

Flexible and Stretchable Circuits for Smart Wearables

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Abstract—Flexible and stretchable circuits have recently gained traction in the market due to the popularity of wearables and the rapid advancement in microsensors, big data and the Internet of Everything. For devices to be truly wearable, they need to conform to the shape of the human body, allowing ease of use, with sensors being pervasive but not intrusive. To allow this, electronics engineers need to shift their mindsets of manufacturing transistors, circuits and sensors on rigid planar surfaces to flexible, multidimensional and free-form substrates. This review manuscript describes the motivation for designing such circuits, its fabrication techniques, design considerations, performance evaluation and applications. It is expected that stretchable circuits will be a new way forward for integrated circuit technology and will continue to push the boundaries of manufacturing processes in the years to come.

Index Terms—Flexible Circuit; Stretchable Circuit; Smart Wearables;

I. INTRODUCTION

Stretchable electronics are inspired by human skin and flesh, which are flexible and stretchable yet fully functional, capable of transmitting and receiving electric signals via neurons. Other than its biomimicry advantages, electronics on flexible substrates have recently received much attention due to advancements in demand for wearables as well as fabrication techniques such as using conductive inks in roll-to-roll manufacturing processes and integration of conductive fibers in smart textiles [1].

Engineers have long since visualized the potentiality of making circuitry that is fluid and can conform to the body as an alternative to rigid chips and boards. Flexible circuitry can enable many functionalities that were previously impossible with rigid circuits. Stretchable electronic skin can be incorporated with multiple sensors on a prosthesis to allow similar capabilities of a real limb. For military usage, uniforms and armors can have embedded, flexible, lightweight impact sensors that could store and provide better information of the injury sustained during combat.

Flexible circuits would also make portable devices more resilient; making circuits wearables like clothing or jewellery. Current, avant-garde research are studying different fabrication techniques that allow circuits to be more pliable. However, rigid chips and circuit boards will still be the most popular type of circuits because they are so inexpensive to manufacture in large quantities. Traditional electronic devices often use rigid substrates due to their reliability, and ability to withstand bending and impact. Compared to rigid circuits, flexible substrates can endure some form bending

and stretching, but it is mostly limited. Reliability and lifetime of flexible substrates are also drastically reduced with the increased number of bending cycles.

A key driver of the popularity of flexible and stretchable circuits is the advent of wearable technology. Wearable technology encompasses the use of electronic devices and microcontrollers on the human body, either as an implant or worn as an external device. Wearables are often used to collect data or physiological parameters from the users. A plethora of wearables such as blood pressure monitors, heart rate monitors, step counters, distance trackers is currently available in the market. The demand for wearables has grown exponentially since a decade ago when wearables were restricted to ECG, EEG and EMG devices. Modern sensors are often unobtrusive, miniature, wireless and are powered by tiny batteries. These sensors are made possible by advances in Micro-Electro-Mechanical-Systems. These microsensors can measure impedance, charge displacement, magnetic fields, light intensities and pressure [2].

This paper intends to provide the reader with an overview of the latest devices in the area of stretchable electronics, its key design considerations, fabrication methods and performance. This paper is organized as follows: Section II describes the different materials or substrates used for flexible electronics and its fabrication techniques, Section III describes the different sensors available and Section IV Discusses and Concludes the write-up.

II. FABRICATION TECHNIQUES AND MATERIALS

A. Flexible and Stretchable Substrates

There are a variety of flexible and stretchable substrates that are available in the market. Flexible substrates have the ability to bend or flex without breaking. Stretchable substrates, on the other hand, have a larger range of motion and are capable of withstanding high mechanical strain while still remaining elastic. In the elastic region, stretchable materials can withstand large deformations under load and recover its original form and shape when the load is removed. Among the characteristics that are needed for any material to be used as the substrate are having a low-modulus with stress/strain responses that can be tailored precisely to match the non-linear properties of biological tissues [3] and it must not be too rigid, too thick, too heavy but must have a conformal contact, intimate integration, and adequate adhesion with natural skin [4].

