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Incorporation of Tissue Engineered Skin Using MEMS Tactile Sensors

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Abstract: For performing daily tasks and preventing the tissues from injury humans require tactile sensation. Wounds that are greater than 4cm diameter will not heal spontaneously. Lost skin can be replaced with tissue engineered skin but this skin will often fail to be reinnervated. Due to reinnervation sometimes the tactile sensatioin is not achieved. Here A silicon based Micro Electro Mechanical Systems (MEMS) is developed in which sensor array that is capable of detecting tactile experiences of the tissue engineered skin. Replacing the animal testing in pharmaceutical industry can also be achieved for experiments regarding tactile experiences.

Keywords: Tissue Engineering, Skin, MEMS Tactile Sensors, Regenerative medicine, Pharmaceutical Testing.

I. Introduction

Fingertip contains biological tactile sensors for tactile sensation is important for performance of daily tasks and prevention of injury. The regeneration of nerves takes place in a limited manner in case of nerve injuries. *The in vitro* in recent years, advances have been made in regeneration of nerve cells and at present fully functional tissue engineered neurons and are not available. Artificial sensing devices with the nervous system increases the possibility of re-creating sensory experiences. Mechanoreceptors emulate the function of mechanical tactile sensors have been developed that emulate the performance of mechanoreceptors, i.e. biological touch sensors and there is a general trend towards bio-inspired designs of sensors.

Tactile sensors are devices or systems that measure a given property of an object or surface through physical contact with it .Tactile senors detect and measure of the spatial distribution of forces on a defined area and they interpret subsequent spatial information. Object shape, texture, temperature, moisture level, pain and other related physical properties are measured.

II. Mechnoreceptors

Human skin is a viscoelastic material. It consists of two main layers: the first layer is the outer epidermis having a thickness of approximately 0.06 - 0.12 mm and the second layer is the dermis having a thickness 10 mm. which is supported below by a layer of subcutaneous
skin surface of the human fingerpad consists of epidermal (papillary) ridges or fingerprints that are approximately 0.1 mm in height and 0.4 mm in width. At the junction between the epidermal and dermal layers there are undulations, known as the intermediate ridges, which consist of irregular, wavy epidermal tissue that extends into and interlocks with the dermis. Each papillary ridge is positioned directly above its corresponding intermediate ridge when mechanical stress is applied to skin via touch, the stress is transmitted through the skin to the embedded mechanoreceptors, which act as transducers, converting the mechanical stimulus into neural signals. There are approximately 17,000 mechanoreceptors innervating the glabrous or hairless skin of the human hand, with the highest density present in the fingertips, the preferred site for haptic exploration. They can be classified into four main types, varying in their structure, function an distribution within skin. Merkel cell complexes, located at the epidermal dermal junction (accounting for about 25% of mechanoreceptors of the human hand), thought to be responsible for coding of surface form and texture.

Meissners corpuscles, located in the dermis (accounting for about 40%of the mechanoreceptors), thought to be responsible for coding of low frequency vibrations. Pacinian corpuscles, located deep in the dermal and subcutaneous layers, thought to be responsible for coding of high frequency vibrations. Ruffini endings, located in the mid dermal layers (accounting for about 20% of the mechanoreceptors), thought to be responsible for the coding of skin stretch.

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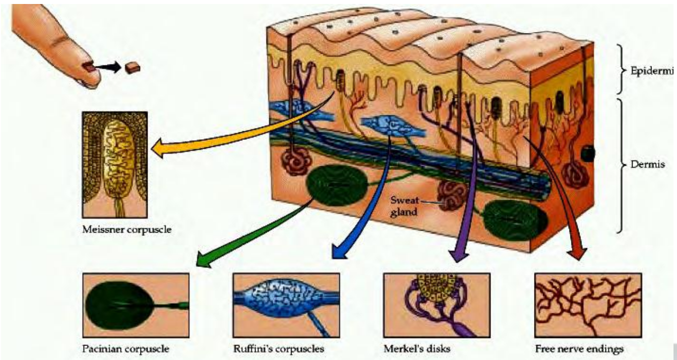


FIGURE: Mechanoreceptors in glabrous skin of the human hand

The mechanoreceptors are innervated by afferent nerve fibres which are nerve fibres that carry impulses from a sensory receptor to the central nervous system. Afferent fibres that innervate mechanoreceptors have conduction velocities between 35 - 70 m/s . The tactile afferent neuron together with its specialised endings (mechanoreceptors) is termed a tactile unit.

III.MEMS TECHNOLOGY

Microelectromechanical systems (MEMS) or Microsystems technology (MST) refers to devices that have characteristic lengths between 1 μm - 1mm,that combine electrical and mechanical components, and that are fabricated using integrated circuit batch-processing technologiese .

