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# Liquid Encapsulation Technology for Microelectromechanical Systems

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## 1. Introduction

Microelectromechanical systems (MEMS) have been extensively studied for over three decades, which has resulted in the prevalence of quite a few commercially available MEMS products in our daily lives, although they are too small to see. In the very beginning of the MEMS success story, people recognized the importance of packaging [1]. MEMS contain mechanical parts, and given their small sizes, they are severely affected by surrounding molecules. Therefore, MEMS are packaged under vacuum, at low pressure, or at least free from water molecules. Water molecules can bridge two separated parts and bring them into contact by the meniscus force, which may lead to permanent adhesion of the parts, known as stiction. This phenomenon must be averted, not only in the packaging, but also in the fabrication of parts. It is not an overstatement to say that researchers go to great lengths to keep their devices dry.

On the other hand, as MEMS technologies advance, a wide variety of applications are expected, some of which the MEMS must handle liquids. For example, drug delivery systems (DDS) that administer medicine to diseased parts at designated times can employ MEMS that are sufficiently small to be implanted and are capable of controlling discharge of the medicine [2-5]. In this application, the MEMS must contain medicine, which is in liquid form in many cases. In addition, MEMS can be used as a portable power source, referred to as power MEMS. Micro gas turbines and certain fuel cells require liquid fuel to generate chemical reactions [6-9]. Micro total analysis systems, or microTAS, are used to manipulate minute aqueous analytes and/or control microfluids to handle samples, such as cells and bacteria, for biochemical analysis [10-14].

Such useful characteristics of liquids are available to expand the design space for innovative MEMS devices. Functional liquids, such as magnetorheological fluid and electroconju-

gate liquids, can be used as micro pumps and actuators [15-16]. Other useful characteristics of liquids include deformability, incompressibility, and high dielectric constant. Hydraulic amplification can be achieved by exploiting the deformability and incompressibility of liquids [17-22]. In addition, highly dielectric liquids can enhance sensor sensitivity while maintaining flexibility [23].

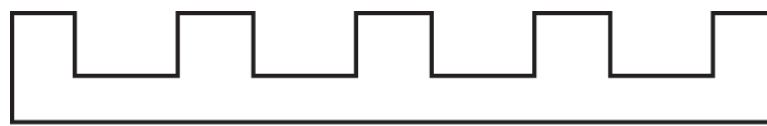
While some applications allow such MEMS devices to bring the liquid from outside, encapsulation of liquid inside MEMS devices is mandatory in other applications. Liquid encapsulation technology can be used to manufacture innovative MEMS devices, such as completely spherical microlenses and hydraulic amplification mechanisms. Various liquid encapsulation technologies have been proposed to achieve these promising applications. The liquid species to be encapsulated and the application must be taken into consideration for the selection of appropriate encapsulation processes. This chapter reviews state-of-the-art liquid encapsulation technologies and their application to the manufacture of innovative MEMS devices that exploit the useful characteristics of the encapsulated liquids.

## 2. Fill and seal technique

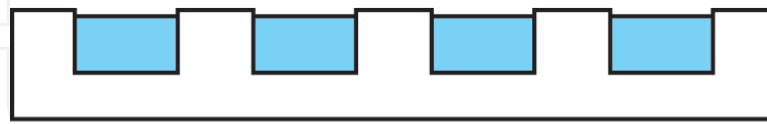
The most straight-forward technique to encapsulate liquids is to dispense liquid into a reservoir and then seal it with another substrate, as shown in Figure 1. The reservoirs can be easily manufactured using conventional MEMS fabrication technologies. Currently, commercially available dispensers are capable of dispensing a minute amount of liquid, as small as several nanoliters. Sealing, or bonding the substrates, is the most critical process.

In the MEMS field, bonding technologies have been widely explored for packaging and manufacturing three-dimensional structures [24-27]. The direct bonding of silicon wafers, anodic bonding of glass substrates, and thermocompression bonding using a metal thin film as an adhesive layer are examples of frequently used technologies. These technologies achieve strong bonding of substrates via covalent bonds; however, these processes have drawbacks when applied to the sealing of a liquid filled reservoirs if they require high temperatures. High temperature processes in the order of several hundreds degrees Celsius may change the properties of the liquid to be encapsulated. For example, in drug delivery systems, it is necessary to maintain the medicinal effect of the encapsulated drug. Fuels for power MEMS applications should not be burnt before the device is completed. In addition, some liquids are volatile, which precludes not only high-temperature, but also vacuum processes.

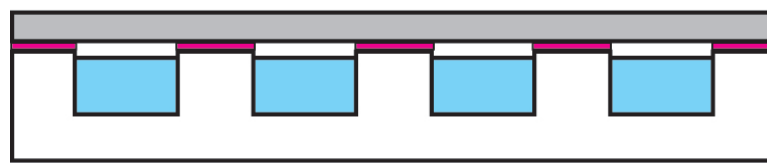
Therefore, in this fill and seal approach, adhesive bonding shown in Figure 1 is the most appropriate technique. The adhesives employed include epoxy, UV curable resin including photoresist, and benzocyclobutene (BCB). Such adhesives solidify after either mixing with curing agents, exposure to UV irradiation, or thermal treatment at low temperatures. Either one-part or two-part epoxy resins can be used, because they do not require high temperature to promote solidification. The chemical reaction progresses with time, even at room temperature, and after solidification, the epoxy achieves strong bonds and is resistant to many chemicals.



(i) Microfabricate cavities.



(ii) Fill the cavities with liquids.



(iii) Seal the cavities via adhesives.

**Figure 1.** Fill and seal approach.

While epoxy is a common adhesive, it is not compatible with conventional MEMS fabrication technology. To achieve reliable and reproducible bonding, the adhesives are preferably spin-coated, which allows the thickness to be controlled according to the spinning speed. In this regard, photoresist is a good candidate. Photoresists are compatible with MEMS fabrication technologies and can be spin-coated, and more importantly, knowledge of their use is well developed. Photoresist is coated on a substrate and then brought into contact with the pairing substrate either before or after the curing processes. A typical curing temperature is around 100 °C. When the contact is performed after curing, the bonding is achieved by a hot melt process at higher temperatures, although lower than 200 °C. Photoresist can be patterned using conventional photolithography to determine the bonding areas. The major drawback of using photoresists as adhesives is the weakness of the bond strength, i.e., they are not designed to function as adhesives. Adhesion between the photoresist and the substrates, as well as the mechanical strength of the photoresist, is designed to be sufficiently strong to survive photolithography processes. Therefore, the bonding may fail due to external forces, either at the interface or within the bulk.

