CHAPTER 2

LITERATURE REVIEWS

2.1   Overview of the relays

Relay is an electrical switch that capable to convert electrical energy into mechanical work or motion will then be used to switch on and off a circuit. In the original form which was invented by Joseph Henry in 1835, the switch is operated by an electromagnet to open or close one or many sets of contacts [6]. After that, solid state relay was made by using the same analogy with the functions of the original electromagnet device with a thyristor or other solid state switching device. This kind of semiconductor relays provide the desired performance in term of switching speed, but then it presents high power consumption and introduce significant losses, and becoming worse at the higher frequencies.

Since relays also can be categorized as an electrical-mechanical switches [6], which mean that it also possible in controlling more than one set of contacts. Thus, the terminology applied to switches is also applicable to relays based on the same explanation [6]. According to this classification, relays can be of the following types as shown in table 2.0. Beside that, the contact mode of the relay can be Normally Open (NO), Normally Closed (NC), or Change-Over (CO) contacts. Normally-open contacts connect the circuit when the relay is activated; the circuit is disconnected while the relay is inactive, and vice versa for normally-closed contact mode. Change-over contacts control more than one circuits where some of the circuits are normally-open and else in normally-closed contact with common terminal.

Table 2.0: Switch configurations

Type	Schematic Symbol	Possible Contact Mode
Single Pole Single Throw (SPST)		NO or NC
Double Pole Single Throw (DPST)		
Single Pole Double Throw (SPDT)		NO and NC, or CO
Double Pole Double Throw (DPST)		

Generally, the applications of a relay is determined by it signal path where the place or circuit to be switched. For instance, if a transmission line like micro strip, waveguide, or antenna is build with it, then it applications will be in wireless communication. Beside that, relays also found to be used in other fields such as automotive, aerospace industrial, power management, and many more when the signal path of the relay is replaced by other type of transmission line. Then, it will be possible to use as an amplifier, protection relays or used to perform some of the electronics function like logic functions and time delay function [6]. Meaning that relays' applications are almost unlimited wherever switching functions with high off-resistance are needed in electronic or electromechanical component.

2.2 MEMS Technology

In recent years, MEMS micro relays are more preferable than other conventional semiconductor based switching devices, such as field effect transistors, due to low loss, low power consumption, absence of inter-modulation distortion and broad band operation from the DC to microwave frequency range [2] for signal and power switching applications. Furthermore, MEMS is an ideal candidate for micro devices due to several reasons. First, many micro-fabrication technologies have been developed since the invention of transistor by W. Schockley, J. Bardeen, and W. H. Braittain in 1947. These technologies have great precision and they are usually batch processes.

Taking direct advantage of these, MEMS can build devices with great precision, minimum assembly, and with lower cost. MEMS devices are also more easily integrated with other integrated circuits to form a more complete system.

Basically, MEMS microrelay is a kind of miniature relay fabricated by using MEMS micro-fabrication technologies which is possible with maturity of microelectronics technology. Indeed, many engineers and scientists in today's MEMS industry are veterans of the microelectronics industry, as the two technologies do share many common fabrication technologies. However, micro systems involve more different materials than microelectronics. Integrated circuits are primary a two-dimensional structure that is confined to silicon die surface, whereas most micro systems involve complicated geometry in three dimensional.

Microrelays have been fabricated through surface and bulk micro-machining, and its have employed in electrostatic [25, 26], electromagnetic [15, 23] and electro thermal actuation mechanism [1, 8, 18, 24], with monostable or bistable structures in lateral and vertical moving contacts. Beside that, one relay has employed liquid metal movement [7]. Since there are so many type of microrelay had been reported all over the world, microrelay with piezoelectric actuation method is believed to be a newly design among others. It is also one of the reasons, why it was chosen as the research topic in this project.

2.3   Elements of Microrelay

The MEMS microrelay proposed in this project consists of three main elements which is the actuator as mechanical part and another two elements are contactor and signal path to form the electronics part. Each of them is carrying their own functions to ensure the relay to work properly. Since, the core element in MEMS device generally consists of two principal components: a sensing or actuating element and a signal transduction unit [5]. So that, the microrelay build in this project will be operated while an input signal is supplied to the actuator transduction unit terminals, and then the actuator of the device will be pushing the contactor to close the gap between two signal

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lines to form a short circuit and signals will be able to transmit over one signal line to the other. The contactor will return to the normal position after withdrawing of the input signals to actuator terminals. This is the reason, MEMS microrelay can potentially have both advantage of mechanical relay and solid state relay.

