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Design and Simulation of RF MEMS Switch for X-band Applications

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Abstract*: *This article presents the design and simulation of RF microelectromechanical systems (MEMS) switch which works at X-band frequency(8-12 GHz). The design consists of a thin micromechanical bridge suspended over a silicon nitride which is used as the dielectric material with 0.1 µm thickness and air gap of switch is 0.9 µm. The design, modelling and simulation are done using the COMSOL Multiphysics 5.1. The designed switch has low actuation voltage, low pull-in voltage, optimum capacitance ratio, low switching time which makes it a perfect switch to work at X-band frequency. The switch has actuation voltage of 5 V, pull-in voltage of 1.58 V, capacitance ratio 66 and switching timing of 35 µs.

Index Terms*: *capacitance ratio, low actuation voltage, low pull-in voltage, MEMS- Microelectromechinal Systems, RF-Radio Frequency, switching time.

I. INTRODUCTION

In recent years, RF MEMS switches have gained potential in wireless and defense communication systems over a wide range of frequency [1]. The RF switches can be categorized into two types MEMS and semiconductor switches. The main issue while dealing with the semiconductor switch is that it offers poor insertion loss in ON state and poor isolation loss in the OFF state, along with this semiconductor switch has high power consumption, low capacitive ratio and operates at the lower frequency [2]. The RF MEMS can be configured into four types they are electrostatic, thermal, magnetostatic and piezoelectric. The electrostatics offers low switching time, low power loss and small size when compared to other configuration but the problem with electrostatics configuration is that it requires high voltage compared to others and reducing the voltage is the challenge [3]. The RF MEMS switch has low insertion loss, good isolation and negligible power consumption, better linear characteristics, lower cost this is the reason RF MEMS switches have one of the most promising applications in micromachining technology [4][5][6].Debajit De et al. proposed RF MEMS capacitive shunt switch which operates perfectly for microwave frequency band applications. The switch has actuation voltages of 1-10 V depending on the design [7]. M. Qamar ul Hassan et al. had designed RF MEMS shunt capacitive switch with effective use of meanders and dimples and obtained actuation voltage to be 59 V and therefore the main drawback of this experiment is very high actuation voltage [8].

A K Sahu et al. had proposed a method to reduce the actuation between 4 V to 5 V with the down-state capacitance of 3.77 pF, spring constant of 1.451 N/m and low capacitance ratio of 37 [9]. Yuhao Liu et al. proposed RF-MEMS shunt capacitive switch for dielectric charging mitigation, the simulation was done on Ansys HFSS and low ON/OFF capacitance ratio is found to be 22 [10]. K Srinivasa Rao et al. presented a comparison of zig zag and three square meandering techniques for the RF MEMS shunt capacitive switch for K-band applications where Si_3N_4 and HFO_2 is used as dielectric materials for three square meanders, Comparing these meandering techniques three square meander step switch gave better results with capacitance ratio of 120.6, pull down voltage of 1.09V and switching time 10.25 µs [11]. B L Reddy et al. designed a capacitive RF MEMS shunt switch with butterfly structured beam to reduce the actuation voltage with the dielectric layer being aluminium nitride (AlN) and it operated in frequency of 5 GHz to 60 GHz. The switch provides a capacitance ratio maximum of 125 at 3 µm air gap, low actuation voltages in the range of 3-10 V [12]. P.Ashok Kumar et al. proposed series-shunt RF MEMS switch on a single quartz substrate to achieve high isolation than that of individual switches and proposed switch with series and shunt capacitive membranes designed with uniform spring and crab leg structure produces high isolation of around 84.7 dB achieved at 26 GHz, return loss less than -60 dB and insertion loss around - 0.09 dB. The up-state and down-state capacitance is found to be 0.24 pF and 14.2 pF and high pull-in voltage 23.5 V was obtained [13]. Nevidita Sharma et al. proposed four different RF MEMS beam structures such as a square beam, rectangular shaped beam, triangular shaped beam and dual beam. The comparison of four different techniques is done by analyzing displacement and capacitive curves in the time domain using COMSOL Multiphysics, time domain analysis of simulation reveals dual beam bridge structures produces better capacitance and displacement curves with a maximum switching speed of 23.6842 ms and displacement of 0.9 µm with a maximum capacitance of 4.7 pF [14]. Yuhao Liu et al. designed an RF MEMS switch with series protection contact achieving high reliability under high power, hot switching conditions. A 100-150 million cycles at 1 W hot-switching and 50 million cycles at 2 W hot-switching measured, further optimization of structure design and contact materials is likely to further increase the hot-switching lifetime up to 100 times [15]. X Rottenberg et al. proposed RF MEMS capacitive series switch using ohmic relays metal-metal

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contact and separate actuation electrode methods.

