Electronic Packaging of Paper-Based Anisotropic Magnetoresistive Sensors

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Abstract

Please note the results of this experiment are being published. Therefore, no data can be released at this time.

Paper may initially seem like a counterintuitive choice for a substrate for electronics but it holds more potential as an engineering material than one may first assume. The low cost and accessibility of paper make it a practical option for creating affordable electronics. Its relatively low thickness, flexibility and biodegradability also offer interesting possibilities for its incorporation into existing systems as a means to further the reach of the internet of things.

The Institute for Micro-Production Technology of Leibniz University in Hannover, Germany is conducting research on paper-based AMR sensors. This report investigates adaptations of electronic packaging methods used to create stacks of these sensors. Four methods were developed and tested to determine the best option in terms of mechanical stability and electrical conductivity of the system. For the first method, a stack is created by way of through paper vias (TPVs), a hole that is cut in the pads of the sensors and then filled with electrically conductive adhesive through the openings on the two sensors to be joined. The second method is called mechanical caulking and connects sensors through pads which have been lined with copper tape backed with conductive adhesive. The connection is created with a small copper rivet which is flattened in place by compressive force. The third method is the stitching method which is inspired by sewing of fabric. A pattern of thin copper wire is stitched on the pad of a sensor that is lined with copper tape backed with conductive adhesive. The wire is then stitched through a second sensor that is treated similarly with copper tape and the stack receives the same pattern through the two layers as was applied to the first sensor alone. The final method is the collapsed daisy chain which is the linear connection of sensors to their neighboring sensors via copper tape backed with conductive adhesive. The row of sensors is then collapsed in an alternating orientation into a single stack.

The three methods of TPVs, mechanical caulking and the collapsed daisy chain all produced good results in terms of mechanical stability and electrical conductivity. The stitching method proved to be a poor method for paper substrates because of the excessive strain caused to the pad around the pattern stitched with copper wire and the limitations of the method in creating stacks with more than two sensors. The best method in terms of both mechanical and electrical qualities was TPVs which caused an acceptable level of increase in the resistance while maintaining a very stable stack that was planar and free from relative rotation between the stack layers.

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Nomenclature

AMR (Anisotropic magnetoresistive) sensor

- Sensor whose electrical resistance changes based on its orientation relative to an imposed magnetic field

CAD (computer aided design)

- A drafting software used to create realistic 3D models

Permalloy

- $Ni_{81}Fe_{19}$
- 81% Nickel and 19% Iron
- Magnetoresistive thin film

Sputter deposition

- Used to deposit a thin film of material onto a substrate
- Inert gas plasma in a vacuum bombards a target material above a substrate. Atoms of the target material are dislodged and fall onto the substrate below.

TPV (Through paper via)

- Electronic packaging method developed to connect sensors through paper substrate with electrically conductive adhesive

TSV (Through silicon via)

- Electronic packaging method used to create a connection through silicon chips

Introduction

With the growing interest in expanding the internet of things, integration of electronics into low cost, accessible materials becomes an essential point of development. Paper is a readily available material that is not only low cost but also boasts other positive characteristics such as flexibility and biodegradability. Because of its prevalent use in everyday activities and processes, paper is a natural choice as an affordable substrate for electronic sensors used to expand the reach of the internet of things.

Some novel advances have been developed in recent research that use paper as a basis and which prove its versatility as an engineering material. Some such developments are the paper microscope [4], paper batteries [10], and Google cardboard, a paper-based virtual reality technology [5]. These examples illustrate that paper has the potential to be used for more than today's typical functions. There is also research being conducted in different areas concerning engineering applications on paper. Pixels have been created on paper through an electrowetting process which traps liquid between two paper surfaces that have been treated to be made hydrophobic [7]. Conversely, microfluidics research utilizes the hydrophilic nature of paper to complete functions such as absorbing samples for medical analysis [6].

Another application is paper-based anisotropic magnetoresistive (AMR) sensors. These sensors exhibit a varying resistance based on the orientation of the current through the sensor relative to the magnetic field to which it is exposed. In this way, the rotational positioning of the sensor can be determined from the output resistance of the system. A thin film coating of permalloy ($Ni_{81}Fe_{19}$) is deposited via sputter deposition on the paper substrate in a meander design with pads for electrical connection on each end. Work conducted at the Institute for Micro-Production Technology of Leibniz University in Hannover, Germany, has determined the optimal characteristics and manufacturing methods for AMR sensors on paper substrate [1-3]. The size of these sensors at current ideal specifications imposes a limitation for the length of the meander and therefore its sensitivity. For this reason, an advantage could be gained from creating a vertical stack of sensors. This method of connection also facilitates miniaturization efforts by increasing the effective length of the meander without increasing the footprint of the sensor.

