

Stretchable Laser-Induced Graphene Elastomeric Sensor Array for Human Stress Monitoring through a Portable Electrochemical Testing Device

Tony Gao, The Webb School of Claremont, Claremont United States,
tonyruotonggao@gmail

Abstract—About one in four American adults suffer from mental illness with over half of them not receiving any treatment or diagnosis. The average time between initial symptoms and treatment sits at around eleven years. Stress is one of, if not the leading cause of mental health disorders, and requires significantly more awareness on its negative ramifications. Therefore, there is an urgent need to develop an affordable, portable, and multifaceted stress-detection/monitoring device. This paper presents a sensor array design using laser-induced graphene with various elastomeric encapsulations to perform electrochemical resistance sensing for stress monitoring purposes. These sensors are successfully created through precise pyrolysis of polyimide using a carbon dioxide laser and encapsulated with polymers such as Styrene-Ethylene-Butylene-Styrene, a thermoplastic elastomer, and other polymers like styrene-isoprene-styrene, a hydrophilic polymer, granting it properties that isolate a specific factor. A skin-impedance, temperature, and humidity sensor array was created to monitor stress and create a stress metric. Preliminary skin-impedance testing was done with a 5% NaCl-water solution and a DI water control to establish efficacy. Afterward, testing with the cold pressor test to induce a sympathetic autonomic stress response was compared to a control standard state. The temperature sensor was tested on a 500 ml beaker from 0°C surface temperature in increments of 10°C. The humidity sensor was tested through hot breaths on the surface of the device. The results of the temperature sensor were extremely precise with an equation of $y=0.0035x+35.125\mu A$ and a r^2 value of 0.9465. The humidity sensor registered spikes $8*10^{-4}A$ and the skin-impedance sensor registered a significantly sharper curve, taking 6.75s to reach $0.0683\mu A$ with the simulated stress compared to 60s for $0.0682\mu A$ for the control. These sensors are combined to create a system with a custom printed circuit board assembly for a lightweight PCBA voltage resistance measurement device in a parallel circuit design for multiple channels was constructed under 0.5 V with the logic of Ohm's Law as the crux of its output and analysis with a Wheatstone Bridge to minimize noise and sensor-sensor interference. Testing was then performed with the cold pressor test on five separate adult males for 60 seconds resulting in an average cold pressure stress conductance of 0.5891 V and a control of 0.455 V, resulting in a current of 2.357 microamps for the cold pressor and 1.82 for the control

Keywords— Skin-Conforming Sensors, Laser-induced Graphene, Material Science, Mental Health, Stress

I. INTRODUCTION

As mental illness becomes increasingly prevalent, it is urgent to create a device for stress monitoring that is precise, stretchable, multifaceted and affordable. Roughly ten percent of Americans adults suffer from serious mental health issues with half reporting serious consideration of suicide. This number is only rising with the mental health crisis at its all time high, hitting teens and young adults the hardest. People afflicted by mental illness suffering severely with risks of cardiovascular and metabolic diseases, substance abuse, unemployment, dropout rate, and more [1]. Stress is one of, if not the leading cause of mental health disorders, and requires significantly more awareness on its negative ramifications. My research objectives are to create a precise, stretchable, and cost-effective sensor array using a variety of elastomer encapsulated Laser-Induced Graphene for human stress detection, create a complete system for portable usage of sensor devices using a Printed Circuit Board Assembly setup and Python algorithm to create a holistic metric for Stress using measured values and to use chronoamperometry and DC voltage to current measurements to test for stress through skin-impedance, temperature, and humidity. Stress and anxiety are mainly tested through biometric sensors, electromyography, accelerometers, temperature sensors, respiration sensors, and activity trackers with an algorithm. Biometric sensors are at the forefront of stress/anxiety sensing technology with techniques like heart rate variability (HRV), skin conductance (Galvanic skin response), and electrodermal activity (EDA) all indicating positive causation and correlation with stress [1]. Biometric Sensors can also be produced and used non-intrusively by a non-professional. Electromyography is the detection of EMG signals within the body, especially in the neck and shoulder regions to detect muscle tension as a result from stress [2]. This approach is however, not completely accurate as it can have many false positive signals from simply flexing or moving. Accelerometers and activity trackers are faced with the same problem as excess movement does not necessarily have causation with stress/anxiety. Temperature sensors record changes in skin temperature that can occur due to stress-induced alterations in blood flow which can increase both skin and core temperature [1]. One drawback to this method would be that outside temperature variability would contribute to different results depending on the outside temperature, though this can be

subsidized by testing a control in the same environment. The approaches this paper uses are GSR skin-conductance/impedance biometric sensors, as they have substantial positive correlation with stress/anxiety [2], and surface temperatures sensors, as the rest of the approaches possess major variables that cannot be accounted for in a real-world setting. My hypothesis is that a Laser-Induced Graphene Sensor array using different elastomer encapsulation properties will provide precise results in the microamps and be skin-conforming, stretchable, robust, and cost-effective with a noise-adjusted PCBA device system for portable measurement.

