Using Chemiresistive Nanomaterials to Develop a Rapid Diabetes Sensor
and Derive a Resistance-Acetone Relationship

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Abstract

Specific nanomaterials have been shown to possess a functional relationship resistance when placed in contact with acetone, which is severely overrepresented in the breath products of patients with medical diabetes. The sensor created will take a form similar to that of an alcohol-based breathalyser commonly used by Police for detecting DUI, it will utilize the chemiresistive property of a unique nanomaterial mixture, tracking resistance changes based upon the presence of acetone. Different Regression Models will be utilized to attempt to quantify acetone level (ppm) when given a resistance-based time series, and also in exposure to other extraneous variables. In addition, Fourier analysis and other physical techniques will be utilized. The end goal is the creation of either a threshold or model which can accurately quantify acetone based on resistance over time.

Introduction

This project began as part of a summer research program, done at NDSU. It is based within Dr. Wang’s Electrical Engineering research group, specializing in nanomaterials and their electrical reactions to external exposures. This project focuses specifically on the reaction of the analyte, acetone, with a mixture of two nanomaterials synthesized within Dr. Wang’s lab. Resistance values of the mixture have been observed to fluctuate when exposed to higher levels of acetone. The goal of this project is to develop a compacted sensor development for handheld medical use and mathematical analysis in an attempt to derive a relationship between acetone and resistance. The sensor prototype was based on an Arduino UNO microcontroller platform, taken from a standard Arduino UNO R3. It included various components, but most crucial is the onboard ohm-meter capable of measuring resistance up to 500K ohms. The prototype existed from previous research work in Dr. Wang’s group. Our goal included developing this model as a compact, handheld, improved code structure and documentation for possible future advancements. The goal was to achieve a device approximately at the scale of an iPhone.

Nanomaterials

MXenes

All MXenes share the same chemical structure, the notation is:

$$\text{M}_n\text{X}_y\text{TeX}$$

(1)

in this formulation: the ‘M’ represents any transition metal, ‘K’ can be a group 3A to 5A metal. The ‘X’ represents functionalities that are left once the etching process is complete. MXenes are derived from an initial MAX phase. The goal of the composition process involves 'etching' out the A layer, leaving the desired two-dimensional MX plane. 

MXenes are known to have incredibly good electrochemical stability, much greater than the majority of their two-dimensional counterparts. This decreases the overall resistivity of the system allowing for easier sensing in the kiloohm range instead of MEGOhms. In addition, MXenes can be synthesized in the liquid phase, allowing for mass production if necessary.

A variety of different MXenes have been discovered and tested for many different purposes. In this work, the blade used for our sensor have been shown in correspondence with the following MXene structure:

Ti3AlC2

(2)

KWO

The substance combined with MXene for the sensing mechanism is commonly referred to as ‘KWO’, and is actually a form of Molecular Sieve (MS), as opposed to just a simple nanorod. Molecular Sieves feature a combination of 1D and 2D nano-scale effects. From a geometry standpoint, one can imagine a 2D nanorod, with ‘spots’ of ingrown nanorods within the plane of that nanorod. KWO is an Orthorhombic Molecular Sieve (OMS), specifically part of the WO3 family. It possesses the following chemical structure:

$$\text{K}_2\text{W}_{12}\text{O}_{28}$$

(3)

In this formulation, each ‘K’ is the center of the ‘nanowire’, with surrounding Tungsten (W) and Oxygen (O). KWO is useful for our purposes because its crystaline structure is remarkably similar to other 1D nanowires, allowing for cohesion with the MXene created for sensing. In addition, KWO exhibits the unique 2D property of enhancing gas absorption and desorption, leading to a much more electrochemically stable substance.

Synthesis

The process of KWO production was remarkably similar to that of MXene. The same methods of in situ HF and MIL6 were utilized. These are both extremely safe and easy for hands-on lab use. Both nanomaterials require a distinct ‘cooking’ and ‘washing’ phase with the use of a conventional oven and a centrifuge, respectively. Various synthesis temperatures can have varying effects on nanomaterial morphology. Future work should be conducted into ideal synthesis temperatures and external conditions for sensor development. Once both nanomaterials have been isolated, their amalgamation is remarkably simple. Both are mixed individually with ethanol to create a ‘paste-like’ substance. These pastes can be mixed together and applied to the sensor slides.