The purpose of this research is to develop a viable electronic packaging method to connect a stack of AMR sensors on paper. Requirements for this method are that it does not destroy the substrate or interrupt the functionality of the sensors while maintaining the positive traits of paper.

Approach

In order to develop a viable electronic packaging method when using paper as a substrate, it is important to consider what makes paper different from traditional substrates like silicon and plastics. Some major differences include porosity, mechanical strength and thermal budget. Paper's high porosity changes the way that the substrate interacts with liquid; it is more apt to absorb into the paper and distribute in an uncontrolled manner. A lower mechanical strength makes paper easier to bend and cut which allows manipulation of the substrate using less force. It also limits the force that can be used to create connections because the stresses can deform the substrate and sacrifice the desired shape of the material. The low thermal budget of paper as compared to traditional substrates makes soldering methods used in many electrical packaging techniques unrealistic.

To maintain the functionality of the AMR sensors when connected in a stack, it is required that the electronic packaging method creates mechanical stability, does not cause interference with the magnetoresistive qualities of the sensor and allows good electrical conductivity. A mechanically stable stack is important because it keeps the meanders parallel. All meanders legs must sustain the same orientation relative to the magnetic field in order to produce a precise measurement of magnetoresistance. In order to prevent hindrance of the readings generated by the sensors, any connecting materials used in the stack cannot have magnetoresistive properties. The purpose of the electronic packaging is to create an electrical connection between the sensors; so, electrical conductivity is of utmost importance. Low resistance in the connections of the stack is desirable to create a situation that is as close as possible to the ideal state of one continuous meander.

Conservation of planarity and exploitation of the inherent properties of paper are key points in full utilization of the positive traits of the paper substrate in regards to the electronic packaging method. The planarity of paper is one its most desirable characteristics and therefore one to avoid impairing. Considering paper's ability to be bent and sheared with minimal application of force relative to other inorganic substrates generates a variety of alternative manufacturing options. The fact that paper is an electrical insulator can also be favorable when developing electronic packaging because the substrate does not need to be insulated from the conductive connection materials.

Development

Four electronic packaging methods were developed with these ideas in mind. The main focus was altering current packaging methods to create short distance, low resistance connections between sensors and produce a stable, planar stack that works well on a paper platform.

Through paper vias

The electronic packaging method that utilizes Through Paper Vias (TPV) was inspired by a state-of-the-art method called Through Silicon Vias (TSV). TSV connections are created through a general process of creating a hole or via in the silicon substrate, insulating the sides of the via with a dielectric material, filling the via with a conductive material, and, finally, connecting terminals [8]. In the case of a paper substrate, this method was adapted to create TPVs on AMR sensors by cutting a via, sputtering a magnetoresistive thin film of permalloy, and filling a stack of two sensors with conductive material through the via and in connection with the thin film pad on each sensor. Because paper is an insulator and not a semiconductor like silicon, the insulation step required in TSV creation can be eliminated for TPVs. The purpose of cutting the vias prior to sputter deposition is to avoid breaking the thin film and also to coat the edges of the via with conductive material to facilitate a good electrical connection. The conductive material used to fill the TPVs is an electrically conductive adhesive composed partially of silver nanoparticles. This material is applied and cured at room temperature making it a viable option for use with the paper substrate.

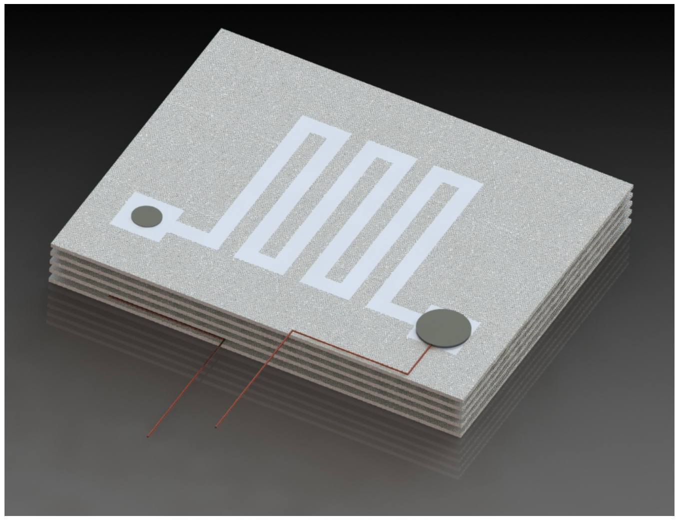

Figure 1. CAD model of TPV method.