Literature Review:

Laser-induced graphene is a new material at the forefront of the material science world and has been specifically used frequently in the flexible sensor and robotics research fields. The reasoning behind graphene's success is the excellent properties it possesses high conductivity, high porosity, and strong interactions between substrates [3]. Laser-induced graphene is using a precise pyrolysis of a polyimide substrate to engrave graphene onto the surface using mechanisms involving the carbonization and graphitization of substrates. The rapid rise in temperature due to the lattice vibrations by the laser breaks the C-O, C=O, and N-C bond, and the material transitions from an sp³- to sp²-hybridized state. The aromatic compounds are then rearranged to form graphitic structures due to the recombination of the C-C bond [6]. An excellent elastomeric substrate for the encapsulation of laser-induced graphene is styrene ethylene-butylene styrene or SEBS. This thermoplastic polymer is used frequently in the field of flexible electronics and sensors due to its porosity, high breathability and waterproofing for usage in skin-conforming sensors/bioelectronic devices including electrophysiological sensors, temperature sensors, hydration sensors, pressure sensors, and electrical stimulators [7]. SEBS also naturally interfaces well with carbon-based conductive materials due to surface area and porosity as well as π - π interactions, a specific interaction of the Van der Waals force, which as graphene has the same hexatomic ring of carbon, can be spontaneously stacked with each other by the π - π interactions among the carbon nanomaterials and phenyl group of SEBS. which results in an excellent interface with the laser-induced graphene [7,8]. Each carbon atom has an electron cloud around it, with a possibility that the electron clouds overlap and that form a bond. The bond with the head on overlap is a sigma bond, with bond with shoulder-to-shoulder overlap being a π bond [4]. Though a π bond is a weaker version of the sigma bond, being usually easier to break apart the pi bond is shoulder to shoulder meaning multiple pi bonds can be constructed rather than sigma bonds [14]. Therefore, the electrons can move freely through the pi bonds. Graphene is essentially the parallel stacking of carbon with each other placed with shoulders sitting next to each other which is why graphene is conductive parallel but not conductive while vertically oriented [14]. Laser etching changes the pi bonds which changes the conductivity and the added encapsulation grants it different properties based on the interactions with the substrate. This is based on molecular

orbital (MO) theory, Testing for stress is decided by a variety of factors, prominently among them in biometrics is skin conductance/impedance. Acute stress triggers peripheral vasoconstriction, causing a rapid, short-term drop in skin temperature in homeotherms. Skin temperature can indicate acute stressor intensity, and demonstrate hormonal, behavioral, and skin thermal patterns. Stress-induced temperature changes appear to reflect a cognitive process. This is not necessarily hormonal but more cognitive. Acute psychological stressors can elicit SIH which is also elevated under chronic stress and psychological challenges are known to increase core temperature in rats [9]. There are four types of skin sympathetic nerves: vasoconstrictor, vasodilator, sudomotor, and pilomotor. Sudomotor nerves are cholinergic and cause sweat secretion (measured as a peak in skin conductance) at increased activity, for example, thermoregulation[10]. Sudomotor nerve activity appeared to be correlated with cardiac activity(which is related to stress) and skin conductance but not with skin blood flow[11]. Additional skin blood flow can be tested with a skin temperature sensor as skin blood flow is directly controlled by thermoregulation using the noradrenergic vasoconstrictor system, a sympathetic active vasodilator system, resulting in 80% to 90% of the substantial cutaneous vasodilation that occurs during whole body heat stress [12].

II. METHOD/RESULT

A. Materials

Toluene, Styrene Ethylene Butylene Styrene (SEBS), Styrene-Isoprene-Styrene (SIS), Polyimide (Kapton), Polypropylene Glycol based Polyurethane (PPGPU), Dextran, Copper tape

B. Skin-Impedance Sensor-

The Skin-Impedance/Conductance sensor is a dual electrode resistance sensor that runs across the skin with a 1cm-by-1cm electrode head made of laser-induced graphene with the reading of resistance and current through a set voltage using chronoamperometry. The resulting resistance curve can be interpreted in slope and final values showing significant differences in a high-stress environment and a control one. The creation of the sensor begins with using a standard Kapton unfilled polyimide film and running a precise pyrolysis through a 6-watt CO₂ laser [3] in a rectangular or specific pattern to create a laser-induced graphene strip. Then, pour 40 ml of Styrene Ethylene Butylene Styrene (SEBS) solution then wait for 24 hours until fully settled into a substrate. Then, using a scalpel, cut out the desired dimensions for the sensor. Another approach is to spincoat dextran(C16) at 1000 rpm for 30 seconds to ensure the film does not stick in the future then move hot plate for 15 mins to ensure dextran solidification. Then, spincoat SEBS at 1000 RPM for 30 seconds to create a thin film of polymer. Ensure before spin coating, the SEBS is fully spread out across the silicon wafer Dissolve dextran in water for 10 hours as then extract polymer film and lay it on top of a glass slide. The thickness of the film should be variable and is not significant to the result. Then transfer the laser-induced graphene onto the SEBS film by pressing it against the film until fully transferred. Afterwards, construct connection wires

