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Assembling surface mounted components on ink-jet printed double sided paper circuit board

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Abstract

Printed electronics is a rapidly developing field where many components can already be manufactured on flexible substrates by printing or by other high speed manufacturing methods. However, the functionality of even the most inexpensive microcontroller or other integrated circuit is, at the present time and for the foreseeable future, out of reach by means of fully printed components. Therefore, it is of interest to investigate hybrid printed electronics, where regular electrical components are mounted on flexible substrates to achieve high functionality at a low cost. Moreover, the use of paper as a substrate for printed electronics is of growing interest because it is an environmentally friendly and renewable material and is, additionally, the main material used for many packages in which electronics functionalities could be integrated. One of the challenges for such hybrid printed electronics is the mounting of the components and the interconnection between layers on flexible substrates with printed conductive tracks that should provide as low a resistance as possible while still being able to be used in a high speed manufacturing process. In this article, several conductive adhesives are evaluated as well as soldering for mounting surface mounted components on a paper circuit board with ink-jet printed tracks and, in addition, a double sided Arduino compatible circuit board is manufactured and programmed.

Keywords: printed electronics, component mounting, conductive adhesives, ink jet, printed circuit board, silver nano particle ink

(Some figures may appear in colour only in the online journal)

1. Introduction

Printed electronics is a rapidly developing field. A great deal of research concerns the development of printed components, where components such as transistors and light emitting devices have been realized as well as sensors [1–19]. Considerable effort has been devoted to the development of manufacturing technologies and system integration, where high speed roll-to-roll processes are preferred to ensure low cost solutions, which is one of the main benefits of printed and flexible electronics.

Often, the substrates used for printed electronics are some type of plastic such as PET or Kapton. This is mainly due to the fact that such substrates have desirable properties for roll-to-roll production of printed electronics, such as low surface roughness, temperature tolerance, dimensional stability and barrier properties against oxygen and water.

An alternative to plastic is to use paper substrate, which has the benefit of being relatively environmentally friendly, recyclable and renewable and which is also inexpensive. Increased interest in research has materialized regarding the use of paper substrates for printed electronics [20–27]. Another benefit is that it is the material of choice for packages of various kinds of goods. One of the major drawbacks is its higher surface roughness, especially in relation to uncoated paper, and it also does not have good barrier properties against oxygen and water. For hybrid electronics, the barrier properties are not an issue and, although surface roughness could be problematic for conductive tracks, generally, the tolerance is much higher than if actual components were to be printed on the substrate.

If paper is used as a substrate for printed hybrid electronics, it opens the possibility of integrating low cost electronic functions directly on packages, even possibly directly in the production line.

The functionality of even the most inexpensive microprocessor or other integrated circuit is, at the present time and for the foreseeable future, out of reach by means of fully printed components.

Therefore, hybrid printed electronics, where conductive tracks printed on flexible substrates are combined with standard electronic components, will probably be among the first commercial solutions. In this case, printed tracks on a flexible substrate act as the traditional circuit board, containing conductive tracks and acting as a carrier for the components. However, it is also possible that some printed functions or components could also be integrated on the substrate, such as printed sensors or printed light emitting devices.

For hybrid printed electronics it is important to consider different methods in relation to mounting components. The use of different types of flexible substrates with thin foil or printed electrodes in different materials means that there is no standardized mounting method.

It is important to produce low resistance electrical contacts between the components and the printed conductive tracks. Moreover, compared to traditional electronic circuit boards, the resistance of the printed interconnecting tracks could contribute a substantial resistance to the total resistance of the system, thus causing a voltage drop from the power source to the component. This will directly waste power that goes to Joule heating, which can be especially problematic if the circuit is to be battery operated.

Another important consideration is how to handle double sided circuit boards that are usually connected using vertical interconnect access (VIA). When designing printed electronics, it can be best to attempt to minimize the use of VIAs, but when using components with a large pin count, such as microcontrollers, it is often not possible to completely avoid them.

In this paper we report different methods to mount and contact standard surface mount device (SMD) components to ink-jet printed conductive tracks on paper substrates. In addition, it is shown how to connect double sided printed paper circuit boards using VIAs.

As a demonstration, a circuit board based on the Arduino Lilypad was developed, ink-jet printed and assembled. The Arduino is a family of microcontroller equipped boards with a common development platform. For these boards, a variety of sensors, actuators and other applications exist, called 'shields', which can be attached and controlled by the Arduino mainboard. The Arduino name and the Arduino logo are registered trademarks of Arduino LLC (USA), Arduino SA (Europe) and its partners.

