Powder River Basin Graphene Inks

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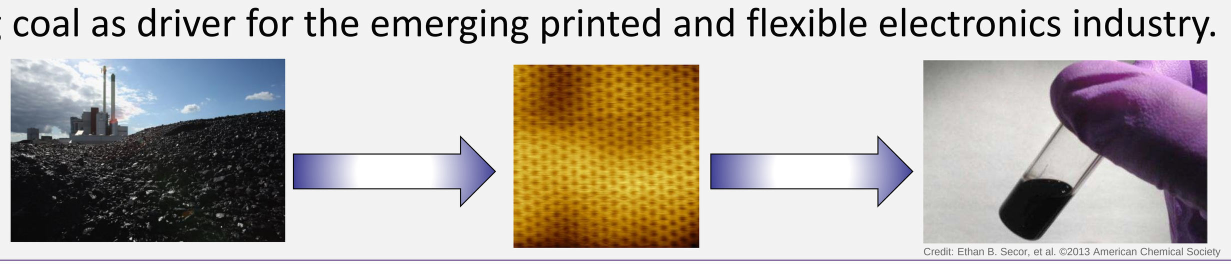
I. Abstract

Graphene, a 2D material comprised exclusively of carbon atoms, has been making its way into flexible electronics due to its incredible strength, high electrical conductivity, and optical transparency.[1] Certain forms of graphene can be used to produce conductive inks,[2] which can be printed on to flexible substrates for applications in wearable biosensors and in emerging agricultural technologies. A more mature carbon based technology is coal. Composed largely of carbonized plant matter, coal has been a major energy source for at least the past ~150 years. However, greenhouse gas emissions from coal power plants and advances in renewable energy technologies are reducing the use of coal for energy production. Hence, a major paradigm shift in coal-based economies is on the horizon. In this work, we merge these two carbon based technologies, highlighting the potential of using coal as driver for the emerging printed and flexible electronics industry.

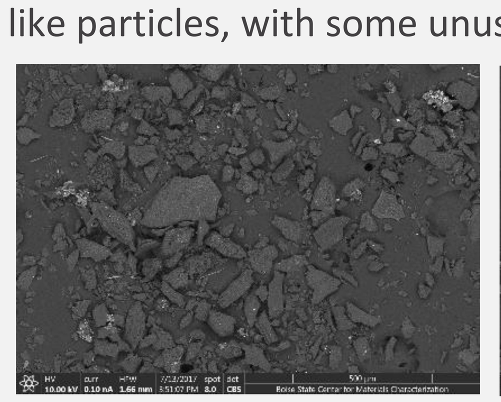


II. Motivation

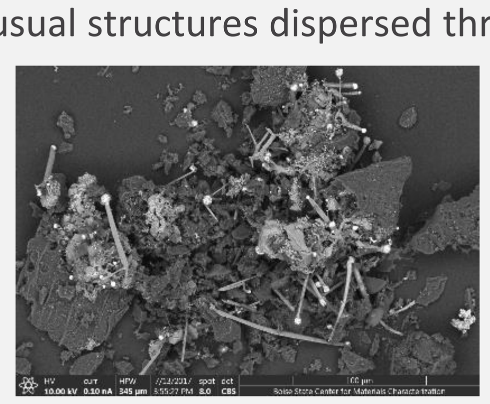
The Powder River Basin, located in parts of Montana and Wyoming, is home to some of the largest coal deposits in the United States, and supplies about 40% of the U.S. coal.[3] With the coal market predicted to decline due to the rise of cheaper alternative sources of energy, this work aims to make use of coal byproducts to develop advanced carbon based materials. In collaboration with the University of Wyoming, we use pyrolyzed coal char synthesized from Powder River Basin coal to produce printable graphene inks for use in flexible electronics applications.

III. Starting Powder

The Scanning Electron Microscope (SEM) images of the pyrolyzed coal char powder, provided by collaborators at the University of Wyoming, generally showed graphite like particles, with some unusual structures dispersed throughout.



