. This process is likely to take considerable amount of time to realize the design of a single switch. In view of this a design methodology is proposed in this paper for designing of MEM Switch(s) based on creating a database containing several MEM Diode architectures and their performance. A software search process is used to retrieve (design) the switches of required performance parameters from the database. This proposed methodology enables the design of switches which satisfies the designer's specifications almost instantaneously.

Operating Principle

MEM Switch is a micro cantilever made up of thin polysilicon or insulator and suspended over the substrate by an anchor [13]. It consist of two metal electrodes which are attached at the ends of both the cantilever and substrate used for switching. When DC voltage is applied between the electrodes, the electrostatic attractive force generated between them [2]. As the bias voltage increases, the electrostatic force between the electrodes also increases resulting in bending of the cantilever [6][14]. When the bias voltage reaches "On" Threshold Voltage, then the bending results in a threshold deflection of the top electrode beyond which the electrostatic force increases without further increase in the voltage and resulting in contact (point contact) to the bottom electrode [2]. In this paper the 'On' Threshold Voltage is taken as the voltage required for the deflection $g(L) = \left(\frac{1}{3}g_0\right)$from the top or $g_0 - g(L) = \left(\frac{2}{3}g_0\right)$from the bottom of the cantilever where the metal electrodes are present [8]. The switch gets released abruptly when the voltage becomes smaller than a voltage (which is called Off Threshold Voltage). The Off Threshold Voltage is much smaller (that is very close to zero voltage) than On Threshold Voltage. The MEM switch is specified by On Threshold Voltage, switching On-Time and Off-Time's and the word threshold voltage is used to refer On Threshold Voltage only [1] [5]. A methodology of designing MEM switch(s) for a given Threshold Voltage, Switching On-Time and Off-Time based on Data Mining Principles is presented in this paper [3]. Following is the description of the various steps involved in the design of a MEM switch for a given set of specifications: a) In the first instance the description of the mathematical equations used to arrive at Threshold Voltage, On-Time, Off-Time is givenb) the results of the calculations using MATLAB are discussed c) Relational DATABASE of calculated performance parameters and the corresponding structural parameters for the 2483 MEM Switches is created d) the search process and the way in which the MEM Switch or switches are retrieved (design) from the database for the given specifications is detailed e) The validity of this method has been checked by designing a few MEM switches as a test case.

MEM Switch Structure and Its Operation

The structure of the Cantilever MEM switch (**AB**) is shown in **Fig.1a** which is a thin layer of *polysilicon* of *modulus of elasticity* (E) and *stiffness* (K_m). It is fixed at **A**, free at **B** and suspended at a height g_0μm over the substrate. The physical dimensions of the cantilever are: length (L), width (W), thickness (T).The electrodes attached at the free end are denoted$\{e_1,e_2\}$; their physical dimensions are length (a), width (b) and the thickness is 2 to 3 A^0 respectively.When DC voltage applied between the electrodes e_1 and e_2, the cantilever is bent as shown in the **Fig. 1b** [2][8]. Upon the sufficient actuation of the cantilever in down ward direction, the electrode e_1 makes a contact with e_2.