Mechanical caulking

Mechanical caulking is an electronic packaging method for traditional substrates in which a gold stud bump on one chip makes connection with a corresponding indentation in another chip by squeezing the bump into the indentation using compressive force that causes plastic deformation of the bump. This process can occur at room temperature and the quality of the connection does not depend on bonding temperature, use of ultrasonic waves, use of underfill, hole diameter, or magnitude of force used [9].

The similarity between this method and the mechanical caulking method for paper substrate lies in the use of mechanical force and plastic deformation of the connection material in order to join the two sensor substrates both physically and electrically. A 1 mm diameter round hole is punched in the center of the pads of each sensor before the permalloy is sputtered. After sputtering, two pieces of copper tape backed with conductive adhesive that are cut to the same size as the pad of the sensor are attached to the pad and the area on the opposite side of the sensor directly behind the pad. The 1 mm diameter hole is again punched through the pad, this time through the copper tape, forcing the excess copper through the hole and consequently lining it with the conductive material. Two sensors that have had the tape applied to the pads are then connected with a 0.6 mm diameter copper rivet that is compressed with long nose pliers. The sensors are aligned such that the permalloy thin film on each sensor is facing the same direction and the legs of the meanders are kept parallel to one another while the rivet is flattened.

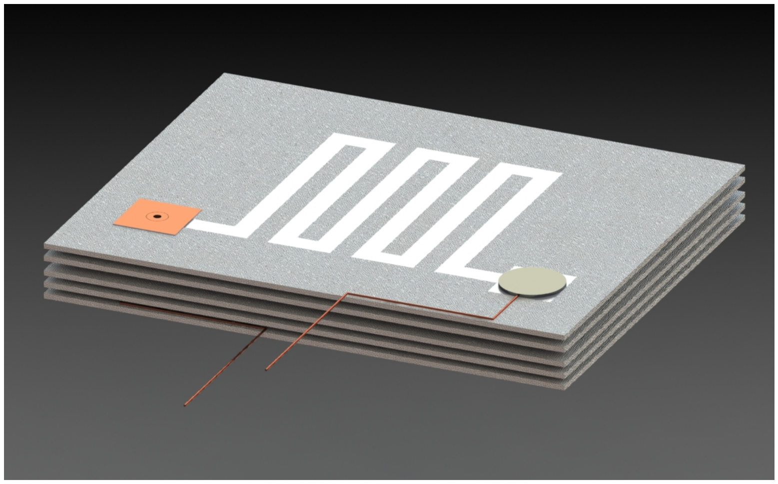

Figure 2. CAD model of mechanical caulking method.

The major purposes of punching the hole prior to the sputtering process are to prevent breaking the coating and to coat the edges of the hole that is created with conductive material. The addition of the copper tape serves to create a more favorable environment for the electronic connection between the copper rivet and the permalloy on the pads of the two sensors. These aspects of the process both aim to aid in decreasing the base resistance of the system.

Stitching method

The stitching method draws its inspiration from the strong mechanical link of textiles that is produced by sewing with a needle and thread. This packaging method connects two sensors using a pattern of 0.1 mm diameter copper wire that lays across the pads. Nine round holes of 0.5 mm diameter are punched through the paper in the area surrounding the pads of the sensors. Permalloy is then sputtered onto the paper substrate. Two pieces of 4x4 mm^2 copper tape with conductive adhesive are attached to the pad of the sensor and the area on the opposite side of the sensor directly behind the pad. The holes are then punched again through the copper tape. During this second punching process, excess copper tape is forced through the openings to make the pathway through the paper substrate more conductive. The copper tape is added in an attempt to create a more conducive connection point for copper wires that lay across the pads. The stitching pattern that was found to be the best option includes wires around the perimeter of the box of the pad, a cross between opposite corners, and a cross between the midpoints of the opposite edges of the perimeter. In order to create the most electrically conductive connection possible, the pattern of wire was stitched on one sensor and then the wire was stitched in the same pattern through a stack of two sensors so that the wire made good contact with both pads, and the sensors maintained the same orientation.