BCB is a promising polymer adhesive that is photo-patternable and compatible with conventional photolithography processes. It can be spin-coated to thicknesses of 5-15  $\mu\text{m}$  at spinning speeds of 1000-6000 rpm [28]. BCB has good chemical resistance, and the most significant advantage of this material is that it does not release any gases during the cure, which does not create pores in the material or contaminate the encapsulated liquid. BCB can be used to bond two substrates by thermocompression bonding. Compression at 230 °C has been attempted, which may limit the species of liquid to be encapsulated. However, BCB has been applied to

seal sodium hypochlorite aqueous solution (NaOCl) for galvanic cells [28]. The paper discusses the BCB thickness and the bond quality determined by the geometry of the bonding areas.

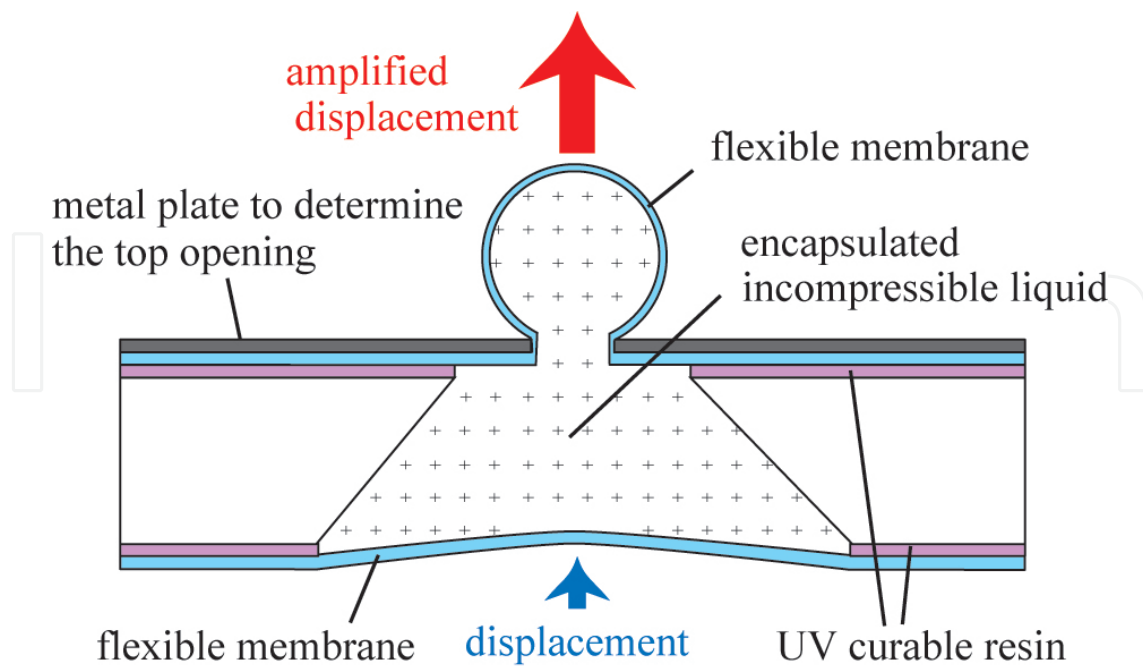
UV curable resins do not require heat treatment, but only UV irradiation. If the MEMS devices are not UV sensitive and one substrate is transparent to UV light, then UV curable resin offers a strong bond after solidification with UV irradiation. Such bonding can even be conducted in liquids [21,22,29] and we have termed this the bonding-in-liquid technique (BiLT).

We have introduced sealing processes that employ polymer adhesives. However, the gas permeable nature of polymers may cause problems of contamination and vaporization of volatile liquids. For example, polydimethyl siloxane (PDMS), which is one of the most frequently used polymers in the fields of MEMS and microTAS, is permeable to gas. However, this permeability can be modified by the addition of different materials [30] or coating with airtight films [31]. Typical polymers are several orders of magnitude more permeable to gas than metals and ceramics [27]. Therefore, sealing with gold stud bumps has been proposed [32], where reservoirs are filled up with the liquids via microchannels and the inlets and outlets of the channels are then plugged with wire-bonding gold. Firstly, a gold ball is formed at the edge of the gold wire by electrical discharge. The ball is then pressed to the opening of the channel using ultrasound. The wire is then cut and the sealing is completed. Helium leak tests were conducted and hermetic sealing was verified using this technique when the hole diameters were less than 40  $\mu\text{m}$ .

The inevitable drawback of the fill and seal approach is the filling rate; it is quite difficult to completely fill a reservoir with a liquid. This is acceptable for some applications, such as drug delivery and fuel supply for power MEMS devices. However, the performance of hydraulic displacement amplification mechanisms (HDAM) is deteriorated by the interfusion of compressible air. When liquids are used as components of sensors, contamination of gas or other liquids will lead to a loss of sensitivity. Therefore, liquid encapsulation techniques that enable complete filling of liquids are mandatory. The author's group developed BiLT, which is a fill and seal approach that enable complete filling [21,22,29].

### 3. Bonding-in-Liquid Technique (BiLT)

HDAMs require complete filling of the reservoir with an incompressible liquid, because gas is much more compressible than liquid. Figure 2 shows a package chamber that has openings at the top and bottom, where incompressible liquid is encapsulated with flexible polymer membranes. The top opening, which is determined by a metal plate, is smaller than the bottom opening; therefore, a small displacement applied to the bottom membrane is amplified at the top, according to the ratio of the openings. The application of HDAM is discussed in section 5.2. The key points in the fabrication of HDAMs are no interfusion of air bubbles and sealing with flexible polymer membranes. Complete filling can be achieved by the direct deposition of a thin film, which is detailed in the following section; however, this technique does not allow the use of flexible membranes. We have developed BiLT [29], which can be employed to overcome this problem.