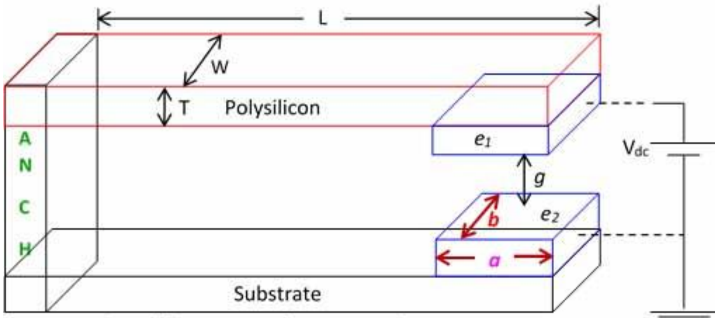

Fig. 1(a) Structure of MEM Switch

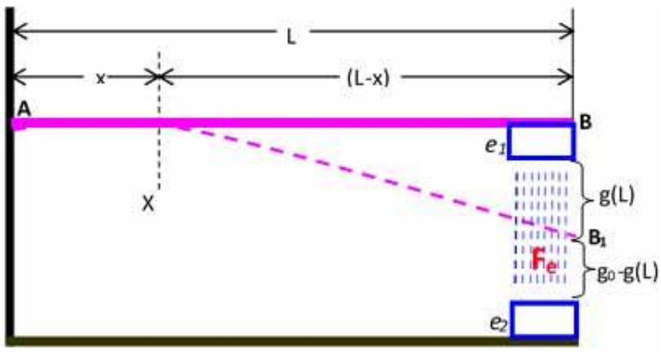

Fig. 1(b) Bending Diagram

Calculation of Performance ParametersV_{th}, t_{on}, t_{off}

A. Threshold Voltage V_{th}

When a step voltage (V_{dc}) is applied between the electrodes e_1 and e_2 of the cantilever, it isbent towards the bottom electrode e_2 (see **Fig.1b)**.The bending of the cantilever (at 'X') is described by means bending moment equation given by Eq. (1)

$$EI\frac{d^2y}{dx^2} = F_e(L-x) \quad \text{Eq.(1)}$$

where'I' is the Moment of Inertia of the cantilever beam, E is Youmg's Modulus.
The Eq. (1) is solved using the following boundary conditions: at **A**, both the deflection and the slope are zero. The solutions of Eq. (1) are given by the Eq. (2) and (3) [15].

$$\frac{dy}{dx} = \frac{F_e}{EI}\left(Lx - \frac{x^2}{2}\right) \quad \text{Eq. (2)}$$

$$y = \frac{F_e}{EI}\left(\frac{Lx^2}{2} - \frac{x^3}{6}\right) \text{Eq. (3)}$$

The Eq's. (2) and (3) are the equations for slope and deflection at any section of the cantilever. The slope and deflection at **B** can be determined by considering $x = L$ in Eqs. (2) and (3). Let the slope and deflection at **B** be i_b and $g(L)$ respectively, then

$$i_b = \frac{F_e L^2}{2EI} \text{Eq.(4)}$$

$$g(L) = \frac{F_e L^3}{3EI} \text{Eq.(5)}$$

The Moment of Inertia of the cantilever beam of rectangular cross-section is given by

$$I = \frac{WT^3}{12} \text{Eq.(6)}$$

where 'W' is the width and 'T' is thickness of the cantilever.
The stiffness (K_m) of this cantilever is characterized by the term called the spring constant and is and is given by [3]

$$K_m = \frac{F_e}{g(L)} \text{Eq.(7)}$$

From Eqs. (5), (6) and (7)

$$K_m = \frac{1}{4} EW\left(\frac{T}{L}\right)^3 \text{Eq. (8)}$$

The two electrodes e_1, e_2 forms a parallel plate capacitor having an overlapping area 'ab' and a spacing of $g_0 - g(L)$. Then the capacitance 'C' between the electrodes is calculated with the Eq. (6)

$$C = \frac{\varepsilon ab}{g_0 - g(L)} \text{Eq. (9)}$$

where $\varepsilon = \varepsilon_0 \varepsilon_r$, ε_0 is permittivity of the vacuum, ε_r is relative dielectric constant of the medium between the two plates.
On the application of the voltage, electric energy 'U' is stored between the electrodes. The electrical energy stored is calculated with the equation (7)

$$U = \frac{1}{2} C V_{dc}^2 \text{Eq. (10)}$$

The magnitude of electrostatic force generated is equal to the gradient of the stored electrical energy with respect to the gap between the plates of a parallel plate capacitor and is given by the Eq. (11) assuming a=b=W [3] [7][16].

$$F_e = \left|\frac{\partial U}{\partial[g_0 - g(L)]}\right| = \frac{\varepsilon ab V_{dc}^2}{2[g_0 - g(L)]^2} \text{Eq. (11)}$$