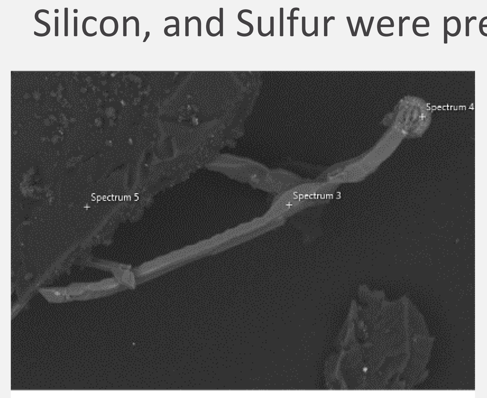
The general graphite like structure of the pyrolyzed coal char powder

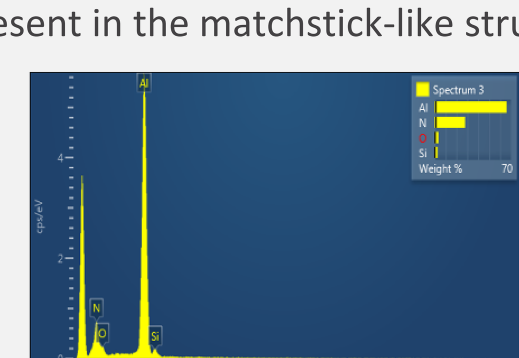


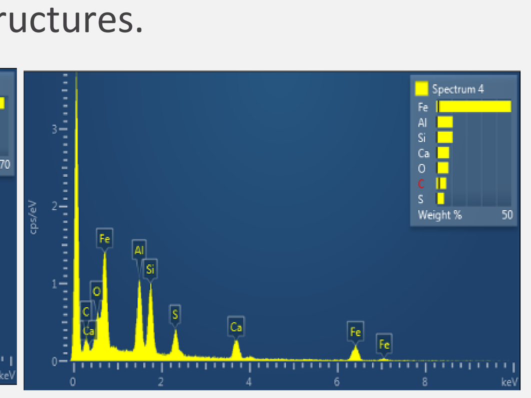
Cluster of unusual matchstick-like structures

Cluster of hexagonal structures

Upon further testing using energy dispersive x-ray spectroscopy (EDS), besides the expected Carbon, traces of various elements such as Iron, Aluminum, Calcium, Silicon, and Sulfur were present in the matchstick-like structures.



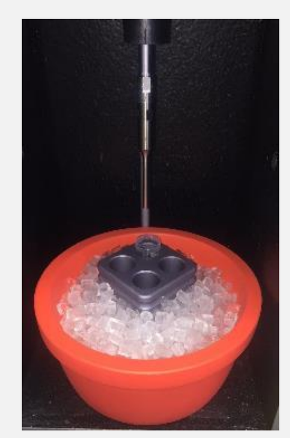




IV. Ink Synthesis

Ink Process:

- Initially, a solution which consists of the coal powder, ethyl cellulose, and isopropyl alcohol must be created which is then sonicated.
- After sonication, this solution is centrifuged. The supernatant is collected and recentrifuged another time.
- After centrifuging the solution, the second time, the supernatant is collected again and salt water is added to the solution, and it is centrifuged again.
- After this centrifuge process, the supernatant is discarded and the precipitant left over is diluted in isopropyl alcohol and poured in a Teflon dish to dry overnight.
- The next day, the dried graphene is collected and dispersed in a solution of 92.5% cyclohexanone and 7.5% Terpineol, which is sonicated and then centrifuged one last time.
- Then you have the finished ink.



Ink solution chilled in an ice bath while sonication

Ink Solution in Teflon dish left to dry overnight

Ink solution in Teflon dish after drying overnight

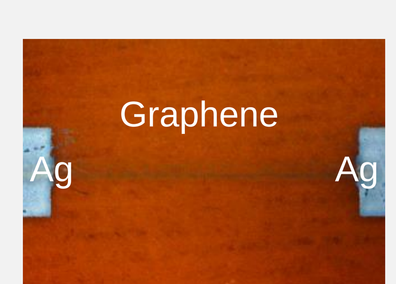
Finished ink

Summary of Ink Process

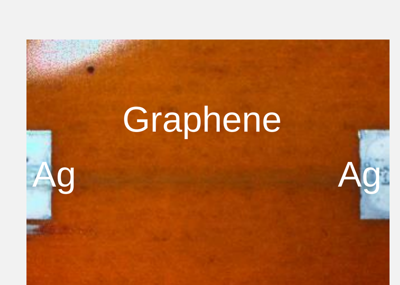
V. Printing

Transfer length Method (TLM) test structures were printed on Kapton using the finished graphene ink and the Dimatix Inkjet Printer. These structures consist of one long line printed in graphene ink and square pads printed in silver ink on top of the graphene line which increase in distance in increments of 1 mm along the line. These silver pads aid in testing conduction because in most cases, printed graphene is very brittle and at risk of breaking under pressure from the probe tip. Since the concentration of the graphene in the ink was low, multiple printing passes were done in order to increase the chances of conductivity and visibility on the Kapton substrate.

