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PROYECTO FIN DE CARRERA

SCREEN PRINTING PARA DISPOSITIVOS ELECTRONICOS

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Quiero mostrar mi mas grato agradecimiento a las personas que siempre han estado apoyandome durante este largo proceso que es graduarse de una ingenieria como telecomunicaciones. Gracias a mi madre y mi hermana Almu por siempre estar ahi, a mis amigos por su apoyo incondicional, y a mi novia Cris que me “supervisaba” mis progresos en el proyecto y siempre me anima. Gracias a todos.

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1. INTRODUCTION

1.1 General information.

During the recent years printing techniques have been increasingly developed in several fields among them electrical and electronics are found. The advantages of using printing over conventional technologies are a reduced number of processing operations, the processes are additive so waste is minimised, the relative cost of equipment and the speed of production. Due to all these facts the interests to comprehend and improve the printing technology is paramount.

The ultimate objective of this technology is to make many different components, such as batteries, displays, sensors, etc., at the same time and out of the same material and techniques, hence saving cost and improving reliability. The fundamentals are the creation of printed circuitry and electronic components using a single continuous process. Being expected the replacement of the traditional Silicon chip by the new emerging printed electronics.

Although the volume and performance of Silicon-based components is on the increase, development costs remain high due to the interconnects and multiple production processes. By the time the printed electronics industry is mature, the costs of manufacturing will be substantially lower and the cost of the final product will only be a fraction of that of today’s semiconductors.

Another benefit offered by printing methods that should be highlighted is the possibility of using a wide range of substrates such as plastic, paper, film and foils.

The principle elements driving market demand for next-generation printed applications include new laws and mandates demanding increased product security and traceability, the growing importance of environment-friendly disposable products and packaging, and the desire to decrease prices for end-consumers.

In the wide range of the printing methods are included lithography, flexography, engraving, screen printing, etc. This document will be focused on screen printing technology showing how this process can provide an interesting approaching to the printed electronics field.

Many of the printed electronics' components are almost entirely screen-printed, so it can be appreciated the importance and scope associated to the development of this printing process.

Conferences and reports on printed electronics usually obsess about just two types—Thin Film Transistor Circuits (TFTCs) and Organic Light Emitting Diodes (OLEDs), which, despite their name, are glowing, moving-color displays—neither of which is available yet on low-cost packaging material. Both will be extremely important one day, but the current status of its investigation and development shows customers have to wait before its availability in the market.

The current performances offered by organic printed electronics can not be compared to the Silicon chips yet, but there are several fields where Silicon technology can not be applied due to its size and rigidity. For instance, smart label industry demands small area devices turning to organic devices as the best choice. Moreover applications where the flexibility in the final product, such as flexible displays, is key turn to printed electronics as a solution.

Many printed electronics commercial applications are already in use, achieving an acceptable inclusion in the current market. Some of them are listed in the next section of this report, in order to show some of their characteristics and their several uses.

2. SCREENPRINTED APPLICATIONS IN THE CURRENT MARKET

2.1 Printed batteries.

There are several companies researching and manufacturing thin and flexible batteries, including Cymbet Corp, Elk River, MN; Infinite Power Solutions, Denver, CO; Intellikraft Ltd, Oxfordshire, U.K; NTK Technologies, Inc, Irvine, CA; Power Paper, Israel; Stone Battery, Taipei, Taiwan; Toshiba Japan, Tokyo; and VoltaFlex Corp., Menlo Park, CA.

Some of these companies only wish to license technology, but some will do small runs as well. Others manufacture in volume. The performance of these batteries varies widely between poor/cheap and the opposite to reflect the wide variety of emerging market needs.

As an alternative, companies such as Lowell, MA's Konarka Technologies and others are trialing printed photovoltaics on low-cost, flexible packaging film.

The current thin flexible battery technology allows us to manufacture either microscopic or macroscopic rechargeable energy sources onto almost any substrate or even built it directly into the final application to provide more robust devices. This integration into the package or IC or LCD can offer amazing advantages like no battery contacts in the system because the battery can be recharged by using inductive or RF means, no need of external battery, reduction in the weight and size of the final system due to the design of an application specific battery and so on.

The power sources are designed by using a high quality and innovative manufacturing process to generate flat and flexible devices. It is possible to perform any shape or size from a few square microns to tens of square centimeters, and from 5 to 25 μm thick.

Some remarkable characteristics of these power sources are:

- Virtually unlimited rechargeable capability exceeding in some cases the 60000 full depth discharge cycles.
- No need of metal case due to the development of lithium free manufacturing processes.
- Low-cost and high volume runs by using a conventional screen printing process.
- Environmentally friendly energy cells according to the international standards which are completely safe due to the lack of heavy metals unlike conventional batteries. They are also biodegradable, non-toxic, non-corrosive, can't explode, burn or overheat and are disposable.
- The use of ultra thin and flexible technologies allows the resistance to mechanical crushing and bending.

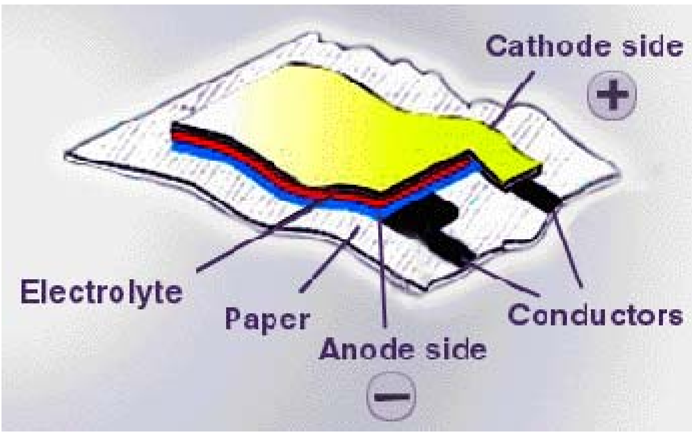

Figure 1. Flexible battery structure

The application fields for the thin batteries are uncountable and its introduction in the market a success. They have been incorporated in RFID tags in order to provide active capabilities in miniature package sizes for increased operating ranges, data storage and transfer, long life performance and resistance to stressing environmental conditions. The key idea is that including the battery in the RFID tag will provide autonomy to the tags due to the improvement in the reception area despite of the losses in terms of energy efficiency and absorption. The tasks carry out by this sort of systems are tracking, monitoring, identification, location, security and authentication.

The thin, flexible batteries have been also introduced in the smart cards market achieving increased functionality and providing a long life performance. Some of the application fields of this sort of cards are identification, entitlement, security, government, health, ID, wireless.

Some microelectronics/semiconductors are able to incorporate the battery powers directly into the electronic circuits or devices to provide distributed power "Direct-on-board" rather than a discrete component. Due to the high battery life cycle it can stay in the system during all its lifetime. The thin batteries can be found in applications such as SRAM, Clock, Microcontroller, IC's, Nanocircuitry, etc.

In the field of the medical implants, these batteries are offering a huge breakthrough due to their ability to combine the highest density energy package with virtually limitless lifetime performance in a safe, solid-state package that can be implanted for life and recharged by using RF or inductive means to avoid the intrusion on the patient's body time and time again. The battery powers are integrated in devices such as implants, monitoring, diagnostic, medication, simulation, TENS (Transcutaneous Electrical Nerve Stimulation), MEMS (Micro-Electro-Mechanical System), optical switching and hearing.

In addition to the last application fields, thin batteries can be found in several more fields such us military applications like smart munitions, fusing, sensing, tracking, monitoring, identification, location, security, authentication, guidance and reconnaissance. Aerospace applications also employ these power sources in satellites and sensors.

2.2 RFID tags and antennas.

Radio frequency identification (RFID) tags is a system of auto identification that uses a wireless communication to transmit several data to a receiver. Technical limitations and cost are the barrier to overcome in order to offer a widespread adoption. It could be used one day to track everything from garments to food or moving transports.

These wireless systems offers an alternative to markets where UPC (Universal Product Code) bar codes can't be utilised in optimal conditions. The gradual replacement of the bar codes in certain products are due to the advantages obtain from RFID in matters like automatic identification of objects wirelessly, without manual scanning or requiring line-of-sight.

Some of the benefits of introducing RFID tagging in a comparison to the bar codes are:

- Several RFID tags can be read simultaneously.
- RFID tags can be read through walls and other obstructions.
  They are not affected by dirty, grease, paint, or other substances that might obscure their presence, that is to say, they can resist and work under unfriendly environment.
- RFID tags can maintain a significant amount of data about the item they identify.
- Certain kind of RFID tags can be erased and reused thereby changing the item information.
- RFID tags can communicate to other devices, i.e., a packaged meal communicating with a microwave oven to set up cooking directions.

The RFID system is composed by three basic elements which interact to carry out the identification process, their description is given in next sections.

2.2.1 The RFID tag or transponder.

This component is placed at the product or asset to be identified. It comprises a piece of integrated circuitry, a small memory and a RF antenna. If a power source is introduced in the circuitry then the system is known as active tag, otherwise it is called passive tag.

Designs can work at different frequencies where the central frequencies of common uses are found around 125 KHz, 13.56 MHz, 900 MHz and 2.45 GHz.

The data capacity of the memory will vary from a maximum of 512 bytes for passive tags to 32 Kbytes for active tags. The memory blocks can be classified into three types according to the read/write process. The different memory blocks to be used are a read only version (RO), a write once read many times version (WORM) and a reads/write version (RW).

The RF antenna can be obtained by screen-printing methods, offering a better choice to an etched copper antenna. New conductive inks are being developed like polymer thick film (PTF), which can be printed over different types of films and substrates (including Polyester, Polycarbonate, FR4, PVC and ABS), decreasing the cost of the antenna from as much as 12¢ down to 1¢ or even lower in a near future. The type of antenna used can be either simple dipoles for 915 MHz frequency operation or more complex coiled shapes for 13.56 MHz systems. Other good features of the PTF antennas are its environmental-friendly additive process, the possibility of high volume production and outstanding electrical and mechanical performance in all ISO tests.

2.2.2 The RFID Reader/writer.

The reader/interrogators can differ quite considerably in complexity, depending upon the type of tags being supported and the functions to be fulfilled. But the overall function is to provide the means of communicating with the tags and facilitating data transfer.

It is composed by some circuitry and an antenna. When using a passive tag the reader generates a RF field that energises the transponder to start a transmission of data. In the case of active tags, the reader's RF field it is employed to turn on the tag, in order, to start up a transmission.

The identification process is the beginning of a communication where the reader recognises the transponder and analyses the transponder's data. When multiple tags want to be read the identification process takes an appreciable period of time and it's not instantaneously. Once the reader selects one tag from the RF field, it proceeds to the acquisition of data and decodification. Algorithms can be employed to check if the received signal is a repeat transmission and may force the tag to cease transmitting data. This kind of interrogation is often known as "Hands Down Polling" and its purpose consists of sorting out the problem of reading several tags in a short time interval.

In order to improve the process of batch reading, several techniques have been developed, among them it can be found the use of multiple readers, multiplexed into one interrogator, but with associated increased in costs.

The antenna design and tuning is an issue to be carried out depending on the specific application to be manufactured, hence it needs to be customised to the particular application providing an optimised reception and transmission.

2.2.3 The host system.

The host system is normally a line of business software application: typically an enterprise resource planning (ERP) system, warehouse management system (WMS), proof of delivery (POD) or proof of collection (POC) system.

RFID tags are simply an automated way to provide input data to the host system, in general speaking its purpose is similar to the standard barcodes. Nonetheless, RFID offers the chance of dynamical update of the data held in the tag.

In all cases, the host system will need specific software to integrate the data provided by the RFID reader/writer.

2.2.4 How does RFID work.

In the case of passive tags, the tag is powered up by the RF field from the reader and transmits its ID to the reader. Other data transmission depends on the protocol between reader and tag.

In the case of active tags, the tag is energised internally by a battery. The tag can be turned on by a suitable RF field from the reader. Then the tag communicates with the reader using pre-determined protocols. After a period of inactivity the tag can turn itself off if allowed by the programming.

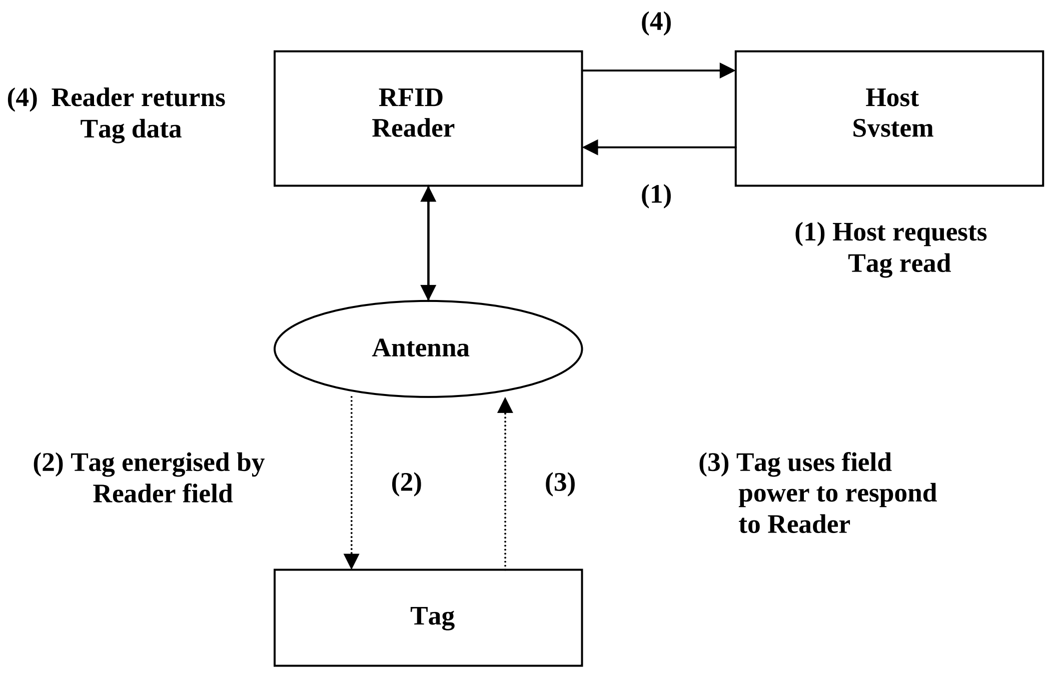

Figure 2. General structure of a RFID system.

2.3 Displays.

In recent times the visual displays field has been pointed as a fruitful market, driving big electronic companies and university research teams to invest in modern technologies, in order to achieve a superb quality in the final products.

Displays are part of many everyday items, thus the interest to improve the performance and characteristics of such common articles. People's demand vary from a lightweight, flat, large and high-resolution TV set to flat and low-power-consumption computer monitors.

Several technologies have their niche market, where the current revenue is worth in tens of billion $ a year and the expectations are to double the incomes in the next 5 years. Among the most important present technologies for displays manufacturing can be named Liquid Crystal Display (LCD), plasma displays, electroluminescent displays (ELD) and field emission displays (FED).

According to the manufacturing process of the last quoted display technologies, only the last two technologies can be implemented almost totally by using screen printing. In the case of electroluminescent displays, two different procedures can be distinguished being thick film ELD and thin film ELD. Only the former is manufactured by employing screen printing technology although the achieved performance in terms of lifetime (10000 hr) and resolution is far from the latter's behaviour (40000 hr lifetime).

Finally let's highlight the major technology in flat printed displays which offer some favourable short-term expectations, and that is field emission displays. Its fundamentals are similar to cathode ray tubes (CRTs) in that it lights screen phosphors with electron beams. Although FEDs shows a significant difference in its internal structure in comparison to CRTs. Instead of being composed by just one electron beam scanning the whole screen, FEDs are composed by an array of pointed microtips (up to 500 million of microtips) that direct electrons to each pixel of the display, allowing the reduction in size of the system to few millimetres in depth.

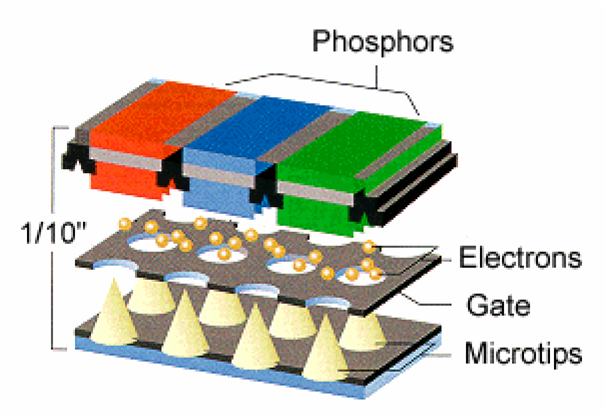

Figure 3. Field Emission Display layout.

Initially several companies were taking part in the development of FEDs, but they pulled out after finding technical difficulties too hard to overcome. Companies like Motorola, Sony and Candescent have quitted the market leaving Pixtech as almost the only manufacturer and developer of such technology.

The benefit of FEDs over the rest of technologies is that it gathers together most of the advantages of ELDs, CRTs and LCDs. For instance, just to mention few of them like low cost, wide viewing angle, rugged, sharpness, low power, high resolution, thin and lightweight.

A new invention for displays manufacturing is the electronic ink (proprietary material of E Ink) which consists of millions of microcapsules. The basis of this technology is a breakthrough developed by combining fundamentals in physics, chemistry and electronics. A microcapsule is basically formed by two pigments of different colours and charges (white positive charged pigments and black negative charged pigments) and a clear fluid that contains the pigments.

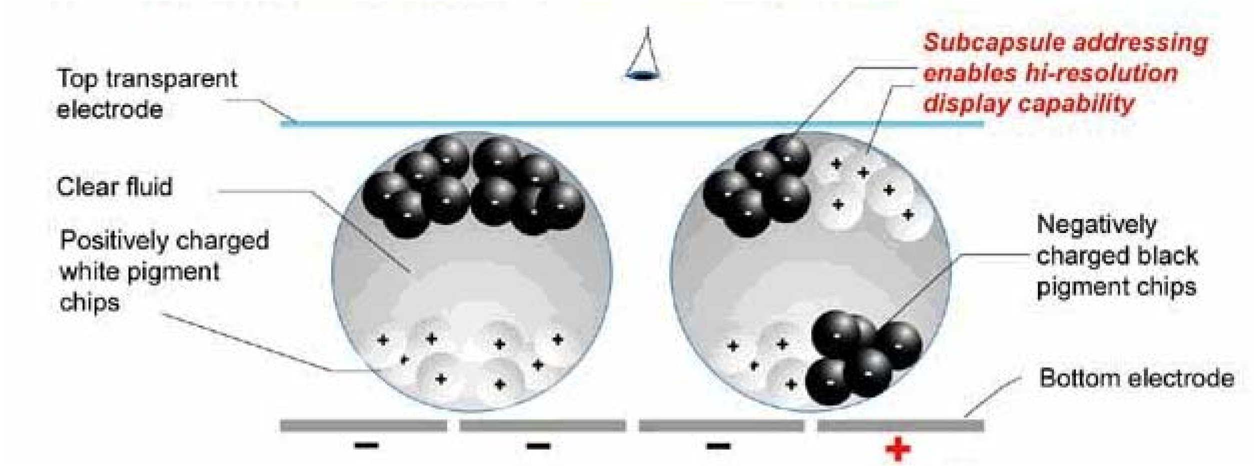

Figure 4. Electronic paper microcapsule structure.

To form an E Ink electronic display, the ink is printed onto a sheet of plastic film that is laminated to a layer of circuitry. The circuitry forms a pattern of pixels that can then be controlled by a display driver. The printed method involved is screen printing and it allows the use of almost any material to be used as substrate like glass, plastic, fabric or even paper.

From a point of view of readability the electronic ink displays offer better contrast and reflectance than most LCDs and quite similar good conditions than printed paper (i.e. newspaper). Another advantage from electronic ink displays is the low power consumption as compared to LCDs or other newer emissive technologies such as OLED, FED or PDP. The reduction in power consumption implies a longer lifetime devices and a possible shrinkage in the batteries' size, hence lighter and smaller displays could be manufactured. The fact of low power consumption can be explained in two points, firstly, they are totally reflective requiring no backlight, and secondly, they have an image state "memory effect" for extended periods of time requiring no power between image states (This means that the pixels are biestable, so that the state of each pixel can be maintained without a continuous power supply action). In contrast, LCDs and newer emissive technologies require constant addressing, and hence power to maintain an image.

2.4 New modern technologies.

2.4.1 Organic light-emitting diodes.

This device is a thin-film light-emitting diode which emissive layer is composed by organic materials. It is basically formed by several layers such as a transparent anode, typically ITO (Indium tin oxide), a cathode, commonly aluminium or calcium, some internal layers that provides certain effect over the electron-hole injection and finally an internal organic layer called emissive layer which is the responsible of emission of light due to the recombination of carriers in its realm.

This technology is mainly focused on developing practical display devices competing with extended and successful technologies like LCD or plasma displays. The fabrication methods currently used are spin coating and physical vapour deposition (PVD), although new manufacturing processes are being introduced such as small molecules, SM-OLEDs (Small Molecules Organic Light-Emitting Diodes), and polymers, PLEDs (Polymer Light-Emitting Diodes). The former method is vacuum deposition oriented which makes the production processes costly and hardly flexible. The latter method although in a much more initial status of development offers a promising benefits due to the no-vacuum deposition usage and the possible application in its production of derived techniques from commercial printing procedures, focusing in inkjet printing and screen printing.

Screen printing, in particular, possesses qualities of great value for the fabrication process such as simplicity, affordability, speed, and adaptability. This technique may be applied to virtually any surface with precision.

The screen printing technology offers a great potential in the development of such a device with a very flexible and inexpensive way of production. The implications of being able to fabricate the OLEDs using a printing technology will be reflected in the final product price, cheaper than typical LCDs or plasma displays.

Unlike other displays which use back-light and unable of showing true black, OLED elements do not produce any light, which allows for a possible infinite contrast ratio. Moreover, the range of colours, view angle and brightness in OLEDs are superior to that offered by LCDs or plasma displays.

However this technology also has some technical issues to be overcome, being the most remarkable one the limited lifetime of the organic material. Especially the blue OLED elements have been lagged behind respect the expected lifetime of a common LCD panel. Several companies are currently researching this aspect and proposing solutions. Another issue is the organic OLED damages due to the intrusion of water inside the display.

OLED technology is making his way through the commercial environment distributing applications as diverse as head-up displays (HUD) in aircraft, displays inside high-end cars, mobile phone displays and even replacement for light bulbs. More futuristic uses include clothing that integrates flexible OLED screens in order to change its colour at the click of a button, or high definition virtual reality rooms where OLED screens cover every surface.

2.4.2 Thin Film Transistor Circuits.

A Thin Film Transistor Circuit (TFTC) is an specific type of field effect transistor made by deposition of thin layers which are a semiconducting active layer, a dielectric layer and metallic contacts. The remarkable layer in such transistors is the conductive layer which composition varies from thin film silicon to conductive plastics.

