STRESS ANALYSIS OF STRETCHABLE THERMAL SENSOR

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Declaration

This journal article is a presentation of my original research work. Wherever contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature, and acknowledgement of collaborative research and discussions. The work was done under the guidance of Dr.Abdullah Aziz Saad, at the Universiti Sains Malaysia, Engineering Campus.

Lee Mei Wen

Date: 6th June 2017

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List of Abbreviation

v	Possion ratio
C_1	Neo-Hookean constant
μ	Initial Shear Modulus
E	Young's Modulus
E_t	Tangent Modulus

ABSTRAK

Kertas ini membentangkan ringkasan untuk prestasi pemodelan litar boleh regang. Untuk teknologi baharu ini, papan boleh regang dapat bengkok dan meregang dengan menggunakan substrat elastomer dan penyambung. Manakala itu, kajian terhadap kesan substrat untuk sifat-sifat mekanikal ke atas reka bentuk antara penyambung adalah penting pada seumur hidup dan kebolehpercayaan untuk litar. Pada masa kini, kebolehpercayaan litar boleh regang merupakan satu masalah apabila ia dibekalkan berterusan oleh tekanan kitaran yang akan menyebabkan ketegangan dan tekanan perubahan semasa tarik dan memampatkan. Tujuan untuk kertas ini adalah membentangkan tekanan dan ketegangan perubahan terhadap bentuk penyambung dan kebolehpercayaan litar boelh regang. Dengan menggunakan Kaedah Unsur Terhingga(FEM), ia dapat menentukan reka bentuk yang lebih baik dan bahan yang sesuai untuk litar boleh regang. Prestasi regangan boleh dinilaikan dekat ketegangan terhadap penyambung dan substrat. Bahan substrat yang sesuai boleh mengurangkan kerosakan semasa pemanjangan.PDMS dan TPU telah dipilihkan sebagai bahan substrat kerana pemanjangan yang tinggi sebelum pecah dan ia membolehkan regangan yang tinggi. Kajian ini menunjukkan kesan tekanan dan ketegangan perubahan kepada reka bentuk untuk papan litar boleh regang dengan menggunakan bahan cadangan terhadap substrat apabilah di pemanjangan yang berbeza.

ABSTRACT

This paper present a summary of the performance of modelling for stretchable circuit. For this new technology, the stretchable board can achieve mechanically bendable and stretchable by using the elastomer based substrate and interconnect. Hence, the study on mechanical properties of substrate effect on design of interconnect is important on the fatigue lifetime and reliability of circuit. Nowadays, the reliability of stretchable circuit is still an existing issue when it continuously supplied by cyclic stresses which will cause the elastic strain deformation during stretch and compress. The purpose of this paper is to present the stress and strain deformation on the interconnect design and reliability of stretchable circuit. By using the Finite Element Method (FEM), it enables to define a more reliable design and suitable material of the stretchable circuit. The stretchability performance can be evaluated on the strain and stress applied to the interconnect and substrate. Suitable material properties of substrate able to offer the less damage during elongation. PDMS and TPU are chosen as material of substrates because of its high elongation before break and it allows high stretchability. This study demonstrates the effect of stress and strain deformation on new design of stretchable board by using proposed material for the substrates at different elongation.

1 INTRODUCTION

Stress and strain deformation to stretchable thermal sensor is one of the performance when it applies to cyclic stress. Stretchable electronic circuit technology offer immediate opportunities in many branches of biomedical science and engineering. Some research has been done on it. [1] The reliability of stretchable thermal sensor is one of the main problem concerning when it supplied for thousand cyclic stresses during and after stretching, their lifetime will decrease drastically [2]. The reliability depends on the behaviour of substrate, metal interconnect and mechanical design. [3]

In general, we find softer substrates and smaller features can yield lower strains and hence larger stretchability. [4]To quantify the strains in the meander, the substrate must be included. When the substrate is stretched in the axial direction, due to the Poisson's effect, the tensile deformation is always accompanied by a lateral contraction as shown in Figure 1. [5]

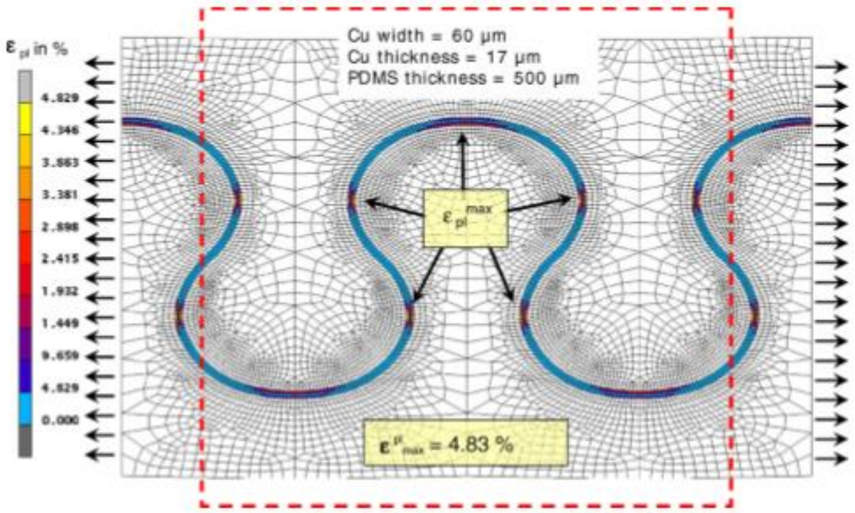

Figure 1: Poisson effect observed during a uniaxial tension for a single conductor line. [5]

The typical technology about the stretchable electronic circuit are discussed such as electrical routing designs, performance analysis and processes. [6] A horseshoe shape was designed because it allows a larger deformation compared with Elliptical and “U” shape. The reliability performance of horseshoe design has increased based on different aspect ratios (period/width). [7, 3] The ratio of width to radius of waves (W/r) is one of the important parameters in analysis and design of the wavy lines. The smaller this ratio the less strain is applied on the line during stretching and reduced amount of change in the resistance of the interconnect [8] [9] For minimal stress, the width(W) of the interconnect should be as small as possible. The design of parameters such as radius and angle will depend on the applications requirements. [10]

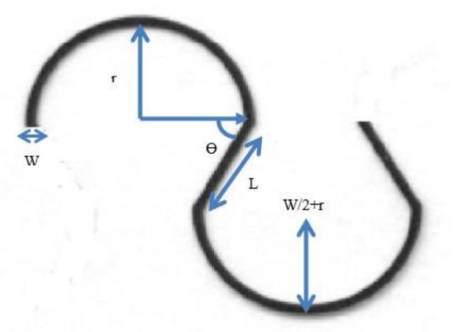

Figure 2: Design parameter of interconnect *[9]*

In this paper, FEM simulations are carried out to maximise stretchability for design of stretchable electronic circuit especially the interconnect. As the required stretchability is not exceed 10%, a horseshoe design is not necessary. [11]For interconnect, by compared the conventional lead free SnAgCu alloys, finally discovered the elastic matrial such as PDMS and TPU which more than 100% deformation and higher reliability have been achieved. [5] [3]

` The aim of this project is to investigate the deformation of stress and strain states on different geometries to the interconnect in a stretchable substrate by using the 3D simulations. In FEM simulation, we focus more on uniaxial stress which means stretch the structure in one direction and fixed the other side. Furthermore, stress-strain analysis to the interconnect design on different material of substrate especially the critical part of stretchable board. To allocate the elastic substrate, PDMS and polyurethane (TPU) have been proposed. Mechanical properties of PDMS was extracted from a tensile test and form results Neo Hookean. For TPU, the Neo Hookean characteristic was getting from website source. Both data are crucial when used for simulation.