2. Experimental details

The substrate used for all experiments was Canon PT-101 photo paper with a thickness of 300 μm and a weight of 300 g m^{-2}. The printer used was a Dimatix 2831 (Fujifilm, USA) ink-jet material printer using 10 pL cartridges. The printing was performed at ambient room temperature and humidity with the printer substrate plate set to a temperature of 30 °C. The ink used was Silverjet DGP-40LT-15C nanoparticle silver ink manufactured by Advanced Nano Products (ANP) (South Korea) with a solid content of about 40–45 wt% silver and a viscosity of 16 cP. Nanoparticle inks generally have to be sintered after printing in order to achieve high conductance, and therefore the tracks were heat treated in a convection oven at 120 °C for 20 min. Electrical sintering was performed on some tracks on the circuit board to further lower the resistance [28, 29].

The experiments were divided into two different parts to evaluate the utilization of standard components on paper substrate. The mounting of SMD components and manufacturing of VIAs was performed first so as to evaluate the resulting contact resistances. After this, an Arduino circuit board was printed, based on a slightly modified Lilypad Simple, using the free to use official CAD layout file.

A set of test patterns consisting of two 7 mm long and 1 mm wide lines with a 1 mm gap in-between was printed. To evaluate the contact resistance between the components and the printed tracks SMD 0 Ω resistors of size 1206 (3.2 mm × 1.6 mm) were mounted across this gap using anisotropic conductive tape, isotropic conductive tape, silver epoxy glue and solder. The samples mounted with silver epoxy were heated in a convection oven at 90 °C for 20 min to harden the glue.

The properties of the conductive adhesives used are summarized in table 1. The resistance values given are as specified by the manufacturer. The anisotropic tape is filled using silver coated particles to make a conductive contact. They are spread out so that there is no contact in-between them in the plane but only between the substrate and the component when the tape is compressed. The bonding pressure is specified to be 0.03–0.10 MPa by the manufacturer and the tape thickness is 50 μm.

For the soldering test, solder paste and solder wire containing 60% Pb and 40% Sn were used. A special soldering iron was used, which had two tips with adjustable distance in the shape of tweezers. To perform the soldering, the iron was set to a temperature of 200 °C, the tips were placed on each side of the component and the paste or wire was applied at the metallic contacts where it was melted and attached to the contact and the silver ink. In this way the tips never touched the very sensitive silver ink and the components were successfully soldered after some adjustment to the technique.

Figure 1 shows the four different component mounting techniques: conductive isotropic tape, conductive anisotropic tape, silver epoxy and solder.

The manufacture of VIAs was performed by laminating two paper substrates with printed tracks back to back. A hole was made through both pieces of paper using a drill tool and a

Table 1. The properties of the conductive adhesives used.

Manufacturer	Adhesive description	Specified resistance
Chemtronics, CW2400	Conductive silver epoxy glue	<0.001 Ω cm
3M, Nr. 9705	Anisotropic (*z*-direction) conductive particle tape	<0.3 Ω contact resistance
3M, Nr. 9713	Isotropic conductive fiber tape	0.5–2.5 Ω contact resistance