The switch produces insertion loss lower than 0.3 dB, higher isolation than 10 dB, operating in a frequency range of 1-10 GHz. The major issue while designing series switches is achieving larger capacitance ratio in range of 100s, very high capacitance ratio obtained was 600 obtained [16]. Ketterl et al. designed a coplanar waveguide (CPW) based single-pole-double-throw (SPDT) X-band RF MEMS switch and high actuation voltage of 35 V was obtained [17]. R. Al-Dahleh et al. proposed a design of RF MEMS capacitive switches which focused on enhancing the performance by a method of introducing the beams into the structure and then analyzing the improvement in down-state capacitance and it was found to be doubled and the up-state capacitance was reduced by half, the simulation was done in HFSS software. The switch's insertion loss is less than -0.1 dB for X-band frequencies. The OFF-to-ON capacitive ratio of 170 is achieved for the dual-warped switch without the use of a thinner dielectric or a high dielectric constant material and high the pull down voltage of 27 V obtained [18].

In our work, we have designed and simulated RF MEMS shunt capacitive switch having features like low actuation voltage, low pull in voltage, optimum capacitance ratio, faster switching action and is operated in 8 GHz to 12 GHz frequency range therefore used for X-band applications.

II. SWITCH DESIGN

The basic structure of shunt capacitive switch is shown in Fig. 1 [19], where tb refers to beam thickness, lb is the length of the beam, g0 is the gap between membrane and signal line dielectric, td is dielectric thickness. The capacitance of OFF-state makes resistive route from transmission line to ground, therefore the transmission of RF
signal after the contact point is stopped as shown in Fig. 2 [20], where Via refers to actuation voltage.

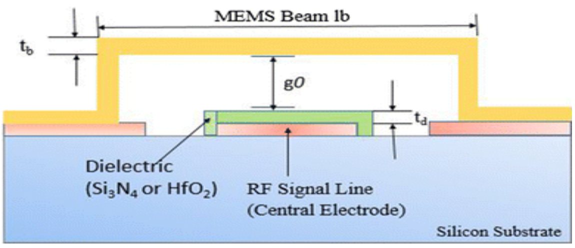

Fig. 1: Basic structure of shunt capacitive switch.

Fig. 2: Shunt capacitive switch in Up-state.

Fig. 3: Shunt capacitive switch in Down-state.

The ON-state switch shown in Fig. 3 [20] is brought from OFF-state to ON-state by applying a DC potential underneath the layer to create an electric field that forms enough electrostatic force to pull down the film on a dielectric, DC voltage is applied between the MEMS bridge and the microwave line. This results in an electrostatic force that causes the MEMS bridge to collapse on the dielectric layer, largely increasing the bridge capacitance by a factor of 30–100. This capacitance connects the T-line to the ground and acts a short circuit at microwave frequencies, resulting in a reflective switch. When the bias voltage is removed, the MEMS switch returns back to its original position due to the restoring spring forces of the bridge.

III. MATHEMATICAL MODELLING

The mathematical modelling is important while designing a switch to analyze the effects of parameters and verify the performance of the switch by calculating theoretical values of a switch. The equivalent T-line circuit diagram of shunt capacitive switch is shown in Fig. 4 [20]. The equation (1) gives shunt impedance of switch.

$$Z_s = R_s + j\omega L + \frac{1}{j\omega C} \quad (1)$$

Where C = Cu is an up-state capacitance or Cd is down-state capacitance depending on the position of the switch, R_s is effective resistance of MEMS bridge, R_{s1} is series resistance due to T-line loss, ω is operating frequency, L is inductance of the circuit, C is the capacitance of the circuit. Depending upon applied voltage, the switch may connect the T-line to the ground, so in the ideal case, shunt switches provide zero insertion loss with zero bias (upstate position) and give infinite isolation when bias is applied(downstate).