2 MECHANICAL BEHAVIOUR OF SUBSTRATES AND INTERCONNECT MATERIALS

The substrate materials used for stretchable electronics are important in term of maximum stretch ability needed in thermal sensor, formation of strain, adhesion between substrate and interconnect. Hence, material characterisation of different substrates are crucial for reliability. The PDMS and TPU materials are presented in this case. Both materials are considering as hyper elastic elastomer model.

Polydimethylsiloxane (PDMS) is a highly cross-linked semi crystalline thermoplastic material. With highly cross linked, it contains low intermolecular forces and high flexibility. It has a chemical formula of $(C_2H_6OSi)_n$ with and its molecular structure of PDMS is shown in Figure 3. Many of these applications are used PDMS due to its useful characteristics. [12]

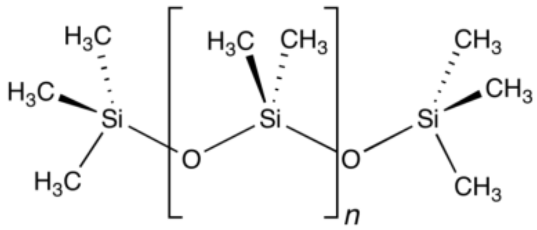

Figure 3: Molecular structure of PDMS *[12]*

The thermoplastic polyurethane (TPU) can described as mechanical performance characteristics of rubber but can processed as thermoplastics. It has high elasticity with high abrasion resistance, nonlinear hypereleastic behaviour and structural versatility. The structure of TPU is shown as Figure 4. TPU can separate into hard and soft segments forming a two phase microstructure. For hard segment, it can form carbonyl to amino hydrogen bonds and aggerate into hard domains whereas the soft segment form soft domain. [13]

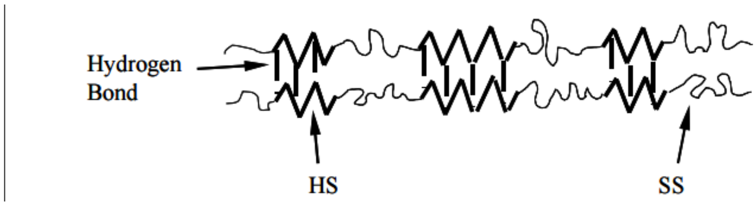

Figure 4: The alternating structure of TPU (a) HS:Hard segment (b) SS: Soft Segment *[13]*

In finite element(FE) calculation, the PDMS and TPU described as elastic polymer which have nonlinear behaviour for the stress-strain curve address effects on the numerical results. Therefore, an accurate stress-strain curve is essential. The elastomer polymer substrate such as PDMS and TPU have their stress-strain curve respectively shown in Figure 5. [14]

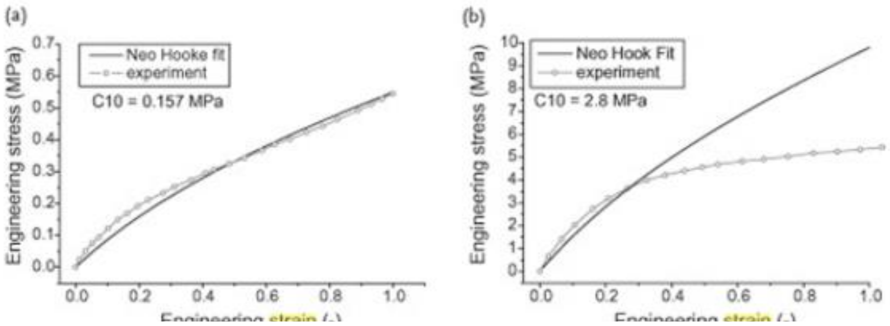

Figure 5: Stress-strain curve of (a)PDMS and (b)TPU [11]

The interconnect of stretchable thermal sensor is copper which modelled as nonlinear plastic behaviour with a Young's Modulus of 117GPa, a Poisson ratio(v) of0.3, a Yield stress of 172.3MPa and a tangent modulus of 1034.2MPa. The stress-strain curve of copper is shown in Figure 6. [14]

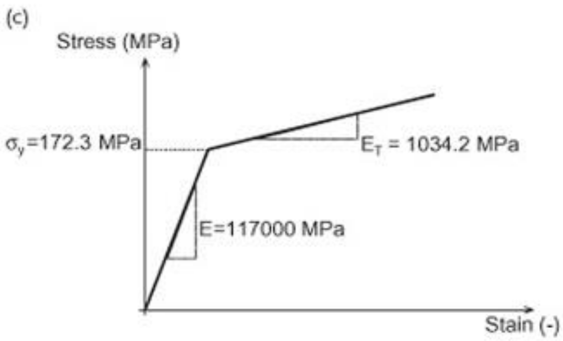

Figure 6: Nonlinear plastic behaviour of copper *[14]*

3 METHODOLOGY

3.1 INTRODUCTION

This chapter represents the Solidworks used in modelling the thermal sensor product and ANSYS Workbench 14.0 used to stimulate the stress and strain analysis in static structural. In simulation, several methods have been done to analysis the parameter correctly.

3.2 MATERIAL

There are two different substrates but same interconnect was demonstrated, 130m thick of TPU and PDMS. The TPU and PDMS is under elastic polymer which have nonlinear behaviour for the stress-strain curve. There are modelled as an incompressible hyperelastic material (ie Neo-Hookean model). The interconnect is copper which modelled as nonlinear plastic behaviour.

3.3 GEOMETRY MODELLING

Before import to Solidwork, the design layout was GTL format and using Gerber Viewer to view shown in Figure 7. The GTL layout then transferred to DXF format through Gerber Union tool which can be import into solidwork in 2D view.

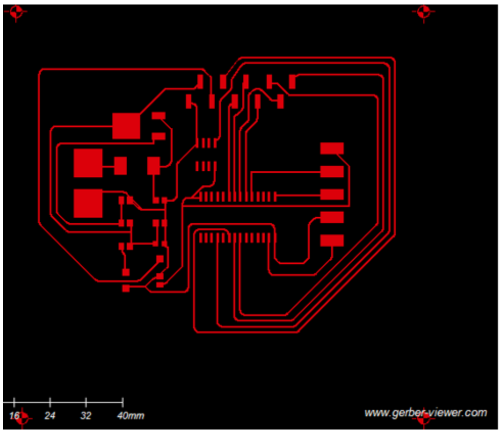

Figure 7: The layout of modelling

The modelling has been done by using Solidworks 2014. When convert the GTL file to DXF file, the line in some part in drawing 2D view Solidwork is not smooth as shown in Figure 8. So, there is edited the drawing manually (Figure 9). Various individual parts of the thermal sensor are determined and assembled as a single part known as Stretchable Board. There are total number of 3 parts after fully assembled. The name and quantity of the individual parts are shown in below Table 1.