This technology can be implemented by using printed electronics procedures, being able to achieve the construction of large area devices such as smart shelves, electronic boards and so on.

The introduction of this technology in the printed electronics field focuses in providing an option to construct devices where the current silicon chips are almost always too expensive, or several components are needed, and the implementation in silicon becomes impractical. A printed TFTC would be able to add good characteristics to the devices in the sense of mechanical flexibility and lightweight.

When a TFTC fabrication out of semiconductor materials is to be implemented, there are several options offered. The selection process will depend on the final application performance to be targeted and the final product price. Hence, the principal parameters to take into account are cost and frequency. These parameters are directly proportional, that means that the higher the frequency of performance, the higher the cost of the device. In order to make a selection a relationship of compromise between the parameters needs to be reached.

Currently TFTCs are being improved in the implementation of high frequency applications where high speed data transfer is paramount. Particularly, it can be mentioned RFID tags.

The idea of improvement consists in modifying any or a combination of parameters involved in the frequency behaviour of the TFTCs, those parameters are following:

- Voltage.
- Carrier mobility.
- Channel length (Source to drain distance in a trasistor).

The possible solutions being approached and assessed currently comprise to improve the printing method to be able to reduce the channel size and to improve the construction materials to cause some effect over the mobility of the TFTCs´carriers.

3. SCREEN PRINTING TECHNOLOGY

3.1 General information.

Screen Printing is an ancient practice, used by different civilizations throughout thousands of years. Its concept is simple: a cut stencil is placed beneath a fine screen through which paint, ink or any paste is allowed to flow. The stancil´s holes allow ink through and onto the surface of the substrate placed directly below. This simple additive method is one of the least expensive methods for printing, but there are approximately ten to fifteen variations of the technology currently used, from basic stencil printing to intricate and complex methods of photoprinting.

Technically speaking, Screen Printing is not a new technique in the area of high-tech component manufacturing. There are many examples of its successful use at different levels of the production cycle.

As the experience in the matter evolved, the screen-printing machines were optimised in terms of reliability, stability and cost-effectiveness for high-volume and low-cost manufacturing applications.

Screen Printing is in fact an easy to manage, one-step process that has been successfully applied to the production of high volume, low cost devices such as RFID transponders. This is likely to become the preferred manufacturing method for UHF tags.

There are several basic advantages offered by this printing method that make the choice worth it. Those advantages are listed next:

- Stability and reliability.
- Cost-effectiveness.
- Low environmental impact.

- Ease of use.
- Flexibility in terms of the substrate materials.
- Easy and reliable Flip Chip assembly

Screen Printing is a “green” and user-friendly process. Unlike subtractive methods such as etching process, it does not involve the use of aggresive chemicals.

Another outstanding characteristics are the affordability of the equipment and the low costs to maintain it, as no extra investments are needed to meet enviromental regulations. To make a practical comparison, to maintain an etching line and treating waste material such as the residue of chemical baths is in fact a very expensive fixed cost per unit of the electronic component processed compared to a screenprinted process.

3.2 Screen printing components and processes.

The screen printing technology offers its simplicity as printing process as a main strong point, in comparison to other procedures more elaborate and complex, where lithography or gravure are included.

The principal of screen printing process is shown in Figure 5. In short, a screen holds the image whilst the ink or paste is held on the upper surface of the screen.

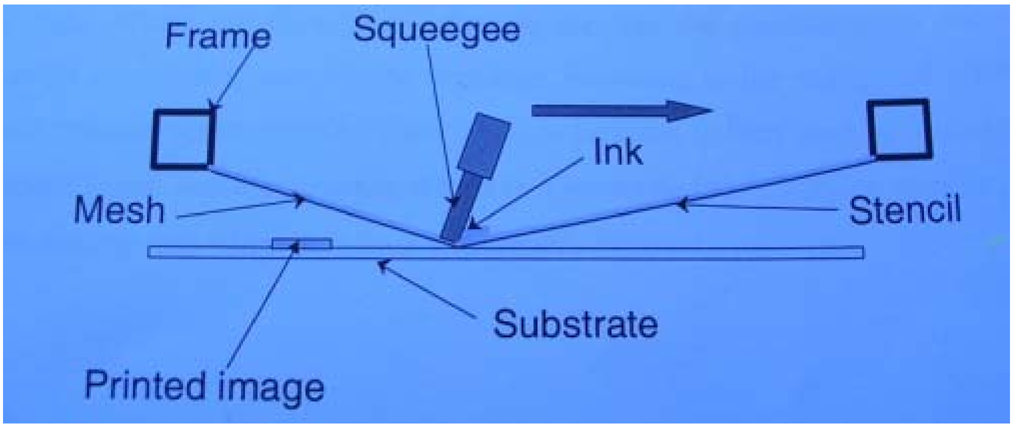

Figure 5. A schematic of the cross section of the screen printing process.

The passage of the squeegee over the screen pushes the ink or paste through the screen to the substrate. Essentially the description of the screen printing system may be dismantled into 4 distinctive components and they are listed next:

- Screen.
- Squeegee (rubber blade).
- Ink.
- Press.

3.2.1 The screen.

The screen plays an important role in the system, because it is the component which carries the image to be printed. The fabrication of the screen involves two separate processes, mesh stretching and mesh preparation which may be further divided into few sub processes.

Firstly, a section of mesh is cut and is tensioned on the frame. The mesh is then bonded to the frame and is held under tension while the adhesive between the mesh and the frame cures (a process that takes approximately 24 hours).

In order to produce the image on the screen, it is first coated with a photopolymeric material which is UV-light-sensitive and then dried. The drying process consists of a physical procedure to harden some areas of the material although it keeps those areas water-soluble.

Immediately afterwards, the film positive is then placed on the photoemulsion and exposed to high intensity UV light. Where the light goes through the film, the photoemulsion undergoes chemical crosslinking making the emulsion insoluble. In the unexposed areas, the stencil remains water-soluble.

Right after, water at high pressure is then used to wash out the unexposed areas and the screen is placed in a moderate temperature drying oven (50ºC) or placed before heating fans where it is finally hardened.

The aforementioned steps are shown in Figure 6, which illustrates the obtaining of the screen.

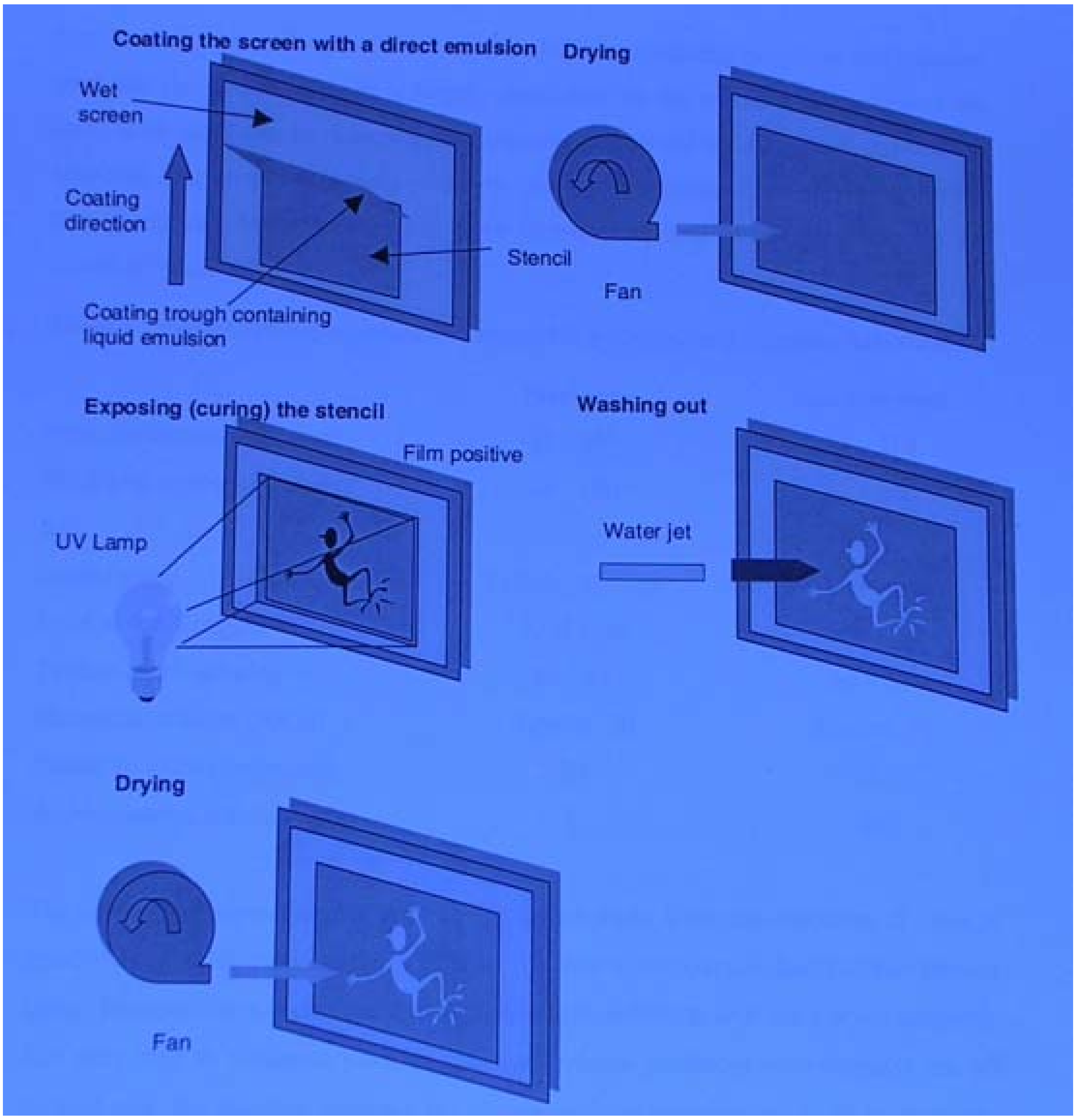

Figure 6. The stencil fabrication process.

When the stencil has dried, a screen is formed which can be split into three different parts:

- The mesh.
- The stencil.
- The frame.

Regarding to the mesh, the most extended forms of mesh for screen printing are stainless steel and polyester. In order to choose between those materials, the required tolerance and the cost are the main criteria to follow. The fabrication of both meshes are similar and it consists in weaving thin threads of material to obtain the fabric structure. Typical mesh characteristics are shown in table 1.

	POLYESTER	STAINLESS STEEL
Mesh thickness range(μm)	31 - 385	40 - 215
Mesh ruling range(threads/cm)	45 - 180	31 - 200
Mesh color	Yellow/Orange	Silver/grey
Load at 1% elongation	40N/cm	15N/cm
Typical mesh opening %	10 – 45	30 - 55
Maximum tension (N/cm)	Approx. 30	Approx. 50
Elastic limit (%elongation)	20	3
Approximate Cost ratio	1	10

Table 1. Typical mesh properties for comparable polyester and stainless steel mesh.

When a mesh is in use a tension is applied, so that it pulls the screen away from the substrate. If there is insufficient tensile force in the screen to overcome the viscous and surface tension forces between the screen/ink and substrate, then the substrate will not release properly. The only way to eliminate possible substrate release problems is to increase the off contact gap (distance between the screen and the substrate). However the increase of the off contact gap involves a downside, affecting on the distortion of the print.

If the size of the final print is crucial, then the off contact gap must be minimised. Although this option shows to be the most appropriate one, it has a considerate effect on the vertical component of tensile force which involves an increase in the mesh tension. Eventually, this mesh tension increase provokes a discrimination in the mesh selection, that is to say, it is recommended to use stainless steel meshes when a high mesh tension needs to be applied and use polyester meshes where accurate control of the print dimensions is not required.

The other benefit of stainless steel meshes is that they provide a great open area (percentage area through which ink may pass compared to the area of the threads). This allows a greater amount of ink to be transferred in every print, which can be relevant in many applications, for example in the production of PCBs where a low resistance track is required.

The drawback of stainless steel meshes are their high costs and delicateness. Being the latter responsible of the deformation of the screen while using them, due to their low percentage of elongation.

Polyester tends to be the choice in the graphic, POS, textile, and packaging industries whereas stainless steel tends to be the option in the electronic and specialised good industries where tolerances and overall frame sizes tend to be smaller.

An important parameter to take into account while designing the mesh is the thickness. This factor determines the maximum ink film thickness that can be printed, indeed thicker meshes implies thicker ink films. For a given mesh ruling the thickness of the mesh is normally represented by the “T” (thin), “S” (standard) and “W” (wide) notation.

The production of mesh is a long and laborious process, especially as the mesh ruling is high. To set up a weaving machine to fabricate meshes around two months are employed, and such machine will be able to weave for about six months.

Another fundamental component of the screen is the stencil which is a controlling factor in determining the ink film thickness and the quality of the print. This element has the function of establishing where the ink can go through the screen and where it can not, and also it provides a seal between the screen and the substrate. The classification of stencil systems can be practically reduced to two systems which are direct emulsions and capillary films.

Direct emulsions are applied to the mesh as a liquid using a superposition of coatings applied to both sides of the mesh. The number of coatings applied and the intermediate drying can have great effect on the printing performance of the screen.

The thickness of the resultant stencil will affect to the printed ink film where the maximum ink film is effectively controlled by the total thickness of the screen. Besides, another stencil parameter which can determine the quality of the printed product is the under screen surface profile, or roughness, produced by the underlying shape of the mesh and the contraction of the stencil during the drying process. In fact, the undulations in the under surface of the screen or roughness can be removed or diminished by applying multi layers of stencil with drying periods between successive layers. This results in a smoother surface and thus an improved seal, yielding printed results close to capillary film standards.

The notation usually applied to the preparation of a direct emulsion stencil is (x + y), where x is the number of layers applied to the upper surface and y is the number of layers applied to the underside.

Capillary films are applied to the mesh as a solid film using a photoemulsion which is mounted on a transparent carrier polyester film. The print quality obtained by the capillary films is generally higher than that of direct emulsions for a number of reasons. The thickness of the capillary films is controlled at the outset and there is little variation in the stencil deposit around the screen. As the lower region of the stencil remains solid throughout the production process, there is a little or no shrinkage during the drying of the upper surface.

For a given print area, the cost of capillary film is approximately an order of magnitude higher than direct emulsions, as there are a number of extra processes during production and there is the cost of the additional carrier film.

After the required image has been printed it is possible to reclaim the screen by removing the stencil from the mesh with some corrosive substance. In this way a single tensioned mesh can be used up to a hundred times before it is necessary to remesh the frame.

Finally, the third and last element that composes the screen is the frame. Its task consists of holding the screen perfectly flat without distorting or warping during the screen preparation and printing. The classification of frames types is based on whether they are fixed or adjustable. By far the most extended type in use in the UK is fixed frames, unlike to the US where adjustable frames dominate.

A fixed frame consists of a rectangular fabrication onto which the screen is bonded with high strength adhesive. The material most commonly used is aluminium. Although steel is cheaper, it is also heavier making handing a problem and providing additional mass which has to be accelerated in any high speed system. Steel also has the problem of corrosion which can locally weaken the frame, provoking warping and introducing a contaminant (rust) into the process.

3.2.2 The squeegee and flowcoat.

The role of the squeegee is to displace the screen to the substrate surface and to generate the necessary hydrodynamic pressure to tranfer the ink flow through the screen. The role of the flowcoat is to redistribute the ink which has not passed through the screen at the end of the print stroke.

Squeegees are generally fabricated of a polyurethane compound, which combines the rigidity required to withstand the hydrodynamic and drag forces imposed on the squeegee with the compliance required to absorb any substrate and screen surface roughness. If the squeegee is not made compliant then the risk of the mesh ripping is increased dramatically and the print may suffer “banding and streaking” where the squeegee is not in contact with the substrate.

Manufacturing the squeegees out of polyurethane involves some problems such as squeegee wear and solvent absorption. The squeegee wear is caused by the friction between the mesh and the squeegee, where normally the most affected component is the squeegee which gets eroded on the tip provoking uneven ink transfer. Regarding to the solvent absorption problem, when the surface of the squeegee is abraded, it is possible that any solvent used in the ink may diffuse into the squeegee. This can result in either squeegee hardening or squeegee softening, depending on the chemistry of the polyurethane and the solvent in question.

The hydrodynamic pressure to force the ink into the empty mesh is a function of the squeegee speed, ink viscosity and squeegee tip geometry. A problem to be overcome is to avoid excess force applied to the squeegee, because this fact can cause tip deformation and distortion resulting in a change in the hydrodynamic pressure and hence the ink transfer. Modern developments in squeegee design can nearly ensure a continuous contact with the mesh, providing tip compliant and preventing squeegee bending.

3.2.3 The ink.

The inherent flexibility of the screen printing process consists of the ability of print almost any ink to any substrate. But this versatile capacity of printing is degraded by the drawback of limitation in what can be achieved with screen inks.

There are several choices regarding to the screen ink selection where the criteria depends on the type of application to be fabricated. Just to mention some of the most common choices, they are solvent-based, water-based and UV.

Unlike other printing technologies where water-based inks are becoming the current ink in use, for screen printing that is not an appropriate solution due to the lack of good properties. Although water-based inks are environmentally-friendly, there is a downside in the productivity, that is to say, this ink is not highly productive.

Although currently the choice is solvent-based inks due to its greater durability, the trend to move towards UV inks is increasing. UV screen inks offer higher production rates and resolution quality, and moreover it generates lower VOC (Volatile Organic Compounds) emissions which means it is an environmentally-friendly product. Other advantages of UV screen inks are the speed in production compared to other technologies and the limited space required by the equipment. Even though this technology has a lot to offer to the current market, there is a main issue in its integration and that is the involved high costs. In terms of equipment, it requires a major investment including a UV curing unit.

Screen inks can generally be characterised as liquid inks, although there are exceptions like in the electronics printing industry where they possess a more paste like properties.

3.2.4 The press.

The broad scope of the screen printing process results in a range of different press designs, although they can be summarised into three generic types and they are the flat bed press, the cylinder press and the rotary press. Out of this classification, it can be highlighted the flat bed presses with a use of about 90% of the current market.

The main characteristics that make the flat bed presses to be the normal choice are its versatility and simplicity. Their versatility comes from the ability of printing almost any thickness of substrate with relatively simple presses.

Within the flat bed presses another classification can be set regarding to the complexity of the press system. The first group includes hand benches which are manually manipulated like in the passage of the squeegee across the screen. This simple type of press is mostly used where production speed and process consistency are not the primary concerns. The second group gathers semi automatic hinge backed flat bed machines which have motors or pneumatics to realize the passage of the squeegee across the screen. This type of press is most commonly used where production speed is not a primary issue, but process consistency is required. The third and last group within the flat bed presses classification is formed by the fully automatic flat bed presses which represent the best choice for high quality and high productivity for thick and delicate substrates.

Although flat bed presses are popular, their maximum production speed is low compared to other presses such as the cylinder presses. The cylinder presses are characterised by their high production speed, however a trade-off between the speed and the costs must be taken into account. The third generic form of press, the rotary press, can be distinguished from the other types by the materials used in its fabrication. This is a very recent innovation (1980´s) and still in active development.

4. SILVER PRINTED LINES EXPERIMENT

4.1 General information.

The printing of functional inks, such as for conductive tracks, sensors and semiconductors, is generally a combination of solids and lines. In order to design a fine line, it is required a consistent width and cross sectional area.

In many instances the behaviour of the component being printed relies on the successful deposition of lines. Where the ink film is being used to conduct electricity, any modification in its height, width and cross sectional area will have an effect on its resistance and subsequently the device performance.

In order to meet certain requirements in the printed device, such as an approximate width and cross sectional area (for instance, in the printing of conductive lines), it is paramount to take into account several parameters of the printing technology to be employed. Those parameters can dramatically affect the final performance of the printed device. To mention just a few, the printing speed, angle and geometry of the squeegee, the mesh material, the screen ink composition, the distance between the screen and the substrate, etc. are all variables to be assessed when designing any printed device.

The samples of printed lines employed to carry out the experiment were screen-printed, and the parameters under study where basically three, the printing speed, the screen ink composition and the mesh material.

In the figure 7 a picture of a silver printed lines sample is shown, where the patterns under assessment are the ones positioned at the left-hand side down corner, and the printed lines selected are the four lines over the frame and the first bottom line.

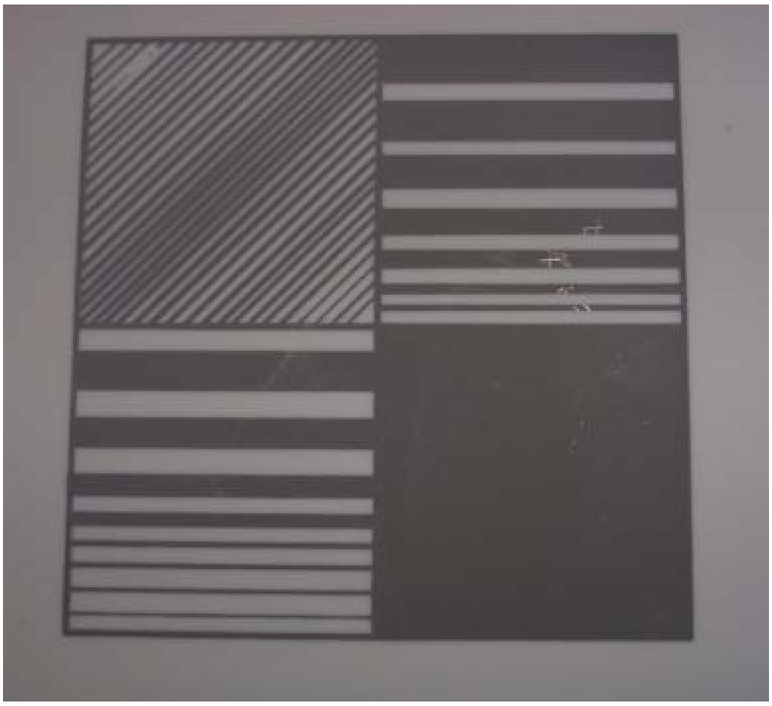

Figure 7. Silver printed lines sample.

The aim of the experiment is to be able to assess in a certain manner how the screen printing parameters affect to the printed silver lines regarding to their influence over the cross sectional area and resistance of the above-mentioned lines.

In order to realize the measurements some equipment is meant to be used. When referring to measure the width, the height and the cross sectional area of the printed lines a white light interferometer is the suitable choice to obtain the lines' profile. After implementing some image processing, an array of data will be obtained including width, height and cross sectional area of the lines, although the intentions will be focused on the evaluation of the cross sectional area. Regarding to the measurement of the resistance of the lines a four point probe is utilized. Further information will be given throughout the document in order to clarify the use and applications of such devices.

4.2 Scenario and procedures.

4.2.1 Printed lines dimensions.

4.2.1.1 Line dimensions obtaining process.

The basis of this experiment is to relate or find a possible relationship between certain screen printing parameters and the printed line dimensions. First of all, it is convenient to define which are the screen printing parameters under test and which possible variants are available for study. Find next the possible choices where any combination of the three parameters can be selected.

