CHAPTER 1: STATE OF ART

1.1 GENERAL SCOPE ON MEMS

A micro-electro-mechanical system (MEMS) is a technology that allows obtaining components between 1 to 1000 micrometers (usually 20 micrometers). Its small dimension and, at the same time, the low power consumption, has become the most important features so as to develop a new technology for nano-scale components. Moreover, the fabrication procedures are as simple as a Microstrip line procedure. There are different types of MEMS depending on its applications; however, this paper is only focused on RF-MEMS.

RF-MEMS are MEMS which are designed so as to be used in receivers or transmitters. The aim of these components is to act as a switch when they are actuated. The basic structure (Figure 1.1a) is a coplanar waveguide (CPW) with a bridge which is supported by two anchors. Another type of bridge that can be used is a cantilever (Figure 1.1b). A part from that, polarizations pads and RF port are needed so as to act the bridge and guide the RF signal respectively.

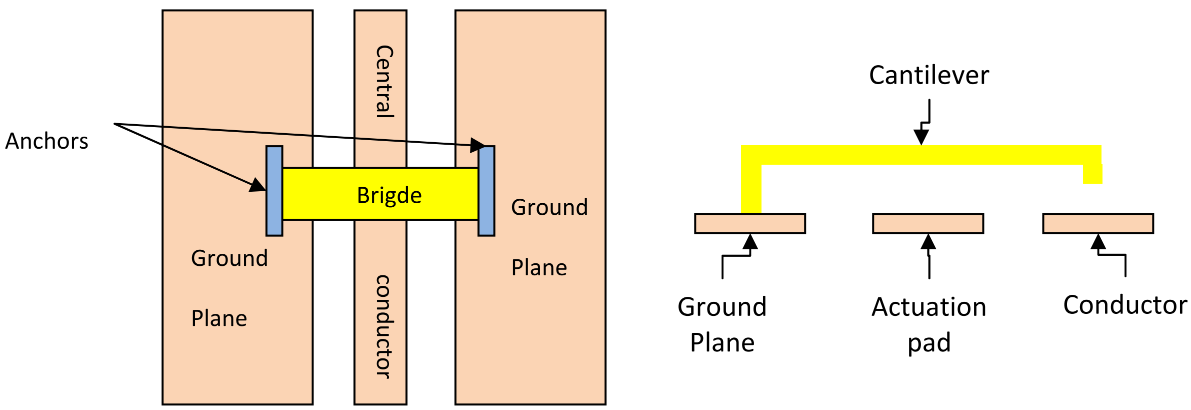

Figure 1.1: a) Schematic of MEMS b) Schematic of MEMS with cantilever cross-section

There are two types of MEMS: Capacitive and Resistive (also called Ohmic or DC-contact). The first one is based on a capacitance between the bridge and the central conductor. When the bridge is not actuated (OFF), the capacitance is very high and the signal injected throw the RF ports passes throw the central conductor. On the other hand, when it is actuated (ON) the central conductor is connected to the ground planes through the bridge and the RF signal does not pass. The second type of MEMS acts on the other way. The central conductor has a small hole in the middle and when the bridge is on the ON position, the central conductor has continuity.

Since all these movements are mechanical, a deep study of the mechanical aspects of the movement of the bridge should be also done. The research on this topic is very wide but is out of the aims of this paper.

The applications of these components are wide and they go from a simple switch to a complex matrix of routing. The possibility of routing the signal is interesting for space applications because satellites can be connected and share information, using a hub satellite, in an efficient way and increasing the throughput. This interconnection is very useful for multimedia services which require a wide bandwidth.

There are different types of switches so as to route the RF signal to different ports but, the most important, from simplest to most complex, are: SPST, SPDT, C-switch, R-switch and T-switch. In this paper, the focusing topic is the routing applications for space satellites using SPDT so below, they will be described.

1.2 TOPOLOGIES OF SWITCH CIRCUITS

1.2.1 SINGLE-POLE SINGLE-THROW (SPST) SWITCH CIRCUITS

Single-Pole Single-throw switches are ideal for time-domain multiplexers systems. They are based on one input and one output and can be either capacitive or resistive. However, for high power applications, resistive switches cannot be used because the metal contact region must handle a large RF current in the down-state position. The configurations used in SPST switches are very simple thus its objective is allow or not allow RF signal passes throw the line.

