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

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Abstract

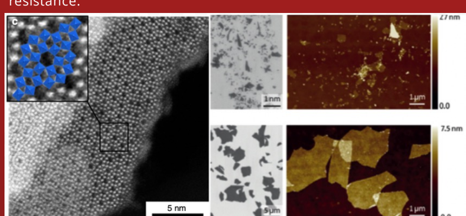
Specific nanomaterials have been shown to possess a functionalizable resistance when placed in contact with acetone, which is severely overrepresented in the breath product of patients with medical diabetes. The sensor created will take a form similar to that of an alcohol-based breathalyzer commonly used by Police for detecting DUIs. 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 levels (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 twofold: 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 Atmel328P-PU microchip, taken from a standard Arduino UNO R3. It included various components, but most crucial is the onboard ohmmeter capable of taking live resistance readings. A functioning prototype existed from previous research work in Dr. Wang's group. Our goals included recreating this model in a compact manner, with improved code structure and documentation for possible future advancements. The goal was to achieve a device approximately at the scale of an iPhone.

The mathematical end of this endeavor, at least in this initial stage, is not statistically rigorous. Delays in prototype assembly and part delivery have caused the newly designed sensor to not yet be assembled. Data is sourced from previous Ph.D. work from Dr. Wang, but if a true mathematical relationship is to be derived, more consistent and continuous data would be required. I hope to continue this project to a point where more accurate metrics can be utilized. For now, we can only investigate where the discrepancies may lie; more samples would be required for finding a true mathematical formulation between acetone exposure and resistance.



Nanomaterials

MXenes

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

$$M_{n+1}X_nT_x \quad (1)$$

In this formulation: the 'M' represents any transition metal, 'X' can be carbon or nitrogen, and 'T' is the surface functionalities that are left once the etching process is completed. Mxenes are derived from an initial 'MAX' powder. The goal of the composition process involves "etching" out the A layer, leaving the desired two-dimensional MX planes.

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 in Megaohms. 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 practical uses. The most promising results for our sensor have been shown in correspondence with the following MXene structure.

$$Ti_3AlC_2 \quad (2)$$

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 nanowire. Molecular Sieves feature a combination of 1D and 2D nano-scale effects. From a geometry standpoint, one can imagine a 2D nanoplane, with 'spots' of ingrained nanowires flush with the surface. KWO is an Octahedral Molecular Sieve (OMS), specifically part of the WO3 family. It possesses the following chemical structure:

$$K_2W_7O_{22} \quad (3)$$

In this formulation, each K sits at the center of the 'nanowire', with surrounding Tungsten (W) and Oxygen (O3). KWO is useful for our purposes because its crystalline structure is remarkably similar to other 1D nanomaterials, allowing for cohesion with the MXene created for sensing. In addition, KWO exhibits the unique 2D property of enhancing proton insertion and de-insertion, 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 MILD were utilized. These are both extremely risk-free 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 slide.

The Sensor

The created nanomaterial pastes are then applied to a gold-plated mechanism called an interdigitated transducer (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, brushed over the array 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 focus specifically on electrical 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 analyte in this reaction.

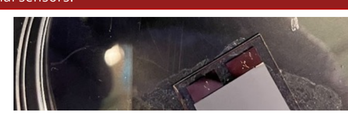
Sensor prototyping consisted of maximizing a previously-created model for size. The prototype presented was extremely large and bulky, and the end goal was to achieve a model at the scale of an iPhone. The original prototype centered around an Arduino UNO R3, a microcontroller designed for ease of use and plug-and-play prototyping. Instead, the new model centered around the Atmel328P-PU 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 needles to track a patient's blood sugar level. In addition, some of these tests involve fasting periods prior to testing, which could prove uncomfortable to some patients. Return time on these types of tests is also an issue. For those in the hospital under critical conditions, the results of these tests will be confirmed in a couple of hours. Otherwise, results will take a few days to process and be returned to patients. This extended wait period could cause medical complications for those who unknowingly could have diabetes.

Acetone is a chemical byproduct found in human breath. It is produced naturally in both our surrounding environment and within the human body. Low levels of acetone are typically created during the breakdown of fat, and, in addition, human bodies can utilize acetone in the processes which create sugar and fat. Higher levels of acetone have been associated with the presence of diabetes.

Diabetes occurs when your blood glucose levels are too high. Typically, glucose is able to enter and feed cells through the use of insulin. Typical diabetic patients do not possess high enough levels of insulin, leaving large amounts of glucose to freely roam their bloodstream. In addition, cells do not gain enough energy, since glucose is unable to permeate their cell membranes. This leaves the body to burn fat in place of glucose. When done in large amounts, higher levels of acetone will be produced and can be detected by external sensors.



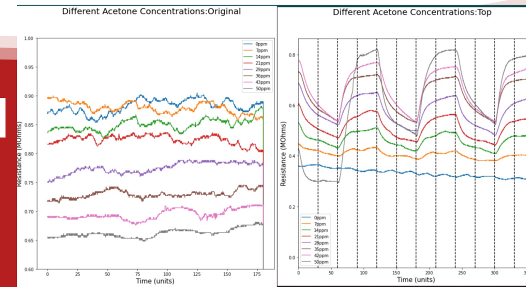


FIGURE 2: Original (L) and Top (R) Acetone-varied Resistance Graphs. These are varied sensing locations.

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 high correlation 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 functionalizable 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 time units and shows greater rates of change for higher exposures of ppm.

Further analysis involved Fourier transforms on the leading 1028 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-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.

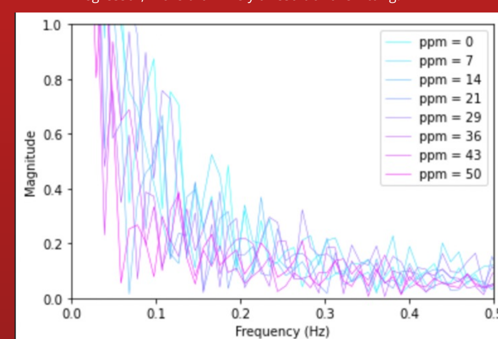


FIGURE 4. Closer examination of the [0,.5] Hz range, which appears to show the most discrepancy in terms of amplitude. Colors go from light blue → light pink in an attempt to quantify ppm w/ color

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