- Printing speed: LOW HIGH
- Mesh material: POLYESTER STAINLESS STEEL
- Screen ink composition: 74% 75% 76% (*)

(*) In the case of screen ink composition, this parameter measures the concentration or percentage of silver in the ink.

Regarding to the mesh material parameter some of the tools employed in the obtaining of the printed lines are displayed next such as the stencil, the screen with stainless steel mesh and the screen with polyester mesh. Their figures are 8, 9 and 10 respectively.

The figure 8 shows the stencil or pattern utilized for the generation of the template on the mesh, this pattern is the negative of the image created on the mesh, that is to say, in the position this stencil is placed when creating the pattern of the mesh is where the screen ink will be able to go through or where there are no obstructions or blocks in the mesh openings. The figures 9 and 10 correspond with the screens generated by using the stencil aforementioned.

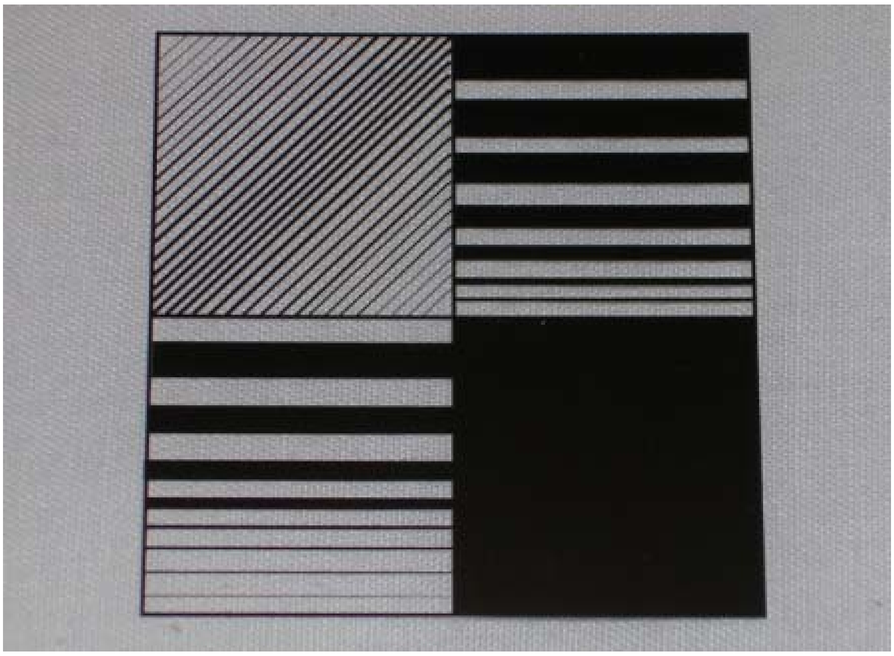

Figure 8. Stencil employed over the mesh material of the screen

Figure 9. Screen with stainless steel mesh

Figure 10. Screen with polyester mesh

The first step to be taken towards the obtaining of the line profiles is to use some image processing software which can assess numerically the line dimensions, and subsequently those numerical data can be processed and study. The image processing tool chosen for this experiment is a white light interferometer and the associated software is WYKO Vision32.

The white light interferometers, or optical profilers are often used in microscopy to measure the surface topography of micro-objects of various nature such as machined parts, IC-packaging modules or in this case printed lines. This device has the advantage of delivering non-contact and high-accuracy 3D topographic measurements.

The software package employed to retrieve the white light interferometer data and responsible to set up the system for proper measurements is called WYKO Vision32 from Veeco. This manufacturer provides metrology and process equipment systems in semiconductor, data storage, telecom, etc.

First of all, before proceeding with the measurements the system settings need to be specified, where the more suitable the settings the more accurate the measurements. In first place, we proceed with the selection of the data display, where the possibilities provided are contour, 2D profile and 3D. The right choice for the experiment in question is 2D profile, afterwards the 2D data will be processed to obtain printed line profile details. In second place, the intensity is set to a position where there are fringes distributed homogeneously all over the capturing data window preview shown on the sample monitor (this monitor shows the action of the light beam on the surface under test). The selection of a suitable intensity is paramount because on one hand low intensity choice can provoke lack of information or blank regions in the acquired image, on the other hand, high intensity can provoke over-saturation of the image and bogus acquired images. And at last but not least, some parameters can be modified in order to affect the measurement results, just to mention a few the PSI mode (Phase-Shift Interferometry) and VSI mode (Vertical-Scanning Interferometry). The former is used to measure smooth profiles with no abrupt changes offering a high resolution and tremendous accuracy, the latter is used to measure profiles with abrupt changes, and the accuracy and the resolution provided are behind the PSI mode ones.

Basically, the scenario for the printing lines dimensions obtaining consists of a silver printed lines sample placed over a rectangular support which is under the white light interferometer lens. Before proceeding with the focus of the white light interferometer towards the sample, it is necessary to select the appropriate magnification lens. The range varies within 2X-50X, moreover an additional zoom can be applied. In the experiment in question, the choice is the 5X lens. In fact, this lens provides a suitable magnification for three lines out of the four lines under test. However, the widest line requires 2X magnification lens in order to appear in total width in the acquired image.

Once the magnification lens is selected, the next step is to focus the system. Basically, the procedure consists of finding a position for the support where homogeneous fringes spread throughout the surface of the sample under test. Now the system is ready for the acquisition of a new image, hence click on File -> New Measurement. In figure 11, it is shown a view of WYKO Vision32 program after retrieving a measurement made with the white light interferometer.

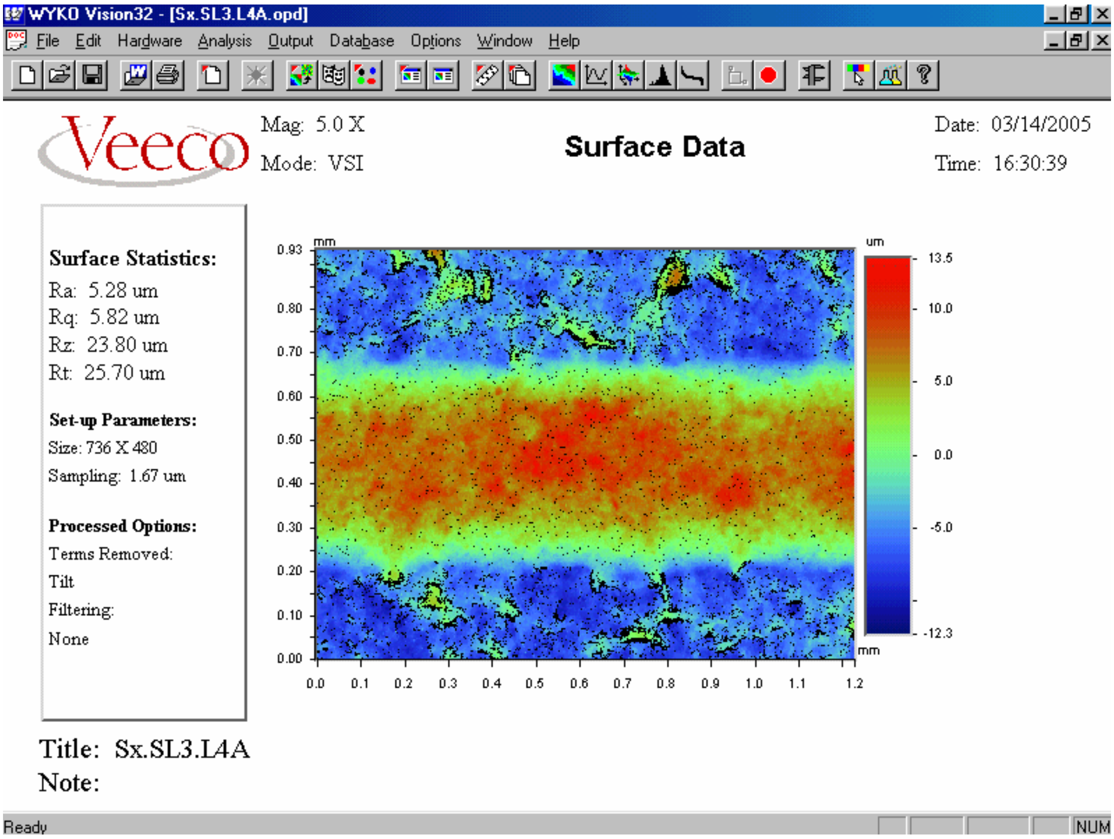

Figure 11. WYKO Vision32 environment after a measurement.

In figure 11, the measurement corresponds with the second line of wider size. The screen printing parameters involved in this measurements are a stainless steel mesh material, a low printing speed and 76% of silver concentration in screen ink. The green and red coloured region at the centre of the image corresponds with the silver printed line. The blue area is the substrate of the sample. The isolated isles placed randomly all over up side and down side of the image are defects in the image that require an after image processing procedure. The idea is to generate by means of any image processing software an average height for the substrate in order to smooth out those imperfections, and consequently to obtain better results.

In the figure 12, an overview of the measuring equipment is presented. Therefore, several devices play a role in the performance of the printed lines dimensions acquisition. Starting from the right-hand side, the first item corresponds with the white light interferometer. This device is supported on a mechanical station which is able to absorb most of the environment vibrations to provide a more accurate acquisition of measurements.

In the middle of the figure 12 a sample monitor can be seen. Its functionality is to provide the image that the white light interferometer is to acquire by showing the interaction of light with the sample´s surface. In fact, this image will be used to set up the position of the lens.

At the left-hand side of figure 12, the computer that runs the analysis software (WYKO Vision32) is displayed.

Figure 12. White light interferometer workstation.

4.2.1.2 Image processing description.

In this section, we will go through the code used for processing the image information before the obtaining of the data. Once the data are obtained, the next step is to analysed those data and extract some conclusions.

First of all, it is necessary to import the WYKO file with extension opd, that contains the image to be processed, into any other software program which converts the image information into numerical data. The choice is to utilize EXCEL as the medium through which evaluate the data. The issue arises when we import the whole image into EXCEL, there is too much information. In this case the solution is to define a subregion within the image and associate half resolution to it. From now onwards, this has to be the procedure to be followed when importing any image into EXCEL. The data resolution obtained after the reduction of information is not affecting to the final results of the experiment.

The half-resolution image is saved as ASCII datasets file. When opening the file with EXCEL the assistant for text importation will show up. Then select delimited data at the first pop up window and comma and tab delimiter at the second pop up window, finally click on the FINISH button and the numerical data associated to the image will appear.

In the figure 13, it is shown how the data look like after importation. These data can be called as “raw” data or data before processing. The next step is to process those data with a macro created in the visual basic editor from EXCEL.

Microsoft Excel - P75.SH3.L4A

Archivo Edición Ver Insertar Formato Herramientas Datos Ventana ?

A1 = Wyko ASCII Data File Format 0

	A	B	C	D	E	F	G
1	Wyko ASCII	0	1				
2	X Size	113					
3	Y Size	184					
4	Block Name	Type	Length	Value			
5	Time	5	9	19:09:34			
6	Date	5	10	02/07/2005			
7	Pixel_size	7	4	0.00334			
8	Wavelength	7	4	80			
9	Aspect	7	4	1.167			
10	Title	5	20	Subregion			
11	Note	5	60	X offset:0 Y offset:0 Resolution: half			
12	RAW_DATA	3	83168				
13	-63.806526	Bad	-69.721115	-78.789856	-79.073051	-83.097572	-87.547424
14	-70.299103	-79.040298	Bad	-79.504601	-78.238235	-84.606842	-86.113113
15	-72.950859	-73.802925	-75.608452	-78.023544	-75.595764	Bad	Bad
16	-72.882149	-73.119141	-76.117477	-74.494537	-84.580223	-79.67231	-97.737335
17	-75.124451	-76.481247	-84.706215	-82.014153	-83.378342	-87.132721	-79.645432
18	-78.600761	-79.145119	-80.343163	-84.39592	-86.302917	-86.410728	-83.354958
19	-79.879311	-74.651764	-72.91188	-80.827881	-92.885002	-89.542885	-83.251068
20	-82.268768	-83.250137	-87.154121	-88.346428	-85.350105	-89.645782	-81.206375
21	-77.71785	-80.259651	-83.246788	-83.063644	-82.431091	-64.421043	Bad
22	-76.027504	-85.034607	-82.057144	-83.66214	-87.816673	-83.826088	-82.34845
23	-69.962799	-79.868759	-80.899483	-84.318504	-90.7584	-86.760742	-87.719162
24	-94.009933	Bad	-82.439476	-82.435379	-78.788269	-79.676537	-80.97477
25	-62.995216	-60.20779	Bad	-78.22641	-80.573112	Bad	-68.884613

Figure 13. Numerical data associated to the image imported into EXCEL.

In the cells placed within (2A,3B) it is defined the size of the obtained information. The Y Size matches the width of the subregion selected, although the associated data are displayed in the horizontal axis of the spreadsheet. Same for the X Size, it matches the length of the subregion defined for the study, although in the EXCEL spreadsheet is displayed throughout the vertical axis. One important parameter is the wavelength, it is expressed in nanometers and its value is 80nm or 0.08μm (cell 7D). Whereas the results will be shown in micrometers. The values obtained at the cells are expressed without units and represent the measurements in the Z axis, in fact those values refer to the number of wavelengths, what means that to obtain the real values the multiplying factor has to be wavelength /1000 (μm). By following this procedure the final results will have a micrometer format. Another important parameter is the Pixel_size, it is expressed in millimeters and its value is 0.00334mm or 3.34μm (cell 8D). Every data cell represent a pixel, that is to say, the distance between two pixels or two cells when referring to the EXCEL spreadsheet is 3.34μm. This conclusion is very practical in the case of the obtaining of the width of the line, where the operation will consists of finding the start and end of the printed line in the spreadsheet, and finally multiply their subtraction by the pixel size expressed in micrometers.

It is convenient to clarify the appearance of “Bad” values in the frame of data. Due to a bad acquisition of data when capturing the image through the white light interferometer, it does appear some blank regions on the image. If the calibration of the device is appropriate, then those blank regions are minimised to single points or pixels. The way of treating these faulty values is by substituting them by the adjoining pixel that contains a proper value.

As it can be seen from the data cells, the values obtained are negative. This portion of the image matches with the upper left-hand side corner of the printed line image (Figure 11), that means, that this section coincides with the substrate. Once the data are converted into micrometer units, then we proceed to calculate the average height of an extensive area from the substrate. Afterwards the average value will be subtracted to the whole image. This is a procedure to normalized the measurements and it gives good results.

In figures 14 and 15, it is shown the same cross-section before and after image processing, respectively. As it can be seen from the figure 13, the profile takes negative values in some sections, unlike figure 14 where an offset is included and the height of the profile is converted into micrometers.

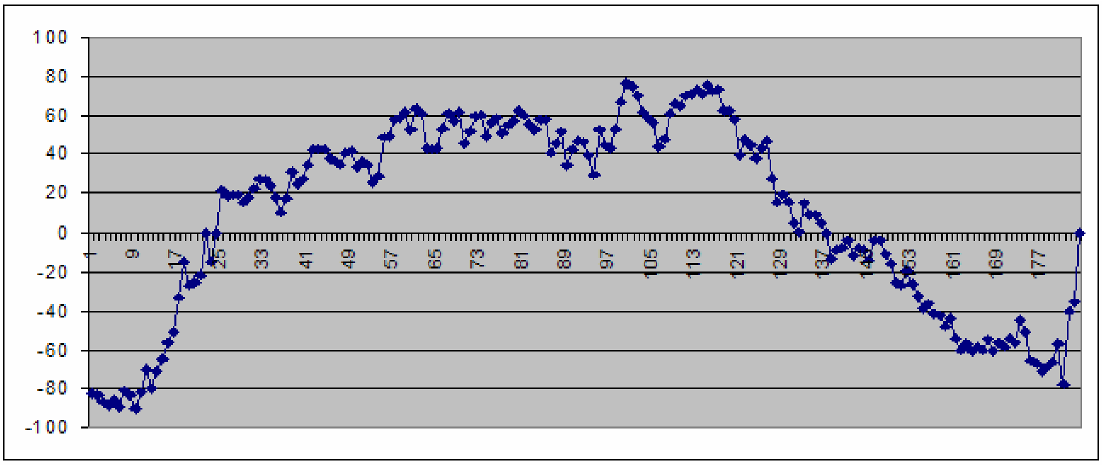

Figure 14. Cross-section before image processing.

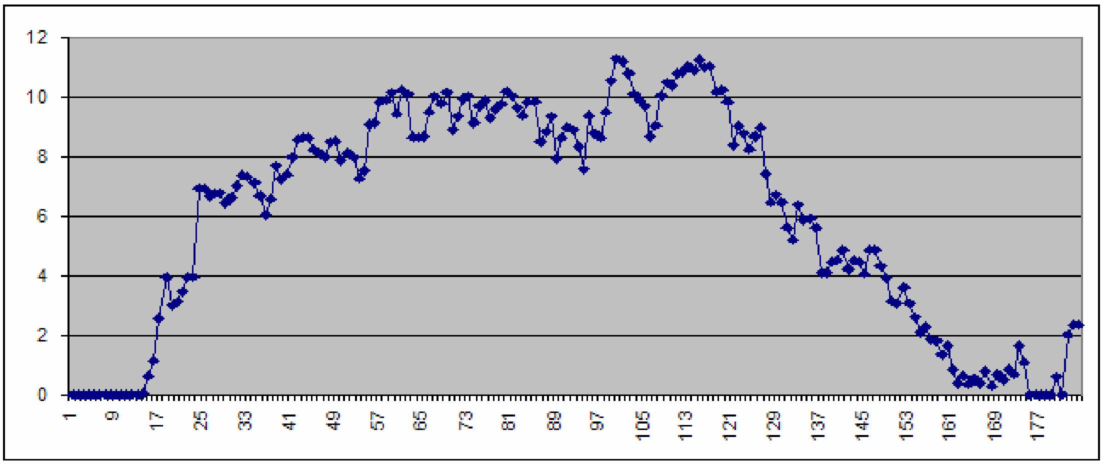

Figure 15. Cross-section after image processing.

4.2.1.3 Image processing coding.

In this section the code employed for processing the data is listed block by block, where every block performs a different task in process. Every piece of code is attached with some extra comments to make easier the understanding for the reader.

- Definition of the variables, pop up window for selection of the number of spreadsheets to be analysed, acquisition of important parameters from the spreadsheet and initialisation of arrays.

```
Sub parameter()

' parameter Macro
' Macro recorded 01/05/05 by Carlos

Dim i As Integer, j As Integer
Dim maximo As Integer
' *** Maximo will store the position of the maximum
Dim nx As Integer, Ny As Integer
Dim PixSize
Dim WaveLength
Dim n, n1, n2

Dim ZeroLev
Dim SumZero(500)

Dim sum(500) ' this is the sum of csa ***
Dim Maxheight(500)

n1 = InputBox("Enter number of first sheet to be analysed ,e.g 1 for sheet1", "First sheet")
n2 = InputBox("Enter number of last sheet to be analysed ,e.g 3 for sheet3", "First sheet")

If n2 < n1 Then Exit Sub
```

```
If n1 <= 0 Then Exit Sub

For n = n1 To n2 ' *** Change these values for each sheet
    Sheets(n).Activate

    ' ** get details ***
    nx = ActiveSheet.Cells(2, 2)
    Ny = ActiveSheet.Cells(3, 2)
    PixSize = ActiveSheet.Cells(7, 4) * 1000
    WaveLength = ActiveSheet.Cells(8, 4)
    ' *** calculate zero level from average of first 8 ***
    ' *** reset sums ***
    For j = 1 To 500
        SumZero(j) = 0
        sum(j) = 0
        Maxheight(j) = 0
    Next
```

Regarding to the variables definition, there are several variables and their functionality can be found as following:

1. The variables i and j are employed for referring to the Y axis and X axis of the image obtained from WYKO Vision32, respectively.

2. The variable maximo is used for referring to the position of the maximum point within a cross-section of the printed line. In the case of the EXCEL spreadsheet, this corresponds to the position of the maximum value within a row of data.

3. The variables nx and Ny are used to store the dimensions of the line, where nx and Ny coincides with the length and the width of the printed line image, respectively.

4. The variable PixSize corresponds with the dimension of the pixels in the image given in millimetres, regarding to the EXCEL

spreadsheet the PixSize is the distance between two neighbouring cells. The WaveLength is used to convert the value of every cell into micrometers units, although at first place the WaveLength value is converted from nanometers into micrometers. After the multiplication operation the cell´s value will contain the height of the image at a particular point or pixel.

5. The variables n, n1 and n2 are used to select the spreadsheet to be analysed at a particular moment. The variable n1 contains the first page to be processed and n2 contains the last one; and n will be used to move through all the spreasheets and activate them one by one.

6. The variables ZeroLev and SumZero(500) are employed to obtain the average height of the substrate, and subsequently this value will be subtracted from all the cells (pixels in the image) to establish a 0 ground level. SumZero(500) is an array that accumulates the average height of slices of the substrate all along the width of the image. ZeroLev stores the average height of the substrate.

7. The variables sum(500) is used to stored the area of all the cross-sectional areas from the line by performing the simpson rule. Another important variable is Maxheight(500) which is employed for the maximum height of each cross-section.

The last section of this portion of code performs the activation of the spreadsheets selected for processing. Also the acquisition of useful parameters is carried out like the sizes of the image, the pixel size and the wavelength. Finally, the initialisation of all the arrays is done.

- Substitution of faulty image values for any adjoining good value.

```
' *** Due to the obtaining of "Bad" values when acquiring
' *** the WYKO output following loop is implemented, changing
' *** the "Bad" value for the adjoining value

Dim m As Integer
Dim goback As Boolean

goback = False

m = 0
For j = 1 To nx
  For i = 1 To Ny
    If ActiveSheet.Cells(j + 12, i) = "Bad" Then
      Do Until ActiveSheet.Cells(j + 12, i + m) <> "Bad"

        If i + m = Ny Or goback = True Then
          m = m - 1
          goback = True
        End If

        If i + m < Ny And goback = False Then
          m = m + 1
        End If

      Loop
      goback = False
      ActiveSheet.Cells(j + 12, i) = ActiveSheet.Cells(j + 12, i + m)
      m = 0
    End If
  Next
Next
```

The algorithm consists of in case of finding a “Bad” value cell, it will be substituted by another cell from the same cross-section. The search of a suitable value starts at neighbouring cells of the faulty one.