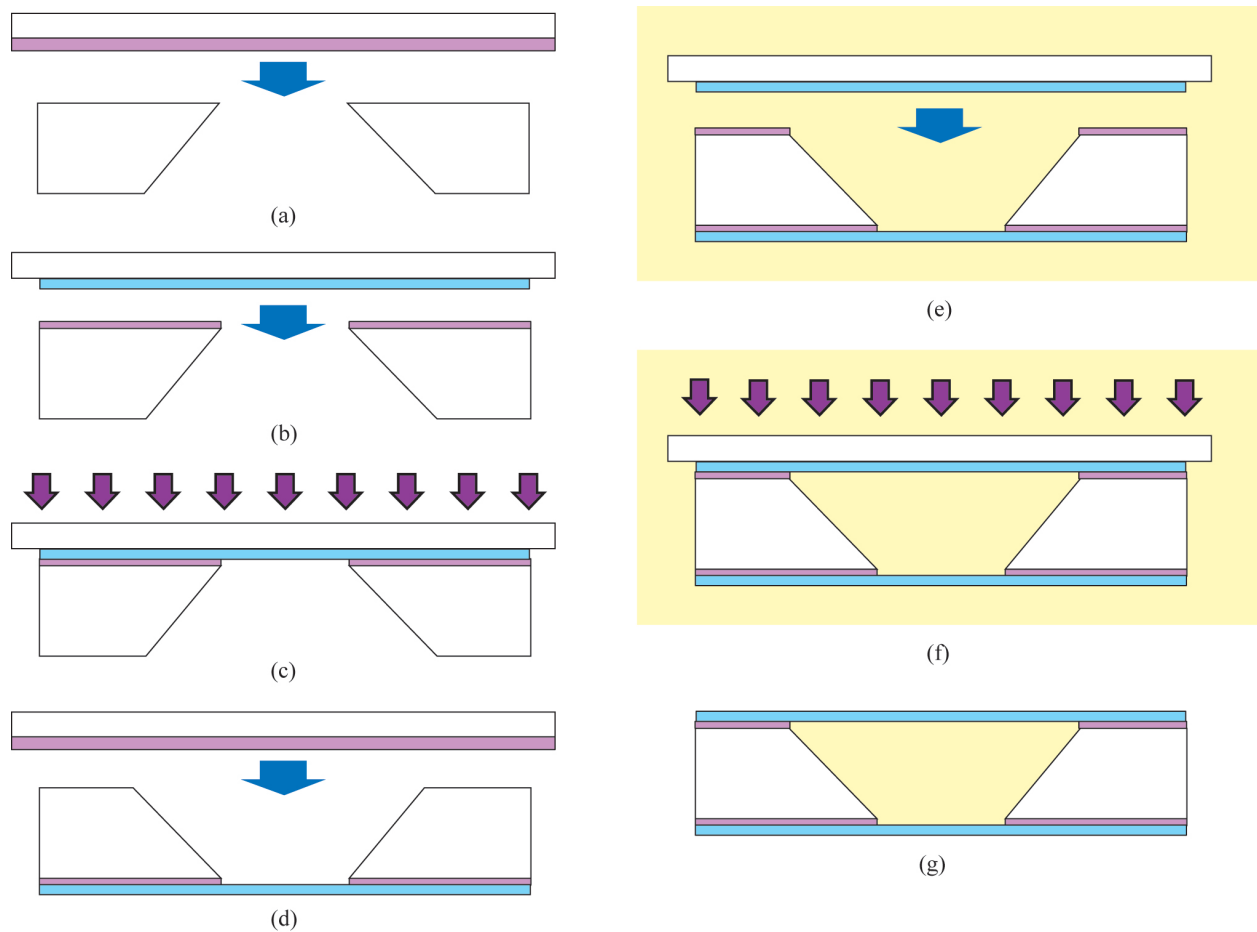


**Figure 2.** Schematic cross-sectional view of HDAM.

Rather than package the MEMS devices vacuum, we considered that if the encapsulating process was conducted in liquid, then the reservoir could be filled without the interfusion of air bubbles. However, one concern was how to successfully bond the membrane to the package chamber in a liquid environment. Therefore, it was decided to use a UV-curable resin (3164 Three Bond, Three Bond Co., Ltd.) that is solidified after UV irradiation, even in a liquid environment. This membrane achieves a tensile strength of 0.85 MPa when cured and the thickness of the resin can be controlled according to the spin-coating speed.

Figure 3 depicts the procedures employed in BiLT. Firstly, a UV resin is coated onto the bonding surface; however, it should be noted that the surface has many cavities for liquid encapsulation. Therefore, the UV resin is spin-coated onto a thick PDMS membrane and then transferred onto the bonding surface by soft contacting the PDMS membrane (Figure 3(a,d)). A sufficient amount of resin needs to be applied to the bonding surface to achieve a good bond, while excess resin may fall into and occupy the cavity during the bonding process. UV resin thicknesses of 80, 120, 160, and 200  $\mu\text{m}$  were tested on PDMS membranes, which correspond to spin-coating speeds of 4000, 3000, 2000, and 1000 rpm, respectively. When silicon was used as the bonding substrate, the transferred thicknesses were 7.9, 8.1, 17, and 27  $\mu\text{m}$ . In case of UV resin thicknesses of 17 and 27  $\mu\text{m}$ , the excess resin flowed into the cavity.

Handling of a flexible thin membrane is not a trivial process. The membrane must be kept flat throughout the bonding process. Therefore, the membrane was spin-coated and cured on a glass substrate. The thickness of the PDMS membrane can be controlled according to the spin-coating speed. During the bonding process, the PDMS membrane must be peeled off the glass substrate. Therefore, the glass surface is coated in advance with a hydrophobic film (CYTOP M, H, Asahi Glass Corporation) to facilitate exfoliation.



**Figure 3.** BiLT process. (a) UV curable resin is transferred onto the bonding surface. (b) A flexible membrane coated onto another substrate in advance is brought into contact with the bonding surface. The membrane is coated onto a hydrophobic layer to facilitate peeling of the membrane from the substrate. (c) UV light is irradiated to cure the UV resin. (d) A second UV curable resin is transferred onto the bonding surface. (e) A flexible membrane is brought into contact with the bonding surface in a liquid environment. (f) UV light is irradiated to cure the resin. (g) Liquid encapsulation without the interdiffusion of air bubbles or deformation of the membrane is achieved.

The substrate with cavities and the flexible membrane on the glass substrate are brought into contact in a liquid environment (Figure 3(e)). UV light is then irradiated onto the bonding surface through the glass substrate and flexible membrane to cure the UV curable resin (Figure 3(f)). Note that the substrate and membrane must be UV-transparent for this process. Figure 4 shows micrographs that confirm liquid (red-dyed deionized (DI) water) encapsulation was completed without the interdiffusion of air bubbles. Excess resin flowed into the cavities for UV resin thicknesses of 17 and 27  $\mu\text{m}$ . No DI water was observed at

the bonding interface. Encapsulation of glycerin was also attempted. Glycerin is non-volatile, so that the volume of the encapsulated glycerin did not change over a period of weeks even when encapsulated with a gas permeable PDMS membrane at ambient pressure and room temperature.