The important parameters to be considered while designing RF MEMS shunt capacitive switch are listed in the following subsection [20].

A. *Pull- Down Voltage*

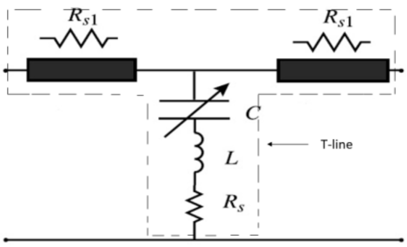

Fig. 4: The circuit of shunt capacitive switch.

The pull-down voltage V_p is very sensitive to dampness, uniformity and other properties of a material is given by equation (2).

$$V_p = \sqrt{\frac{8k\ g_0^3}{27\ \varepsilon_0 A}} \quad (2)$$

Where g_0 is the gap between membrane and signal line dielectric, A is the area of contact, k is spring constant of meanders, ε_0 is permittivity of free space.

B. *Up-State Capacitance*

The Up-state capacitance of the MEMS shunt switch calculated using equation (3).

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$$C_u = \frac{\varepsilon_0 A}{g + \frac{t_d}{\varepsilon_r} + C_f}$$

(3) Where A is capacitance area, g is air gap, t_d is dielectric thickness, ε_r is relative dielectric constant, , ε_0 is permittivity of free space. C_f is fringing capacitance, the up-state fringing capacitance for MEMS shunt capacitive switches is between 0.2 and 0.4Cpp for most switches and the down-state fringing capacitance reduces to less than 0.05Cpp.

C. *Down-State Capacitance*

The down-state capacitance of MEMS switch can be calculated using equation (4).

$$C_d = \frac{\varepsilon_0 \ \varepsilon_r \ A}{t_d} \quad (4)$$

Where A is capacitance area, t_d is dielectric thickness, ε_r is relative dielectric constant, ε_0 is permittivity of free space.

D. *Capacitance Ratio*

Capacitance ratio is the ratio of down-state capacitance to the up-state capacitance is calculated using equation (5).

$$\frac{C_d}{C_u} = \frac{\frac{\varepsilon_0 \ \varepsilon_r \ A}{t_d}}{\frac{\varepsilon_0 \ A}{g + C_f + \frac{t_d}{\varepsilon_r}}} \quad (5)$$

Where A is capacitance area, g is air gap, t_d is dielectric thickness, ε_r is relative dielectric constant, C_f is fringing capacitance, ε_0 is permittivity of free space.

E. *Spring Constant*

The spring constant of a material is an important parameter because it influences pull-in voltage of the switch, it depends on thickness of the beam and is given by equation (6) [20].

$$k = 4Yw * \left(\frac{t}{l}\right)^3 \quad (6)$$

Where Y is Young's Modulus, w is Width of beam, t is the thickness of beam, l is length of the beam.

F. *Switching Time*

The rate at which the switch toggles from one state to the another is given by equation (7).

$$t_s = 3.67 \ \frac{V_p}{V_s \ \ \omega_0} \quad (7)$$

Where V_p is the pull-in voltage, V_s is applied voltage, ω_0 is the resonant frequency of the switch.

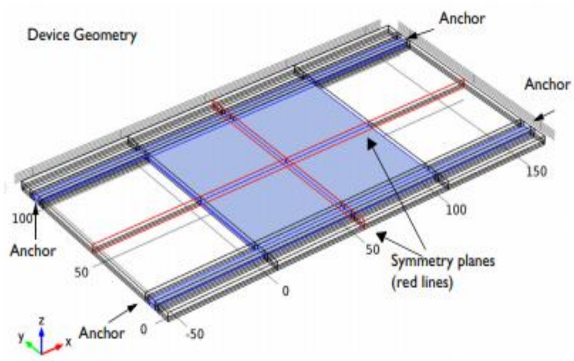

Fig. 5: The structure of switch designed in COMSOL.

