Design of a MEMS relay based on SOI fabrication technology

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Abstract. The deployment of MEMS relay for high power switching applications requires a matrix-like arrangement of many single MEMS relay units. For consistent performance the sameness of the individual switches representing the array is crucial. We present the design, simulation and fabrication of a MEMS relay based on silicon-on-insulator (SOI) technology. The measurement results show high accordance with simulations confirming the predictability and thereby the homogeneity of SOI-based MEMS relays.

1. Introduction
The requirements of an electrical relay are quite clear: to control a high power circuit by an isolated low power circuit. However, both established solutions Electro-Mechanical Relay (EMR) and Solid State Relay (SSR) miss the target. EMR demands for a high actuation voltage, is only capable for low frequency applications due to the slow response time and suffers from comparatively short lifetimes due to the metal-contact wear out. Regarding SSR, the control signal is not electrically isolated. Hence, an opto-coupler unit is needed limiting switching time, size and overall costs. MEMS relay combine the advantages of EMR and SSR: low power consumption, small insertion losses in the closed state, high isolation in the open state, low harmonic distortion, high radiation resistance and wide operating temperature range [1]. However, MEMS relays are to date only applied in low power applications. For high power applications the matrix-like arrangement of single MEMS relay units has to be enlarged. An illustration of the MEMS-matrix and the linear relationship of power and number of switches in series and in parallel are shown in figure 1 (a) [2]. Ensuring constant performance of each single MEMS relay unit over a wide area puts high requirements on accuracy of the fabrication process and ageing behavior. To pave the way for high power applications this paper proposes a MEMS relay operation principle based on SOI fabrication technology.

2. Design and operation principle
The circuit diagram and the physical structure of the SOI-based MEMS relay are schematically shown in figure 1 (b) and (c), respectively. The key element is a movable Si-cantilever with two constrictions and a metallic pad at the bottom end of the beam. The driving electrode is situated between both constrictions, whereas the signal electrodes are positioned beneath the metallic pad of the beam. In the off-state the beam is in a horizontal position. By applying the pull-in voltage to the driving electrode, the beam bends towards the electrode under electrostatic force. In the on-state the metallic pad is in contact with both signal electrodes and closes the signal circuit. In contrast to common operation principles [3, 4] the movable cantilever itself is non-metallic and non-current-carrying. Thus, a key
drawback of alternative MEMS relay designs, creeping of the metal contact, is prevented intrinsically. Besides, due to the characteristic of Si as a single crystalline material, its shape, including width, length and thickness can be fabricated with maximum precision. Though, in the proposed design the closed loop requires two contacts to be closed. Therefore, the constrictions were added with the first right next to the beam’s suspension primary minimizing the stiffness of the cantilever to guarantee for small actuation voltages, whereas the second constriction at the further end minimizes primary the torsional stiffness to ensure good electrical contact.

![Image](327x503 to 525x615)

**Figure 1.** MEMS relay array circuit diagram with corresponding power equation (a). Single channel circuit diagram (b) and schematic physical structure (c) of the presented SOI-based MEMS relay.

3. Analytical model

For small scale devices the fabrication is quite time- and cost- consuming. Therefore, it is favorable to estimate the switching performance before setting up first test devices. In the following, the computational methods to simulate the SOI-based MEMS relay are introduced. The simulated characteristics are presented together with the experimental results in section 5.

The analytical model is based on a spring-mass system with the effective mass $m$ and the spring constant $k$ of the cantilever, the damping factor $b$ and the initial distance of the electrodes $g_0$ [5, 6, 7]. The geometrical parameters and the sectional plane (SP) are indicated in figure 2 (a), the spring-mass model and the used simplified 1D geometry are illustrated in figure 2 (b) in a cross-sectional view (SP-SP). First, the electrostatic force $f(y)$ is approximated by equation (1) with the applied voltage $U$ and the electric field constant $\varepsilon_0$.

