Printed Electronics for Body-worn RFID Sensor

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Abstract

This thesis is concerned with a body-worn RFID sensor fabrication using an inkjet printer. The research aims to explore designing a user-friendly body-worn RFID Sensor, and the development of a simpler fabrication method.

This thesis will explain why chosen conductors printing onto Tattoo paper would not be possible in this research. And how to resulted as they were not able to survive more than 3 hours on human skin and the flexibility and stretchiness of the paper damaged the circuit. This will relate to the reason why mounting the printed circuits to the tattoo paper is a delicate procedure.

Tegaderm Film is chosen due to it is thicker than Tattoo paper, and with different characteristics. So, this thesis also will introduce the methods, benefits, and differences between printing electronics on tattoo paper and Tegaderm film. Body-worn RFID sensors using Tegaderm film also will be introduced.

Acknowledgement

I would like to thank Prof. John Batchelor and Dr Robert Horne for their guidance, helpful explanations, and supervision during this project. I would also like to thank Dr Paul Taylor, Nathan Brabon, and all of the technical staff of the Engineering lab for their passionate help and assistance.

Nomenclature

List of Abbreviations

CST	computer simulation technology
FR4	flame retardant 4
Gen 2	generation-2
HF	higher frequency
IC	integrated chip
LF	lower frequency
PCB	printed circuit board
RF	radio frequency
RFID	radio frequency identification
UHF	ultra-high frequency
EMG	electromyogram

List of Symbols

°C	Degrees Celsius
Ω	ohm
λ	wavelength
MHz	megahertz
N	nano
pF	picofarad
nH	nanohenry
f	frequency
R	resistance
R_L	load resistance
Rs	source resistance
mm	millimetre
cm	centimetre

Contents

Chapter 1

1. Introduction

Since today's technology, on-skin electronics are aimed at user-friendly, low-cost, and easy fabrication. RFID is a common piece of wireless technology used for security, real-time location systems, and access control. The RFID tag's antenna can be fabricated on a low-cost dielectric substrate, which is lightweight and mass-producible Therefore, tattoo paper and Tegaderm film were initially chosen as the substrates.

Chapter 2 will introduce topics related to this research with explanations. Those topics are RFID, antenna, and electromyogram patch, and why those topics are related to this research.

Research motivation, instruments, and materials used in the research will be introduced in the project description. A simple outline of the project also will be introduced.

Printing Methodology using an Inkjet printer to print conductor on Tattoo paper will be introduced in Chapter 4. And the Characteristics on the first conductor used in this research will be introduced in the next chapter.

As this research is on printed electronics for body-worn RFID sensors, stretchable circuit designs will be required, and the designs will be explained in Chapters 7 and 8. A different printing methodology on different substrates with different conductors will also be investigated and introduced in this thesis. The second printing methodology will be explained in Chapter 9, and circuits with stretchable design in Chapter 10.

This thesis is investigated printed electronics for body-worn RFID sensors, so an RFID circuit containing an antenna and the sensor will be introduced in Chapter 11, and extra related investigation and measurement in Chapter 12. At the end of this thesis will give a conclusion about the results that came out of this research, and further research can be done on this project.

Chapter 2

2. Literature Review

2.1 Introduction

This literature review covers the topics used in the project for RFID on-skin sensors, from the structure of Radio Frequency Identification to the application of on-skin electronics.

2.2 Radio Frequency Identification

RFID is a form of wireless communication technology used to identify an object or living creature by using either electromagnetic or electrostatic coupling in the radio frequency portion of the electromagnetic spectrum. An RFID system contains RFID Tag, antenna, and RFID reader "and requires a computer database for associating each RFID tag to its identity. RFID tags are connected to an antenna that transmits the tag's ID data to an RFID reader. The RFID reader is then able to send the received data to the database containing all of the system IDs. Data received may require decoding. RFID tags are termed active or passive, based on how they are powered. UHF RFID tags operate within the 866 MHz to 869 MHz bands in Europe. RFID tags used at ultra-high frequencies (860MHz-960MHz), due to the read distance has up to 10 meters range and cost would be cheaper than other passive RFID tags, for example, RFID tags used at high frequency (13.56MHz) and low frequency (125kHz).

2.2.1 On-Skin Electronics Application

Veronica Sanchez-Romagurea et al. successfully engineered an inkjet-printed low-cost passive UHF RFID skin-mounted tattoo paper tags based on silver nanoparticle inks. Printed UHF RFID on-skin tags have a read range of 12-68cm depending on the size of the antenna. UHF RFID tags print using an inkjet printer with silver nanoparticles. Jetted inks at 30^{o}C and sintered at 135^{o}C [1], as the temperature will damage the tattoo paper during sintering for curing the conductor [2].

Other than on-skin passive UHF RFID tags, there are more on-skin electronics applications, for example, the work of John A. Rogers et al. engineered Skin-Integrated Devices with Soft, Holey Architectures for Wireless Physiological Monitoring. In the application, stretchable shape tracks(conductors) are used, and this allows the device able to be bending, twist, and stretch [3].

2.2.1.1 Other Printing Techniques

With thesis about Flexible Hybrid Electronics (FHE) from Yasser Khan et al [4]. Other than Inkjet printing, screen printing, gravure printing, blade coating, slot-die coating, and spray coating also are printing techniques in printed electronics. Screen printing has used a squeegee to transfer ink through the screen after a flood bar is used to spreads the ink over the screen. this is a good choice for printing interconnects and passive circuit elements as it is possible to get a thickness of about 100 micrometres, and it is a fast and high-volume printing technique. Gravure printing is transferring the ink to the substrate using a cylinder by rolling over the substrate. A doctor blade is used to wipe the excess ink from the cylinder after the inks are transferred to the cylinder. This printing technique is the most promising roll-to-roll printing technique able to produce a high-resolution at about $10ms^{-1}$. Doctor blades are also used in blade coating and slot-die coating to blanket coat a thin film on the substrate. However, blade coating does not have a continuous ink supply, but slot-diet does. The viscosity of the inks used for blade coating and slot-die coating is fairly low, so the thickness of printed electronics will be thin as less than 1 micrometre. Spray coating is an efficient and fast printing technique that can be obtained patterns of more than 0.1millimetre width and with a controllable thickness of about 1 micrometre using stencils. But prototyping is required as well as in large-scale manufacturing for spray coating. Passive electronic components interconnect, and antennas in FHE also can be manufactured using spray coating as Thielens et al reported a spray-coated antenna that works in the ultra-high frequency radio-frequency identification (UHF RFID) band [5].

In those different printing techniques, film roughness and design flexibility will be the important factors for printing electronics. As the substrate will be damaged during the sintering of the conductor [2], so always want to keep the substrate has no damage before sintering. Higher design flexibility allows more various designs that use printing techniques.

2.2.1.2 Integrated Circuits (ICs)

Silicon ICs are an integral part of flexible hybrid electronics, various methods with various materials have been utilized to mount electronic components and ICs onto flexible substrates in the past few years.[4] The most common rigid components are silicon ICs used in FHE, as they are used for communication, data storage and simple/complex signal processing. ICs with 4-48 contact pads have a size of 2-10mm in length & width and 0.5-2mm in thickness, some of the packages contain entail leads but some do not. However, ultrathin silicon ICs with about 25 micrometres thick have been created and ICs can be bent to a radius of curvature of 5mm.Other than thinned rigid silicon ICs, silicon on polymer substrate IC also has been fabricated. This silicon on polymer IC is ultrathin and flexible for FHE usage, and with ultrathin thick.

2.2.1.3 Surface Mounted Devices (SMD)

Surface-mounted devices such as resistors, capacitors and inductors (passive components) also are integrated parts of FHE. As capacitors and inductors are used for impedance matching in RF applications and will be explained in section 2.3.2. SMD has a variety of sizes, for example, 0402 components have a size of 1mm*0.5mm and 0603 components have a size of 1.6mm*0.8mm. However, if the required components value is high and it is possible to print flexible passive components with printing techniques, printed components usually require a large footprint for usage[4]. Precise alignment accuracies are required for placing the chip pads to printed conductors due to the size of contact pads on the ICs and SMDs. Mounting ICs and SMDs still a challenge due to pressure and heat that may damage the chips [4] or substrates [2]. Conductive adhesives adhere (or tape) can be used for connecting SMDs to printed circuits, but these connections are not as reliable as solder connections. Solder connections can be using printable inks, low-temperature solder or low-temperature conductive paste.

2.2.1.3 Printed Power Sources

Another challenge in FHE is proving adequate electrical power to the systems. A lot of modern power sources of commercially available batteries are rigid cylindrical and coin, which are bulky and hard to use. The coin battery is easier to use than the cylindrical battery as they are thinner and smaller, but as coin battery is rigid to cause discomfort wearing on the skin. [4] Stretchable and flexible batteries also will be required in FHE, and the battery can be made by using silver-zinc and zinc-manganese which are less toxic and reactive compared to rechargeable chemistries.

2.2.1.4 Application of FHE

Flexible, stretchable and conformable electronic devices can mould the curves of the human body that rigid electronic devices cannot do, so health care is the biggest and one of the main application areas of flexible hybrid electronics. Most of the bio-signals like temperatures, heart rate, respiration rate blood pressure and pulse oxygenation can be measured by using FHE. Flexible and stretchable body-worn sensors without causing discomfort can use for health monitoring outside the hospital which can cut the cost and time of hospital stays.

Electrocardiogram (ECG) and photoplethysmogram (PPG) are the common bio-signals measured using FHE systems in recent years. [4]Other than ECG and PPG, a sensor on the wrist band is engineered by Gao et al to measure potassium, sodium, glucose, and lactate concentration in the sweat of the users[6]. Kim et al developed a mouthguard containing a Bluetooth transceiver and a sensor for monitoring salivary uric acid levels[7]. Khan et al designed a sensor measuring the oxygenation of volunteers under normal and ischemic conditions by using arrays of organic light-emitting diode (OLEDs) and organic photodetectors (OPDs) to measure blood and tissue oxygenation [8]. There are not only sensors used in FHE, display modules also can be used in FHE. The display can be placed as a part of FHE to show how information/data. With visualized information, users able are to use the devices without a host device. For FHE usage, the display needs to be flexible, low power, printable and also want to be low cost and stretchable. [4] For example, Yokota et al. demonstrated an extremely thin seven-segment display fabricated with chemical vapour deposition[9].

Other than health monitoring on the human body, FHE also can use for monitoring object changes [4] as the FHE is designed as stretchable, so it can be used to measure the level of stretches such as stretches from plants growing and stretches caused on material by bending.

2.3 Antenna

An antenna is a metallic structure used for transmitting and receiving electromagnetic signals and can be of various shapes and sizes. Antennas are commonly used for broadcasting signals over vast distances and are used for satellite communications, the internet, and television. One of the most important antenna parameters is the antenna gain, this parameter will affect directivity (how good the antenna can transmit the power in a certain direction) and efficiency, so the antenna read range also will be affected by the antenna gain.

2.3.1 Loop Antenna

A Loop antenna is a radio antenna consisting of a loop that can be of various shapes and sizes. A single-turn small transmitting loop is considered small if the conductor used in the loop antenna has a length $<\lambda/10$[10]. A Loop antenna is designed for use at ultra-high frequencies(UHF), with a conductor length of 10mm is engineered in CST Microwave Studio^{TM} by Paul S. Taylor and John C. Batchelor. The Loop antenna is placed in a human mouth equivalent model and able to be read from 20-80cm depending on the angle of the antenna.

2.3.2 Matching Network

An antenna might not have the expected impedance for an RF chip, due to the limit of the application. So, a matching network will be applied for turning the antenna impedance and making the antenna impedance get close to the expected required impedance from the RF chip. Components used in the matching networks for loop antennae are inductors and capacitors[3], which a simple inductor-capacitor (LC) circuit can use to match a wide range of impedance in RF circuits. L matching network is chosen by this matching network able to correspond to the situation for either Low-pass or High-pass Is required when $Rs<R_L$, $Rs>R_L$.[11]

2.3.3 Antennas with Printing Techniques

Screen printing and inkjet printing are the most common printing technique for printing antennas, but other printing techniques also can be used for printing antennas. [4] Ultra-high frequency (860MHz-960MHz)and license-free Industrial scientific and medical (ISM) frequency bands (around 2.45GHz and 5GHz) are the most studied frequency band that use printing techniques.

2.4 Electromyogram Patch

Electromyography (EMG) measures electrical activity in muscle response and helps to detect neuromuscular abnormalities. An EMG patch is a conductor patch used for measuring the electromyogram (EMG)signal to show muscle activity. An EMG patch contains 2 electrode patches that can be of various shapes and sizes, those 2 patches will connect to an analogue circuit for receiving the EMG signals.[12]

2.5 Summary

With the results, the printed conductor can use for placed on the skin using tattoo paper[1], print an EMG patch used on the skin need to be designed in a stretchable shape for able to sustain more stretches. The inkjet printing technique is chosen by it has high design flexibility and low film roughness[4]; it has a limited print area, but this will not be an issue due to the body-worn RFID sensor will be designed in a small size. Due to the inkjet conductors needing to print on tattoo paper, a low-temperature cured conductor is required[2]. As this sensor is an RFID application, an antenna needs to be used contains in the sensor. The body-worn devices will be easy to use with a limited size, so a matching network will help improve the antenna performance[3]. Other than EMG patches, other sensors are also able used on printed conductors, for example, temperature, electrocardiogram, vibration, etc.

Chapter 3

3. Project Description

3.1 Research Motivation

Since the Covid-19 pandemic, a lot of public buildings in China have instruments at the entrance for measuring body temperature. Most of the instruments measure the body temperature by using an infrared thermometer. However, the infrared thermometer only has about 15cm as the ideal distance for use and correctly monitoring the temperature. But an RFID tag with a temperature sensor also can be used for measuring the body temperature within up to 10 meters range. Also due to a large number of people would get COVID-19 in a short period, so the motivation is to find an easy method able to fabricate an on-skin sensor tag in a short time. Sensor tags also need to be user-friendly and lightweight, as the RFID sensor tags cannot effects people's daily life, and actions without causing discomfort. Skin-based temperature sensing is considered as an example application in this project which investigates the manufacture by printing of RFID sensing electronics on very soft substrates which are comfortable for long-term mounting on the skin.

3.2 Materials & Instruments Used

Tattoo Paper

The first skin mountable substrate considered was temporary Tattoo A4 Paper used in the research is the tattoo paper provided by The Magic Touch. This Temporary Tattoo A4 Paper contains two different types of sheets, a tattoo sheet, and an adhesive sheet.

Figure 3.1: Tattoo sheet

Figure 3.2: Adhesive sheet

A tattoo sheet, Fig 3.1, has the characteristics of thin cardboard but with one single water-repellent surface. A water-repellent surface is a side used for printing flexible conductors. The adhesive sheet, Fig 3.2, contains three layers similar to double-sided adhesive tape. It is used for sticking the printed circuit to the object/skin. The process to place the circuits on an object/skin requires certain amounts of water and pressure. (https://www.themagictouch.co.uk/product-category/the-magic-touch/transfer-paper/temporary-tattoo/)

Tegaderm Film

Figure 3.3: Different Styles Tegaderm Films

Tegaderm Transparent Film Dressing Frame Style provide by 3M^{TM} is a waterproof transparent thin stretchable plastic sheet with a single sticky surface (https://www.3m.co.uk/3M/en_GB/p/d/b00035590/). It is designed to protect wounds or/and secure devices to the skin. Tegaderm Film also can use as a barrier to protect against external contaminants such as viruses and bacteria. Tegaderm Film Frame Style has a layer with the characteristic of thin cardboard under the Tegaderm layer to protect the adhesive part of the Tegaderm Film.

Other than the Frame Style, there has a Roll Style (https://www.3m.co.uk/3M/en_GB/p/d/b00035572/) that was able to cut the Tegaderm Film to the preferred shape and size. Tegaderm Film Roll Style also has a layer under the Tegaderm layer to protect the adhesive part of Tegaderm Film, but different to Frame Style as the adhesive protection layer is a soft and very thin plastic layer.

Voltera V-One PCB Printer & Ink

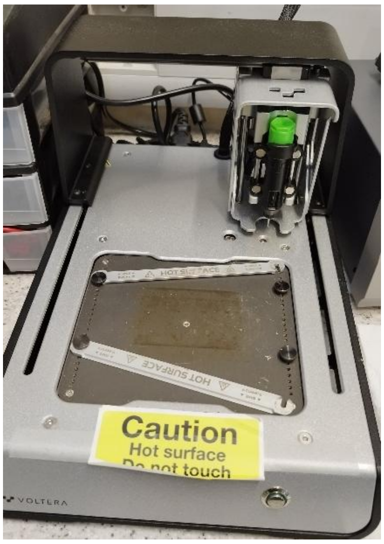


Figure 3.4: Voltera V-One PCB Printer

Figure 3.5: Voltera Conductive Inks

A PCB Printer provided by Voltera (https://www.voltera.io/store/v-one) was used to print conductors on substates including Flame Retardant (FR) board, as well as flexible sheets. The software used for this PCB Printer allows reading the Gerber image (.gbr) file created from other software.

The Voltera V-One PCB Printer can control the amount of conductor inkjet output and baking temperature in detail.

Voltera Flex2 Ink is the second-generation flexible conductive ink that allows higher conductivity, better printing resolution, and bending performance, it is recommended to heat at 160°C for 30 minutes (https://www.voltera.io/store/consumables/flex-2-conductive-ink).

PE874 Conductor Paste

Figure 3.6: PE874 Conductive Paste

A silver-bearing conductor with high recovery stretchability is provided by DuPont™ Intexar™ This stretchable conductor can be cured for sintering at 130°C for 15 minutes. (https://www.dupont.com/content/dam/dupont/amer/us/en/mobility/public/documents/en/PE874.pdf).

9703 Conductive Adhesive Tape

Figure 3.7: 9703 Conductive Adhesive Tape

3M 9703 Conductive adhesive tape has the characteristics of double-sided adhesive tape, and this tape is used to connect the components to the circuit. 9703 tape recommend to be applied between 15°C – 70°C, also applying higher temperatures helps to remove adhesive parts of the tape (https://docs.rs-online.com/7336/0900766b8113fa52.pdf).

3.3 Outline of Project

All circuits have been printed using a 'Voltera V-One PCB printer' onto 'Voltera flexible conductor'. Circuits will be printed with the inkjet printing technique, onto tattoo papers and Tegaderm films. The conductor used in this research will be Voltera Flex2 Conductor and PE874 Conductor paste, see Section 3.2.

Tattoo paper will be used as the first substrate for printing Voltera Flex2 Conductor onto it, which is used for measuring the conductor resistance changes with different sintering temperatures and times. Various stretchable tracks will be designed and printed, the resistance of the conductor also will be measured and printed stretchable tracks will test the strength by placing on the human body. As this research is for Body-worn RFID sensors, EMG patches will also be designed and printed on tattoo paper, and strength tests also will be done by placed on the human body.

Due to the Tegaderm Film characteristic, stretches from the skin are applied less to the printed circuit compared to using Tattoo paper. Mounting Tegaderm film on the skin requires less pressure applied to the circuit due to the way uses of Tegaderm film, so the circuit can mount on the skin with less risk of circuit get damage.

The method used to mount the printed circuit onto Tattoo paper to the skin is only able to place extra layers on the top of the circuit after being mounted on the skin, to protect the circuit from friction and pressure. But with Tegaderm film, extra layers can be placed before mounting the circuit onto the skin. This allows for investigating the robustness of the circuits with an overlay substrate, and the test will be done by placed on the human body.

Since PE874 Conductor paste is a stretchable and flexible conductor compared to Voltera Flex2 Conductor only a flexible conductor, PE874 conductor paste is used instead.

Printed circuits with PE874 will also perform strength tests on the human body, and simply LED circuits will be printed and placed on the human body for testing the performance of the conductor and conductive adhesive tape.

Antennas used for wireless transmission will be printed using the inkjet printing technique and the antennas will be tested in air, on human equivalent phantom (a block of ham) and the human body. As the antenna may not have a good impedance matching, a matching circuit (or matching network, see Section 2.3.2) will be developed, and the antenna with a matching network will also be tested in air, on human equivalent phantom (a block of ham) and the human body.

Chapter 4

4. Printing Methodology on Tattoo Paper

The first fabrication method is using tattoo paper as a substrate with Voltera flexible conductor inkjet as the conductor for the circuit.

Fabrication Steps

1. Cut the tattoo sheet to be the same as the size FR board and stick the tattoo sheet on the FR board using double-sided adhesive tape, Fig4.1.

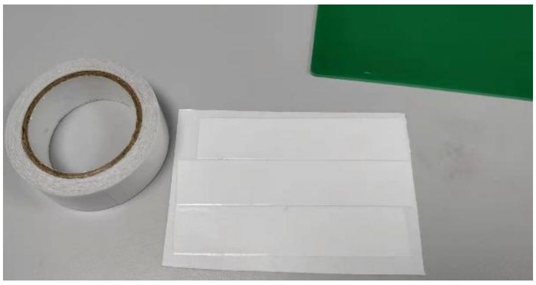


Figure 4.1 Tattoo sheet with Adhesive tape

This helps keep the tattoo sheet flat during the process of printing circuits, otherwise, there would be gaps under the tattoo sheet, and it would be the risk the print conductor has uneven thickness.

2. Place the FR board on Voltera V-One Printer, then print the circuit on the tattoo sheet. When setting up the Voltera V-One printer software an important step is to tune the gear on the dispenser in order to allow for more accurate control. Ensure the gear is turned 45 degrees in order to allow more accurate control of the ink jetting, the notch in the middle of the dispenser gear is helpful for this as seen in Fig 4.2.