1) Polydimethylsiloxane (PDMS)

The material that is very often used as a substrate for stretchable circuits is polydimethylsiloxane (PDMS). It is a staple material in the BioMEMS area and a transparent elastomer with Young's modulus of about 100MPa [5]. It is also found in shampoos (dimethicone makes hair shiny and slippery), caulking, lubricating oils and heat-resistant tiles. PDMS is optically clear and is generally considered to be inert, non-toxic and non-flammable [6].

PDMS is prepared by mixing an elastomer with a curing agent. The resulting mixture can be cast onto patterned or flat low-surfaced energy substrates. PDMS is also very popular as a substrate for biomedical microdevices, to make microfluidic structures and stretchable interconnects [5]. This material also has drawbacks. One of the major fabrication problems when using PDMS is its low adhesion to thin metallic films. This creates problems when PDMS is used with metallic sensors, circuitry and its interconnects.

2) Polyimide

Polyimide is another material under MEMS which is suitable as a substrate for flexible circuits. It is a type of polymer that has good chemical resistance, mechanical strength and thermally stable up to 400°C [5]. Usually, polyimides are available either as semi-cured sheets or as a solution that can be spin-coated for example Kapton and Dupont. One of the polyimide's special characteristics is that many properties of the films like its thermal expansion coefficient, Young's modulus, and dielectric constant can be adjusted or customized during synthesis.

3) Polyethylene Terephthalate (PET)

Polyethylene terephthalate (PET) is a commercially available flexible substrate, which is produced in the form of sheets. PET is a strong thermoplastic that is thermally stable up to about 250°C and can conform to typical body curvatures. In its natural form PET is hydrophobic, however, when exposed to plasma, this PET can be made hydrophilic [5]. These properties allow easy bonding with PDMS without the necessity of adhesives. Its flexibility, stable form and modifiable hydrophilicity makes it a suitable substrate for flexible sensors.

4) Polytetrafluoroethylene (PTFE)

Polytetrafluoroethylene is popularly known as Teflon. PET has a wide range of applications, ranging from non-stick cooking pans to beakers. PTFE is also used to treat carpets and fabrics to make them stain resistant. What's more, it's also very useful in medical applications. Because human bodies rarely reject it, it can be used for making artificial body parts [7]. PTFE is a fluorocarbon solid, as it is a high-molecular-weight compound consisting wholly of carbon and fluorine. PTFE is hydrophobic: neither water nor water-containing substances wet PTFE, as fluorocarbons demonstrate mitigated London dispersion forces due to the high electronegativity of fluorine. PTFE has one of the lowest coefficients of friction of any solid [7].

5) Polyethylene

Polyethylene is among the most common polymer that is seen every day. It is present as grocery bags, shampoo bottles, children's toys, and even bullet-proof vests. It is an adaptable material, and its particle consists of a long chain of carbon molecules, with two hydrogen atoms appended to every carbon

atom. As a material, polyethylene is low in strength, hardness and rigidity. However, this allows it to be very ductile, have low friction and high impact strength. It shows strong creep under persistent force, which can be reduced by addition of short fibers.

Polyethylene consists of nonpolar, saturated, high molecular weight hydrocarbons, making it similar to paraffin in terms of chemical behavior. Overall, polyethylene is partially crystalline due to its symmetric molecular structure in which its individual macromolecules are not covalently linked. Its high crystallinity makes polyethylene dense, and both mechanical and chemically stable. It is highly non-absorbant to water where its gas and water vapor permeability (only polar gases) is lower than for most plastics. Polyethylene is highly permeable to gases, oxygen, carbon dioxide and flavorings. In terms of adhesion, polyethylene cannot be imprinted or stuck together without pretreatment.