The Sensor

The created nanomaterial pastes are then applied to a gold-plated mechanism called an integrated transistor detector (IDT). IDTs are commonly used in many SAW-based electronics, such as bandpass filters, delay lines, resonators, and sensors. Typically, acoustic wave sensors are created by combining IDTs or other patterned electrodes with piezoelectric crystals. Our sensor utilizes the combination of KWO and MXene, brazed over the active portion of a gold output IDT.

The sensor used for this project exhibits electrochemical properties similar to many other created electrochemical sensors. A chemical sensor is a device that converts chemical data, ranging from the concentration of a single sample component to complete composition analysis, into an analytically usable signal.

Electrochemical sensors function through two input signals, such as current (I), Voltage (V), or Resistance (R). Our sensor focuses on differences in resistance that become apparent in samples with and without acetone, which performs as the anode in this reaction.

Sensor prototyping consisted of maximizing a previously-created model for the prototype presented to an extremely large and bulky, and the end goal was to achieve a model at the scale of an iPhone. The final model included an Arduino UNO R3, a microcontroller designed for ease of use and plug-and-play prototyping. Instead, the new model centered around the Arduino UNO R3 microchip. This is the same chip that is embedded within the Arduino UNO R3. It can be easily removed and utilized without the accessories of the UNO, saving design space.

Diabetes and Acetone

Currently, the most viable method for diabetes detection involves the use of a blood test. Almost all tests are invasive and involve the use of a blood test. Almost all tests are invasive and involve the use of a blood test. Currently, the most viable method for diabetes detection involves the use of a blood test. Almost all tests are invasive and involve the use of a blood test. Currently, the most viable method for diabetes detection involves the use of a blood test. Almost all tests are invasive and involve the use of a blood test. Currently, the most viable method for diabetes detection involves the use of a blood test. Almost all tests are invasive and involve the use of a blood test. Currently, the most viable method for diabetes detection involves the use of a blood test. Almost all tests are invasive and involve the use of a blood test. Almost all tests are invasive and involve the use of a blood test. Currently, the most viable method for diabetes detection involves the use of a blood test. Almost all tests are invasive and involve the use of a blood test. Currently, the most viable method for diabetes detection involves the use of a blood test. Almost all tests are invasive and involve the use of a blood test. Currently, the most viable method for diabetes detection involves the use of a blood test. Almost all tests are invasive and involve the use of a blood test. Currently, the most viable method for diabetes detection involves the use of a blood test. Almost all tests are invasive and involve the use of a blood test. Currently, the most viable method for diabetes detection involves the use of a blood test. Almost all tests are invasive and involve the use of a blood test. Currently, the most viable method for diabetes detection involves the use of a blood test. Almost all tests are invasive and involve the use of a blood test. Currently, the most viable method for diabetes detection involves the use of a blood test. Almost all tests are invasive and involve the use of a blood test. Currently, the most viable method for diabetes detection involves the use of a blood test. Almost all tests are invasive and involve the use of a blood test. Currently, the most viable method for diabetes detection involves the use of a blood test. Almost all tests are invasive and involve the use of a blood test. Currently, the most viable method for diabetes detection involves the use of a blood test. Almost all tests are invasive and involve the use of a blood test.

FIGURE 1: Original (a) and Top (b) Acetone-varied Resistance Graphs. These are varied sensing locations.

Data Analysis and Regression

Physical Patterns can be ascertained from the scale of ppm exposure given in these graphs. The original sensing location shows a highly-regulated relationship between ppm exposure and lower initial resistance readings. There also appears to be more variability present in lower ppm exposed samples. The top samples display slightly different patterns, although both seem functionally in reference to ppm. These samples display an opposite effect in regard to starting resistance; lower ppm suggests lower starting resistance. There are also a set of clear points of inflection present in these graphs. The first change occurs at ~65 ppm units and shows greater rates of change for higher exposures of ppm. Further analysis involved Fourier transforms on the leading 1928 data points of each sample. Results for this were promising, specifically when analyzing ppm in correlation with the DC value. Attempts were made to utilize regression models to ascertain a resistance-per-ppm relationship. Models included linear, exponential, polynomial, Random-Forest, and MLPRegressor. More accurately stratified data would be required to produce a consistent relationship. The only model with promising results was MLPRegressor, more than likely a result of overfitting.

FIGURE 2: Original (a) and Top (b) Acetone-varied Resistance Graphs. These are varied sensing locations.

References