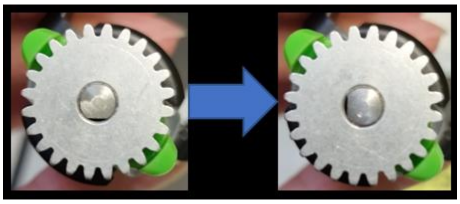
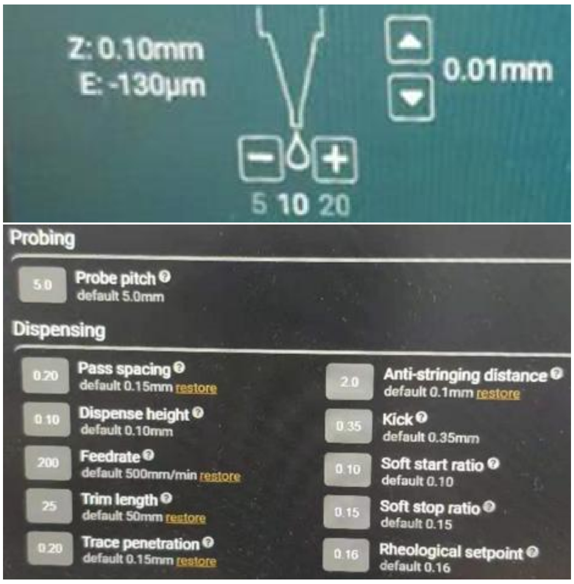


Figure 4.2: Inkjet Preparation

3. With regards to the setting of the Voltera V-One PCB Printer for printing circuits shown in Fig 4.3. The variables that will affect the ink output amount are the ‘E’ parameter and Feedrate. The ‘E’ parameter is the biggest factor used to control inkjet output, as it is the factor to change the amount of ink that will be pushed out. Feedrate is the sub-factor that will change the inkjet output amountas a higher Feedrate will increase the printing speed. At higher print speeds, the

quality of the tracks is compromised as breaking or unconnected points will occur due insufficient ink being jetted onto the print substrate. Dispensing height refers to the distance between nozzle and print substrate and is another variable that could affect the quality of print. If the dispensing height is too low, there will be a risk of damage to the print substrate. If the height is too high, the printed conductor will be less accurate.



Probing

5.0 Probe pitch
default 5.0mm

Dispensing

0.20 Pass spacing
default 0.15mm restore

0.10 Dispense height
default 0.10mm

200 Feedrate
default 500mm/min restore

25 Trim length
default 50mm restore

0.20 Trace penetration
default 0.15mm restore

2.0 Anti-stringing distance
default 0.1mm restore

0.35 Kick
default 0.35mm

0.10 Soft start ratio
default 0.10

0.15 Soft stop ratio
default 0.15

0.16 Rheological setpoint
default 0.16

Figure 4.3: Voltera Setting

4. Bake (heat) the circuit (including the underlying FR4 board and tattoo sheet). A temperature of 135°C for 60 minutes was found to be optimal for ink conductivity and robustness according to the measurements reported in Section 2.2.1. The baking temperature is set under the recommended temperature due to a higher temperature will damage the tattoo sheet [2].

5. Place components on the circuit using 9703 conductive adhesive tape.

Figure 4.4: Applied Conductive Adhesive Tape to Printed Conductor

Place conductive adhesive tape on the printed conductor and remove the release liner, the adhesive layer will break the printed conductor as pictured in Fig 4.4. To reduce the risk of adhesive tape breaking the printed conductor when removing the release liner, apply pressure to the adhesive tape (use any tools that will not damage the printed conductor) and heat the adhesive tape (using a heat gun) at 160°C for no more than 20 seconds. After the adhesive tape has cooled enough as to not get burned, apply pressure to the tape again and then use a tweezer to remove the release liner.

6. Apply the adhesive sheet on the circuit and remove the circuit-included tattoo sheet from the FR board, Fig 4.5.

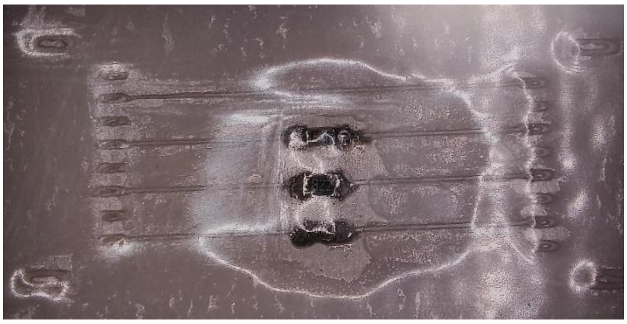


Figure 4.5: Adhesive sheet applied to Printed Circuit

7. Remove the plastic layer used to protect the adhesive part from the adhesive sheet and make sure the adhesive part is applied to the circuit, make sure the adhesive part is applied on to the circuit as pictured inf Fig 4.6.

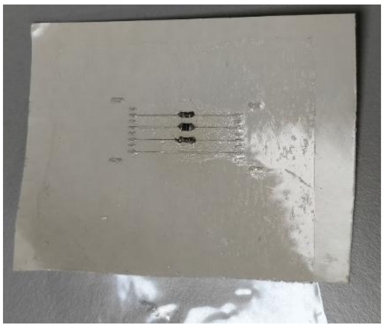


Figure 4.6: Release Liner removed on Printed Circuit

8. Place the circuit on the object/skin, then apply water to the tattoo sheet. After enough amount of water is applied to the tattoo sheet, the tattoo sheet will be easy to remove from the circuit.

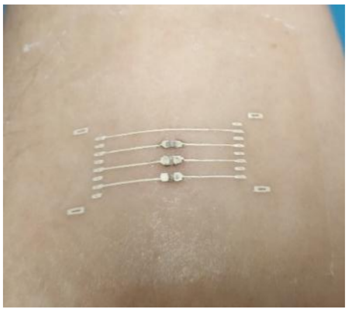


Figure 4.7: Printed Circuit Placed on Skin

Chapter 5

5. Printed track Characteristics on FR-4 Substrate and Tattoo Transfer Paper

5.1 Straight Tracks Printed used Voltera Flex2 Ink on FR-4 Substrate

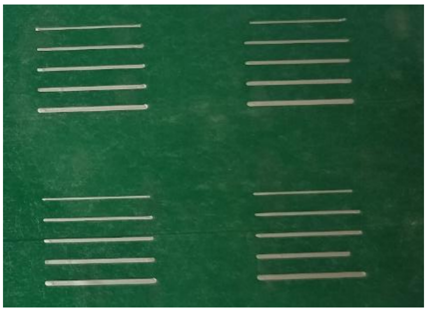


Figure 5.1: Printed Tracks on FR-4 Substrate

The first test is made up of 15 samples of printed straight 15mm long tracks pictured in Fig 5.1. Each sample is printed with different widths on the FR-4 substrates and baked at different temperatures/times in order to find out the temperature and time that produces the track with the lowest resistance(Ω).[A1]

Average Resistance[Ω] for Tracks Bake in Difference Temperature & Time						
Temperature [°C]	Time [minutes]	Track width [mm]				
		0.25	0.35	0.45	0.55	0.65
90	40	0.678	0.453	0.373	0.283	0.218
	50	0.688	0.473	0.380	0.285	0.228
	60	0.535	0.383	0.295	0.230	0.190
100	40	0.780	0.455	0.323	0.258	0.198
	50	0.333	0.215	0.168	0.143	0.120
	60	0.253	0.258	0.200	0.160	0.133
120	30	0.333	0.220	0.173	0.135	0.110
	40	0.300	0.185	0.143	0.113	0.093
	50	0.370	0.225	0.178	0.145	0.128
130	30	0.240	0.180	0.133	0.110	0.095
	40	0.337	0.247	0.168	0.150	0.128
	50	0.348	0.175	0.138	0.108	0.088
140	30	0.323	0.205	0.163	0.125	0.105
	40	0.368	0.243	0.190	0.133	0.108
	50	0.300	0.193	0.148	0.113	0.095

Table 1: Average Resistance from Different Width Tracks Sintered in Different Temperatures & Time

The average resistance for each track that were sintered at different temperatures and times were measured using a multimeter and shown in Table 1.

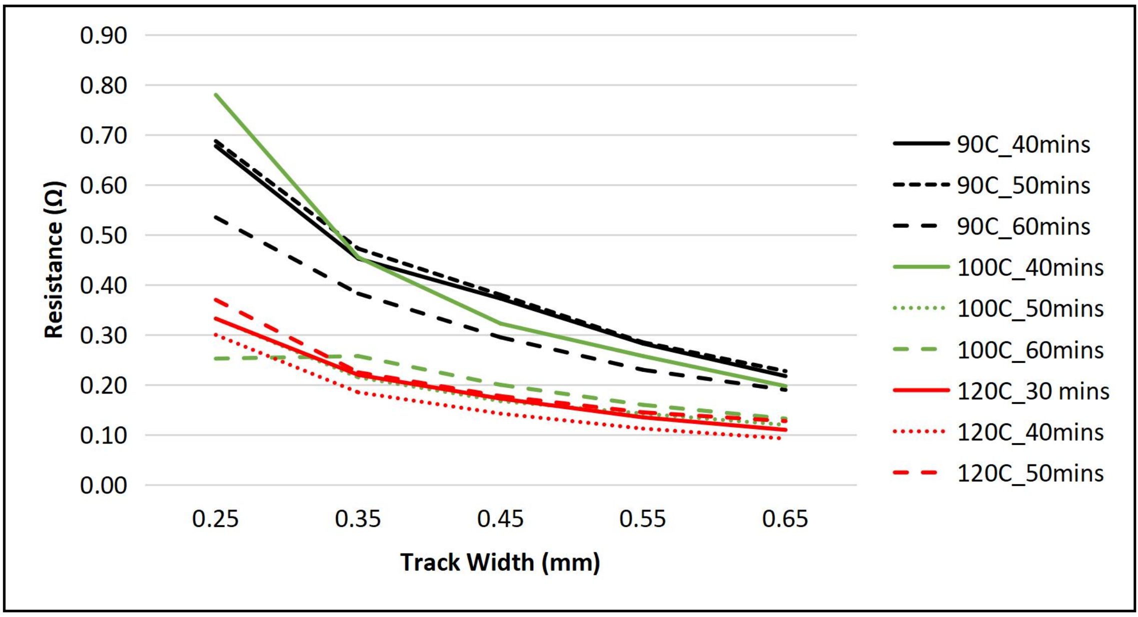


Figure 5.2: Different Width Tracks Average Resistance sintered in 90°C,100°C,120°C with Different Time

The observed results of measured resistance of tracks sintered at 90°C show that tracks sintered for 60 minutes have lower resistance than 40 mins. Tracks sintered at 100oC for different times give similar results compared to tracks at 90oC. Sintering the tracks for a longer time give less track resistance. Tracks sintered at 120 for all 3 different tested times gave the lowest resistance when compared to the other temperatures. All tracks sintered at 120oC with a wider width than 0.35mm have the lowest resistance, this would make sense as the larger cross-sectional area would allow for more current to pass through the conductor and therefore have a lower resistance.

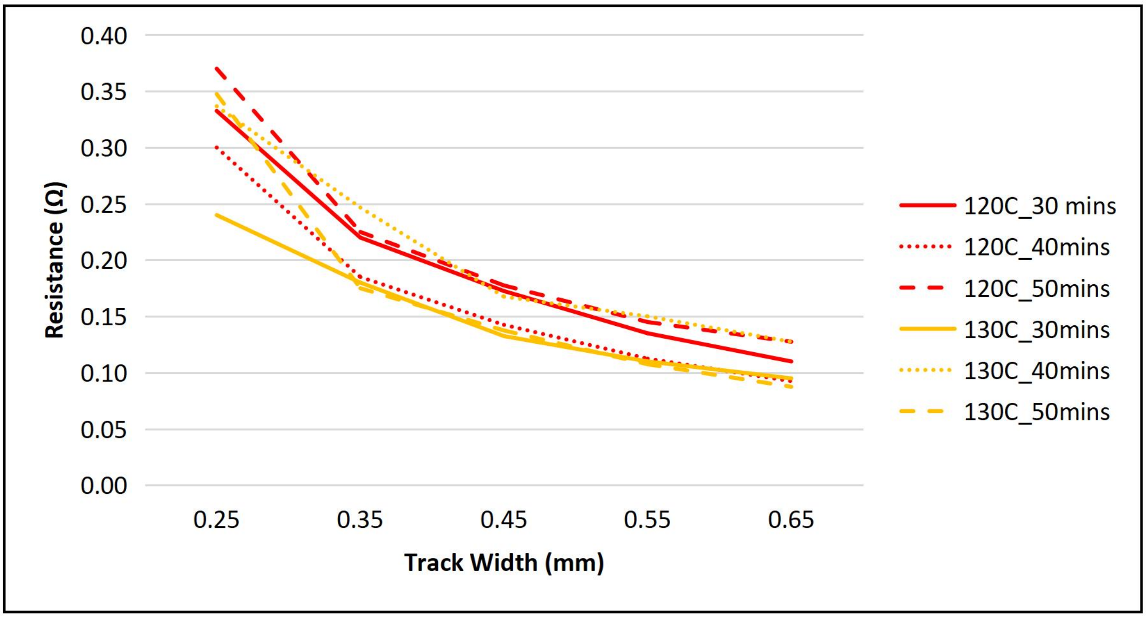


Figure 5.3: Different Width Tracks Average Resistance sintered in 120°C,130°C with Different Time

Fig 5.3 shows the results of measured average resistance for printed tracks sintered at 120°C and 130°C. Tracks sintered at 120°C for 40 minutes, 130°C for 30 minutes and 50 minutes have similar resistance. Referent to the results of average resistance in Table 1, differences in the track resistance are lower than 0.1Ω. Therefore, the conductor cured at 120°C for 40 minutes has a condition similar to the conductor sintered at 130°C for 30 minutes and 50 minutes. However, due to tracks being printed individually for sintering at different temperatures and times, there would be a difference in the track thickness between each other.

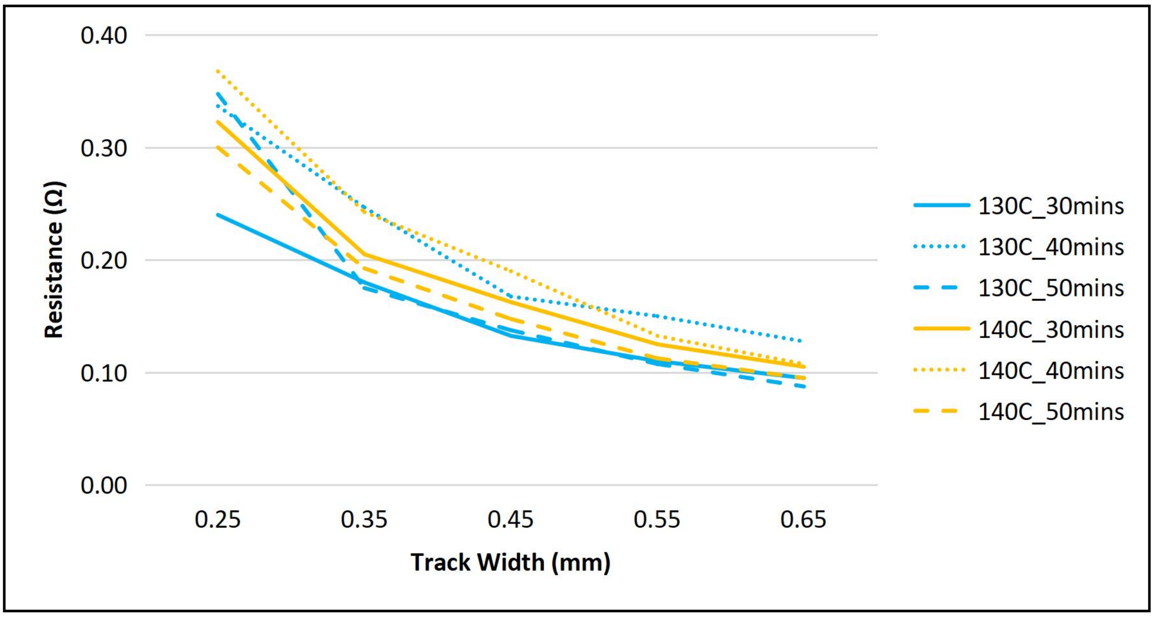


Figure 5.4: Different Width Tracks Average Resistance sintered in 130°C,140°C with Different Time

Compare the measured resistance for tracks sintered at 130°C and 140°C. In Fig 5.4. Track resistance measured from tracks sintered at 140°C is higher than tracks resistance measured from tracks sintered at 130°COverall the results of all measured resistance in Table1, tracks with more width have lower resistance due to the increased cross-sectional area of printed tracks area increased. [1]

Recommended bake setting for curing Voltera Flex 2 Ink is at 160°C for 30 minutes Flex 2 Ink is 160°C for 30 minutes as seen in section 3.2. However, there is significant risk of the tattoo sheet being damaged at temperatures higher than 135, therefore the bake was run for longer in order to make up for the lower temperature.

The conductor temperature was measured using an infrared thermometer during sintering. The measured result was approximately 130°C, so the printed conductor is accurately sintered below 140°C. With the results shown bake for 120°C, 130°C and 140°C produced similar resistance. Therefore, there is not any advantage to curing the flexible conductor with a temperature higher than 135°C [1].

5.2 Straight Tracks on Tattoo Sheet on Tattoo Sheet, 120^{o}C Study

As the resistance measured from the track sintered at 120^{o}C and 130^{o}C are similar. In order to reduce the risk of damage to the tattoo sheet the flexible conductor was sintered at 120^{o}C. As the curing temperatures are lower than recommended, the time curing the conductor will be extended to 40 minutes and 50 minutes.

120C for 40 mins						
Track width[mm]	0.4	0.45	0.5	0.55	0.6	0.65
Sample 1	0.21	0.18	0.17	0.12	0.11	0.13
Sample 2	0.21	0.2	0.17	0.13	0.12	0.13
Sample 3	0.21	0.19	0.17	0.12	0.13	0.13
Sample 4	0.2	0.18	0.18	0.14	0.14	0.13
Sample 5	0.18	0.18	0.16	0.14	0.13	0.14
Average	0.202	0.186	0.17	0.13	0.126	0.132

Table 2: Resistance of Tracks sintered at 120^{o}C for 40 minutes on Tattoo sheet

120C for 50 mins						
Track width[mm]	0.4	0.45	0.5	0.55	0.6	0.65
Sample 1	0.21	0.18	0.18	0.14	0.13	0.13
Sample 2	0.2	0.18	0.18	0.14	0.14	0.12
Sample 3	0.19	0.15	0.17	0.15	0.13	0.13
Sample 4	0.17	0.15	0.17	0.15	0.13	0.13
Sample 5	0.21	0.18	0.18	0.14	0.13	0.11
Average	0.196	0.168	0.176	0.144	0.132	0.124

Table 3: Resistance of Tracks sintered at 120^{o}C for 50 minutes on Tattoo sheet

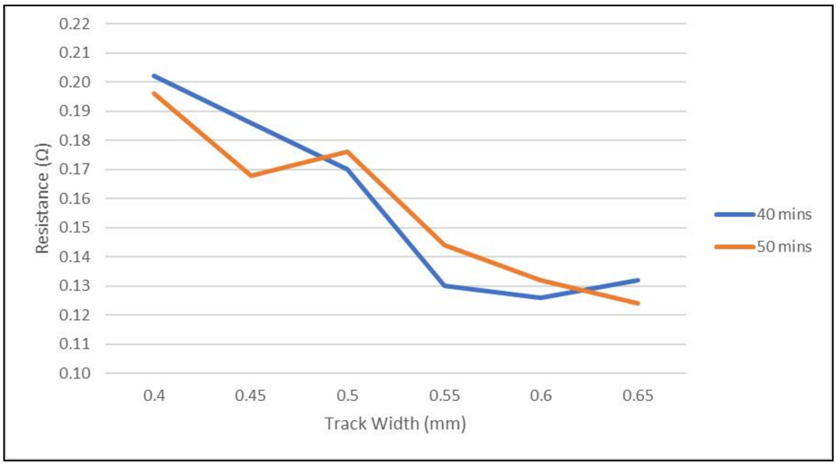


Figure 5.5: Average Resistance of Tracks sintered at 120^{o}C for Different Times on Tattoo sheet

In Fig 5.5, the average resistance measured from the tracks sintered at 120^{o}C for 40 minutes has similar results compared with the tracks cured at 120^{o}C for 50 minutes. However, measured results from tracks with track widths of 0.5mm, 0.55mm and 0.6mm sintered for 40 minutes have lower resistance than tracks sintered for 50 minutes.

Chapter 6

6. Stretchable Tracks Designs

6.1 Simple Stretchable Tracks Design

While Sections 5 investigated printed straight tracks for resistance, it is necessary to consider track design in the case of stretching which will occur on the skin. Therefore an investigation is carried out with tracks using a serpentine shape cured at 120C for 40, 50 and 60 minutes. Resistance is measured to establish performance.