6) Thermoplastic Polyurethane (TPU)

Thermoplastic polyurethane (TPU) is an elastomer that is fully thermoplastic. It is melt-processable, which means that it can be processed using, extrusion, injection, blow and compression equipment. It can also be vacuum-formed or solution-coated. TPU can also be colored through a number of processes. But more so than any other thermoplastic elastomer, TPU can provide a considerable number of physical property combinations making it an extremely flexible material adaptable to dozens of uses [8].

After intensive testing thermoplastic polyurethane (TPU) foil (thickness 50-100um) showed the best properties to be used as the substrates in the textile industry. TPU's melting point is about 170 °C. This low melting point allows it to be used as an adhesive for other materials such as fabrics. Its biocompatibility, abundance in the market and low pricing make it popular especially in the textile industry. Among of its household usage examples are as rubber bands for underwear and as a coating for raincoats [8].

B. Mechanical Design for Stretchable Circuits

In conforming to the requirement of stretchable electronics, the electrical routings must possess high mechanical stretchability, deformability and adaptability as well to meet the requirements of smart wearables. Conductive wires with more stretchability will have less strain and more uniform conductivity under tensile condition. The stretchability of the electrical routings arises from its routing design and the forms of the stretchable conductor itself. The serpentine geometry is one of the commonly used routing designs for pure solid metals such as gold, copper and silver. The design parameters of serpentine geometry are arc radius, R , arc angle, θ , straight section of routing, L , and routing width, W as shown in Figure 1 [9]. For coplanar design, the theoretical strain of a fully stretched routing is given by:

$$\epsilon_{\text{coplanar type}} \left(\theta, \frac{L}{R} \right) = \frac{2\theta + \frac{L}{R}}{2\sin\theta + \frac{L}{R}\cos\theta} - 1 \quad (1)$$

The theoretical strain, $\epsilon_{\text{coplanar type}}$ is a function of θ and $\frac{L}{R}$. Simulation model¹⁰ shows the relationship between θ , $\frac{L}{R}$ and $\frac{W}{R}$ with PDMS as the substrate and gold as the routing wire with 10.6% allowable strain. With fixed $\frac{W}{R}$ the stretchability performance can be increased with increasing θ

up until 115° , but reduced drastically within range $115^\circ < \theta < 120^\circ$. In this range large routing angles will cause the strain in the conductive wires to be magnified with the pulling force in the substrate. This is known as the transition region where the fracture mode changes from tension to compression. With routing angle beyond 120° , the stretchability performance remains low.

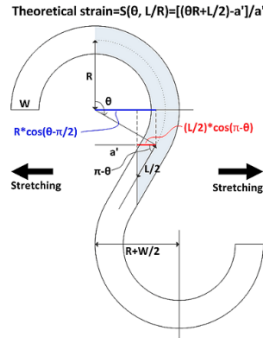


Figure 1: Concepts of a serpentine routing [9]

Apart from serpentine geometry, digital wave and triangular wave geometry are also commonly used. However, the sharp edges in the digital and triangular wave geometry experiences much higher strain compared to the curvy geometry hence increases the possibility of breakage [9][11].

Another factor that can improve the stretchability performance of the circuit is the design of stretchable conductor itself. The stretchable conductor can be in the straight form, wavy form, wrinkly form, island bridge form, and conductive-elastomeric form. The straight wire form normally used in stretchable microelectrode array (SMEA) [12-13] as a sensor to pick up human brain activities by monitoring the changes in brain electrical impulses. The gold wire for example with straight wire form will break between 2% - 10% of tensile strain depending on the tensile rate and the wire thickness¹⁴.

Wavy wire form can increase the stretchability performance depending on the controlling parameters which are the width, wavelength, thickness, and pitch. A smaller ratio of W/R (width/radius) can produce better stretchability performance [15] since it lowers internal routing strain that occurs during a tensile test. This also increases the maximal allowable tensile strain for the wavy routing. However, smaller routing widths cause electrical resistance to increase and makes the structure easier to break. These two issues can be resolved by introducing the design of multi-tracks while keeping similar stretchability performance.