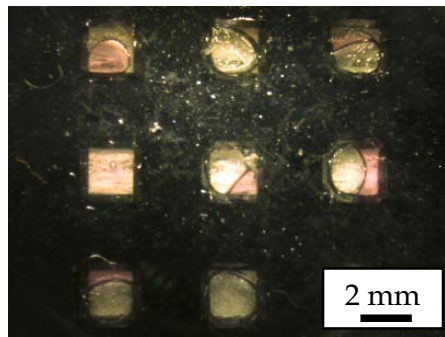
In HDAM, encapsulated liquids are sealed with flexible membranes at both the top and bottom sides of the package chamber. When the encapsulation/bonding process is conducted in air and not in liquid, the difference in the density of the air and liquid result in bowing of the membrane. Note that the membranes must be kept flat during the bonding processes of BiLT.

The bond strengths were investigated by conducting 180° peel tests on PDMS membranes and silicon substrates bonded using BiLT in DI water, glycerin, phosphate buffer solution (PBS), isopropyl alcohol (IPA), and acetone, and also in air as a reference. The silicon substrate used in the experiments did not contain bonding cavities. The bond strengths of the samples were measured as a function of time (1, 6, 24, 72, and 168 h) using a dynamic mechanical analyzer (RSAIII, TA Instruments). The test procedure involved one edge of the PDMS membrane being manually peeled from the silicon substrate and the unbonded area of the silicon substrate being clamped. The peeled PDMS membrane was then pulled in the direction parallel to the bonding interface at a speed of 3 mm/min until it peeled off, and the shear stress required to peel the PDMS membrane from the silicon substrate was measured. The results are shown in Figure 5. The bonding resin was dissolved in both IPA and acetone solution, and thus bonding was unsuccessful when conducted in these solutions, while the bonding strengths of the other samples were comparable. The bond strengths increased with time, most likely due to continuing chemical reaction of the UV-curable resin over time. The bonding strengths after 1 week were more than 4 times greater than those obtained after 6 h. Peel tests conducted within 72 h of bonding revealed failure of the resin, while failure occurred at the interface between the resin and PDMS membrane when measured after 1 week. This indicates that failure occurred within the resin until the resin was sufficiently cured and this is why the bonding strengths in air, DI water and PBS were similar; 1 week after bonding, the bonding strengths achieved by bonding in air and using BiLT were comparable.

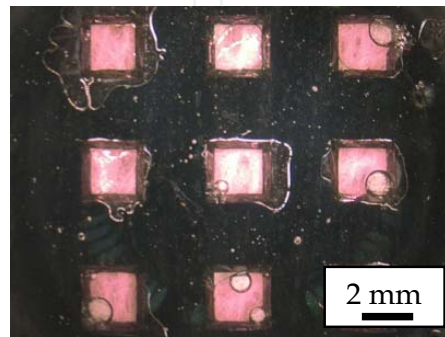
The developed BiLT enables complete liquid filling with various membranes. Many species of liquids can be encapsulated using BiLT, unless the liquids dissolve the UV resin. This feature is crucial in manufacturing HDAM and sensors, which will be introduced in section 5. Complete filling can be achieved by direct deposition of a thin film, as introduced in section 4; however, this process can only be used to encapsulate non-volatile liquids, and the type of sealing membrane is also limited. The major drawback of this technology is that the substrate must be UV-transparent and the device should not contain UV-sensitive materials. For example, dye-sensitized photovoltaic cells, which are employed as transparent solar cells and optical sensors, require the encapsulation of electrolytes. However, BiLT cannot be used for encapsulation, because the cells have dyes that degrade after being exposed to UV.



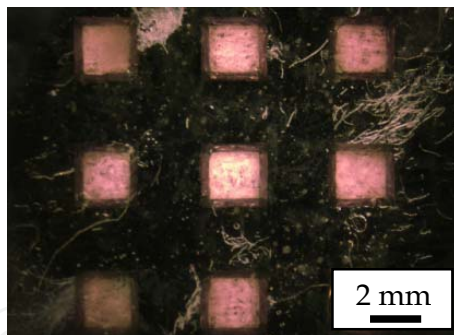
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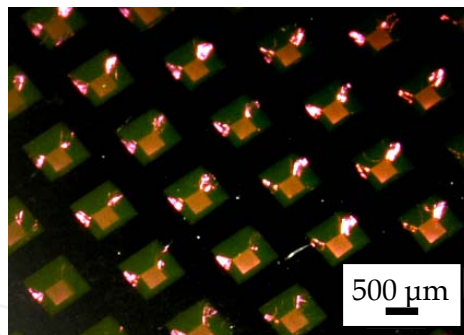
(a)



(b)

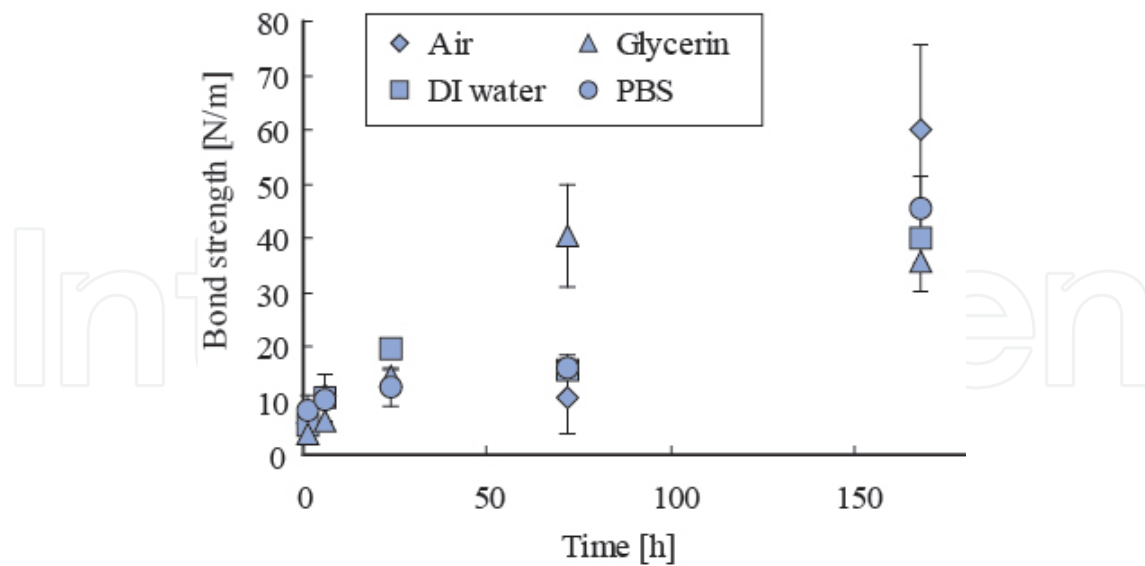


(c)



(d)

**Figure 4.** Bonding results for resin thicknesses of (a) 27, (b) 17 and (c) 8.1  $\mu\text{m}$ . Red-dyed water was encapsulated into the cavities. The transparent parts in the cavities are excess resin. When a certain amount of resin was used, excess UV resin or air was found in the cavities, as shown in (d).