- Calculation of average height of the substrate and subtraction of this value to every single cell from the EXCEL spreadsheet (or pixel from the image).

```
' **** loop through and work out average substrate level ***
  For j = 1 To nx
    For i = 1 To 10 ' ** First 10 are the substrates **8
      SumZero(j) = SumZero(j) + ActiveSheet.Cells(j + 12, i)
    Next
    ' ** calc average ***
    SumZero(j) = SumZero(j) / 10
    ' *** add average to zerolev **
    ZeroLev = ZeroLev + SumZero(j)
  Next
  ' *** work out average
  ZeroLev = ZeroLev / nx

  ' *** Takes things to zero ***
  For j = 1 To nx
    For i = 1 To Ny
      If ActiveSheet.Cells(1, 5) <> "DONE" Then
        ' Take out reference substrate ****
        ActiveSheet.Cells(j + 12, i) = ActiveSheet.Cells(j + 12, i) - ZeroLev
        ' **** Take out zero values ****
        If ActiveSheet.Cells(j + 12, i) < 0 Then ActiveSheet.Cells(j + 12, i) = 0
        ActiveSheet.Cells(j + 12, i) = ActiveSheet.Cells(j + 12, i) *
        WaveLength / 1000

        ' **** Record maximum height ****
      End If
      If ActiveSheet.Cells(j + 12, i) > Maxheight(j) Then
        Maxheight(j) = ActiveSheet.Cells(j + 12, i)
        maximo = i
      End If
     Next
   Next
```

The first piece of code defines an algorithm to calculate the average height of the substrate, which consists of specifying a region within the substrate that covers all its length long. The width dimension for abovementioned region is defined as 10 pixels size, which provides enough accuracy for the calculations. An important requirement to be fulfilled when obtaining the image to be analysed from the WYKO Vision32 software is to select a subregion within the image which substrate width at each side of the printed line is at least one fifth of the line´s width. Moreover that subregion should contain as less imperfections at the substrate as possible, because this fact can affect the final average height obtained.

In the second section of the code the average level for the substrate is subtracted from every pixel, and also they are multiplied by a factor composed by the wavelength divided by 1000. After the last operation, every cell will contain a micrometer scale value. Another point covered is the finding of the maximum point in every cross-section of the line, which will be useful to find the end of the printed line (making use of the maximo variable).

- Obtaining of the start and end of the printed line, and also the width of the line in micrometers.

```
' *** Find width of line *****
    Dim LineStart, LineEnd
    Dim Startfound As Boolean, Endfound As Boolean
    Dim k As Integer
    Dim ave, Foundval
    Dim NextCell, zerocell As Boolean

    For j = 13 To nx + 12
        Startfound = False
        Endfound = False
        i = 1

        ' *** Find beginning of line ****
        Do Until i >= Ny Or Startfound = True
```

```
        If ActiveSheet.Cells(j, i) > 0 Then
            Foundval = ActiveSheet.Cells(j, i)
            ' *** Check average over 10 next ***
            For k = i To i + 10
                zerocell = False
                NextCell = ActiveSheet.Cells(j, k)
                If NextCell = 0 Then
                    zerocell = True
                    Exit For
                End If
                ave = ave + NextCell
            Next

            ave = ave / 10

            ' average of next 10 greater than current value
            If zerocell = False And ave >= Foundval Then
                LineStart = i
                Startfound = True
            End If
        End If
        i = i + 1
    Loop

' *** Find end of line
i = maximo
Do Until i >= Ny Or Endfound = True
    If ActiveSheet.Cells(j, i) > 0 Then
        ' *** only true if next values are small ***
        ave = ActiveSheet.Cells(j, i + 1) + ActiveSheet.Cells(j, i + 2) +
        ActiveSheet.Cells(j, i + 3)
        ave = ave / 3

         If ave < 1 Then   ' next three are very small values then end = true
             LineEnd = i
             Endfound = True
         End If
    End If
```

```
            i = i + 1
        Loop
    ActiveSheet.Cells(j, Ny + 4) = LineStart
    ActiveSheet.Cells(j, Ny + 5) = LineEnd
    ActiveSheet.Cells(j, Ny + 6) = (LineEnd - LineStart) * PixSize
Next
```

The first section of the code consists of finding the beginning of the printed line for every cross-section. Basically, the algorithm developed performs a search of the wanted cell by following the next steps:

1. Location of the first cell different to zero value in a cross-section.

2. Calculate the average value of the next set of ten cells following the initial cell different to zero. In case that any of the cells that composes the array is equal to zero value, then the search and average calculation starts from the first cell different to zero on.

3. Once calculated the average value of the ten cells and none of them has a zero level value, then it is proceeded to compare the average value with the first cell of the array or initial cell selected (beginning of the line, if corroborating all the requirements). In case that the average value is greater than the value of the initial cell, then that cells is chosen as the beginning of the line (it is very likely that the cell was the beginning of the line, due to the growth in height of the cross-section, although in rare case can occur that any isolated isles or imperfections in measurements produce this result).

The second section of the code describes the criterion to find the end of the printed line. The steps to fulfil this task is explain next:

1. Select the starting point as the maximum point for each

cross-section and, it is proceed to find the end of the line onwards.

2. Accumulate in the variable ave the average value of the three subsequent values to the initial cell, where the point of start is the maximum height value.

3. Compare the value of ave with a small reference value, according to this experiment the selected lower limit is 1. The condition to determine whether the selected cell is the end of the printed line or not, depends on the value of ave being smaller than the reference limit.

4. Finally, the values obtained for the beginning cell, the end cell and the width of the printed line are stored in the EXCEL spreadsheet for every cross-section.

- Calculation of the cross sectional area by implementing the simpson rule numeric method.

```
' *** Perform simpson rule ****
  Dim area
  Dim H1, H2

  For j = 1 To nx
    LineStart = ActiveSheet.Cells(j + 12, Ny + 4)
    LineEnd = ActiveSheet.Cells(j + 12, Ny + 5)
    sum(j) = 0
    For i = LineStart To LineEnd - 1
      ' *** Get height of both sides of trapesium
      H1 = ActiveSheet.Cells(j + 12, i)
      H2 = ActiveSheet.Cells(j + 12, i + 1)
      area = PixSize * (H1 + H2) / 2
      sum(j) = sum(j) + area
    Next
```

```
        ' *** output integral and height to right of info ***
        ActiveSheet.Cells(j + 12, Ny + 2) = sum(j)
        ActiveSheet.Cells(j + 12, Ny + 3) = Maxheight(j)
    Next
```

The first piece of code performs the simpson rule to calculate the area under the curve. The procedure to follow consists of measuring the area generated by polygons defined by a one pixel wide base and the union by a straight line at the top of the extremes of the pixel as shown in figure 16.

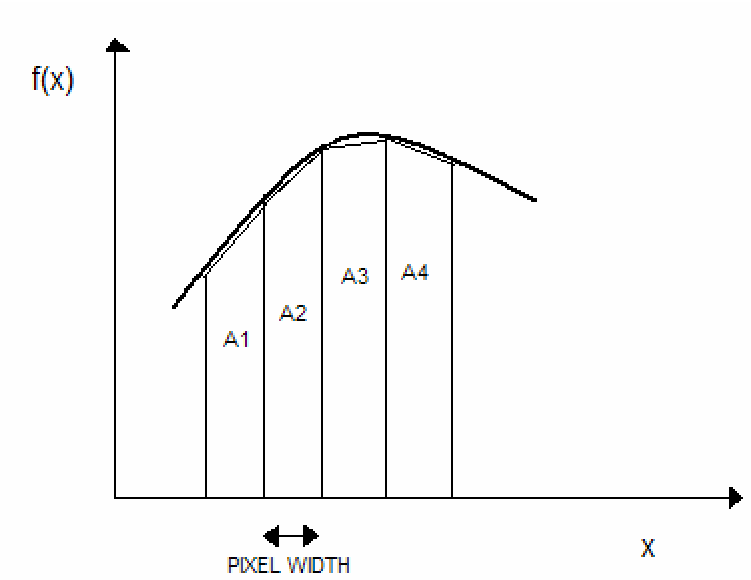

Figure 16. Example for a simpson rule application and polygons definition.

Basically, the program retrieves the values of the beginning and end of the current cross-section calculated previously, and every two cells it assesses the area defined within the polygon (for instance, A1, A2, and so on, could be the area within the polygon defined by two neighbouring cells or pixels). Once the area of one cross-section is achieved the process moves on to the next cross-section until the printed line´s area has been totally characterised. The last lines of the code store the information of the cross-section area and maximum height at two columns at the end of the processed data within the EXCEL spreadsheet.

4.2.1.4 White light interferometer measurements.

An extensive set of measurements is carried out and its results will be listed throughout this section. Before starting with the data listing, it is convenient to specify concretely which are the lines under study and how the data will be presented. According to the figure 17, the four lines under test are pointed out.

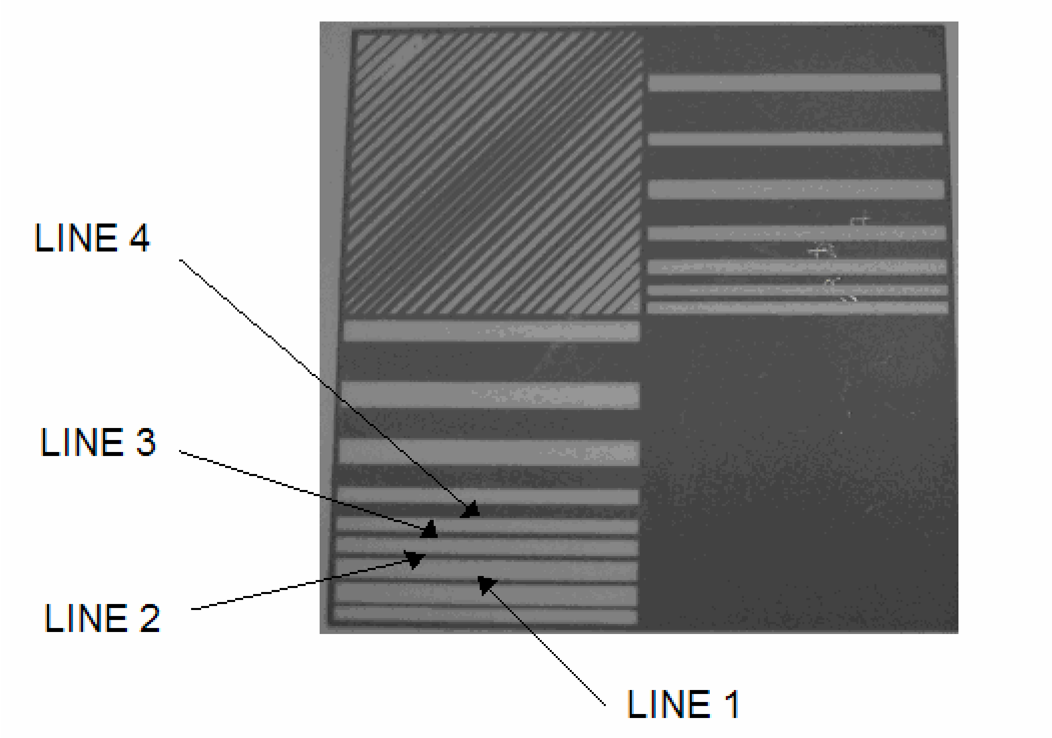

Figure 17. Silver printed lines under test.

Another point before presenting the tables is to explain the number of samples and measurements taken for each possible experiment configuration. Regarding to the number of samples per configuration, there are three samples to measure at every particular configuration. For instance, an existing configuration is 74% silver ink concentration, stainless steel mesh material and high printing speed, and for this particular configuration there are three samples to be assessed (similar as with any other configuration).

Moreover, the measurements are carried out at both ends of every line, what means that the total number of measurements per configuration is six.

The information displayed in the tables consists of dimension parameters obtained after the image processing, that is to say, the cross sectional area, the maximum height and the width of the printed lines are the data to be shown. In order to be consistent with the results, it will be provided the average and standard deviation for each of the aforementioned parameters. Those statistics will be obtained as a result of applying the calculations all over every cross-section that composes the associated EXCEL spreadsheet for a particular printed line configuration.

As a summarisation of the previous paragraph, the figure 18 is displayed. It shows on top of the associated column of data the obtained parameters calculated for all cross-sections.

				CROSS-SECTIONAL AREA	MAXIMUM HEIGHT			WIDTH
		STANDARD DEVIATION		179.0180092	1.073859545			30.1642967
		AVERAGE		3913.906881	13.80755339			486.812389
2.32827134	4.37163158	4.37163158		3604.916257	12.04151902	15	157	474.28
3.11826966	4.01863918	2.29856214		3685.543775	12.43907022	16	156	467.6
3.94366598	4.21302478	3.55349454		3711.221372	13.33167342	16	156	467.6
4.5068479	4.20720534	2.93910566		3700.66522	13.87765422	17	156	464.26
3.98008358	3.8414419	2.4861915		3727.044565	13.6503959	16	157	470.94
3.8620155	3.81504638	3.81504638		3754.480158	13.0306547	15	157	474.28
3.3576463	3.6349983	3.6349983		3688.936058	12.02590006	14	158	480.96
2.01041574	2.37362958	2.37362958		3652.552928	11.30006022	14	159	484.3
2.98947902	2.60205302	1.46332134		3645.85801	11.30868638	14	160	487.64
2.22169262	2.22169262	1.75284102		3658.637212	11.26959086	14	159	484.3
1.97123366	2.15957438	1.8999611		3658.167461	11.23947678	14	160	487.64
1.70495494	2.12004894	1.85055526		3668.826998	11.39723126	14	159	484.3
1.2167479	1.95517166	1.5647795		3585.275967	11.52790262	13	159	487.64
1.96006422	2.14727214	1.11562758		3602.280706	11.08840254	14	159	484.3
0.71098278	0.32396254	1.0192271		3635.975685	12.1263115	12	159	490.98
0.58509014	0.3536311	0.63102702		3741.131192	12.56877542	11	159	494.32
0.55306222	0.26439862	1.02569838		3803.665688	12.7249571	14	161	490.98
0.98807022	0.63753278	0.63753278		3803.512718	14.48875534	9	159	501
1.12488358	1.12488358	0.80105174		3876.487792	14.52272446	9	159	501
0.64414622	1.08095382	0.30147718		3901.046559	14.30578654	10	158	494.32
2.22624678	0	1.90908062		3938.451311	14.0894011	10	158	494.32
1.52816142	2.15328446	2.45343214		3938.752476	13.15349166	11	150	464.26
1.32956374	2.6732927	2.21863534		3957.391213	13.67373822	10	152	474.28

Figure 18. Calculation of the average and standard deviation values of the cross-sectional area, maximum height and width of the printed line under test.

Just to add some explanatory notes to the figure 18, the block of data at the left-hand side corresponds with the height of every pixel of the image, where each row is a cross-section of the printed line under test. Besides, the columns of data at the right-hand side come from the calculated dimension parameters for each cross-section. The third and fourth columns are used to store the beginning and end of the printed line, respectively. By using these data and the pixel size, the width of the line is achieved and shown in the fifth column on the right-hand side.

The tables are listed next and they are organised firstly by printed lines and secondly by screen printed parameters (mesh material type, printing speed and screen ink composition).

- Printed line 1.
  1. Screen Ink Composition 74%.

Mesh Material	Printing Speed	Cross-sectional Area (μm2)		Maximum Height (μm)		Width (μm)	
		Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Stainless	High	1728.15	209.78	10.95	1.35	263.12	28.22
Stainless	High	1851.67	218.77	11.55	0.99	267.42	38.49
Stainless	High	1704.39	151.15	10.50	0.74	266.08	25.64
Stainless	High	2036.62	167.53	11.74	1.01	291.01	40.68
Stainless	High	1831.85	153.84	11.55	1.35	271.62	27.27
Stainless	High	1624.39	311.40	10.35	1.47	257.21	34.70
Stainless	Low	1178.57	146.80	8.51	1.14	231.74	24.72
Stainless	Low	1516.78	175.42	9.99	1.18	249.72	24.73
Stainless	Low	1401.26	174.87	9.28	0.85	244.21	21.13
Stainless	Low	1414.07	174.83	9.53	0.86	242.64	21.93
Stainless	Low	1790.56	371.88	10.86	1.87	270.46	40.04
Stainless	Low	1806.78	170.97	11.08	1.01	266.89	38.81
Polyester	High	1541.03	367.18	8.84	1.71	316.93	45.02
Polyester	High	2245.87	324.49	11.08	1.63	374.74	39.64
Polyester	High	2061.95	224.51	10.78	1.87	330.38	29.60
Polyester	High	2590.62	433.33	11.69	1.52	374.86	44.96
Polyester	High	1948.57	335.11	10.61	1.56	340.65	45.68
Polyester	High	1661.87	211.27	9.73	1.17	293.57	34.15
Polyester	Low	1600.32	120.98	9.41	1.35	304.61	29.86
Polyester	Low	1850.13	299.31	10.16	1.36	337.07	43.29
Polyester	Low	1733.92	168.98	10.51	1.96	315.73	44.35
Polyester	Low	1676.22	262.98	9.25	1.23	334.24	43.51
Polyester	Low	2164.74	295.48	11.63	1.30	335.43	38.75
Polyester	Low	2205.20	465.01	11.48	2.92	381.38	51.32

Table 2. Printed line 1 with 74% silver concentration in ink.

2. Screen Ink Composition 75%.

Mesh Material	Printing Speed	Cross-sectional Area (μm2)		Maximum Height (μm)		Width (μm)	
		Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Stainless	High	1799.08	179.09	11.02	1.07	274.56	25.05
Stainless	High	2214.77	272.21	12.43	1.31	297.09	29.92
Stainless	High	2095.57	178.65	12.15	1.06	280.66	36.80
Stainless	High	1901.57	194.40	10.70	0.94	290.43	47.46
Stainless	High	2305.52	424.73	12.07	1.40	324.66	60.50
Stainless	High	1603.43	156.92	10.03	0.99	263.62	20.32
Stainless	Low	1630.28	140.30	9.02	0.42	285.67	36.09
Stainless	Low	1809.87	178.04	10.43	0.73	286.34	40.41
Stainless	Low	2186.47	265.33	12.36	1.29	307.36	45.78
Stainless	Low	1944.67	230.98	11.48	1.21	293.07	39.65
Stainless	Low	1622.77	244.25	10.17	0.94	276.67	41.52
Stainless	Low	1651.42	180.98	10.19	0.92	279.45	53.21
Polyester	High	2101.87	396.34	10.64	1.85	352.86	47.29
Polyester	High	2729.46	270.52	11.82	1.13	418.66	33.90
Polyester	High	2542.29	237.01	11.69	1.14	373.14	29.82
Polyester	High	2776.12	305.11	11.76	1.20	422.20	33.31
Polyester	High	2610.33	284.10	20.49	2.27	350.30	34.61
Polyester	High	2130.97	332.49	11.20	1.51	325.73	29.63
Polyester	Low	2059.36	205.74	11.20	1.09	317.57	26.80
Polyester	Low	1757.56	180.54	9.24	1.03	349.79	50.60
Polyester	Low	2158.84	184.39	11.07	1.22	338.19	45.87
Polyester	Low	1748.40	200.64	9.02	1.03	362.58	44.51
Polyester	Low	2143.82	297.37	10.62	1.95	371.17	47.72
Polyester	Low	1401.29	298.97	8.56	2.36	329.30	31.66

Table 3. Printed line 1 with 75% silver concentration in ink.

3. Screen Ink Composition 76%.

Mesh Material	**Printing Speed**	**Cross-sectional Area (μm2)**		**Maximum Height (μm)**		**Width (μm)**	
		Average	**Standard Deviation**	**Average**	**Standard Deviation**	**Average**	**Standard Deviation**
Stainless	High	2689.23	268.86	14.11	1.56	334.44	37.50
Stainless	High	2299.44	147.43	12.96	0.92	292.25	30.71
Stainless	High	2524.90	204.81	13.61	1.29	328.39	38.88
Stainless	High	2125.34	181.27	12.39	1.42	277.22	28.30
Stainless	High	2458.29	244.45	12.77	1.46	330.27	55.30
Stainless	High	2322.75	143.54	11.65	1.05	303.56	30.87
Stainless	Low	1748.93	102.85	11.86	0.95	223.59	18.02
Stainless	Low	2104.98	145.16	12.51	0.94	263.51	27.36
Stainless	Low	1839.45	175.94	12.00	1.72	256.28	15.20
Stainless	Low	2357.21	188.88	12.61	1.14	313.48	32.89
Stainless	Low	2204.46	217.62	12.17	1.24	297.14	39.21
Stainless	Low	2142.16	202.67	12.44	1.01	282.24	33.59
Polyester	High	2416.14	145.90	11.49	0.76	359.45	42.53
Polyester	High	2056.10	166.43	10.99	0.68	305.80	26.76
Polyester	High	2692.06	379.97	11.75	1.23	388.79	49.64
Polyester	High	2188.42	271.73	10.88	1.09	324.35	324.35
Polyester	High	2349.16	299.28	11.89	1.73	343.88	35.92
Polyester	High	2276.35	172.40	10.63	0.70	335.25	23.28
Polyester	Low	2005.05	178.46	10.74	0.81	302.38	33.65
Polyester	Low	1835.88	103.71	9.68	0.74	313.90	29.32
Polyester	Low	2314.85	199.84	11.12	0.84	352.64	47.04
Polyester	Low	2078.96	242.05	10.26	0.88	330.75	32.75
Polyester	Low	2555.33	128.66	11.97	0.73	350.60	25.96
Polyester	Low	2229.73	168.62	12.39	1.06	334.17	37.84

Table 4. Printed line 1 with 76% silver concentration in ink.

- Printed line 2.
  1. Screen Ink Composition 74%.

Mesh Material	Printing Speed	Cross-sectional Area (μm2)		Maximum Height (μm)		Width (μm)	
		Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Stainless	High	3300.45	327.79	14.51	1.48	400.04	51.57
Stainless	High	3605.26	329.50	15.21	1.41	409.57	45.24
Stainless	High	2548.03	193.58	12.15	1.23	343.93	44.68
Stainless	High	2595.14	196.82	13.01	1.63	326.93	32.61
Stainless	High	3024.96	178.87	14.90	1.63	348.25	44.52
Stainless	High	3005.96	183.87	13.63	0.90	345.45	28.76
Stainless	Low	2730.16	202.99	13.25	1.10	331.51	38.82
Stainless	Low	2687.04	122.47	12.87	0.83	342.05	35.97
Stainless	Low	2909.78	303.03	12.82	1.00	391.99	59.70
Stainless	Low	2803.14	184.63	14.91	1.89	345.26	35.06
Stainless	Low	2792.54	230.81	13.12	0.94	344.15	36.84
Stainless	Low	3037.20	302.98	14.57	2.16	362.55	42.84
Polyester	High	2962.59	259.19	11.91	1.06	439.96	52.98
Polyester	High	2624.64	225.39	11.07	1.31	413.99	27.41
Polyester	High	2235.44	244.07	10.56	1.27	395.84	46.38
Polyester	High	3081.90	319.89	11.98	1.26	449.91	51.47
Polyester	High	2532.53	241.73	11.03	1.24	424.03	52.85
Polyester	High	2892.71	277.45	12.16	1.42	456.99	56.53
Polyester	Low	1939.19	267.69	9.48	1.02	362.76	49.05
Polyester	Low	2216.66	236.05	10.19	1.12	397.27	40.56
Polyester	Low	2056.30	318.44	10.22	1.71	358.89	45.00
Polyester	Low	2528.94	531.21	11.13	1.73	457.76	74.68
Polyester	Low	2478.78	167.99	11.30	1.36	391.01	34.82
Polyester	Low	2481.29	280.20	10.38	1.68	470.27	61.43

Table 5. Printed line 2 with 74% silver concentration in ink.