Metal wires that are wrinkled can also exhibit good stretchability performance. This wavy structure is extended to a non-coplanar plane by prestretching the substrate, followed by deposition/evaporation and etch of metal patterns via a shadow mask [16]. The release of pre-strained substrate creates the surface topography of routings through the residual stress. This method removes the residual stress in the substrate while increasing theoretical strain of routings.

Island-bridge form is the wire design where the wire can move comfortably without substrate limitations [17-18]. This design will have the wires buckled and peeled off of the substrates. Device with buckled routings can have a prestrain from the substrate and can give excellent stretchability for up to 140% [18].

Alternatively, the electrical conductor can be made elastic to increase its stretchability performance. This can be done by forming conductive-elastomeric form of routing with an elastic electrical conductor made of silicon rubber combined with amounts of electrically conductive particles [19].

The nanomaterial is one of the materials used since it is chemically stable and highly conductive dopant¹⁹. Silver nanowires (AgNWs) are also being used in making conductive elastomers where it can be stretched over 80% and having a conductivity of $5285 \text{ S}\cdot\text{cm}^{-1}$ while under 50% of tensile strain.

C. Fabrication methods

Mesh screen printing method is perhaps the among the simplest methods to form conductive printed patterns. Using this technique, the pattern of the device is made on a stencil or a mesh. Stencils can be made on wood or metal structures and are usually laser cut to form patterns. Screen meshes are first made using commercial image editing software such as Adobe Illustrator which are then transferred on fabric screens as shown in Figure 2. The screen mesh is covered with a protective layer known as emulsions which determine the thickness of the printed designs. The resolution of the printed pattern is determined by the screen mesh which is usually measured in terms of threads per inch. Very fine designs can have resolutions of up to 300 threads per inch. Conductive ink pastes (Ag, Cu and Au NPs) can be used to print the designs on different substrate materials. This is usually followed by a drying process, also known as sintering. Figure 3 illustrates designs of circuits printed on Micropore which is a commercial surgical tape.

D. Effect of Sintering on Conductivity and Extensibility of Screen-printed Circuits

Sintering is the process of welding particles together below the ink's melting point. Sintering temperature and duration can influence the shape of the printed ink-paste's microstructures. It has been shown that when Ag nanopaste is sintered at 150°C for 15 min, 30 min, 45 min and 60 min, the Ag microstructures evolve from being discrete particles to forming clusters and finally forming long interconnections [9]. At 45 min, the organic solvent matrix decomposes and the Ag nanoparticles form inter-particle necking [9]. At 60 min, long interconnection forms due to the sintering effect which consolidates the Ag clusters. Formation of conductive paths decreases the resistivity of the electrodes, as shown in Figure 4 where the electrical resistivity is approximately 20 times lower than the resistivity of the electrodes with 10 min of sintering. Extensibility is defined as the maximum value of strain along the x-axis which can be calculated using the following:

$$\epsilon_{max} = (L_{max} - L) / L \quad (4)$$

III. MODELING OF STRETCHABLE CIRCUIT DESIGNS

The most basic concept that is needed in order to make a stretchable circuit is to have the metal lines, which the geometry can come in a variety of shapes and designs and are embedded or laid on some sort of elastomeric substrates. There are hundreds of varieties of geometry that can be designed for stretchable circuits. The main factors of consideration for stretchable circuits are its conductivity and

capability to revert to its original shape after undergoing deformation or stretch [10]. In recent years, several designs of metal lines have been reported designed for stretchable circuits such as the U shape, the zigzag shape and lastly the horseshoe shape [11]. These different geometries were fabricated on PDMS and analyses were made on which

geometry is more resistant to strain. For these designs, Ag metal lines were fabricated on PDMS. Finite Analysis Element (FEA) software such as COMSOL or Coventorware can be used to analyse the substrate and how the geometrical metal lines affect its stress.