The force F_e tends to decrease the gap between the electrodes by '$g(L)$' μm, which gives the deflection of the beam. The mechanical restoring force (F_m) developed by the stiffness of the plate (K_m) and is given by Eq. (12)

$F_m = K_m g(L)$Eq. (12)

Under static equilibrium condition, the Mechanical Restoring Force (F_m) and Electrostatic force (F_e) both are equal in magnitude but opposite in direction is given by

$F_e = -F_m$Eq. (13)

i.e,

$\frac{\varepsilon ab V_{dc}^2}{2[g_0 - g(L)]^2} = K_m g(L)$Eq. (14)

From the equation (14) the voltage at which e_1 makes a contact with e_2 is given by

$V_{dc} = \sqrt{\frac{2K_m}{\varepsilon ab} g(L)[g_0 - g(L)]^2}$Eq. (15)

At beyond a threshold voltage the electrostatic force dominates over the mechanical force and the beam is pulled almost instantaneously to words the substrate and contact is made. The voltage V_{th} from which the electrostatic force is greater than the mechanical force can be obtained by differentiating Eq. 15 w.r.t the deflection g and is given by [4][9]

$V_{th} = \sqrt{\frac{8K_m}{27\varepsilon ab} g_0^3}$Eq. (16)

where V_{th} is the equilibrium voltage at this point also called as the 'Threshold Voltage'.

B. On-Time t_{on}

When the voltage applied between the electrodes e_1 and e_2, then the cantilever is deflected towards e_2 by '$g(L)$' μm. The deflection '$g(L)$' of the cantilever from the top (initial position) due tothe force F_e is described by the differential Eq. (17) [6] [7] [10][11]

$m_e \ddot{g}(L,t) + c\dot{g}(L,t) + K_m g(L,t) = F_e$Eq. (17)

From equation (11)$F_e = \frac{\varepsilon ab V_{dc}^2}{2[g_0 - g(L)]^2}$, 'm_e'is the effective mass which is equal to $0.35(LWT)\rho$, 'c' is Viscous damping coefficient.

The Eq. (14) is a one-dimensional non-linear 2nd order differential equation and Finite difference method is used to solve this equation. From Eqs. (11) and (17) we get

$m_e \frac{d^2 g(L,t)}{dt^2} + c\frac{dg(L,t)}{dt} + K_m g(L,t) = \frac{\varepsilon ab V_{dc}^2}{2[g_0 - g(L,t)]^2}$Eq. (18)

Which may be written in the form of difference equation as

$$m_e\left[\frac{g(L,t)_{n+1}-2g(L,t)_n+g(L,t)_{n-1}}{\Delta t^2}\right]+c\left[\frac{g(L,t)_{n+1}-g(L,t)_{n-1}}{\Delta t}\right]$$
$$+K_m g(L,t)_n=\frac{\varepsilon abV_{dc}^2}{2[g_0-g(L,t)_n]^2}$$

Eq. (19)

$m_e[g(L,t)_{n+1}-2g(L,t)_n+g(L,t)_{n-1}]+c[g(L,t)_{n+1}-g(L,t)_{n-1}]\Delta t+K_m g(L,t)_n\Delta t^2=\frac{\varepsilon abV_{dc}^2}{2[g_0-g(L,t)_n]^2}\Delta t^2$ Eq. (20)

$g(L,t)_{n+1}=\frac{g(L,t)_n(2m_e-K_m\Delta t^2)}{m_e+c\Delta t}+\frac{[\varepsilon abV_{dc}^2/2\{g_0-g(L,t)_n\}^2]\Delta t^2}{m_e+c\Delta t}-\frac{g(L,t)_{n-1}(m_e-c\Delta t)}{m_e+c\Delta t}$ Eq. (21)

where 'n' represents the deflection at n^{th} point. The initial conditions are

$$at\Delta\mathrm{t}=0,(i)g(L,t)_{-1}=0\ (ii)g(L,t)=0\ (iii)\dot{g}(L,t)=0\ (iv)\ddot{g}(L,t)=\frac{\varepsilon abV_{dc}^2}{2g_0^2}$$