2.3.1 Actuator

Mechanical switching of MEMS relays or switches is achievable by various actuation mechanisms including electrostatic, electrothermal, piezoelectric and electromagnetic actuations, but so far only three major types of actuation mechanism have been reported extensively investigated in the past. Piezoelectricity mechanism only found to use in micropump design [9] and other devices except for switching. Table 2.1 as shown below summarized the specifications of the four main mechanism actuation methods:

Table 2.1: Different configurations of MEMS Devices [10]

Actuation Mechanism						
	Voltage (V)	Current (mA)	Power [b] (mW)	Size [c]	Switching Time (µs)	Contact Force (µN)
Electrostatic	20-80[a]	0	0	Small	1-200	50-1000
Thermal	3-5	5-100	0-200	Large	300-10000	500-4000
Magnetostatic	3-5	20-150	0-100	Medium	300-1000	50-200
Piezoelectric	3-20	0	0	Medium	50-500	50-200
Movement						
Vertical	Typical result in small size device					
Lateral	Typical result in large size device					

The driven voltage for electrostatic mechanism marked with [a] can be reduced to 5V using low spring constant designs, but at the expense of stickiness and reliability. Power

is virtually zero with an electrostatic or permanent magnetic field hold. Piezo actuators also present capacitive loads and dissipate virtually no power in static operation [12]. The size also can be made quite small with the use of vertical design. Every mechanism has their different strengths and weaknesses, depending on the application field requirements. Based on table 2.1, electrostatic and piezoelectric actuation modes are the only mechanism where giving high speed in switching time with average contact force and low power consumption. These make electrostatic mechanism is the most used in MEMS actuator designs and then electrostatic actuation microrelays also have been reported in literature in as far as 1979 [2].

Piezoelectricity will be the best choice for application with RF fields especially in signal transmission of telecommunication because the piezoelectric effects are related to electric fields. Meaning that, the piezo actuators do not produce magnetic fields nor are they affected by them. So, piezo devices are especially well suited for applications where magnetic fields cannot be tolerated. Furthermore, the piezoelectric effect continues to operate even at temperatures close to $0˚K$. Beside that, it requires no maintenance and is not subject to wear because they have no moving parts in the classical sense of the term [12].

2.3.1.1 Piezoelectricity actuation

The phenomenon of piezoelectricity was discovered in the late nineteenth century. It was observed that piezoelectric materials generate an electric charge when they are under mechanical stress (direct effect of piezoelectricity) and it also would be able to produce a mechanical deformation or force when an electric field is applied to them (inverse effect of piezoelectricity) [4]. The piezoelectric actuation relies on the deformation of structures caused by the motion of internal charges as a result of an applied electrical field [11]. Basically, the materials used are not naturally occurring piezoelectric materials. Rather, they are synthesized materials and must be electrically poled in order to exhibit significant piezoelectric effects. The external electric fields will exert a force between the centers of positive and negative charges, leading to an elastic strain and changes of dimensions depending on the field polarity. So, piezoelectric

effects are strongly orientation dependent and then the piezoelectric materials needs to be poled in a particular direction to provide a strong piezoelectric effect, although some materials exhibit natural or spontaneous polarization [4].

Since only inverse effect of piezoelectricity will be used to design the mechanical path of the microrelay, it can be similarly described by a matrix form constitutive equation. In this case, the total strain is related to both applied electric field and any mechanical stress, according to this following formula as:

$$s = ST + dE \tag{2.0}$$

where s is the strain vector and S is the compliance matrix or short circuit compliance of transducer [13]. The notation T is representing the mechanical stress, E is the electrical field applied and d denotes the constants of the piezoelectric material. The equation (2.0) can be expanded to full matrix form as below:

$$
\begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \\ s_5 \\ s_6 \end{bmatrix} =
\begin{bmatrix}
S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\
S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\
S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} \\
S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} \\
S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} \\
S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66}
\end{bmatrix}
\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} +
\begin{pmatrix}
d_{11} & d_{21} & d_{31} \\
d_{12} & d_{22} & d_{32} \\
d_{13} & d_{23} & d_{33} \\
d_{14} & d_{24} & d_{34} \\
d_{15} & d_{25} & d_{35} \\
d_{16} & d_{26} & d_{36}
\end{pmatrix}
\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \tag{2.1}
$$

The electromechanical coupling coefficient is another important non-dimensional quantity representing the performance of piezoelectric transducer [13]. This is the ratio of mechanical work available to electrical energy stored in the transducer. The coupling coefficient depends on the type of material, mode of stress and the polarization of the electric field. For linear piezoelectric material, coupling coefficient can be represented as

$$\eta = \frac{d}{S\varepsilon} \tag{2.2}$$

where ε denoted the permittivity of material.