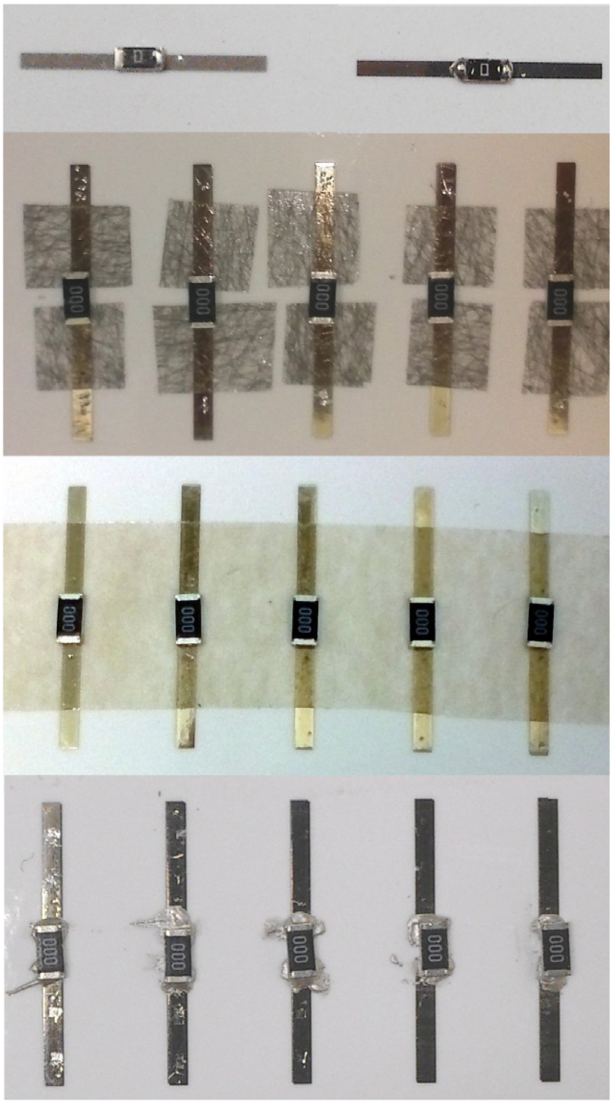

Figure 1. Contact resistance test samples consisting of 0 Ω resistors mounted across a gap between printed silver lines. From left to right: isotropic conductive tape, anisotropic conductive tape, silver epoxy glue and solder.

0.6 mm diameter copper VIA rivet was inserted and crimped using a hand press tool (Bungard, Germany). Such a crimped VIA rivet is shown in figure 2. It was found that after inserting the rivet it was necessary to cover both sides with silver epoxy to ensure a good electrical contact and mechanical stability.

The resistance was measured by means of a Keithley 2400 source meter using the four-wire technique and the resistance of the silver tracks was subtracted in order to obtain only the resistance added by both contacts to the component, which was then divided by two to obtain the resistance for one contact point. An average resistance value for each method was obtained from measurements on ten resistors mounted with each type of conductive adhesive and solder and ten VIAs from the circuit boards. In addition, the standard deviation was calculated.

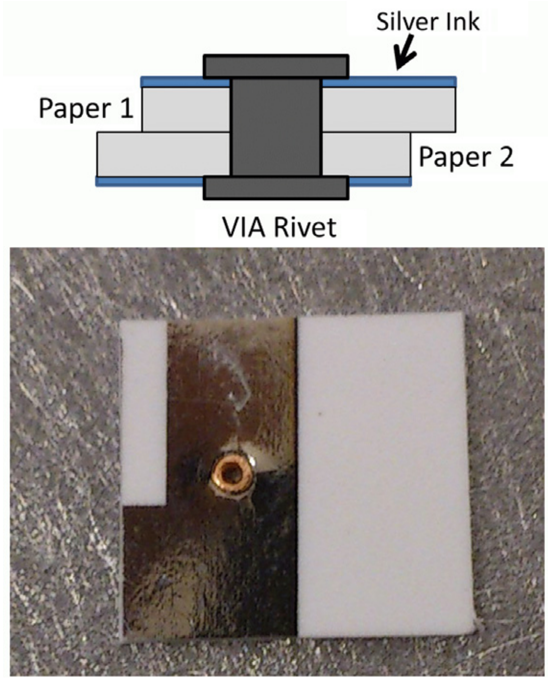

Figure 2. A VIA copper rivet mounted through two layers of paper contacting the silver conductors on both sides.

The bond strength of the tapes and glues between the 1206 SMD resistors and the substrate was tested by pulling the resistors straight up while measuring the force necessary to remove them from the substrate.

Scanning electron microscopy (SEM) was used to characterize the interfaces between the component and the substrate on the tape and glue samples, which are the most unusual, and were expected to give the most information from such investigation. The samples were embedded in plastic casting and polished. The samples were positioned along the silver track so that the end of the component where one of the metal contacts was situated was examined.

Differential scanning calorimetry (DSC) measurements were performed on the silver ink using a DSC 822e from Metler Toledo. 10 μl of silver nanoparticle ink was placed in a 40 μl aluminum crucible; the lid was pierced several times before sealing. The measurement was performed from 25 °C to 300 °C at a heating rate of 5 °C min^{-1}. As reaction gas,

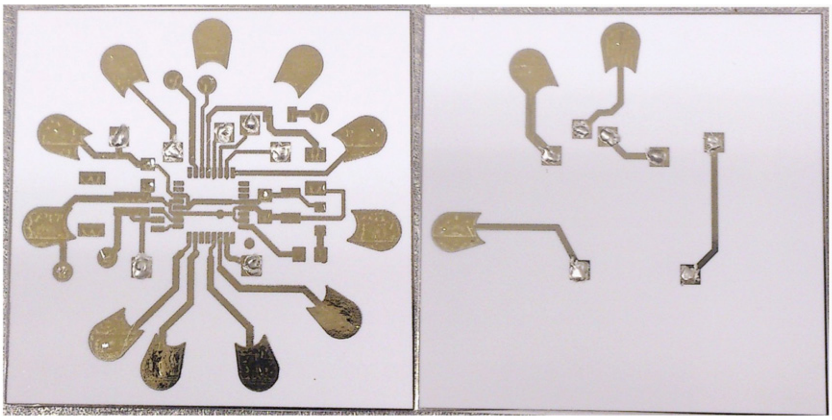

Figure 3. Both sides of a double sided paper circuit board with VIAs visible at the square pads, where some silver epoxy covers the VIA rivets.