The solutions of the Eq. (21) gives the time that is needed to reach the equilibrium position of the cantilever for any applied voltage. The switching On-Time is assumed to be the time that is needed for the tip of the cantilever to reach the equilibrium position corresponding to the Threshold Voltage. Hence the On-Time has been calculated using the voltage V_{dc} equal to the threshold voltage given in Eq. (15). The calculations have been carried out using MATLAB software.

C. Off-Time t_{off}

Off-Time is the time needed for the cantilever to reach its initial position from e_2(where the contact is made) when the voltage 'V_{dc}' made to zero, that is, $F_e=0$. This time has been obtained by solving the Eq. (17) for 'F_e' equal to zero. The switching Off-Time is calculated by

$g(L,t)_{n+1}=\frac{g(L,t)_n(2m_e-K_m\Delta t^2)}{m_e+c\Delta t}-\frac{g(L,t)_{n-1}(m_e-c\Delta t)}{m_e+c\Delta t}$ Eq. (22)

The initial conditions are, $(i)F_e=0(ii)at\Delta t=-1$ and $\Delta t=0$ the deflection is $\left(-\frac{1}{3}\right)g_0$. These calculations are made using MATLAB software.

Relational Database

The performance of 2483 MEM switches (Threshold Voltage, Switching On-Time and Off-Time) with dimensions in the range L=20µm to 80µm, W=5µm to 40µm, T=0.1µm to 0.4µm with a gap of 1µm and 1.5µm are calculated using MATLAB software. The structural parameters used for the calculation of device performance are given in the **Table.1.**

Table 1: Parameters of The MEM Triode Switch

Symbol	Quantity	Values or Ranges			
E	Young's Modulus	1GPa $\rightarrow$ 120×10^9 N/m^2			
ϵ_0	Permittivity of air	1 $\rightarrow$ 8.854×10^{-12} F/m			
m_e	Effective mass	1 $\rightarrow$ 0.35(LWT)ρ Kg			
ρ	Density of Polysilicon	1 $\rightarrow$ 2300 Kg/m^3			
L	Ranges of lengths of the beam between anchor and control electrodes (μm)	20-54	45-55	55-65	60-80
W	Ranges of widths of the beam between anchor and control electrodes(μm)	5-17	5-17	25-35	20-40
T	Ranges of thicknesses of the beam between anchor and control electrodes(μm)	0.1	0.1	0.2	0.1-0.4
a	Ranges of lengthsof the control electrodes(μm)	5-17	5-17	25-35	20-40
b	Ranges of widths of the control electrodes(μm)	5-17	5-17	25-35	20-40
g_0	Ranges of gap between the control electrodes(μm)	1	1.5	1.5	1

'*L*', '*W*', '*a*', '*b*' dimensions are incremented by1μm.'*T*' dimensions in last column are incremented by 0.1μm.

For these MEM switches the Threshold Voltage, switching On-Time and Off-Times along with corresponding structural parameters are stored in the tabular form as shown in the **Fig.2**.