Piezoelectric actuators are often used in conjunction with cantilever or membranes for sensing and actuations purpose. The details analysis of the model with multi layers of materials, at least one of them being a piezoelectric layer will only be described in chapter 3 as the design methodologies. In this chapter, this mechanism will

be described by using some complex formulae taken from a book written by Chang Liu [4]. For a single cantilever as shown in figure 2.0 with two layers, one elastic and one piezoelectric, joined along one side, the beam bends into an arc when the piezoelectric layer is subjected to a longitudinal strain, S_{long}. The radius of curvature can be found by

$$\frac{1}{r} = \frac{2|S_{long}|(t_p + t_e)(A_p E_p A_e E_e)}{4(E_p I_p + E_e I_e)(A_p E_p + A_e E_e) + (A_p E_p A_e E_e)(t_p + t_e)^2} \qquad (2.3)$$

Where A is the cross sectional area of the piezoelectric and the elastic layer; Young's modulus of the piezoelectric layer and elastic layer are denoted as E; t is representing the entire layer thickness and I denoted the cross sectional inertial for a rectangular cross section which is given as equation (2.4) [14]. The value of I is direct proportional vary with the width, w and it thickness, t.

$$I = \frac{wt^3}{12} \qquad (2.4)$$

The vertical displacement at any location (x) of the cantilever can be estimated by the following formula:

$$\delta(x) = r - r.\cos(\phi) \approx \frac{x^2 d_{ij} E(t_p + t_e)(A_p E_p A_e E_e)}{4(E_p I_p + E_e I_e)(A_p E_p + A_e E_e) + (A_p E_p A_e E_e)(t_p + t_e)^2} \qquad (2.5)$$
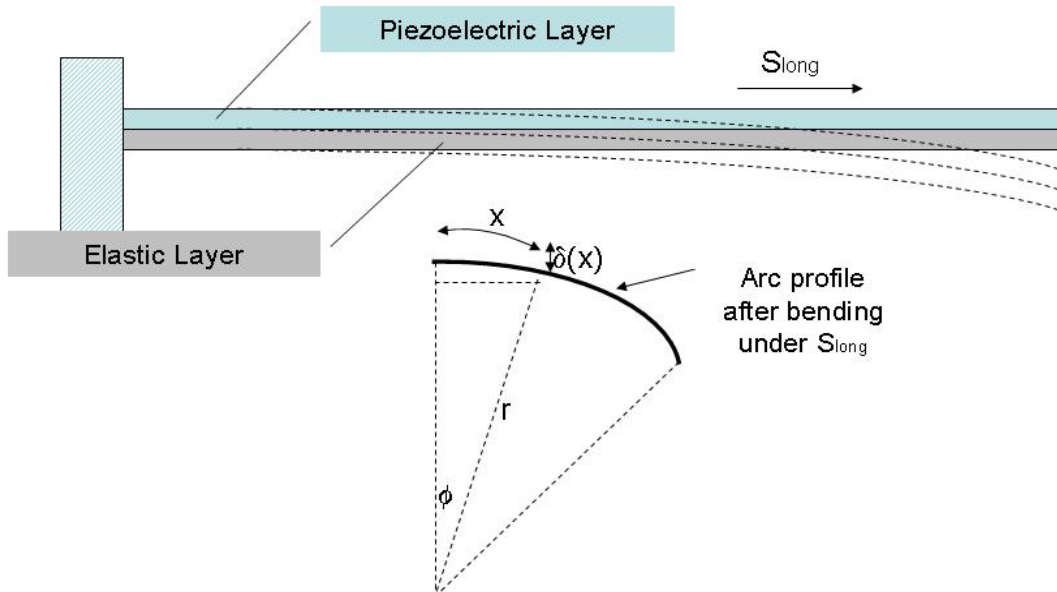
Figure 2.0: Bending of a piezoelectric bimorph

2.3.2   Contact Bar

The function of a contact bar is used to connect two signal lines whenever the actuator of the relay is activated to push or pull down the contact bar to make a close circuit connection between the two lines. The mechanical design must be taken into account to achieve a better relay contact. As shown in figure 2.1, the upper element is the contact crossbar, which can move vertically to the two contacts at the lower position. In order to identify the ideal contact shape, these various contact geometry have been fabricated and tested [8]. The result showed that all of these have worse contact resistance than flat-flat contact.