50 ml min^{-1} of air was used (inlet temperature: 20 °C, relative humidity: 49%).

As a demonstration, a test circuit pattern consisting of a slightly modified Arduino Lilypad Simple was printed using two layers of ink. The Lilypad Simple double sided circuit board design was modified by removing and shifting some VIAs to clear the area beneath the microcontroller so as to simplify the assembly process. Some SMD components were changed to larger package sizes and the external crystal was removed to simplify the circuit; some tracks were also widened to lower the track resistance. The printed and assembled board is shown in figure 3. The top and bottom sides were cut out and mounted back to back using double sided tape before the VIAs were manufactured.

The main component of the Arduino Lilypad is the Atmel Atmega 328p microcontroller, which is a 7 mm × 7 mm sized 32 pin thin quad flat package (TQFP). Additional components were four capacitors, two resistors and one LED.

The microcontroller was mounted using anisotropic tape, due to the small pin pitch, while the other components were mounted using silver epoxy.

After mounting the components an Arduino boot loader was flashed into the microcontroller using an Atmel AVRISP mkII programmer and the Arduino IDE software.

3. Results

The contact resistances achieved for one contact point using the conductive adhesives, solder and VIA rivets are summed up in table 2 together with the standard deviation. The lowest resistance is achieved with the silver epoxy. The anisotropic tape and solder gave similar, but higher, resistances. The isotropic conductive tape gave an even higher resistance and, in addition, a much larger standard deviation.

The measured pull off strength together with the standard deviation is shown in table 3, where it can be noted that the solder gives the strongest bond between the component and the silver track.

The sheet resistance of the printed silver tracks was measured to be 2.4 Ω/Sq after oven sintering and could be further lowered to 0.1 Ω/Sq with electrical sintering.

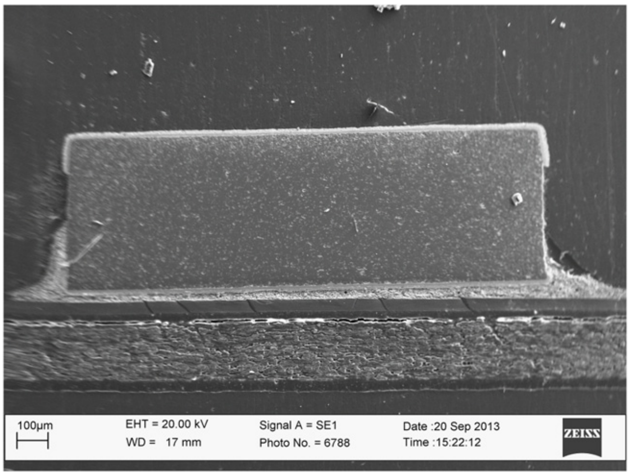

Figure 4. SEM micrograph showing a cross sectional overview of the resistor, silver epoxy and paper substrate. The secondary electron mode is used.

Table 2. Resistance of the mounted 1206 sized SMD components.

Mounting method	Resistance (Ω)
Silver epoxy	0.4 ± 0.15
Anisotropic tape	1.4 ± 0.45
Isotropic tape	15 ± 11
Solder	1.5 ± 0.3
VIA rivet	1.45 ± 0.61

The pictures from the SEM characterization are shown in increasing magnification for the silver epoxy in figures 4–6, for the isotropic tape in figures 7 and 8 and for the anisotropic tape in figures 9 and 10.