ID	SNO	L	W	T	LE	WE	g0	vth	ton	toff
1	1	20µm	5µm	0.1µm	5µm	5µm	1µm	5.01584148035232	2.60E-06	8.00E-07
2	2	20µm	6µm	0.1µm	6µm	6µm	1µm	4.57933864719006	2.60E-06	8.00E-07
3	3	20µm	7µm	0.1µm	7µm	7µm	1µm	4.24008884263517	2.60E-06	8.00E-07
4	4	20µm	8µm	0.1µm	8µm	8µm	1µm	3.96662744857575	2.60E-06	8.00E-07
5	5	20µm	9µm	0.1µm	9µm	9µm	1µm	3.74011536885532	2.60E-06	8.00E-07
6	6	20µm	10µm	0.1µm	10µm	10µm	1µm	3.54849288342677	2.60E-06	8.00E-07
7	7	20µm	11µm	0.1µm	11µm	11µm	1µm	3.38363443701618	2.60E-06	8.00E-07
8	8	20µm	12µm	0.1µm	12µm	12µm	1µm	3.2398387700906	2.60E-06	8.00E-07
9	9	20µm	13µm	0.1µm	13µm	13µm	1µm	3.11297179174753	2.60E-06	8.00E-07
10	10	20µm	14µm	0.1µm	14µm	14µm	1µm	2.99995293277363	2.60E-06	8.00E-07
11	11	20µm	15µm	0.1µm	15µm	15µm	1µm	2.89843332727876	2.60E-06	8.00E-07
12	12	20µm	16µm	0.1µm	16µm	16µm	1µm	2.80658652664149	2.60E-06	8.00E-07
13	13	20µm	17µm	0.1µm	17µm	17µm	1µm	2.7229680148293	2.60E-06	8.00E-07
14	14	21µm	5µm	0.1µm	5µm	5µm	1µm	4.66229015822515	2.80E-06	8.00E-07
15	15	21µm	6µm	0.1µm	6µm	6µm	1µm	4.25659192324869	2.80E-06	8.00E-07
16	16	21µm	7µm	0.1µm	7µm	7µm	1µm	3.94128343847451	2.70E-06	8.00E-07
17	17	21µm	8µm	0.1µm	8µm	8µm	1µm	3.68712058665432	2.70E-06	8.00E-07
18	18	21µm	9µm	0.1µm	9µm	9µm	1µm	3.47659377225156	2.70E-06	8.00E-07
19	19	21µm	10µm	0.1µm	10µm	10µm	1µm	3.29849434605319	2.70E-06	8.00E-07
20	20	21µm	11µm	0.1µm	11µm	11µm	1µm	3.14527018426435	2.70E-06	8.00E-07
21	21	21µm	12µm	0.1µm	12µm	12µm	1µm	3.01162237298592	2.70E-06	8.00E-07
22	22	21µm	13µm	0.1µm	13µm	13µm	1µm	2.893708569729	2.70E-06	8.00E-07
23	23	21µm	14µm	0.1µm	14µm	14µm	1µm	2.78866560523644	2.70E-06	8.00E-07
24	24	21µm	15µm	0.1µm	15µm	15µm	1µm	2.6943103762763	2.70E-06	8.00E-07
25	25	21µm	16µm	0.1µm	16µm	16µm	1µm	2.60894532918867	2.70E-06	8.00E-07
26	26	21µm	17µm	0.1µm	17µm	17µm	1µm	2.53122788940071	2.70E-06	8.00E-07
27	27	22µm	5µm	0.1µm	5µm	5µm	1µm	4.34845129960608	2.90E-06	9.00E-07
28	28	22µm	6µm	0.1µm	6µm	6µm	1µm	3.97009755276979	2.90E-06	9.00E-07
29	29	22µm	7µm	0.1µm	7µm	7µm	1µm	3.67604119181346	2.90E-06	9.00E-07
30	30	22µm	8µm	0.1µm	8µm	8µm	1µm	3.43900918377836	2.80E-06	9.00E-07
31	31	22µm	9µm	0.1µm	9µm	9µm	1µm	3.2426720983005	2.80E-06	9.00E-07

ecord: 16 of 2483 No Filter Search

Figure 2: Print Screen of The Sample Records Stored in MS ACCESS Relational Database. LE, WE- Are Length and Widthsof the Electrodes

It represents a typical table and is created using MS-ACCESS relational data base. The design of a MEM switch is based on the searching of this database for a given set of specifications (i.e. performance of the switch). The searching is effected by the software program written in 'JAVA' language and the data is retrieved from the data base.

