ULTRA THIN SMART ELECTROPALATOGRAPHY SYSTEM TO ASSIST LINGUISTIC AND MEDICAL DIAGNOSIS

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ABSTRACT

This research reports an ultra thin smart electropalatography (EPG) system with a thickness of less than 30 µm, approximately one hundredth the thickness of a commercial device. The system incorporates 112 channels and employs various sensing modes such as proximity, touching, and pressing. These functionalities are achieved through parylene processing, leveraging capacitive sensing on the EPG sensing membrane. Salient features of the system include an extremely thin and flexible film sensor structure, enhancing wearer comfort; capacitive sensors capable of proximity, contact, and press sensing, indicating the relative positions of the tongue concerning the membrane; a higher channel count enabling high-resolution tongue touching maps during speech; and complete wireless supporting circuits for real-time data visualization.

KEYWORDS

Thin film Electropalatography (EPG), biosensor, parylene, microfabrication, wireless sensing

INTRODUCTION

Electropalatography (EPG) is a system that monitors contact patterns between the tongue and hard palate during articulation. It has wide applications in articulation disorders and other types of disease involving speaking difficulties. A therapist has used an EPG system to help patients with speech sound disorder (SSD) improve quality of life [1]; improve recovery and correct residual articulation disorder for cleft palate patient after surgery; identify and improve the unclear articulation pattern for Down syndrome patients [2]; improve the pronunciation of hearing disorder speakers [3]; and evaluate recovery and accelerate rehabilitation for patients suffering from traumatic brain injury [4].

Besides its traditional applications, an EPG system, when combined with an acoustic analysis system, can capture changes in tongue movement patterns, such as reduction in the range of motion and velocity, along with other potential biomarkers for Parkinson's Disease (PD) and schizophrenia. This data can provide supporting evidence for the early diagnosis of affected individuals [5]. Moreover, the EPG system also contributes to the advancement of human machine interface (HMI). Andreasen [6] used an EPG system to interact with a personal computer with high accuracy, while Horne [7] used a certain palate region on the EPG device for specific computer commands. All research indicates that EPG has high potential to be used as part of the HMI and even Virtual Reality environment.

A pseudo-palate sensor is the main component in the EPG system that has an electrode array for tongue movement detection as shown in Figure 2(a). The recorded pattern can serve as biomarkers for a range of therapy and diagnosis purpose. Some EPG devices [8] use resistive sensors capable of detecting contact locations, while others provide pressure values [9]. Traditional and commercial EPG devices employ metal electrodes to detect the contact between the tongue and upper palate, most of which use the resistive sensing mechanism. For example, Articulate Instruments used the resin infused electrode arrays as pseudo palate, while Smart Palate system used the polyimide packaged flexible printed circuit board. Other valuable information for diagnosis like distance before contact is only reported in [4], [10].

Though the EPG device has a long history and has been extensively used, there remain challenges that prevent the broader adoption of itself. First, most commercial EPG devices are thick (2~3 mm) and constructed with rigid materials whose bulkiness and lack of flexibility could result in poor wearing comfort which may impede natural pronunciation. While EPG devices have demonstrated three sensing modes -proximity distance sensing, contact sensing and pressure sensing-no more than 2 sensing methods are typically integrated into a single device. The data captured by the sensor can lack thoroughness and precision in charting the tongue's movement. Furthermore, the sensing resolution of an EPG device is often constrained by the channel count, typically ranging from 30 to 90, which may not provide sufficient resolution to capture detailed nuances and subtleties. Moreover, most EPG devices are tethered with wires that need to come out of mouths for data transmission and powering, limiting the patients' tongue position and lip movement. Last, certain commercial EPG systems require customization and manual assembly, resulting in costs that can soar to several thousand dollars, making them not very economical.

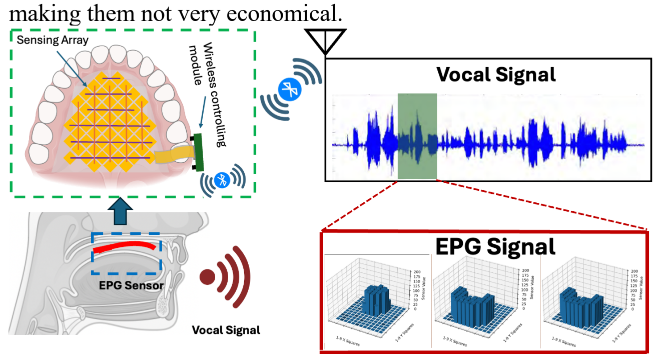

Figure 1: Schematic demonstration of data collection and analysis of a SELMA device.