Despite being simple, some modifications can be done so as to improve the RF specifications. In literature, different kinds of procedures are defined so as to improve aspects like the dielectric charging, the bridge dimensions, tunable components, etc.

For example, in [1] an SPST is designed taking into account the velocity of the movement of the bridge (Figure 1.2). The four beams at the corners of the switch provide an effective spring constant to return the switch to its non energized position when the voltage is removed. The position of the four tabs of the switch, NE, NW, SE, and SW were measured during actuation to determine the response of the spring to the actuation waveform.

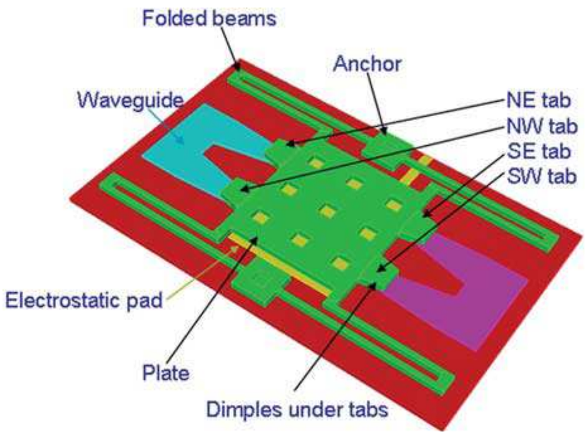

Figure 1.2: Scheme of the SPST of [1]

Initially the bridge is actuated using a pulse that allows starting the movement and after a while no voltage is applied and finally a smaller voltage is applied so as to keep the position. The deceleration occurs during the time that there is no voltage applied. The values of the voltage as well as the duration of the pulses are defined studying the mechanical movement of the bridge. As a result, the actuation time is optimized and the damage of the MEMS produced by the rebound of the bridge is reduced on each actuation.

1.2.2 SINGLE-POLE DOUBLE-THROW (SPDT) SWITCH CIRCUITS

Single-Pole Double-Throw switches are more sophisticated than the previous one. In this case there is one input and two outputs and it requires coordination between the different elements so as to route the signal to the correct port. In fact, the most complex part of the design is to decide the structure that will be used. The literature describes different types of topologies that will be explained below as well as different techniques to optimize the designs.

λ/4 topologies

The relevant range of frequencies is Ku-Band (11-15GHz) where [2] describes an SPDT that provide high isolation and low insertion loss. The design consists of a tee with a MEMS switch at each of the output arms. The switch is placed at a distance of a quarter guided wavelengths from the tee junction (Figure 1.3). When one of the switches is actuated, an open circuit is seen by the input port so the RF signal is routed to the non-actuated switch. It is important to take into account that the response is repeated at odd multiples of the central frequency. This is because of the translation of the RF short into an open at odd multiples of λ/4.

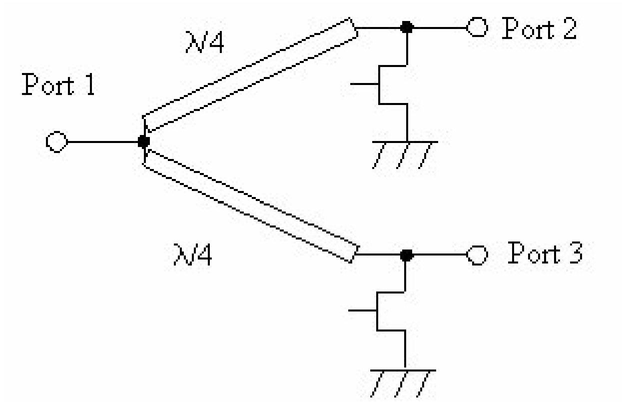

Figure 1.3: Scheme of the SPDT presented in [2]

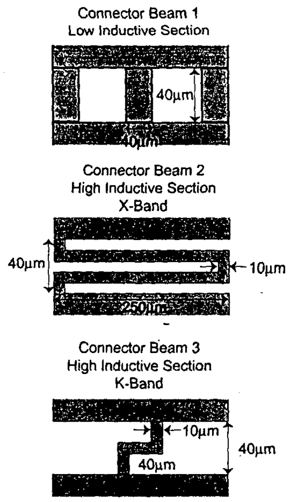

Figure 1.4: Configurations of the connections of the pads

At the same time, [2] uses two different types of connections between actuation pads and center pad (Figure 4). The top one has low inductive properties but the others (meanders) have high inductive properties. With this elements, SPDT circuits have excellent performance at X and K-band [3]. Moreover, it can be extended to higher frequency ranges where the smaller arms of λ/4 allow use this circuit for wireless applications.