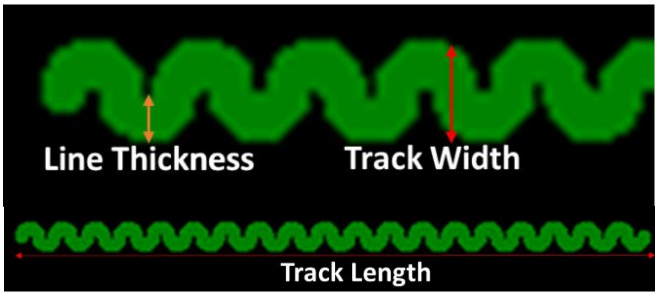


Figure 6.1: Changed Parameters in Designs

Unit[mm]	Design 1	Design 2	Design 3	Design 4	Design 5
Line Thickness	0.3	0.3	0.35	0.4	0.45
Track Width	0.6	0.7	0.75	0.8	0.85
Track Length	15.6	15.5	15.55	15.65	15.65

Table 4: Design Parameters for Stretchable Tracks

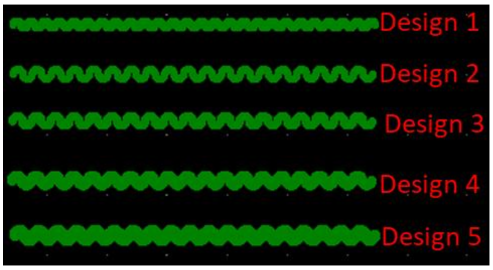


Figure 6.2: Design Shown in '.gbr' File

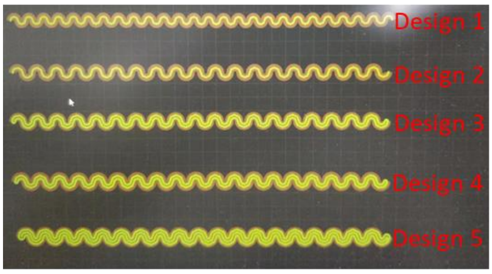


Figure 6.3:Design read in Voltera Software

Stretchable tracks, Fig 6.1, designs used the parameters in Table 4. Those stretchable tracks are designed for investigating the resistance difference between the changes and the track strength when placing the tracks on human skin using tattoo paper.

Design 3 and design 4 shown in the Gerber image file do have different line thickness, Fig 6.2, but when the file is loaded into Voltera software, Fig 6.3, design 3 and 4 have the same line thickness. Therefore, design 3 and design 4 will have similar resistance.

Due to the performance of the Voltera software, line thickness can only be recognised to 1 decimal place.

120C for 40 mins					
Track width[mm]	Design 1	Design 2	Design 3	Design 4	Design 5
Sample 1	0.4	0.46	0.24	0.22	0.12
Sample 2	0.37	0.42	0.23	0.21	0.14
Sample 3	0.4	0.47	0.23	0.24	0.12
Sample 4	0.41	0.52	0.22	0.25	0.16
Sample 5	0.37	0.45	0.25	0.25	0.16
Sample 6	0.44	0.53	0.26	0.26	0.17
Average	0.39833333	0.475	0.2383333	0.2383333	0.145

Table 5: Stretchable Track Resistance Cured at 120^{o}C for 40 minutes

120C for 50 mins					
Track width[mm]	Design 1	Design 2	Design 3	Design 4	Design 5
Sample 1	0.4	0.51	0.24	0.22	0.13
Sample 2	0.42	0.46	0.23	0.25	0.16
Sample 3	0.42	0.47	0.23	0.23	0.17
Sample 4	0.42	0.58	0.2	0.25	0.17
Sample 5	0.4	0.47	0.26	0.25	0.17
Sample 6	0.41	0.53	0.27	0.27	0.17
Average	0.41166667	0.5033333	0.2383333	0.245	0.1616667

Table 6: Stretchable Track Resistance Cured at 120^{o}C for 50 minutes

120C for 60 mins					
Track width[mm]	Design 1	Design 2	Design 3	Design 4	Design 5
Sample 1	0.37	0.46	0.23	0.21	0.13
Sample 2	0.35	0.41	0.2	0.2	0.14
Sample 3	0.41	0.44	0.22	0.23	0.16
Sample 4	0.35	0.44	0.19	0.23	0.15
Sample 5	0.37	0.44	0.24	0.25	0.16
Sample 6	0.39	0.49	0.26	0.28	0.17
Average	0.37333333	0.4466667	0.2233333	0.2333333	0.1516667

Table 7: Stretchable Track Resistance Cured at 120^{o}C for 60 minutes

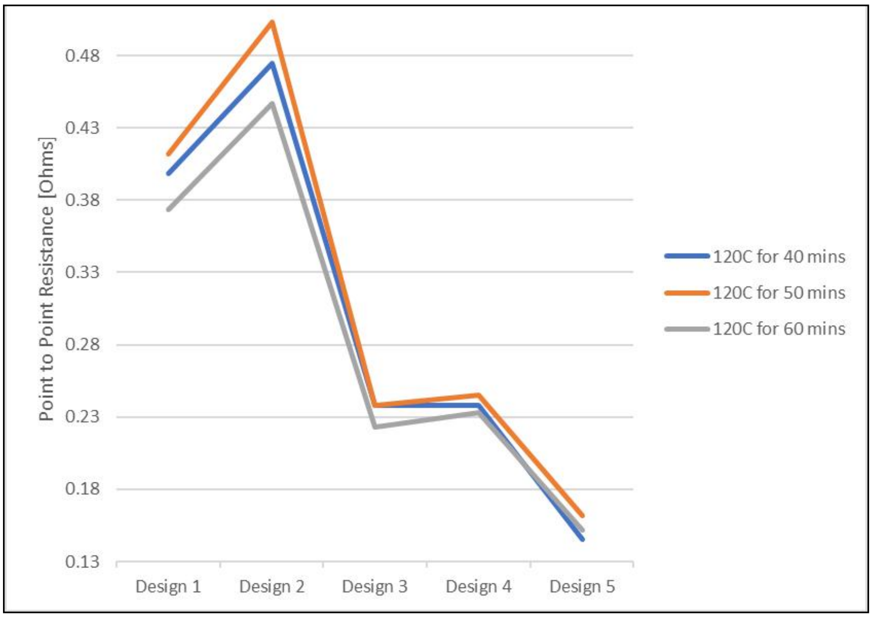


Figure 6.4: Average Resistance of Stretchable Track Cured at 120°C in Different Time

Results of measured resistance compared with printed stretchable design tracks sintered at 120°C for 40, 50 and 60 minutes, lowest resistance is given by the tracks sintered for 60 minutes, Fig 6.4. Tracks sintered for 50 minutes given the highest track resistance, and tracks sintered for 40 minutes has the resistance between the results of tracks sintered for 50 minutes and 60 minutes.

Even the tracks sintered for 60 minutes have the lowest resistance, but the difference compared to the track's resistance sintered for 40 minutes and 50 minutes is less than 0.1Ω. Therefore, to prevent the tattoo sheet get damaged sintering printed tracks at 120°C for 40 minutes will be the best sintering setting for curing conductors on tattoo sheets.

6.2 Strength Test for Simple Stretchable Design on Arm

To test the strength of printed stretchable design tracks in Section 6.1 by using the fabrication method, see Section 4.

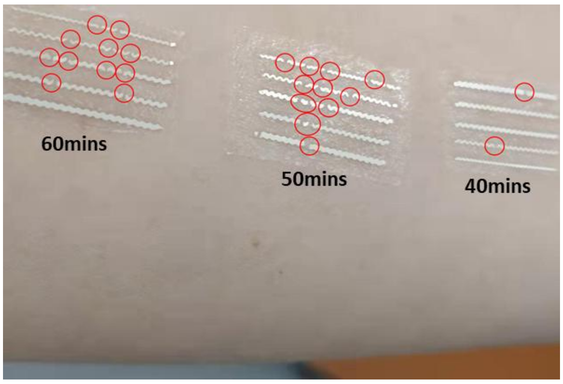


Figure 6.5: Printed Stretchable Design Tracks on Arm(a)

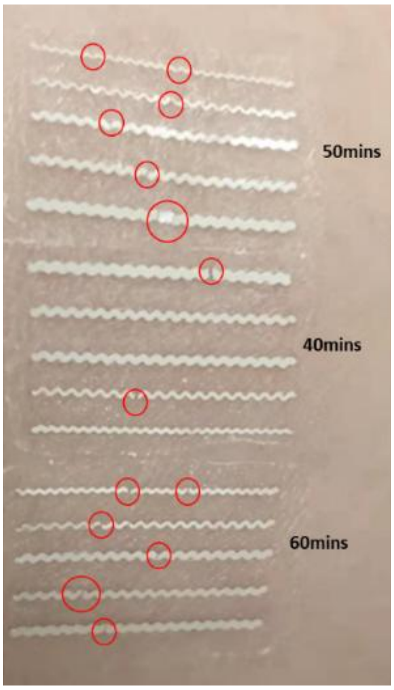


Figure 6.6: Printed Stretchable Design Tracks on Arm(b)

Placed the printed tracks on arm to test the track's strength, Fig 6.5, tracks were sintered for 40 minutes. Tracks with designs sintered for 60 minutes, and tracks with designs 1,3 and 4 are sintered for 40 minutes and did not break.

As the human skin will give different levels of stretches, place another sample for tracks sintered for 50 minutes and 60 minutes next to the tracks sintered for 40 minutes, Fig 6.6. This is used to reduces the difference in stretches given by different positions of the arm. However, all new placed stretchable tracks are broken. Therefore, printed tracks sintered for 50 minutes, and 60 minutes are firmer than the tracks sintered for 40 minutes.

Chapter 7

7. EMG Patch Designs & Strength Test

7.1 EMG Patch Designs

7.1.1 First EMG Patch Design

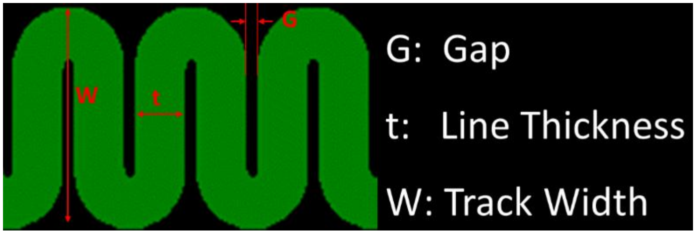


Figure 7.1: Stretchable Tracks Design Parameters

Due to print resolution, the previous stretchable tracks design, Section 6.2, did not print in a clear wave shape, and therefore maximum stretch levels able to sustain by printed tracks will be low.

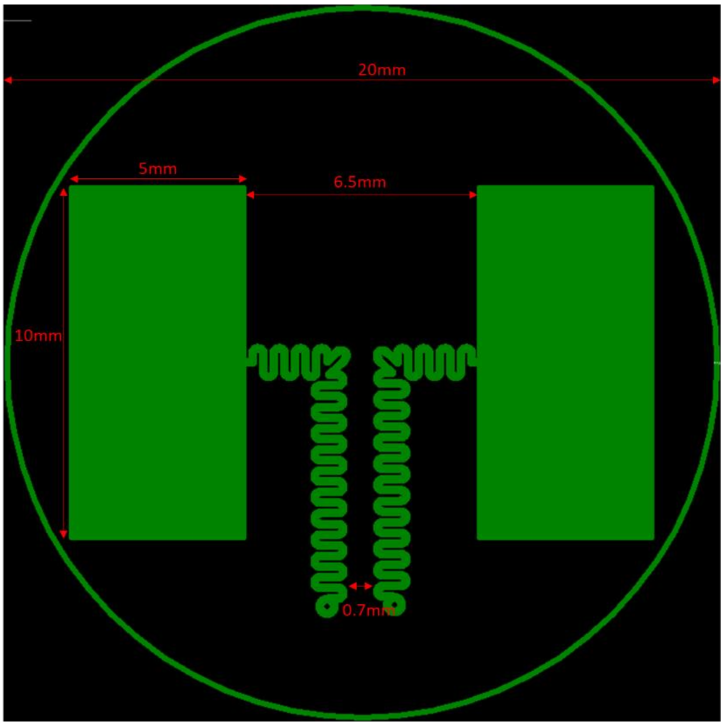


Figure 7.2: EMG Patch Design(a)

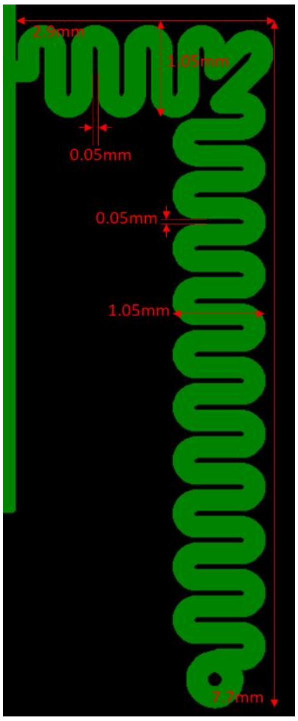


Figure 7.3:EMG Patch Design(b)

Stretchable Tracks Design Parameters	
Line Thickness	0.25
Gap	0.05
Track Width	1.05

Table 8: Stretchable Tracks Parameters used in First EMG Patch Design

In order to make the Voltera V-One Printer able to print the stretchable tracks in a clear wave shape, the gap and track width was increased to a line thickness of 0.25mm. EMG patch designed in a limited area of a circle has a radius of 10cm and the patch size is 5mm*10mm, Fig 7.2 & Fig 7.3. As shown in the parameters in Table8, the line thickness is 0.25mm in the Gerber image file, but the line thickness is 0.3mm when the file is loaded in Voltera.

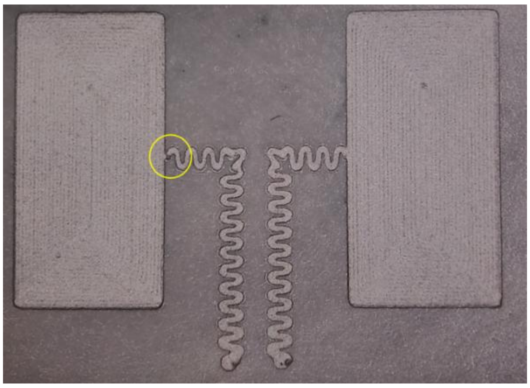


Figure 7.4: Printed EMG Patch on Tattoo Sheet

Tracks of EMG patch printed on tattoo sheet shown in Fig 7.4 did print in a clear wave shape but the connection between the tracks patch at left side did not fully print to print error (yellow circle).

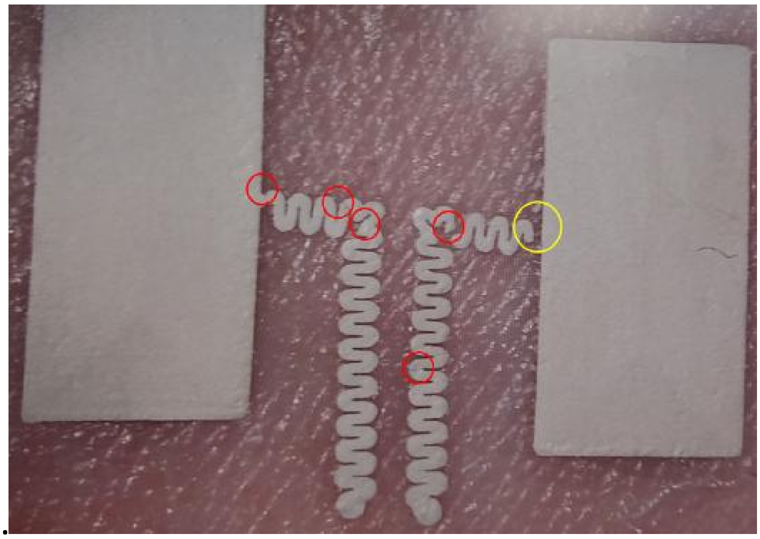


Figure 7.5: Printed EMG Patch Mounted on Skin

After placing the EMG patch on the skin using an adhesive sheet, Fig 7.5, the connection between tracks and patch did not connect as expected. Stretches are produced by twisting the arm and broke the stretchable tracks. When closely examined, most of the breaks are between the horizontal tracks and vertical tracks.

7.1.2 Second EMG Patch Design

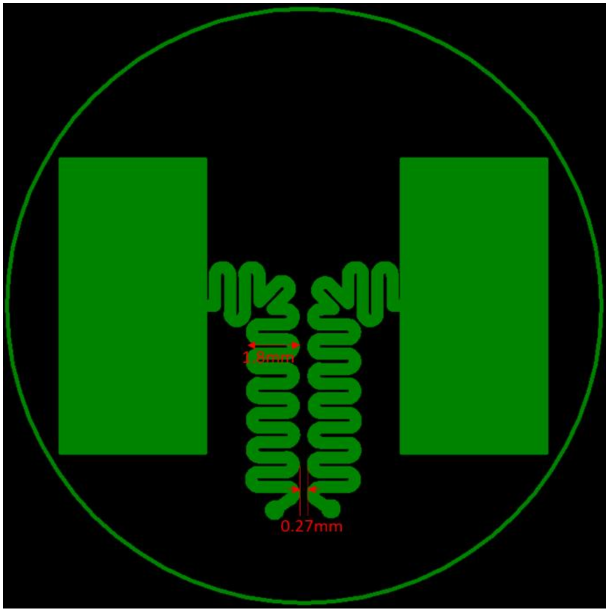


Figure 7.6: EMG Patch Design with Extended Track Width

As the track breaks may be cause by the tracks not being able to be withstand the stretches from the arm, the width of the track was increased in order to provide more strength as seen in Fig 7.6.

Stretchable Tracks Design Parameters			
Sample	Line Thickness[mm]	Gap[mm]	Tracks Width[mm]
1	0.2	0.1	1.3
2	0.3	0.05	1.3
3	0.3	0.05	1.3

Table 9: Stretchable Tracks Parameters used in Second Patch Design

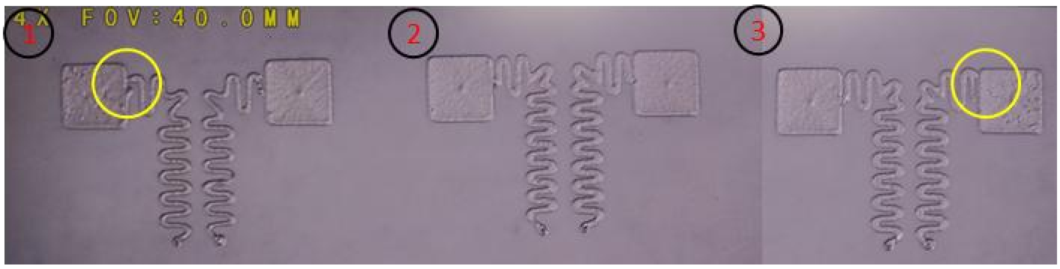


Figure 7.7: Printed EMG Patch with Extended Track Width on Tattoo Sheet

The new EMG patch design, Fig 7.7, made changes to track width and line thickness. Track length and the gap remained the same as in the previous design in Table 9. As this iteration of the patch was designed to investigate the strength of the stretchable tracks on human skin, the size of the patch was decreased in order to reduce the amount of conductor used.

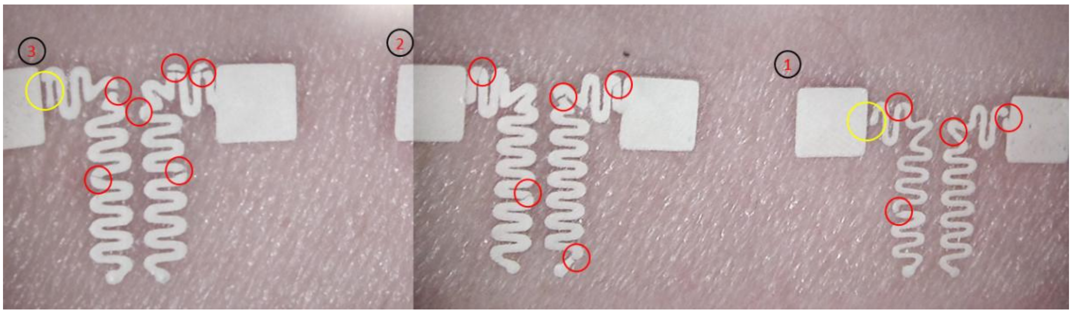


Figure 7.8: Printed EMG Patch with Extended Track Width on Human Skin(Arm)

Print errors (yellow circles) occurred on sample 1 and sample 3, Fig 7.7. When placing the samples on the skin as shown in Fig 7.8 ,sample 1 has fewer breaks compared to the other 2 samples. The results showed increasing line thickness would not help increase the strength of stretchable tracks.

Figure 7.9: Connection Point of Horizontal tracks & Vertical tracks

However, compared with the previous result in Section 7.1.1, tracks still were breaking around the area that the horizontal tracks and vertical tracks connected, shown in Fig 7.9.

7.1.3 More EMG Patches with Different Tracks and Connection Point Designs

The results from previous designs in Section 7.1.2 show all samples have broken around the connection point between horizontal tracks and vertical tracks, Fig 7.9.

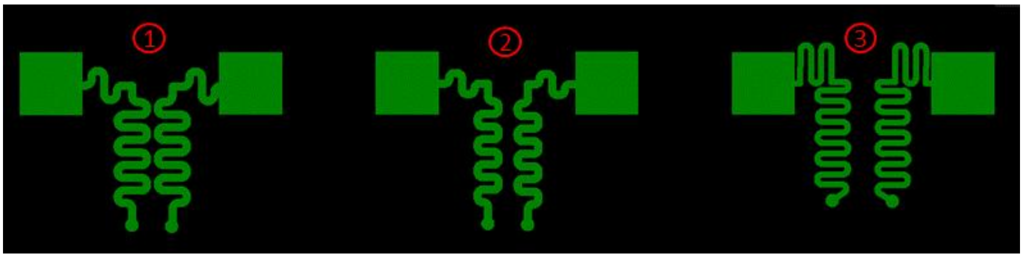


Figure 7.10: EMG Patch Design with More Different Shape Stretchable Tracks

Therefore another test was required with some alterations to the connection shape, Fig 7.10, in order to sustain the stretches applied to the connection point between horizontal tracks and vertical tracks, Fig 7.9.