In this work, this paper reports an extremely thin smart electropalatography for linguistic and medical application (SELMA) system with a membrane thickness of less than 30 µm, approximately one hundredth the thickness of a commercial device. The system incorporates 112 channels and employs all three sensing modes: proximity, touching, and pressure sensing. Capacitance sensing mechanism is used for all sensing modes at different sensing ranges.Also, a fully wireless and stand-alone read-out board and an application is realized (Figure 1).

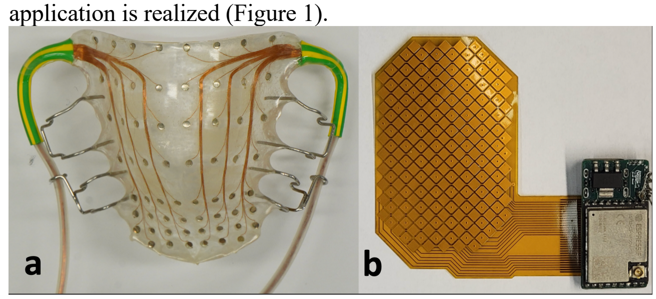

Figure 2: Commercially available EPG device (a) and fPCB version of SELMA device and the customized read-out circuit (b).

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SELMA SYSTEM DESIGN

Sensing Mechanism

The capacitance sensing mechanism stems from the electromagnetic field interactions which can be described by Maxwell equations [11]. Capacitive sensing in this paper focuses on electric field behavior in the low-frequency regime leading to a quasi-static approximation of the equations. The simplified equation of Gauss's Law for electricity is

$$\nabla \cdot \boldsymbol{E} = \frac{\rho}{\epsilon} \quad (1)$$

In this equation, E, ρ, and ϵ represent the electric field, the charge density, and the permittivity of the medium, respectively. This equation describes how the electric field diverges from charges. Also, the electric field can be derived from the gradient of a scalar potential $\boldsymbol{\phi}$,

$$\boldsymbol{E} = -\nabla\boldsymbol{\phi} \quad (2)$$

By combining these principles, the Poisson Equation for electrostatics is shown as

$$-\nabla \cdot (\boldsymbol{\epsilon}\nabla\boldsymbol{\phi}) = \boldsymbol{\rho} \quad (3)$$

This equation relates the electric potential in a certain area to the distribution of electric charge.

In practice, capacitive sensors measure changes in the electric field or potential by detecting the displacement current, which can be linked to the charge on an electrode with the surface area $\boldsymbol{\Gamma}$ as

$$\boldsymbol{q} = \int_{\Gamma} \boldsymbol{\epsilon E dr} \quad (4)$$

Therefore, the capacitance C can be determined using the charge q and the voltage V through the relationship C=q/V.

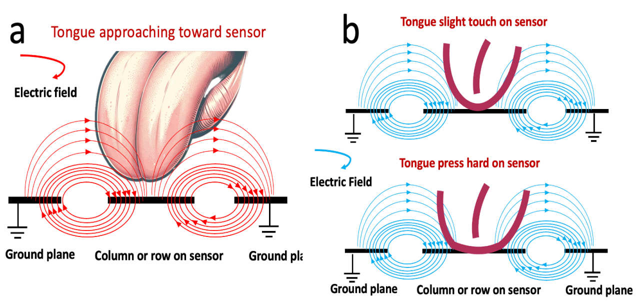

Figure 3: Mechanism of proximity sensing mode (a) and contact & pressure sensing mode (b).

Capacitive sensors utilize two primary methodologies for sensing: mutual capacitance and self-capacitance. In mutual capacitance sensing, an electrical signal is applied to one electrode, designated as the transmitter, while a separate electrode acts as the receiver. Objects introduced into the space between these two electrodes disrupt the electric field, modifying the resultant displacement currents and, consequently, the measured capacitance values.

Conversely, in self-capacitance sensing, a single electrode serves as both the transmitter and receiver simultaneously. This configuration assesses the electric charge that the electrode can sustain relative to a ground reference. The proximity of an object alters this capacitance by providing an alternative electric field path, thereby effectively increasing the effective capacitive 'plate' area between the electrode and ground. Essentially, the object assumes a role similar to that of the second electrode in mutual capacitance sensing, affecting the displacement current in a similar manner.