When examining figures 4 and 5, it can be seen that the epoxy glue is filling the space between the component and the silver track without large voids. It is also going up the sides of the component, thereby securing it more to the substrate. The thickness of the layer varies from 20 to 70 μm. The photo paper substrate can be seen to contain an ink absorbing top coating that is 50 μm thick, a bottom coating of the order of

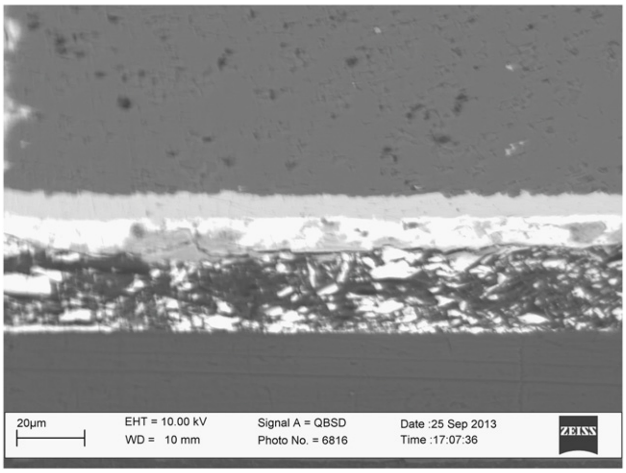

Figure 5. SEM micrograph showing a cross sectional magnification of the resistor, top, metal contact, silver epoxy, silver ink and top coating on the paper. The backscatter mode is used, so heavy elements appear brighter.

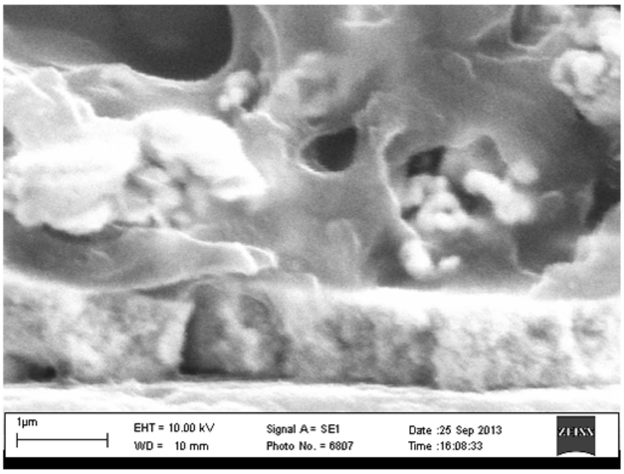

Figure 6. SEM micrograph showing a cross sectional magnification of the silver epoxy that can be seen to contain voids and pores in the μm range. The layer of printed silver ink is visible at the bottom and is estimated to have a thickness of about 700 nm.

Table 3. Pull off strength of 1206 sized SMD components.

Manufacturer	Pull off strength (N)
Silver epoxy, CW2400	7.2 ± 2.1
Anisotropic tape, 9705	4.0 ± 0.4
Isotropic tape, 9713	2.0 ± 0.3
Solder	23.0 ± 1.3

10 μm followed by the actual wood fiber containing paper substrate and a back coating of the order of 25 μm.

Figure 5 is acquired using a backscatter mode, in which the heavier elements show up more brightly, thus the metallic content is more visible. It can be seen that the silver epoxy is filled with silver particles in the form of flakes in the μm scale that are mixed with adhesive filler in an approximately 50:50 ratio. The printed silver ink layer is barely visible at the interface between the glue and the top coating.

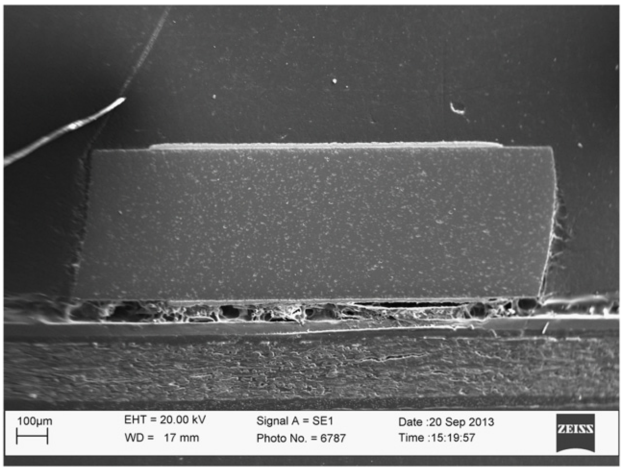

Figure 7. SEM micrograph showing a cross sectional overview of the resistor, isotropic tape and paper substrate. The secondary electron mode is used.