Another types of configurations presented in literature follow similar configurations than the one presented before (Figure 1.5). They are more complex so they require more sophisticated methods so as to have good properties in isolation and insertion loss. These other topologies have more switches so the power consumption is bigger.

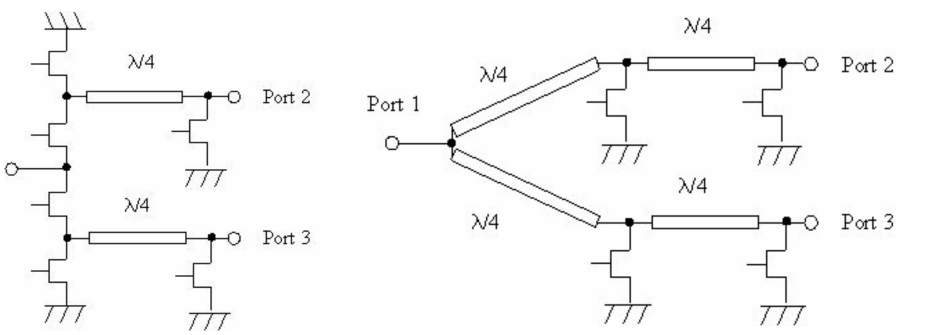

Figure 1.5: Possible configuration of SPDT using λ/4 lines

SPDT with Capacitive and Resistive MEMS

This group concerns about the combination of capacitive and resistive switches. Resistive switches are used not only to give continuity to the line when actuated, but also to provide an open circuit in the tee junction. On the other hand, capacitive switches are used so as to provide higher isolation in upper frequencies.

The design presented in [4] both resistive and capacitive switches are used (Figure 1.6). Moreover, it also uses a tee junction as the design presented before. The air bridges in the tee junction are useful so as to eliminate undesired modes of propagation.

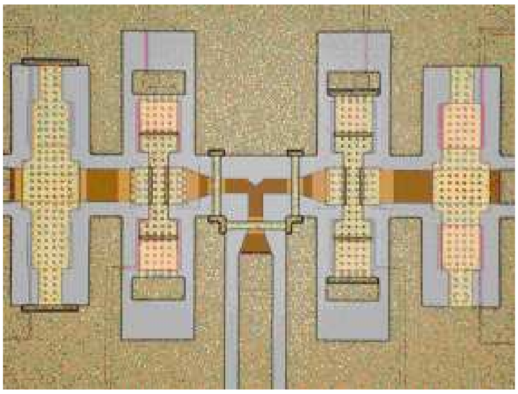

Figure 1.6: Photo of the SPDT of [3]

The resistive switches are as close as possible to the tee so as to provide an open circuit when they are not actuated. In order to improve its ohmic contact, a bridge with lateral contact wings and a bottom electrode consisting of five gold plated bumps is used. On the other hand, when they are actuated, at a voltage of 50V, the bridge enables the signal transmission.

Different types of combinations are possible so as to reach different aims despite having the tee junction topology. Moreover, depending on the design and type of the MEMS used, the capabilities will be also different. A part from MEMS, other types of passive circuits can be added (filters, transmission lines, stubs, etc.)

For example, in [5] the objective is to decrease the actuation voltage using piezoMEMS (Figure 1.7) made of lead zirconate titanate (PZT). PiezoMEMS are devices that external forces applied to single crystals of quartz and several other minerals generate a charge on the surface of these crystals. The charge is roughly proportional to the applied mechanical stress.

These switches have been measured to have low actuation voltage with great RF characteristics from DC to 65 GHz. At the same time, the design incorporates a filter that provides insertion loss, percent bandwidth, and rejection performance similar to off-chip crystal filters and surface acoustic wave devices.