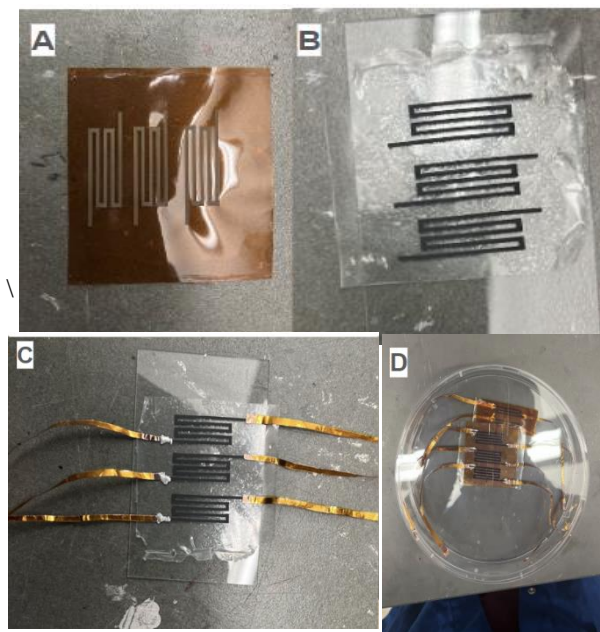
by reinforcing 3mm wide copper wiring with Kapton tape then using silver epoxy to adhere the wiring to the electrodes. Silver epoxy is used as its conductance would not interfere with the resistance of the electrodes due to its lower resistance than the head of the system. Then reinforce the whole system with Kapton, especially the connection areas, to increase the robustness of the sensors



Figure 1: Completed Skin-Conductance/Impedance Sensor, unconnected.

C. Surface Temperature Sensor-

The Surface Temperature sensor is a single electrode resistance thermistor that records temperature according to an equation from the current using chronoamperometry. An equation can be made from the current recorded in Celsius and can be interpreted to the specific temperature at any time. The creation of the sensor begins with using a standard Kapton unfilled polyimide film and running a precise pyrolysis through a 6-watt CO₂ laser [3] in a long, snake-like, pattern to create a laser-induced graphene strip. Afterwards, construct connection wires by reinforcing 3mm wide copper wiring with Kapton tape then using silver epoxy to adhere the wiring to the electrodes. Silver epoxy is used as its conductance would not interfere with the resistance of the electrodes due to its lower resistance than the head of the system. Then, use Styrene Isoprene Styrene (SIS) to encapsulate the graphene as a substrate to instill a hydrophobic property that isolates temperature as the tested variable. Then reinforce the whole system with Kapton, especially the connection areas, to increase the robustness of the sensors.



Process of Sensor Assembly: A: Laser Induced Graphene of Polyimide, B: Transferred LiG onto SEBS C: Connected SEBS with kapton-reinforced wiring through silver epoxy then encapsulated in respective Polymer (SIS, PPG PU)

D. Humidity Sensor

The Humidity sensor is a single electrode resistance sensor that records humidity according to an equation from the current using chronoamperometry. The sensor outputs significant spikes in current from a standard current level according to humidity of the environment around it. The creation of the sensor begins with using a standard Kapton unfilled polyimide film and running a precise pyrolysis through a 6-watt CO₂ laser [3] in a long, U-like, pattern to create a laser-induced graphene strip. Afterwards, construct connection wires by reinforcing 3mm wide copper wiring with Kapton tape then using silver epoxy to adhere the wiring to the electrodes. Silver epoxy is used as its conductance would not interfere with the resistance of the electrodes due to its lower resistance than the head of the system. Then, use polypropylene glycol-based polyurethane to encapsulate the graphene as a substrate to instill a hydrophilic property that isolates humidity as the tested variable. Then reinforce the whole system with Kapton, especially the connection areas, to increase the robustness of the sensors.

E. Preliminary Skin Impedance Testing with Palmsens

The skin-impedance sensor was tested through using chronoamperometry through a Palmsens 4 potentiostat in a electrolyte DI water setup using 2.5 g of NaCl to make a 5% NaCl-Water solution and a control DI water setup to establish efficacy. A DC voltage of 0.5 V is run through the device which records the current in microamps four times a second. Chronoamperometry is run for 60 seconds to record the current in microamp. Impedance Spectroscopy using the Palmsens 4 was also ran in the aims of experimenting with the most efficient method of testing for skin conductance. Chronoamperometry was more appealing of an option as the necessary complexity and cost of creating a impedance-spectroscopy capable microcontroller were too much and too inefficient to be

considered a viable replacement. The primary goal of this experiment to establish the efficacy of the setup

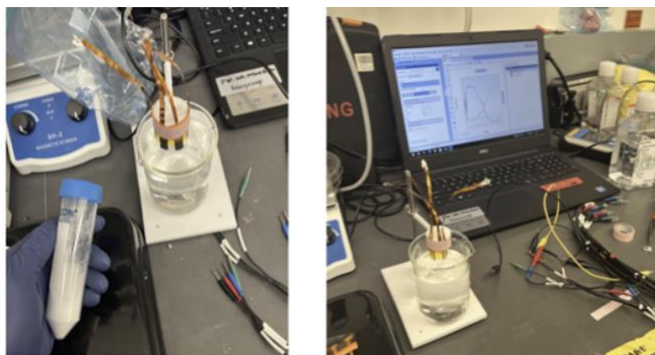


Figure 2: Electrolyte testing of Skin-Impedance Sensor to test for Efficacy using NaCl compared to DI Water using chronoamperometry and Impedance spectroscopy on a Palmsens 4