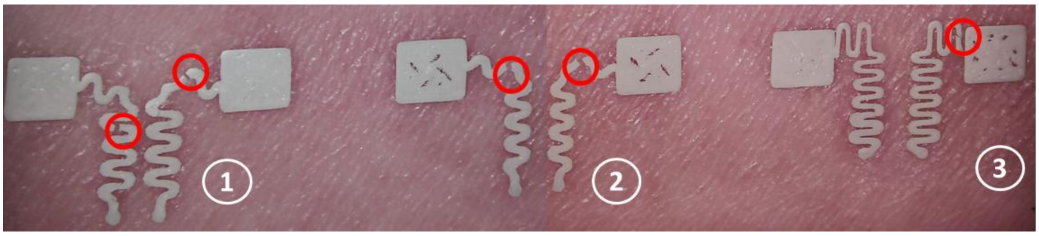


Figure 7.11: EMG Patch Design with More Different Shape Stretchable Tracks on Skin

The sample was placed on the skin to test the track's strength, Fig 7.11, sample 1 and sample 2 still had breaks between the connection point between horizontal and vertical tracks. However, sample 3 did not have any breaks around the connection point between horizontal and vertical tracks. But sample 3 has a break on the track near the patch.

7.2 Stretchable Tracks Design used Arc Shapes

7.2.1 Arc Shapes used Track Designs on EMG Patch

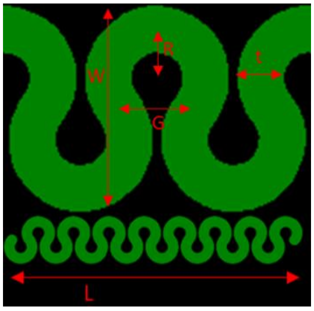


Figure 7.12: Design Parameters for Stretchable Tracks use Arcs

To investigate another method to increase the strength of stretchable tracks when placed on skin, design new stretchable tracks by combine used of arc shapes.

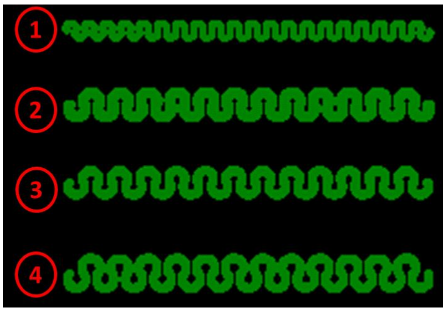


Figure 7.13: Stretchable Tracks Design used Arc shapes

Unit[mm]	Radius(R)	Thickness(t)	Gap(G)	Width(W)	Length(L)
Design 1	0.15	0.2	0.26	0.61	10.62
Design 2	0.2	0.3	0.42	0.99	10.62
Design 3	0.22	0.25	0.42	0.94	0.57
Design 4	0.23	0.25	0.4	1.10	10.62

Table 10: Parameters of Stretchable Tracks Design used Arc shapes

Parameters used in designs 3 and 4 in Table 10 were a line thickness of 0.25mm, however the line thickness became 0.3mm when printed on a tattoo sheet using a Voltera V-One printer.

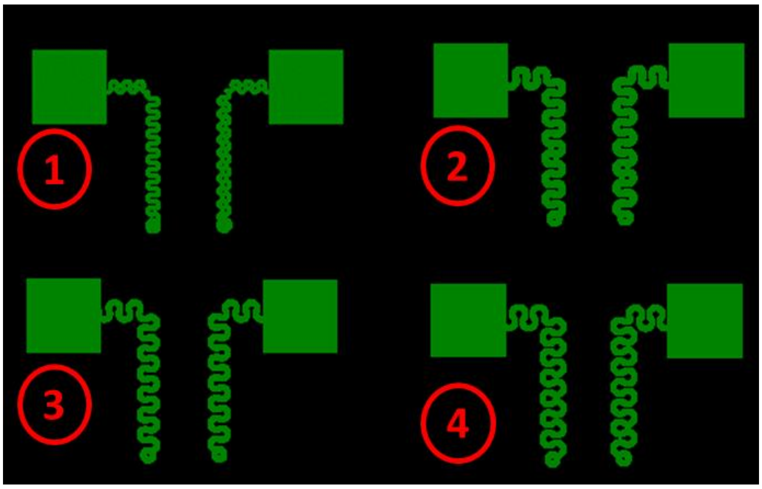


Figure 7.14: EMG Patches Design used Stretchable Tracks(made used Arcs)

4 new stretchable tracks were designed as seen in, Fig 7.13, based on the parameters in Table10 and were applied to EMG patch designs shown in Fig 7.14. The result was that the right-angle connection does have the strength to sustain the stretches, Section 7.1.3.

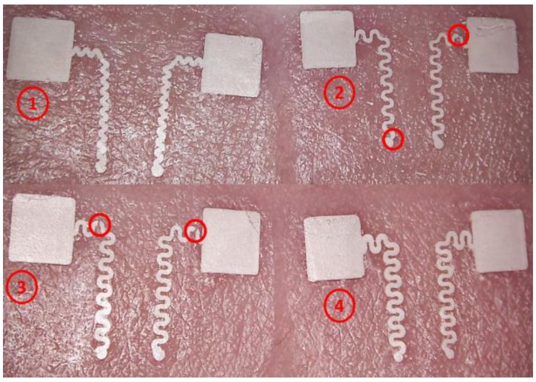


Figure 7.15: Breaks on EMG Patch Designs when Placed on Skin

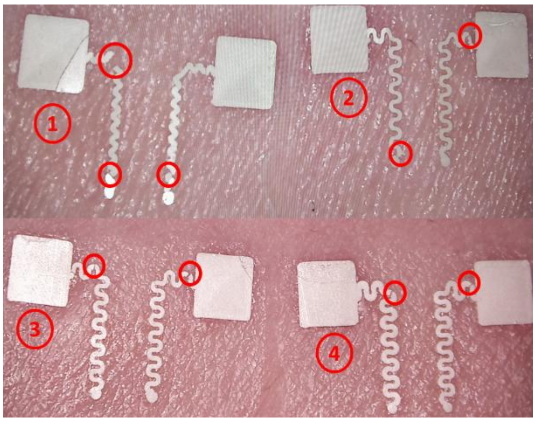


Figure 7.16: Breaks on EMG Patch Designs after Twisted Arm

Placed printed EMG patches on the skin, Fig 7.15, due to the conductor output amount settings on the Voltera, design 2 has a thinner line thickness compared to designs 3 and 4.

Stretches from the twisted arm were applied to the EMG patch, Fig 7.16. The connection between horizontal tracks and vertical tracks of both of the tracks in design 2 sustained the stretches without breaking the tracks. But there was a break around the connection between the tracks and patch on the right side. So the stretches applied to the right side tracks are less than the left side tracks.

In designs 3 and 4, Fig 7.16, due to the connection between the patch and right side tracks being broken, a similar situation happened as in design 2. Fewer stretches are applied to tracks, and the connection between horizontal tracks and vertical tracks can sustain the stretches.

Results from the test showed a right-angle shape connection between the horizontal track and the vertical track has the strength to sustain the stretches. But most of the tracks do not have enough strength to sustain the process of placing the printed EMG patches on the skin.

7.2.2 Stretchable Track Design with Increased Line Thickness

After the results of the previous test, the effect of increased track strength by increasing the line thickness was investigated. Due to the Voltera printer mainly being used for PCB design there was difficulty in adjusting the thickness via the software therefore the line thickness was increased manually by increasing the output of ink.

With the previous samples test, Fig 7.16, design 1 and design 4 where the most suitable for sustaining the skin Application. Design 1 in Fig 7.14 did not print in a clear wave shape due to limitations with the Voltera printing resolution, so the line thickness of design 4 was used.

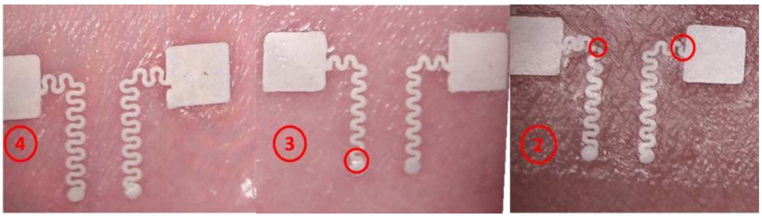


Figure 7.17: Breaks on EMG Patches when Placed on Skin(a)

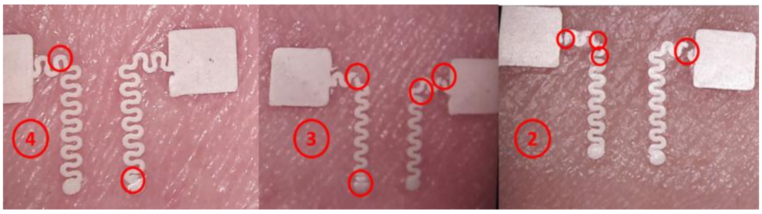


Figure 7.18: Breaks on EMG Patches after applied Stretches on Skin(a)

EMG patches were printed with designs 2,3 and 4 in Fig4.14 but with line thickness of 0.3mm, and placed on the arm, Fig 7.17. Design 2 is the only sample that did not survive the skin application in one piece.

After the patches were applied, in order to test the endurance of the EMG patch, the arm was twisted. As can be seen in Fig 7.18, only design 4 did not break under the duress

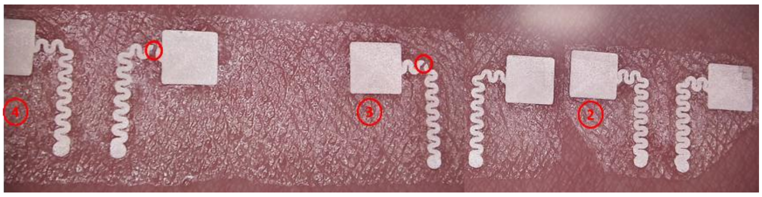


Figure 7.19: Breaks on EMG Patches when Placed on Skin(b)

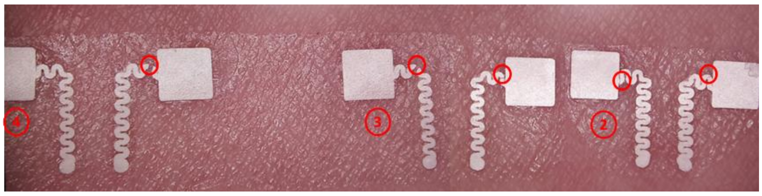


Figure 7.20: Breaks on EMG Patches after applied Stretches on Skin(b)

More samples of designs 2,3 and 4 were created to further test the track strength. As the tracks of design 2 of the EMG patch broke during the skin application process in the last test, The line thickness was increased via the ink output method by increasing the 'E' parameter mentioned in Section 4. The result shows tracks of design 2 increased the line thickness sustained from the process of placing on the skin, Fig 7.19. In designs 3 and 4, one of the tracks from each sample is sustained by each process placed on the skin.

Following skin application stretches were applied to EMG patches by twisting the arm again, Fig 7.20 shows that design 4 has no breaks, design 2 on the other hand only has breaks around the patch and the joint area remains intact. The stretches cause a new break to appear in design 3 on the right track. All EMG patch designs broke around the patches.

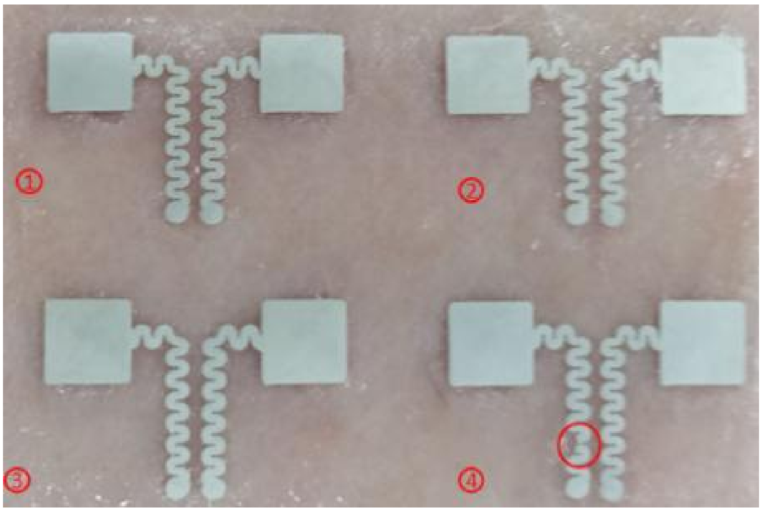


Figure 7.21: More EMG Patches based on Design 4 with Wider Line Thickness

More samples based on design 4 were then printed however this time the output amount of the ink was increased to increase the line thickness once more as pictured in Fig 7.21. In sample 4, there was a print error on the left-side tracks resulting in a break.

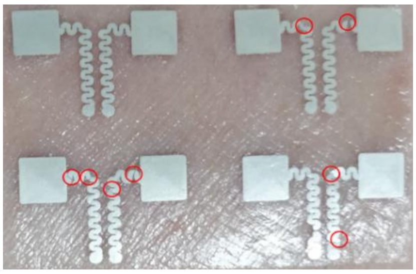


Figure 7.22: EMG Patches on Skin after 1 hour

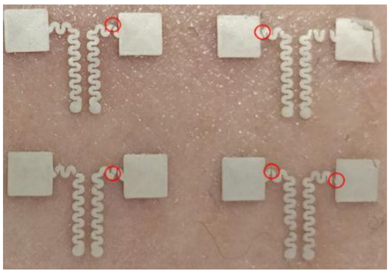


Figure 7.23: EMG Patches on Skin after 2 hours

The Samples were checked 1 hour after being placed on the skin. All samples have broken tracks except sample 1 as seen in Fig 7.22. A majority of the breaks on the tracks occured around patches and the connections between horizontal tracks and vertical tracks.

The Samples were checked again after another 1 hour pictured in Fig 7.23. One half of sample 1 did not break after being stretched for 2 hours, however the other half broke near the patch. Similarly Samples 2, 3 and 4 all broke near the patch.

7.2.3 Different Shape Connections between Horizontal and Vertical Tracks

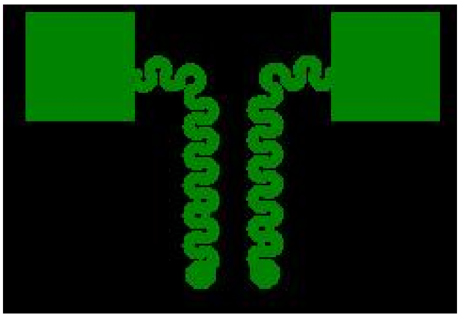


Figure 7.24: EMG Patches with Different Shape Connections

Fig 7.24 shows the new design created based on the results of the previous tests. In the new design the shapes used to connect the horizontal tracks and vertical tracks have been changed.

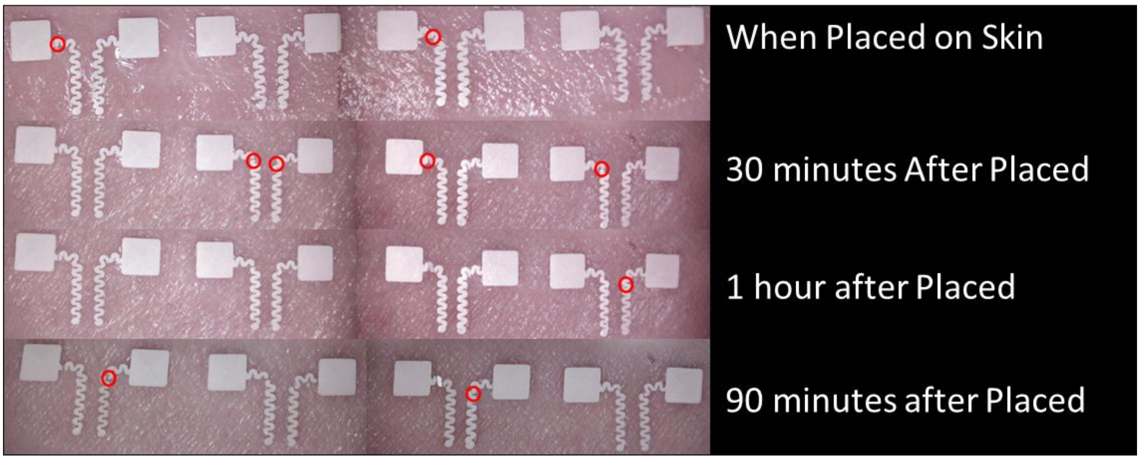


Figure 7.25: New EMG Patches Test on Skin

The 4 identical samples of the new design were placed on the skin in order to test the new designs strength, the results of which can be seen in Fig 7.25, 6 of the tracks did not break during the application process. However after 30 minutes, multiple breaks happen around the patch and joint area. Only 3 tracks did not break under the stretches for 30 minutes. After another 30 minutes, one more track breaks and at 90 minutes all of the samples have breaks.

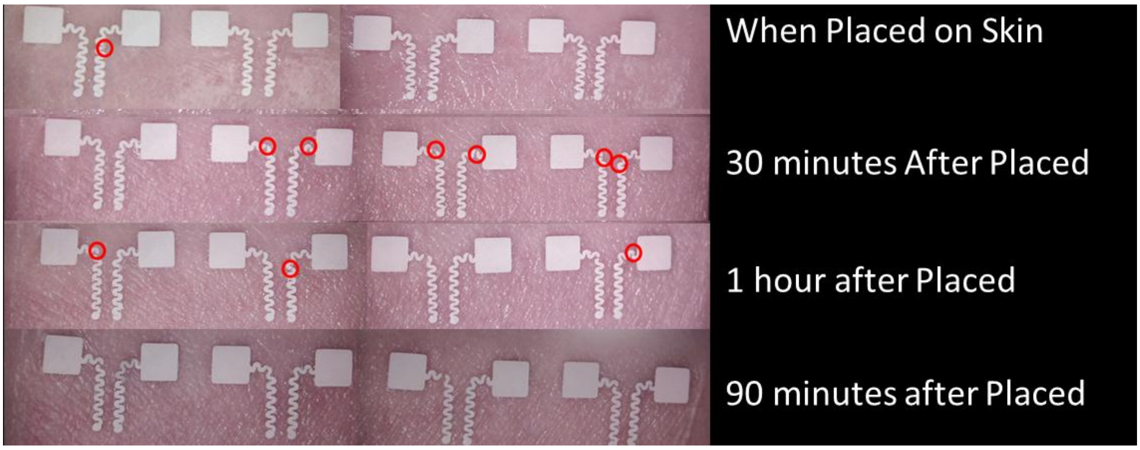


Figure 7.26: More Tests for New EMG Patches Design on Skin

The test was then repeated with the same design in order to collect more data Fig 7.26. A majority of the tracks survived the application process this time however 30 minutes after being applied only 1 track remained unbroken.

Interestingly, the position of all of the breaks on the tracks are around the patches or joint area. Additionally all of the tracks were broken by the 1 hour mark of the test.

Chapter 8

8. More Stretchable Track Designs With Various Tracks Designs

As can be seen from the results of the previous test, all of the breaks that occurred during the stretch testing happened in either the patch area or the joint area. Therefore a new design must be created with adjustments that reinforce these problem areas.

8.1 Increased the Connections between Tracks and Patch

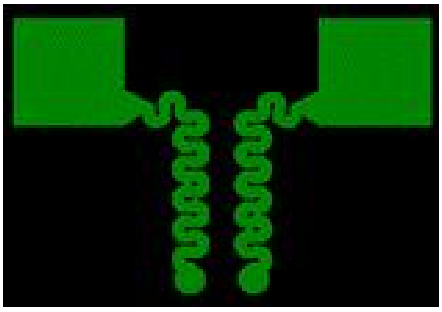


Figure 8.1: EMG Patch Design with Increased Connections

In order to prevent the previously mentioned breaks, the area of the vertical tracks was increased as can be seen in Fig 8.1. The patch to track area was also reinforced by adding a triangle shape as well as the overall length of the horizontal tracks being reduced.

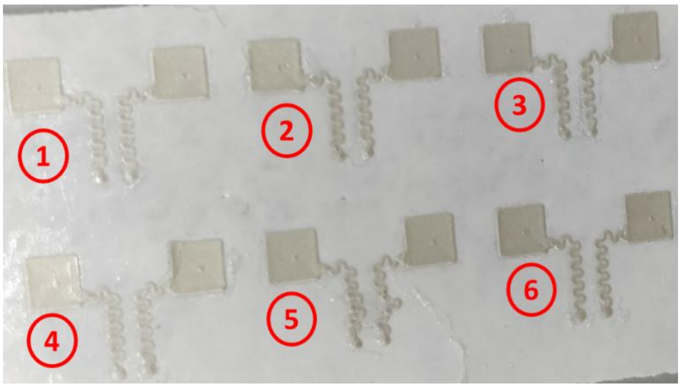


Figure 8.2: Printed EMG Patches on Tattoo Sheet

During the application of the adhesive sheet to the printed EMG patches, Sample 5 was damaged as can be seen in Fig 8.2. So the results from sample 5 can be ignored.

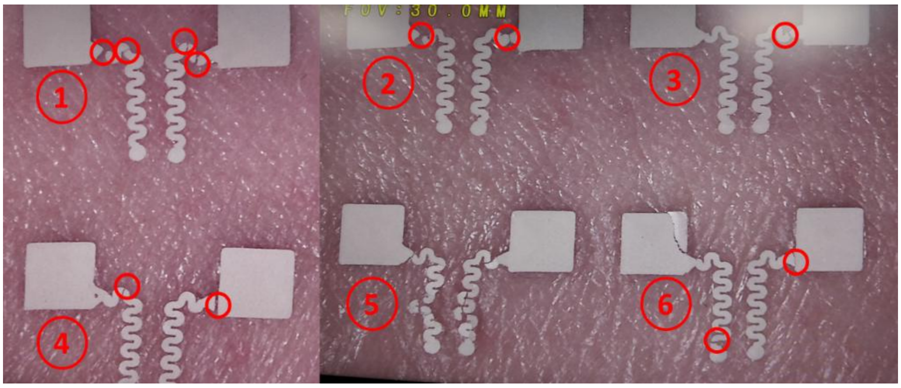


Figure 8.3: Printed EMG Patches Placed on Skin

The newly printed EMG patches were placed on the skin, Fig 8.3. However, a large amount of tracks break during the process of placing the EMG patches on the skin. All of the samples (ignoring number 5) broke in the same problem areas as the previous test which indicates this new design did not help increase the strength of the connection between tracks and patches.