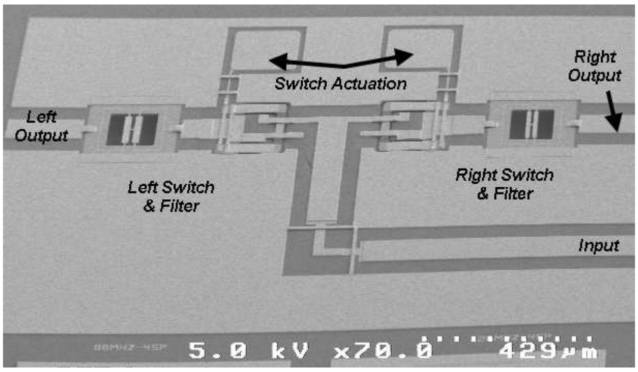

Figure 1.7: PZT MEMS switch with its filters

The switch in Figure 1.7 is actuated at 7 Volts and it presents a flat S21 response of -60dB. This unusual S21 value is still under investigation but it is thought it is due to current shunting around the open switch effectively reducing its isolation. The isolation in this case is better than -40dB and the insertion losses are about -0.4dB from DC to 500MHz. These results and an actuation voltage lower than 10V, show that piezoMEMS are interesting for spatial applications since they do not need a high voltage actuation providing but, at the same time, the design should be adapted to higher frequencies.

Another example is [6] whose topology is radically different from the ones presented before. In this case, with a low voltage actuation (12V) the designed membrane can reach four different positions, each of these positions has its function as can be seen in Figure 1.8. With this configuration it is possible to control the movement of the membrane acting only the desired parts.

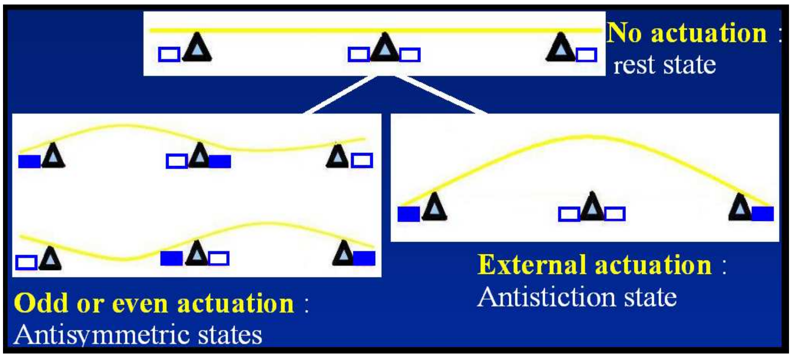

Figure 1.8: Illustration of the four states of the structure. Triangles stand for pillars and rectangles for electrodes. The filled rectangles correspond to the actuated ones.

The free flexible membrane has an antisiction system which avoids one of the most important types of failures of MEMS: stiction failure. It is done with an active electrostatic restoring force that avoids high adhesion contact between metals.

Using this type of MEMS, the SPDT is designed as can be seen in Figure 9. The ground planes are connected to a radial stub which creates an RF ground instead of having a pad for the ground reference. The design not only have the topology presented in the previous point (using λ/4 lines), but also works in the same way (the actuated part do not let the signal pass).

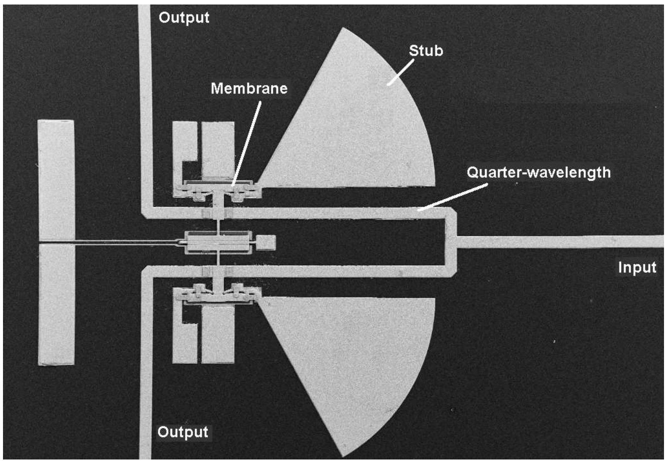

Figure 1.9: View of the SPDT in [6]

As a result, the return loss is below -20dB between 17GHz and 30GHz so there is a wide band operation and the isolation is greater than 40dB at 20GHz. This demonstrates that the design works in a wide band and, at the same time, is suitable for the K-Band.