2. Screen Ink Composition 75%.

Mesh Material	**Printing Speed**	**Cross-sectional Area (μm2)**		**Maximum Height (μm)**		**Width (μm)**	
		Average	**Standard Deviation**	**Average**	**Standard Deviation**	**Average**	**Standard Deviation**
Stainless	High	2744.74	220.67	13.28	1.79	344.77	20.90
Stainless	High	3125.27	211.76	14.50	1.15	354.14	32.35
Stainless	High	3118.21	465.90	14.29	2.02	357.20	43.99
Stainless	High	3032.45	256.83	13.74	0.91	352.29	36.98
Stainless	High	2493.54	208.45	12.01	0.82	337.20	29.42
Stainless	High	3083.63	386.64	13.80	1.49	367.54	46.48
Stainless	Low	2793.86	256.69	12.65	1.27	366.14	34.34
Stainless	Low	2755.55	189.22	12.58	1.04	368.81	37.22
Stainless	Low	3238.99	340.73	14.46	1.30	368.14	38.44
Stainless	Low	3232.10	507.51	14.48	1.58	370.58	53.08
Stainless	Low	3111.46	331.68	14.62	1.56	357.07	41.20
Stainless	Low	2906.38	357.12	12.99	1.37	376.40	51.06
Polyester	High	2003.86	222.92	9.58	1.33	381.84	30.24
Polyester	High	3093.41	297.18	12.01	1.80	464.15	38.95
Polyester	High	2701.63	292.61	11.91	1.73	421.11	46.76
Polyester	High	2571.97	203.69	10.48	1.15	457.70	47.94
Polyester	High	2360.04	309.01	10.57	1.29	396.35	31.68
Polyester	High	2609.73	214.08	10.79	1.30	432.53	41.92
Polyester	Low	2371.50	342.01	10.53	1.25	381.91	37.70
Polyester	Low	2724.36	285.96	11.88	1.26	416.17	47.49
Polyester	Low	2229.85	212.67	10.11	1.18	385.13	48.63
Polyester	Low	2164.25	218.63	9.63	1.21	426.87	41.42
Polyester	Low	3071.18	356.93	12.13	1.21	456.03	50.92
Polyester	Low	2710.46	232.57	11.61	1.56	443.42	39.75

Table 6. Printed line 2 with 75% silver concentration in ink.

3. Screen Ink Composition 76%.

Mesh Material	Printing Speed	Cross-sectional Area (μm2)		Maximum Height (μm)		Width (μm)	
		Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Stainless	High	3596.08	186.60	15.34	0.79	379.82	35.11
Stainless	High	3123.44	108.52	14.28	0.87	351.34	24.85
Stainless	High	2982.74	281.87	14.61	1.06	336.24	31.90
Stainless	High	3047.46	135.55	13.70	1.18	341.28	15.13
Stainless	High	3082.74	185.44	14.44	1.07	345.56	29.72
Stainless	High	3201.64	133.51	15.13	1.04	352.41	31.86
Stainless	Low	3070.51	141.26	14.89	0.99	324.48	37.33
Stainless	Low	3112.47	178.54	14.03	0.56	341.02	37.22
Stainless	Low	2714.95	148.47	12.35	0.92	341.60	24.33
Stainless	Low	2661.70	167.32	12.38	0.88	345.45	27.53
Stainless	Low	2694.13	175.98	12.29	0.99	349.65	36.94
Stainless	Low	2872.83	181.62	13.64	0.83	340.17	27.65
Polyester	High	3194.53	171.04	12.92	0.96	418.52	50.10
Polyester	High	3139.33	220.59	13.13	0.76	413.30	48.61
Polyester	High	3549.24	158.47	14.70	1.02	386.35	22.24
Polyester	High	2861.06	130.41	12.28	0.75	384.19	32.62
Polyester	High	2811.51	198.72	12.51	1.18	359.59	27.72
Polyester	High	3087.83	219.66	13.01	1.30	389.58	32.57
Polyester	Low	2704.07	210.10	22.85	0.66	376.81	40.77
Polyester	Low	3147.41	135.92	13.79	1.34	402.97	31.01
Polyester	Low	3040.13	139.90	13.82	0.82	365.86	20.80
Polyester	Low	2451.69	125.53	10.98	0.51	354.11	25.61
Polyester	Low	2882.27	201.05	12.34	1.15	395.11	28.18
Polyester	Low	2972.09	217.40	14.18	0.90	388.32	46.38

Table 7. Printed line 2 with 76% silver concentration in ink.

- Printed line 3.
  1. Screen Ink Composition 74%.

Mesh Material	Printing Speed	Cross-sectional Area (μm2)		Maximum Height (μm)		Width (μm)	
		Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Stainless	High	4224.32	490.56	16.33	2.91	453.95	35.51
Stainless	High	4538.32	229.29	16.51	1.09	482.35	59.43
Stainless	High	4411.65	390.61	16.85	2.38	464.17	44.69
Stainless	High	4052.91	152.35	16.47	1.73	414.14	20.78
Stainless	High	4534.82	242.52	16.46	1.27	459.99	35.08
Stainless	High	4739.55	355.27	16.77	1.87	514.40	50.65
Stainless	Low	3991.03	235.62	15.35	0.92	443.58	45.34
Stainless	Low	3636.84	252.60	14.43	1.68	420.66	33.94
Stainless	Low	3534.86	294.94	14.52	1.96	403.46	35.90
Stainless	Low	3696.46	274.66	13.93	1.12	443.02	41.78
Stainless	Low	4238.17	384.42	15.50	1.67	456.90	32.00
Stainless	Low	3779.24	192.76	14.41	1.13	436.24	39.64
Polyester	High	3299.79	273.64	12.67	1.32	441.43	46.35
Polyester	High	3584.13	441.11	12.19	1.11	526.05	58.41
Polyester	High	3555.57	385.04	13.13	1.38	481.55	45.99
Polyester	High	3364.01	347.63	12.29	1.10	474.05	38.33
Polyester	High	3496.34	318.64	12.78	1.18	477.28	50.68
Polyester	High	3091.96	270.75	12.25	1.35	441.23	37.22
Polyester	Low	2575.13	319.49	11.06	1.29	394.66	27.54
Polyester	Low	2976.69	371.57	11.22	1.39	480.14	50.69
Polyester	Low	3039.96	275.92	11.49	0.96	442.63	34.43
Polyester	Low	3024.06	316.26	11.15	1.03	485.42	45.55
Polyester	Low	3065.22	233.44	12.39	1.73	449.15	42.58
Polyester	Low	2329.76	398.72	9.79	1.62	425.19	48.29

Table 8. Printed line 3 with 74% silver concentration in ink.

2. Screen Ink Composition 75%.

Mesh Material	Printing Speed	Cross-sectional Area (μm2)		Maximum Height (μm)		Width (μm)	
		Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Stainless	High	3416.69	243.87	13.72	1.83	431.39	44.79
Stainless	High	4515.33	399.74	16.58	1.53	472.20	50.87
Stainless	High	3919.61	183.08	14.89	1.25	433.60	28.00
Stainless	High	3973.68	191.99	15.61	1.38	424.59	27.84
Stainless	High	4170.59	383.35	15.62	1.79	459.97	48.01
Stainless	High	3751.84	247.88	14.69	1.17	424.15	26.49
Stainless	Low	4126.58	225.83	15.46	0.80	445.45	33.42
Stainless	Low	4075.70	291.69	15.48	1.76	447.11	32.66
Stainless	Low	4342.30	418.54	15.35	1.29	457.79	43.96
Stainless	Low	3817.32	298.63	14.30	1.25	423.75	29.19
Stainless	Low	4205.52	370.19	15.78	1.77	446.12	36.49
Stainless	Low	3979.18	323.80	14.81	1.39	434.54	30.64
Polyester	High	3900.82	372.91	13.59	1.13	463.08	37.83
Polyester	High	3267.92	388.66	11.75	1.24	509.53	204.93
Polyester	High	3993.05	243.37	14.06	1.51	500.64	38.52
Polyester	High	3399.02	230.82	12.33	1.59	493.19	46.52
Polyester	High	3180.21	358.65	13.02	2.14	451.85	41.27
Polyester	High	3535.39	266.81	12.70	1.44	495.37	47.79
Polyester	Low	3963.85	317.50	12.82	0.97	532.47	51.25
Polyester	Low	3570.85	297.22	13.22	1.26	505.67	41.10
Polyester	Low	3093.75	242.44	11.62	1.21	458.89	39.03
Polyester	Low	3076.56	196.66	11.81	1.23	471.96	39.60
Polyester	Low	2261.14	160.02	10.02	1.15	399.17	30.42
Polyester	Low	3470.16	479.78	12.72	1.93	534.37	44.41

Table 9. Printed line 3 with 75% silver concentration in ink.

3. Screen Ink Composition 76%.

Mesh Material	Printing Speed	Cross-sectional Area (μm2)		Maximum Height (μm)		Width (μm)	
		Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Stainless	High	4855.55	186.09	16.86	0.84	462.03	37.49
Stainless	High	4925.72	167.43	17.02	0.84	465.55	37.86
Stainless	High	4310.58	176.42	16.14	0.93	402.56	17.65
Stainless	High	4711.90	221.99	16.64	0.70	449.19	32.36
Stainless	High	4244.22	257.89	15.86	1.00	420.27	30.44
Stainless	High	4576.17	162.65	16.11	0.58	437.84	29.36
Stainless	Low	3548.95	133.31	15.21	1.23	366.16	26.74
Stainless	Low	4182.04	175.30	15.11	0.71	433.55	36.72
Stainless	Low	3985.81	213.40	15.25	1.10	403.44	19.66
Stainless	Low	4987.51	265.35	17.75	0.99	467.32	35.32
Stainless	Low	4462.26	234.75	16.04	0.97	444.32	39.42
Stainless	Low	4229.8	253.42	15.54	0.89	422.72	21.42
Polyester	High	4027.27	256.85	15.17	1.15	438.69	27.55
Polyester	High	3645.97	303.44	13.31	1.07	433.78	31.34
Polyester	High	3518.98	205.00	13.12	0.71	436.08	35.76
Polyester	High	3340.67	194.95	12.60	0.69	427.57	30.54
Polyester	High	3435.48	251.12	13.28	0.92	419.97	33.71
Polyester	High	3617.92	222.20	13.71	1.34	432.73	35.81
Polyester	Low	3217.88	396.30	12.67	1.00	419.12	66.07
Polyester	Low	3081.54	337.66	12.54	1.02	398.77	25.40
Polyester	Low	3636.43	216.28	13.31	1.07	445.82	26.84
Polyester	Low	3192.71	433.97	12.46	1.21	419.41	50.75
Polyester	Low	2660.37	281.62	11.66	1.29	386.12	27.33
Polyester	Low	3214.98	340.96	13.88	1.03	417.64	59.12

Table 10. Printed line 3 with 76% silver concentration in ink.

- Printed line 4.
    1. Screen Ink Composition 74%.

Mesh Material	Printing Speed	Cross-sectional Area (μm2)		Maximum Height (μm)		Width (μm)	
		Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Stainless	High	8633.56	392.71	15.67	1.24	936.86	47.26
Stainless	High	9453.44	321.22	16.41	1.14	961.97	52.56
Stainless	High	8705.48	1034.20	16.17	2.70	924.92	47.00
Stainless	High	9181.65	909.33	18.54	4.02	919.59	30.62
Stainless	High	8076.93	452.52	12.39	1.55	836.54	43.99
Stainless	High	7922.84	509.30	11.39	2.49	808.81	36.40
Stainless	Low	8968.67	330.85	15.79	0.86	958.70	59.67
Stainless	Low	7682.01	342.40	13.75	0.96	905.97	27.01
Stainless	Low	8417.91	366.38	15.36	1.35	922.06	46.51
Stainless	Low	9342.94	265.45	16.87	1.21	949.46	39.36
Stainless	Low	9459.67	579.62	15.89	1.37	956.79	36.07
Stainless	Low	7689.38	512.50	14.15	1.25	934.34	41.56
Polyester	High	9240.78	405.49	16.15	1.12	961.60	58.01
Polyester	High	9081.36	326.13	16.03	1.14	943.37	44.87
Polyester	High	9366.51	1019.21	17.07	2.69	939.21	48.09
Polyester	High	7478.23	349.47	12.62	1.13	1070.29	56.08
Polyester	High	7404.71	380.59	11.63	1.10	1024.52	42.62
Polyester	High	8204.00	945.00	12.52	0.86	1054.73	126.66
Polyester	Low	6966.99	242.19	11.73	1.27	1005.25	42.72
Polyester	Low	6719.03	290.26	11.91	0.94	1000.42	44.52
Polyester	Low	7932.03	378.29	12.91	1.35	1015.93	44.56
Polyester	Low	6799.88	293.90	11.55	1.24	1038.93	46.71
Polyester	Low	7790.59	550.31	17.75	1.94	1032.09	45.61
Polyester	Low	6530.22	317.46	12.08	2.27	1037.10	40.65

Table 11. Printed line 4 with 74% silver concentration in ink.

2. Screen Ink Composition 75%.

Mesh Material	**Printing Speed**	**Cross-sectional Area (μm2)**		**Maximum Height (μm)**		**Width (μm)**	
		Average	**Standard Deviation**	**Average**	**Standard Deviation**	**Average**	**Standard Deviation**
Stainless	High	10566.13	279.07	18.41	1.36	972.04	31.58
Stainless	High	9363.93	356.26	16.52	1.31	954.58	28.75
Stainless	High	9639.34	258.99	16.79	1.14	973.00	34.17
Stainless	High	9092.11	271.48	15.08	0.90	983.09	35.46
Stainless	High	10107.04	433.57	17.85	1.21	988.25	40.55
Stainless	High	10161.28	353.81	17.09	1.66	1010.76	53.20
Stainless	Low	9463.86	418.75	15.45	0.82	997.32	45.23
Stainless	Low	9767.49	492.06	16.00	1.56	990.17	36.40
Stainless	Low	9355.04	274.34	15.64	1.36	970.61	26.99
Stainless	Low	8311.54	438.24	14.34	1.06	984.02	47.88
Stainless	Low	9985.00	291.96	17.04	1.30	1023.73	53.92
Stainless	Low	7259.52	395.32	13.65	1.49	941.85	40.56
Polyester	High	8096.32	399.00	12.60	0.95	1048.45	49.11
Polyester	High	8913.26	356.90	13.45	1.14	1083.56	42.40
Polyester	High	8200.36	553.31	12.81	0.86	1077.04	40.94
Polyester	High	9003.45	305.70	13.64	1.12	1079.26	59.01
Polyester	High	7321.13	323.36	12.60	1.45	1027.66	32.90
Polyester	High	8237.62	380.66	13.58	1.40	1061.36	44.92
Polyester	Low	8291.09	652.08	12.72	1.18	1064.38	72.68
Polyester	Low	7420.72	443.05	12.04	1.35	1076.20	52.23
Polyester	Low	6982.89	273.13	11.11	0.91	1037.83	34.98
Polyester	Low	8061.73	424.39	12.21	0.94	1091.14	57.91
Polyester	Low	7023.54	401.00	11.36	0.94	1043.18	47.08
Polyester	Low	7599.29	509.43	12.00	1.00	1070.98	40.29

Table 12. Printed line 4 with 75% silver concentration in ink.

3. Screen Ink Composition 76%.

Mesh Material	Printing Speed	Cross-sectional Area (μm2)		Maximum Height (μm)		Width (μm)	
		Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Stainless	High	13256.42	643.88	20.63	1.16	1004.84	38.89
Stainless	High	12843.06	571.88	19.88	1.19	1011.20	41.83
Stainless	High	13600.37	497.16	20.75	0.91	1043.45	53.78
Stainless	High	13687.89	785.60	20.68	1.31	1029.93	41.61
Stainless	High	13720.36	295.64	21.10	0.99	999.19	33.53
Stainless	High	13295.06	456.18	19.25	1.13	1016.62	45.73
Stainless	Low	12003.57	392.00	18.20	0.76	997.10	46.28
Stainless	Low	12342.44	572.58	18.00	1.65	1048.74	65.38
Stainless	Low	13529.51	326.83	20.76	0.94	1037.05	45.12
Stainless	Low	13065.35	458.69	19.68	1.02	1041.29	59.05
Stainless	Low	13351.58	398.28	19.82	0.73	1055.17	49.01
Stainless	Low	12660.41	374.99	17.91	0.85	1033.43	44.45
Polyester	High	10685.69	509.03	15.21	0.75	1084.14	61.83
Polyester	High	9467.50	718.54	14.00	1.08	1022.35	44.60
Polyester	High	9437.83	393.28	14.33	0.89	1017.44	42.57
Polyester	High	10113.16	591.92	14.62	1.05	1049.87	58.53
Polyester	High	10942.49	442.63	15.31	1.21	1110.00	75.97
Polyester	High	10265.04	385.47	16.06	1.31	1059.23	61.54
Polyester	Low	8703.43	397.61	14.14	1.99	1004.17	41.59
Polyester	Low	8443.99	502.32	13.29	1.16	999.19	49.86
Polyester	Low	8925.92	453.93	13.47	1.09	1021.63	44.25
Polyester	Low	10149.01	651.85	18.49	1.04	1049.61	52.96
Polyester	Low	9975.34	341.41	14.25	0.95	1062.34	58.48
Polyester	Low	9722.70	638.24	13.40	1.03	1030.28	61.63

Table 13. Printed line 4 with 76% silver concentration in ink.

4.2.2 Printed lines resistance.

4.2.2.1 Line resistance obtaining process.

The proceedings for this section are similar to the 4.2.1, first of all, giving a general description of the fundamentals of the measurement procedure used in the printed line resistance values obtaining. In the second place, some extra information of the current experiment will be added, in order to clarify some theoretical/practical points.

As starting point, it is necessary to select a device that can be able to measure the resistance of thin layers. Finally coming to the conclusion that the appropriate device to carry out the resistance measurements is a 4-point probe. A general sketch of a 4-point probe is shown in figure 19.

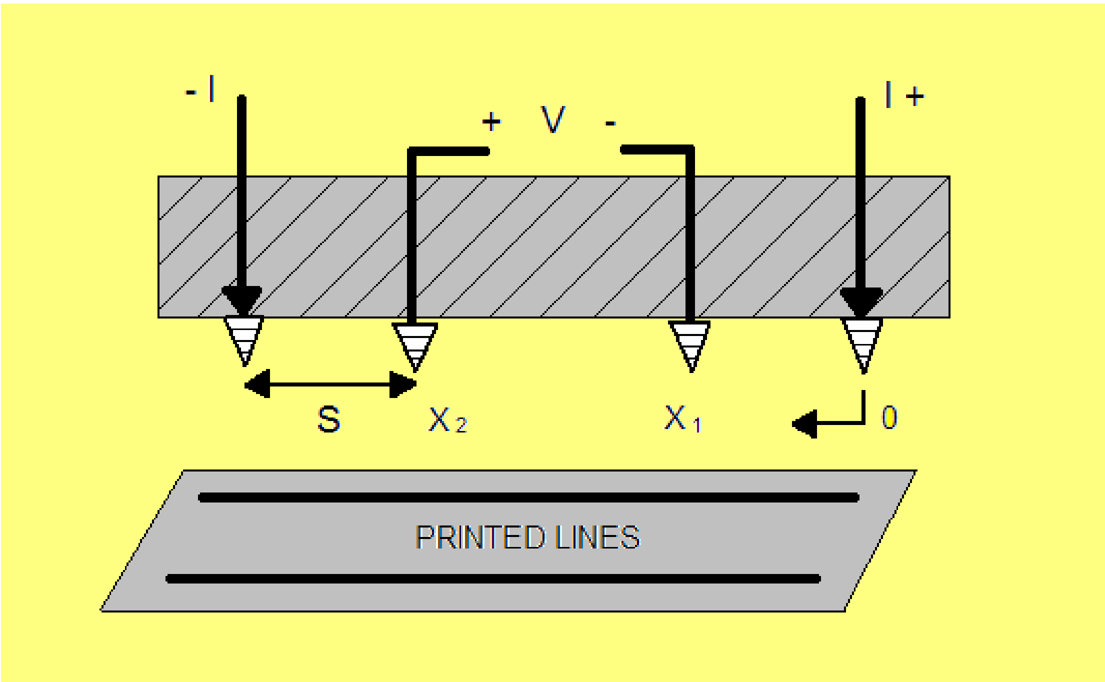

Figure 19. General sketch of a 4-point probe.

Basically, this device is characterised by possessing four tungsten metal tips with finite radius which will be used in couples to achieve the resistance measurement. Regarding to the basis of operation, the two outer probes are utilized to supply current to the sample under test by using a high impedance current source (to make the supplied current practically independent of the device under test). The inner two probes performs as a voltmeter and are used to determine the voltage that drops in the sample under test. Once the voltage is obtained and known the current supplied by the outer probes, the resistance associated to the region enclosed within the X_2 and X_1 points can be estimated. It is worth to comment in the resistance measurement, that the typical probe spacing, S, is 1 mm.

Once the practical resistance measurements, using the 4-point probe, are carried out the tip distances are to be established. Therefore, the separation between the two right-most tips is already fixed by theory to 1 mm. However, the distance between the voltage tips (internal measuring tips) needs to be set. In this particular experiment, the tip separation is set up to 20.5 mm, and this setting is maintained fixed throughout all the measurements.

The data to be acquired in this particular study is the resistance, although it is also very practical to provide information about the conductivity of the printed lines under test. Next the formula to obtain the value for the conductivity is listed.

$$\sigma = \frac{Length}{\mathrm{Re}\,sis\,\tan ce * Area}$$

Formula 1. Conductivity formula.

Nevertheless, a modification in the aforementioned expression is applied to include the information of the cross-section at both ends of the printed line under test. In short, the conductivity is weighed using the two cross-sectional values obtained for every line (two cross-sectional values are obtained for every printed line during the white light interferometer measurements). So the definite formula employed is shown next.

$$\sigma = \frac{Legth}{Resistance * \left(\frac{Area_1 + Area_2}{2} \right)}$$

Formula 2. Conductivity formula including both cross-sectional values acquired for the printed line during the white light interferometer measurements.

The conductivity value can contribute worthwhile information, in the sense of printing homogeneity. Initially, it is obvious to think that the conductivity of the screen ink should be the same if the material composition is not altered. In fact, this idea is right, however due to imperfections in the printing process the printed line is not totally homogeneous in terms of cross-section. This matter explains the occurrence of different conductivity results for the same screen ink composition (due to different resistance and cross-section values). In coming sections the conductivity results will be analysed.