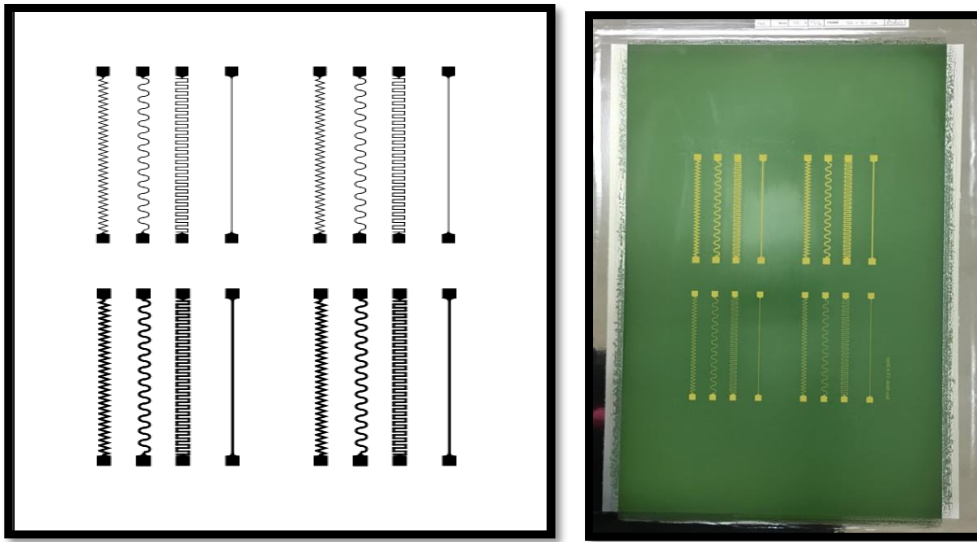


Figure 2: Circuit designs using Adobe Illustrator (left) and Screen mesh (right)

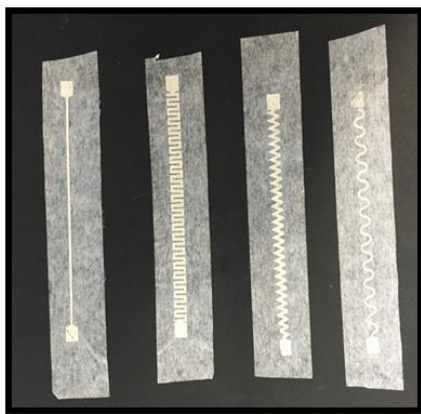


Figure 3: Screen-printed electrodes on Micropore

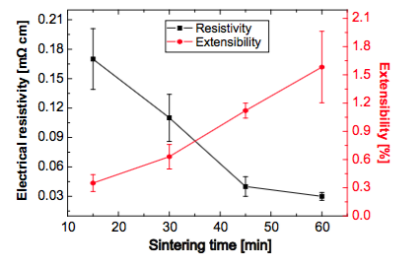
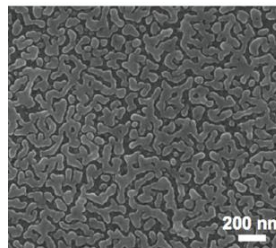


Figure 4: FE-SEM micrographs of Ag circuits sintered at 150 °C for 60 minutes [9] (left); Electrical resistivity and extensibility of the single-line circuits sintered at 150 °C for various lengths of time [9] (right)