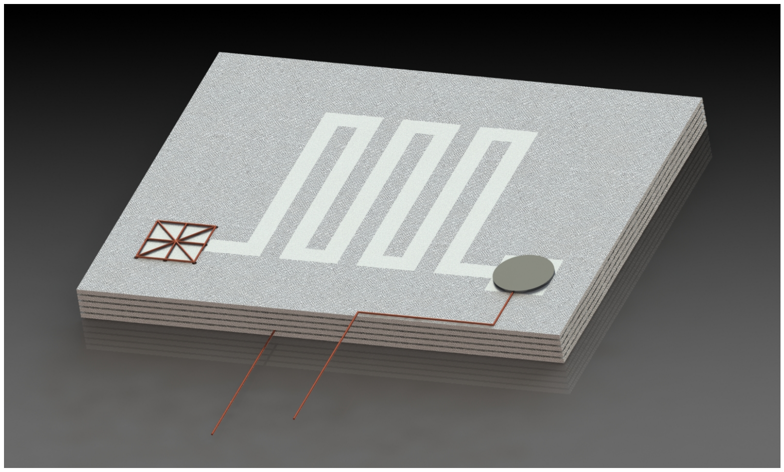

Figure 3. CAD model of stitching method.

Collapsed daisy chain
For the collapsed daisy chain method, copper tape with conductive adhesive is used to connect sensors in a linear manner. The connected row of sensors is then collapsed by folding on the tape connections and creates a stack in which the sensors are of alternating orientation. This method begins with uncut, sputtered sensors. A piece of tape of copper tape with conductive adhesive is placed such that it fully covers the pads of two adjacent sensors. All of the sensors are connected to its neighboring sensors in this way before the stack is folded. A square of paper insulation is inserted between the sensors where the piece of copper tape is folded such that it would touch another tape connection; this is done to prevent short circuits. No insulation is placed between the pieces of tape that fold onto themselves because there is no fear of a short circuit in this case.

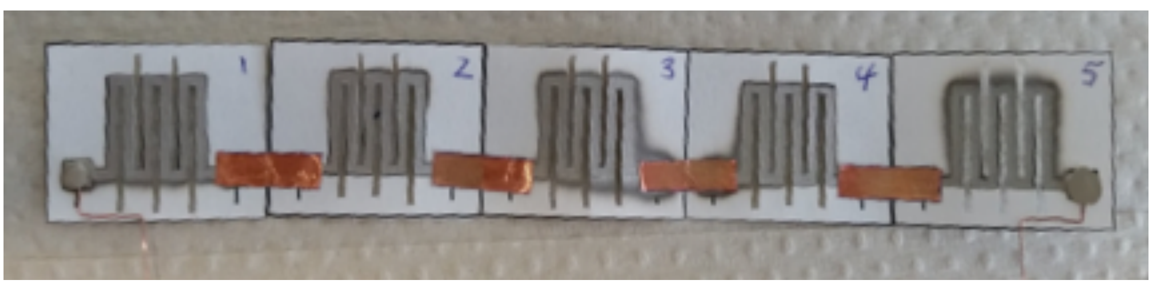

Figure 4. Collapsed daisy chain method prior to folding.

Results
Because the purpose of the electronic packaging method is to create a low resistance electrical connection between the sensors, a major performance metric is the increase in electrical resistance of the system caused by the connections. Another important aspect of the stack is mechanical stability. The sensors should maintain a position such that the legs of the meanders are parallel to one another and the stack stays planar.

For the purposes of testing, non-ideal sensors were created to fabricate prototypes and analyze initial results for mechanical stability and electrical conductivity. The non-ideal sensors were created using all of the same optimal techniques but the sputter deposition was performed for a shorter duration so the thickness of the coating was less than that of an ideal sensor. The non-ideal sensors exhibit a higher resistance than the ideal sensors but the thickness of all non-ideal sensors is the same to allow comparison among those stacks in the testing phase.

Through Paper Vias

The method of TPVs was tested by connections of two and three non-ideal sensors with known resistances. In this way, it was found that two connected sensors caused an increase in electrical resistance of 69% whereas a connection of three sensors caused an increase of 160%. Three stacks of five ideal sensors with resistances that were not specifically known were also combined using TPVs. Resistances on these ideal stacks were measured to be within a realistic and acceptable range of values. The mechanical stability of all sensor combinations was sturdy and did not allow rotation at the connection points or separation of the layers of sensors and therefore maintained good planarity.