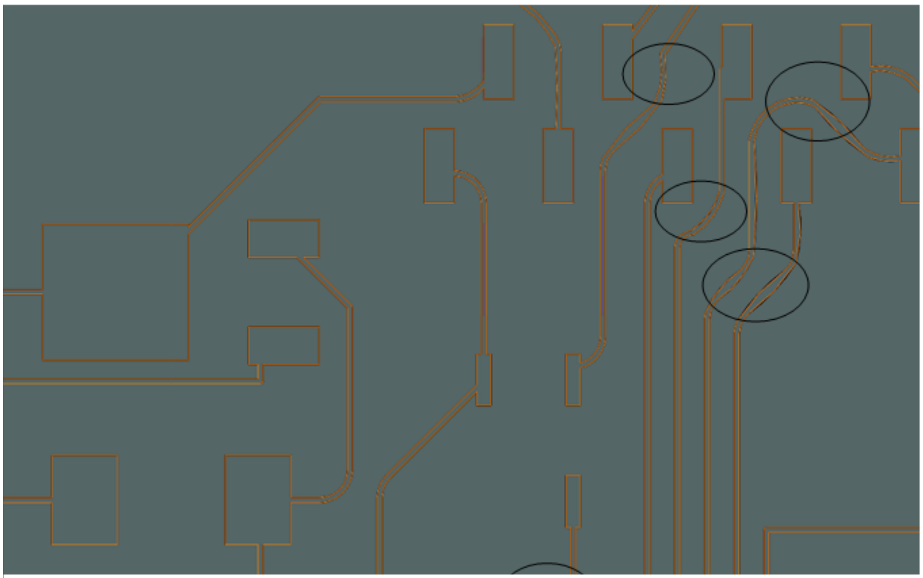

Figure 8:The circles show that the part of drawing which is not smooth

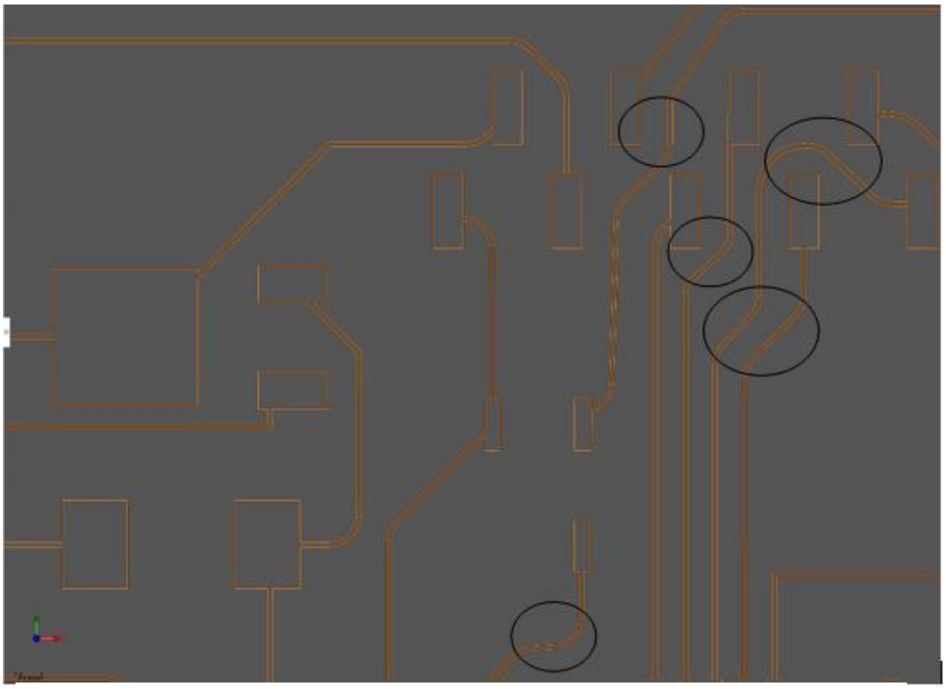

Figure 9:The circles show not smooth has been edited manually

Table 1: Individual Part Name and Quantities in Assembly

Number	Part Name	Quantity
1	Substrate	1
2	Interconnect ink	1

The shape and dimensions of the stretchable board is illustrated in below. The dimensional of length and height for stretchable board are shown in Figure 10 respectively. The thickness of substrate is 0.5mm (Figure 11) whereas thickness of ink is 0.018mm (Figure 12).