File date:	2023-08-03 13:21:22						
Measurement:	Impedance Spectroscopy						
Notes:							
Date and time:	2023-08-03 13:19:12						
CH 1: Fixed at 41 freqs							
req / Hz	neg. Phase / °	Idc / uA	Z / Ohm	Z' / Ohm	Z'' / Ohm	Cs / F	
50000	4.948595069	-1.266002855	2592.756384	2583.091882	223.6559838		1.42E-08
39716.41016	4.347395781	0.5457401276	2603.019739	2595.53025	197.3182281		2.03E-08
31547.86719	4.444535973	-0.2439022664	2615.093539	2607.229475	202.6540936		2.49E-08
25059.38133	4.658693085	-0.415068762	2622.407689	2613.751213	212.9006368		2.98E-08
19905.35938	4.500026924	-0.3740787506	2653.687706	2645.487236	208.2056117		3.84E-08
15811.38667	5.318442055	-0.8924055481	2669.389192	2657.877157	247.4285718		4.07E-08
12559.43262	3.165238733	-12.50629395	2691.955624	2687.848903	148.6383277		8.53E-08
9976.311523	5.587395333	-0.4885196686	2716.391207	2705.457505	264.6733175		6.03E-08
7924.46582	6.220108961	-0.4942471145	2758.008027	2742.559293	298.9155878		6.72E-08
6294.626953	6.676247873	-0.4866123199	2800.172515	2781.18435	325.5452715		7.77E-08
5000	7.341962582	-0.4971027374	2821.212793	2798.081997	360.5256697		8.83E-08
3971.641113	8.533556804	-0.4889965057	2870.20747	2838.431675	425.9067369		9.14E-08
3154.786621	8.896458677	-0.4966259003	2905.599481	2870.643451	449.3489965		1.12E-07
2505.936279	9.934628619	-0.495672226	2972.378557	2927.80844	512.8079835		1.24E-07
1990.535889	11.22803571	-0.4861354528	3153.295131	2957.58237	567.1211546		1.36E-07
1581.138794	12.99633336	-0.4870891871	3040.460338	2964.907246	673.5904473		1.49E-07
1255.943237	14.91347781	-0.4996937604	3119.35474	3014.281046	802.7874647		1.58E-07
997.8311646	16.16955525	-0.3709855488	3115.163513	2991.933236	867.5132393		1.84E-07

Graph 2: Electrolyte testing of Skin-Impedance Sensor to test for Efficacy using NaCl compared to DI Water Impedance Spectroscopy Data using Palmsens

F. Surface Temperature Testing with Palmsens

The temperature sensor was tested through increments of 10 C on the surface of a 500 mL beaker on a hot plate with two thermometers to determine temperature of the system. Initially, ice was placed within the beaker to cool the surface down to 0 degrees Celsius. Using chronoamperometry through a Palmsens 4 potentiostat, a DC voltage of 0.5 V is run through the device which records the current in microamps four times a second. Chronoamperometry is run for 60 seconds to record the current in microamps then paused until the next increment. The hot plate was then turned up until the temperature reached 10 degrees Celsius and then the process was repeated. This process was repeated in increments of 10 degrees Celsius for 60 seconds each, culminating in a maximum of 50 degrees Celsius surface temperature tested with a low of 0 degrees Celsius. The data consists of approximately 300 seconds and possesses significant precision in the measurement of temperature through the construction of an equation. The results of the temperature sensor showed extreme precision and efficacy through constructing an equation of $y=0.0035x+35.125\mu A$ and a r^2 value of 0.9465. This current can then be interpreted and plotted into a graph format.

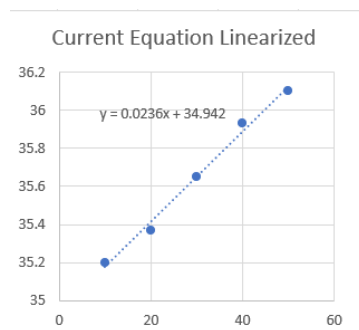
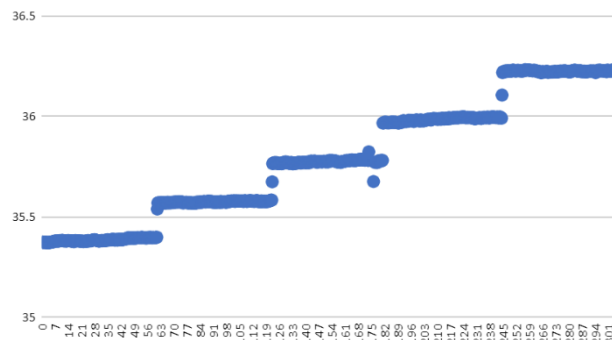


Figure 3: Temperature Sensor surface testing on 500 mL beaker in increments of 10 °C using chronoamperometry on a Palmsens 4 Potentiostat



Graph 3 and 4: Temperature Sensor surface testing on 500 mL beaker in increments of 10°C using chronoamperometry on a PalmSens 4 Potentiostat data in microamps plotted over 300 seconds in intervals of 60 seconds per 10 degrees Celsius.



Graph 5: Temperature Sensor surface testing on 500 mL beaker in increments of 10°C using chronoamperometry on a Palmsens 4 Potentiostat data in microamps plotted over 300 seconds in intervals of 60 seconds per 10 degrees Celsius linearized to equation.