The SELMA sensor employs the self-capacitance sensing approach and would have proximity and pressure sensing by using the fringing field capacitance as shown in Figure 3(a), (b). The sensor will experience a higher electric field when the tongue acts as the ground, potentially interfering with the existing electric field between the sensor ground and sensor pad.

Upon touching in Figure 3(b), the tongue's deformation increases coverage area, and the sensor's top layer becomes thinner, enabling the detection of contact and pressure.

SELMA Device Design

The new EPG system concept is shown in Figure 1, where the thin film sensor array detects capacitive signal changes. The signals are transferred to the local microcontroller for data processing, further wirelessly transmitted through Bluetooth to a PC or smartphone for visualization. We previously reported a flexible EPG device with active shielding layer made from silver nanowire (AgNW) and Polydimethylsiloxane (PDMS) [12]. In this work, we first tested a new capacitive sensing array pattern with 112 channels on flexible printed circuit board (fPCB) with a customized readout circuit for untethered wireless operation as shown in Figure 2(b).

A crossed array pattern shows two ground planes serving as the sensing structure, where each column and row acts as an independent capacitor with ground. As shown in Figure 3(a), when the tongue approaches and touches the sensor, its proximity changes the parasitic capacitance between the metal pad and ground.

The cross-finger array is composed of row and column elements, each functioning as an individual channel. All squares reside on the primary metal layer, with each row element connecting to its corresponding square via a trace on the same layer. This cross-finger structure captures the two-dimensional coordinates of tongue movement with greater resolution than traditional single-electrode methods, as it allows for more channels within the same count. Traces on the second metal layer link the squares within each column element through dielectric via connections as shown in Figure 4(b). Additionally, every sensing element is linked to the ZIF (zero insertion force) connector using this second metal layer. By adopting this design, we've managed to reduce the total number of layers from five to three compared to similar devices. This reduction in layer count decreases the overall thickness, thereby enhancing the device's flexibility and the wearer's comfort.

Readout Circuit Design

A compact customized readout circuit has been designed and implemented to facilitate the integration of the SELMA device into the mouth. This circuit features wireless data transfer capabilities powered by a Bluetooth module, small enough to fit inside the mouse along with the SELMA device. The board connects to the SELMA sensor by ZIF connector, and the system is powered by a button lithium-ion battery. The sensing data, which is wirelessly transferred to the mobile app or PC, is visualized into a 3D column plot.

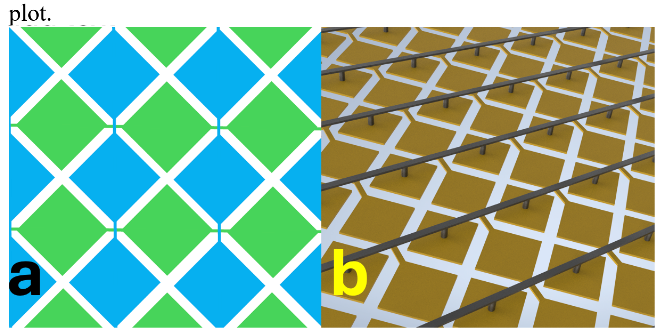

Figure 4: Pattern of SELMA sensing array (a) and 2 layer metal approach to r the pattern (b).

SENSOR TESING

The sensor functions are separated into proximity and pressure sensing with different metrics. The proximity sensing measures relationship between distance and capacitance change while the pressure sensing focuses on pressure level and capacitance reading. Both experiments are conducted in the same condition where the pressure gauge and distance are measured. The experiment setup for the proximity sensing and pressure sensing is shown in Figure 5(a) and 5(b), respectively. The sensor pad is placed on a grounded flat copper plate while the conductive gauge head controls the distance and pressure. The conductive top and bottom setup is to mimic the property of tongue and upper palate. The sensor response is a converted capacitance reading that correlates with the circuit parameters. This converted reading is more sensitive than the raw capacitance reading, so we directly use the output of the sensor reading in this work.