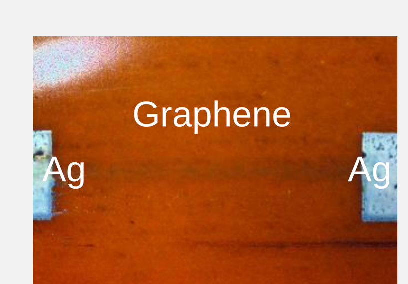
TLM structure Printed on Kapton



Graphene Ink Line – 30 printing passes.



Graphene Ink Line- 25 Printing Passes



Graphene Ink Line – 20 Printing Passes

VI. Results

Electrical characterization, current vs. voltage for each increasing distance along the TLM structure, indicated that the ink was indeed conductive. These resulting current and voltage characteristics for each distance were plotted as shown in Fig. 1. The inverse slope of each line provides the resistance exhibited along each increasing distance. The tested distances started from 2mm and increased by 1mm thereafter until 7mm. The resistance vs. distance was plotted as shown in Fig. 2. Generally, there is a positive linear relationship between distance and resistance, which was expected if conductivity was present. The resulting resistances have shown to be substantially large. This may be due to the low concentration of the graphene ink, resulting in a variable range hopping mechanism of conduction, as opposed to phonon-limited conduction as in metals.

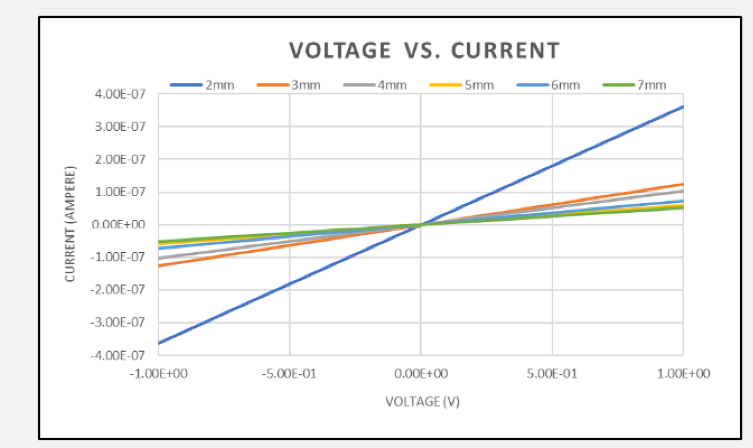


Fig. 1: Voltage vs. current graph of different distances on the TLM structure

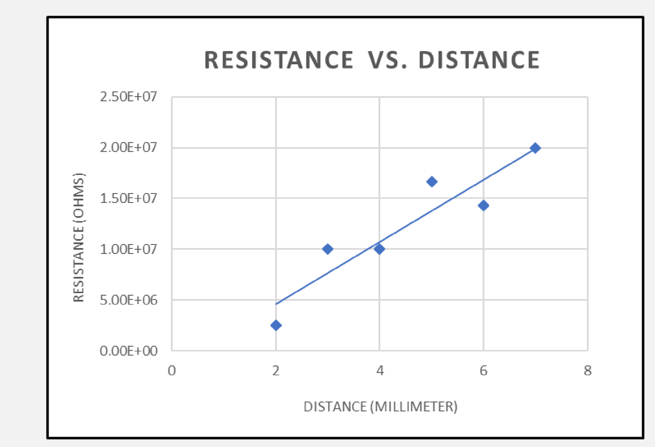


Fig. 2: Resistance vs. distance graph

VII. Conclusion

Overall, ink created from pyrolyzed coal char, a coal byproduct, printed with 30 passes in a TLM structure, proved to be conductive. The starting pyrolyzed coal char powder showed traces of various elements such as Iron, Aluminum, and Calcium. Since the sample was not pure carbon, this may have contributed to the ink's conductive properties. However, additional analysis and higher concentration inks are needed for further evaluation of conduction mechanisms. Although a high resistivity was present, ink produced from coal byproduct illustrates a promising future for the emergence of the coal sector in the flexible electronics market while promoting recyclability and sustainability.

VIII. References

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[2] Torrisi, Felice, et al. "Inkjet-printed graphene electronics." *ACS Nano* 6.4 (2012): 2992-3006.
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