Since now, all the presented MEMS have its bridge anchored and the applied voltage is used so as to deform the membrane till the desired place. Another type of MEMS is also possible and provides lower actuation voltage (5V approx.) because the electrostatic force needs to overcome only the weight of the movable part.

The anchorless bridge is presented in [7] and it is a movable contact pad which is never deformed by elastic forces. The glass acts as a support of the bridge in off-state and, on the other hand, in on-state, the bridge is moved so as to connect the contact pads with the CPW as can be seen in Figure 1.10. The most important part of this design is the glass situated under the bridge which is called housing glass.

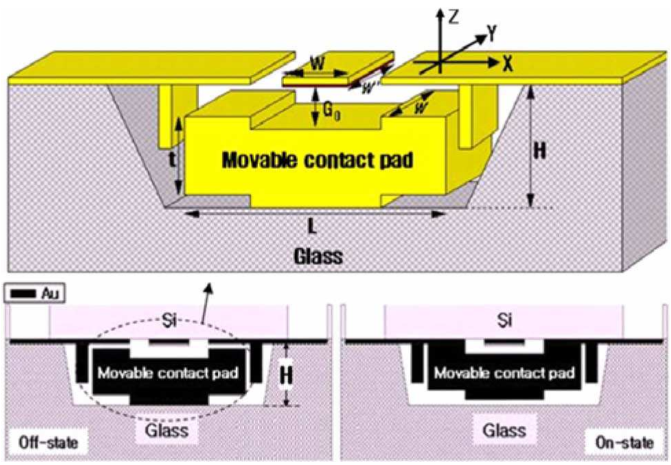

Figure 1.10: Schematic of the anchorless MEMS

Another critical part of the design is the spacing between the movable part and the pull-up electrode. If the spacing is small, the actuation voltage is also small but, at the same time, the isolation is small,

This design is though so as to have high reliability because the contact area is big (100umx100um). After 200 billion cycles the actuation voltage is kept constant and isolation and insertion loss have acceptable values.

Despite all the advantages of the anchorless contact, there is one disadvantage. The problem is that a displacement of the movable contact of more than 28° makes the actuation voltage increases because the pad is obstructed by friction between movable contact and the guard poles. This disadvantage is critical in space applications because during the launch, the payload suffer vibrations that could move the contact pad as will be seen in following parts.

SPDT with MEMS using cantilevers

In 2006 Teravicta Technologies developed TT712 which uses a cantilever. This type of MEMS presents high performance and high reliability despite being fabricated with metal deposition processes. In Figure 1.11, it is that this chip has a circular bridge which is called Hard Force Disk Actuator (patent) [8]. This actuator has three contact zones which assure that the force on the active electrical contact is highly uniform and repeatable. This results in a very low loss, highly repeatable contact configuration.

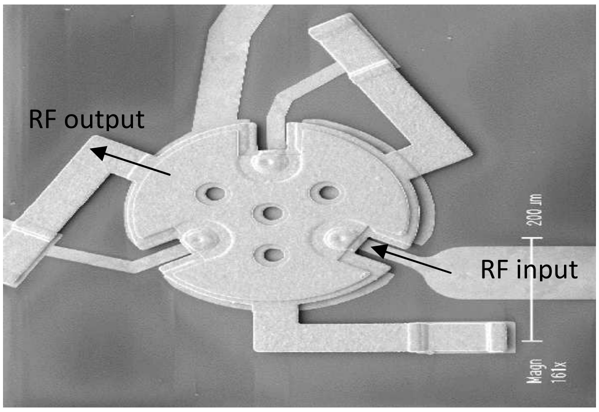

Figure 1.11: Hard Force Disk Actuator

The large restoring force of this design is required to provide reliable (stiction free) operation. Although this results in a relatively high switch voltage (68V), low voltage operation (3 - 5V) can be achieved through the use of a charge pump IC (TT6820QFN) that is capable of driving up to three independent banks of RF MEMS switches.

Using a structure with Y-junction and two HFDA’s, an SPDT is designed providing good properties from DC to 7GHz [9]. However, it is possible to improve the range of frequencies until 26.5GHz by changing packaging as proposed in [10].

1.3 RELIABILITY IN SPACE APPLICATIONS

The combination of low mass, low power consumption, small volume and possible integration with control and sense electronics makes MEMS technology suitable for space applications. However, the reliability in this field is more complex than on Earth because the environmental conditions are extremely variable. It is important to consider the type of conditions that the MEMS should afford so as to design the device according to them.