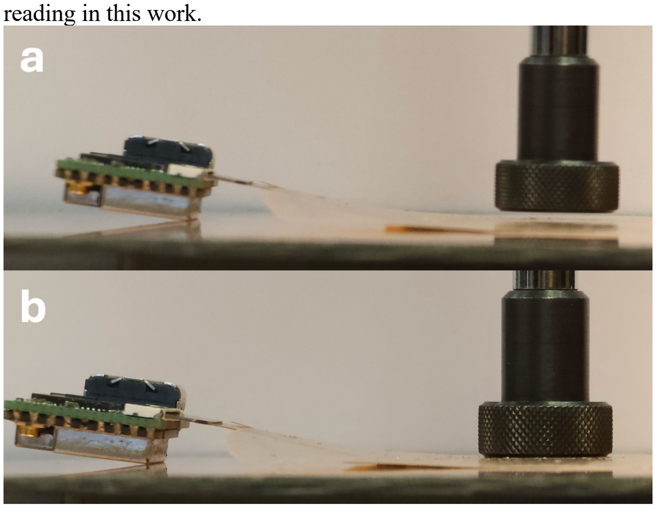

Figure 5: Proximity sensing test setup (a) and contact & pressure sensing mode test setup (b).

Proximity Sensing

The proximity sensing range begins with slight contact between the gauge head and the sensor pad and extends to the point where the sensor reading decreases to zero, spanning from 0 to approximately 2.2 mm. As shown in Figure 6 (a), the sensor reading in log scale is plotted with the distance change, the error is initially small and increases when it approaches to the sensor detection limit.

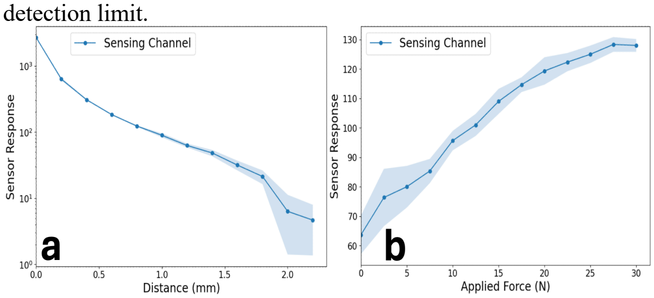

Figure 6: Sensor response of proximity sensing (a) and pressure sensing (b)

Pressure Sensing

The pressure sensing capability of the SELMA system comes from both the increase in contact area due to material deformation (like the tongue) and the reduction in gap resulting from compression of the elastic layer on top of the sensor pad. While capacitance is not directly correlated with pressure, they nonetheless exhibit a linear relationship within the pressure range achievable by the tongue and palate.

Since the distance between the gauge head and sensor pad is small and hence shows higher capacitance readings, we use raw capacitance values for sensing. As shown in Figure 6 (b), the linear relationship can be found between the force applied and the sensor reading.

Data Visualization with Mobile Interface

To better visualize the tongue position and movement, we have developed an interface to plot the sensor data into a real time 3D map. As shown in Figure 7 (a), when the pressure gauge head approaches the sensor pad, the columns at the corresponding place start to rise and keep growing indicating the pressure gauge head enters the proximity sensing mode region.

When the gauge head touches the sensor, the columns rise much faster as pressure applies which matches well with the single cell measurements.

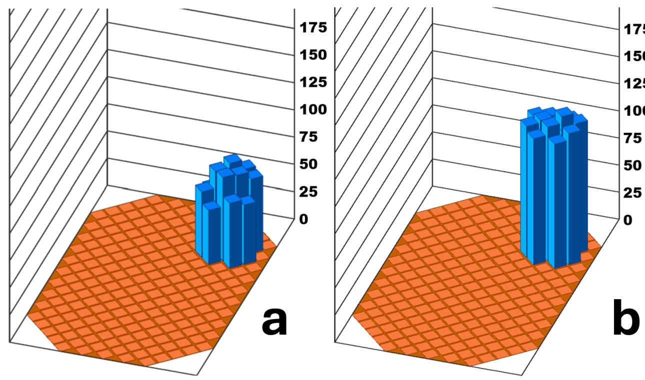

Figure 7: Sensing pattern wirelessly processed and displayed on user interface for proximity (a) and pressure sensing (b)