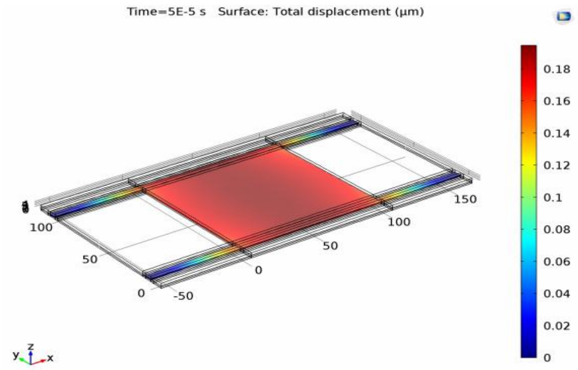

Fig. 6: The RF MEMS switch before simulating.

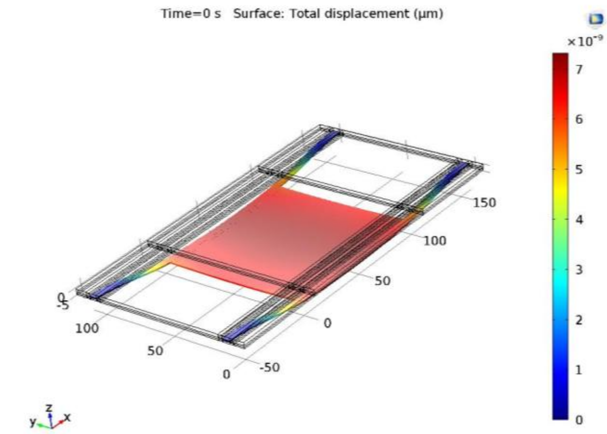

Fig. 7: The RF MEMS switch deformation after simulating.

IV. COMSOL MODELLING

The design of shunt capacitive switch consists of a polysilicon square plate which is suspended 0.9 µm above a thin film of silicon nitride which has a thickness of 0.1 µm with a dielectric constant of 7.5. The plate is anchored to the substrate by four rectangle flexures at its corners but it is electrically isolated from its substrate as shown in Fig. 5.

The voltage of 1 mV is applied to the polysilicon plate, the applied voltage is then increased to the set actuation voltage. The switch remains in off state before applying actuation voltage, this is shown in Fig. 6. The applied potential is greater than required pull-in voltage and switch pulls

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down on to the nitride which is shown in Fig. 7, this results in sudden and significant change in capacitance of the device. The coloured vertical bar in Fig. 7 maps each colour to different displacement distance in the switch and shows the state of the switch when the actuation voltage is applied and the polysilicon layer is pulled onto to the nitride layer and switch goes from OFF state to ON state. To avoid mesh to zero thickness because it violates the mathematical formula designed, the mesh falls into the silicon nitride layer with thickness 0.1 µm as the structure deforms. The mid-point of the smoothed step function is chosen to be above the height of the dielectric layer so that when the polysilicon is in contact with the nitride layer, the dielectric constant in the domain takes the value of the nitride dielectric constant throughout the domain.

V. RESULTS AND DISCUSSION

The RF MEMS shunt capacitive switch was designed and the simulation RF MEMS switch complete analysis was done in COMSOL Multiphysics 5.1. The capacitance and displacement response was obtained for different values of dielectric thickness, air gap and actuation voltage. The following section explains complete analysis with supporting graphs. Fig. 8 and Fig. 9 shows the capacitance and displacement response for parameters in Table I. In Fig. 8 and Fig. 9, each colour indicates a value of a dielectric thickness of the switch. As the thickness of the dielectric is decreased below 0.1 µm, due to non-uniformity of the dielectric the capacitance and displacement response was found to non-linear and if we decrease the dielectric thickness below 0.1 µm results in pinhole problems in dielectric layer. Dielectric layer thickness also decides whether the dielectric layer will be able to withstand the actuation voltage applied without breakdown.