Regarding to the laboratory equipment employed for the resistance measurements, it is composed by several units. In terms of software, the measuring unit uses ICS (Interactive Characterization Software from Metrics Technology Inc. Version 3.5.2). In terms of hardware, the system includes a work station, a Hewlett Packard 4142 source measurement unit, a connector interface and a 4-point probe Karl Suss MP4.

The ICS software provides easy set up for complex instrumentation through an interactive Microsoft Windows graphical user interface and requires no programming by the end user.

In order to configure the ICS software for the acquisition of resistance measurements, the Setup Editor is utilized. This is an option from the toolbar which offers measurement routines without writing a single line of code. The selection of the Device Under Test (DUT) is done by clicking on the source button, where the appropriate choice is “RES” (Resistance). Subsequently, its test fixture connections are created by clicking on the Source Unit button. Afterwards five different terminals (GNDU, SMU1, SMU2, SMU3, SMU4) are listed in a pop-up window at the right-hand side of the monitor's screen, where GNDU is assigned to one of the terminals as the ground and any of the other connectors can be chosen as the other end terminal. In the current experiment SMU2 is selected as one of the ends of the resistor (Printed line under test).

Next step consists of configuring the SMU2 for the measurements' acquisitions. By double clicking on the SMU2 icon, a pop-up window appears to set up the type of measurement to accomplish. Voltage and current are to be selected for resistance measurements, also the sweeping parameters are to be set up giving the start and stop current values and the number of samples to be acquired.

The last step before the obtaining of the resistance values is the plot set up, where voltage against current is the right option. Then click on the measure button and the graph will be generated.

Once the V-I graph has been generated, it is proceeded to import the aforementioned graph into an excel spreadsheet to calculate the slope of the curve which represents the resistance for the printed line under test.

In figure 20 an overview of the resistance measuring unit is shown. At the right-most side the 4-point probe can be found. At the left-hand side the other devices can be seen, where the Hewlett Packard 4142 is placed at the bottom, on its top the work station and the top-most the interface connector.

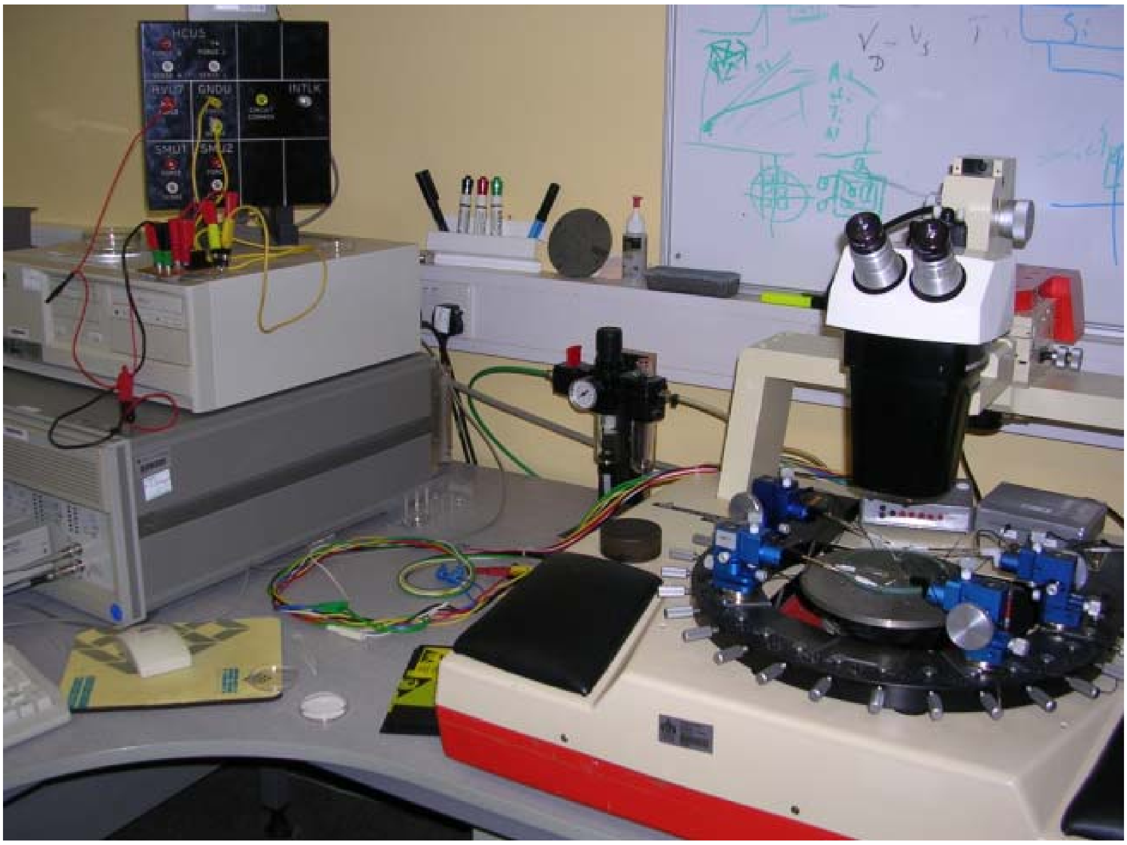

Figure 20. Overview of the resistance measuring unit.

4.2.2.2 4-Point probe measurements.

Throughout this section, all the resistance measurements carried out with the 4-point probe will be displayed in several tables as seen in section 4.2.1.4 for the white light interferometer measurements. The resistance measurements are applied to the same printed lines under test as in section 4.2.1.4 (Figure 16), being in total four lines. Regarding to the parameters under test and scenarios, the possible configurations of screen printed parameters are exactly the same as in previous sections (combinations composed by one of each possible values for the mesh material, the printing speed and the screen ink silver concentration). In order to clarify the last comments, it is convenient to refresh which are the screen printing parameters under test and which possible variants are available for study. Find next the possible choices where any combination of the three parameters can be selected.

- Printing speed: LOW HIGH
- Mesh material: POLYESTER STAINLESS STEEL
- Screen ink composition: 74% 75% 76% (*)

(*) In the case of screen ink composition, this parameter measures the concentration or percentage of silver in the ink.

The only remarkable difference with respect to the white light interferometer measurements is that instead of having six data per configuration, only three are obtained. The reason for this reduction of data is that the resistance only is needed for calculation once per line (resistance calculated all along the line) while the cross-section evaluation is done at both ends of the line. However the number of measurements is well enough to extract certain conclusions about the influence of the screen printing parameters over the printed lines resistance. The tables with the resistance measurements are listed next.

- Printed line 1.

Screen ink silver concentration	Mesh material	Printing speed	Resistance (Ω)	Conductivity (S/cm)
74%	Stainless	High	15.2026	7533.64
74%	Stainless	High	16.6729	6573.31
74%	Stainless	High	17.0527	6956.44
74%	Stainless	Low	21.6995	7010.02
74%	Stainless	Low	18.8161	7739.71
74%	Stainless	Low	16.6813	6832.39
74%	Polyester	High	16.9974	6369.68
74%	Polyester	High	16.0782	5480.94
74%	Polyester	High	18.1085	6271.06
74%	Polyester	Low	17.0833	6955.63
74%	Polyester	Low	18.0617	6656.61
74%	Polyester	Low	18.1991	5656.27
75%	Stainless	High	14.3147	7135.76
75%	Stainless	High	14.1594	7244.19
75%	Stainless	High	11.6055	9037.74
75%	Stainless	Low	14.0191	8501.32
75%	Stainless	Low	14.0884	7044.53
75%	Stainless	Low	13.3777	9360.49
75%	Polyester	High	13.4964	6287.42
75%	Polyester	High	12.2393	6298.62
75%	Polyester	High	11.3533	7616.66
75%	Polyester	Low	12.6782	8472.53
75%	Polyester	Low	14.0368	7475.59
75%	Polyester	Low	14.1456	8175.85

Table 14.1 Printed line 1 resistance measurements table(74% and 75%).

Screen ink silver concentration	Mesh material	Printing speed	Resistance (Ω)	Conductivity (S/cm)
76%	Stainless	High	6.8972	11915.88
76%	Stainless	High	8.1153	10864.35
76%	Stainless	High	7.6399	11225.79
76%	Stainless	Low	7.9378	13402.39
76%	Stainless	Low	8.6971	11233.25
76%	Stainless	Low	9.0262	10636.14
76%	Polyester	High	7.8277	11711.83
76%	Polyester	High	8.0583	10425.04
76%	Polyester	High	8.0178	11055.26
76%	Polyester	Low	8.2201	12985.85
76%	Polyester	Low	8.8915	10494.64
76%	Polyester	Low	8.1203	10551.75

Table 14.2 Printed line 1 resistance measurements table(76%).

- Printed line 2.

Screen ink silver concentration	**Mesh material**	**Printing speed**	**Resistance (Ω)**	**Conductivity (S/cm)**
74%	Stainless	High	10.7286	5533.91
74%	Stainless	High	12.7630	6245.97
74%	Stainless	High	10.1999	6665.06
74%	Stainless	Low	10.9500	6911.86
74%	Stainless	Low	11.4806	6251.17
74%	Stainless	Low	12.0577	5832.71
74%	Polyester	High	12.2330	5998.66
74%	Polyester	High	11.2526	6852.30
74%	Polyester	High	12.1541	6217.88
74%	Polyester	Low	14.6155	6750.10
74%	Polyester	Low	14.1864	6303.03
74%	Polyester	Low	13.3924	6172.17
75%	Stainless	High	7.3578	9492.86
75%	Stainless	High	6.9084	9649.05
75%	Stainless	High	7.9425	9255.77
75%	Stainless	Low	8.8608	8338.04
75%	Stainless	Low	9.3091	6806.11
75%	Stainless	Low	8.9008	7654.45
75%	Polyester	High	9.3653	8588.64
75%	Polyester	High	8.7808	8854.06
75%	Polyester	High	8.9692	9198.01
75%	Polyester	Low	11.8228	6805.28
75%	Polyester	Low	11.0490	8444.83
75%	Polyester	Low	10.6851	6636.73

Table 15.1 Printed line 2 resistance measurements table(74% and 75%).

Screen ink silver concentration	Mesh material	Printing speed	Resistance (Ω)	Conductivity (S/cm)
76%	Stainless	High	5.6835	10735.68
76%	Stainless	High	5.2712	12898.60
76%	Stainless	High	6.8839	9477.89
76%	Stainless	Low	5.5270	11997.66
76%	Stainless	Low	5.9237	12872.98
76%	Stainless	Low	6.0365	12200.58
76%	Polyester	High	6.0998	10612.06
76%	Polyester	High	6.2996	10152.96
76%	Polyester	High	6.1932	11221.87
76%	Polyester	Low	6.6979	10461.15
76%	Polyester	Low	6.7353	11084.36
76%	Polyester	Low	6.6572	10519.93

Table 15.2 Printed line 2 resistance measurements table(76%).

- Printed line 3.

Screen ink silver concentration	**Mesh material**	**Printing speed**	**Resistance (Ω)**	**Conductivity (S/cm)**
74%	Stainless	High	8.9125	5249.88
74%	Stainless	High	10.1548	4769.89
74%	Stainless	High	8.9885	4918.27
74%	Stainless	Low	9.6694	5558.80
74%	Stainless	Low	9.6338	5885.30
74%	Stainless	Low	9.5704	5343.42
74%	Polyester	High	10.1410	5873.10
74%	Polyester	High	10.4517	5669.14
74%	Polyester	High	9.9153	6276.31
74%	Polyester	Low	9.7575	7568.50
74%	Polyester	Low	10.7143	6310.44
74%	Polyester	Low	11.1914	6790.62
75%	Stainless	High	7.4129	6972.88
75%	Stainless	High	7.6076	6827.76
75%	Stainless	High	6.8808	7521.19
75%	Stainless	Low	7.5219	6645.41
75%	Stainless	Low	7.8224	6423.53
75%	Stainless	Low	7.7773	6440.98
75%	Polyester	High	7.6013	7524.08
75%	Polyester	High	7.2575	7642.42
75%	Polyester	High	7.4338	8212.74
75%	Polyester	Low	7.8930	6894.07
75%	Polyester	Low	8.7590	7586.17
75%	Polyester	Low	8.6271	8292.13

Table 16.1 Printed line 3 resistance measurements table(74% and 75%).

Screen ink silver concentration	**Mesh material**	**Printing speed**	**Resistance (Ω)**	**Conductivity (S/cm)**
76%	Stainless	High	4.0522	10344.22
76%	Stainless	High	3.3464	13579.38
76%	Stainless	High	3.6557	12715.27
76%	Stainless	Low	3.8950	13615.74
76%	Stainless	Low	4.1622	10977.61
76%	Stainless	Low	4.3170	10926.45
76%	Polyester	High	4.3949	12157.83
76%	Polyester	High	4.6045	12980.74
76%	Polyester	High	4.4393	13093.96
76%	Polyester	Low	5.6899	11438.75
76%	Polyester	Low	5.2625	11408.43
76%	Polyester	Low	5.8256	11978.69

Table 16.2 Printed line 3 resistance measurements table(76%).

- Printed line 4.

Screen ink silver concentration	Mesh material	Printing speed	Resistance (Ω)	Conductivity (S/cm)
74%	Stainless	High	2.6458	8567.62
74%	Stainless	High	3.1044	7383.56
74%	Stainless	High	3.6733	6976.12
74%	Stainless	Low	2.8018	8788.50
74%	Stainless	Low	2.7367	8435.15
74%	Stainless	Low	2.7315	8752.71
74%	Polyester	High	3.5710	6266.40
74%	Polyester	High	3.3764	7208.84
74%	Polyester	High	3.6985	7102.17
74%	Polyester	Low	3.3656	8901.11
74%	Polyester	Low	4.0250	6914.47
74%	Polyester	Low	4.1447	6907.54
75%	Stainless	High	2.3519	8746.95
75%	Stainless	High	2.3289	9398.57
75%	Stainless	High	2.1324	9486.31
75%	Stainless	Low	2.1449	9939.56
75%	Stainless	Low	2.3229	9990.81
75%	Stainless	Low	2.3242	9668.92
75%	Polyester	High	2.7633	8722.93
75%	Polyester	High	2.7598	8635.38
75%	Polyester	High	2.7580	9554.65
75%	Polyester	Low	2.9937	8716.65
75%	Polyester	Low	3.2270	8445.08
75%	Polyester	Low	3.1707	8842.95

Table 17.1 Printed line 4 resistance measurements table(74% and 75%).

Screen ink silver concentration	Mesh material	Printing speed	Resistance (Ω)	Conductivity (S/cm)
76%	Stainless	High	1.2892	12185.17
76%	Stainless	High	1.0663	14090.57
76%	Stainless	High	1.1699	12972.49
76%	Stainless	Low	1.2957	12997.25
76%	Stainless	Low	1.3586	11347.35
76%	Stainless	Low	1.4659	10752.41
76%	Polyester	High	1.6538	12301.47
76%	Polyester	High	1.6500	12709.58
76%	Polyester	High	1.6366	11812.76
76%	Polyester	Low	2.9930	7988.74
76%	Polyester	Low	1.8679	11507.14
76%	Polyester	Low	1.8065	11521.87

Table 17.2 Printed line 4 resistance measurements table(76%).

4.3 Experiment conclusions.

First of all, it is convenient to brief the steps followed to get all the measurements and how they will be organised in this section, secondly the summarised data will be listed and subsequently several graphs will be displayed to extract some relevant information about how the experiment parameters affect the final results.

In order to refresh which are the screen printing parameters under test and which possible variants are available for study, find next the possible choices where any combination of the three parameters can be selected as a possible printed line configuration.

- Printing speed: LOW HIGH
- Mesh material: POLYESTER STAINLESS STEEL
- Screen ink composition: 74% 75% 76% (*)

(*) In the case of screen ink composition, this parameter measures the concentration or percentage of silver in the ink.

Basically, in previous sections two different experiments were carried out, a dimensional printed line acquisition and a resistance line obtaining. The former was evaluated by employing a white light interferometer device (information available in section 4.2.1.1 Line dimensions obtaining process and also in section 4.2.1.2 Image processing description), and after a suitable post-processing of the acquired image some worthwhile data were obtained such as **cross-section**, **maximum height** and **width** of the different silver printed lines. The latter is an experiment which makes use of a 4-point probe as the device to characterise the **printed line resistance** (more information in section 4.2.2.1 Line resistance obtaining process).

Once the procedures followed in previous sections have been refreshed, let's see how to summarise all the available information into a more compact format. Thus, there are several acquired values for every printed line that need to be averaged.

In the case of the line dimension acquisition, there are 6 different dimensional values which will be averaged as one. These values correspond with 3 samples with the same configuration, in terms of screen printing parameters, plus two more measurements per sample, at both ends of the line under test. Additionally, the standard deviation of the values also will be averaged to offer information about the dispersion of the data.

In the case of the line resistance obtaining, there are 3 different values which will be averaged as one. These values correspond with 3 samples with the same configuration, in terms of screen printing parameters. Additionally, the standard deviation of the values also will be averaged to offer information about the dispersion of the data.

It should be remarked before extracting any conclusions that the measurements obtained for the printed lines' dimensions should be used as a guidance only and not as a definitive rule of design, due to possible flaws in the measurements' obtaining. The possible defects can come from the fact that the dimensions are calculated within the range of sight given by the white light interferometer, however this measuring coverage corresponds with a small region of the whole length of the printed line. Maximum effort was applied in the sense of selecting a very regular and representative region of the line under test, and two measurements per line were obtained to average the values. Although the results could not be 100% accurate, they are good enough to give an idea of the interaction between the different printing parameters and the results obtained.

Next the tables that gather all the information available for every particular printed line are listed.

- Printed line 1.

Mesh Material	Printing Speed	Cross-sectional Area (µm2)		Maximum Height (µm)		Width (µm)		Resistance (Ω)		Conductivity (S/cm)	
		Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
74%											
Stainless	High	1796.18	202.08	11.11	1.15	269.41	32.50	16.3094	0.9771	7021.13	483.42
Stainless	Low	1518.18	202.46	9.88	1.15	250.94	28.56	19.0656	2.5184	7194.04	480.84
Polyester	High	2008.32	315.98	10.46	1.58	338.52	39.84	17.0614	1.0167	6040.56	487.15
Polyester	Low	1871.76	268.79	10.41	1.69	334.74	41.85	17.7814	0.6084	6422.84	680.49
75%											
Stainless	High	1986.66	234.33	11.40	1.13	288.50	36.68	13.3599	1.5213	7805.90	1068.18
Stainless	Low	1807.58	206.65	10.61	0.92	288.09	42.78	13.8284	0.3919	8302.11	1170.76
Polyester	High	2481.84	304.26	12.93	1.52	373.82	34.76	12.3630	1.0769	6734.23	764.22
Polyester	Low	1878.21	227.94	9.95	1.45	344.77	41.19	13.6202	0.8176	8041.32	511.90
76%											
Stainless	High	2403.33	198.39	12.92	1.28	311.02	36.93	7.5508	0.6139	11335.34	534.26
Stainless	Low	2066.20	172.19	12.27	1.17	272.71	27.71	8.5537	0.5582	11757.26	1455.67
Polyester	High	2329.71	239.29	11.27	1.03	342.92	83.75	7.9679	0.1231	11064.04	643.44
Polyester	Low	2169.97	170.22	11.03	0.84	330.74	34.43	8.4106	0.4194	11344.08	1422.10

Table 18. Summarisation of all the characteristics of line 1 with all parameters previously weighed.

- Printed line 2.

Mesh Material	Printing Speed	Cross-sectional Area (µm2) Average	Cross-sectional Area (µm2) Standard Deviation	Maximum Height (µm) Average	Maximum Height (µm) Standard Deviation	Width (µm) Average	Width (µm) Standard Deviation	Resistance (Ω) Average	Resistance (Ω) Standard Deviation	Conductivity (S/cm) Average	Conductivity (S/cm) Standard Deviation
74%											
Stainless	High	3013.30	235.07	13.90	1.38	362.36	41.23	11.2305	1.3533	6148.31	571.86
Stainless	Low	2826.64	224.49	13.59	1.32	352.92	41.54	11.4961	0.5040	6331.91	544.09
Polyester	High	2721.64	261.29	11.45	1.26	430.12	47.94	11.8799	0.5447	6356.28	443.33
Polyester	Low	2283.53	300.26	10.45	1.44	406.33	50.92	14.0648	0.6206	6408.43	303.04
75%											
Stainless	High	2932.97	291.71	13.60	1.36	352.19	35.02	7.4029	0.5185	9465.89	198.02
Stainless	Low	3006.39	330.49	13.63	1.35	367.86	42.56	9.0236	0.2481	7599.53	767.44
Polyester	High	2556.77	256.58	10.89	1.43	425.61	39.58	9.0384	0.2983	8880.24	305.53
Polyester	Low	2545.27	274.80	10.98	1.28	418.26	44.32	11.1856	0.5810	7295.61	998.81
76%											
Stainless	High	3172.35	171.92	14.58	1.00	351.11	28.10	5.9462	0.8378	11037.39	1730.20
Stainless	Low	2854.43	165.53	13.26	0.86	340.40	31.83	5.8291	0.2676	12357.07	458.16
Polyester	High	3107.25	183.15	13.09	1.00	391.92	35.64	6.1975	0.1000	10662.30	536.22
Polyester	Low	2866.28	171.65	14.66	0.90	380.53	32.13	6.6968	0.0391	10688.48	344.10

Table 19. Summarisation of all the characteristics of line 2 with all parameters previously weighed.

- Printed line 3.

Mesh Material	Printing Speed	Cross-sectional Area (µm2)		Maximum Height (µm)		Width (µm)		Resistance (Ω)		Conductivity (S/cm)	
		Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
74%											
Stainless	High	4416.93	310.10	16.57	1.88	464.83	41.02	9.3519	0.6963	4979.35	245.75
Stainless	Low	3812.77	272.50	14.69	1.41	433.98	38.10	9.6245	0.0501	5595.84	272.83
Polyester	High	3398.63	339.47	12.55	1.24	473.60	46.16	10.1693	0.2693	5939.52	308.99
Polyester	Low	2835.14	319.23	11.18	1.34	446.20	41.51	10.5544	0.7302	6889.85	634.87
75%											
Stainless	High	3957.96	274.99	15.19	1.49	440.98	37.67	7.3004	0.3762	7107.28	365.73
Stainless	Low	4091.10	321.45	15.20	1.38	442.46	34.39	7.7072	0.1621	6503.31	123.37
Polyester	High	3546.07	310.20	12.91	1.51	485.61	69.48	7.4309	0.1719	7793.08	368.22
Polyester	Low	3239.39	282.27	12.04	1.29	483.76	40.97	8.4264	0.4666	7590.79	699.04
76%											
Stainless	High	4604.02	195.41	16.44	0.82	439.57	30.86	3.6848	0.3538	12212.96	1675.05
Stainless	Low	4232.73	212.59	15.82	0.98	422.92	29.88	4.1247	0.2135	11839.93	1538.11
Polyester	High	3597.72	238.93	13.53	0.98	431.47	32.45	4.4796	0.1104	12744.18	510.94
Polyester	Low	3167.32	334.47	12.75	1.10	414.48	42.59	5.5927	0.2939	11608.62	320.85

Table 20. Summarisation of all the characteristics of line 3 with all parameters previously weighed.