THIN FILM DEVICE FABRICATION

As the sensor array design and sensing function has been validated by the fPCB prototype, we translate it to a thinner and more flexible, biocompatible, and thermal plastic material platform such as using parylene. Parylene C can be comformally coated and is compatible with microfabrication. Also, it is widely used in medical electronic devices. Moreover, Parylene C can be thermally molded into intricate 3D shapes such as the contour of a pseudo-palate, to achieve superior shape replication. This ensures improved contact between the device and the patient's palate. A test structure is designed with 3 layers of parylene, 2 metal layers and corresponding via and opening structure. Microfabrication techniques using parylene are shown in Figure 8. The fabrication process starts with a bare silicon wafer, which is used for a handle substrate (regardless of its orientation.). The first 6 µm thick parylene layer is deposited on top of the wafer followed by a metal sputtering deposition with 50 nm of chromium and 200 nm gold. Then the pattern of the sensing array is transferred to the metal layer by wet etching. The X-axis of the sensor pad array is connected with metal lines on the first metal layer, while the vertical array and the connection between the sensor and I/O pin have to be achieved by the second layer metal trace and via holes. The second 6 µm thick parylene is deposited on top of the metal pad followed by a patterned RIE etching to open the via holes connecting the vertical array of the sensor pads. Then, the second metal layer with the same composition and thickness as those of the first metal layer is deposited using sputtering, followed by patterning using photolithography and wet etching to define the traces and vias for connection. The third layer of parylene is then coated on the device for passivation while additional photolithography and etching processes open the I/O pins.

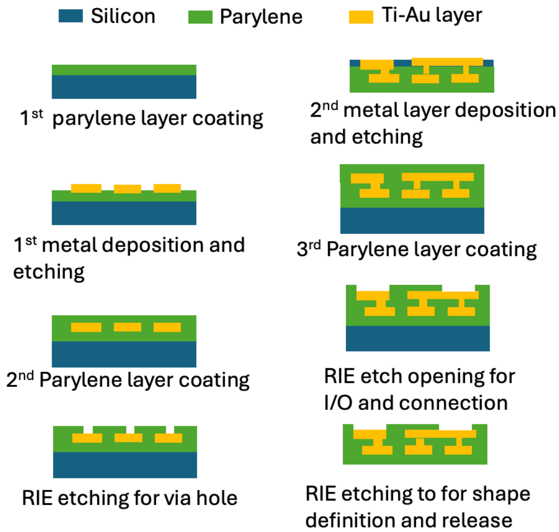

Figure 8: Fabrication steps of parylene process for SELMA device.

The final photolithography and RIE etching steps define the shape of the SELMA sensor and remove the surrounding parylene for the releasing purpose. Then the entire wafer is submerged into DI water and the parylene-metal sensor is clearly separated from the silicon due to the surface tension as shown in Figure 9 (b) and the details of sensor patterns in Figure 9 (a).
The stand-alone parylene packaged sensor can now be molded into the upper palate shape for better wearing comfort and accurate sensing thanks to the thermal plastic property of parylene whose glass transition temperature is 80 ºC.

With the validated process and approach, we are developing a fully functional SELMA sensor system, featuring a palate-shaped parylene thin film, a higher channel count, and output pins compatible with the read-out board.

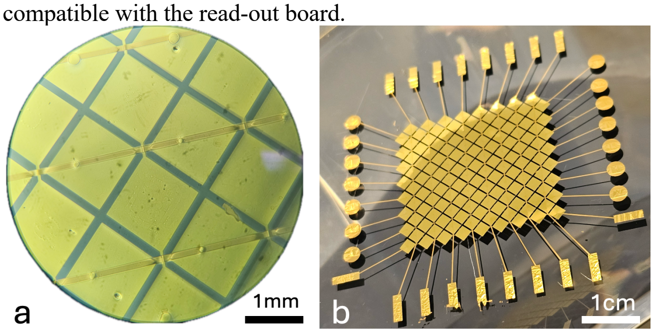

Figure 9: Fabrication results of parylene packaged sensing test structure. Details under an optical microscope (a) and device release from the substrate (b).

CONCLUSION

In this research, we developed a wearable, flexible, high resolution capacitive sensing system for tongue movement and position mapping powered by proximity, pressure and contact sensing modes. The design is first validated in a form of fPCB and then evolved to a microfabricated parylene platform. The SELMA EPG sensor system is one of the most versatile smart EPG to date thanks to its high channel counts, extremely thin thickness, and multi-modality sensing including proximity, contact, and pressure sensing modes.

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