A MEMS system may consist of a micromechanical sensor, actuator and microelectronic circuit in a single device. The techniques and practices involved in the development of devices with micron scale dimensions is termed Microengineering.

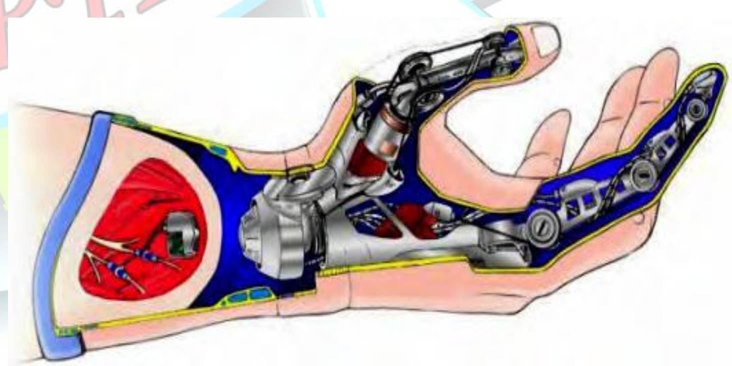
MEMS devices have applications in a range of industrial and medical sectors. Some popular examples include digital mirror displays, inkjet printheads and nozzles, automotive safety systems (such as integrated accelerometers for airbag deployment), biomedical sensors and drug delivery systems. Advances in the semiconductor integrated circuit (IC) industry have played a significant role in the growth and progress of the MEMS field. The development of ICs began in 1958 and a trend in this technology has been for the number of transistors in a chip to double every 18 months. This is referred to as Moore's law and is related to the decrease in device sizes made possible because of advances in silicon processing.

MEMS devices and structures are fabricated using techniques borrowed from the IC industry, such as patterning with lithography, deposition, and etching as well as a range of specifically designed micromachining techniques.

MEMS technology allows the realization of an array of such sensors that can be incorporated within a small area allowing high spatial resolution and a robust design which is highly desirable in robotics, medical and industrial fields. For packaging such sensors, the general trend has been towards materials mimicking the mechanical properties of skin. To date, materials such as silicone elastomers have been used for packaging sensors. Incorporation of sensors into tissue engineered skin has not been previously explored but is important both within regenerative medicine, in the context of implantable sensors and bio hybrid systems. It is also relevant in the pharmaceutical industry for applications where it is important to mimic the contact conditions generated when human skin comes into contact with textured stimuli for characterisation of surfaces. This paper explores the integration of designed silicon based MEMS sensors with tissue engineered skin.

The following figure shows a schematic of a prosthetic device known as "The Cyberhand" which is developed by a team led by Carrozza. The device aims to replicate the sensory and motor capabilities of the human hand. Biological signals are harnessed to control the device and sensory feedback is allowed by stimulating specific nerves with signals processed from embedded tactile sensors.

IV. CYBERHAND USING TACTILE SENSORS



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V. Tissue Engineered Skin

For testing the response of MEMS sensors embedded within tissue engineered skin, the sensors were first coated with a 200 nm layer parylene (poly-para-xylylenes) through a chemical vapour deposition process. This forms a biocompatible barrier which also protects the chip from moisture and corrosive effects of the biological environment. The tissue engineered skin was then directly placed over the sensors for testing. The skin was held in place by surface tension and no adhesive layer was applied.

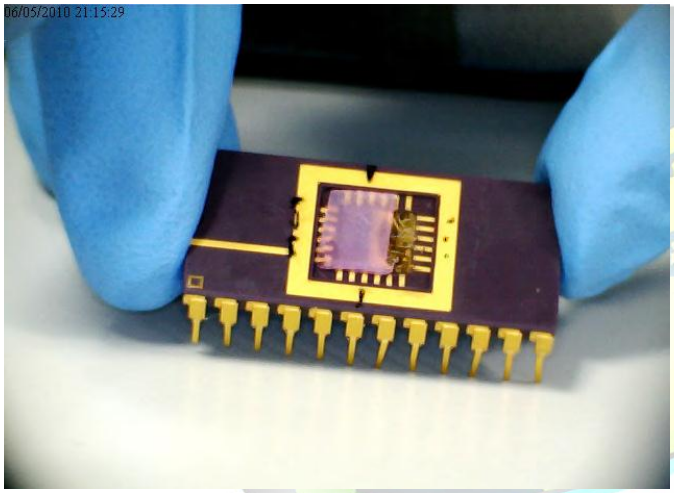

Figure: Tissue engineered skin applied onto sensor surface

Capacitive sensors:

Capacitance is the electrical property which exists between two conductors separated by an insulator. It indicates how much charge can be stored in a conductor at a given potential. Capacitors are electrical components that have the ability to store electrical energy. They consist of two conducting surfaces separated by an insulating/dielectric medium. The capacitance can be defined as the ratio between the charge Q stored in the plates and the potential V between the plates. The unit of capacitance is the C =Q/V

The capacitance C between two conducting parallel plates separated by an insulator (neglecting
fringing effects) is given by

$C = \varepsilon_0 \varepsilon_r A / d_0$ where ε_0 is the permittivity of free space (8.854 _ 10^{-12} F/m), ε_r is the dielectric constant of the medium between the plates (1 for air), A is the area of the plates and d_0 is the distance between them.