Mechanical caulking

Stacks of two and three non-ideal sensors with known resistances were created using the method of mechanical caulking. The combination of two of these sensors gave rise to an increase in resistance of 48%; the stack of three sensors caused an increase of 71%. Three stacks of five ideal sensors with resistances that were not specifically known were also combined using this method. These resistances were found to be satisfactory for the applications but in the stacks of the ideal sensors, the base resistance increased more with the mechanical caulking method than with the TPV method. Mechanical caulking also created a fair level of mechanical stability. There was more allowed rotation than the TPV method but the planarity was maintained comparably well.

Stitching method

Stitching was found to not be an ideal electronic packaging method for a paper substrate. Problems with this method were identified not only in the feasibility of fashioning connections between sensors but also in the large increase of electrical resistance generated. The method was found to be impractical due to the difficulty of connecting more than two sensors. Because of the length of the needle used to make the connections, connecting more than two sensors requires the sensor to be bent greatly which causes excessive breakage to the meander and decreases its effectiveness. As can be seen in Figure 5, the way that the wire passes through the paper substrate was also found to cause extreme deformation of the substrate at the pad which is undesirable. A stack of two sensors of known resistance was created using the stitching method and yielded an increased resistance of 297% which was found to be outside of the acceptable range. This, in combination with the infeasibility of formation, led this method to be abandoned before a stack of ideal sensors was created.

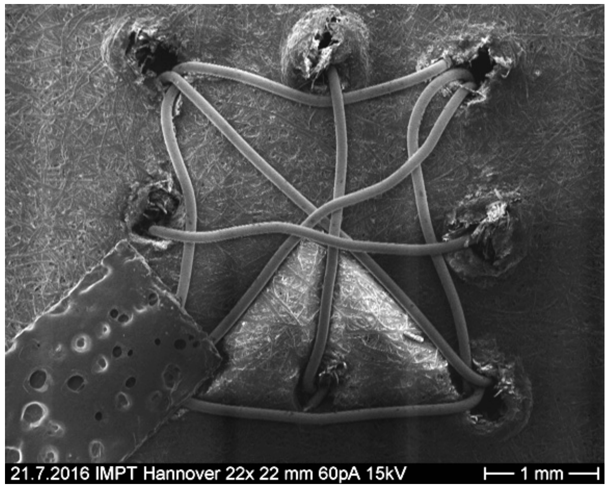

Figure 5. Scanning Electron Microscope (SEM) photo depicting deformation caused by the stitching method.

Collapsed daisy chain

The collapsed daisy chain was tested using stacks of two and five non-ideal sensors with known resistances. The stack of two sensors showed an increase in resistance of 23% and the stack of five sensors had an increase of 37%. The method was then applied to produce a stack of five ideal sensors of unknown resistance. The final resistance of these stacks was found to be very close to the assumed ideal and therefore well within the limit for an acceptable increase due to the addition of electronic packaging. The mechanical stability of the output stacks was fair but not flawless. The connections created by the tape allowed some rotation of the sensors relative to one another and the planarity of the stack was compromised. The layers tend to separate because there is nothing explicitly holding them on top of one another; the sensors have an inclination to return to the linear form they existed as prior to folding.

Conclusions

Test results for the stacks of ideal sensors demonstrate that the methods of TPV, mechanical caulking and the collapsed daisy chain all produced acceptable increases in electrical resistance and had fair to good mechanical stability. All three are therefore open for consideration as the connection method for AMR sensors on paper. Though the collapsed daisy chain yielded the lowest increase in resistance, the mechanical stability of the stack leaves something to be desired. The stack of five ideal sensors produced using the mechanical caulking method had a fairly low increase in electrical resistance; however, it caused the highest increase in base resistance of the three methods examined. Mechanical caulking also did not create a stack that was completely stable mechanically. The TPV performed the best overall with a good combination of a low increase in the base resistance, the second best of the three methods after the collapsed daisy chain, and great mechanical stability that both maintained planarity and prevented rotation of the sensors relative to one another which is important for the functionality of the stack.

It must be acknowledged that this research has only considered the electrical conductivity and mechanical stability of the systems created. The investigation of the best electronic packaging method in terms of functionality has not yet been completed and could hold the key to determining the best option for forming stacks of AMR sensors.

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