8.2 Reduced the Track Length

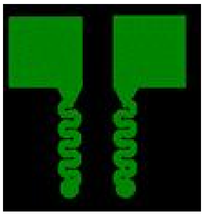


Figure 8.4: EMG Patch Design with Track Length Reduced

Following the previous tests failure, a New EMG patch design was created which removed the join all together in the hopes of removing the problem area all together as can be seen in Fig 8.3. Previously, most of the breaks were on vertical tracks, not horizontal tracks (see section 7.2). The triangle shapes used for increasing the strength of the connection between the patches and tracks was implemented in this design again.

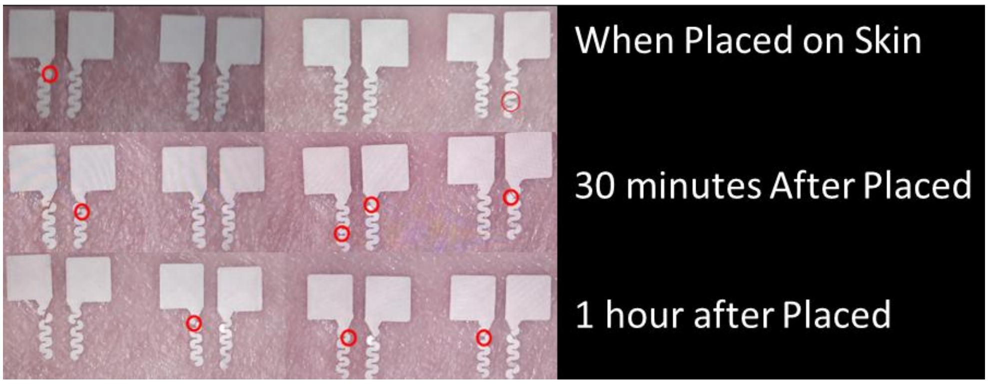


Figure 8.5: Track Length Reduced EMG Patch

Fig 8.5 shows 6 tracks survived the skin application process. After 30 minutes, 3 tracks break and by the time 1 hour has passed only 1 track remains unbroken. 7 out of 8 tracks broke and all the broken tracks have breaks between the patches and tracks, so the triangle shape did not help to increase the strength of the connection between tracks and patches.

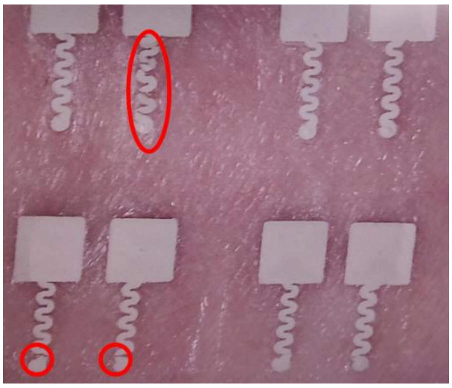


Figure 8.6: EMG Patches with Short Tracks on Skin

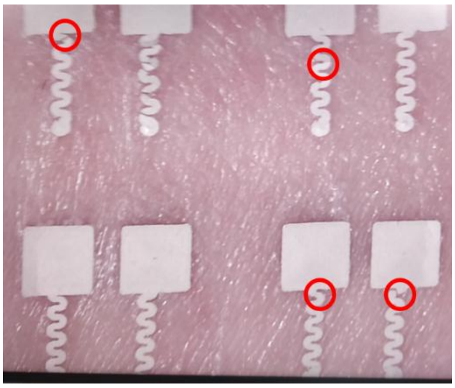


Figure 8.7: EMG Patches with Short Tracks after Stretches Applied

Following the results of the previous test, the triangle shapes did not help increase the strength of the connection between patches and tracks. Based on the previous designs in Fig 8.4, a new design was implemented removing the triangle all together as can be seen in Fig 8.6. The test was then repeated with this new design. 5 tracks survived the application process but only 1 track did not break after stretches were applied as shown in Fig 8.7. Only 3 out of 8 tracks do not have breaks around the connection between patches and tracks. So connecting vertical stretchable tracks directly to the patches proved to increase the strength.

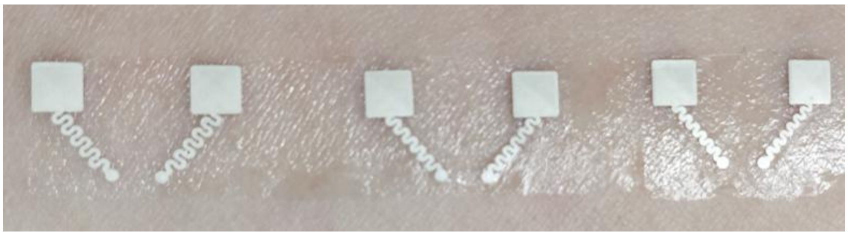


Figure 8.8: EMG Patches Designs use Diagonal Stretchable Tracks on Skin

Another possible design method is to make the tracks diagonal as opposed to straight or with a right angle. Initial application looked promising, no damage could be seen during the step placed on the skin.

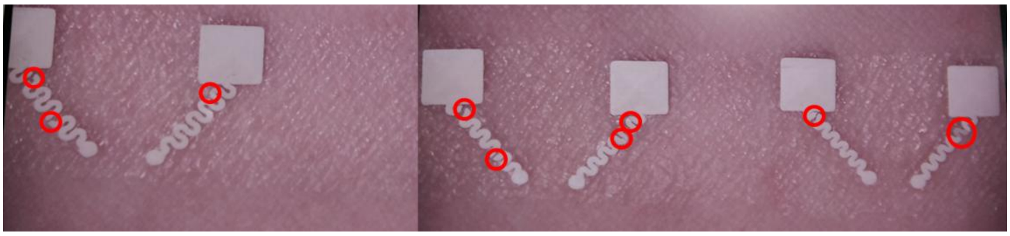


Figure 8.9: On-skin EMG Patches Designs use Diagonal Stretchable Tracks after Stretches Applied

However after the stretches were applied, Fig 8.9 shows that all tracks break at the track-patch connection point. Therefore, diagonal direction stretchable tracks do not have better strength than the samples that used stretchable tracks in the horizontal and vertical direction.

8.3 Quick Summary of Using Tattoo Paper

Using tattoo paper to place printed circuits whilst a relatively inexpensive method, has many flaws. The adhesive is too strong resulting in most stretching of the skin causing breaks in the tracks. Additionally the application method requires the user to place pressure on the circuits, once again allowing for possible damage to occur. The preparation of the sample also is unsuitable as when placing the adhesive sheet on a printed circuit there is a risk to break the circuit. With all these things in mind, a better method of application is required since the tests show that the circuits are too fragile to be used with tattoo paper.

Chapter 9

9. Printing Methodology on Tegaderm Film

With the results used in the first fabrication method, Section 4, tattoo paper is not suitable for placing printed circuits on the skin, then changed method for use of Tegaderm Films.

Fabrication Steps

1. Cut the Tegaderm Film to be the same as the size FR board and stick the Tegaderm Film on the FR board using double-sided adhesive tape, Fig 9.1.

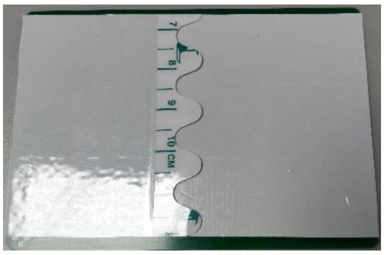


Figure 9.1: Tegaderm Film on FR-4 board

Place the FR board on Voltera V-One Printer, then print the circuit on to the Tegaderm Film. Similarly to the previous method, when setting up the Voltera V-One printer software an important step is to tune the gear on the dispenser in order to allow for more accurate control. Ensure the gear is turned 45 degrees, the notch in the middle of the dispenser gear is helpful for this as seen in Fig 9.2.

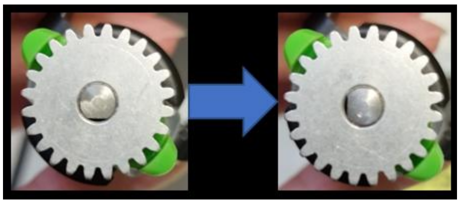
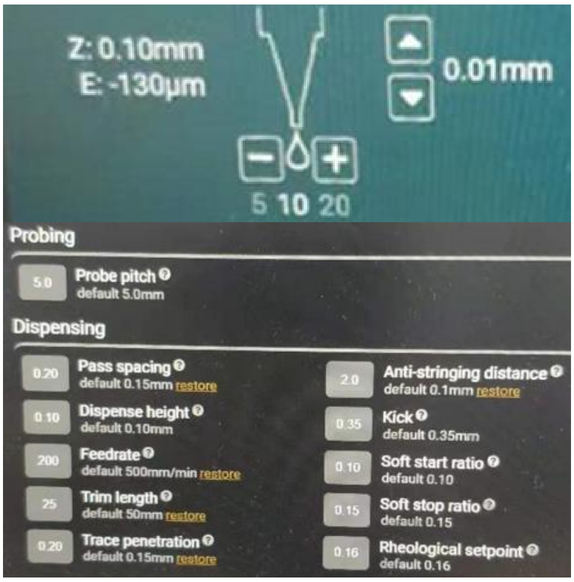


Figure 9.2: Inkjet Preparation

2. With regards to the setting of the Voltera V-One PCB Printer for printing circuits shown in Fig 9.3. Again the variables that will affect the ink output amount are the ‘E’ parameter and Feedrate. The ‘E’ parameter is the biggest factor used to control inkjet output, as it is the factor to change the amount of ink that will be pushed out. Feedrate is a sub-factor that will change the inkjet output amount as a higher Feedrate will increase the printing speed. At higher print speeds, the quality of the tracks is compromised as breaking or unconnected points will occur due insufficient ink being jetted onto the print substrate. Dispensing height refers to the distance between nozzle and print substrate and is another variable that could affect the quality of print. If the dispensing height is too low, there will

be a risk of damage to the print substrate. If the height is too high, the printed conductor will be less accurate.



Z: 0.10mm
E: -130µm

0.01mm

5 10 20

Probing

5.0 Probe pitch
default 5.0mm

Dispensing

0.20 Pass spacing
default 0.15mm restore

0.10 Dispense height
default 0.10mm

200 Feedrate
default 500mm/min restore

25 Trim length
default 50mm restore

0.20 Trace penetration
default 0.15mm restore

2.0 Anti-stringing distance
default 0.1mm restore

0.35 Kick
default 0.35mm

0.10 Soft start ratio
default 0.10

0.15 Soft stop ratio
default 0.15

0.16 Rheological setpoint
default 0.16

Figure 9.3: Voltera Setting

4. Bake (heat) the circuit (including the underlying FR4 board and Tegaderm Film). A sintering temperature of 120oC for 40 minutes was found to be optimal for ink on Tattoo sheet conductivity and robustness according to the measurements reported in Section 5.2. The baking temperature is set under or the same as the recommended temperature as higher temperatures may damage the Tegaderm Film.

5. Place components on the circuit using 9703 conductive adhesive tapes.

Figure 9.4: Applied Conductive Adhesive Tape to Printed Conductor

Place conductive adhesive tape on the printed conductor and remove the release liner, the adhesive layer will break the printed conductor as pictured in Fig 9.4. To reduce the risk of adhesive tape breaking the printed conductor when removing the release liner, apply pressure to the adhesive tape (use any tools that will not damage the printed conductor) and heat the adhesive tape (using a heat gun) at 160oC for no more than 20 seconds. After the adhesive tape has cooled enough so as to not get burned, apply pressure to the tape again and then use a tweezer to remove the release liner.

6. Apply another Tegaderm Film (Roll style) on the top of the circuit, to protect the circuit from friction and pressure. Also place a small Tegaderm film on the components to hold the components and apply more pressure as can be seen in Fig 9.5.

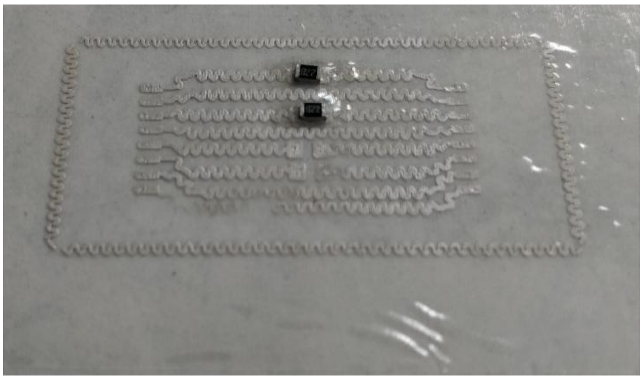


Figure 9.5: Overlay substrate on Circuits

7. Remove the Tegaderm layer from Tegaderm Transparent Film Dressing Frame Style then place it on the object/skin. And the placed circuit should look like the circuit in Fig 9.6.

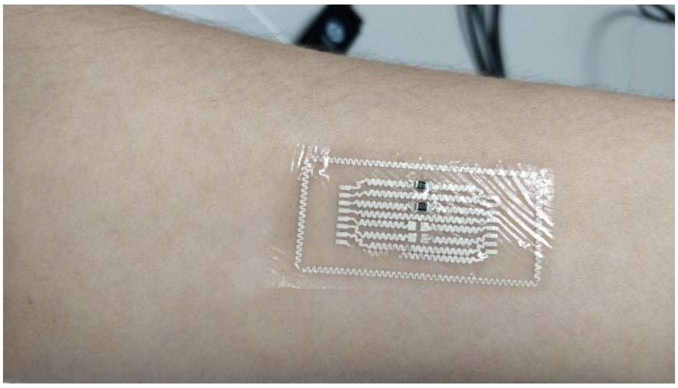


Figure 9.6: Printed Circuit placed on Skin

Chapter 10

10. Circuit designs Printed on Tegaderm

10.1 Stretchable Track Designs on Tegaderm Film

10.1.1 Use Tegaderm Film Roll style

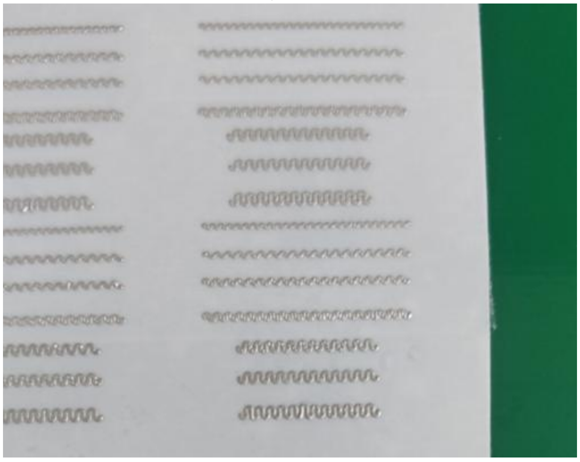
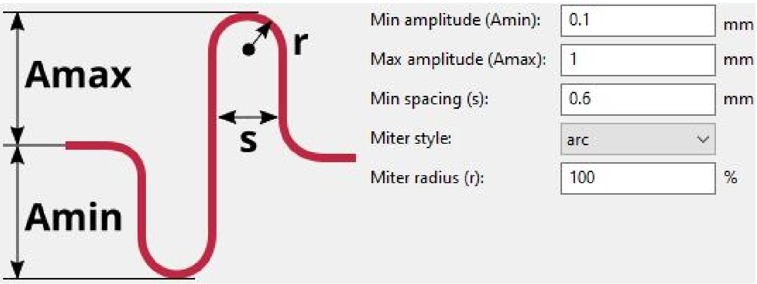


Figure 10.1: Stretchable Tracks Printed on Tegaderm Film Roll Style

The first step was to attempt to print the stretchable design tracks on the Tegaderm film to test the characteristics of the film when used in conjunction with the Voltera V-One PCB Printer.

Figure 10.2: Sintered Printed Tracks on Tegaderm Film

The printed conductor was sintered at 120°C for 40 minutes however as can be seen in figure 10.2, the Tegaderm film shrinks due to the heat.



Min amplitude (Amin): 0.1 mm
Max amplitude (Amax): 1 mm
Min spacing (s): 0.6 mm
Miter style: arc
Miter radius (r): 100 %

Figure 10.3: Parameters used in Tracks Design for Print on Tegaderm

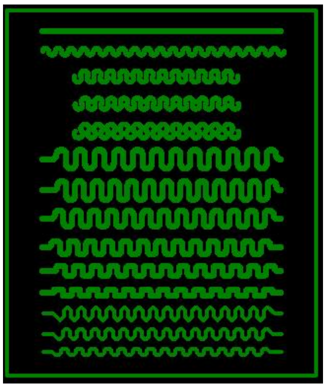


Figure 10.4: New Tracks Design use on Tegaderm

Sample	Amin[mm]	Amax[mm]	s[mm]	Miter Style	r[%]
1	0.1	0.6	0.56	Arc	100
2	0.1	0.5	0.5	Arc	100
3	0.1	0.4	0.4	Arc	100
4	0.1	0.3	0.3	Arc	100
5	0.1	0.2	0.2	Arc	100
6	0.1	0.1	0.2	Arc	100
7	0.1	0.4	0.2	45 degree	100
8	0.1	0.3	0.2	45 degree	100
9	0.1	0.2	0.2	45degree	100

Table 11: Parameter of New Tracks Design used on Tegaderm

As the Voltera can be used for printing flexible conductors on Tegaderm Film, 9 new tracks were designed and put into the Gerber image file with the old designs, Fig 10.4. The new track designs used the parameters shown in Table 11.

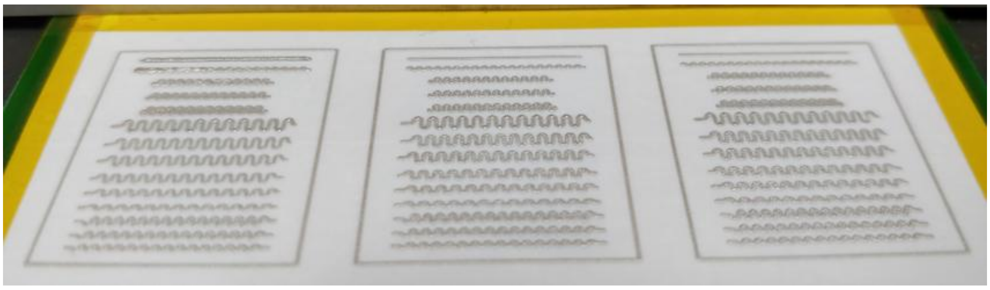


Figure 10.5 Printed New Designs on Tegaderm

As the Tegaderm film would have shrunk when sintering conductors, Fig 10.5, tape was placed around the Tegaderm film in order to stop the film from warping when heat is applied.

Figure 10.6: Sintered Samples on Tegaderm

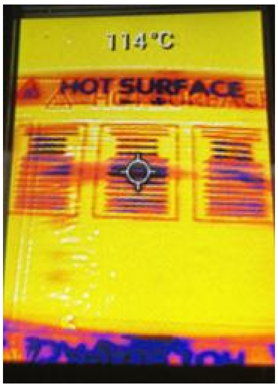


Figure 10.7: Temperature Measured during Sintering

However, this proved insufficient as the Tegaderm film shrank again as can be seen in Fig 10.6. The reason it is important to prevent the Tegaderm film from shrinking is because air gaps will occur which causes the conductor to not be sintered at an even temperature as can be seen in Fig 10.7. The Air gaps produced by Tegaderm film shrinking causes the temperature to drop to 114°C when the sintering temperature is set at 120°C.

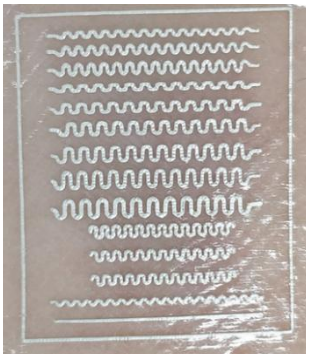


Figure 10.8: Printed Sample Placed on Arm

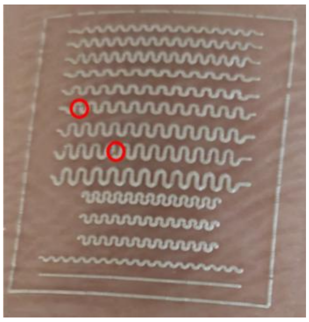


Figure 10.9: Printed Sample After Stretches Applied

The printed Samples however did cure on Tegaderm film well despite the Tegaderm film shrank by the heat. The sample was removed from the FR-4 board using a cutter and placed on the skin. Placing Tegaderm film on the skin does not require any liquid, so the process of placing the printed circuit is simpler than using tattoo paper, Fig 10.8. No breaks on the tracks occur during the placing process.

After conducting the same stretch testing to the Tegaderm samples, Fig 10.9, only 2 tracks were damaged. Compared with samples printed on tattoo papers, samples printed on Tegaderm Film Roll Style are far more flexible and are less brittle due to the characteristic of the Tegaderm film.

Figure 10.10: More Printed Samples on Tegaderm

More samples were printed on the Tegaderm film Roll style and the tape placed again at the edge of the Tegaderm film, Fig 10.10. The same results are produced however due to the air gaps made by the heat under the Tegaderm film.