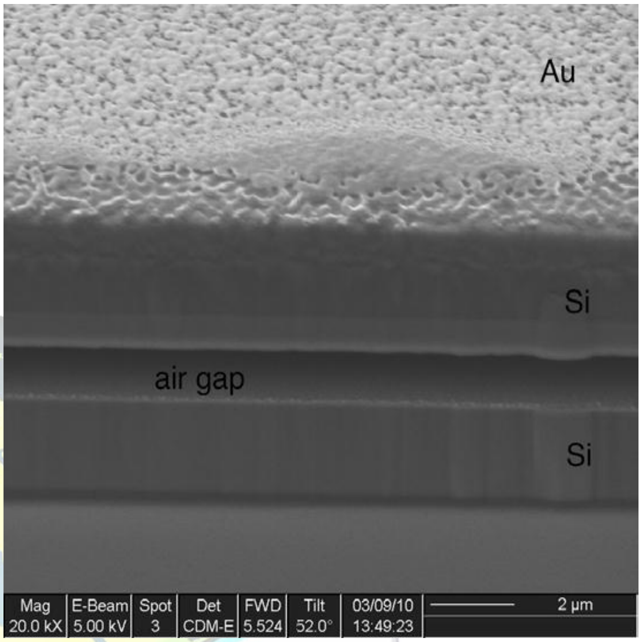

Figure: Cross Section of Capacitive Sensor.

The magnitude of capacitance is a function of the geometrical dimensions of the conducting plates and the dielectric medium. In capacitive sensors a change in a physical parameter (such as the distance between the two plates due to applied pressure) causes a change in the capacitance that is monitored and used to provide information on the applied statics. A significant amount of work has been carried out on the development of MEMS based capacitive pressure sensors. Most commonly, such devices employ a deformable diaphragm that deflects due to variation in pressure. In a similar manner, capacitive tactile sensors employ a sensing diaphragm which, under applied load, deflects towards a fixed substrate. This results in a change in the capacitance between the two plates that increases as a function of the applied pressure.

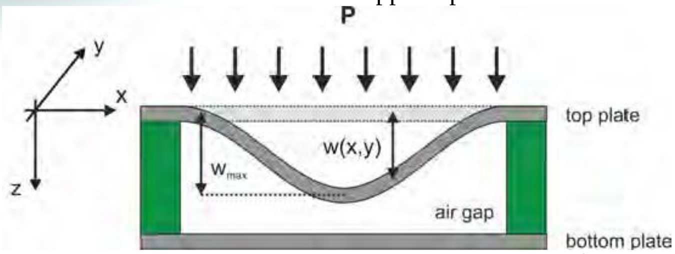

FIGURE: Pressure P applied to sensing diaphragm causes a deflection w(x) as a function of position, with the maximum deflection wmax

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VI. CHOICE OF MATERIAL

The presented capacitive sensors are fabricated with single crystal silicon diaphragms. Silicon is commonly used in micromechanical sensors because of its well established electrical and excellent mechanical properties. It is an anisotropic crystalline material whose elastic behaviour depends on its orientation relative to the crystal lattice [101]. It is widespread in the IC and MEMS industries for the following reasons :

The material is cheap and readily. It is a semiconductor whose resistivity can be adjusted from sub-mΩ cm to several kΩ cm by the process of doping. The existence of its various well established processing techniques. The possibility for integration with signal conditioning electronics.

Single crystal silicon has attractive mechanical properties in terms of its high strength which exceeds steel, high fracture strength and reproducible mechanical and electrical properties. The tensile yield strength of silicon is 7 GPa. Its Young's modulus (E) depends on the crystallographic orientation and varies from 130 - 180 GPa. The electrical properties of silicon can be modified by adding impurities (elements from group III and V of the periodic table). By adjusting doping concentrations, a range of material resistivities varying from 0.001 - 10000 cm can be attained. Dopants are introduced into silicon either by using ion implantation (by firing energetic ions directly onto silicon) during epitaxial growth or by diffusion from solid or gaseous sources.

Following implantation, thermal annealing processes are carried out to limit any damage caused by ion bombardment, and to move dopant atoms into substitutional sites in the silicon crystal where they become electrically active.