- Printed line 4.

Mesh Material	Printing Speed	Cross-sectional Area (µm2)		Maximum Height (µm)		Width (µm)		Resistance (Ω)		Conductivity (S/cm)	
		Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
74%											
Stainless	High	8662.32	603.21	15.10	2.19	898.12	42.97	3.1412	0.5147	7642.43	826.73
Stainless	Low	8593.43	399.53	15.30	1.17	937.89	41.70	2.7567	0.0392	8658.79	194.50
Polyester	High	8462.60	570.98	14.34	134	998.95	62.72	3.5486	0.1622	6859.14	516.09
Polyester	Low	7123.12	345.40	12.99	1.50	1021.62	44.13	3.8451	0.4196	7574.37	1148.99
75%											
Stainless	High	9821.64	325.53	16.96	1.26	980.29	37.29	2.2711	0.1206	9210.61	403.93
Stainless	Low	9023.74	385.11	15.35	1.27	984.62	41.83	2.2640	0.1031	9866.43	172.96
Polyester	High	8295.36	386.49	13.11	1.15	1062.89	44.88	2.7604	0.0027	8970.99	507.36
Polyester	Low	7563.21	450.51	11.91	1.05	1063.95	50.86	3.1305	0.1217	8668.23	203.31
76%											
Stainless	High	13400.53	541.72	20.38	1.12	1017.54	42.56	1.1751	0.1115	13082.74	957.47
Stainless	Low	12825.48	420.56	19.06	0.99	1035.46	51.55	1.3734	0.0861	11699.00	1163.00
Polyester	High	10151.95	506.81	14.92	1.05	1057.17	57.51	1.6468	0.0090	12274.60	449.01
Polyester	Low	9320.07	497.56	14.51	1.21	1027.87	51.46	2.2225	0.6680	10339.25	2035.61

Table 21. Summarisation of all the characteristics of line 4 with all parameters previously weighed.

Some useful extra information to be included, in order to facilitate the understanding of the measurements acquired, is the mesh dimensions. Basically, the information in this respect consists of providing the width in micrometers of each of the printed lines on the mesh template for every mesh implementation (Polyester and Stainless steel).

The usefulness of this information is especially focused on the comparison of the printed lines' theoretical and printed shape. The values shown in table 22 are the actual lines' width on the mesh material, hence the theoretically printed lines' width. However, the current printed lines' width printed are somewhat different due the flow process that occurs after the printing process.

Width (μm)	**Line 1**	**Line 2**	**Line 3**	**Line 4**
Polyester	160.20	272.89	351.88	1050.67
Stainless Steel	141.41	239.19	333.10	1031.33

Table 22. Width of the mesh template for every printed line.

The analysis of the information will be assessed by following two directions. On one hand, the screen printing parameters will be related to the cross-section and the resistance data, providing a description of how the different parameters' configurations affect the results. On the other hand, the width, the maximum height and the conductivity data will be employed to describe how the parameters under test affect the shape of the lines' profile.

First of all, and in order to offer a better understanding of the extraction of the conclusions, some figures representing the printed lines' cross-section for every configuration are provided (Cross-section in μm2). Therefore, the cross-section is depicted as a function of the screen ink silver concentration, following a segmented line representation. At every silver concentration, there are 4 possible configurations Stainless Steel-High Speed, Stainless Steel-Low Speed, Polyester-High Speed and Polyester-Low Speed where each of them is displayed, and subsequently analysed.

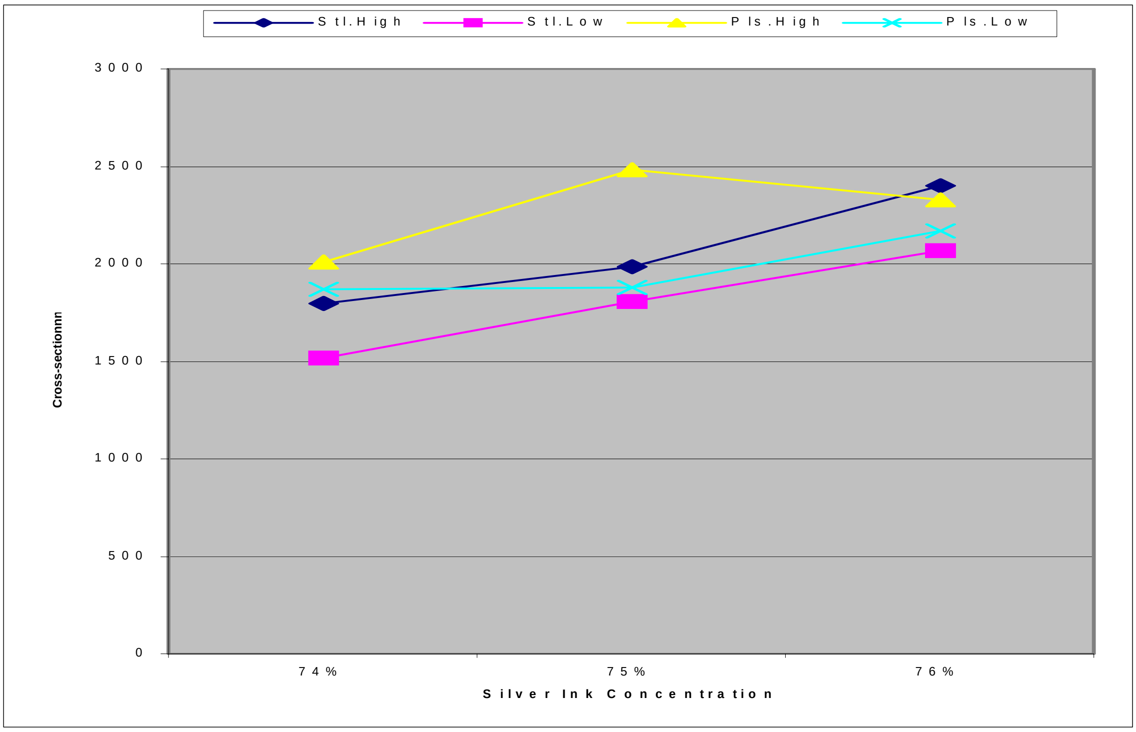

Figure 21. Printed line 1 Cross-section – Silver concentration representation.

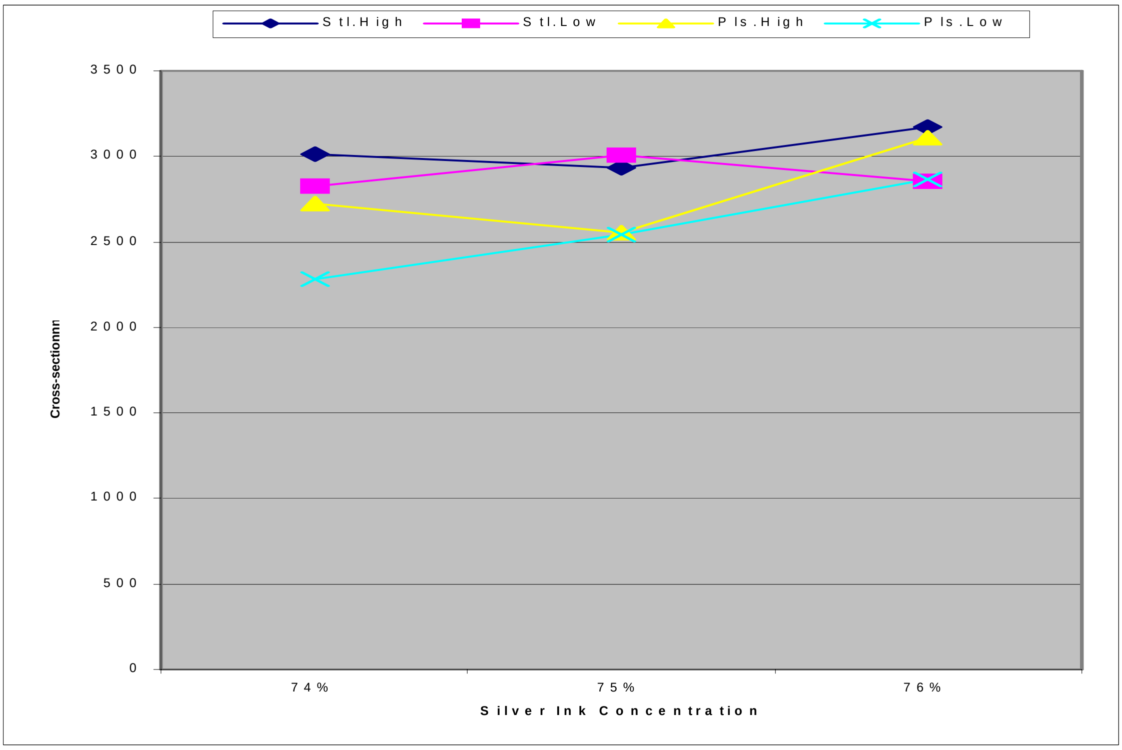

Figure 22. Printed line 2 Cross-section – Silver concentration representation.

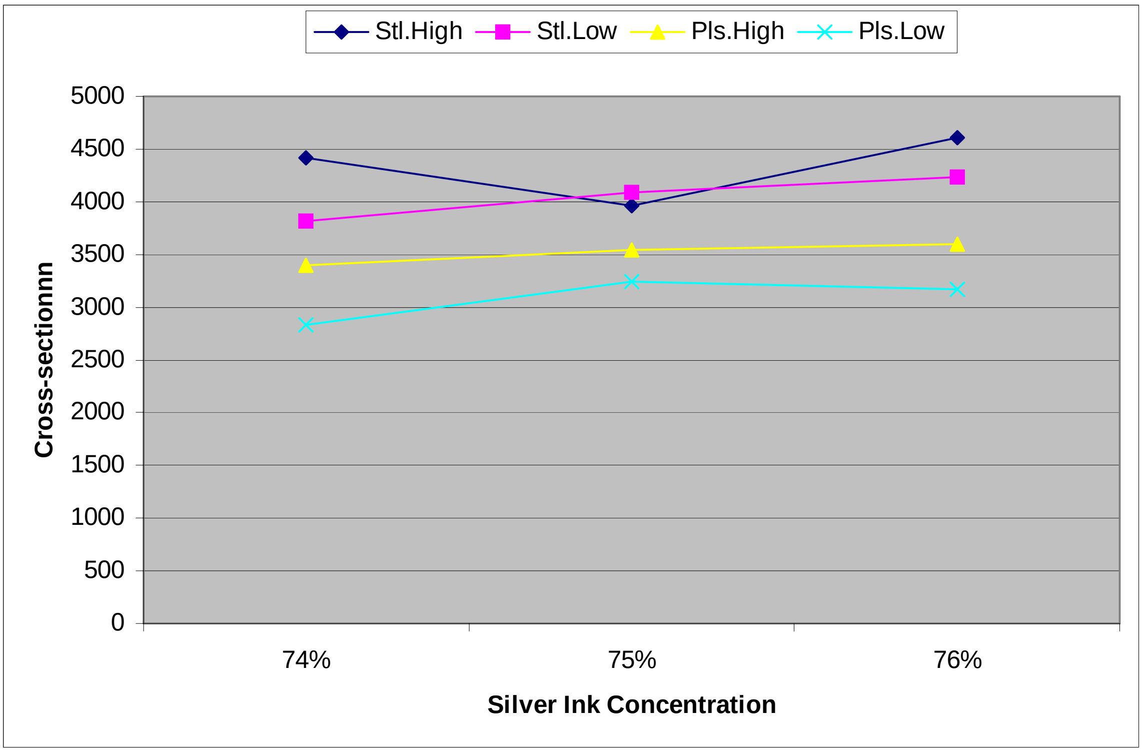

Figure 23. Printed line 3 Cross-section – Silver concentration representation.

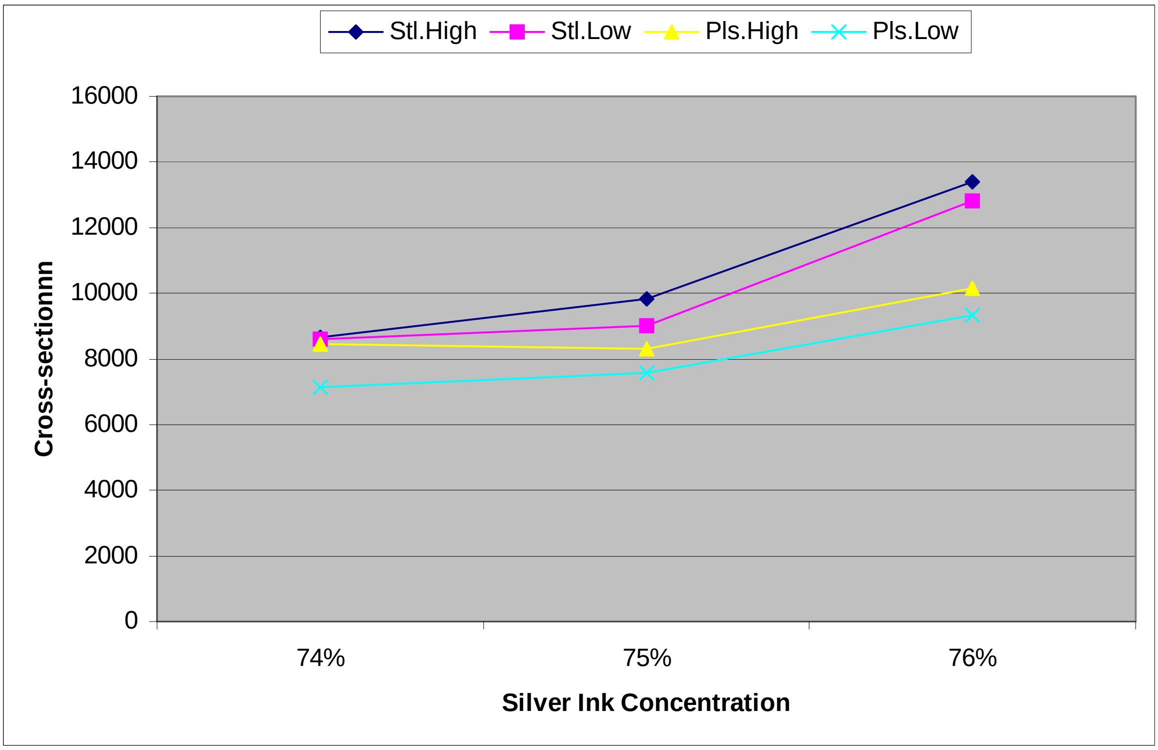

Figure 24. Printed line 4 Cross-section – Silver concentration representation.

A suitable procedure to extract conclusions is to compare the screen printing parameters one by one, that is to say, in first instance the printing speed is assessed, proceeding in second instance with the mesh material and finally the screen ink concentration.

Regarding to the printing speed parameter the results obtained are :

- 91.67% High Speed produces greater Cross-sectional Area.
- 8.33% Low Speed produces greater Cross-sectional Area.

Regarding to the mesh material parameter the results obtained are classified into two group of data, due to the finding of two different tendencies in the results:

1. Printed line 1

- 16.66% Stainless Steel mesh produces greater Cross-sectional Area.
- 83.33% Polyester mesh produces greater Cross-sectional Area.

2. Printed lines 2, 3 and 4

- 94.44% Stainless Steel mesh produces greater Cross-sectional Area.
- 5.56% Polyester mesh produces greater Cross-sectional Area.

Finally, the screen ink concentration parameter is assessed:

- 81.25% 76% silver ink concentration produces greater Cross-sectional Area.
- 18.75% 75% silver ink concentration produces greater Cross-sectional Area.

- 75% 75% silver ink concentration produces greater Cross-sectional Area.
- 25% 74% silver ink concentration produces greater Cross-sectional Area.

As it can be seen from the analysis of the measurements, greater cross-sections can be very likely obtained by selecting high printing speed, bigger silver concentrations in ink and depending on the line's width by using either polyester or stainless steel.

The appropriate selection of a particular configuration of the screen printing parameters will depend on the kind of application to be achieved, in the case of searching for a fine printed line, it is obvious that the cross-section should be minimised. Therefore, the suitable solution in this particular case should be to select 74% screen ink silver concentration, stainless steel and low printing speed. In the case that the implementation is to be to achieved with a great cross-section, the best solution would be to select high printing speed, great ink silver concentration and stainless steel mesh material.

Once the cross-section data has been characterised, the next step is to analysed the resistance results (Resistance values in Ω). First of all, let's start providing some figures as a help in the interpretation of the information. Each of these figures corresponds with each the printed lines under test.

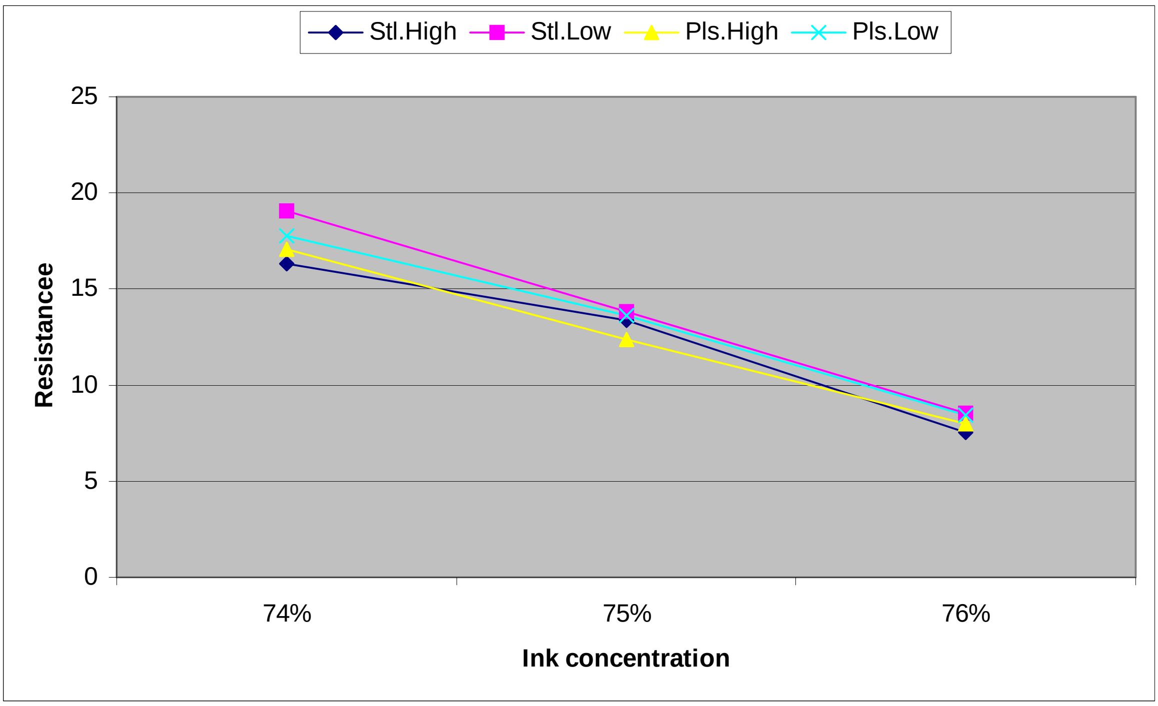

Figure 25. Printed line 1 Resistance – Silver concentration representation.

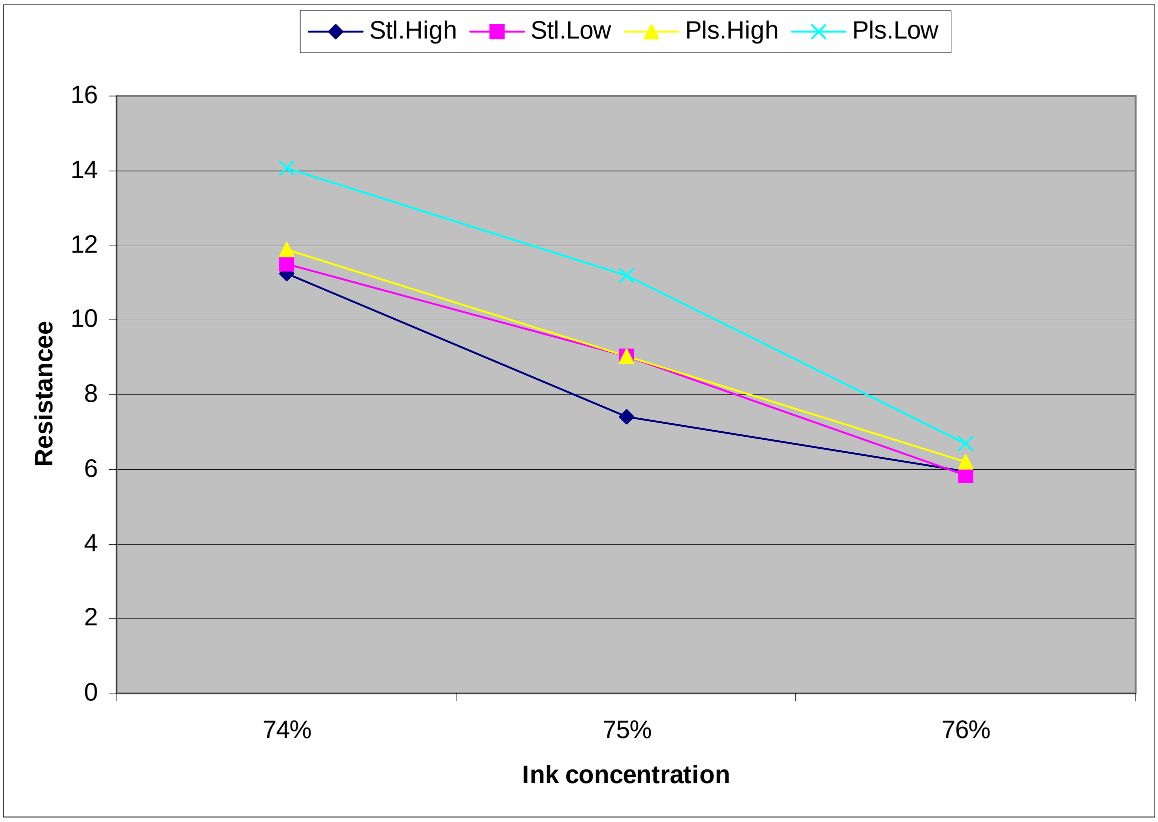

Figure 26. Printed line 2 Resistance – Silver concentration representation.