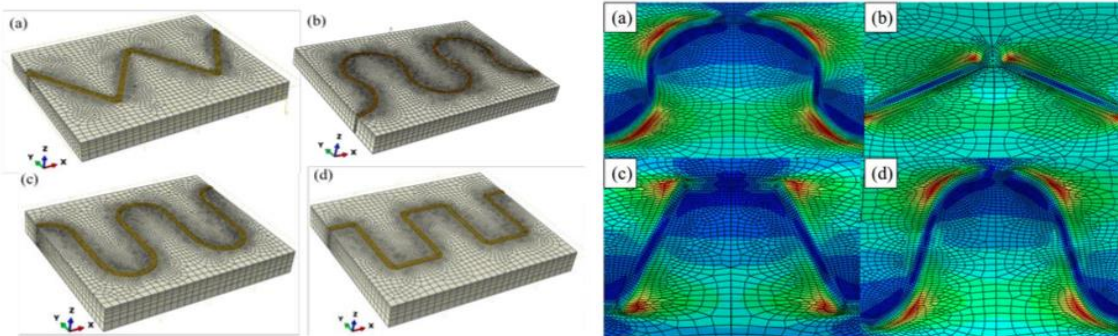


Figure 5: Left: Finite element modelling of Stretchable Electronics. (a) Zigzag shape structure (b) Horseshoe shape structure, (c) U shape structure (d) Rectangle shape structure¹³. Right: Von Mises stress at 60% tensile strain. (a) horseshoe shape structure (b) Zigzag shape structure (c) rectangle shape structure (d) U shape structure¹³

IV. FLEXIBLE ELECTRONIC DEVICES

Sensors detect signals and change physical changes such as temperature, displacement, pressure, light into readable electrical signals. Currently, there are numerous wearable sensors in the market such as blood pressure monitors, electrocardiogram (ECG) [12], electromyography (EMG)[13], electroencephalography (EEG) [14], which are often integrated with fabric.

An example of sensors integrated into clothing is shown in Figure 6. A group of researchers from Eindhoven developed a smart jacket capable of monitoring vital signs of newborns at neonatal intensive care units. The smart jackets for infants are equipped with ECG sensors, which can continuously monitor the baby's heart activities, breathing, and yet are comfortable enough to be worn over 48 hours. The sensors are also tested for leakage current, hygiene and infection risks and allergenic reactions.

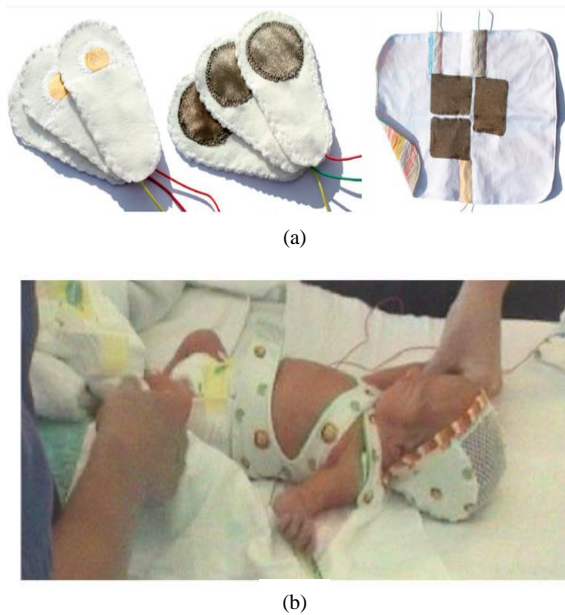


Figure 6: (a) Textile ECG sensors (b) Smart jacket with embedded textile sensors for infants [12][15]

Other than monitoring electrical signals produced by the human body using EEG, EMG or ECG, position sensors such as gyroscopes, accelerometers and magnetoresistive sensors can also be used to analyse movements in a human body [16]. An example of this application is for gait analysis of osteoarthritis and stroke patients [17]. Using these sensors, the trajectory and acceleration of knee and ankle are analysed to characterize the severity of the osteoarthritis in the patients.

Another less intrusive method of gait analysis is via miniature capacitive or tactile sensors, which are embedded in the patients' footwear. The external force can be measured via compression or change in separation distance between two parallel plates that correspond to change in capacitance. When an array of these sensors is placed in the patient's footwear, a plantar pressure measurement at different points can be obtained and gait analysis for the patient can also be derived. As shown in Figure 8, the sensor is composed of a lower electrode, PDMS dielectric layer, an upper electrode and a PDMS bump layer. The bump layer provides a point of contact between the skin and the sensor and also ensures that pressure is evenly distributed. The two electrodes form the capacitive parallel plate sensor.