Figure 2.1: Contact geometry explored [9]

Non flat shapes are hard to have a balanced contact force on each of the two contacts. There are few reasons stated by Jin Qiu in his paper [8]. First, it may be caused by non-flat edges have more variation during the mask making and photolithography steps, so the position errors are larger than flat ones. Second, all of these non-flat shapes have point contact in 2D, while an equal amount of shape variation is more significant for points or sharp corner than for flat edges. Several configurations shown in Figure 2.1 have the contact surface not perpendicular to the crossbar motion. Friction can occur in these cases, which makes the contact positions unpredictable.

2.3.1.1 Contact force and gap

The contact electrode plays a key role in the development of a microrelay and therefore the contact resistances for three typical materials used in relays are studied for different forces and are represented in figure 2.2 [15]. It can be seen that the resistance

decreases as the contact force increases and converges to around 2Ω. The residual value is the sum of the resistance at the contact point and due to the external circuits. The resistance values using silver is found to vary owing to the formation of nonconductive compounds such as AgO on its surface. Based on figure 2.2(b), the contact force needed for stable resistance is the lowest for gold where is less than 100μN. As shown in figure 2.2(b), open contact forces are limited to between 0 and 20μN. Figure 2.3 shows that the voltage between 300 and 350V for a gap between 0.5 and 5μm. When the gap is larger than 5μm the voltage increase rapidly, and over 8μm the voltage is larger than 650V. Meaning that, when the gap is larger than 1μm the breakdown voltage will be greater than 300V and it is high enough for most signal processing devices.
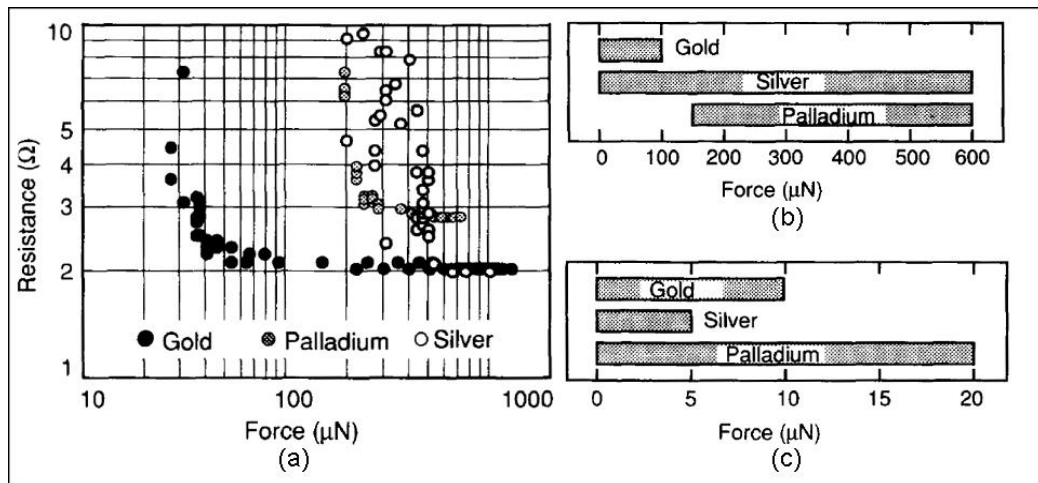
Figure 2.2: Variation of contact resistance with contact force for three common materials [15]. (a) Relationship between on-resistance and contact force. (b) Contact force needed for stable resistance. (c) Contact force needed for completely open contact.
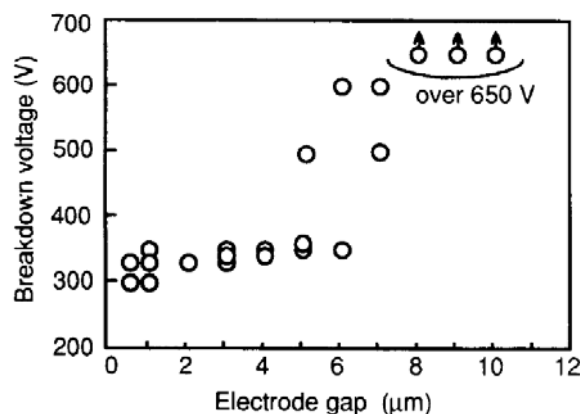
Figure 2.3: Relationship between breakdown voltage and electrode gap [15]