**Figure 5.** Bond strength after BiLT in different media as a function of time.

#### 4. Liquid encapsulation by direct deposition of a thin film

Thin film deposition onto a solid is typically conducted under vacuum. Some liquids, such as silicone oil and ionic liquids, have extremely low vapor pressure and do not evaporate under vacuum. A thin film of metal or polymer can be directly deposited onto such low-vapor-pressure liquids. A thin silver film was deposited onto an ionic liquid to manufacture a mirror for a space telescope [33].

Parylene, or poly(para-xylylene), is widely used in fields of MEMS and microTAS due to favorable characteristics, such as transparency, mechanical strength (3.2 GPa), biocompatibility, gas sealing efficacy, and has the ability to be conformally coated using chemical vapor deposition [34-36]. Parylene has been used to form a microspring with a low spring constant [37] and as a substrate and/or a protective layer for the manufacture of microelectrodes [38]. In addition, the surfaces of PDMS microchannels have been coated with parylene to protect against protein adsorption [39].

The typical pressure for parylene deposition is several pascals. Therefore, liquids with vapor pressures less than this can remain in the liquid phase during the parylene deposition process. Binh-Khiem et al. proposed parylene on liquid deposition (POLD), where parylene is directly deposited onto a low-vapor-pressure liquid, such as silicone oil [34-36]. A feature of liquids is that sufficiently small droplets can have perfectly spherical shape due to surface tension; however, when the droplets are not small, the shape is deformed by gravity. Spherical droplets can be used as lenses. The focal length of a lens is in the same order as the lens diameter; therefore, small lenses enable compact optical systems. POLD can be used to form spherical microlens arrays; transparent liquid can be directly deposited onto silicone oil droplets. A film is formed at the droplet surface, so that no air is included in the lens, i.e., a filling rate of 100%

is achieved. Parylene is more flexible than metals; therefore, by integrating electrodes beneath the liquid lens coated with parylene, the lens can be deformed to vary the focal length according to the voltage applied to the electrodes [34].

The direct deposition on liquid approach enables perfect liquid encapsulation with good reproducibility. The useful characteristics of parylene or specific metals can be exploited; however, the disadvantage is that the liquids to be encapsulated must be non-volatile and the type of sealing material is limited. For example, this approach cannot be applied to HDAM, because it is preferable to seal the liquid with flexible membranes.

## 5. Applications of liquid encapsulation technology

### 5.1. Drug delivery

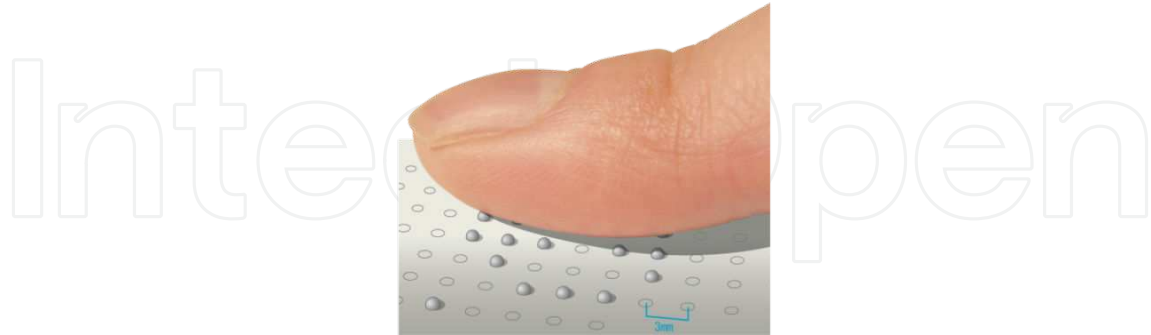
In DDS, the release of medicine is designed so that the drug efficacy is high. MEMS-based DDS are expected to convey medicine to the vicinity of diseased sites by exploiting the small MEMS size and drug release occurs when appropriate. Santini et al. proposed the controlled release of drugs from cavities that were sealed with a thin gold layer [2]. The thin gold layer is used as an anode and an electrochemical reaction occurs, with subsequent dissolution of the gold film and release of the encapsulated medicine. Drug delivery is thus controlled by electrical control of the reaction.

In this application, the fill and seal approach is employed to maintain the quality of the medicine as a priority. The package chambers are prepared with a thin gold layer as the bottom surface. Drugs are dispensed into the chambers and then sealed with a water-proof membrane using epoxy adhesive. Details of this process can be found in the literature [2].

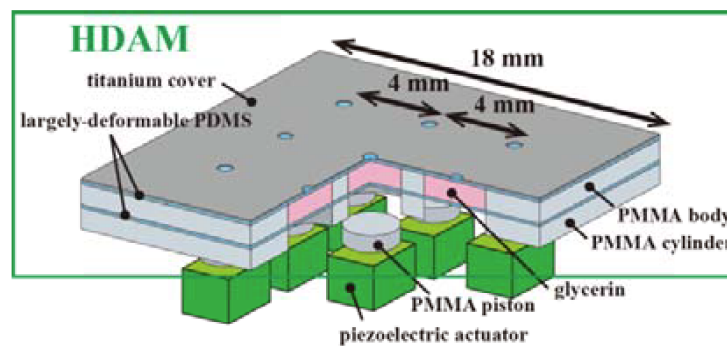
### 5.2. Hydraulic amplification

Some MEMS applications require large displacement of several tens of micrometers. High-flow-rate microvalves are one such application. To satisfy the requirements, hydraulic amplification has been reported that utilizes incompressible fluid in a microchamber with an input surface that is larger than the output surface [17-20]. Another example is a tactile display [21,22]; Figure 6 shows an illustration of an array of MEMS actuators that mechanically deform the fingertip and stimulate tactile receptors. These receptors typically require skin deformation of several tens of micrometers, which could be facilitated by hydraulic amplification. Tactile displays are developed to offer a new approach to human-machine interface for virtual reality applications and interactive devices such as pointing devices or game controllers, and also to support visually impaired persons. In the microvalve applications, a working fluid can be used as an incompressible fluid for hydraulic amplification. However, tactile displays cannot afford to have an external fluidic system to drive a working fluid; therefore, complete encapsulation of the liquid is necessary. In addition, the sealing membranes must be flexible. HDAMs have been successfully developed by encapsulating incompressible and non-volatile glycerin in microchambers with flexible and largely deformable PDMS membranes (mixture of DC 3145