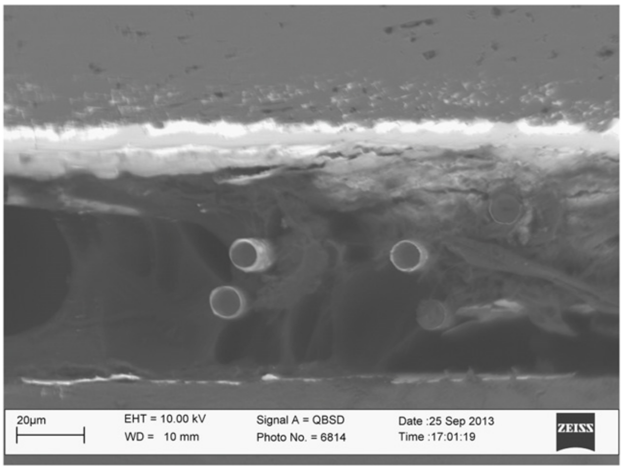

Figure 8. SEM micrograph showing a cross sectional magnification of the resistor, top, metal contact, isotropic tape, silver ink and top coating on the paper. The conductive fibers can be seen together with adhesive binder material. The backscatter mode is used, so heavy elements appear brighter.

In figure 6 a higher magnification picture is shown and the printed silver ink layer is visible at the bottom with a thickness of about 700 nm. The crack and slight delamination of the silver ink, visible to the left of the picture, are from the polishing. On top of the ink, the silver epoxy can be seen to contain voids and pores within the μm range.

Figure 7 shows an overview picture of the resistor mounted with isotropic tape, which contains conductive fibers. The tape can be seen to contain voids in which no conductive fibers or adhesive filler are visible. A small delamination is seen between the component and the tape, which is most probably a result of the polishing procedure. In figure 8, a magnified part of the tape and contact is shown in backscatter mode. Here, five of the conductive fibers have been cut and their cross sections are visible, showing their diameter to be about 10 μm. The printed silver ink is visible at the bottom on top of the paper coating.

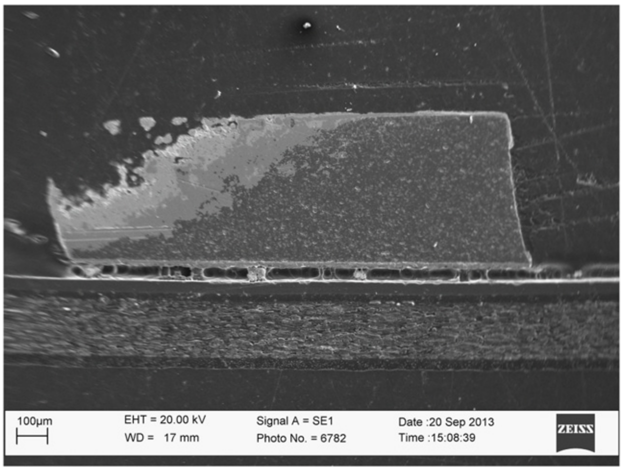

Figure 9. SEM micrograph showing a cross sectional overview of the resistor, anisotropic tape and paper substrate. The secondary electron mode is used.

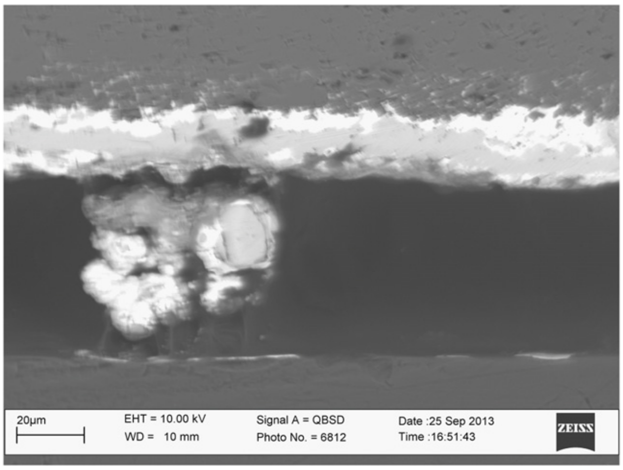

Figure 10. SEM micrograph showing a cross sectional magnification of the resistor, top, metal contact, anisotropic tape, silver ink and top coating on the paper. A conductive particle can be seen. The backscatter mode is used, so heavy elements appear brighter.

In figure 9 an overview picture is shown of the resistor mounted with anisotropic tape, which contains conductive particles. It can be seen that there are fairly few particles; the density is estimated to be about 30 particles per mm^2. Adhesive filler is also visible, but it appears to be less than for the isotropic tape shown in figure 7.

A magnification of one of the conductive particles is shown in figure 10, where the diameter is estimated to be about 60 μm. It is evident that it has no contact with the printed silver ink and what is most probably adhesive filler is visible beneath the particle going down to the silver ink layer. The delamination could, in this case, be caused by the polishing.