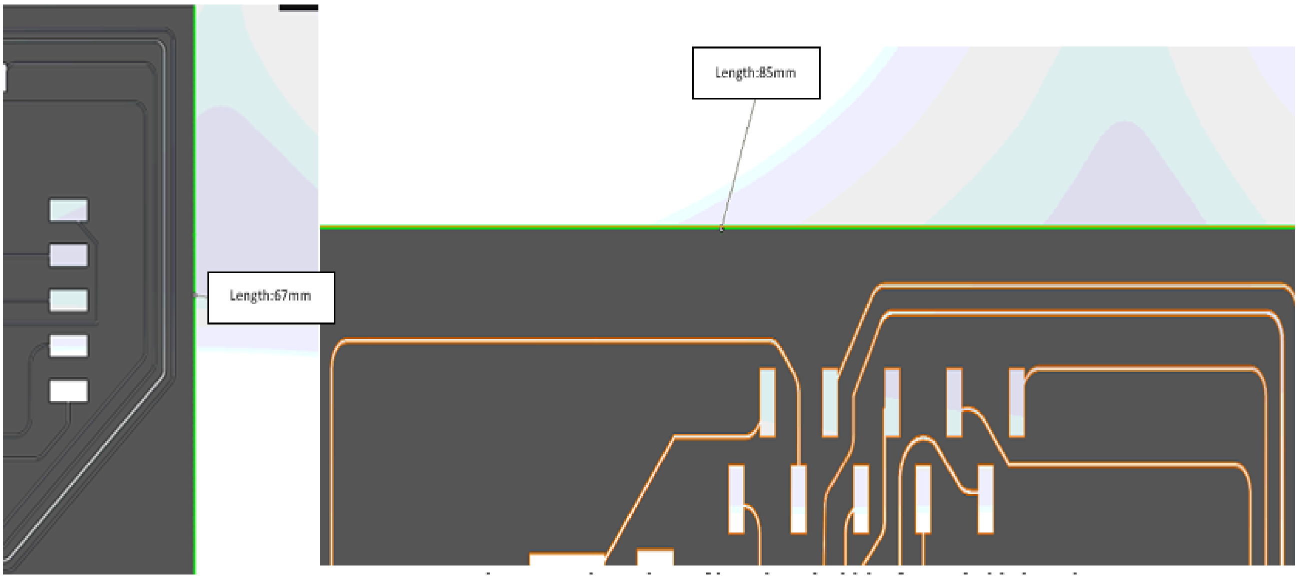

Figure 10: Dimensions of length and width of stretchable board

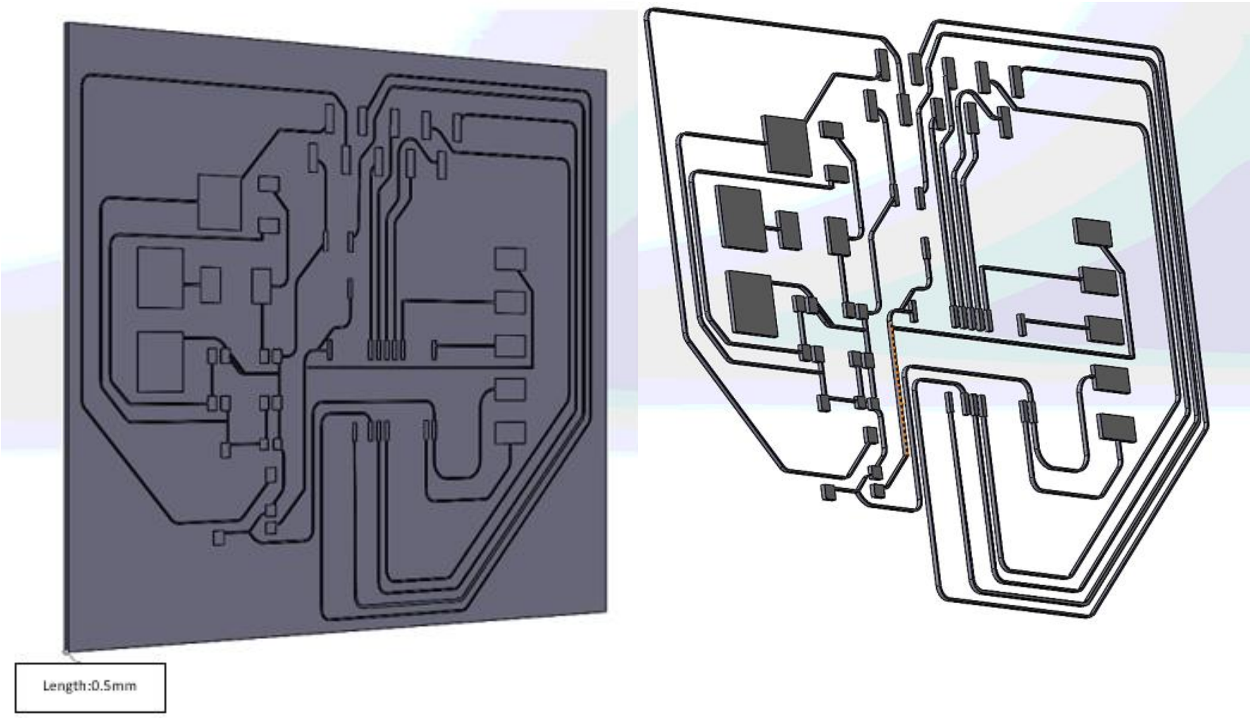

Figure 11: Dimension of thickness and isometric view of stretchable board

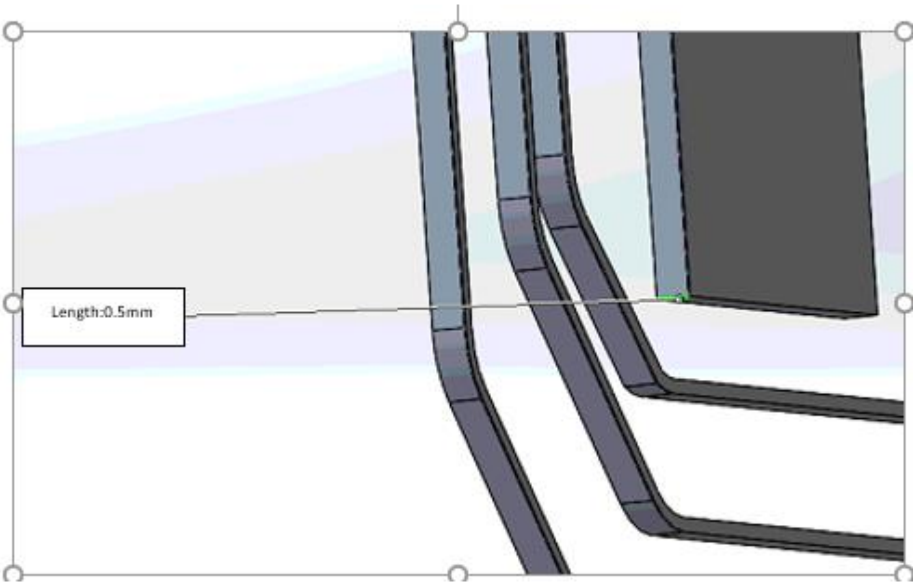

Figure 12: Isometric view of interconnect ink

3.4 ANSYS WORKBENCH ANALYSIS

By using the ANSYS Workbench 14.0, we had to stimulate the stress and strain analysis toward the modelling. In this section, we compare the performance between two different substrate materials by using same design.

In ANSY Workbench 14.0, the material properties for the different parts of the stretchable board has been setup. This can be done either selecting the material from source of engineering data or inserting new material by using parameters of material properties. A suitable meshing parameter has been inserted to increase the accuracy of performance. Result of different displacements toward the stretchable board have observed based on stress and strain analysis. For further information, this can be obtained at following sub sections.

3.4.1 Material properties

In Ansys Workbench 14.0, the material properties are edit in engineering data based on the behaviour and characteristic of each material. This is allowed us to specific the material properties based on our experimental data or source from website. The materials for each part are labelled as shown in Table 2.

Table 2: Material of modelling (Appendix A)

Number	Part Name	Material
1	Substrate	PDMS or TPU
2	Interconnect	Copper

These are the material properties specified in engineering data Ansys Workbench. These can be differentiated into two part such as non-linear hyperelastic Neo Hookean model (Table 3) and non-linear plastic model (Table 4)

a) Non-linear hyperelastic Neo Hookean model such as PDMS and TPU shown in Table 3 (Details of Engineering data are shown in Appendix A)

Table 3: The material properties for PDMS and TPU

Material Properties	PDMS	TPU
Neo-Hookean constant, C_1(MPa)	0.08	0.15
Initial Shear Modulus, μ (MPa)	0.16	2.8

Table 4: The material properties for copper

Material Properties	Copper (Interconnect)
Young's Modulus, E (GPa)	117
Poisson Ratio, v	0.3
Yield Stress (MPa)	172.3
Tangent Modulus, E_t (MPa)	1034.2

3.4.2 Static structural analysis

In this section, different setting has been setup based on the condition of analysis. The simulation will be covered geometry modelling, meshing of modelling, contact region setting and analysis setting.