G. Humidity Testing with Palmsens

The humidity sensor was tested in a very simple fashion that displays significant results. Using chronoamperometry through a Palmsens 4 potentiostat, a DC voltage of 0.5 V is run through the device which records the current in microamps four times a second. This current can then be interpreted and plotted into a graph format. The testing was done through six hot breaths on the sensor in intervals of 15 seconds for a total time of 100 seconds in order to establish efficacy of the device. The average control value of the device sat at 35.8 microamps with spikes up to 0.0014 deviation from normalized current or 8×10^{-4} A amps. This result demonstrates the sensitivity the humidity sensor possess. Figure 3 demonstrates the data and the sensitivity of the device.

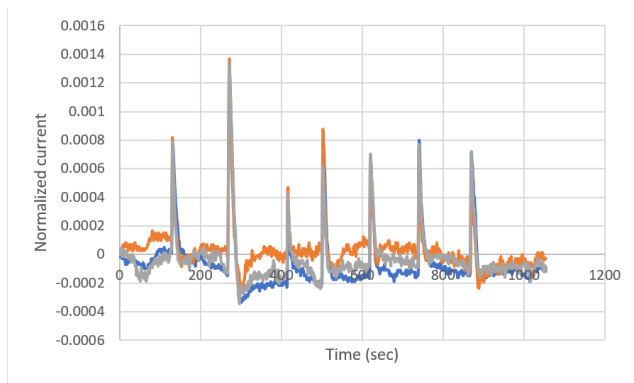


Figure 4: Humidity Sensor data over 1000 deciseconds (1/10 a second) tested with hot breaths on the surface of the electrode head on the sensor

H. Human Testing with Palmsens

Human testing with the skin-impedance sensor was conducted through the cold pressor test to induce a sympathetic autonomic stress response in contrast to a standard normal state which are both measured by the Palmsens 4 potentiostat with a DC voltage of 0.5 V that is run through the device, recording the current in microamps four times a second. There will be no exposed wires, as all connections will be fully covered with Kapton. Voltage is outputted through the Palmsens 4 setup that is battery-operated into the sensor at 0.5 volts, and current(amps) is recorded over time through chronoamperometry. This process sets a baseline for the subject's skin conductance level, a control value for the subject. Voltage for electrodermal testing is recommended and most commonly set at 0.5 V for optimal comfort and safety. The subject sticks their right hand into an ice bucket for 30 seconds to induce sympathetic autonomic stress from the cold pressor test to artificially simulate stress. Voltage is then outputted into the sensor at 0.5 volts and recorded through chronoamperometry for the current(amps) for 30 seconds. This process tests for the amount of skin conductance through chronoamperometry for the current curve occurring over 30 seconds after artificially inducing sympathetic autonomic stress through the cold pressor

test, which measures the subject's skin conductance after a stress stimulus. The skin-impedance sensor registered a significantly sharper curve, taking 6.75s to reach 0.0683μA with the simulated sympathetic stress compared to 60s for 0.0682μA for the control. This shows a significant difference in the speed of conductance when under stress and establishes causation and correlation between elevated levels of stress and anxiety and the skin-conductance current readings of the LiG sensor.

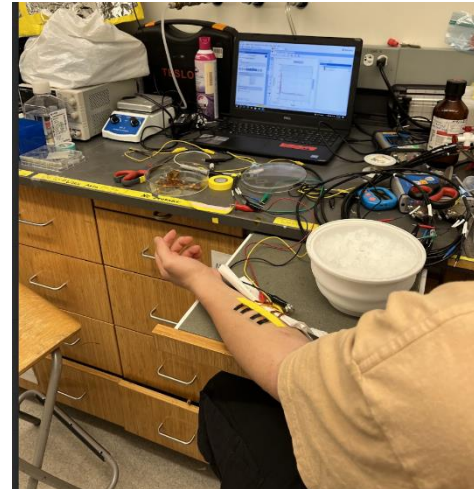


Image 3: Subject under Cold Pressor Test to induce sympathetic autonomic stress while measuring skin-conductance through Chronoamperometry on a Palmsens 4 Potentiostat

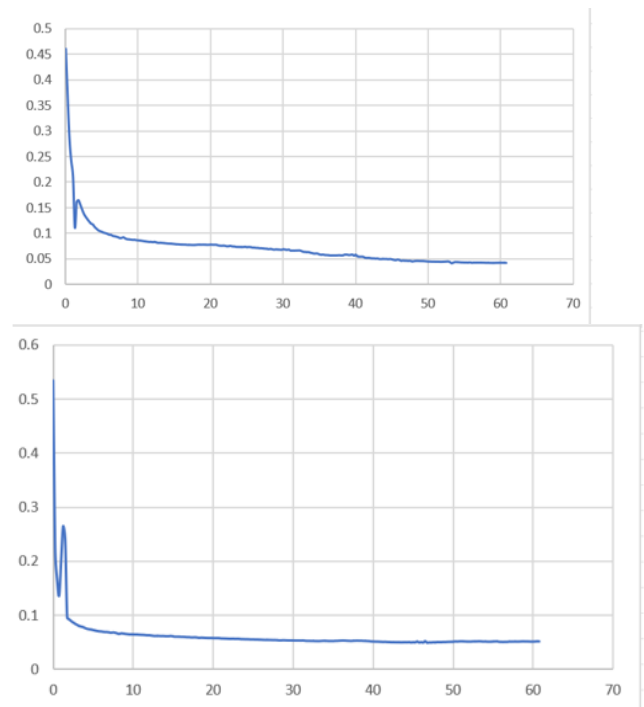


Figure 5: Both Graphs are Skin-impedance human data over 60 seconds with the cold pressor test to induce autonomic sympathetic stress, High stress.