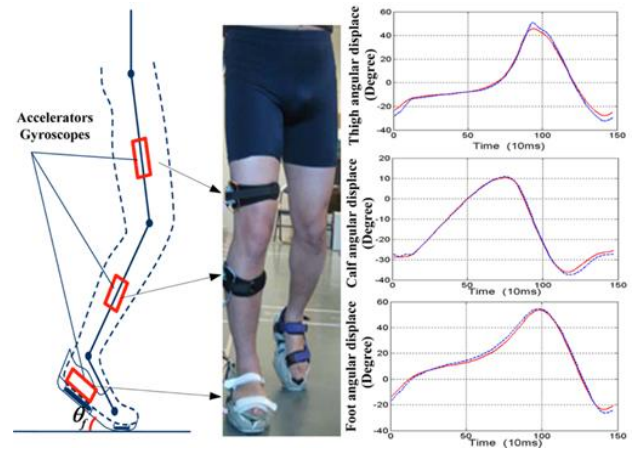


Figure 7: Left: Gait analysis of osteoarthritis using accelerometers and gyroscopes. Right: Calf, thigh and foot angular displacement versus time [19]

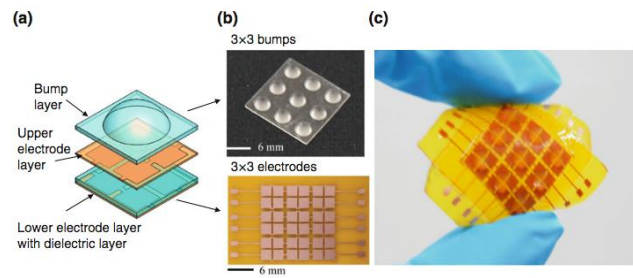


Figure 8: (a) Single capacitive sensor (b) 3x3 array of bumps and 3x3 array of electrodes (c) Flexible tactile sensors on substrate [18]

Nature is often the best inspiration. A common practice for researchers is to adopt wavy geometries such as buckle and serpentine in an effort to improve the elasticity of circuit structures. A different approach has been adopted by current researchers are to develop novel substrates which mimic rose-petals allow omnidirectional stretching and printing of metal electrodes [19]. These bioinspired substrates use real rose petals as molds for its replication. Different from other stretchable circuits, E-petal substrates create topographic surfaces, which inhibits propagation of microcracks in a conducting layer placed on top of it. An example of this work is shown in Fig. 9. Utilizing the petal for the substrate allows different shapes of stretchable electrodes to be deposited. These structures show superior mechanical strength compared to those fabricated on planar substrates.

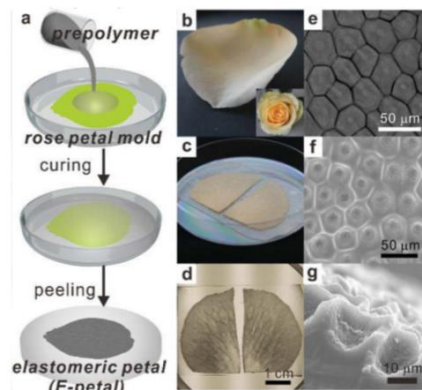


Figure 9: (a) Fabrication flow of E-Petals. (b) a fresh yellow rose petal, (c) rose petals taped on bottom of a petri dish, and (d) as-made E-petals. SEM images of (e) natural rose petal, (f) topography, and (g) cross-section of E-petals, respectively. [19]

V. CONCLUSION

It can be seen that flexible and stretchable circuits will continue to push the boundaries of integrated circuit processing technology. The manufacturing processes for this type of circuits is still in its infancy where there are still numerous problems such as poor conductivity, yield and reliability that still needs to be solved. In terms of materials, there is a lot of opportunity for research and development of new conductive inks, perhaps incorporated with nanoparticles, to improve its quality. This field of research also allows possibilities of new design geometries of circuits and its substrates.

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