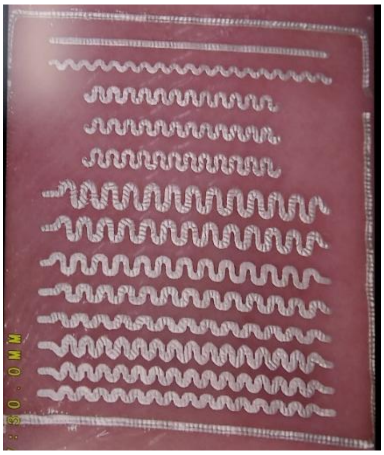


Figure 10.11: Printed Sample Placed on Skin used Tegaderm

The newly printed samples were placed on the skin and stretch tested. This time, none of the tracks break, Fig 10.11. This indicates the conductor printed Tegaderm film can sustain stretches for a longer time than the conductor printed on the tattoo sheet.

Figure 10.12: Reduced Area held by Tape

The area of the Tegaderm film held by tape was reduced and a short investigation of the effect of using the tape to stop Tegaderm film from shrinking by heat was run, Fig 10.12. What was found was that using tape does stop Tegaderm film from shrinking by heat, but air gaps will still be produced by heat under Tegaderm film.

10.1.2 Use Tegaderm Film Frame Style

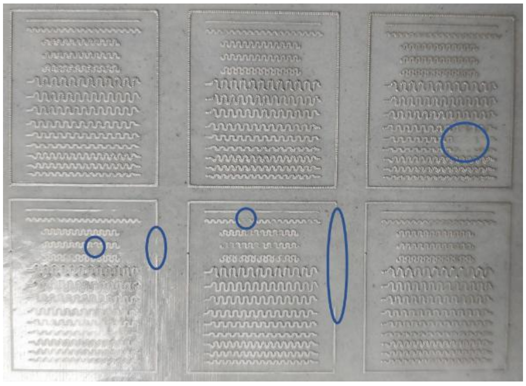


Figure 10.13: Stretchable Tracks Design Printed on Tegaderm Frame Style

Previous results show that the Tegaderm film Roll style is not suitable for heating for curing the conductors, so instead a method using the Tegaderm film Frame style as the substrate was explored. The conductor were sintered at 120oC for 40 minutes. The Samples that were printed on the Tegaderm film Frame did show print errors (blue circles) that occured due to the Tegaderm film not being level on the FR-4 substrate, Fig 10.13.

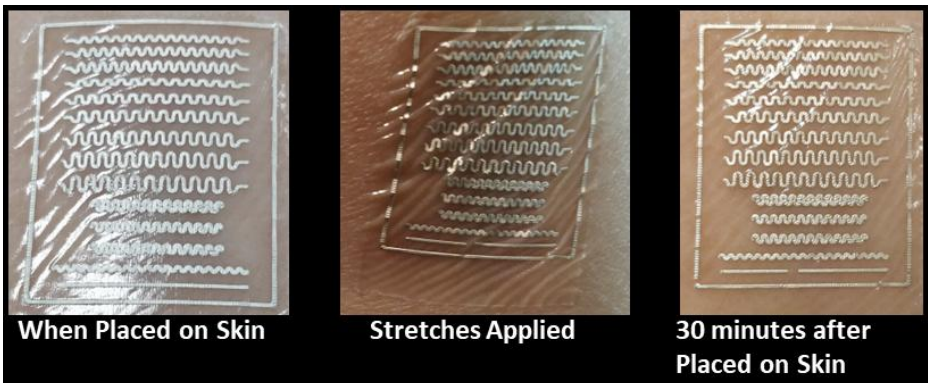

When Placed on Skin
Stretches Applied
30 minutes after Placed on Skin

Figure 10.14: Strength Test of Printed Sample on Skin(a)

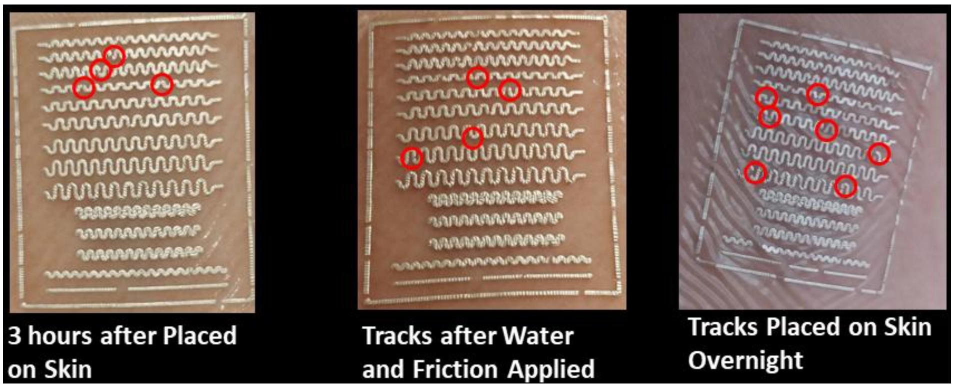

3 hours after Placed on Skin
Tracks after Water and Friction Applied
Tracks Placed on Skin Overnight

Figure 10.15: Strength Test of Printed Sample on Skin(b)

To test the new printed conductor strength, it was once again placed on skin as can be seen in Fig 10.14. Without placing a Tegaderm layer on the top of the sample as a protection layer, no breaks occurred on the stretchable design tracks after 30 minutes.

2 hours after the sample on the skin was placed there was still no change, however by the 3 hour mark 3 tracks were damaged. When checked 3 hours after being placed on the skin, Fig 10.15. During which water and friction had been applied to the sample (due to having taken a shower in daily life) only 4 new breaks on the tracks could be seen. After wearing the sample overnight, more breaks were caused by the pressure and stretches during sleep. However, this sample did not have a protection layer, and therefore it would have been easier for external force to cause the breaks on the tracks.

10.2 Stretchable Tracks with Components on Tegaderm Film

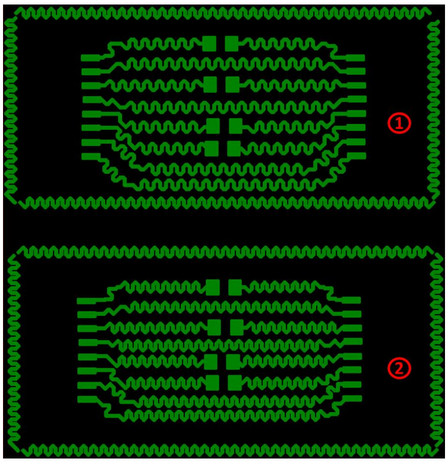


Figure 10.16: Designs Used for Place Components

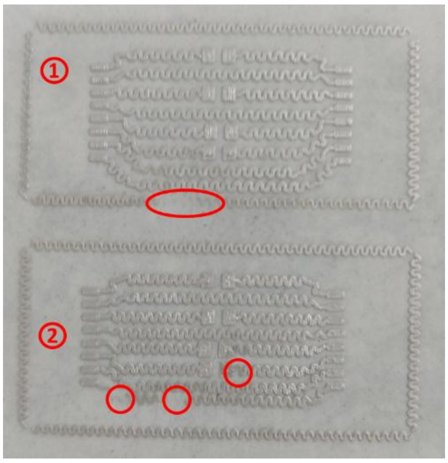


Figure 10.17: Printed Samples on Tegaderm

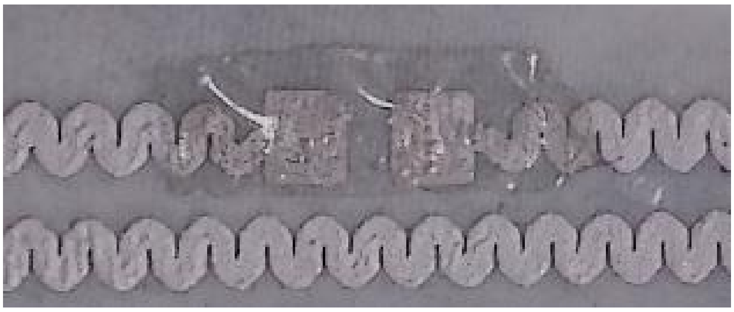


Figure 10.18: Conductive Adhesive Tape Applied on Printed Conductor

2 new samples were designed for testing place components on the printed conductor, Fig 10.16 & Fig 10.17. conductive adhesive tape was used to stick the component onto the printed conductor. Fig 10.18. The printed Tegaderm samples have print errors for the same reason as in the previous sample, the Tegaderm film was not placed flat on the

FR-4 board. Sample 1 and sample 2 have the same line thickness and track width but sample 2 has less gap.

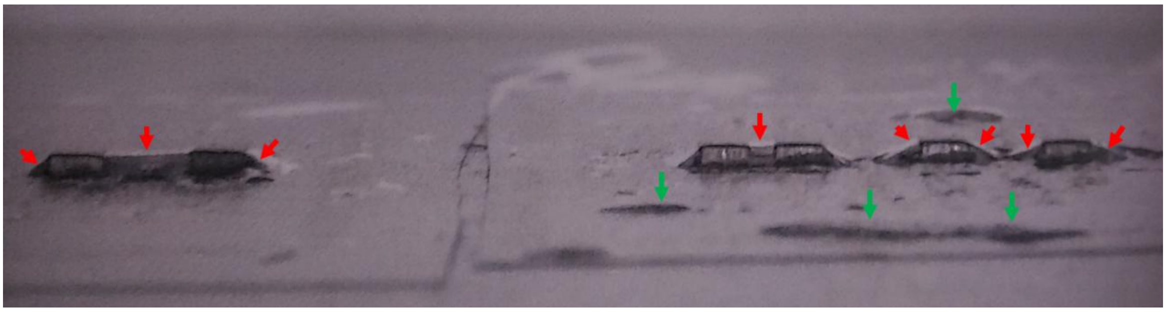


Figure 10.19: Samples Applied Protection Layer on the Top

After connecting the components to the tracks using conductive adhesive tape, a single layer of Tegaderm film (Roll style) was applied on the top of the sample, Fig 10.19. This Tegaderm layer works as a protection layer for holding the components on the conductive adhesive tape. Otherwise, the components have a high risk to be removed by external friction. When the Tegaderm layer (protection layer) is placed, air bubbles(pointed by green arrows) may occur. Additionally there can be air gaps(pointed by red arrows) around the components, but this will not affect the protection layer to protect the circuit from external frictions.

10.2.1 Sample 1 Test on Arm

Figure 10.20: Sample 1 Strength Test on Skin

Sample 1 was placed on the skin to test the strength of the printed conductor on Tegaderm film with a protection layer, Fig 10.20. After applying external friction and water (shower) and wearing the sample overnight, no breaks occurred from the conductor.

10.2.2 Sample 2 Test on Arm

Figure 10.21: Sample 1 Strength Test on Skin

Sample 2 was placed on the skin to conduct the same test as sample 1, Fig 10.22. This yielded the same results as sample 1, no breaks occurred despite external friction and water applied to the sample. Therefore, the Tegaderm layer is extremely effective as a protection layer and helps to protect the printed conductors. The Tegaderm protection layer is only able to be used in the printing methodology in Section 9. As using the printing methodology in Section 4, the printed conductor would break during the skin application process and the protection layer is only able to be placed after placing the printed circuit on the skin.

10.3 LED Circuit on Tegaderm Film

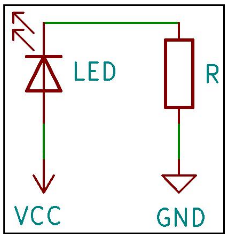


Figure 10.23 Simple LED Circuit LED

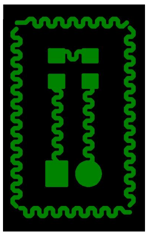


Figure 10.24: Circuit with Stretchable Tracks

The previous test showed the components are able to be connected using conductive adhesive tape and components can be protected by a Tegaderm film to prevent the components from separating from the circuit. Therefore, in order to investigate the lifetime of the printed conductor a LED circuit was designed. Fig 10.23. The tracks used in LED circuits, Fig 10.24 are also designed as stretchable tracks. Printed LED circuits on Tegaderm film were sintered at 120^{o}C for 40 minutes..

10.3.1 LED Circuit used Voltera Flex2 Conductor

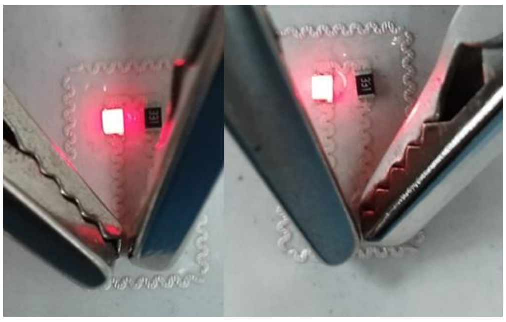


Figure 10.25: Printed LED Circuit on Tegaderm

Placed components on 2 samples, and before placing the protection layer, test the LED circuit's works by attaching a multimeter in diode mode, Fig 10.25. 2 LED circuits work on the Tegaderm film without any problem.

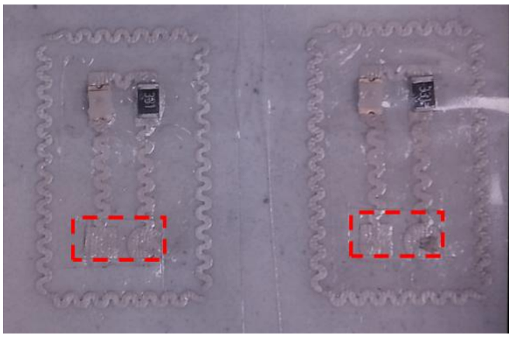


Figure 10.26: Protection Layer applied on LED Circuits

Before placing the protection layer onto the samples, a rectangle was cut at the middle of the protection layer, Fig 10.26, to allow the LED circuit to be attached to the multimeter through the protection layer after being placed on the skin.

Figure 10.27: Frist LED Circuit Test on Skin

The first LED circuit was tested on the skin by attaching a multimeter to the LED circuit, Fig 10.27. The multimeter was set in diode mode and only produced a low voltage and current to the LED circuit, so it would not have had any risk to shock. The first LED circuit was still able to light up when the power source was attached without any problem.

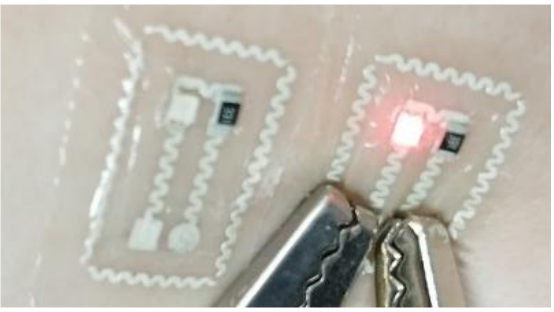


Figure 10.28: Second LED Circuit Test on Skin

The second LED circuit was placed on the skin near the first LED circuit and the same test was performed . The second LED circuit also lit up without any problems., Fig 10.28.

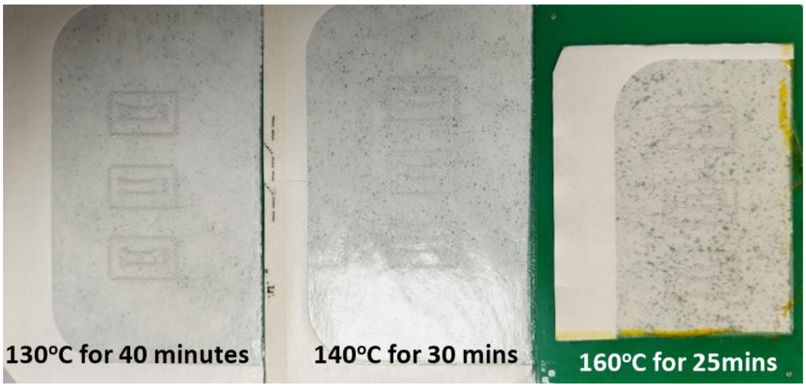


Figure 10.29: Sintering Conductor in Different Temperature & Time

Voltera Flex2 conductor ink is recommended for curing by sintering at 160°C for 30 minutes, see Section 3.2, so sintering the conductor used in LED circuits in higher temperatures for curing the conductor. Fig 10.29. When sintering the LED circuits at 130°C for 40 minutes, the layer under the Tegaderm film layer started getting damaged, and the damage on the bottom layer caused by sintering at 140°C for 30 minutes causes difficulty to see the circuits on the Tegaderm film. Tegaderm Film sintered at 160°C for 25 minutes, causing damage to the bottom layer making the printed LED circuits on Tegaderm film are hard to see, this would cause problems when placing components to the circuits.

10.3.2 LED Circuit used PE874 Conductor Paste

Since Voltera Flex2 Conductor Ink recommends sintering at 160°C for 30 minutes and sintering Tegaderm Film at 160°C for 30 minutes will cause damage to the bottom layer. The used conductor was changed to PE874 conductive paste as PE874 conductive paste recommends sintering the conductor at 130°C for 15 minutes.

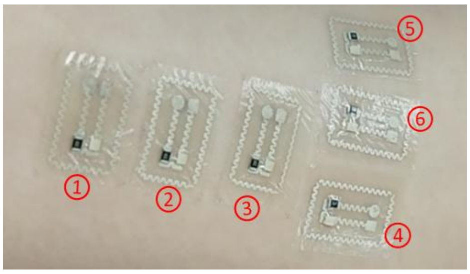


Figure 10.30: PE874 used LED Circuits Placed on Skin

Using the same design, 6 LED samples were printed used PE874 conductive paste, Fig 10.30. the LED circuits was then Placed on the skin to test the performance of the circuits.

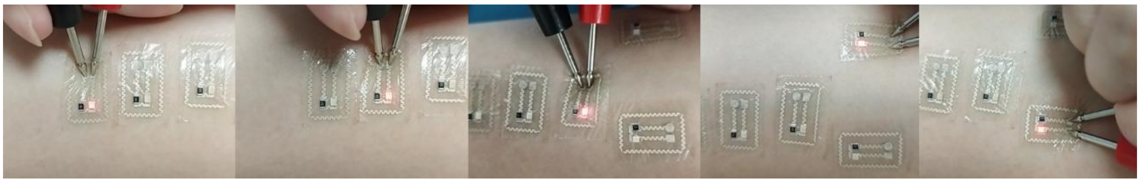


Figure 10.31: PE874 Used LED Circuit 1 to 5 Test on Skin

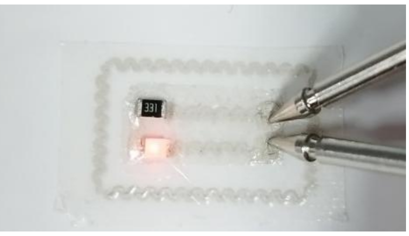


Figure 10.32: LED Circuit 6 Test on Solid Surface

The LED circuits were tested on the skin by attaching them to a multimeter, but only circuits 1 to 5 lit up on the skin, Fig 10.31. To check the circuit did not break during the process of placing it on the skin, the LED circuit was removed from the skin and placed on a solid surface, Fig 10.32 and the multimeter was attached to the circuit. LED circuit 6 lit up on a solid surface so the tracks did not break. This implies the skin is too soft and does not make a good connection between the multimeter and LED circuit.

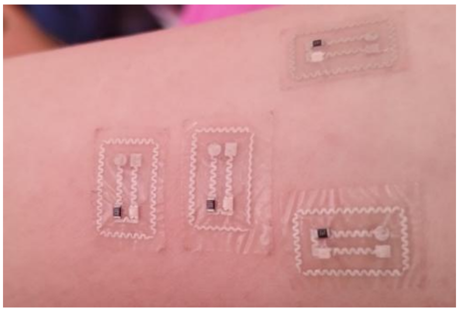


Figure 10.33: Fifth Day After Placed LED Circuits on Skin

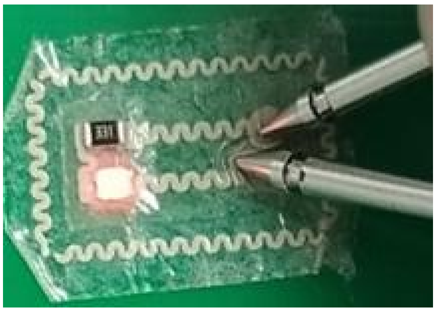


Figure 10.34: LED Circuit 1 on the Fifth Day After Placed on Skin

On the 5th day after placing the LED circuits on the skin, the circuit was removed from the skin during sleep due to external friction Fig 10.33. But the LED circuit was still able to be lit up by attaching a multimeter after being placed on a solid surface, Fig 10.34.

For longer time LED circuits are mounted on the skin, the connection is difficult to make between the multimeter and the circuit, due to the conductive adhesive tape getting damaged by external friction and water as the Tegaderm layer (protection layer) does not cover the area used for attaching the multimeter. On the 7th day the LED circuits placed were not able to be lit up on the skin by attaching the multimeter.

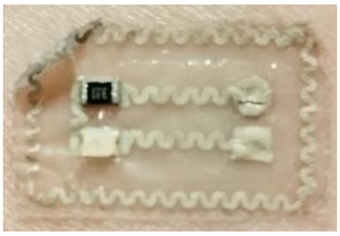


Figure 10.35: LED Circuit on Skin on 8th Day

To test the longest time LED circuit able to mounted on skin, did not remove the LED circuits from the skin even the LED circuit no longer works. However, the LED circuit starts pulling off from the skin on the 8th day after being placed on the skin, Fig 10.35.