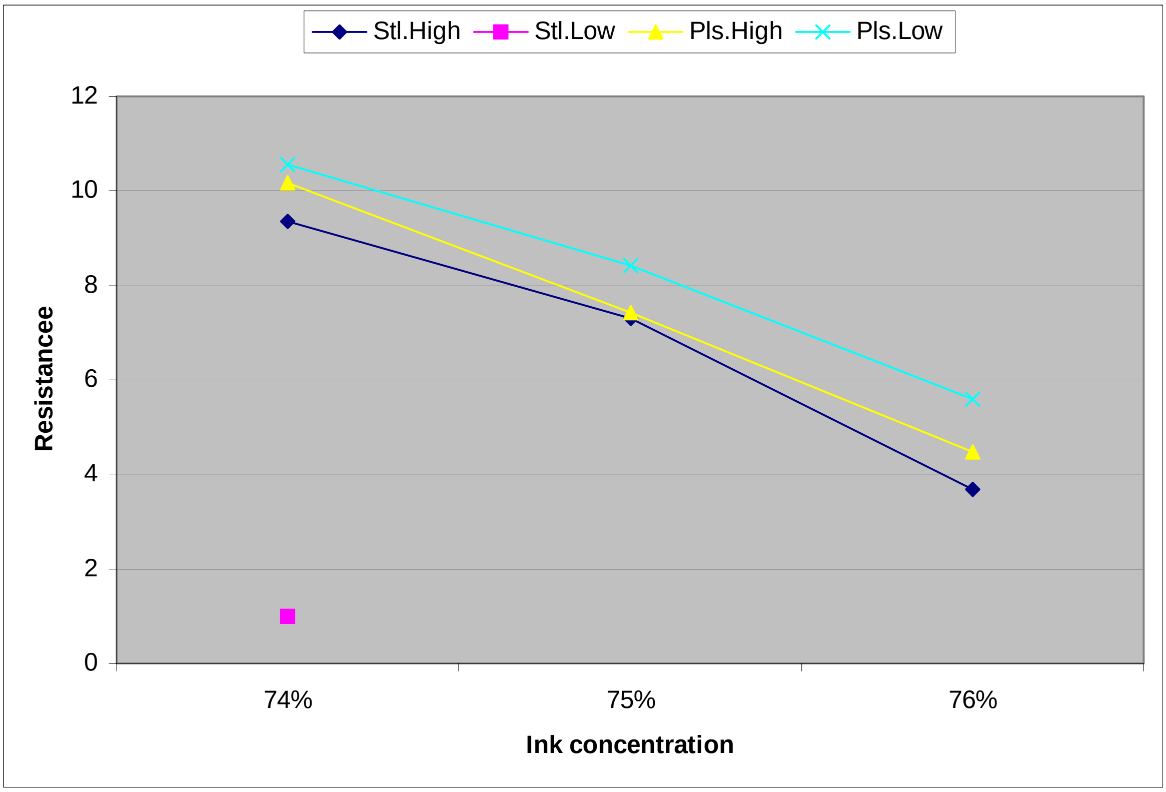

Figure 27. Printed line 3 Resistance – Silver concentration representation.

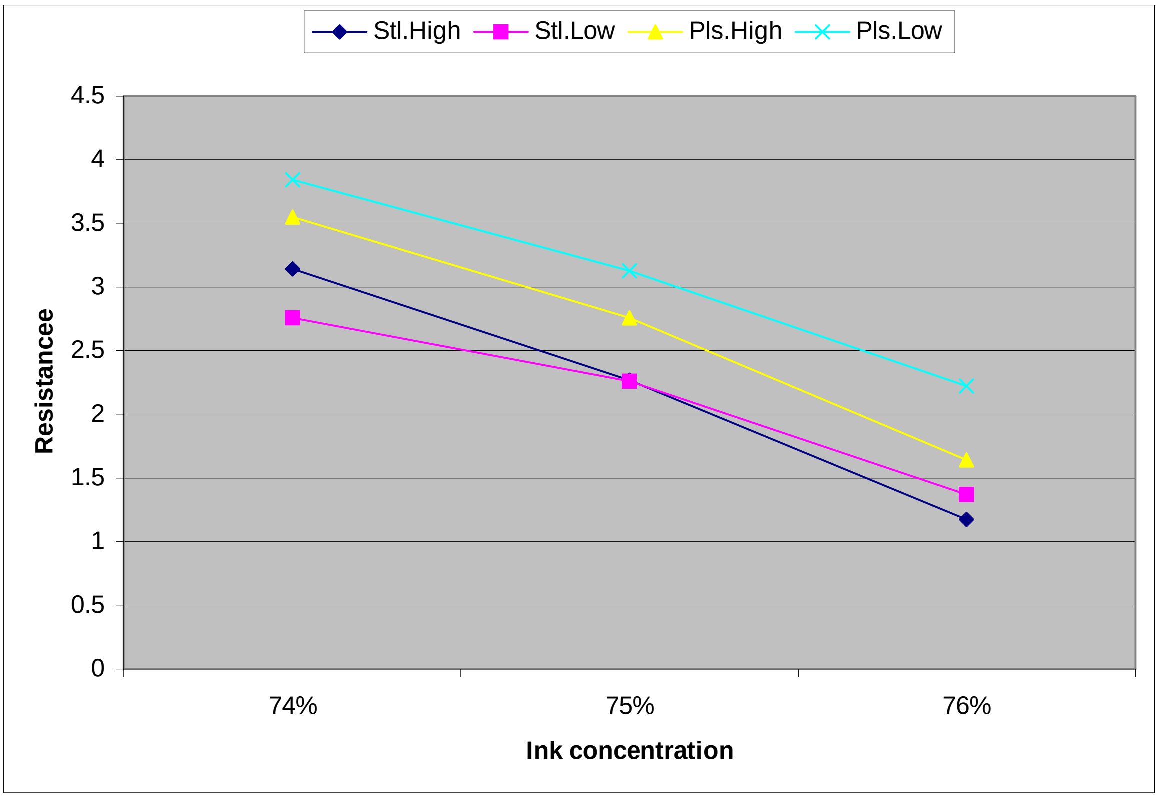

Figure 28. Printed line 4 Resistance – Silver concentration representation.

The procedure to analyse the resistance results will be similar to the one employed in the case of the cross-section´s assessment by analysing the screen printing parameters one by one. In first instance the printing speed is assessed, proceeding in second instance with the mesh material and finally the screen ink concentration.

Regarding to the printing speed parameter the results obtained are :

- 87.5% Low Speed produces greater Resistance.
- 12.5% High Speed produces greater Resistance.

Regarding to the mesh material parameter the results obtained are classified into two group of data, due to the finding of two different tendencies in the results:

1. Printed line 1

- 66.67% Stainless Steel mesh produces greater Resistance.
- 33.33% Polyester mesh produces greater Resistance

2. Printed lines 2, 3 and 4

- 0.00% Stainless Steel mesh produces greater Resistance.
- 100% Polyester mesh produces greater Resistance.

Finally, the screen ink concentration parameter is assessed:

- 100% 74% silver ink concentration produces greater Resistance than 75% and 76% silver ink concentrations.
- 0.00% 75% silver ink concentration produces greater Resistance than 74% silver ink concentration.

- 100% 75% silver ink concentration produces greater Resistance than 76% silver ink concentration.
- 0.00% 76% silver ink concentration produces greater Resistance than 75% silver ink concentration.

As it can be seen from the analysis of the measurements, greater resistances can be very likely obtained by selecting low printing speed, lower silver concentrations in ink and depending on the line's width by using either polyester or stainless steel.

The appropriate selection of a particular configuration of the screen printing parameters will depend on the kind of application to be achieved, in the case of searching for a fine printed line with a minimum power consumption, it is obvious that the resistance should be minimised. Therefore, the suitable solution in this particular case should be to select 76% screen ink silver concentration, polyester mesh material and high printing speed. This solution is directly related to the selection of a greater cross-section, because the greater the cross-section the smaller the resistance. However in case a fine line is to be achieved, a trade-off has to be establish between the size of the printed line and the final resistance.

For instance, once a printed line's maximum width is established as a requirement of the design, then the resistance could be minimised by using a particular screen printing settings. By these means, the cross-section can be slightly increased while trying to keep the width smaller than the maximum value required.

One fact that is worth mentioning is the silver ink concentration, in the sense of added price to the final product. Normally, any application is designed in order to minimised the power consumption, and referring to the printed lines directly related to the optimisation of their resistance. This means that because we want the power consumption to be reduced to values as low as possible, then obviously the resistance values should be kept to the minimum. However, this fact is directly related to the printed lines' cross-section, in the sense that the higher the cross-section the smaller the resistance, and this also means the more the use of silver ink material and the higher the expenditures in the manufacturing process. Therefore, this is an important constraint in the design process, a real trade-off between price and performance.

So far, the results analysed have been the corresponding to the resistance and the cross-section of the printed lines. From this point on, it is proceeded to the analysis of the rest of the results towards the obtaining of some conclusions in the respect of printed lines' shape. First of all, the width is analysed parameter by parameter.

Regarding to the printing speed parameter the results obtained are classified into two group of data, due to the finding of two different tendencies in the results:

1. Printed line 1,2 and 3

- 88.88% High Speed produces greater Width.
- 11.12% Low Speed produces greater Width.

2. Printed lines 4

- 16.67% High Speed produces greater Width.
- 83.33% Low Speed produces greater Width.

Regarding to the mesh material parameter the results obtained are:

- 12.5% Stainless Steel mesh produces greater Width.
- 87.5% Polyester mesh produces greater Width.

Finally, the screen ink concentration parameter is assessed:

- 18.75% 74% silver ink concentration produces greater Width than 75% and 76% silver ink concentrations.
- 62.5% 75% silver ink concentration produces greater Width than 74% and 76% silver ink concentrations.
- 18.75% 76% silver ink concentration produces greater Width than 74% and 75% silver ink concentrations.

As it can be seen from the last results, the influence of the screen printing parameters over the printed lines' width is conspicuous and obvious. In most of the cases the aim will be to reduce to a minimum the width in order to implement a fine line, in this respect the solution would consist of selecting low printing speed and either 74% or 76% silver ink concentrations. The mesh material can not be directly related from the last results, due to the different width values for the polyester mesh template and the stainless steel mesh template as seen in table 22.

In order to extract some information from the mesh materials, it is necessary to obtain first the relative line width. Which consists of two factors where one of them is obtained by dividing the maximum width for a particular printed line sample using a certain mesh material by the actual width of the mesh template for that particular printed line. The other factor is obtained by dividing the minimum width for a particular printed line using a certain mesh material by the actual width of the mesh template for that particular printed line. The table 23 contains the relative line width factors for every printed line and is listed as follows.

Relative Line Width	Line 1	Line 2	Line 3	Line 4
Polyester Low factor	2.09	1.39	1.18	0.95
Polyester High factor	2.33	1.58	1.38	1.01
Stainless Steel Low factor	1.77	1.42	1.27	0.87
Stainless Steel High factor	2.20	1.54	1.40	1.00

Table 23. Relative line width factors for every printed line size.

From table 23 it can be deduced how the mesh material affects over the printed lines' width. Therefore, polyester meshes generally produce greater widths than stainless steel meshes, although stainless steel meshes possesses bigger mesh openings what allows an easier paste flow. In case a fine line is to be manufactured, then the appropriate choice is a stainless steel mesh.

Regarding to the conductivity values, the results obtained for the samples printed using the same silver ink concentration should match. However it can be seen from tables 18, 19, 20 and 21 that the actual values for a particular silver concentration vary for every sample. This fact occurs due to the roughness of the printed surface, which ideally should be as smooth and pinhole-free as possible. Nevertheless, the selection of a convenient screen printing parameters' configuration can help in this respect, in order to obtain smoother results.

Now it is turn to utilize the maximum height and the average height to address the conclusions towards the printed lines' shape. Where the average height is calculated by dividing the cross-section by the width. Basically, the idea is to assess how the different configurations produce diverse heights. By combining the height and the width results, it can be deduced that it is possible to contribute somehow to the final shape line by selecting a particular screen printing parameters configuration.

Next the table 24 shows the average height and the maximum height values for three of the four printed lines. The reason of not displaying the fourth line is due the fact that the aforementioned values follow a trend, being enough with three of the lines to extract trustworthy conclusions.

Mesh Material	**Printing Speed**	**Line 1**		**Line 2**		**Line 3**	
		Average Height (μm)	**Maximum Height (μm)**	**Average Height (μm)**	**Maximum Height (μm)**	**Average Height (μm)**	**Maximum Height (μm)**
74%							
Stainless	High	6.67	11.11	8.32	13.9	9.50	16.57
Stainless	Low	6.05	9.88	8.01	13.59	8.79	14.69
Polyester	High	5.93	10.46	6.33	11.45	7.18	12.55
Polyester	Low	5.59	10.41	5.62	10.45	6.35	11.18
75%							
Stainless	High	6.89	11.4	8.33	13.6	8.98	15.19
Stainless	Low	6.27	10.61	8.17	13.63	9.25	15.2
Polyester	High	6.64	12.93	6.01	10.89	7.30	12.91
Polyester	Low	5.45	9.95	6.09	10.98	6.70	12.04
76%							
Stainless	High	7.73	12.92	9.04	14.58	10.47	16.44
Stainless	Low	7.58	12.27	8.39	13.26	10.01	15.82
Polyester	High	6.79	11.27	7.93	13.09	8.34	13.53
Polyester	Low	6.56	11.03	7.53	14.66	7.64	12.75

Table 24. Average height and maximum height values for lines 1,2 and 3.

From table 24, it can be seen that generally the average and the maximum height values perform similarly. Therefore, the maximum height can offer a rough idea of the distribution of the height of the printed line. Although a better approach can be done by means of using the average height values for every printed line configuration. Some information can be inferred in this way of a very likely distribution ink pattern.

By assessing the average height values, it can be easily observed which is the trend followed. Hence, the configuration which generally provides the maximum height values is the stainless steel and high printing speed one, where the bigger the silver concentration, the bigger the height obtained. This configuration is followed by stainless steel and low printing speed, coming next polyester and high printing speed, and finally polyester and low printing speed configuration.

Comparing this results with the cross-section and width results, it can be extracted some interesting key points, in the sense of the production of fine lines. Clearly speaking, when producing a fine line (printed line 1, in this experiment) certain requirements should be fulfilled like a good average height for low resistance, a minimised width and smooth surface to avoid the existence of pinholes for good performance when designing multiple layer devices such as OLED applications. Therefore, a very good solution is to choose stainless steel mesh material due to the good effects regarding to the average height. Moreover the stainless steel samples are characterised for producing smaller widths than the polyester ones, and a smoother surface. The selection of the printing speed implies a trade-off between the width and the height of the printed line, that is to say, high speed produces greater width and height than the low speed, which is good for the resistance but increases the final size. In the case of low printing speed, it behaves inversely to the high speed. And finally, the screen ink silver concentration offers good qualities where the bigger the concentration, the lower resistance and the greater the final size and price.

So, the selection of the screen printing parameters is application dependant and it is a factor to be taken into account before stepping ahead in the design. Thus, the final performance and price will be directly related to the solution selected.

5. IMPLEMENTATION OF AN APPLICATION

The information obtained for the screen printing parameters under study can be very practical, especially when approaching the implementation of a printed application that requires the fabrication of fine lines. Although the parameters involved in the printing process can reach up to 50, the ones that forms this study can give a good approximation of the characteristics that can be finally achieved. For instance, the physical and electrical characteristics can be effectively estimated and a feasibility study can be carried out from the information obtained.

The results of this project where actively used by the Printing and Coating Department of the University of Wales Swansea in order to develop a printed application. In fact, due to the confidentiality of the project not many details can be provided but a direct relation can be established when carrying out the feasibility study.

The project consisted of several stages described as follows:

1. **Material resource.**

   This stage of the project will require technical specifications of the materials required for the trial, primarily the ink and the screen. The ink resistivity, ink drying, etc. are issues to be taken into account when deciding the screen ink material. The ink film thickness required will be used to determine the mesh characteristics like mesh ruling, mesh material, etc, in order to provide a suitable thickness and roughness.

   At the end of this stage recommendations for a commercial ink system which will provide the necessary physical and electrical properties will be provided.

2. **Small scale prototype.**

   This stage will require the printing of several layers such as a possible adhesion promoter, tracks in X direction, dielectric layer 1, dielectric layer 2, tracks in Y direction followed by an insulator. The dielectric layer is printed twice in order to provide a flatter surface for the second conductive layer and to ensure that there is no electrical contact between the horizontal and the vertical conducting lines.

Samples of all the processes will be produced in order to study the characteristics of every printed layer, for instance obtaining measurements of the intermediate film thickness and roughness.

3. Analysis of prototype.

This stage will examine the physical and electrical characteristics of the samples obtained in the previous stage, providing a functional testing of the prototype. The aim of this stage is to assess the possible reduction of the line thickness and the use of a single dielectric layer. White light interferometry will be used to measure the conductor layer thickness and width, and the interlayer roughness of the dielectric layers.

4. Full size prototype.

Refinement of the manufacturing procedure through the potential elimination of the second dielectric layer and the use of thinner lines are the aims of this final stage.

In the figure 29, the practical design or final draft of the application is shown, where due to confidentiality issues the numerical characteristics have been hidden.

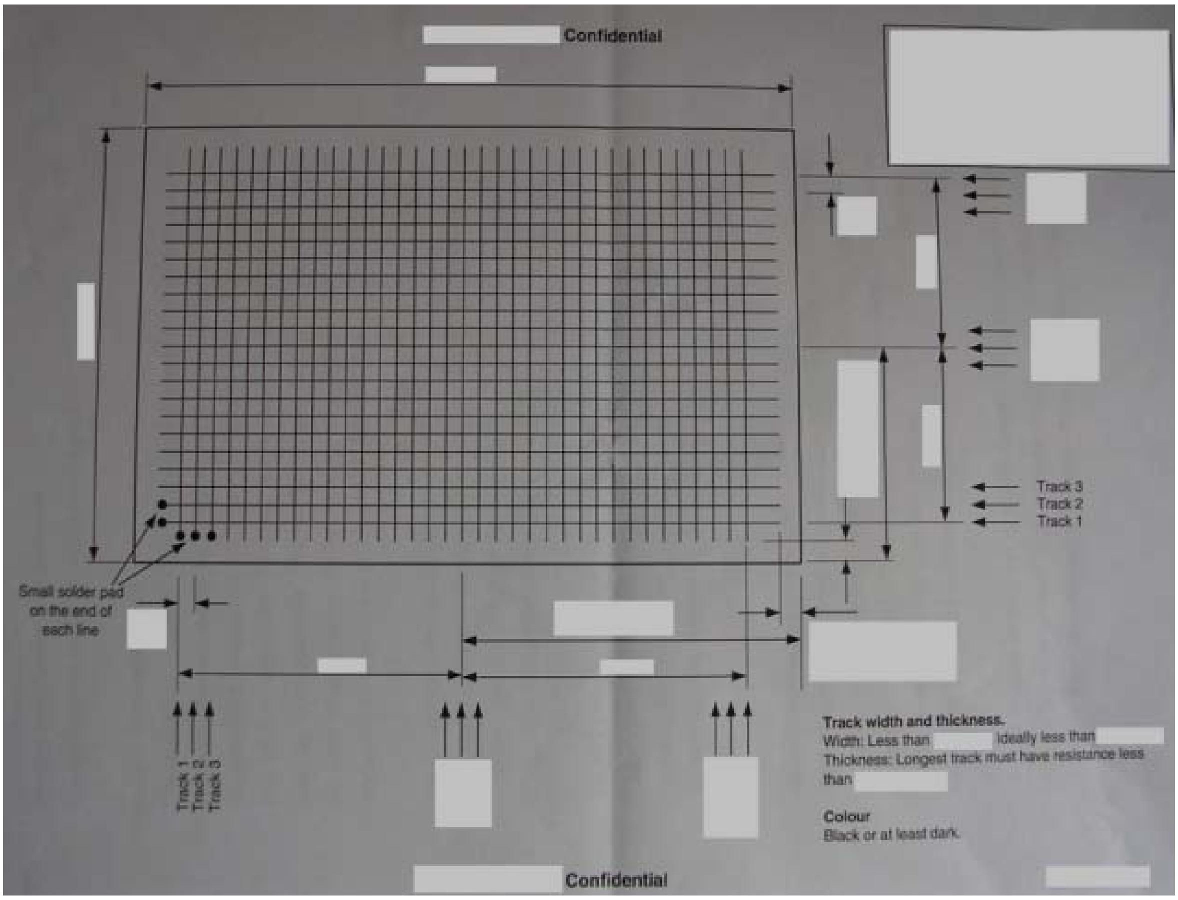

Figure 29. Digitiser design of a printed fine lines application.

When analysing the requirements and constraints of the design proposed and comparing them to the lab experiment results shown in section 4 of this report, it was assessed the impossibility of a successful execution of the project. Basically, the resistance and lines' width limitations of the conductive layers were too strict to allow a workable implementation.

A possible solution could be to increased the concentration of silver in the screen ink, in order to decrease the value of the resistances. However, this choice will directly affect to the final product's price by making it much costly. Moreover, the printing process will be especially affected in terms of the rheology and flow process, and this fact will imply poor performance of the application due to inconsistencies in the conductive printed layers.

6. FINAL CONCLUSIONS

In this report the screen printing method has been introduced and assessed as a possible choice to manufacture electronics. Therefore, it possesses several good conditions to have a niche market such as the low cost of the equipment and the maintenance involved, the speed of production, the versatility of being able to print devices very extended in the current market like thin batteries, flexible displays, RFIDs components, etc. Moreover, it produces environmental-friendly devices fulfilling the environment regulations. Once this technology is mature, it can be a possible successor for silicon chips in devices where rigidity is a key issue.

The intentions in this report have been focused in the obtaining of optimal fine printed lines. Clearly speaking, when producing a fine line (printed line 1, in this experiment) certain requirements should be fulfilled like a good average height for low resistance, a minimised width and smooth surface to avoid the existence of pinholes for good performance when designing multiplayer devices such as OLED applications. Therefore, a very good solution is to choose stainless steel mesh material due to the good effects regarding to the average height. Moreover the stainless steel samples are characterised for producing smaller widths than the polyester ones, and a smoother surface. The selection of the printing speed implies a trade-off between the width and the height of the printed line, that is to say, high speed produces greater width and height than the low speed, which is good for the resistance but increases the final size. In the case of low printing speed, it behaves inversely to the high speed. And finally, the screen ink silver concentration offers good qualities where the bigger the concentration, the lower resistance and the greater the final size and price.

So, the selection of the screen printing parameters is application dependant and it is a factor to be taken into account before stepping ahead in the design. Thus, the final performance and price will be directly related to the solution selected.

7. REFERENCES

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8. **http://microlab.berkeley.edu/labmanual/chap8/8.13.html**
   It provides a white light interferometer manual for a WYKO system.

9. **http://microlab.berkeley.edu/ee143/Four-Point_Probe/**
   It provides a description of a four point probe composition and operation procedure.

10. Chapter 5: Screen Printing.

It provides general information about the screen printing process and its components. This chapter belongs to the module "Printing technologies" taught by the Department of Printing and Coating from the University of Wales Swansea.

11. http://www.metricstech.com/ics/ics.shtml.

It provides a general description of the ICS unit for the resistance measurements.

8. LIST OF FIGURES

9. LIST OF TABLES