Table I: Input Parameters for variation of dielectric thickness

Parameters	Values
Actuation voltage	5 V
Air gap	0.9 µm
Dielectric material	Silicon nitride

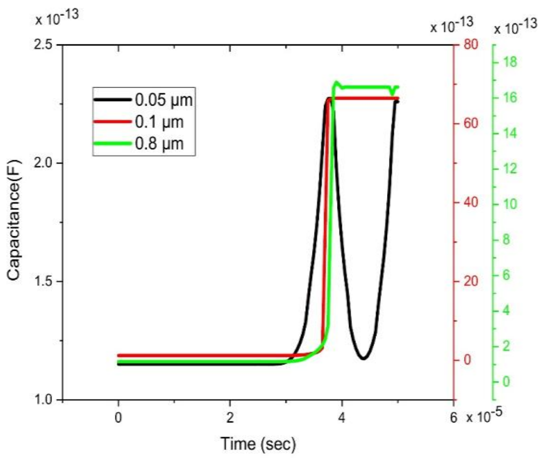

Fig. 8: Capacitance response for variation of dielectric thickness.

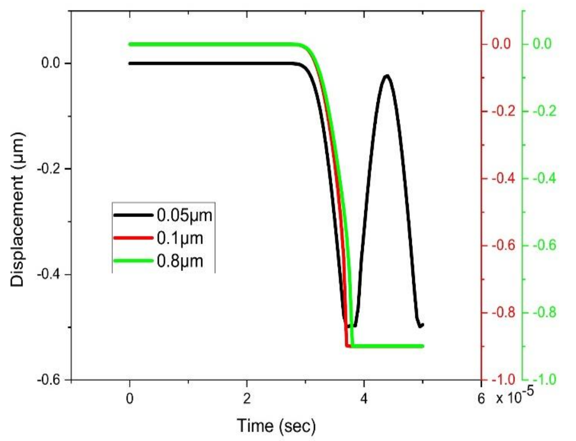

Fig. 9: Displacement response for variation of dielectric thickness.

Table II : Input Parameters for variation of air gap

Parameters	Values
Actuation voltage	5 V
Dielectric thickness	0.1 µm
Dielectric material	Silicon nitride

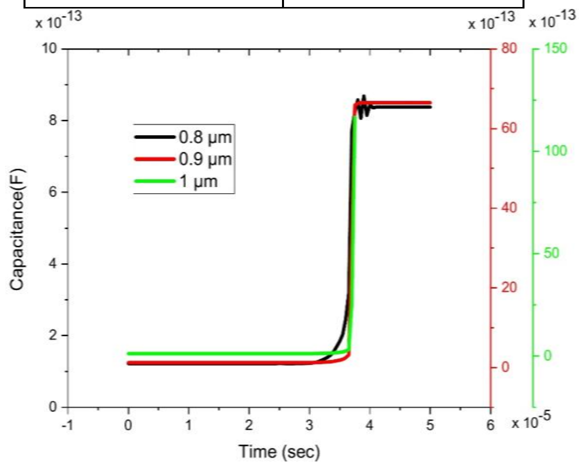

Fig. 10: Capacitance response for variation of air gap.

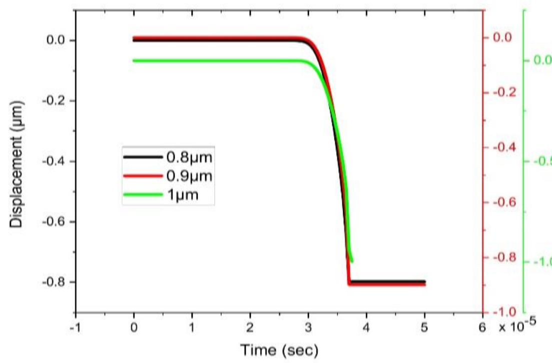

Fig. 11: Displacement response for variation of air gap.

This is the reason the dielectric layer is typically 0.1 µm and 0.15 µm thick in all MEMS switches built. The down-state capacitance may be degraded if the dielectric

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layer is not perfectly flat. It can be deduced that switch gives the best performance for a dielectric thickness of 0.1 µm. Fig. 10 and Fig. 11 shows the capacitance and displacement response for the parameters mentioned in Table II. In Fig. 10 and Fig. 11, each colour indicates a value of air gap of the switch. The low height switches have faster switching action but the tradeoff will be the reduction in the capacitance ratio 20-40 [20], therefore to get the optimum switching time and capacitance ratio the air gap was set at 0.9 µm and deviations from this point results in a deviation from ideal response. It can be deduced that switch gives the best performance for an air gap of 0.9 µm. The capacitance and displacement response of the switch for the parameters in Table III is shown in Fig. 12 and Fig. 13 respectively. The actuation voltage was initially changed from 4 V to 5.5 V in steps of 0.5V, the capacitance and displacement response obtained was plotted for all variations to analyze the behaviour of the switch and it was found that switch gives best results when actuation voltage is 5 V and the response goes linear as the actuation voltage increases.