Search Method

A search program has been developed and the whole process of arriving at the MEM switches for the given specifications follows the flow chart given in **Fig.3.**

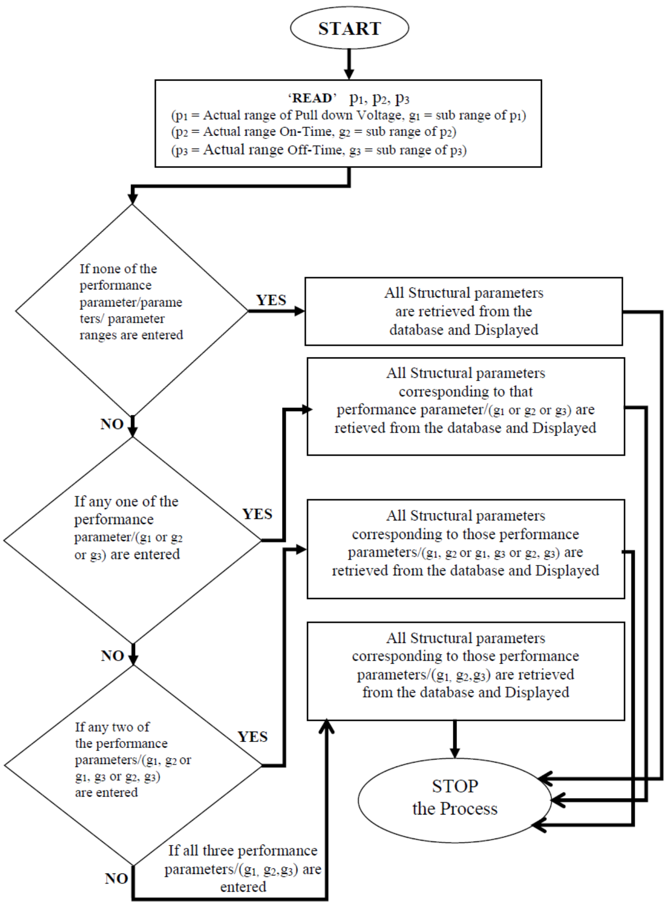

Fig. 3 Flow chart for search process

The performance parameters V_{th}, t_{on}, t_{off}of2483 switches are in the range 0.23v to 5v, 2.6μs to 7.7μs and 0.8 μs to 3μs and these ranges are represented by 'p_1', 'p_2' and 'p_3'. The process starts with searching of MEM switches after entering 'p_1'or 'p_2' or 'p_3' or combination of two or three in sub ranges denoted by 'g_1', 'g_2' and 'g_3'. For example, if the sub range of 'p_1' i.e. 'g_1' is entered, the structural parameters of the switches corresponding to 'g_1' can be searched and retrieved. Thereafter the tool searches the sub range 'g_1' for the devices with performance parameters 'p_2' in the sub range 'g_2'. This resultant group of MEM switches satisfies both 'p_1' and 'p_2'. This process can be repeated with 'p_3'. If the specifications are not within the range of the data base will give an indication that *no records found*. To facilitate the process to be carried out easily a GUI named *Measurement table* has been developed and is shown in **Fig.4a to Fig.5b**. The Measurement table consists of *user panel* and *range panel*. The range panel provides information on available ranges of performance parameters stored in the database**.** Based on this information the designer will be given a prompt to enter the performance parameters in the user panel**.** This process is examined in test cases given in **Fig.4a to Fig.5b**.