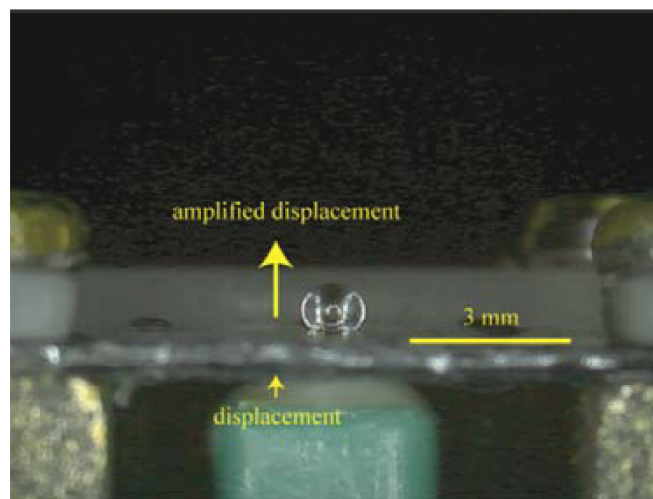
CLEAR and RTV thinner, Dow Corning Toray Inc.) via UV curable resin using BiLT. Figure 2 shows a schematic of a HDAM [21,22].



**Figure 6.** Tactile display that employs an array of MEMS actuators.



(a)



(b)

**Figure 7.** Large displacement MEMS actuator array that consists of HDAM with glycerin-filled cavities prepared using BiLT, and piezoelectric actuators. (a) Schematic image of HDAM, and (b) micrograph showing the large deformation of a PDMS membrane.

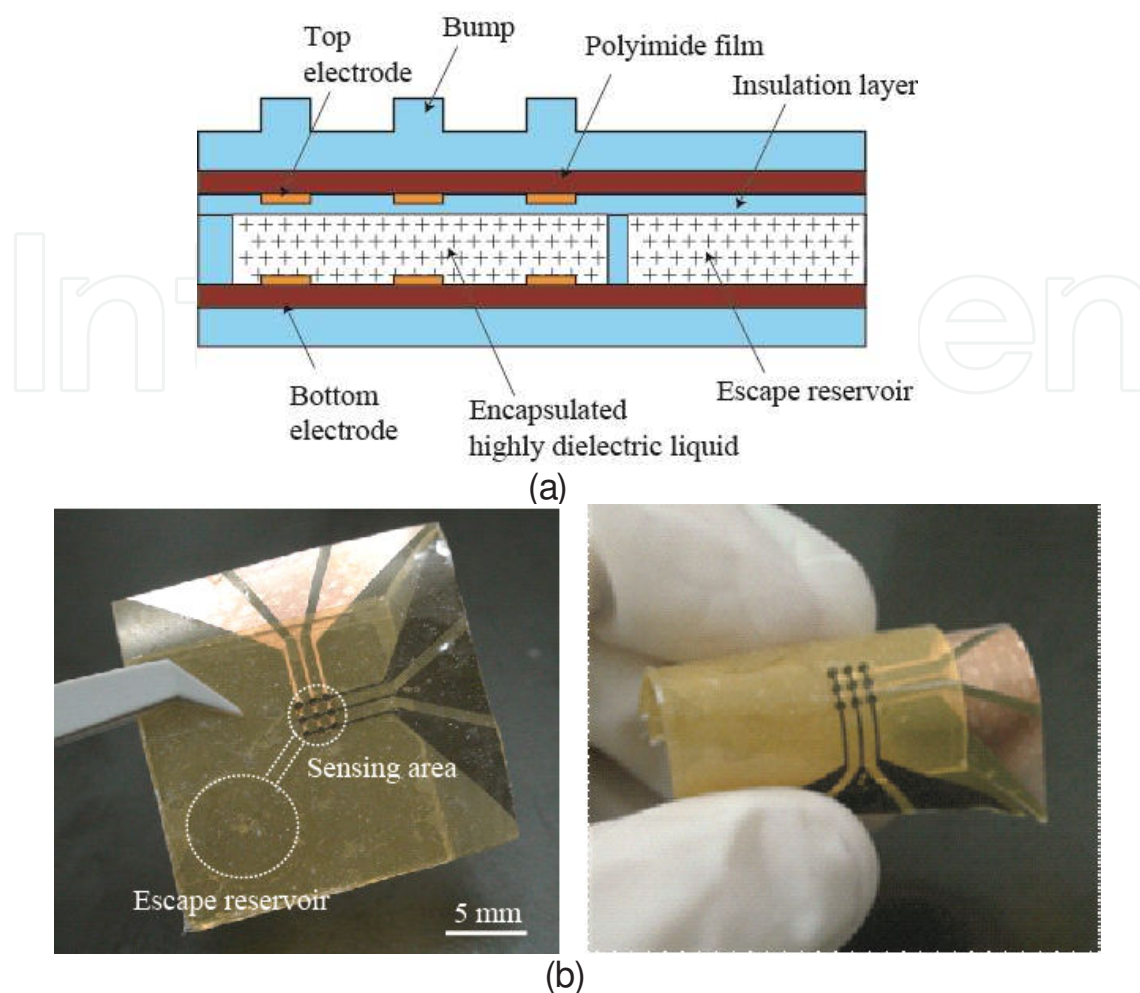
The HDAM shown in Figure 7(b) was combined with piezoelectric actuators and applied to develop large-displacement MEMS-actuators, with a particular aim to application in MEMS-based tactile displays [21,22,40]. When applied to a vibrational Braille code display, it was experimentally verified that the large-displacement HDAM could display Braille codes more efficiently than a static display. This is because both fast and slow adaptive tactile receptors could be used to detect the displayed patterns when individual cells were vibrated at several tens of hertz [40]. When the actuation of the large displacement MEMS actuators was controlled both spatially and temporary, different surface textures, such as rough and smooth, could be displayed.

### 5.3. Flexible capacitive sensor

Highly sensitive pressure sensors are expected to be applied in humanoid robots and medical instruments to detect tactile sensation, which would enable safe physical interaction with the environment, including human contact. MEMS-based capacitive sensors that have simple structures composed of electrodes and a dielectric component have been widely studied, due to good compatibility with MEMS fabrication technologies. Capacitive sensors require not only high sensitivity, but also flexibility to detect the pressure applied to curved surfaces. Silicon-based MEMS capacitive sensors have been developed; however, silicon is brittle, which makes it difficult for the sensors to conform to a curved surface. Therefore, polymer-based flexible sensors have been proposed and demonstrated. Polymer-based flexible sensors are typically used to maintain flexibility with air as the dielectric; however, air has a relatively low dielectric constant. A solid dielectric may enhance the sensitivity, but impairs the flexibility of the sensor. Therefore, a polymer-based capacitive sensor that uses a dielectric liquid has been proposed, as depicted in Figure 8 [23]. DI water and glycerin have high relative dielectric constants of approximately 80.4 and 47; therefore, the proposed sensor with such liquids can have high sensitivity while maintaining flexibility. The capacitance of the electrodes increases when pressure is applied to the device. PDMS is used as a structural material in this device. An escape reservoir is designed to allow an incompressible liquid, such as DI water and glycerin, to move from the cavity between the electrodes when pressure is applied to the sensor, which allows the flexible sensors to deform and vary the capacitance. The proposed microsensor has been fabricated, and both high sensitivity and flexibility have been experimentally demonstrated.