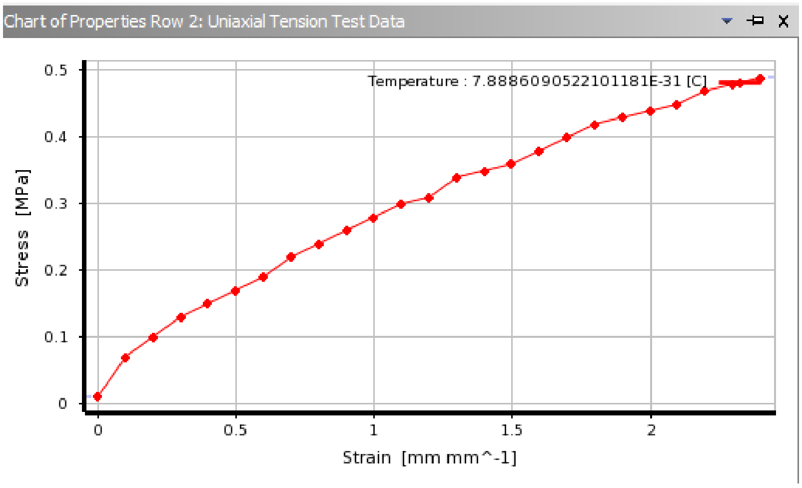

Figure 13: Appendix B Input of Neo Hookean Material properties (Stress-strain curve of PDMS)

In the meshing, the mesh quality is very important to get the accurate result. There are few parameters have been set. The sizing for relevance centre and span angle are set from coarse to medium. Then, we set the Advanced Size Function as Proximity and Curvature. By this control, the "Proximity" setting provides a means to refine the mesh in regions of the model which located closely together. The "curvature" setting can be provided a way to refine the curved features model without using local controls. The quality of meshing had been improved than used auto meshing function as shown in Figure 14. The total number of nodes and elements are 1755576 and 319068.

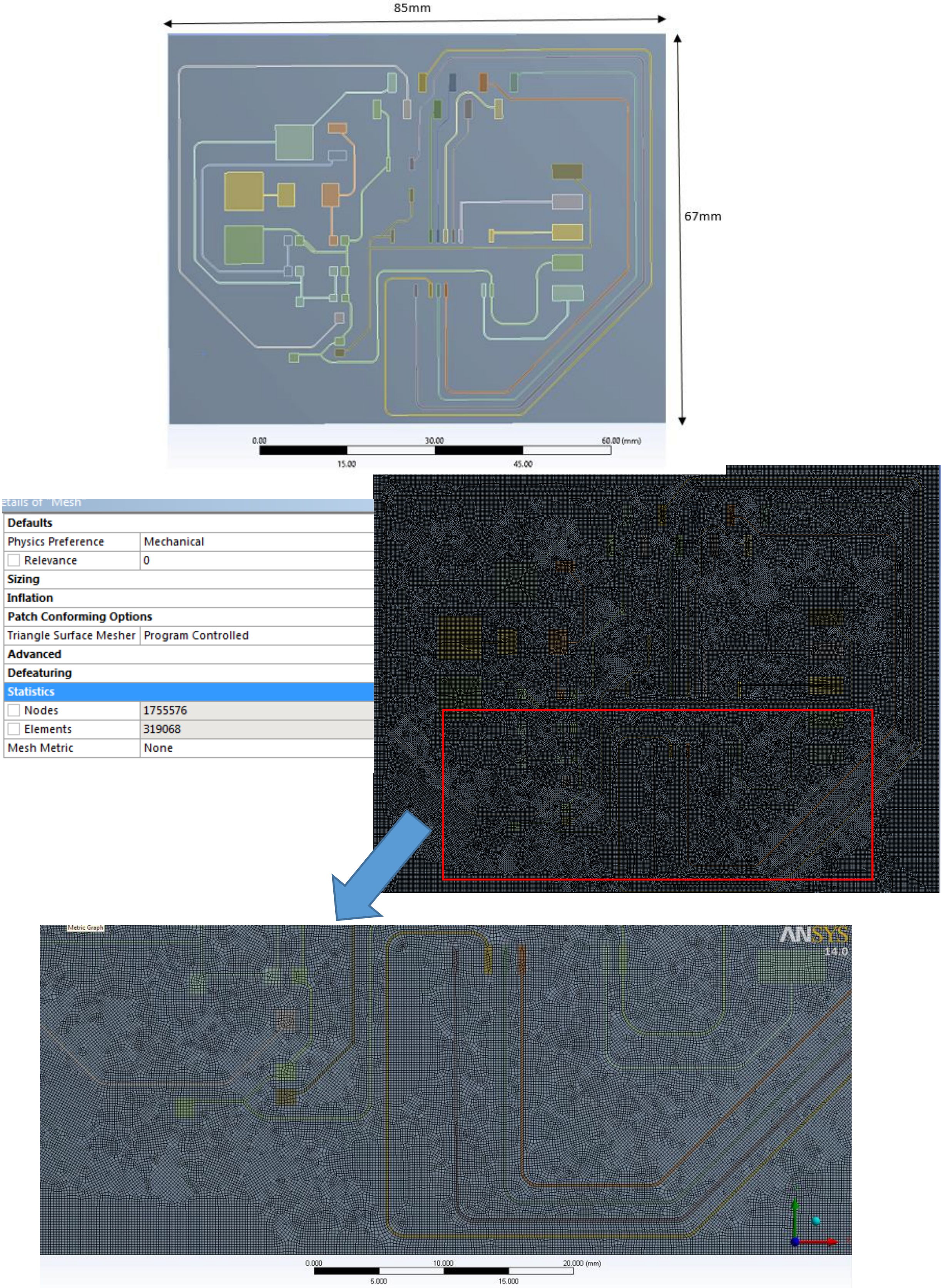

Figure 14: Geometry and mesh density used for modelling

The “Analysis settings” details provide several controls over the solution process. For this work, we focus on the uniaxial load apply on the stretchable thermal sensor. For uniaxial load, we put support to fix one directional and supply displacement on the other side of surface which allows the board move in translational displacement in x directional. The value of displacement in x-axis is 0.05mm whereas the y and z directions are 0 means the direction is constrained. In “Solution setting”, the results have shown on equivalent elastic strain and equivalent stress.

4 RESULT AND DISCUSSION

4.1 INTRODUCTION

The result shown in this chapter includes the static structural analysis where the stress and strain occurred when different displacement applied on it. With the result obtained, we can analysis the reliability of stretchable board depends on the interconnect design and material of substrate. In this simulation, we apply the uniaxial stress on the stretchable board to analysis its performance based on different displacement and different material of substrate.

To analysis the stress and elastic strain deformation clearly, we focus on few critical zones of model. As it can observe the maximum stress and elastic occur at different zone based on different material of substrate where the transition from rigid to stretchable section is present. The value of stress and elastic region in different zones of the board based on different elongation have been shown. The elastic strain was considered as damage criterion. Hence, the deformation of elastic strain and stress are much important to determine the reliability of stretchable board.