VII. FABRICATION OF TACTILE SENSOR ARRAY

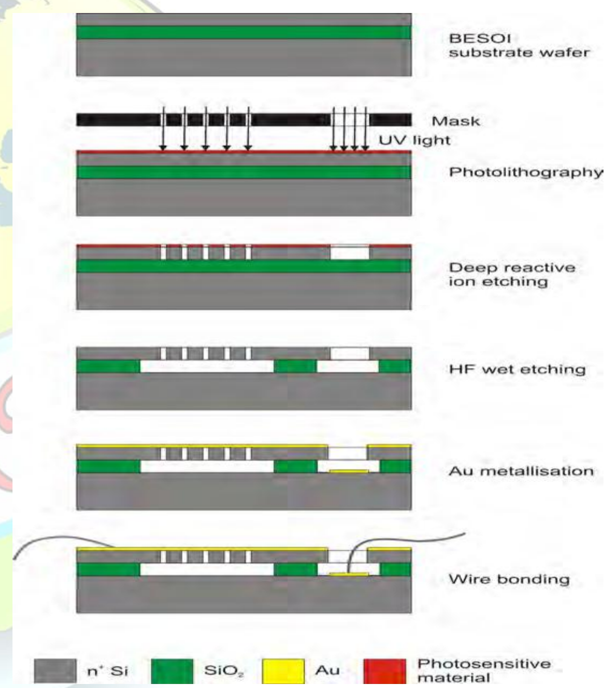
Silicon-on-insulator (SOI) substrates Silicon-on-insulator wafers (SOI) are laminar structures which consist of three main layers:

A thin top layer of silicon in which functional structures are patterned, an embedded middle insulating silicon oxide layer (buried oxide) and below this a thick bulk silicon layer (handle wafer). SOI wafers are widely used commercially in IC semiconductor device fabrication as they provide a way to increase the speed performance of CMOS circuits while also reducing power requirements.

The use of SOI wafers in the fabrication of MEMS devices allows for a straightforward creation of free standing structures by simple processes. This is done by using the oxide as a sacrificial layer, so that structures in the device layer can be released using hydrofluoric acid (HF) wet etching techniques. The most commonly referred techniques in the literature for producing SOI wafers are the Synthesis by Implanted Oxygen (SIMOX) and Bonded and etched back SOI (BESOI) techniques.

In the SIMOX technique, an oxygen implantation step is carried out followed by a high temperature (> 1300 _C) annealing step. For wafers manufactured using this method, the buried oxide thickness is limited to 800 – 1000 Å.

The fabrication of Bonded and etched Silicon on oxide wafers (BESOI) is schematically shown in the figure. Two wafers, one of which is covered with a thick oxide layer, are



Applications of tactile sensors:

Tactile sensors have an extensive range of applications across a number of domains. In the following, some major applications are described.

Medical applications:

Surgery Tactile sensors can be used to provide surgeons conducting Minimal Invasive Surgery (MIS) with a "sense of feel" allowing remote assessment of tissue health and its safe manipulation.

Diagnostic screening, by providing information on tissue properties such as elasticity, tactile sensors can be used for

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cancer screening prosthetic and orthotic devices Tactile sensors can be used to restore loss of tactile sensations for people with amputations or sensory neuropathihe.

Industrial/manufacturing processes:

In industry, tactile sensors can be used to automate manufacturing processes such as assembly, machining, sorting and stacking. Pharmaceutical Cosmetic and pharmaceutical industries employ tactile sensors to characterize the feel of different surfaces or substances in order to classify their attractiveness. Robotics Tactile sensors are implemented in robots to allow task execution such as object identification, grasping, manipulation and to enable safe interaction in unstructured environments.

VIII. Conclusion

The use of MEMS technology in implementing a bio-inspired tactile sensing device was explored in this thesis. Such an approach has numerous advantages, such as the possibility for batch fabrication, high performance. The sensitivity of the designed sensors was found to be sufficient so as to allow the decoding of textures at stimulus magnitudes (force and indentation) similar to that applied by the human fingertip during surface exploration. The performance, small size, low cost and the potential for integration of sensors and associated electronics on a single chip.

Future work:

Although a linear array of 4 sensors has been developed in this work to demonstrate a proof of concept, using the same processes outlined in this thesis, a two dimensional array can easily be implemented. This would allow the acquisition of a greater amount of tactile data at a single contact instance between the sensing device and the surface. Further, as demonstrated, by varying the geometrical dimensions of sensing diaphragms, sensors varying in sensitivity can be implemented. Thus, by incorporating sensors of different diaphragm dimensions on a single chip, a sensing device with a wider dynamic range can be achieved. In this paper, the development and characterization of a silicon based MEMS sensor has been shown, which is capable of detecting forces in the sub mN range. Tissue engineered epidermis has also been developed that can be applied to the surface of these sensors. Tactile stimulation experiments are currently being conducted on MEMS sensors incorporated into tissue engineered epidermis.

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