10.3.3 Multiple Layer Circuits on Tegaderm Film

Figure 10.36: Double Conductive layer LED Circuits on Tegaderm Film

Multiple layer structures will increase the uses of printing circuits on Tegaderm film and able to simplify the circuits, reducing the circuit size. So designed a simple multiple-layer circuit by placing a LED circuit on top of another LED circuit, Fig 10.36. This circuit is used for testing the capability of the Voltera V-One printer for printing multiple-layer structure circuits.

Multiple layer structure circuit printed by print and cure the bottom LED circuit then place a Tegaderm film to the area the top LED circuit will be printed on. Print the top LED circuit and cure the circuit at 130°C for 40 minutes due to there being 2 extra layers under the top LED circuit compared to a single conductor layer structure circuit.

The height of the print area is different due to there being a conductor layer and Tegaderm film. So, without breaking the printed layer and Tegaderm layer, the top LED circuit needs to be printed by increasing the distance between the nozzle (used for outputting conductor) and Tegaderm film. But the print quality will be reduced when the distance between the nozzle and Tegaderm film is increased, as the right-side sample, Fig 10.36 did not print in good quality.

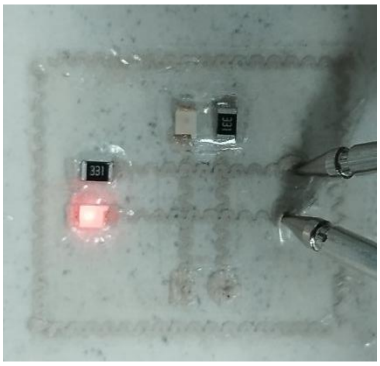


Figure 10.37: Double Conductive Layer Circuit Test in Tegaderm

Components are placed on the printed conductor using conductive adhesive tape, but only the LED circuit on the top layer is lit up. Fig 10.37. Multiple structure layer circuit is possible to make but needs to take complex steps, and the conductor at the bottom layer will be difficult to define the problems.

Chapter 11

11. RFID Sensor Designs Printed on Tegaderm Film

A simple RFID sensor will contain a sensor, an RF chip, a matching network, and an antenna, EM4325 is chosen due to it is an RF chip and contains a temperature sensor[13], which allows the RFID sensor design only to need to use one IC chip, a matching network and an antenna.

11.1 Loop Antenna on Tegaderm Film without Matching Network

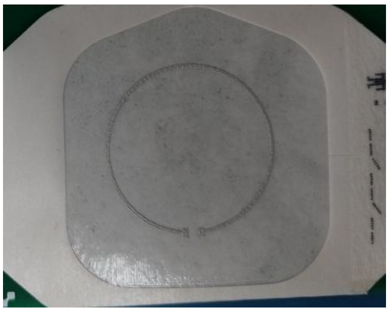


Figure 11.1: Printed Loop Antenna on Tegaderm

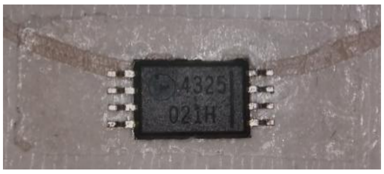


Figure 11.2: EM4325 connected to Antenna

A 10 cm circle loop antenna is designed with a diameter of 3.183cm, Fig 11.1 and an EM4325 chip is connected to the antenna using conductive adhesive tape, Fig 11.2. EM4325 is used due to this IC chip containing a temperature sensor, and using EM4325 as a temperature sensor only needs to use ANT+ and Vcc contact leads to the antenna[13]. An RFID reader is used for testing to ensure the EM4325 is connected to the antenna.

Figure 11.3: Read Range Test of Loop Antenna2

The RFID reader is also used to measure the read range of the antenna. The protection layer is not placed on the top of the antenna before ensuring the circle loop antenna can be read by an RFID reader. The measured read range of the 10cm loop antenna is approximately 15.5cm as pictured in Fig 11.3.

Figure 11.4: Loop Antenna on Skin

A Loop antenna was placed on the skin to test the strength, and as in the previous test, placed a protection layer is placed onto the antenna before placing the antenna on the skin. Fig 11.4 shows the Antenna placed on the skin, and an RFID reader is used to test the loop antenna, but the loop antenna is not able to be read by the reader after being placed on the skin.

11.2 Resistance between EM4325 and Antenna

Figure 11.5: Conductive Tape Resistance in Sample 1

Figure 11.6: Conductive Tape Resistance in Sample 2

As the conductive tape has resistance would affect the matching network used for matching the EM4325 and loop antenna, due to the value required in the matching network will be changed. Conductive adhesive tape resistance is measured by measuring the resistance between the EM4325 pins and the conductor. In sample 1, Fig 11.5, tape resistance is about 3Ω. But in sample 2, Fig 11.6, the resistance of conductive adhesive tape has tape resistance of 1.4Ω and 0.9Ω measured from the pin connected to the antenna. The resistances of the conductive adhesive tape are inconsistent due to the EM4325 did not have a good connection to the antenna. And this will affect the for applying a matching network to the antenna.

Sample	Tape Resistance[Ω] between antenna and	
	ANT+	VSS
1	3.3	2.9
2	1.4	0.9
3	1.9	0.7
4	0.8	0.7
5	0.9	0.5
6	0.9	0.8

Table 12: Measured Tape Resistances

In order 4 more samples with the same design are made and used to measure the conductive adhesive tape resistance between EM4325 and the antenna and the results show in Table12. Sample 1 is the only sample of the EM4325 pins that did not be heated and applied small pressure. The measured resistance of sample 1 is higher than other samples, therefore conductor adhesive tape works in better performance (with less resistance) with heat and pressure applied when placing components.

11.3 Loop Antenna on Tegaderm Film with Matching Network

Measured Antenna Impedacne on FR-4 Board With Conductive Adhesive Tape		
Loop Antenna Size[cm]	Real Impedance[Ω]	Imaging Impedacne[Ω]
8	62.161	-163.24
10	228.69	602.755
14	241.93	305.335

Table 13: Antenna Impedance Measured On FR-4 board

Measured Antenna Impedacne on Skin With Conductive Adhesive Tape		
Loop Antenna Size[cm]	Real Impedance[Ω]	Imaging Impedacne[Ω]
8	98.034	-306.85
10	58.696	-55.158
14	98.645	-26.977

Table 14: Antenna Impedance Measured on Skin

The measured antenna impedance when placed on FR-4 board shown in Table 13, and Table 14 showns the measured antenna impedance when placed on human skin. Measurement is preform by used VNA (vector network analyser) is set to measure the antenna impedance at the frequency of 866MHz.

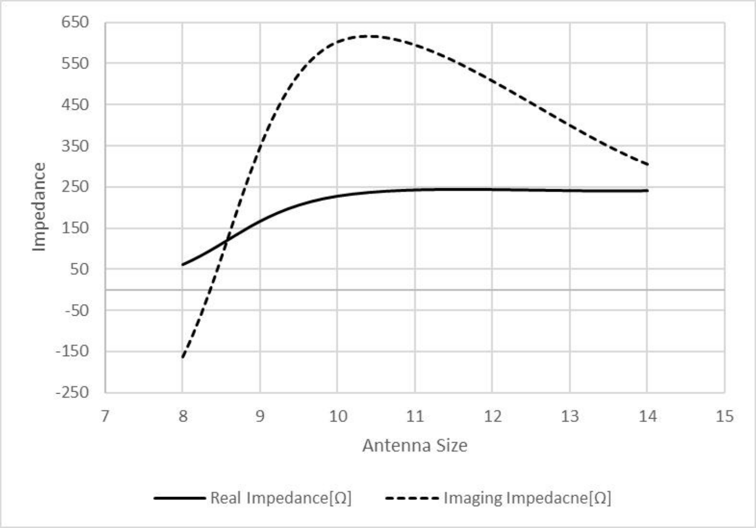


Figure 11.7: Measured Antenna Impedance with Conductive Tape on FR-4 Board

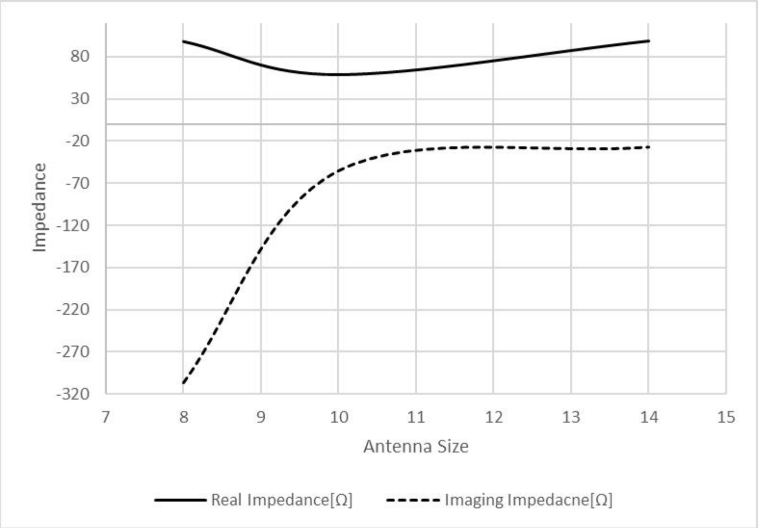


Figure 11.8: Measured Antenna Impedance with Conductive Tape on Human Skin

Mathcing Network Variables for Loop Antenna on Human Skin with Condcutive Adhesive Tape						
Antenna Size[cm]	Zs[Ω]	Zl[Ω]	Calculated L[nH]	Calculated C[pF]	Suitable L[nH]	Suitable C[pF]
8	23.3-j145	98.034-j306.85	55.19	0.6138	56	1
10	23.3-j145	58.696-j55.158	34.93	1.655	33	1.5
14	23.3-j145	98.645-j26.977	34.72	2.792	33	3.3

Table 15: Variables of Matching Network

Due to the conductive adhesive tape having unstable resistance, in order antenna impedance is measured with the conductive adhesive tape placed. Components values used in the matching network, in Table 15, is be calculated based on the measured antenna impedance when conductive adhesive tape is placed.

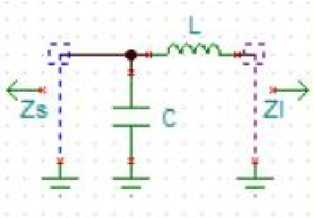


Figure 11.9: L Matching Network

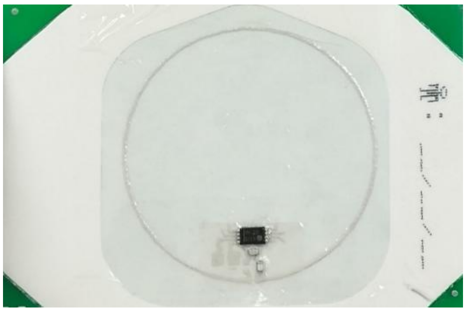


Figure 11.10: Loop Antenna with Matching Network

In order to test the L matching network as pictured in Fig 11.9, a 14cm loop antenna is designed for with the printing methodology in section 9. A protection layer was also placed on the top to apply pressure to the components and protect components from external friction, Fig 11.10.

Figure 11.11: Read Range Test for 14cm Loop Antenna on FR-4 Board with Matching Network.

The read range of the 14cm loop antenna with a matching network is measured using an RFID reader. Compared to the loop antenna that did not has a matching network, see section 11.1, the read range did increases with a matching network. The read range for the 14cm loop antenna with a matching network is more than approximately 30cm. But this is the result compared to a 14cm loop antenna with a matching network and a 10cm loop antenna without a matching network.

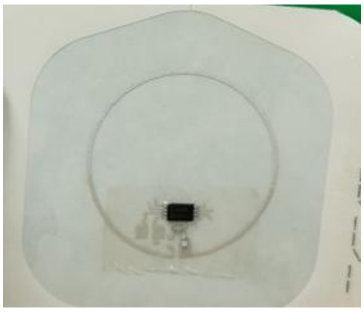


Figure 11.12: 10cm Loop Antenna on FR-4 Board with Matching Network

Figure 11.13: Read Range Test for 10cm Loop Antenna on FR-4 Board with Matching Network

In order a 10cm loop antenna with a matching network is printed for testing the read range, Fig 11.12. However the read range of the 10cm loop antenna with a matching network is approximately 6cm, which is less than the read range without a matching network as resulted in section 11.1.

Figure 11.14: Read Range Test for Loop Antenna on Skin with Matching Network.

As the 14cm loop antenna with a matching network has a longer read range, the antenna is placed on the arm in order to test the read range again using an RFID reader. But the antenna cannot be read until the antenna is touching the RFID reader as pictured in Fig 11.14.

Antenna Read Range Test used Different Component Values on FR-4 Board			
Antenna size[cm]	Inductor[nH]	Capacitor[pF]	Estimate Read Range[cm]
8	56	1	13
		1.5	Cannot be read
		2.2	10
10	33	1	15
		1.5	20
		2.2	10
14	33	2.2	10
		3.3	25
		4.7	15

Table16: Read Range of Printed Loop Antenna with Different Components in Matching Network

Printed more loop antennae in different sizes, in order to perform more tests on matching networks with different value capacitors used. Test Results show in Table 16 that the 10cm and 14cm loop antennas using the components have the closest value to the calculated values and have the longest read range compared to other same-size loop antennas. However, an 8cm loop antenna using a 56nH inductor and 1.5pF capacitor was not able to be read by the RFID reader, as this problem would cause by the connection issue between the EM4325 chip and the antenna.

Measured Antenna Impedacne on FR-4 board Without Conductive Adhesive Tape		
Loop Antenna Size[cm]	Real Impedance[Ω]	Imaging Impedacne[Ω]
8	36.188	156.592
10	111.7285	459.3735
14	300.137	61.152
15	227.047	103.609

Table 17: Antenna Impedance Measured on FR-4 board

Measured Antenna Impedacne on Ham Without Conductive Adhesive Tape		
Loop Antenna Size[cm]	Real Impedance[Ω]	Imaging Impedacne[Ω]
8	60.233	-14.895
10	76.156	-6.339
14	79.797	-24.459
15	73.625	-23.885

Table 18: Antenna Impedance Measured on Human Equivalent Phantom

Measured Antenna Impedacne on Skin Without Conductive Adhesive Tape		
Loop Antenna Size[cm]	Real Impedance[Ω]	Imaging Impedacne[Ω]
8	108.4285	-68.6375
10	77.3745	-52.3185
14	91.0035	-5.99
15	115.345	-9.785

Table 19: Antenna Impedance Measured on Human Skin

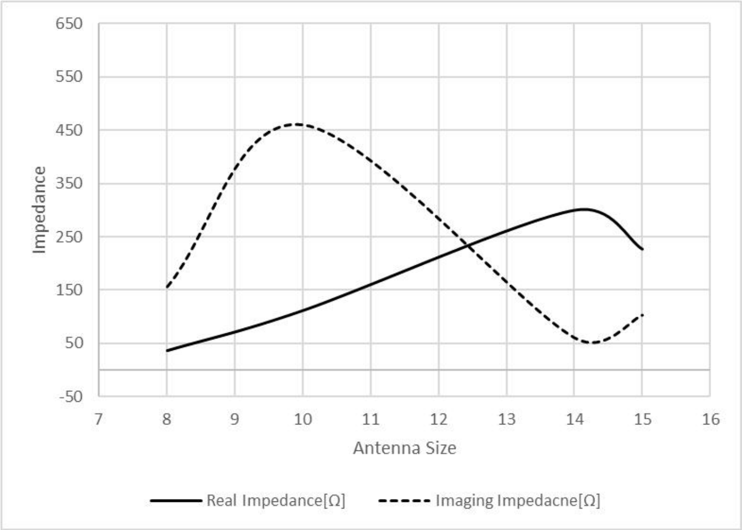


Figure 11.15: Measured Antenna Impedance without Conductive Tape on FR-4 Board

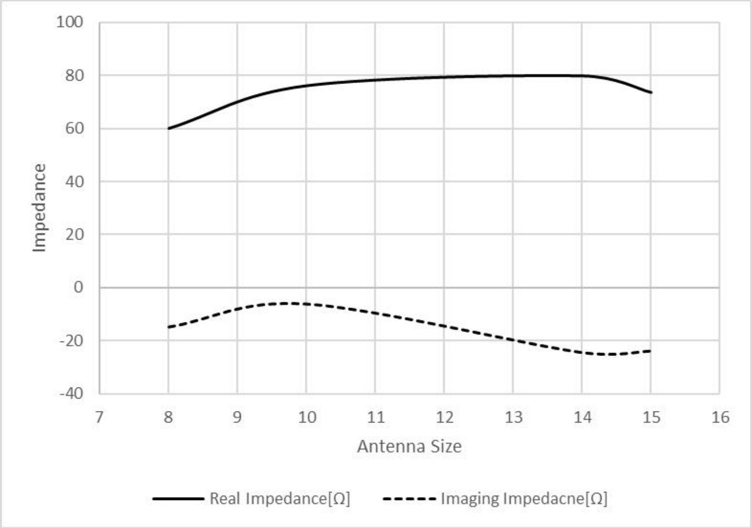


Figure 11.16: Measured Antenna Impedance without Conductive Tape on a block of Ham

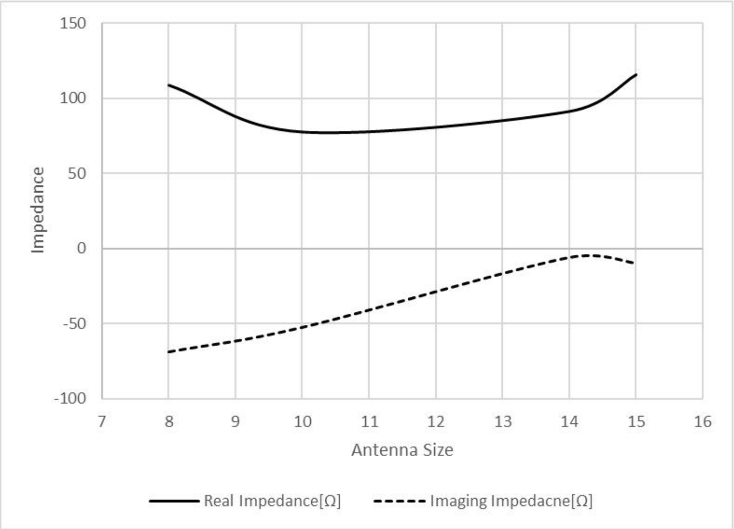


Figure 11.17: Measured Antenna Impedance without Conductive Tape on Human Skin

As the conductive adhesive tape can produce a low resistance connection between components and printed conductors by applying certain heat and pressure. More samples are printed in order to measure more accurate antenna impedance without a conductor adhesive tape placed. Measured antenna impedance, when placed on FR-4 substrate is in Table 17, Table 18 for the results when placed on a block of ham(human equivalent phantom), and Table 19 for when placed on human skin.

Matching Network Variables for Loop Antenna on Human Equivalent Phantom without Conductive Adhesive Tape						
Antenna Size[cm]	Zs[Ω]	Zl[Ω]	Calculated L[nH]	Calculated C[pF]	Suitable L[nH]	Suitable C[pF]
8	23.3-j145	60.233-j14.895	32.3	3.085	33	3.3
10	23.3-j145	76.156-j6.339	33.13	3.428	33	3.3
14	23.3-j145	79.797-j24.459	33.74	2.844	33	3.3
15	23.3-j145	73.625-j23.885	33.41	2.833	33	3.3

Table 20: Matching Network Variables for Loop Antenna on Human Equivalent Phantom

Matching Network Variables for Loop Antenna on Human Skin without Conductive Adhesive Tape						
Antenna Size[cm]	Zs[Ω]	Zl[Ω]	Calculated L[nH]	Calculated C[pF]	Suitable L[nH]	Suitable C[pF]
8	23.3-j145	108.428-j68.638	36.71	2.077	39	2.2
10	23.3-j145	77.375-j52.319	35.04	2.092	33	2.2
14	23.3-j145	91.004-j5.990	33.97	3.305	33	3.3
15	23.3-j145	115.345-j9.785	35.2	3.024	33	3.3

Table 21: Matching Network Variables for Loop Antenna on Human Skin

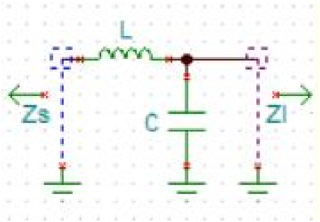


Figure 11.18: Changed L Matching Network

The position of the components is changed, Fig 11.18, as the measured antenna impedance is different to the measured antenna impedance with conductor adhesive tape placed.

11.4 Loop Antenna Test with Human Equivalent Phantom

Antenna Read Range Test with New L Mathicng Network				
Atnenna Size[cm]	Indcutor[nH	Capacitor [pF]	Estimate Read Range on FR-4[cm]	Estimate Read Range on Ham[cm]
8	33	3.3	0	0
10	33	3.3	0	0
14	33	3.3	11	0
15	33	3.3	10	0

Table 22: Read Range Test Results Use New L Matching Network

Figure 11.19: Loop Antenna with Matching Network on Ham

Based on new results from antenna impedance measurements. One of the loop antenna in each size is printed, in order to measure the read range of the loop antennas with new matching networks. Table 22 shows the read range of all loop antennas with the new matching network when placed on an FR-4 substrate. 8cm and 10 cm loop antenna with the new matching network cannot be read by an RFID reader when placed on either FR-4 substrate or a block of ham (human equivalent phantom). 14cm and 15cm loop antennas with the new matching network can be read by the RFID reader with a read range of approximately 10cm when placed on an FR-4 substrate. However, 14cm and 15cm loop antenna with cannot be read by an RFID reader when placed on a block of ham.