### 5.4. Dye-sensitized photovoltaic cell

Dye-sensitized photovoltaic cells are currently attracting widespread scientific and technological interest as a high efficiency, low-cost, and transparent alternative to inorganic solar cells. Figure 9 shows a schematic illustration of the structure and operation principle of the dye-sensitized photovoltaic device. The cell consists of two electrodes and an encapsulated liquid electrolyte that contains iodide and triiodide ions. The cathode is a highly porous nanocrystalline semi-conductive titanium dioxide ( $\text{TiO}_2$ ) layer, in many cases consisting of  $\text{TiO}_2$  nanoparticles, deposited on a transparent electrically conductive glass.  $\text{TiO}_2$  absorbs only UV light; therefore, dye is adsorbed onto the  $\text{TiO}_2$  layer to utilize the light with a wider range of wavelength. The counter electrode (anode) is a transparent electrically conductive glass with a platinum catalyst. The device is transparent and is colored according to the dye employed.



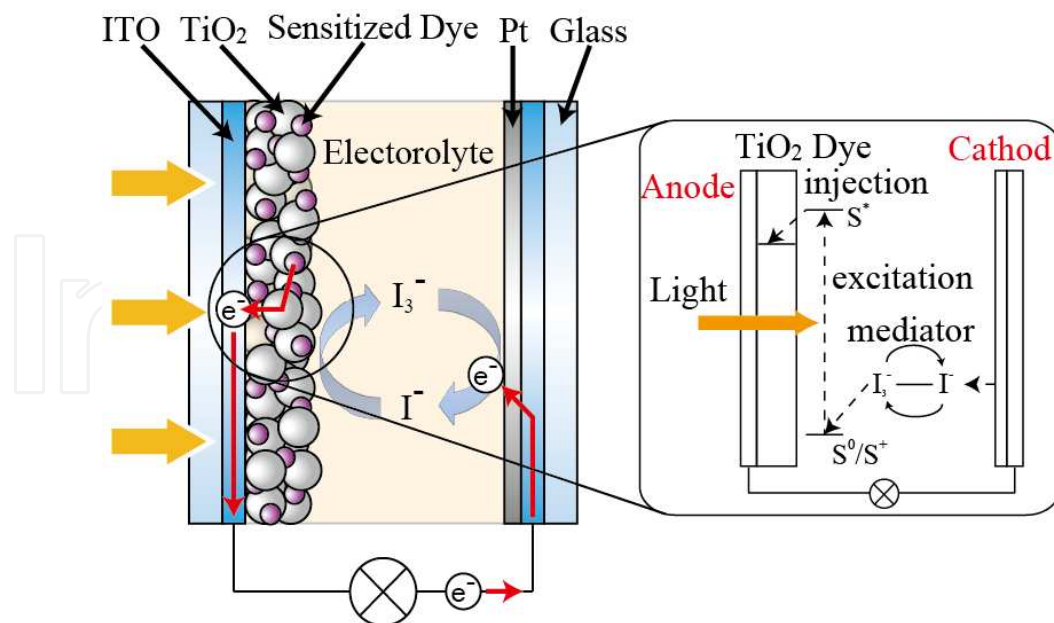
**Figure 8.** a) Cross-sectional view of a capacitive sensor with encapsulated liquid dielectric to enhance the sensitivity while maintaining flexibility. (b) Fabricated capacitive sensor.

When light passes through the electrically conductive transparent glass electrode, the dye molecules are excited and transfer an electron to the semiconducting  $\text{TiO}_2$  layer via electron injection. The electron is then transported through the  $\text{TiO}_2$  layer and collected by the conductive layer on the glass. The mediator ( $\text{I}^-/\text{I}_3^-$ ) undergoes oxidation and regeneration in the electrolyte. Electrons lost by the dye molecules to the  $\text{TiO}_2$  layer are replaced by electrons from the iodide and triiodide ions in the electrolyte, thereby generating iodine or triiodide, which in turn obtains electrons at the counter electrode, culminating in a current flow through the external electrical load. This is the mechanism for the conversion of light energy received by the device to electricity [41]. This device has an interesting feature in that it reacts strongly to light that enters through the  $\text{TiO}_2$  layer.

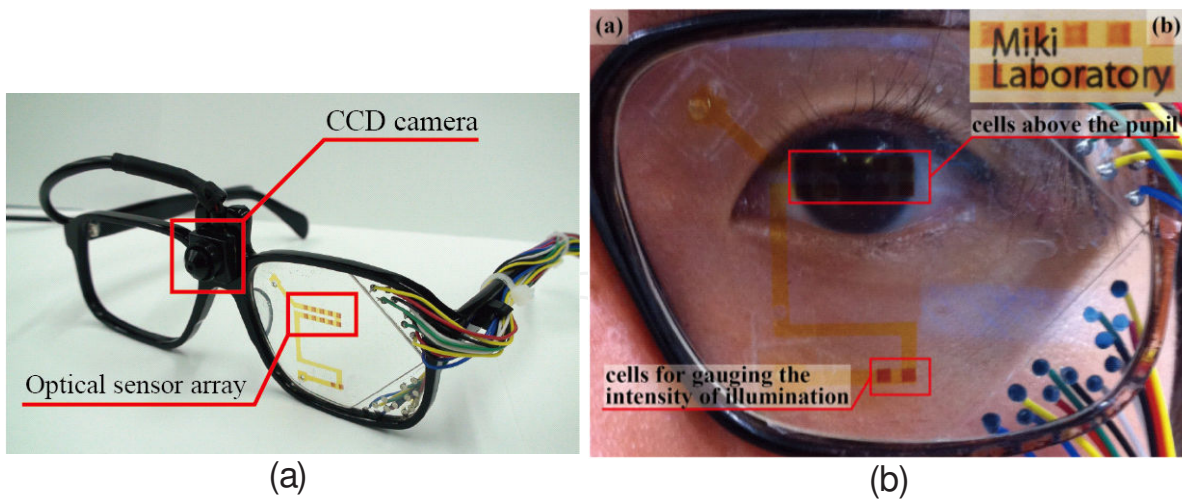
The dye-sensitized photovoltaic cell has been conventionally studied as a solar cell, where miniaturization was not considered. However, when the cells are microfabricated and arrayed, they can be used as a transparent optical sensor. Shigeoka et al. proposed to microfabricate a transparent optical sensor on eyeglasses, which could detect the pupil position by detecting reflection from the eye, as shown in Figure 10 [42]. The light reflected from the pupil is

considered to be smaller than that from the white. The sensor reacts strongly to light from the  $\text{TiO}_2$  electrode side, i.e., when the  $\text{TiO}_2$  layer electrode is faced towards the eyes, it detects only the light reflected from the pupil and white of the eye, without being affected by the light incident on the device from the environment.