2.3.3 Signal Path

One of the principle requirements of RF MEMS design is to design of a transmission line structure that has to be a circuit element in a microwave integrated circuit (MIC) [13]. The structure, which is a planar configuration, has the property that its characteristic impedance is determined by the dimensions in a single plane.
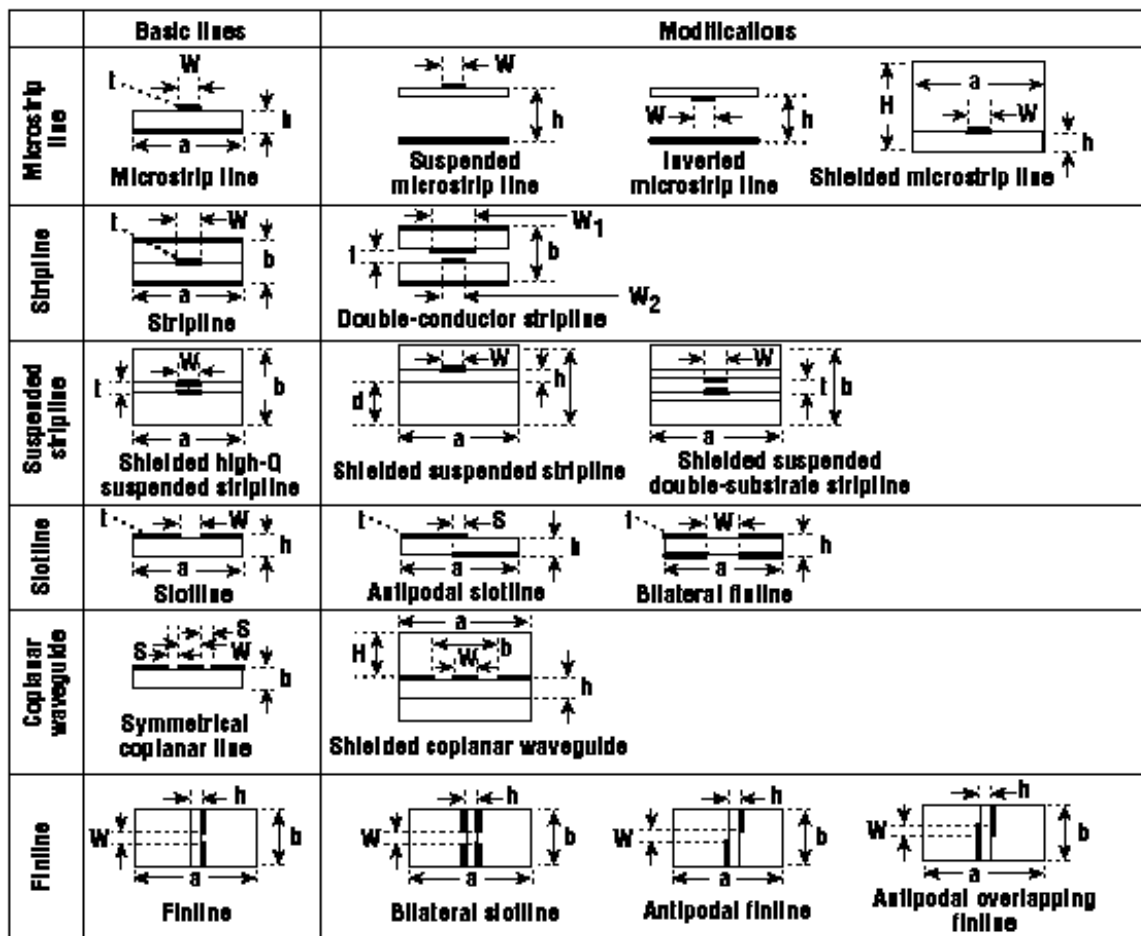

Figure 2.4: Different configurations of planar transmission lines used in MICs [16]

There are a number of different transmission lines generally used for MICs as shown in figure 2.4, where microstrip line still is the most commonly used MICs transmission line. It is because of its advantages such as small size, low cost, no cutoff frequency, ease of active device integration, use of photolithographic method for circuit production, good repeatability and reproducibility. However, each type has its

advantages with respect to others. The different configurations that have been so far discussed are transversally infinite in extent, which deviates from reality. Covering the A shielded microstrip line with housing as shown in some of the configuration in Figure 2.4 are to provide mechanical strength, EM shielding, germetization, and heat sinking in the case of high power applications. A comparison of the various transmission lines types as shown in figure 2.4 was summarized in table 2.2.

Table 2.2: A comparison of various transmission-line types [16]

Transmission Line	Q Factor	Radiation	Dispersion	Impedance Range	Chip Mounting
Microstrip (dielectric) (GaAs, Si)	250 100-150	Low High	Low	20-120	Difficult for shunt, easy for series.
Stripline	400	Low	None	35-250	Poor
Suspended stripline	500	Low	None	40-150	Fair
Slotline	100	Medium	High	60-200	Easy for shunt, difficult for series.
Coplanar waveguide	150	Medium	Low	20-250	Easy for series and shunt
Finline	500	None	Low	10-400	Fair