1.3.1 FAILURE MODES

Failure modes depend on the materials used for the device, the fabrication approach, the packaging and finally the design. There are two types of failure modes of MEMS [7]:

- Mechanical: Until now, the most studied one and based on the intuitive assumption that it must be the moving parts that lead to failures. The types of failures are: stiction and wear, fatigue, plastic deformation, delamination, curvature change and shock and vibration induced fracture.
- Electrical: they dominate because the thin films have been optimized for mechanical properties at the expensed of electrical ones. The types are: short and open circuits, arcing across small gaps, electrostatic discharge (ESD), dielectric charging and corrosion.

The material whose characteristics have been studied more extensively is Silicon. In particular, it is know how to make Silicon suspension beams that exhibit no fatigue and no plastic deformation. The way is to ensure that there is no metal in the silicon, for the plastic deformation, and to operate in a dry ambient, for the fatigue.

In space missions, normally, are considered radiation, vacuum, thermal shock and vibration. However, other factors could be considered like atomic oxygen or plasmas.

Radiation effects

Silicon and metal mechanical properties are mostly unchanged during the space mission and, at the same time, silicon is intrinsically radiation hard so the MEMS are also resistant to radiation. However, electronics control should be shielded because radiation typically causes latch-up or single event upsets.

One of the typical failures is due to trapped charge in dielectric films. This charge makes decrease the sensitivity of the device so the actuation voltage increases. The solution proposed by [8] consists on eliminate part of the dielectric so as to not trap the charges. Jet Propulsion Laboratory (California Institute of Technology) developed RF switches that showed no change in operation at doses up to 150kRad but the dose was reduced to 10kRad for a different design.

Vacuum conditions

In space, devices operate in high vacuum but there are two reasons why it occurs. These reasons are that the device is not well-packed and that the device absorbs/generates more than few mW of heat. None of them are probable because MEMS do not dissipate more than few microwatts and package techniques and tests are reliable.

The important issue is the package of the device. Some experts opine that all MEMS should be packaged despite not being exposed to extreme conditions. A hermetic package with welded or soldered seals can guarantee that the device will operate under a well defined atmosphere for times in excess of 20 years. Moreover, it prevents the MEMS from possible issue of outgassing, mass loss and contamination.

Thermal variations

The range of temperatures in a space mission is very large. Normally, in a LEO orbit the range goes from -80°C to +100°C but in other types of missions the range could become bigger. These variations can lead to failure of the die bond and to delamination of the layers. Moreover, the curvature of free-standings surfaces consisting of more than one material could be also affected.

One solution is to use monolithic process so all the materials have the same Coefficient of Thermal Expansion (CTE) but this is technologically difficult. Again, the package of the MEMS plays an important role so as to isolate the device from external agents.

Vibrations and Mechanical shock

During the launch the payload suffer from vibrations of the movement of the engines. The amount of vibration depends on the launcher but, as a model, it can be considered a sine whose frequency is between 5Hz and 10Hz and whose amplitude is between 3 and 20G.

However, MEMS are not very affected for these forces because they are not heavy. The forces that act over the MEMS follow the Newton's second law (F=m*a) but the mass of the MEMS is so small that the resulting forces are a few mN. Of course, if the design is not accurately the failures appear before, so, it is important to avoid stress concentration on sharp corners.

1.3.2 METHODS OF INCREASING RELIABILITY

The most common problem in MEMS is adhesion of the surface-micromachined mechanism to the surface (stiction). This can occur during the fabrication of the MEMS or afterwards due to the dielectric charging [12]. There are different methods to avoid it:

- Make mechanisms stiff in vertical position
- Use large cutouts in gears and other structures
- Minimize the overlapping surface area between flat parts.

Apart from the problem of the stiction, designers should take into account the technology that is going to be used. This means that the fabrication processes and the packaging will influence in the final result. For example, if the process has lots of conductive particles, the design cannot employ electrostatic comb drives (particles can be lodged between the comb fingers and short them together).

Regarding to the package, it is important to realize if the package is designed for a surface-micromachined mechanism. The aim of the package is to protect the device from particles, humidity and handling but, it can generate problems such as outgassing of water vapor from the die-attach adhesive.

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