In the following, the spring constant is determined by equation (2) with the width ratio between plate and proximal restriction $\kappa$ and the Young’s modulus $E$.

$$m \ddot{y} + b \dot{y} + ky = f(y) = \frac{\varepsilon_0 W (L_1-a) U^2}{2 (g_0-y)^2}$$

$$k = \frac{24 E I \kappa}{3 (L_1-a)(L_1+a)+2\kappa a^2 (a+3L_1)+12 aL_1(L_1-a)(\kappa-1)}, \text{ with } I = \frac{w c h^3}{12}$$

![Image](348x119 to 519x177)

**Figure 2.** Schematic depiction of the SOI-based MEMS relay design: Geometry with the designation of dimensions (a), sectional plane (b) and different design variant types (c).
The presented analytical model is utilized to approximate, among others, the pull-in voltage and the switching time of nine different geometry design variants, schematically illustrated in figure 2 (c). Dependent on the stiffness of the cantilever the performance of the SOI-based MEMS relays differ, although all variants show theoretical response times below 10 µs.

4. Fabrication

The nine design variants shown in figure 2 (c) were fabricated in parallel following a two-wafer process routine with the cantilever being structured using a SOI wafer substrate and the signal circuit being fabricated on a glass wafer. In the final process step, the structured SOI wafer and the structured glass wafer are combined via Au-Si eutectic bonding. The main process steps are shown in figure 3.

Figure 3. Schematic of SOI wafer (A) and glass wafer (B) process flow plus schematic cross-section of the final SOI-based MEMS relay (C).

Figure 3 (A0) depicts the layer sequence of the initial SOI wafer substrate. In the first process step, the substrate is coated with a metal layer via magnetron sputtering to generate the contact pad and the electrical connection metallization between SOI- and glass- conducting layer (A1). The second lithography process creates the etching mask to shape the cantilever by Deep-Reactive-Ion-Etching (DRIE) of the Si-device layer (A2). Afterwards, the cantilever is released from the supporting substrate by backside etching of the Si-handle layer and etching of the buried oxide to generate free-standing cantilevers (A3). To adjust the initial gap height with maximum accuracy a glass wet etch process was developed. The distance, the cantilever has to cover, is set to 1.5 µm with an error of 1.1 % (B1). In the following, the glass-wafer is metallized by physical vapor deposition (PVD) to generate the signal electrodes, the driving electrode and the corresponding connections by a lithography and wet etching routine (B2). As the final process step, the two pre-structured wafers are combined via Au-Si eutectic bonding at 390 °C (C).

Figure 4. SEM micrograph of SOI wafer prior to wafer bonding plus zoomed contact area (a) and optical microscope image of the final SOI-based MEMS relay recorded through the glass wafer (b).
5. Experimental results
The measurements were performed on wafer-level with a four-point-probe measurement setup. The actuation voltage was determined by ramping up the pulsed DC control voltage. By exceeding a certain pull-in voltage, the cantilever bends downward closing the signal circuit. This routine is labelled with \textit{off \rightarrow on} in figure 5. Afterwards the measurement is repeated in the opposite manner, going from the closed state to the open state by reducing the driving voltage. This measurement routine is named \textit{on \rightarrow off}, respectively. To determine the response time, the actuation voltage is increased step-wise from 100\% pull-in voltage to 200\% while measuring the duration between excitation and closed signal circuit. Figure 5 (a) shows the variation of actuation voltage with measurement routine and sample number for one design variant, (b) shows the correlation between actuation voltage and switching time for different MEMS relay design variants. The corresponding theoretical estimations derived from the analytical model introduced in section 2 are included.

![Figure 5](image)

\textbf{Figure 5.} Actuation voltage determined by two different measurement routines (a) and switching time versus actuation voltage normalized to pull-in voltage (b) of different SOI-based MEMS relay design variants as indicated. The corresponding simulated characteristics are included.

6. Conclusions
A SOI-based MEMS relay is presented and analyzed starting with the development of a concept utilizing a non-metal movable cantilever and its analytical expression. The fabricated SOI-based MEMS relay geometry design variants all reveal response times below 10 µs by electrostatic actuation with driving voltages in the order of 50 V at negligible current of few pA. The measurements show high accordance with the analytical model statements, revealing the accuracy and predictability of the fabrication process. The results illustrate that the achievements in SOI processing can be used to enlarge MEMS relay devices in the literal sense by optimizing the homogeneity of the MEMS-matrix and with this, figuratively, extend the MEMS application area to the field of power electronics.

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