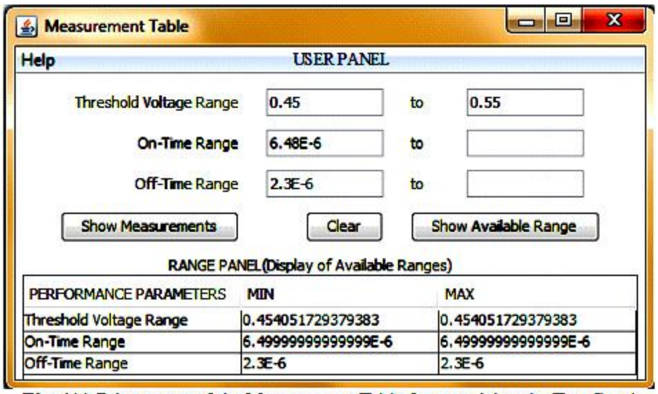

Fig. 4(a) Print screen of the Measurement Table for examining the Test Case1

Fig. 4(b) Print screen of the structural parameters retrieved from the database

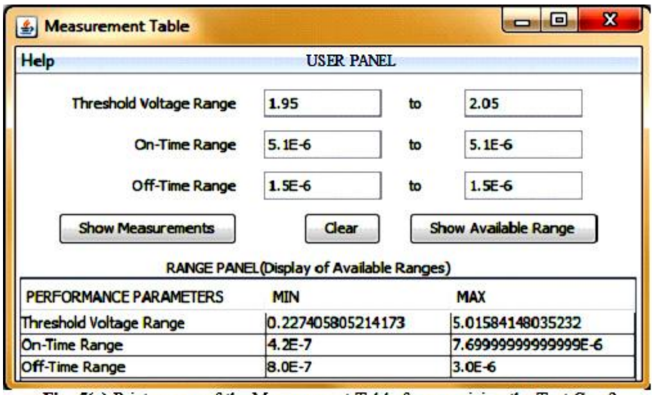

Fig. 5(a) Print screen of the Measurement Table for examining the Test Case2

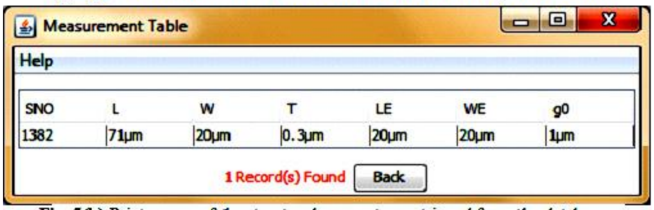

Fig. 5(b) Print screen of the structural parameters retrieved from the database

The Measurement table in **Fig.4a** consists of both user panel and range panel. The Range panel displays available ranges ofperformance parameters of 2483 MEM switches. The User panel displays one set of performance parameters of the range panel enterd in the narrow range. The **Fig.4b** display of the structural parameter valuesretrieved from the database which satisfies the performance parameters enterd in the user panel of **Fig.4a**. The user panel of **Fig.5a** displays the second set of performance parameters of the range panel enterd in the narrow range. The **Fig.5b** displays the structural parameter valuesretrieved from the database which satisfies the performance parameters enterd in in the user panel of **Fig.5a**. If the ranges are to be narrowed based on the MEM switches suggested by the search process/designer one may decide to narrow down the range and repeat the process.

Discussion of Results

A data base for MEM switches has been created which comprises of all MEM switches in the ranges L=20µm to 80µm, W=5µm to40µm, T=0.1µm to0.4µm for g_0 =1µm and 1.5µm. The search program proposed and implemented has been used effectively for carrying out the search of switches with the given performance parameters. Several test cases have been examined and the switches satisfy the given parameters have been obtained through this process. Thus this approach enables to pick the right MEM switch for the given specifications in small time. In other words design of the MEM switches with given specifications is made possible through the search process. Two typical test cases are given in **Fig.4** and **Fig.5**.From these test cases it is clear that MEM switches could be designed reasonably well with this database and search process. It has been found that the design has been completed in few second's which includes start of the search process, entering the specifications and retrieving the structural parameters corresponding to the specifications which are entered. The actual time taken by the computer is of the order of fraction of a second. To the best of our knowledge the fast design approach is not available in the literature.

Conclusion

This paper attempts to develop a design process based on the database of pre-calculated values and a search process. This database of course is restricted to certain ranges of parameters as discussed above and can be extended to the specifications outside these values. The design cycle time of MEM switches is considerably reduced by this process and real time decision making becomes easy and fast.

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