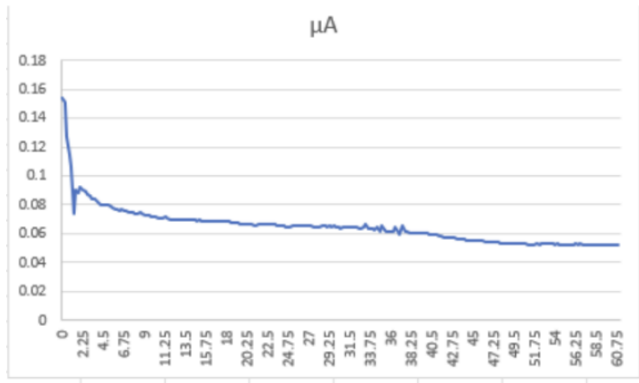


Figure 6: Skin-impedance human data over 60 seconds with the cold pressor test to induce autonomic sympathetic stress, No Stress

G. PCBA Device Creation

As potentiostats are extremely costly and bulky in size, there is a need to create a miniaturized device for resistance testing. Beginning with a simple parallel circuit design consisting of a DC voltage of 0.5 V and the recording of current, glaring issues with the original plan became obvious. Referencing many online potentiostat/electrochemical microcontroller testing devices [12], a preliminary circuit design was constructed without an oscillator as the implementation of one would substantially impact the cost to limited performance results. Four models were constructed but due to the high precision of the sensors, noise became a significant issue within the reception of the signal. For real-world testing, the signal to noise ratio is not sufficient contrary to a lab's-controlled environment. This issue was approached in two ways, an amplifier, and a Wheatstone Bridge. An amplifier simply increases the signal as well as the noise. With a bigger signal the background noise can be altered by holding the measurement steady and taking out signals from the chaotic background as the background noise is very different from the signals. This approach however proved unsuccessful as there were too many channels for the sensors resulting in too much noise. This approach only works for one sensor, but with multiple sensors occurs a problem. All the sensors have similar signal-noise ratio, and they are all in close proximity resulting in an mixing of signals and noise as each sensor gives off both. This brings the approach of a an electronic structure called a "Wheatstone Bridge" which is used to separate the random noise compared to the actual change in CV/VA [13]. The structure is a bridge with four resistances connected side to side in parallel and is used to suppress noise and amplify signals. The logic behind it stands that if the measured resistance is severely bigger than the actual resistance, measuring the small unknown resistance will be easier as the total resistance can be measured and by adding a large resistance, the total measured resistance is easier to read can then be reverse read to get the unknown actual resistance. As resistance and current is proportional relation in accordance to Ohms Law, a small

alteration in resistance results in a significant change in current. This process is an application of a nonlinear magnification of the signal. This is done upon the device by adding larger resistances around the bridge section of the PCBA. A total of four types of PCBA circuit designs were created but this is the most efficient of the few.

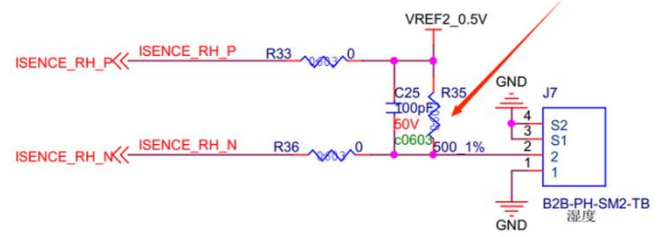


Figure 7: PCBA resistance testing channel setup, DC

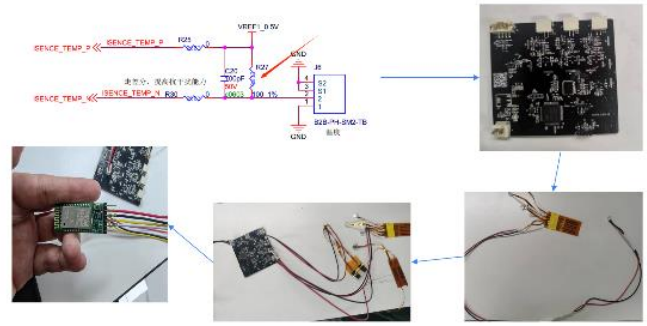


Figure 8: Process in creating the PCBA from circuit design to manufacturing.

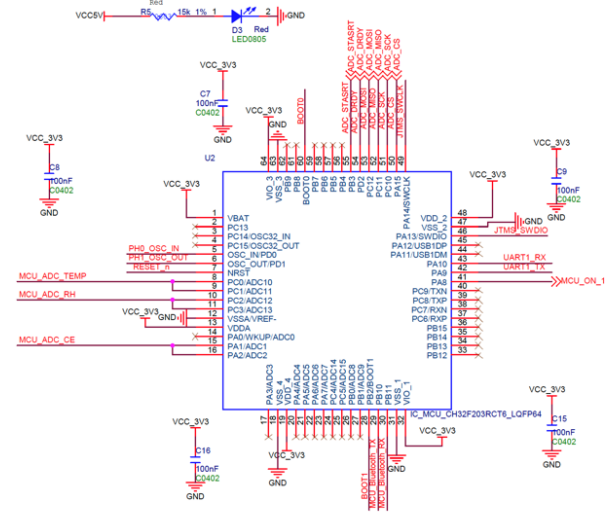


Figure 9: Wheatstone Bridge setup to add resistance to alter the signal-noise ratio for easier measurement.