Figure 11 shows the DSC curve of the silver nanoparticle ink. In the figure, there are two oxidation peaks to be seen, which probably correspond to the sintering of the particles. The peak temperature (T_c) for the two peaks are 210 °C and 250 °C respectively. It is well known that the particles have a high surface energy and that they attempt to reduce their

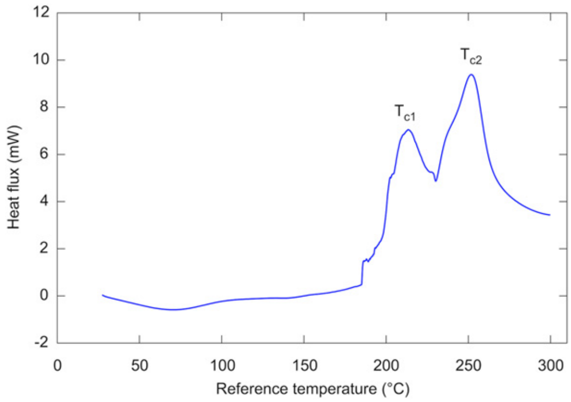

Figure 11. DSC curve of the silver nanoparticle ink versus reference temperature, exotherm reaction upwards. Measurement performed using an aluminum crucible. The sintering of the silver nanoparticles probably occurs at about 210 °C where the first exothermic peak can be seen in the curve.

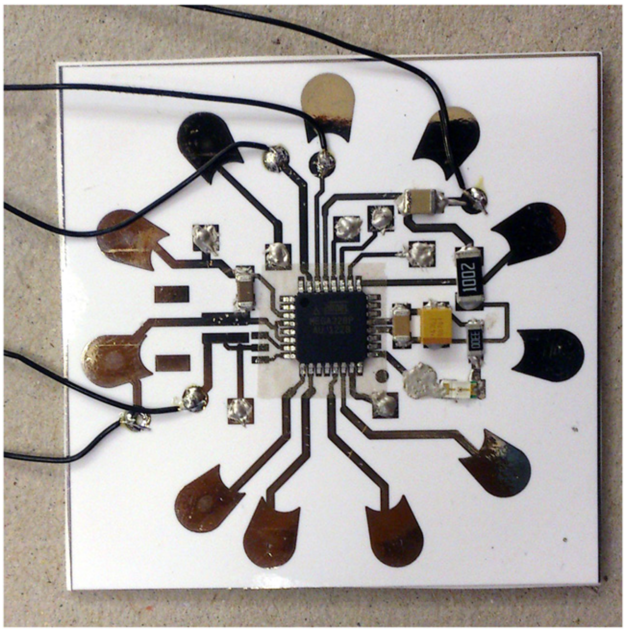

Figure 12. Finished and fully functioning Arduino circuit board.

surface area by aggregation [30], and this is seen in the DSC curve as an exothermic feature. Depending on the type of filling polymer this can be conducted in more than one step [31, 32].

Figure 12 shows the completed Arduino board with wires attached to connect it to a computer. It is fully functional and runs at 8 MHz speed on the internal oscillator.

4. Discussion

Hybrid printed electronics has the potential to be one of the first commercial methods to introduce printed electronics to the market on a larger scale. This is because the use of standard components means that the cost for components will be fairly low, especially in simpler circuits with a low component density. There is also the possibility of using advanced circuits, such as microcontrollers, that, at present, do not have equivalence among printed components. A flexible, cheap substrate such as paper with printed tracks reduces the cost. The printed circuit could also be manufactured directly onto a package, poster or other paper product thereby using an already existing substrate.

When designing printed electronics containing circuits that operate at frequencies in the MHz range it is of interest to consider what impact the increased resistance of the printed tracks can have on the operation. Compared to tracks on standard circuit boards, the increased track and connection impedance can cause additional radiated electromagnetic interference (EMI). In particular, the increased impedance between decoupling capacitors and microcontroller supply voltage pins will lead to a significant change in the EMI emission of the circuit. However, the increased impedance could also be used to create a low pass filter in order to gain additional control on the signal tracks.

The combination of standard components with large scale production of roll-to-roll printing, or other high volume manufacturing, involves some obstacles, some of which have been addressed in this paper. First of all, the mounting method of choice in electronics production is, naturally, soldering. For paper substrates with printed tracks this poses a problem. First of all, the soldering process may not be compatible, or at least it is not optimized, for such substrates. Also, the regular soldering process, in which soldering paste is applied to boards that pass through pick and place machines and end up in a soldering oven, is far from the desired roll-to-roll processes associated with printed electronics research and development.

The soldering tests performed here indicate that it is possible to use soldering to mount components on paper substrates. In this case a different technique from the standard one was used, where a tweezer shaped soldering iron heated up the sides of the component and did not touch the silver ink layer, which is sensitive to such high temperatures. Soldering resulted in by far the most mechanically stable bonding to the silver track of the tested methods, with a pull off strength of 23 N compared to the second best result for silver epoxy which had 7.2 N.