Antenna Read Range Test with New L Mathicng Network				
Atnenna Size[cm]	Indcutor[nH	Capacitor [pF]	Estimate Read Range on FR-4[cm]	Estimate Read Range on Ham[cm]
8	33	3.3	0	0
10	33	3.3	0	0
14	33	3.3	25	0.5
15	33	3.3	30	4

Table 23: Read Range Test for New Printed Loop Antennas

Figure 11.20: Read Range Test of 15cm Loop Antenna with New Matching Network

More samples are printed in order to measure more accurate data. New printed 8cm and 10cm loop antennas have the results, Table 23, as the same as the previous test in Table 22. But the new printed 14cm and 15cm loop antennas can be read by the RFID reader when placed on a block of ham, Table 23, and the read range when placed on FR-4 substrate is also longer than the previous samples, Table 22.

As only 14cm and 15cm are the only loop antennas that can be read by an RFID reader, more 14cm and 15cm loop antennas will be printed in order to test more matching networks. As the 14cm and 15cm loop antennas can be read by an RFID reader when placed on a block of ham as shows in Table 23. So 14cm and 15cm loop antennas, in Table 22, when placed on a block of ham should be able to be read by the RFID reader. Therefore, this issue would be caused by the connection between the components and printed conductor

.

14cm loop antenna Estimate Read Range[cm]			15cm loop antenna Estimate Read Range[cm]		
Sample	FR-4	Ham	Sample	FR-4	Ham
1	35	10	1	25	8
2	15	3	2	25	8
3	30	15	3	30	10
4	15	5	4	25	5
5	30	8	5	35	10
Average	25	8.2	Average	28	8.2

Table 24: Read Range Test with Loop Antenna without Conductive Adhesive Tape

5 more samples of 14cm and 15cm loop antennas are printed but without using conductive adhesive tape for connections, in order to investigate the connection issue. Components are placed on the printed conductor before being cured, which allows the components to be boned on the printed conductor when sintering.

Table 24 shows the read range of all newly printed samples is more than 10cm when placed on FR-4 substrate, and loop antennas can be read by an RFID reader when placed on a human equivalent phantom.

14cm loop antenna has the longest loop of approximately 35cm when placed on FR-4 substrate, and the shortest read range is approximately15cm. The longest read range is approximately 15cm and the shortest read range is approximately 3cm when the loop antenna placed on a block of ham.

Compared the read range of 14cm loop antenna and 15cm loop antenna. read range of 15cm loop antenna when placed on a block of ham is more even, but the longest read range is less than 14cm loop antennas.

With the read range measurements in Table 24, the connection between the components and printed conductor does affect the loop antenna read range. Due to the read range is improved without using conductive adhesive tape at connections.

11.5 Quick Conclusion of Using Tegaderm Film

PE874 conductor pastes are chosen as the conductor used to print on the Tegaderm layer, due to it can be cured with sintering at 130oC for 15 minutes. Conductive adhesive tape can use for connecting components and printed conductors on Tegaderm film. But the conductive adhesive tape is not the best material to use for the connection, as unstable resistance will be produced by the adhesive tape.

Without using conductive adhesive tape, a 14cm and a 15cm loop antenna with an L matching network using a 33nH inductor and 3.3pF capacitor able to work on a human equivalent phantom, with an average of the read range of approximately 8.2cm. As the values of the components used in the matching network when the loop antenna is placed on a human equivalent phantom and human skin are similar, a block of ham is a good human equivalent phantom to use. Therefore, with a better method to connect the components to the printed conductor, the printed loop antenna can work on human skin. But due to the human equivalent phantom having a flat surface, the loop antenna may work less efficiently when placed on a lopsided surface..

Chapter 12

12. Extra Investigation & Measurements for Antenna Impedance Measured with Battery Placed

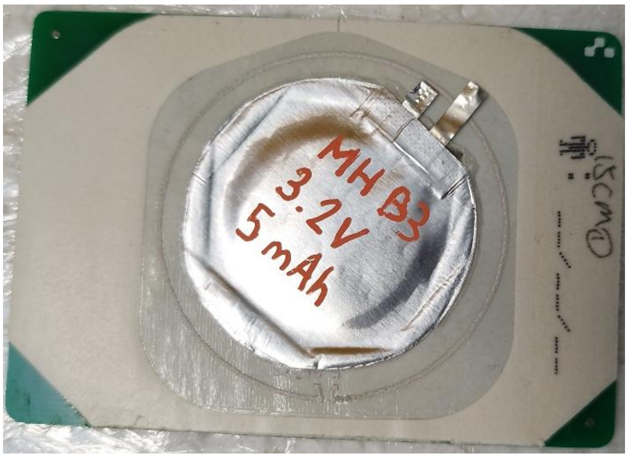


Figure 12.1: Antenna Impedance Measured with Battery on FR-4 Board

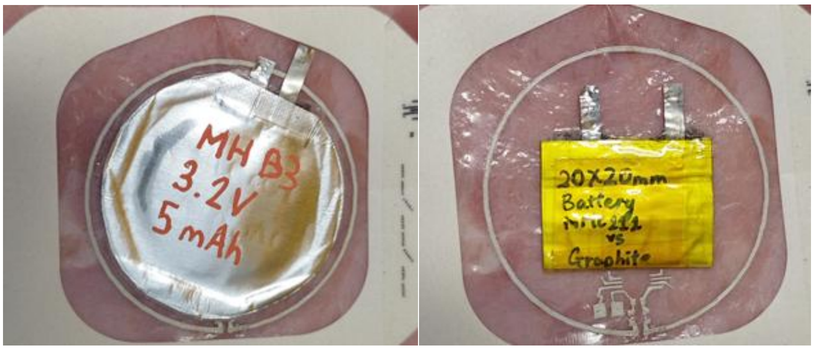


Figure 12.2: Antenna Impedance Measured with Battery on Ham

Figure 12.3: Antenna Impedance Measured with Battery on Human Skin

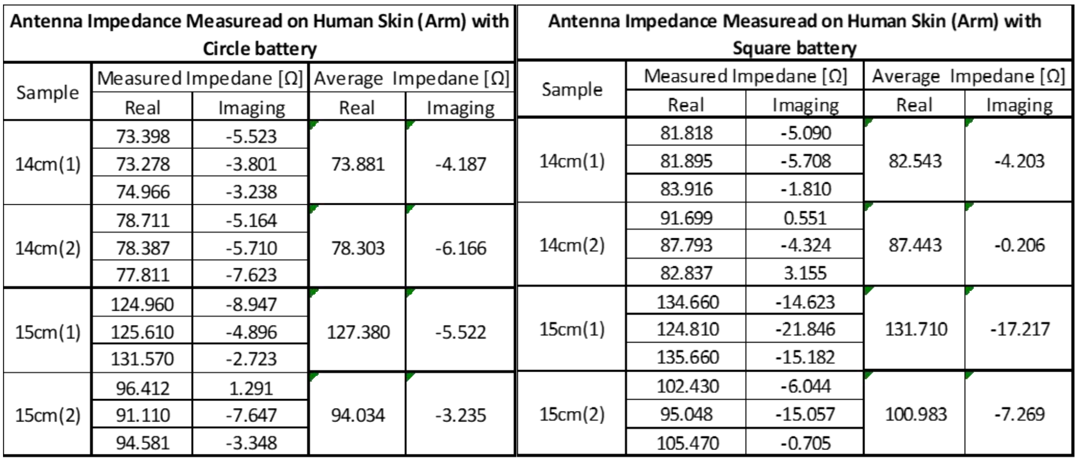
EM4325 can be used in battery-assisted passive (BAP) mode, so a battery is placed in the middle of the loop antenna and measured the antenna impedance using Vector Network Analyser. Antenna impedance will be measured on two 14cm and two 15 cm loop antennas, three measurements will be taken on each antenna which allows for calculating the average value. Two types of batteries used in this measurement are designed and made by the University of Kent. Antenna impedance with battery is measured on FR-4 board, Fig 12.1, human equivalent phantom, Fig 12.2 and human skin, Fig 12.3. Antenna impedance measured is due to a large size battery will affect antenna performance if the battery edge is too close to the antenna. The circle battery has a size of 4cm in diameter and the square battery has a size of 4cm^2.

Antenna Impedance Measuread on FR-4 Board with Circle battery					**Antenna Impedance Measuread on FR-4 Board with Square battery**				
Sample	Measured Impedane [Ω]		Average Impedane [Ω]		Sample	Measured Impedane [Ω]		Average Impedane [Ω]	
	Real	Imaging	Real	Imaging		Real	Imaging	Real	Imaging
14cm(1)	236.330	25.238	238.590	28.635	14cm(1)	250.160	46.281	253.823	39.782
	239.960	25.950				254.380	37.791		
	239.480	34.718				256.930	35.274		
14cm(2)	282.620	54.942	285.967	57.422	14cm(2)	226.640	58.480	225.773	56.320
	291.680	58.884				226.350	56.670		
	283.600	58.441				224.330	53.811		
15cm(1)	270.430	57.349	270.690	48.695	15cm(1)	280.110	87.335	279.677	86.283
	270.050	45.765				281.590	87.137		
	271.590	42.971				277.330	84.377		
15cm(2)	255.520	81.691	264.353	79.841	15cm(2)	280.380	52.029	280.513	50.083
	260.540	85.374				281.590	49.677		
	277.000	72.457				279.570	48.544		

Table 25: Antenna Impedance with Battery on FR-4Board

Antenna Impedance Measuread on Human Equivalent Phantom (Ham) with Circle battery					**Antenna Impedance Measuread on Human Equivalent Phantom (Ham) with Square battery**				
Sample	Measured Impedance [Ω]		Average Impedance [Ω]		Sample	Measured Impedance [Ω]		Average Impedance [Ω]	
	Real	Imaging	Real	Imaging		Real	Imaging	Real	Imaging
14cm(1)	74.935	-10.640	73.921	-13.080	14cm(1)	76.058	-22.098	77.420	-20.718
	72.413	-14.586				77.712	-21.623		
	74.414	-14.014				78.489	-18.433		
14cm(2)	85.143	-16.872	81.557	-20.815	14cm(2)	85..06	-16.872	83.619	-20.815
	77.244	-24.976				81.338	-24.976		
	82.284	-20.598				85.900	-20.598		
15cm(1)	76.231	-13.986	73.415	-16.561	15cm(1)	73.600	-13.986	68.526	-16.561
	68.820	-19.159				62.910	-19.159		
	75.194	-16.537				69.069	-16.537		
15cm(2)	71.857	-19.786	68.184	-21.486	15cm(2)	73.614	-19.786	72.737	-21.486
	63.269	-23.286				69.143	-23.286		
	69.425	-21.385				75.454	-21.385		

Table 26: Antenna Impedance with Battery on Human Equivalent Phantom



Antenna Impedance Measuread on Human Skin (Arm) with Circle battery				
Sample	Measured Impedane [Ω]		Average Impedane [Ω]	
	Real	Imaging	Real	Imaging
14cm(1)	73.398	-5.523	73.881	-4.187
	73.278	-3.801		
	74.966	-3.238		
14cm(2)	78.711	-5.164	78.303	-6.166
	78.387	-5.710		
	77.811	-7.623		
15cm(1)	124.960	-8.947	127.380	-5.522
	125.610	-4.896		
	131.570	-2.723		
15cm(2)	96.412	1.291	94.034	-3.235
	91.110	-7.647		
	94.581	-3.348		

Antenna Impedance Measuread on Human Skin (Arm) with Square battery				
Sample	Measured Impedane [Ω]		Average Impedane [Ω]	
	Real	Imaging	Real	Imaging
14cm(1)	81.818	-5.090	82.543	-4.203
	81.895	-5.708		
	83.916	-1.810		
14cm(2)	91.699	0.551	87.443	-0.206
	87.793	-4.324		
	82.837	3.155		
15cm(1)	134.660	-14.623	131.710	-17.217
	124.810	-21.846		
	135.660	-15.182		
15cm(2)	102.430	-6.044	100.983	-7.269
	95.048	-15.057		
	105.470	-0.705		

Table 27: Antenna Impedance with Battery on Human Skin

Table 25 shows the results of measured antenna impedance of 14cm and 15 cm loop antenna without a battery placed.14cm loop antenna impedance was 300.137+j61.152 that measured on FR-4 substrate without a battery placed, and 15cm loop antenna impedance of 227.017+j103.609 was be measured, see table 17. Compared the results of antenna impedance measured of 14cm and 15cm on FR-4 substrate with a battery placed. 14cm loop antenna impedance has more changes than 15cm loop antenna as expected, that 14cm is smaller and the battery edge is closer to the antenna.

Impedance measurement also made on the loop antennas when placed on a block of ham (human equivalent phantom). 14cm loop antenna impedance of 79.797-j24.459 is measured on a block of ham without battery placed, and 15cm loop antenna impedance is 73.625-j23.885 is measured. Table 26 shows the measured antenna impedance of 14cm and 15 cm loop antenna when placed on a block of ham with a battery placed. Antenna impedance changes has been measured, but the impedance difference measured on a block of ham between a battery placed and without a battery placed is smaller than measured on FR-4 substrate.

14cm loop antenna impedance of 91.0035-j5.99 and 15cm loop antenna impedance of 115.345-j9.785 is measured when placed on human skin without a battery placed, see table 19. 14cm loop antenna impedance difference between battery placed and without a battery placed is higher than 15cm loop antenna impedance difference as expected. The measured impedance difference when placing a square battery is smaller than when placing a circle battery as expected as the squre battery is smaller than the circle battery. But the difference between using a circle battery and a square battery is less than 10%, as so the difference is between use a circle battery and the square battery will not affect a lot on the loop antennas when placed on human skin.

Chapter 13

13. Conclusion & Evaluation

With the printing methodology on the Tattoo paper in section 4, due to the adhesive layer being thin between the human skin and the printed conductor, it is suitable to use for EMG or ECG applications. However, the printed conductor is weak and cannot sustain the stretches from the skin, even the pressure applied to the conductor during the process of placing the printed circuits on the skin, will risk breaking the printed circuits. With the use of tattoo papers, the tattoo sheet will remain stuck to the printed circuit before being placed on the skin, so this means a protective layer is unable to be applied before placing printed circuits on the skin. A protection layer only can be applied to the printed circuits after being placed on the skin, but there is no reason to protect the broken printed circuits if printed circuits break during the process of placing the circuits on the skin.

Circuits on tattoo paper are suitable for use by firm conductors, for example, copper, and aluminum. Circuits printed using Voltera Flex2 conductor ink and PE874 conductive paste are too weak to use in conjunction with tattoo paper placed on human skin.

Using Tegaderm film as circuit substrate, circuits printed using the Voltera Flex2 conductor ink and PE874 conductive paste are able to sustain the pressure during the application process and also are quite resilient to stretches. Loop antenna with EM4325 is a design used as an RFID sensor used to measure the temperature and temperature sensor is contained in the EM4325 chip.

9703 conductive adhesive tape was used to connect the components on the printed conductor and holding the components on the circuits. Printed LED circuits work on human skin with 9073 conductive adhesive tapes however, the loop antennas did not work on human skin. This is as the LED and the resistor are the only components on the LED circuit. In the RFID, there is the EM4325, inductor and capacitor which is comparatively more. This results in the pin and connnection area of the EM4325 being much larger then that of the LED circuit. Due to this when the RFID sensor is removed from the FR-4 substrate, the connection between EM4325 and the printed conductor will be more affected by stretches. When an alternative design was printed with more RFID sensors without using 9703 conductive adhesive tapes the RFID sensors worked and had a longer read range compared to the RFID sensors that used 9703 conductive tapes.

RFID sensors can work with an average read range of more than 8cm on a human without using the 9703 conductive adhesive tapes. Therefore, with a better connection method, the antenna read range will be more stable.

With regards to future designs, 14cm and 15cm loop antennas have the space inside the loop antenna to add more components in order to increase the RFID sensor functions. Also, 14cm and 15cm loop antennas allow for a battery above the circuit without covering the antenna allowing for more power to apply to the circuits. With more power being applied to the circuit the read range can be increased. RFID sensor designs using Tegaderm film allows less risk on human skin due to Tegaderm film being a stretchable plastic film as well as plastic being a good insulator.

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Appendix

A1. Measured Resistance of Tracks sintered on FR-4 Substrate

Following Results shown the measured resistance of sintered tracks used to calculated the average resistance in section 5.1

Measured Resistance of Tracks sintered at 90°C

90 degrees for 40 minutes					
resistance(Ω)	Track Width(mm)				
Sample	0.25	0.35	0.45	0.55	0.65
1	0.61	0.42	0.34	0.26	0.21
2	0.69	0.44	0.39	0.30	0.24
3	0.71	0.46	0.35	0.29	0.21
4	0.70	0.49	0.41	0.28	0.21

90 degrees for 50 minutes					
resistance(Ω)	Track Width(mm)				
Sample	0.25	0.35	0.45	0.55	0.65
1	0.65	0.44	0.36	0.28	0.22
2	0.75	0.55	0.43	0.37	0.29
3	0.7	0.47	0.4	0.25	0.2
4	0.65	0.43	0.33	0.24	0.2

90 degrees for 60 minutes					
resistance(Ω)	Track Width(mm)				
Sample	0.25	0.35	0.45	0.55	0.65
1	0.29	0.27	0.23	0.2	0.18
2	0.49	0.39	0.29	0.22	0.17
3	0.67	0.4	0.28	0.22	0.19
4	0.69	0.47	0.38	0.28	0.22

Measured Resistance of Tracks sintered at 100°C

100 degrees for 40 minutes					
resistance(Ω)	Track Width(mm)				
Sample	0.25	0.35	0.45	0.55	0.65
1	0.79	0.37	0.30	0.27	0.21
2	0.89	0.58	0.31	0.22	0.19
3	0.72	0.38	0.33	0.27	0.19
4	0.72	0.49	0.35	0.27	0.20

100 degrees for 50 minutes					
resistance(Ω)	Track Width(mm)				
Sample	0.25	0.35	0.45	0.55	0.65
1	0.22	0.17	0.13	0.12	0.11
2	0.37	0.22	0.17	0.14	0.12
3	0.36	0.22	0.17	0.14	0.12
4	0.38	0.25	0.20	0.17	0.13

100 degrees for 60 minutes					
resistance(Ω)	Track Width(mm)				
Sample	0.25	0.35	0.45	0.55	0.65
1	0.24	0.22	0.18	0.15	0.13
2	0.25	0.27	0.21	0.17	0.14
3	0.26	0.27	0.20	0.17	0.13
4	0.26	0.27	0.21	0.15	0.13

Measured Resistance of Tracks sintered at 120°C

120 degrees for 30 minutes					
resistance(Ω)	Track Width(mm)				
Sample	0.25	0.35	0.45	0.55	0.65
1	0.30	0.20	0.17	0.13	0.10
2	0.30	0.22	0.17	0.13	0.11
3	0.35	0.22	0.17	0.13	0.11
4	0.38	0.24	0.18	0.15	0.12

120 degrees for 40 minutes					
resistance(Ω)	Track Width(mm)				
Sample	0.25	0.35	0.45	0.55	0.65
1	0.21	0.15	0.12	0.10	0.09
2	0.29	0.19	0.14	0.11	0.09
3	0.35	0.20	0.15	0.12	0.09
4	0.35	0.20	0.16	0.12	0.10

120 degrees for 50 minutes					
resistance(Ω)	Track Width(mm)				
Sample	0.25	0.35	0.45	0.55	0.65
1	0.29	0.19	0.17	0.14	0.12
2	0.43	0.26	0.19	0.15	0.15
3	0.38	0.22	0.17	0.15	0.11
4	0.38	0.23	0.18	0.14	0.13

Measured Resistance of Tracks sintered at 130°C

130 degrees for 30 minutes					
resistance(Ω)	Track Width(mm)				
Sample	0.25	0.35	0.45	0.55	0.65
1	0.22	0.17	0.12	0.10	0.09
2	0.22	0.15	0.12	0.11	0.11
3	0.20	0.19	0.14	0.11	0.09
4	0.32	0.21	0.15	0.12	0.09

130 degrees for 40 minutes					
resistance(Ω)	Track Width(mm)				
Sample	0.25	0.35	0.45	0.55	0.65
1	0.25	0.21	0.14	0.13	0.11
2	0.38	0.27	0.17	0.16	0.13
3	0.38	0.26	0.18	0.16	0.13
4	1.91	0.38	0.18	0.15	0.14

130 degrees for 50 minutes					
resistance(Ω)	Track Width(mm)				
Sample	0.25	0.35	0.45	0.55	0.65
1	0.20	0.12	0.11	0.09	0.08
2	0.40	0.22	0.13	0.11	0.09
3	0.41	0.18	0.15	0.12	0.09
4	0.38	0.18	0.16	0.11	0.09

Measured Resistance of Tracks sintered at 140°C

140 degrees for 30 minutes					
resistance(Ω)	Track Width(mm)				
Sample	0.25	0.35	0.45	0.55	0.65
1	0.27	0.20	0.15	0.14	0.11
2	0.39	0.22	0.19	0.12	0.12
3	0.31	0.20	0.16	0.12	0.09
4	0.32	0.20	0.15	0.12	0.10

140 degrees for 40 minutes					
resistance(Ω)	Track Width(mm)				
Sample	0.25	0.35	0.45	0.55	0.65
1	0.31	0.19	0.15	0.13	0.11
2	0.35	0.21	0.15	0.12	0.11
3	0.45	0.29	0.21	0.13	0.10
4	0.36	0.28	0.25	0.15	0.11

140 degrees for 50 minutes					
resistance(Ω)	Track Width(mm)				
Sample	0.25	0.35	0.45	0.55	0.65
1	0.25	0.18	0.14	0.12	0.10
2	0.42	0.25	0.20	0.13	0.10
3	0.35	0.22	0.14	0.11	0.10
4	0.18	0.12	0.11	0.09	0.08