In Fig. 12 we can see that when actuation voltage has deviated away from 5 V on either side, the response goes non-linear and therefore from this analysis we can conclude that the designed switch gives best results when actuation voltage is set at 5 V. Referring to the capacitance and displacement graphs in Fig. 12 and Fig. 13 we can deduce that capacitance changes more rapidly as compared to displacement because of non-uniformity of dielectric constant in the gap [21].

It remains fairly constant for the first 30 µs and then makes a sudden jump at this point, most of the bridge is in contact with the film and the displacement here is 0.9 µm, so the bridge has fully closed the gap between them. Table IV shows parameters and their optimized values obtained after experimental analysis. The performance of the designed switch is analyzed by comparing practically obtained values in COMSOL with theoretical values obtained from the equations discussed in the earlier section.

Table III: Input Parameters for variation of an actuation voltage

Parameters	Values
Dielectric thickness	0.1 µm
Air gap	0.9 µm
Dielectric material	Silicon nitride

Table IV: Parameters for best performance of the designed switch

Parameters	Values
Actuation voltage	5 V
Dielectric thickness	0.1 µm
Air gap	0.9 µm
Dielectric material	Silicon nitride

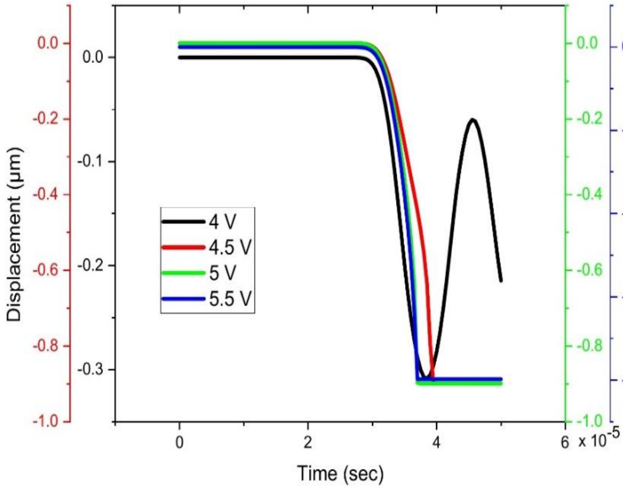

Fig. 12: Displacement comparison graph for various actuation voltage.

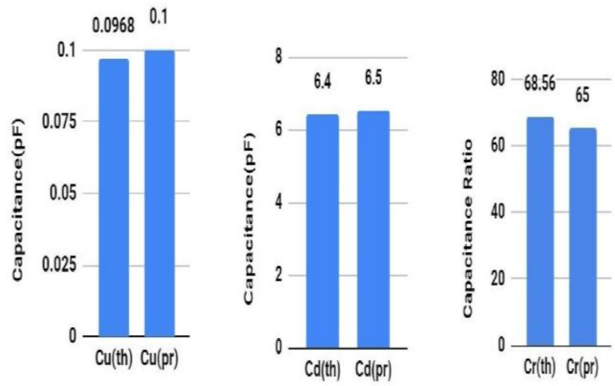

Fig. 13: Theoretical and practical comparison of Up-state capacitance, Down-state capacitance and capacitance ratio.

Table V: Comparison of various other works with our work

Paper Number → **Parameter ↓**	[7]	[8]	[12]	[15]	[17]	[18]	Our work
Frequency range (GHz)	1-40	5-40	1 - 45	0 - 40	0 -10	8-12	8 - 12
Dielectric material	Silicon nitride	Silicon nitride	Aluminium nitride	-	-	Silicon nitride	Silicon nitride
Actuation voltage(V)	1-10	4 -5	5-11	29	35	27	5
Capacitance ratio	-	37	125	-	-	170	66
Air gap(µm)	3.8	2.0	1.0 - 3.0	0.9	-	2.6	0.9
Switching time(µs)	-	-	-	45.10	-	-	35
Pull-in voltage(V)	-	4-5	-	-	-	27	1.58

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