Another option is to use conductive glue and tape, some of which have been investigated in this work. Here, it is possible to imagine the application of such adhesive in a roll-to-roll process and, in particular, the application of tape at higher speed is a viable option.

Each of the conductive adhesives has some drawbacks and benefits.

The conductive silver epoxy provides a mechanically stable contact, although not as good as solder, and has the lowest resistance in this survey. When examining the interface with SEM it can be seen that the epoxy is deposited in a layer without any large voids and is in contact with the whole contact area of the component and the silver ink. The volume of conductive silver particles is seen to be approximately 50% when examining the backscatter image in figure 5.

When examining at larger magnification, some smaller voids and pores are visible.

The printed silver ink layer is $\sim$700 nm, as is shown in figure 6. The ink layer appears to be homogeneous and does not have any large voids.

One drawback is that such glue can be difficult to apply to the substrate and there is the risk of a short circuit between conductive lines.

Anisotropic tape can be applied across several conductive tracks without a short circuit because the tape is only conductive in the z-direction. This is a major benefit, especially when mounting components with a small pitch, such as the microcontroller used for the Arduino board. In this case the use of glue would increase the risk of a short circuit. As seen in the SEM pictures in figures 9 and 10, there are relatively few particles making up the actual conductive contact, estimated to be 30 particles per mm^2. Because of this, the tape is vulnerable to delamination; a gap of only some μm means that the electrical contact is lost and with a low particle density the resistance quickly increases and electrical contact is easily lost altogether.

The bond is not as good as with solder or glue, only 4 N, and the stability over time is something that also has to be considered.

Isotropic tape, like silver epoxy, has the drawback that it could short circuit tracks. This, together with the relatively large contact resistance and low bond strength of 2 N, makes the use of such tape limited. When studying the SEM pictures in figures 7 and 8 the conductive fibers are visible. It can be seen that there are large voids without any fibers or adhesive, although a small delamination could have occurred because of the polishing process. The fibers must be connected with both the contact of the component and the silver ink. Considering the SEM pictures, it is seen that the fibers are not directly pressed against the contact of the component and the silver ink. It is likely that often a smaller number of the fibers make the conductive contact. This could explain the high resistance obtained with this tape. However, one benefit is that it is not as sensitive to minor delamination as the anisotropic tape.

Considering the DSC measurement shown in figure 11, it can be seen that, in order to obtain complete sintering of the ink, it is probable that a temperature of at least 210 °C is necessary. This has not occurred when heating in the oven at 120 °C, and for this a much higher temperature is required. The additional electrical sintering performed lowers the resistance compared to the oven treated samples, and in this case the local temperature in the ink can be momentarily higher than the 120 °C achieved in the oven without damaging the paper substrate.

The flexibility of the whole paper circuit board will, in the main, be limited by the size of the components as well as the printed tracks and paper substrate. The tapes will be sufficiently flexible to be bent but the anisotropic tape can start to delaminate and increase the contact resistance.

The resistance of the printed tracks and contacts will add up to the total resistance of the hybrid printed paper circuit. When adding the contact resistances of the components and VIAs this can be considerably higher than for a regular copper circuit board with soldered components. It is therefore of importance to attempt to minimize all sources of resistance while, at the same time, considering manufacturing concerns and cost.

The Arduino demonstration circuit shows that it is possible to manufacture double sided circuit boards with an advanced functionality. The most difficult component to mount is the microcontroller which has a large number of pins with a small pitch. Anisotropic conductive adhesive is the most promising way to mount such components.

The manufactured Arduino circuit is a fully working board. It is possible to attach Arduino extension boards, called 'shields', to add functionalities such as sensors, or communicate with Wi-Fi, Bluetooth or RFID. These could in many cases also be manufactured on a paper substrate to form printable units that can be connected together, depending on the application.

5. Conclusion

Several conductive adhesives and solder have been evaluated for mounting SMD components on paper circuit boards. The lowest resistance was achieved with silver epoxy, which gives a resistance of 0.5 Ω for each contact and provides a mechanically stable contact. The anisotropic tape gives a higher resistance of 1.4 Ω but has the added benefit of being possible to apply across conductive tracks without the risk of a short circuit. Soldering is a promising technique because it gives stable contacts and would be an interesting method for mass production.

It has been shown that it is possible to use a paper substrate with printed ink-jet tracks as a double sided circuit board for a circuit with advanced functionality.

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