4.2 ELASTIC STRAIN ANALYSIS

The effect of applying load to two different material of substrates were simulated by using Ansys Workbech 14.0. Both of this substrate has same dimensional such as length, width and thickness. In the simulation, the interconnect was using copper. The effect of the substrate on the interconnect was observed. 0.05mm, 0.5mm, 3mm displacements were applied to the stretchable electronic circuit. Figure 15 and Figure 16 show the result of applying 0.05mm displacement to PDMS and TPU substrate respectively. From table 5 and table 6, the amount of elastic strain for all the zone increase when applied displacement increased. The maximum strain was occurred at substrate.

For Table 5, the maximum elastic strain dropped at zone 3 for all the displacement. For zone 4, the amount of elastic strain was 1.008% with 0.857mm elongation when at displacement 0.05mm. The elastic strain increased to 11.02% and 20.38% when the displacement at 0.5mm and 3mm. However, the average mean value for equivalent elastic strain at 0.05mm, 0.5mm and 3mm are 0.8556%, 9.009% and 14.689% respectively.

From Table 6, the maximum elastic strain located at zone 1 for all the displacement. For zone 1, the value of elastic strain was 0.969% with 0.824mm elongation when at displacement 0.05mm. The elastic strain increased to 8.563% and 15.86% when the displacement at 0.5mm and 3mm. The average mean value for equivalent elastic strain at 0.05mm,0.5mm and 3mm are 0.669%, 7.685% and 14.4%.

We observed that PDMS material has higher strain than TPU material for different displacement. However, the percentage difference considers small.

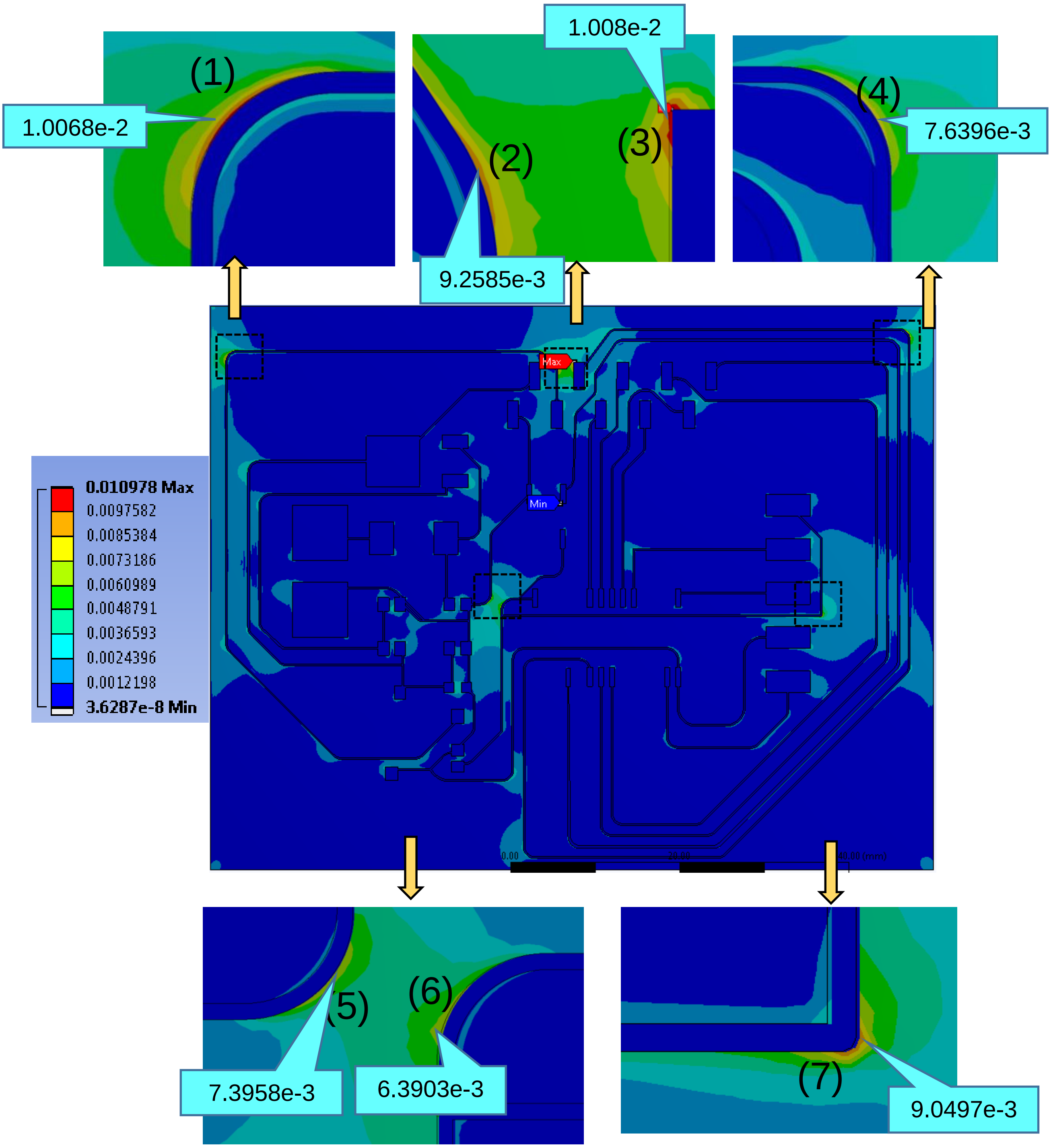

Figure 15: Equivalent elastic strain in copper interconnect for a uniaxial test at 0.05mm elongation (PDMS substrate)