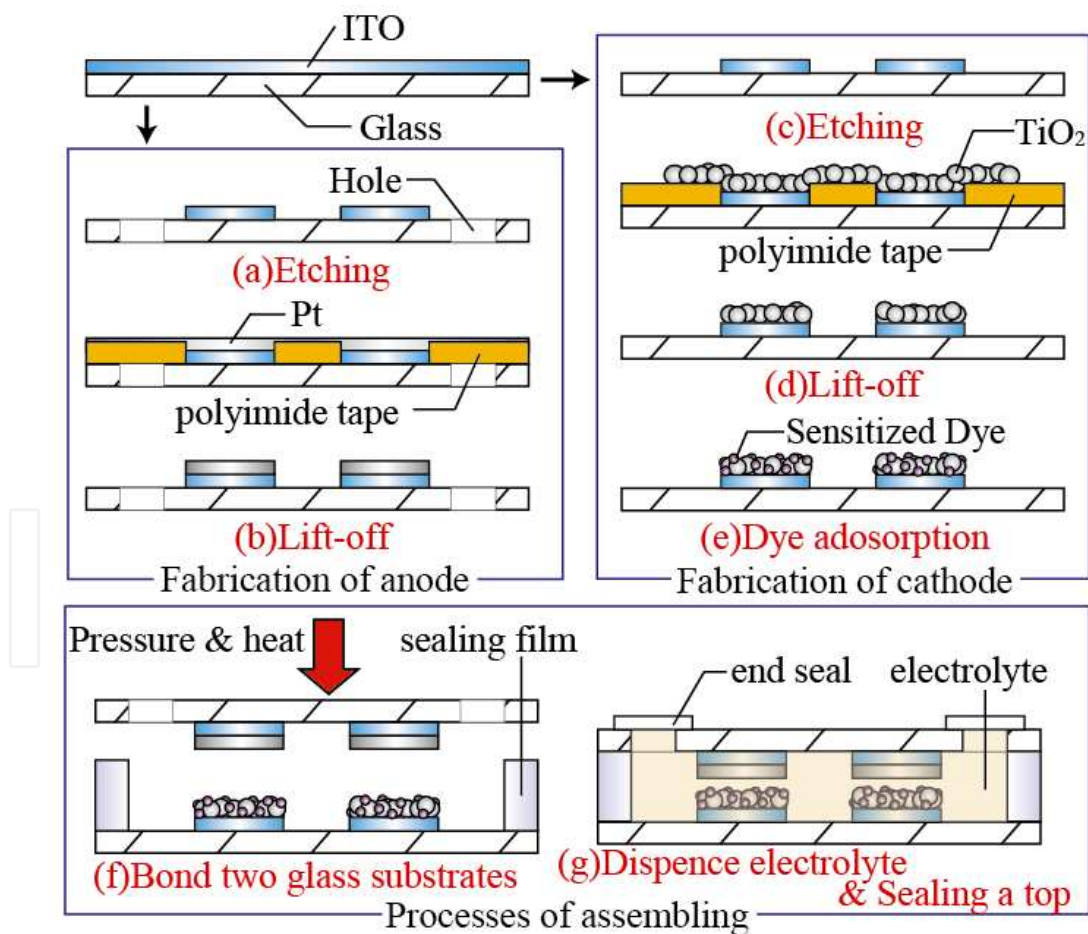
Figure 11 shows a schematic of the processes used for fabrication of this device. The most critical part is encapsulation of the electrolyte. The conductive layer (ITO) is firstly patterned on the glass substrate using photolithography.  $\text{TiO}_2$  nanoparticles are patterned on the cathode using a lift off process. The device is subsequently annealed in air at  $450^\circ\text{C}$  for 60 min and then dipped in a ruthenium-containing dye solution for 60 min to ensure the dye is adsorbed onto the  $\text{TiO}_2$  nanoparticles. The two glass substrates are bonded via a hot melt film and application of 600–800 kPa at  $100^\circ\text{C}$ . Lastly, the liquid electrolyte is flowed from the inlet hole into a channel between the two electrodes, and then the inlet and outlet holes are covered by end seals. The dyes used are UV sensitive; therefore, BiLT was not applicable to this liquid encapsulation process, and the fill and seal approach was used instead. However, the filling rate of the electrolyte was quite high and no interdiffusion of air between the electrodes was observed. An array of the dye-sensitized photovoltaic devices successfully detected the pupil position. The line-of-sight (LOS) was successfully deduced [42, 43] from the obtained pupil position and the front image of the subject, acquired using a CCD camera on the eyeglasses.



**Figure 9.** Structure and operation principle of the dye-sensitized photovoltaic device.



**Figure 10.** a) Array of dye sensitized photovoltaic cells patterned onto eyeglasses to detect the pupil position. The electrolyte was encapsulated between the electrodes. (b) Photograph of the sensor when worn by a subject.



**Figure 11.** Fabrication process to produce an array of dye-sensitized photovoltaic devices. The fill and seal approach was employed to encapsulate the electrolyte (g).



## 6. Conclusion

This chapter has reviewed liquid encapsulation technologies and their applications to the manufacture of innovative MEMS devices that exploit the useful characteristics of liquid; liquid is deformable and liquid droplets form a perfectly spherical shape by surface tension. Other liquids have high relative dielectric constants. Liquids can be used as drugs for DDS and fuels for power MEMS. Appropriate liquid encapsulation technologies must be selected according to the liquid to be encapsulated. The fill and seal approach, bonding-in-liquid technique, and direct deposition of a thin film were discussed in this chapter, all of which have both advantages and disadvantages.

The use of liquid in MEMS packaging is quite a new technology. The author is convinced that more and more liquid encapsulation technologies will be developed and contribute to the further development of innovative liquid-encapsulating MEMS devices.

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