H. In-Situ Sensor Testing

This experiment will attach the Laser-Induced Graphene (LIG) sensors to the subject's hand through an adhesive commercial hydrogel. Then attach the sensor to the PCBA microcontroller device. This LIG sensor will test for skin conductance. The LIG sensor is designed and assembled by myself and will be

constructed from the following components. There will be no exposed wires, as all connections will be fully covered with Kapton. Voltage is outputted through an Arduino PCB board setup that is battery-operated into the sensor at 0.5 volts, and current(amps) is recorded over time DC voltage to resistance to current conversion using Ohms Law in $I=V/R \cdot A$. This voltage will be held at 0.5 volts, controlled through the Arduino. Voltage for electrodermal testing is recommended and most commonly set at 0.5 V for optimal comfort and safety. The subject sticks their right hand into an ice bucket for 30 seconds to induce sympathetic autonomic stress from the cold pressor test to artificially simulate stress. Voltage is then outputted through an Arduino PCB board setup into the sensor at 0.5 volts and recorded after artificially inducing sympathetic autonomic stress through the cold pressor test, which measures the subject's skin conductance after a stress stimulus. The expected extremes of the noise boundaries are 0.2 microamps of noise resulting in changes larger than 0.2 microamps derived from Ohms Law being significant. This experiment should be completed shortly.

H. Machine Learning Algorithm

A machine learning algorithm was created using Simple Thresholding and One Class SVM type method, two algorithmic approaches using Python and Numpy which measures spikes or abnormalities in a data file. This algorithm will import the data outputted by the sensors and detect where the datapoints exceed a threshold of abnormality set by the algorithm. This was constructed using VS Code with Numpy and SKlearn.

III. DISCUSSION

In this research, three sensors were used to test for biomarkers related to stress and anxiety for mental health monitoring purposes. A skin-temperature sensor, humidity sensor, and skin-conductance sensor was created. The temperature sensor, as seen on Figure 4 and 5, resulted in extreme precision and efficacy and constructed an equation of $y=0.0035x+35.125\mu A$ and a r^2 value of 0.9465 that can be used to determine temperature based off current. The sensor was tested in increments of 10 degrees Celsius and showed accuracy and precision in its measurement with groupings around temperatures that rose by an average of 0.22 microamps of difference per 10 degrees Celsius with a margin of roughly 17% space in distribution within a specific change per ten degrees Celsius of temperature. These results show a very direct positive relationship between the increase in current and increase in temperature, a positive trendline and equation that is depicted in figure 4 and 5. For the humidity sensor, the average control value of the device sat at 35.8 microamps with spikes up to 0.0014 deviation from normalized current or $8 \cdot 10^{-4}$ A amps, showing very significant sensitivity as shown in figure 6, demonstrating a very positive relationship between spike in humidity and change in current (ΔA). This result demonstrates the sensitivity the humidity sensor possesses and the spikes it achieves.

For the Skin-Conductance sensor, the sensor reads within 0.001 microamps of difference under an in-situ setting, a very accurate

measurement. Using 30 seconds of artificially inducing sympathetic autonomic stress through the cold pressor test, the skin-conductance sensor registered a significantly sharper curve, taking 6.75s to reach $0.0683\mu A$ with the simulated sympathetic stress compared to 60s for $0.0682\mu A$ for the control. This shows a significant difference in the speed of conductance when under stress and establishes causation and correlation between elevated levels of stress and anxiety and the skin-conductance current readings of the LiG sensor. It also demonstrates the relationship between a steeper or flatter curve of time-current to stress and establishes a trend in higher stress resulting in steeper curves as the skin is more conductive.

To make the system portable and applicable to a real-world environment in opposed to simply being a lab-exclusive equipment, a lightweight PCBA voltage resistance measurement device in a parallel circuit design for multiple channels was constructed under 0.5 V with the logic of Ohm's Law as the crux of its output and analysis. As the device itself is not powerful and does not perform to the complexity of a true potentiostat, the noise levels it possesses were initially great. This was subsidized using a Wheatstone Bridge setup (figure 9) that enabled a larger signal-noise ratio to be read through the addition of larger resistors which was then reverse read to uncover the smaller resistance, the device reads using $I=V/R \cdot A$ with the numbers respectively being $I=V/(500 \cdot 50)$ which the device outputs a voltage to reverse engineer into the current.

Human in-situ testing will then be performed using the device and sensor setup which will test upon various subjects under the cold-pressor test. Finally, a machine learning algorithm using Simple Thresholding and One Class SVM, two algorithmic approaches using Python and Numpy which measures spikes or abnormalities in a data file, is being created. This algorithm will import the data outputted by the sensors and detect where the datapoints exceed a threshold of abnormality set by the algorithm.

My hypothesis was affirmed through these results with significance and my data is consistent with my experiment objectives and hypothesis. Future work on a more complex machine learning algorithm trained by a large quantity of datasets would prove very effective in metricizing and analyzing the data exported and can help interpret a lot of signals into figures. This is being worked on right now, though the biggest limitation with this is the amount of datasets available as my sensors are exclusive/novel and specific. This can be mitigated from more testing on more people to create a larger dataset for training.