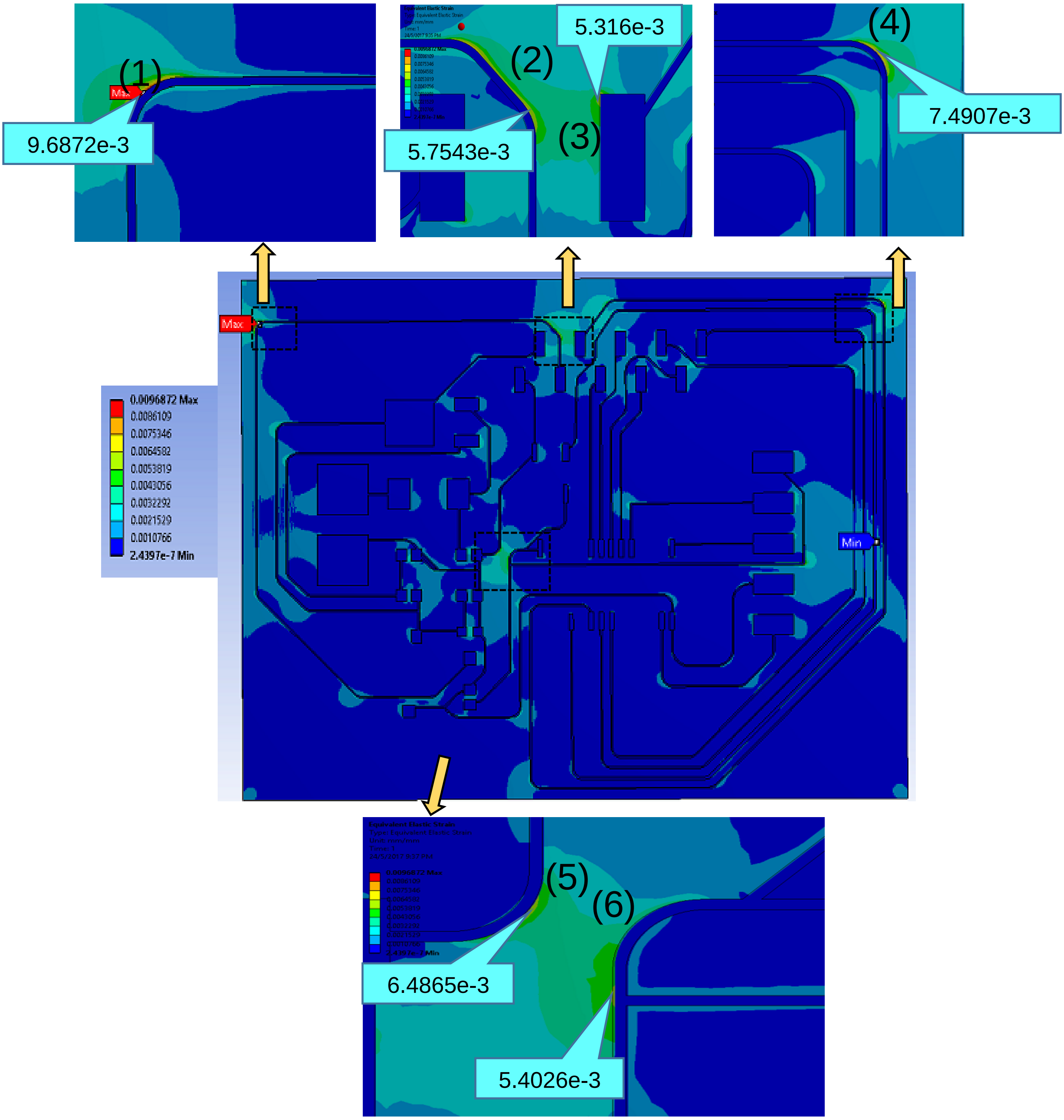

Figure 16: Equivalent elastic strain in copper interconnect for a uniaxial test at 0.05mm elongation (TPU substrate)

Table 5: Equivalent elastic strain (in per cent) at different zones for different elongations (PDMS)

Strain zone	0.05mm	0.5mm	3mm
1	1.007	10.52	16.43
2	0.926	9.860	15.03
3	1.008	11.02	20.38
4	0.764	8.590	13.44
5	0.740	6.339	12.87
6	0.639	5.952	12.21
7	0.905	10.78	12.46
Mean	0.8556	9.009	14.689

Table 6: Equivalent elastic strain (in per cent) at different zones for different elongations (TPU)

Strain zone	0.05mm	0.5mm	3mm
1	0.969	8.563	15.86
2	0.575	7.430	14.23
3	0.531	7.231	13.89
4	0.749	8.232	15.21
5	0.649	7.865	14.45
6	0.540	6.789	12.76
Mean	0.669	7.685	14.4

4.3 EQUIVALENT STRESS ANALYSIS

Two different substrates were simulated and we analysed the effect of applying stress to them. Figure 17 and 18 show the stress result of applying 0.05mm displacement to PDMS and TPU substrate respectively. High levels of stress are observed in the corner of interconnect. This stress could lead to breakage in the interconnect and affect the performance of electric circuit. Different displacements have applied toward the model such as 0.05mm, 0.5mm and 3mm elongation. Table 7 and 8 show the amount of stress for all the zone increase when applied displacement increased. The maximum stress occurred on the interconnect of substrate.

For Table 7, the maximum stress occurred at zone 5 for all the displacement. The amount of stress on zone 5 was 12.74MPa when at displacement 0.05mm. The stress value increased to when the displacement increased to 40.78MPa and 67.45MPa when at displacement 0.5mm and 1mm. The average values are 8.61MPa, 31.66MPa and 55.56MPa respectively when at displacement 0.05mm,0,5mm and 3mm.

From Table 8, the maximum stress dropped at zone 4 for all the displacement. For 0.05mm displacement, the amount of stress on the corner was 51.925MPa. When the structure was stretched to 0.5mm and 1mm, the stress increased to 78.32MPa and 97.67MPa respectively. When at displacement 0.05mm, 0.5mm and 3mm, the average values are 27.71MPa, 65.30MPa and 93.14MPa respectively.

We observed that the stress applied on the copper interconnect of TPU substrate is much higher than PDMS substrate. However, it is still inside the elastic region of copper even at higher displacement due to the yield stress of copper is 172.3MPa.