IV. CONCLUSION

The key successes that have been achieved through this experimentation is the successful creation, design and implementation, significant results, and accuracy for a stretchable, skin conforming resistance sensors.. This was created using Laser-induced Graphene in a elastomeric encapsulated substrate of SEBS and other specialized polymers for resistance sensing purposes. The surface temperature sensor created measures precisely and establishes a direct positive correlation between current and temperature in the form of a

linear equation in $y=0.0035x+35.125\mu A$ and a r^2 value of 0.9465. The humidity sensor showed extreme sensitivity (figure 6) with a baseline at 35.8 microamps with spikes up to 0.0014 deviation from normalized current or $8 \times 10^{-4} A$ amps, displaying a positive causal relationship between humidity spikes and current spikes. The Skin-Conductance sensor was successful through in-situ testing with the cold pressor test with a result of 6.75s to reach $0.0683\mu A$ with the simulated sympathetic stress compared to 60s for $0.0682\mu A$ for the control, demonstrating significant difference in the speed of conductance when under stress and establishes causation and correlation between elevated levels of stress and establishes a trend in higher stress resulting in steeper curves as the skin is more conductive. A lightweight PCBA voltage resistance measurement device in a parallel circuit design for multiple channels was constructed under 0.5 V with the logic of Ohm's Law and a Wheatstone Bridge to minimize noise and sensor-sensor interference. A machine learning algorithm was constructed to effectively analyze and metricize the data recorded into a holistic metric for stress using a simple thresholding and one-class SVM type algorithm. In the future, a heartbeat sensor, glucose sensor, and other variety of electrochemical biomarker sensors will be constructed and added onto the array to create an extremely comprehensive device. Further machine learning work will be done to construct a powerful algorithm for detection and analysis of the data and creating a metric.

ACKNOWLEDGMENT

The author greatly appreciates Prof. Zhenan Bao at Stanford University for the helpful discussion and mentorship for this research.

REFERENCES

[1] Wu T, Luo Y, Broster LS, Gu R, Luo YJ. The impact of anxiety on social decision-making: behavioral and electrodermal findings. *Soc Neurosci.* 2013;8(1):11-21. doi: 10.1080/17470919.2012.694372.

[2] Sara Pourmohammadi, Ali Maleki, Stress detection using ECG and EMG signals: A comprehensive study, *Computer Methods and Programs in Biomedicine*, Volume 193, 2020, 105482, ISSN 0169-2607,

[3] Daniela V. Lopes, Nuno F. Santos, Jorge P. Moura, António J.S. Fernandes, Florinda M. Costa, Andrei V. Kovalevsky, Design of laser-induced graphene electrodes for water splitting,

[4] Brian Jacobus Jozefus Timmer and Tiddo Jonathan Mooibroek , Intermolecular π - π Stacking Interactions Made Visible. *J. Chem. Educ.* 2021, 98, 2, 540–545 Publication Date: December 4, 2020

[5] Wang, H., Zhao, Z., Liu, P. et al. A soft and stretchable electronics using laser-induced graphene on polyimide/PDMS composite substrate. *npj Flex Electron* 6, 26 (2022).

[6] Yadong Xu, et al. "Multiscale porous elastomer substrates for multifunctional on-skin electronics with passive-cooling capabilities." December 23, 2019, 117 (1) 205-213 Wang Jianhao, Deng Xiangyi, Xie Yuan, Tang Jiefu..."An Integrated Transcriptome Analysis Reveals IGFBP7 Upregulation in Vasculature in Traumatic Brain Injury " *Frontiers in Genetics*, Vol 11 2021, ISSN=1664-8021

[7] M.Q. Jian, ... Y.Y. Zhang. "Challenge and Opportunities of Carbon Nanotubes." *Industrial Applications of Carbon Nanotubes*, 2017.

[8] Herborn KA, Graves JL, Jerem P, Evans NP, Nager R, McCafferty DJ, McKeegan DE. Skin temperature reveals the intensity of acute stress. *Physiol Behav.* 2015

[9] Valkenburg, A., Niehof, S., van Dijk, M. et al. Skin conductance peaks could result from changes in vital parameters unrelated to pain. *Pediatr Res* 71,

[10] Macefield VG, Wallin BG . The discharge behaviour of single sympathetic neurones supplying human sweat glands. *J Auton Nerv Syst* 1996

[11] Charkoudian N. Skin blood flow in adult human thermoregulation: how it works, when it does not, and why. *Mayo Clin Proc.* 2003 May;78(5):603-12. doi: 10.4065/78.5.603. PMID: 12744548.

[12] Herborn KA, Graves JL, Jerem P, Evans NP, Nager R, McCafferty DJ, McKeegan DE. Skin temperature reveals the intensity of acute stress. *Physiol Behav.* 2015

[13] Li, Z. et al. Preparation of laser-induced graphene fabric from silk and its application examples for flexible sensor. *Adv. Eng. Mater.* 2100195 (2021). Lin, J. et al. Laser-induced porous graphene films from commercial polymers. *Nat. Commun.* 5714 (2014).

[14] Thakuria, Ranjit & Nath, Naba & Saha, Binoy. (2019). The Nature and Applications of π - π Interactions: A Perspective. *Crystal Growth & Design*. 19. 10.1021/acs.cgd.8b01630.