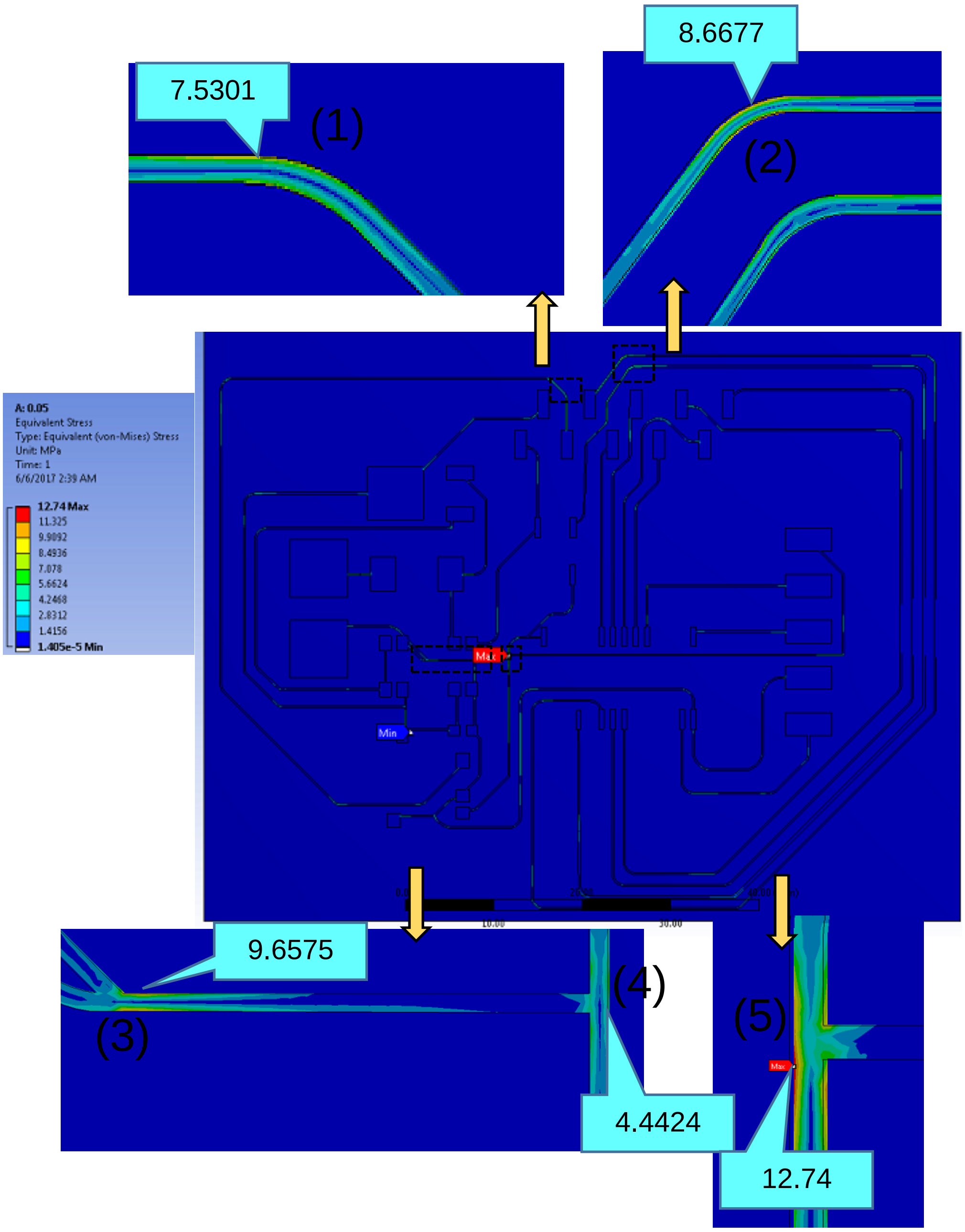

Figure 17:Equivalent stress in copper interconnect for a uniaxial test at 0.05mm elongation (PDMS substrate)

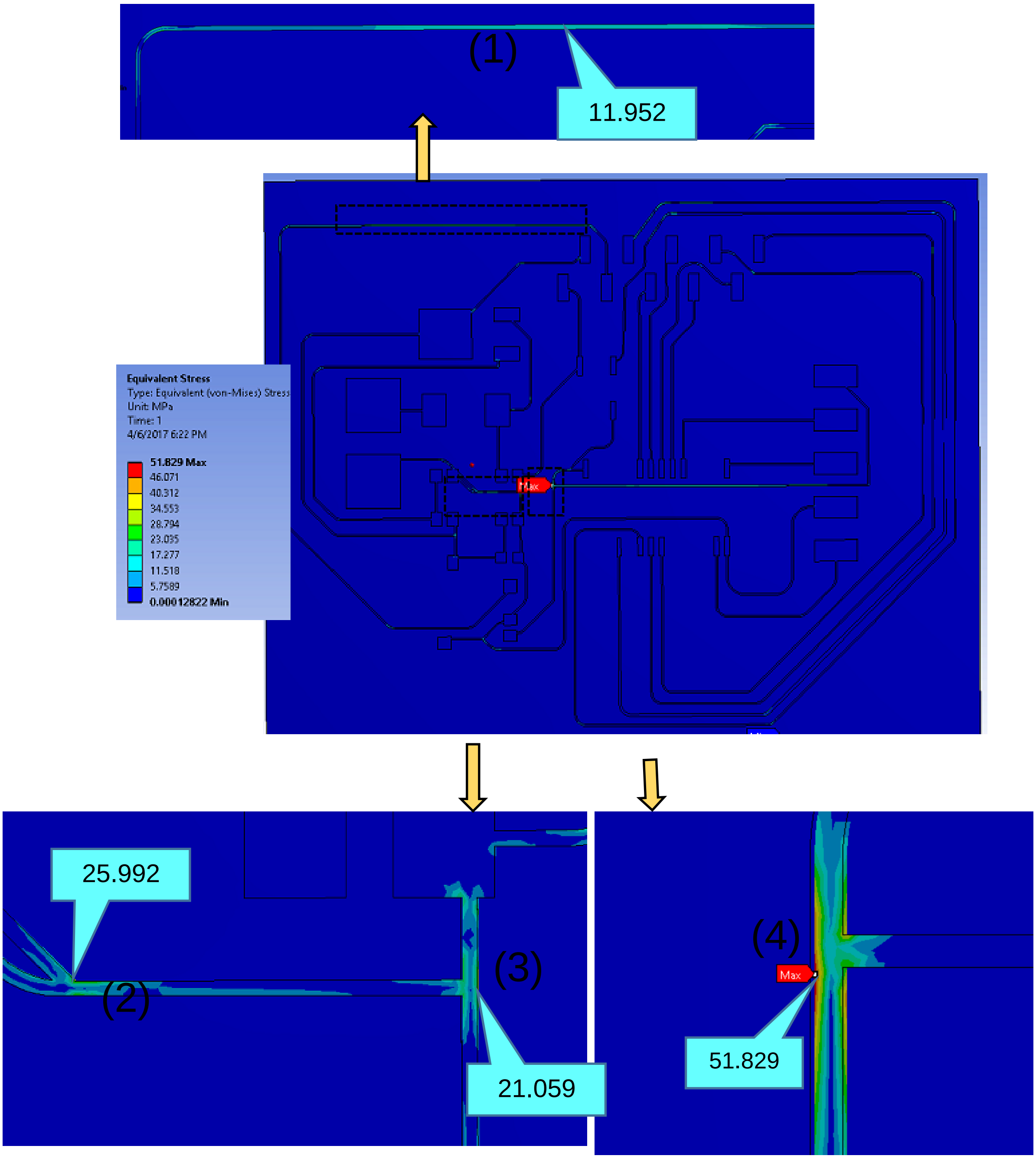

Figure 18: Equivalent stress in copper interconnect for a uniaxial test at 0.05mm elongation (TPU substrate)

Table 7:Equivalent stress (in MPa) at different zones for different elongations (PDMS)

Stress zone	0.05mm	0.5mm	3mm
1	7.5301	21.34	50.12
2	8.6677	36.76	53.45
3	9.6575	38.97	57.22
4	4.4424	20.45	49.54
5	12.74	40.78	67.45
Mean	8.61	31.66	55.56

Table 8:Equivalent stress (in MPa) at different zones for different elongations (TPU)

Stress zone	0.05mm	0.5mm	3mm
1	11.952	50.34	89.34
2	25.992	67.32	94.31
3	21.059	65.23	91.24
4	51.829	78.32	97.67
Mean	27.71	65.30	93.14

As it was observed in the material's characterisation, TPU material has greater engineering stress than PDMS material based on stress-strain curve (Figure 5). It shows that TPU material is more rigid than PDMS material.

From overall result of stress and strain analysis, more damage is observed in the TPU substrate and its copper interconnect. Although TPU material has lower equivalent strain analysis than PDMS material, their percentage different is lesser. When at equivalent stress analysis, TPU material has higher stress than PDMS material even at low deformation. The maximum stress was applied on the copper interconnect. So, copper interconnect of PDMS material has lower equivalent stress hence less damage on its conductor line. This proves that softer materials are preferred for allowing large elongations without permanent damage in the interconnect. [3]